# Testing of Power Transformers

## Routine tests, Type tests and Special tests

ABB

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under participation of

**Åke Carlson**

**Jitka Fuhr**

**Gottfried Schemel**

**Franz Wegscheider**

1st Edition
published by

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# Preface

Remember school days? Nothing caused more excitement than the teachers' announcement of a test. Because a test confirms what you know, if you can apply in real life what you have learned in a classroom, under strict, rigorous and controlled conditions. It is a chance to demonstrate excellence.
Testing of power transformers seems like a similar experience; and therefore ABB undertook to write this book.

Transformer testing has developed considerably over the past years. It evolved from the simple go-no-go verdict into a sophisticated segment within transformer manufacturing. In this book we have laid down important aspects on transformer testing in order to enhance the understanding of the testing procedures and its outcome.

The book represents the collective wisdom of over 100 years of testing power transformers. It has been written for transformer designers, test field engineers, inspectors, consultants, academics and those involved in product quality.

ABB believes that the knowledge contained in this book will serve to ensure that you receive the best power transformer possible. The more knowledgeable you are, the better the decisions you will take.

Zürich, October 2003

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*Explanation to the vocabulary*

*The authors vocabulary in the test book is based on IEC Standards. There are no really important differences between the vocabulary applied in IEC and IEEE (ANSI) Standards. The only exception is the use of the words „earth"/"earthed" (according to IEC) and „ground"/"grounded" (according to IEEE).*

# Testing of Power Transformers

## 1. Introduction

# 1. Introduction

## 1.1 Why transformer testing?

Tests serve as an indication of the extent to which a transformer is able to comply with a customer's specified requirements; for example:

- Loading capability
- Dielectric withstand
- Further operating characteristics

Tests are also part of a manufacturer's internal quality assurance program. A manufacturer's own criteria have to be fulfilled in addition to requirements specified by customers and applicable standards.

Differing requirements are generally combined and published in national and international standards. The primary Standards Organizations are IEC and ANSI. These standards are often used directly to develop national standards. IEC is the abbreviation for International Electro-technical Commission and ANSI stands for American National Standard Institute, Inc.

In the electric area, ANSI has to a great extent delegated the writing and publication of standards to IEEE, the Institute of electric and Electronics Engineers, Inc.

The IEC and IEEE Standards specify the respective tests that verify compliance with the above requirements; e.g.:

Temperature rise tests to verify loading capability, see section 11

Dielectric tests to demonstrate the integrity of the transformer when subjected to dielectric stresses and possible over-voltages during normal operation, see section 2.

No-load and load loss measurements, short-circuit impedance measurements, etc. to verify other operating characteristics.

## 1.2 Types of tests

The IEC 60076-1 [1] and IEEE Std C57.12.00 [50] Standards distinguish between the following types of tests:

- Routine tests
- Type- or design[1] tests
- Special- or other[1] tests

### Routine tests

*Routine tests* are tests required for each individual transformer.

Typical examples:
Resistance measurements, voltage ratio, loss measurements, etc.

### Type- or design tests

*Type or design*[1] *tests* are conducted on a transformer which is representative[2] of other transformers, to demonstrate that these transformers comply with specified requirements not covered by routine tests.

Typical example:
Temperature rise test.

### Special- or other tests

*Special- or other*[1] *tests* are tests other than type- or routine tests agreed to by the manufacturer and the purchaser.

Typical example:
Measurement of zero-sequence impedance, sound level measurement, etc.

[1] *Term used in the IEEE Standards [50], [51]*

[2] *"Representative" means identical in rating and construction, but transformers with minor deviations in rating and other characteristics may also be considered to be representative [1].*

**Note:**

Depending on the respective standard and the maximum system voltage, certain dielectric tests, such as lightning impulse tests, for example, may either be routine tests, type tests or special tests, (see section 2, table 1 and 2). The same is true for switching impulse tests.

## 1.3 Test sequence

As the Standards do not lay down the complete test sequence in an obligatory basis, it is often the source of long discussions between customer and manufacturer.

On the other hand the test sequence for dielectric tests is generally fixed in IEC and IEEE Standards.

Following all existing standard regulations and recommendations concerning this matter followed by recommendations of the authors, see section 1.3.3.

### 1.3.1 IEC Standards

IEC 60076-3 (2000) [3], clause 7.3

"The dielectric tests shall, where applicable and not otherwise agreed upon, be performed in the sequence as given below:

- Switching impulse test
- Lightning impulse test (line terminals)
- Lightning impulse test (neutral terminal)
- Separate source AC withstand test (Applied voltage test)
- Short-duration induced AC withstand voltage test including partial discharge measurement
- Long-duration induced AC voltage test including partial discharge measurement"

This test sequence is in principle obligatory; but allows other agreements between customer and manufacturer.

IEC 60076-1 (2000) [1], clause 10.5

"In deciding the place of the no-load test in the complete test sequence, it should be borne in mind that no-load measurements performed before impulse tests and/or temperature rise tests are, in general, representative of the average loss level over long time in service. Measurements after other tests sometimes show higher values caused by spitting between laminate edges during impulse test, etc. Such measurements may be less representative of losses in service".

This test sequence is a recommendation and not obligatory.

### 1.3.2 IEEE Standards

IEEE Std C57.12.90 [51], clause 4.3

"To minimize potential damage to the transformer during testing, the resistance, polarity, phase relation, ratio, no-load loss and excitation current, impedance, and load loss test (and temperature-rise tests, when applicable) should precede dielectric tests. Using this sequence, the beginning tests involve voltages and currents, which are usually reduced as compared to rated values, thus tending to minimize damaging effects to the transformer."

Also this test sequence is recommendation and not obligatory.

IEEE Std C57.12.90 [51], clause 10.1.5.1

"Lightning impulse voltage tests, when required, shall precede the low-frequency tests. Switching impulse voltage tests, when required, shall also precede the low-frequency tests.

For class II power transformers, the final dielectric test to be performed shall be the induced voltage test."

This test sequence is obligatory.

### 1.3.3 Recommendation of the authors

Taking into account all IEC- and IEEE regulations and recommendations and based on their own experience the authors propose the following test sequence:

- Ratio, polarity and phase displacement
- Resistance measurement
- No-load test (followed, if specified, by the sound level test)
- Load loss and impedance
- Zero-sequence impedance test (if specified)
- Dielectric tests:
    - Switching impulse (when required)
    - Lightning impulse test (when required)
    - Separate source AC voltage test
    - Induced voltage test including partial discharge test.

The test sequence of the tests preceding the dielectric test can be slightly changed due to test field loading or other operational reasons.

## 1.4 Remarks concerning this test book

This test book has an initial chapter covering dielectric integrity in general (section 2), since verification of dielectric integrity is the result of different types of successful dielectric tests. The first chapter is then followed by descriptions of each individual test.

The individual tests and measurements are covered in greater detail in the following sections (sections 3 to 18):

- Measurement of winding resistance (R), section 3.
- Measurement of voltage ratio and vector group (phase displacement) (R), section 4.
- Measurement of impedances and load losses (R), section 5.
- Measurement of no-load loss and no-load current (R), section 6.
- Separate source AC withstand voltage test (R), section 7.
- Induced voltage test (R alternatively also S), section 8.
- Partial discharge test (R alternatively also S), section 9.
- Impulse test (R and T), section 10.
- Temperature rise test (T), section 11.

- Measurement of zero-sequence impedances (S), section 12.
- Short circuit withstand test (S), section 13.
- Sound level measurement (S), section 14.
- Test on on-load tap-changers and dielectric tests on auxiliary equipment (R), section 15.
- Measurements of the harmonics of the no-load current (S), section 16.
- Measurement of insulation resistance (S), section 17.
- Measurement of the dissipation factor (tan $\delta$) of the insulation capacitances or insulation power-factor tests (S), section 18.

**Note:**

R = Routine test

T = Type test

S = Special test

The individual test items may be interwoven and carried out as part of a combined average to verify certain characteristics, such as resistance measurement.

Several aspects have been considered regarding the tests and test procedures, such as:

- Purpose of the test and what is to be achieved by a specific test.
- Means of generating the supply voltage and current for the test.
- Means to measure or indicate the test object response.
- Means to verify the integrity of the test object.
- Means to verify presence or absence of damage caused by a specific test.

Symbols and abbreviations in this test book follow present IEC Standards where applicable.

# Testing of Power Transformers

## 2. Dielectric integrity and its verification

# 2. Dielectric integrity and its verification

Dielectric tests are intended to verify transformer integrity in the event of voltage stresses which can appear during normal as well as abnormal operation.

Normal operation is defined as long time exposure to voltages close to rated voltage at the transformer terminals, together with possible transient over-voltages.

In general, over-voltages are split into three categories:

- Over-voltages in the power frequency range with a duration in the order of seconds.
- Switching over-voltages with a duration in the order of a fraction of a second.
- Lightning over-voltages with a duration in the order of microseconds.

The different groups of over-voltages have also been considered in a test code, which may identify one or several tests, to be conducted either as individual or combined tests. The actual test code for a particular object depends primarily on the size and rated voltages of the object, as well as the standard specified for the transformer.

## 2.1 References / Standards

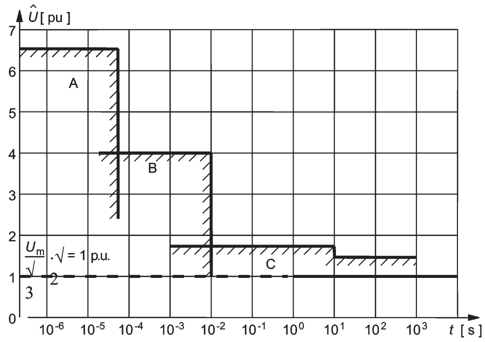
- IEC 60076-3 (2000): Power transformers – Part 3 : "Insulation levels, dielectric tests and external clearances in air" [3].
- IEEE C57.12.90-1999: IEEE Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers, clause 10: "Dielectric tests" [51].
- IEEE C57.12.00-2000: IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers [50].

## 2.2 General

Test voltages are primarily sinusoidal AC voltages, but they also include transient impulse voltage. DC voltages may be used when valve transformers (e.g. HVDC transformers) are tested, but such tests are outside the scope of this test book.

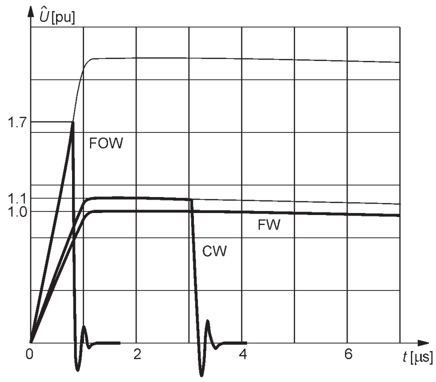
The present test program has its roots in a test code based on short time AC-tests at voltages considerably higher than normal operating voltages. Later on it was found that additional voltage shapes, i.e. transient voltages, could better describe the stresses during abnormal conditions, such as lightning and switching operations.

Originally the dielectric test was like a go/no-go test, where the test object either passed the test or it broke down electrically. Later on, more sophisticated diagnostic tools were introduced and today the measurement of partial discharges has become an indispensable tool.




A = lightning over-voltage
B = switching over-voltage
C = temporary over-voltage

***Figure 2.1:*** *Over-voltages in high voltage networks*




FW = full wave
CW = in tail chopped wave
FOW = in front chopped wave

***Figure 2.2:*** *Lightning impulse wave shapes*

## 2.3 Voltages appearing during operation

In addition to its normal operating voltage, a voltage which is close to rated voltage, a transformer will be subjected to different types of over-voltages. Depending on the duration of the over-voltage they are generally called:

- Lightning over-voltage
- Switching over-voltage
- Temporary over-voltage

Magnitudes and duration for each category are shown in figure 2.1.

### 2.3.1 Lightning over-voltages

The amplitude of a lightning over-voltage caused by atmospheric discharges is a function of the lightning current and the impulse impedance at the strike location. Waves propagate along the line starting at the location of the voltage strike. For an observer along the line, the wave is uni-polar and it increases to a peak value within a few microseconds (wave front) and decays back to zero within about a hundred microseconds.

As they propagate, the traveling waves become deformed and dampened by line impedance and corona discharge. Protection equipment such as surge arresters and spark gaps, either individually or in combination, prevent extreme surges from entering the object to be protected, e.g. a transformer. The insertion of arresters or spark gaps and the protection provided may in turn introduce a steep voltage breakdown, which can be seen as a chopped lightning impulse at the transformer terminals.

### 2.3.2 Switching over-voltages

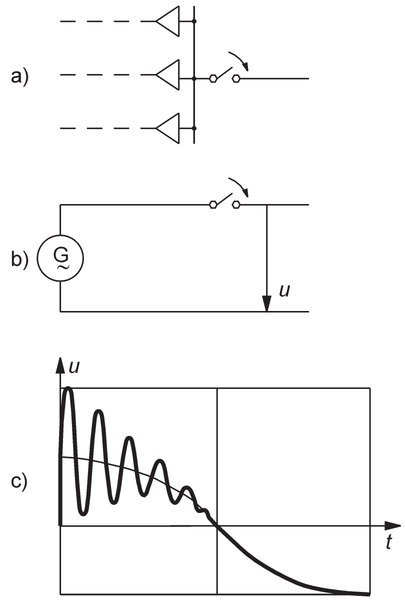
Switching operations in high-voltage networks cause transient phenomena, which may lead to over-voltages. Figure 2.3 shows an example of a switching impulse over-voltage when switching in an overhead line

The shape and duration of switching impulse over-voltages vary, depending on the switching operation and the configuration of the network.

### 2.3.3 Temporary over-voltages

Temporary operating and non-operating over-voltages are caused by the following:

- load rejection:
  over-voltage of 1,1 to 1,4 pu, several seconds
- single-phase short-circuit:
  over-voltage of 1,2 to 1,73 pu depending on neutral point configuration
- Ferro resonance (saw-tooth oscillations)
- Ferranti-effect
- other resonance oscillations

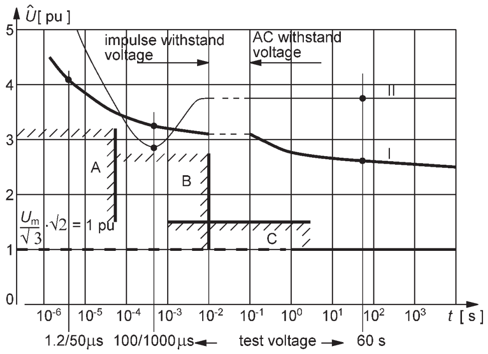



a) = configuration of network
b) = equivalent diagram
c) = oscillogram of switching impulse voltage

***Figure 2.3:*** *Switching impulse over voltage when connecting an overhead line*

For example:

| Switching operation | Switching over-voltage |
|---|---|
| Switching in a HV switchgear | Steep front |
| Switching off unloaded transformers | Heavily damped duration 1000 to 2000 µs |
| Switching unloaded HV overhead lines | Lightly damped duration 100 to 1000 µs |




A = lightning impulse over-voltage
B = switching impulse over-voltage
C = temporary over-voltage
Diagram I = oil insulation
Diagram II = air insulation

***Figure 2.4:*** *Basic representation of withstand voltage*

## 2.4 Verifying transformer major insulation electric strength

The basic relationship of the withstand voltage of conductor insulation to earth as a function of over-voltage duration can be seen in figure 2.4.

Curve I represents the fundamental behavior of the major insulation (to earth) for transformers. The electric strength and therefore the life decrease with the duration of AC voltage stresses. The actual life is, of course, also dependent on other factors such as, insulation construction, oil purity, temperature, partial discharge, etc. A test is specified for each duration area A, B, and C:

Area A
verifying the lightning impulse withstand voltage 1,2 / 50 µs

Area B
verifying the switching impulse withstand voltage ≥100 / ≥1000 µs

Area C
verifying the AC test withstand voltage, 60 s (see sections 7 and 8)

The three test voltages are shown in curve I of figure 2.4. The magnitude of the withstand voltages (test voltages) is dependent on the highest voltage for equipment $U_m$ and is defined in IEC and IEEE .

As a comparison, curve II in figure 2.4 shows the withstand voltage characteristic of air insulation clearances in networks where $U_m \geq 245$ kV. It is worth noting the significant decrease in withstand voltage in the area of switching over-voltages and the subsequent increased stress at rated frequency.
The switching impulse test is required here in every case whereas an additional AC voltage test is not necessary.

## 2.5 Test voltages

Present test codes specify alternating test voltages as well as transitory impulse voltages.

### 2.5.1 Alternating voltages

Alternating test voltage may either consist of a voltage electrically energizing a circuit, which in the context of the Standards is called a *Separate source test* voltage, or a voltage across two terminals of a winding, needed to conduct a test called an *Induced voltage test.*

Traditionally the duration of the alternating test voltage has been one minute, which is the so-called one-minute test at low frequency (a frequency close to the normal power frequency). For voltages considerably above rated value during an induced voltage test, the core will saturate unless frequency is increased in proportion to the test voltage. Tests at increased frequency generally lead to a reduction in test duration in proportion to the selected frequency. This is based on the philosophy that permissible stresses not only depend on the duration of the test but also on the number of times voltage is applied.

For large high-voltage transformers, the short-time induced voltage test has often been replaced nowadays by a combination of a long-time induced voltage test with measurements of partial discharges, together with a switching impulse test. The switching impulse is then considered decisive for insulation integrity, while the level of partial discharges is a qualitative measure of the insulation.

### 2.5.2 Impulse voltages

Basically there are two types of transient impulse voltages; one that is of short duration and is called *Lightning impulse* and one that is of long duration and is called *Switching impulse.* A steep voltage rise and a relatively fast decay characterize the lightning impulse, which has a duration in the range of about a hundred microseconds. On the other hand, the switching impulse has a front time about one hundred times longer than the lightning impulse. The total duration of the switching impulse is generally ten to twenty times longer than the lightning impulse.

For a lightning impulse, the length of the winding conductor is long compared to the propagation speed of the impulse along the conductor. The wave characteristics of the winding have to be considered. For a switching impulse the rate of change in voltage is low enough to permit a model where wave characteristics can be ignored and transformer behavior is similar to that under normal AC voltage and power frequency conditions.

The polarity of the impulse is generally selected to be negative in order to reduce the risk of random voltage breakdown on the air side of the transformer bushing. In a highly divergent dielectric field, like the one that occurs around the air terminal of a bushing, there is a great risk of random voltage breakdown in the air if an impulse of positive polarity is applied.

## 2.6 Test requirements

### 2.6.1 IEC-philosophy

IEC 600776-3 [3] defines the following dielectric tests, which shall be performed in the sequence given below:

- **Switching impulse test (SI) for the line terminals** (see section 10*)
- **Lightning impulse test (LI) for the line terminals** (see section 10*)
- **Lightning impulse test (LI) for the neutral** (see section 10*)
- **Separate source AC withstand voltage test (applied potential test)** (see section 7*)
- **Short duration induced AC withstand test (ACSD)** (see section 8*)
- **Long duration induced AC voltage test (ACLD)** (see section 8* and 9*)

  This test is not a design-proving test, but a quality control test. It verifies partial discharge-free operation of the transformer under operating conditions.

The requirements and tests for the different categories of windings are specified in the above-referenced IEC Standard (see table 1).

** The reference number given is not related to the referenced IEC Standard, but to the sections of this booklet.*

# 2. Dielectric integrity and its verification

Table 1: Requirements and tests for different categories of windings, adapted from IEC 60076-3 [3]

| Winding category | Highest voltage for equipment $U_m$ [kV] | Tests: LI | SI | ACLD | ACSD | | AC |
|---|---|---|---|---|---|---|---|
| | | | | | Single-phase phase-to earth test | Three-phase phase-to phase test | Separate source test |
| **Uniform insulation** | $\leq 72{,}5$ | T* | NA | NA* | NA | **R** | **R** |
| | $72{,}5 < U_m < 170$ | **R** | NA | S | NA | **R** | **R** |
| | $170 < U_m < 300$ | **R** | **R**** | **R** | NA | S** | **R** |
| | $\geq 300$ | **R** | **R** | **R** | NA | S | **R** |
| **Non-uniform insulation** | $72{,}5 < U_m < 170$ | **R** | NA | S | **R** | **R** | **R** |
| | $170 < U_m < 300$ | **R** | **R**** | **R** | S** | S** | **R** |
| | $\geq 300$ | **R** | **R** | **R** | S | S | **R** |

Symbols: **R** Routine test T Type test
S Special test NA not applicable

### 2.6.2 IEEE / ANSI philosophy [51]

Transformers shall be designed to provide coordinated low frequency and impulse insulation levels on line terminals and low frequency insulation levels on neutral terminals. The primary identity of a set of coordinated levels shall be its basic lighting impulse insulation level (BIL).

The IEEE Standards divide power transformers into two different classes due to system voltage and transformer type influence insulation levels and test procedures:

- Class I: power transformers with high voltage windings rated 69 kV and below
- Class II: power transformers with high voltage windings rated from 115 kV through 765 kV

The following dielectric tests are defined:

- **Switching impulse test** (see section 10*)
- **Lightning impulse test on line terminals and on transformer neutral** (see section 10*)
- **Applied voltage test** (see section 7*)
- **Induced voltage test** (see section 8*)
- **PD measurement** (see section 9*)
- **Insulation power-factor test** (see section 18*)
- **Insulation resistance test** (Megger test) (see section 17*)

** The reference number given is not related to the referenced IEEE Standard, but to the section of this booklet.*

**Notes:**

* In some countries, for transformers where $U_m < 72{,}5$ kV, LI tests are required as routine tests, and ACLD tests are required as routine or type tests.

** If the ACSD test is specified, the SI test is not required. This should be clearly stated in the enquiry document.

Table 2: Requirements and tests for different categories of windings, adapted from IEEE C57.12.00 [50] and IEEE C57.12.90 [51]

| Winding category | Highest system voltage [kV] rms | Tests | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Lightning impulse full wave test | Lightning impulse chopped wave | Lightning impulse front-of-wave | Switching impulse phase-to ground | Long duration AC with PD-test | Short duration AC Three-phase phase-to-phase test | Short duration AC Single-phase phase-to-ground test | Applied voltage test |
| **Class I** Non-graded isulation | < 115 | D/O | D/O | O | O | NA | **R** | NA | **R** |
| **Class I** Graded isulation | | D/O | D/O | O | O | NA | **R** | **R** | **R** |
| **Class II** | ≥ 115 < 345 | **R** | **R** | O | O | **R** | NA | NA | **R** |
| | 345 and above | **R** | **R** | O | **R** | **R** | NA | NA | **R** |

**Symbols:**

| | |
|---|---|
| **R** | Routine test |
| D | Design test |
| O | Other test |
| NA | Not applicable |

IEEE [51] defines the following test sequence:

Lightning impulse test tests, when required, shall precede the low-frequency tests (AC voltage tests). Switching impulse tests, when required, shall also precede the low-voltage tests.
For Class II power transformers, the final dielectric tests to be performed shall be the induced voltage test.

### 2.6.3 Repeated dielectric tests [3]

For transformers that have already been in service and have been refurbished or serviced, dielectric tests shall be repeated at test levels reduced to 80% of the original value. Exceptions of this rule are long duration AC induced tests (ACLD) – according IEC – which shall always be repeated at the 100% test level.

Repetition of tests required to prove that new transformers having been factory tested, continue to meet the dielectric requirements is always performed at 100 % of test level.

## 2.7 Examples for dielectric routine tests

For examples of dielectric routine tests, see appendix A 2.

# Appendix A 2

# Dielectric integrity and its verification

## A 2.1 Examples

### Example 1

For a three-phase transformer according to IEC [1], [3]:

Rated voltage: 65 / 15 kV; both uniformly insulated;
YNyn connected,

HV $U_m$ = 72,5 kV; LV $U_m$ = 17,5 kV;

Insulation levels:

- HV and HV-neutral: LI / AC 325 / 140 kV
- LV and LV-neutral: LI / AC 95 / 38 kV

Routine tests:

- Applied voltage test: (see section 7)
  - HV and HV-neutral: 140 kV
  - LV and LV-neutral: 38 kV
- Induced voltage test: (see section 8)

  Three-phase (phase-to-phase) test

  Three-phase LV-supply with:
  32 kV (= 2,15·15) to obtain 140 kV phase-to-phase;
  corresponding 2,15 times turn-to-turn voltage.
- LI test only as type test.

### Example 2

For a three-phase transformer according to IEC [1], [3]:

Rated voltage: 240 / 60 / 24 kV; YNyn connected,

- HV line $U_m$ = 245 kV
- HV neutral $U_m$ = 72,5 kV
- MV line and neutral $U_m$ = 72,5 kV uniform insulation
- LV line $U_m$ = 24 kV d-connected

Insulation levels:

- HV line terminals: SI / LI 850 / 1050 kV
- HV neutral: LI / AC 325 / 140 kV
- MV line terminals: LI / AC 325 / 140 kV
- MV neutral: LI / AC 325 / 140 kV
- LV line terminals: LI / AC 125 / 50 kV

Routine tests:

- SI test with 850 kV (see section 10)
- LI test with 1050 kV (see section 10)
- LI test with 325 kV (see section 10)
- Applied voltage test (see section 7)
  - HV and HV neutral with 140 kV
  - MV with 140 kV
  - LV with 50 kV
- Induced ACLD voltage test (see section 8) with PD measurement (see section 9)
  - Three-phase LV-supply to obtain $U_P = 1{,}7\ U_m / \sqrt{3} =$ 240 kV to earth or 415 kV phase-to-phase; corresponding to about 1,73 times turn-to-turn voltage.
    PD measurement at 1,5 $U_m / \sqrt{3}$ = 212 kV to ground during 30 minutes.
    PD measurement should also be performed at 1,1 $U_m$

### Example 3

For a single-phase auto transformer according to [1], [3]:

Rated voltage: 400 / 150 / 24 kV;

- HV line $U_m$ = 420 kV, auto connected
- MV line $U_m$ = 170 kV
- HV and LV neutral $U_m$ = 17,5 kV
- LV line $U_m$ = 24 kV d-connected

Insulation levels:

- HV: SI 1050 / LI 1300 - AC 38 kV
- MV: LI 650 - AC 38 kV
- LV: LI 125 / AC 50 kV

Routine tests:

- SI test with 1050 kV (see section 10)
- LI test with 1300 kV (see section 10)
- Applied voltage test (see section 7)
  - HV, MV and common neutral with 38 kV
  - LV with 50 kV
- Induced ACLD voltage test (see section 8) with PD measurement (see section 9).
  - Single-phase LV-supply to obtain
  - $U_P = 1{,}7\ U_m / \sqrt{3} =$ 412 kV; corresponding to 1,7 times turn-to-turn voltage.
    PD measurement at 1,5 $U_m / \sqrt{3}$ = 363 kV to earth during 60 minutes.
    PD measurement should also be performed at 1,1 $U_m$.

### Example 4

For a three-phase transformer according to IEEE, Class I; [50], [51]:

Rated voltage: 65 / 15 kV, YNyn connected, non-graded insulation.

Insulation levels:

HV BIL = 350 kV; LV BIL = 110 kV;

- Low frequency insulation level: HV: 140 kV
- Low frequency insulation level: LV: 34 kV

Routine tests:

- Applied voltage test, see section 7
  - HV and HV-neutral: 140 kV
  - LV and LV-neutral: 34 kV
- Induced voltage test (phase-to-phase); (see section 8)
  - Three-phase LV supply with 26,5 kV (= 115·15/65) to obtain 115 kV between the phases according to column 2 of table 7 of [50]
- Lighting impulse test only as design or "other" test.

### Example 5

For a three-phase transformer according to IEEE, Class II; [50], [51]:

Rated voltage 130 / 15 kV; YNyn connected, graded insulation.

Insulation levels:

- HV: Nominal system voltage: 138 kV, BIL 550
- HV: Neutral: nominal system voltage: 25 kV
- LV: Nominal system voltage: 15 kV, BIL 110 kV

Routine tests:

- Impulse test with 550 kV, see section 10
- Applied voltage test (see section 7)
  - HV and HV-neutral: 34 kV
  - LV and LV-neutral: 34 kV
- Induced voltage test with PD measurement, see section 8 and 9

  Long duration phase-to-phase test with symmetrical three-phase LV supply.:

  Enhancement level of 145 kV (phase to earth) and an "one-hour-level" of 125 kV (phase to earth), according to column 6 and 5 of table 6 of [50].

# Testing of Power Transformers

## 3. Measurement of winding resistance

# 3. Measurement of winding resistance

## 3.1 References / Standards

- IIEC 60076-1 (2000), clause 10.2
  "Measurement of winding resistance" [1]
- IEEE Std C57.12.90-1999, clause 5:
  "Resistance Measurements" [51]

  **Note:**

  Measurement of winding resistance is a **routine test** according to the IEC Standard [1] and the IEEE Standard [50].

## 3.2 Purpose of the test

Winding resistance serves a number of important functions like:

- Providing a base value to establish load loss
- Providing a basis for an indirect method to establish winding temperature and temperature rise within a winding
- Inclusion as part of an in-house quality assurance program, like verifying electric continuity within a winding.

## 3.3 General

Winding resistance is always defined as the DC-resistance (active or actual resistance) of a winding in Ohms [Ω].

**Temperature dependence**

It should be noted that the resistivity of the conductor material in a winding – copper or aluminium – is strongly dependent on temperature. For temperatures within the normal operating range of a transformer the following relationship between resistance and temperature is sufficiently accurate:

$$R_2 = R_1 \frac{C + \Theta_2}{C + \Theta_1}$$

where:

$R_1$ = resistance at temperature $\Theta_1$
$R_2$ = resistance at temperature $\Theta_2$
$\Theta$ = temperature in °C
$C$ = constant which is a function of material type

IEC [1] specifies:

$C$ = 235 for copper
$C$ = 225 for aluminium

IEEE Standard [51] specifies a somewhat different value for copper: $C = 234{,}5$

This is why any value of resistance given without reference to the corresponding temperature is meaningless.

It should also be mentioned that resistance measurement is an indirect method of establishing winding temperature. The winding temperature at an arbitrary temperature can therefore be established by repeating resistance measurement.

(Winding temperature should be measured according to the Standards referenced in clause 3.1).

### Winding characteristics at resistance measurement

When measuring its resistance, a winding presents not only a resistance, but also a large inductance.

When a voltage is applied across the two terminals of a winding, the relationship between voltage and currents can be described as follows:

$$u = R \cdot i + C\frac{\partial \Phi}{\partial t} \quad \text{alt} \quad u = R \cdot i + L\frac{\partial i}{\partial t}$$

where:

$u$ = applied voltage, instantaneous value

$i$ = supplied current, instantaneous value

$\frac{\partial \Phi}{\partial t}$ = time derivative of winding flux induced by the current

$C$ = constant

$L$ = inductance, note that $L$ is current-dependent

$\frac{\partial i}{\partial t}$ = current derivative

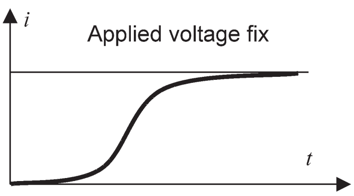



***Figure 3.1:*** *Current-time characteristic applying a DC-voltage at a transformer winding*

Figure 3.1 shows the function $i(t)$ between current and time when a fix DC-voltage is applied to a transformer winding.

For a non-saturated transformer core, the inductance can be infinite in the first approximation. As long as the flux derivative term in the above equation produces a non-negligible result, there will be considerable error in the resistance measurement, where resistance is defined as applied voltage divided by delivered current.

For more details, see clauses A 3.1 and A 3.2.

### 3.4 Principle and methods for resistance measurement

There are basically two different methods for resistance measurement: namely, the so-called "voltmeter-ammeter method" and the bridge method.

#### 3.4.1 "Voltmeter-ammeter Method"

The measurement is carried out using DC current. Simultaneous readings of current and voltage are taken. The resistance is calculated from the readings in accordance with Ohm's Law. This measurement may be performed using conventional analog (rarely used nowadays) or digital meters; however, today digital devices such as Data Acquisition Systems (DAS) with direct resistance display are being used more and more.

**Measurement with voltmeter and ammeter**

The measuring circuit is shown in figure 3.2.

Resistance $R_X$ is calculated according to Ohm's Law:

$$R_X = \frac{U}{I}$$

The advantage of this method is the simplicity of the test-circuit. On the other hand, this method is rather inaccurate and requires simultaneous reading of the two instruments.

**Resistance measurement with Data Acquisitions Systems (DAS) or Power Analyzers** [202]

The same principal is also used by Data Acquisition Systems (DAS) and Power Analyzers.

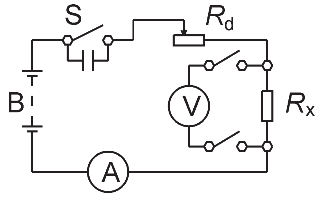
The two methods provide simultaneous and automatic records of currents and voltages, see figure 3.3.

#### 3.4.2 Resistance measurement using a Kelvin (Thomson) Bridge

This measurement is based on the comparison of two voltage drops: namely, the voltage drop across the unknown winding resistance $R_X$, compared to a voltage drop across a known resistance $R_N$ (standard resistor), figure 3.4.

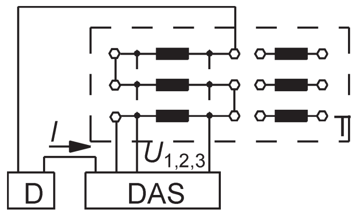
DC-current is made to flow through $R_X$ and $R_N$ and the corresponding voltage drops are measured and compared.

The bridge is balanced by varying the two resistors $R_{dec}$ and $R_V$, which have relatively high resistance values. A balanced condition is indicated when the galvanometer deflection is zero, at which time the following relationship holds:



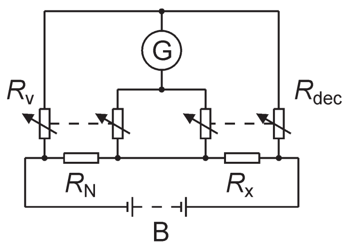

$R_X$ = unknown resistance (transformer under test)
$R_d$ = regulating resistor
S = circuit-breaker with protective gap
B = DC source

*Figure 3.2: Voltmeter - ammeter method measuring circuit*




D = DC source
DAS = Data Acquisition System
T = transformer with the unknown resistance

*Figure 3.3: Power Analyzer measuring circuit*




$R_X$ = unknown resistance (transformer under test)
$R_N$ = standard resistor
$R_{dec}$ = decade resistor
$R_V$ = variable resistor
G = galvanometer
B = DC source

*Figure 3.4: Kelvin (Thomson) Bridge method*

$$R_X = R_N \frac{R_{dec}}{R_V}$$

The influence of contact resistances and the connection cable resistances (even of the connection between $R_X$ and $R_N$) can be neglected.

Figure 3.9 in clause A 3.3 shows an actual test laboratory connecting circuit for measuring resistance using a Kelvin (Thomson) Bridge with external standard resistors.

The advantage of the bridge method is its high accuracy. On the other hand, the test circuit is more complicated; and the handling of the bridge requires some experience.

## 3.5 Measuring procedure

### 3.5.1 General

After switching on the DC voltage source, readings must not be taken until the current has reached a steady state. Switching phenomena cause induced voltages that influence the resistance value readings, see figure 3 in section 3.3 and clause A 3.2.

### 3.5.2 Voltmeter-ammeter method

Value of the DC-current used for measurement:

Maximum value:
10 % of the rated winding current, (IEEE Standard [51] permits 15 %).

Minimum value:
about 1,2 times the magnetizing current crest value.

For details and an explanation see clause A 3.2.

The following steps must be performed:

- The winding to be measured must be connected according to figure 3.2.
- The volt- and ammeter readings must be carried out simultaneously.
- The voltmeter leads must be independent of the current leads and must be connected as closely as possible to the terminals of the winding to be measured.
- To protect the voltmeter from damage due to off-scale deflections, the voltmeter should be disconnected from the circuit before switching the current on or off.

Measuring circuit for the “voltmeter-ammeter method” carried out using a Data acquisition systems e.g. power analyzer is shown in figure 3.3.

Requirements for the measuring equipment, see clause A 3.1.

### 3.5.3 Measurement using a Kelvin (Thomson) Bridge

The bridge must be connected to the transformer winding according to figure 3.4. Standard resistor $R_N$ and variable resistor $R_V$ must be selected so that the full range of the decade resistor is used. The measurement is performed by varying the decade resistor $R_{dec}$ and successively increasing the galvanometer sensitivity until zero deflection is observed on the instrument.

The unknown resistance is then:

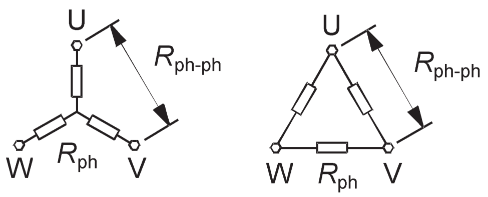
$$R_X = R_{dec} \frac{R_N}{R_V}$$

The ratio $R_N / R_V$ is usually ten, the numerical value of the unknown resistance can thus be directly read on the decades.

For measuring equipment requirements, see clause A 3.1.

## 3.6 Interpretation of the measured values

For three-phase transformers either the phase resistances $R_{ph}$ or the line-to-line resistances $R_{ph\text{-}ph}$ are measured, see figure 3.5.




star-connection $R_{ph\text{-}ph} = 2 \cdot R_{ph}$
delta-connection $R_{ph\text{-}ph} = {}^2/_3 \cdot R_{ph}$

***Figure 3.5:*** *Resistance measurement for star- or delta-connection*

## 3.7 Examples

For examples of the different resistance measuring methods, see clause A 3.4.

## 3.8 Uncertainty in resistance measurements

IEEE Standard [50] requires a test system accuracy ± 0,5 % for resistance measurements and ± 1°C for temperature measurements.

#### Voltmeter-ammeter method:

Using analog instruments the uncertainty is typically 0,5 % (accuracy class 0,2 for instruments and 0,1 for standard resistors used for current measurement).

For digital instruments a typical uncertainty is 0,15 % (0,025 for instruments, 0,1 for standard resistor).

#### Bridge method

The bridge method normally has an uncertainty of 0,1 %.

Because resistance is inevitably linked to a temperature, which can be measured practically with an uncertainty of ± 1°C (corresponding to ± 0,4 % in resistance), the total measuring uncertainty for winding resistance is between 0,5 - 0,9 %.

# Appendix A 3
# Measuring winding resistance

## A 3.1 General requirements on equipment

### DC source

To reduce the error from the current derivative it is important to supply the measuring circuit with a constant current source.

Traditionally a more or less constant current source was based on a voltage source with a large resistor in series. Such a current source was obtained by a high capacity accumulator with a series resistor.

Modern current sources are built on electronic circuits, which are capable of providing a predefined current within a wide voltage range.

### Circuit breaker

If the DC measuring current is switched off quickly, a thyristor equipped discharging circuit or a protective gap limits the self-inductance voltage created in the winding (inductive kick). It also reduces contact-wear on the circuit breaker.

### Adjustable series resistor

(specially when an accumulator is used as DC source)

This resistor is not only necessary to adjust the desired measuring current, but especially to reduce the time required for the current to reach its steady state value; it should be a non-inductive resistor made of a material with a small temperature dependence in series with the DC source see figure 3.2.

### Ammeter and voltmeter

Instead of conventional analog instruments, nowadays digital voltmeters and ammeters (Multi-meter) are commonly used. The standards allow – of course – the use of conventional instruments.

### Kelvin (Thomson) Bridge

Use of external reflecting galvanometers with a high sensitivity is recommended for balancing the bridge. It should be noted that the resistance of the potential leads should be lower than 0,01 Ω. In addition, the two leads should have about the same resistance values. The resistance of the connection lead between $R_X$ and $R_N$ should not exceed 20 to 50 times $R_X$. A regulating resistor $R_d$ should not be located in between $R_X$ and $R_N$, see figure 3.9

## A 3.2 Value of the DC-current of measurement

(see also section 3.5)

Maximum value:

To avoid an inadmissible winding temperature rise during the measurement, the DC-current should be limited to a maximum 10 % of the rated current of the corresponding winding.

Minimum value:

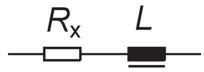
The lower limit of the DC-current is given by the following considerations:

The measuring circuit for all resistance measuring methods consists of a DC-source and a transformer winding fixed around an iron core as represented by the following equivalent circuit, see also section 3.3 and figure 3.6.

Winding inductance is strongly dependent on current and displays the following characteristic for transformers, see figure 3.7.

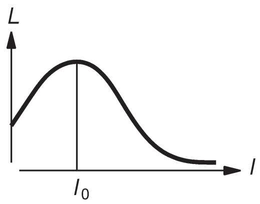
As the measuring circuit time-constant is given by the relation $L/R$, the current-time characteristic differs quite significantly when switching on the DC-source, depending on the measuring current value (magnetizing current), see figure 3.8.

Therefore, the DC measuring current should be at least 1,2 times higher than the crest value of the magnetizing current to be sure to saturate the iron core.



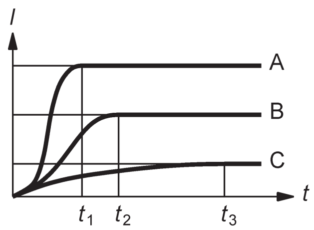

$R_X$ = unknown resistance of the winding (in the range 1 mΩ to 10Ω)
$L$ = no-load inductance of the winding (in the range 1 H to 100 H)

***Figure 3.6:*** *Equivalent circuit of a transformer winding*



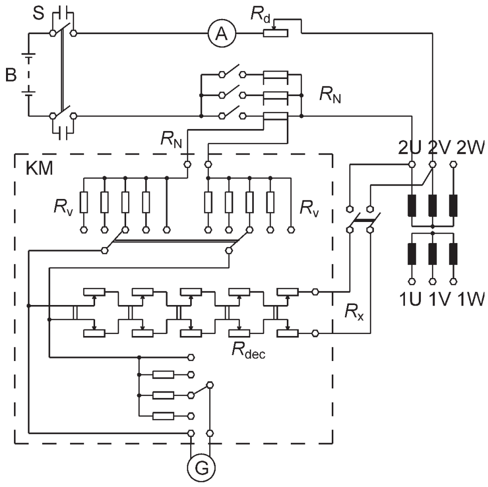

$L$ = inductance of the transformer winding
$I$ = current of the measurement, magnetizing current
$I_0$ = no-load current

***Figure 3.7:*** *Inductance of transformer winding as a function of the current*




A = iron core fully saturated
B = iron core less saturated
C = iron core not saturated
$t_{1,2,3}$ = time until current of measurement is stable

***Figure 3.8:*** *Time to steady state depends on the degree of saturation*




$R_X$ = unknown resistance (transformer under test)
$R_N$ = standard resistor
$R_{dec}$ = decade resistor
$R_V$ = variable resistor
$R_d$ = regulating resistor
G = galvanometer
B = DC source
S = circuit breaker with protective gap
KM = Kelvin (Thomson) Bridge

***Figure 3.9:*** *Kelvin (Thomson) Bridge measuring circuit*

| | | |
|---|---|---|
| HV: | 1U-1V | 685,60 mΩ |
| | 1V-1W | 685,40 mΩ |
| | 1W-1U | 685,90 mΩ |
| | Average: | 685,63 mΩ |
| LV: | 2U-2V | 1,182 mΩ |
| | 2V-2W | 1,182 mΩ |
| | 2W-2U | 1,180 mΩ |
| | Average: | 1,181 mΩ |

*Measuring uncertainty: < 0,1 %*
*(does not include measuring uncertainty of temperature measurement)*

| | $R_{dec}$ [ohm] | $R_x$ [ohm] |
|---|---|---|
| 1U-1V | 857,21 | 0,85721 |
| 1U-1W | 857,26 | 0,85726 |
| 1V-1W | 857,42 | 0,85642 |

*Measuring uncertainty about 0,1 %*
*(does not include measuring uncertainty of temperature measurement)*

## A 3.3 Kelvin (Thomson) measuring circuit

Figure 3.9 shows an actual connecting circuit in a test laboratory for resistance measurement using a Kelvin (Thomson) Bridge with external resistance standards.

## A 3.4 Examples

### A 3.4.1 Voltmeter-ammeter-method using a Data Acquisition System (power analyzer)

DC source: 30 A, 50 V;

Power analyzer: Type D6100 (LEM-Norma)

$\Theta_C$ = 24,5 °C

### A 3.4.2 Resistance measurement with a Kelvin (Thomson) Bridge

HV winding, $\Theta_C$ = 22,5 °C

$$R_X = R_{dec} \frac{R_N}{R_V}$$

$R_V$ = 100 Ω

$R_N$ = 0,1 Ω

# Testing of Power Transformers

## 4. Verification of voltage ratio and vector group or phase displacement

# 4. Measuring voltage ratio

## 4.1 References / Standards

- IEC 60076-1 (2000), clause 6: "Connection and voltage displacement symbols for three-phase transformers", clause 10.3: "Measurement of voltage ratio and check of phase displacement" [1]
- IEEE Std C57.12.90-1999, clause 6: "Polarity and phase relation test", clause 7: "Ratio tests" [51]

**Note:**

Measurement of voltage ratio and verification of the vector group or phase displacement is a **routine test** according to IEC Standard [1] and to IEEE Standard [50].

## 4.2 Purpose of measurement

Measuring the voltage ratio and the phase displacement are of interest primarily because of their bearing on the parallel operation of two or more transformers.

## 4.3 General

### 4.3.1 Vector group and phase displacement

The individual windings of polyphase transformers can be connected in star, delta, or zigzag depending on the application. The phase displacement between the windings is between 0° and 360° depending on the connection method. Parallel operation of transformers requires that the no-load ratio and the vector group is the same to avoid circulating currents.

### 4.3.2 IEC Standard [1]

Vector groups according to IEC 60076-1, see figures 4.1 and 4.2.

Vector groups and their characteristics are defined for three-phase transformers. The vector diagram of the high voltage winding is actually placed on a clock face so that the tip of vector I (1U) is at 12 o'clock. When the vector diagram for the low voltage winding is placed on top with the same phase orientation, the direction of vector I (2U) identifies the clock number of the vector group, see figures 4.3 and 5.4. For a zigzag connection the winding half closest to the terminals determines the terminal markings. If the winding half closest to the terminals is on limb V, the terminal is also called 2V.

For three-phase transformers the phase angle of the intermediate and low voltage winding is referenced to the high voltage winding for the vector group; e.g. YNyn0d5, see figure 4.4.

The externally accessible neutral is identified by the letter N or n; e.g. Dyn11, see figure 4.4.

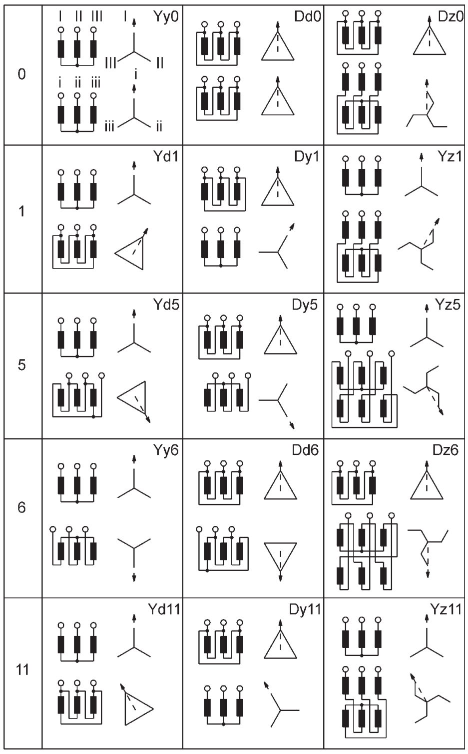



*Figure 4.1: Common connections IEC 60076-1 [1]*

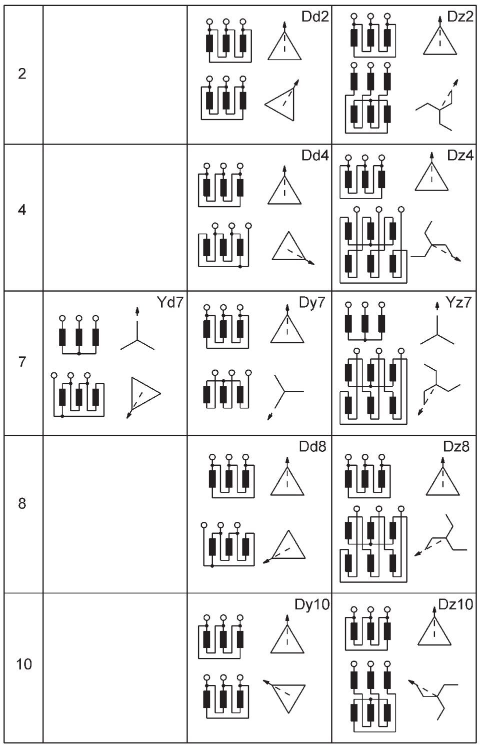



*Figure 4.2: Additional connections IEC 60076-1 [1]*

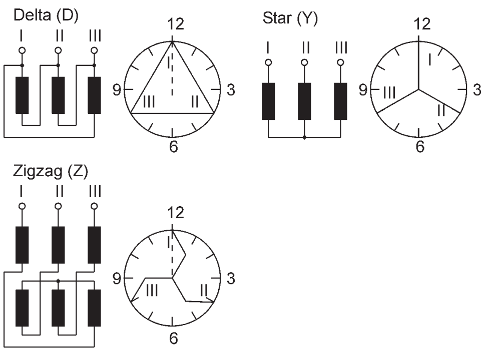



***Figure 4.3:*** *Illustration of clock-number notation IEC 60076-1 [1]*

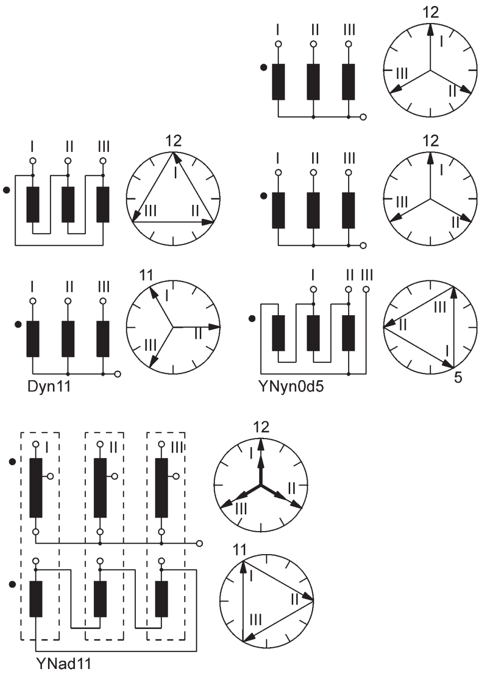



***Figure 4.4:*** *Examples of clock-number notation IEC 60076-1 [1]*

For special vector groups the designation is normally according to the phasor diagram: auto-transformer, see figure 4.4.

### 4.3.3 IEEE Standard [51]

The corresponding vector groups can be found in IEEE Standard C57.12.90; Figures 7 and 8 are essentially the same as the IEC vector groups. The designation of the terminals is $H_1$, $H_2$ and $H_3$ for the high voltage side and $X_1$, $X_2$ and $X_3$ for the low voltage side.

## 4.4 Measuring the voltage ratio

The voltage ratio can be determined by using either of two methods: by directly measuring the voltages with a voltmeter, or by using ratio bridges. For the first method the result is determined from two measured voltages – the primary and secondary voltage of the transformer under test. When a ratio bridge is used the error or the actual ratio value can be read directly.

The *maximum relative ratio error*, or the percentage deviation of the actual to declared ratio value, is defined in the Standards.

IEC 60076-1, clause 9 [1]:
Principal tapping for a specified first winding pair: the lesser of ± 0,5 % of the declared voltage ratio or 0,1 times the actual short-circuit impedance. Other taps on the first winding pair and other winding pairs must be agreed upon, and must not be lower than the smaller of the two values stated above.

IEEE Std C57.12.00, clause 9 [50]:
± 0,5 % of the rated voltage of the windings and their taps.

The term “voltage ratio” is defined as the theoretical voltage ratio (turns ratio):

$$r = \frac{N_p}{N_s} = \frac{E_p}{E_s}$$

where:

$r$ = voltage ratio
$E$ = open-circuit voltage
$N$ = number of turns
$p$ = primary
$s$ = secondary

The ratio error when using two voltmeters is:

$$r_{decl} = \frac{U_{pN}}{U_{sN}} \qquad r_{act} = \frac{U_p}{U_s}$$

$$f = \frac{r_{act} - r_{decl}}{r_{decl}} \cdot 100 \ (\%)$$

where:

$r_{decl}$ = declared ratio value
$r_{act}$ = actual ratio value
$U_{pN}$ = primary rated voltage
$U_{sN}$ = secondary rated voltage
$f$ = relative ratio error in %

When ratio bridges are used the ratio error can either be read directly or the actual ratio value is shown, in which case the error can be calculated as follows:

$$f = \frac{r_{act} - r_{decl}}{r_{decl}} \cdot 100 \ (\%)$$

To avoid measuring errors, care must be taken not to load the transformer under test excessively with voltmeters and voltage transformers when using the two voltmeter method. The method can provide adequate results for starting transformers and arc-furnace transformers. The measuring bridge can be applied for any transformer connection method and any rated voltage when intermediate voltage transformers are used.

The measurement principle is based on the compensation method and is similar to the one using test equipment for measuring transformers as per Schering-Alberti, except that the $RC$-circuit required to determine the phase-angle error is missing. The measuring uncertainty of this method is ± 0,1% and thus complies with Standards' specifications. The transformer under test is not loaded, or only very lightly loaded, when the bridge is balanced. A standard voltage supply between 100 – 250 V AC (at the rated frequency of the transformer under test), which is available almost anywhere, is normally all that is required for the measurement. When using the measuring bridge to determine the ratio, the phase displacement is checked at the same time.

## 4.5 Test circuit

### 4.5.1 Ratio measurement using two voltmeters

The principle circuit is the same for all transformer vector groups, see figure 4.5. The transformer is fed from the high voltage side to avoid dangerous voltage levels. Intermediate voltage transformers may be required in the circuit. The voltmeter on the low voltage side should have a high input resistance to keep the transformer loading to a minimum.

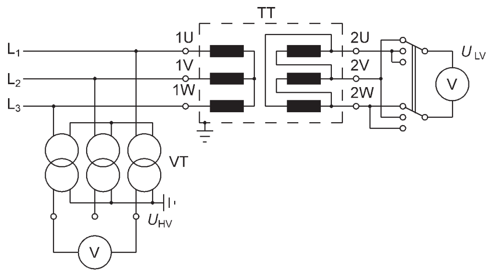



*Figure 4.5: Voltage ratio measurement using two voltmeters*

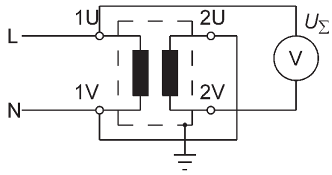



*Figure 4.6:* *Connection for additive polarity test*

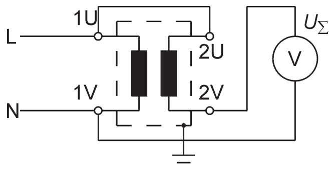



*Figure 4.7:* *Connection for subtractive polarity test*

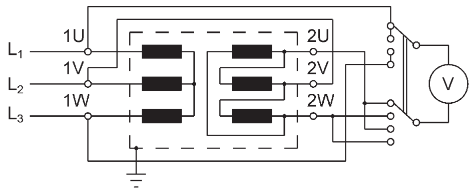



*Figure 4.8:* *Polarity test and connection test on three-phase transformer using one voltmeter*

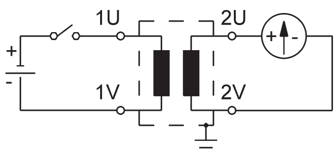



*Figure 4.9:* *Basic analog ratio bridge circuit*

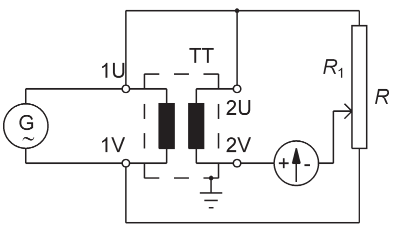



*Figure 4.10:* *Basic circuit of ratio bridge*

## 4.5.2 Polarity test using voltmeters

### Single-phase transformers

For single-phase transformers the polarity can be either additive or subtractive. The low voltage winding is connected in series with the high voltage winding, either in phase or in opposite phase. For additive determination of polarity, if the phase displacement is correct, see figure 4.6:

$$U_\Sigma = U_p + \frac{U_p}{r}$$

and for subtractive determination of polarity, see figure 4.7:

$$U_\Sigma = U_p - \frac{U_p}{r}$$

### Polyphase transformers

The vector group must be checked for three-phase transformers. This is done by connecting a terminal from the low voltage side to a terminal on the high voltage side, see figure 4.8. When a three-phase supply is connected to the high voltage winding, potential differences appear between the open terminals and are used to determine the vector group (refer to Section 4.6).

## 4.5.3 Polarity check using DC current

This method establishes the polarity of single and three-phase transformers by briefly switching on a DC current source at the high voltage winding, see figure 4.9. The polarity is shown on a polarized voltmeter connected to the low voltage side.

## 4.5.4 Voltage ratio and polarity test using a ratio bridge

The measurement principle relies on the compensation method, see figures 4.10 and 4.11.

The high and low voltage windings are connected in opposition by using transformers or decade resistances and the voltages are compensated. If there is a phase displacement between the voltages which are being compensated, the bridge can no longer be adjusted. In other words, if the bridge is connected properly, the winding polarity is determined at the same time. The voltage ratio measurement is usually carried out using a single-phase supply. A three-phase supply is only required for special vector groups. If the supply voltage is not suited to the transformer to be tested, intermediate voltage transformers can be used with the measuring bridge to extend the measuring range.

Figure 4.11 shows the circuit diagram of a modern Tettex ratio meter bridge, which differs from a voltage divider type conventional bridge.

The measuring bridge must be connected in relation to the respective transformer vector group, see figure 4.12 and 4.13.

### 4.5.5 Voltage ratio measurement for three-phase transformers

As a rule, the voltage ratio of three-phase transformers can be measured using a single-phase supply, as long as the distribution of magnetic flux in the core is taken into consideration. Only windings, winding segments and winding combinations which have the same magnetic flux applied, can be compared with one another. The measuring circuit can be derived from the phasor diagram of the test transformer's vector group, compare figure 4.14. The two voltages which are to be compared must be in phase and have the same orientation. This is achieved by ensuring that the high and low-voltage terminals are correctly connected.

The example in figure 4.14 shows that it is not always phase voltages which are being compared. The measuring bridge must therefore be adjusted to reflect the so-called measured / declared ratio value.

$r_{mdecl} = k \cdot r_{decl}$

$r_{mdecl}$ = declared ratio value for the corresponding measuring circuit

$$r_{decl} = \frac{U_{pN}}{U_{sN}}$$

where:

$U_{pN}$ or $U_{sN}$ = primary or secondary voltage rating

The following voltages are compared as shown in figure 4.14:

$$\frac{1U - 1V1W}{2U - 2W}, \frac{1V - 1W1U}{2V - 2U}, \frac{1W - 1U1V}{2W - 2V}$$

(1V1W, 1W1U, 1U1V – each galvanically connected)

In this case, $k$ is: $k = \frac{1{,}5}{\sqrt{3}}$

$$r_{mdecl} = \frac{1{,}5}{\sqrt{3}} \cdot r_{decl}$$

For vector groups Yy0 and Yy6, the following must be taken into consideration:

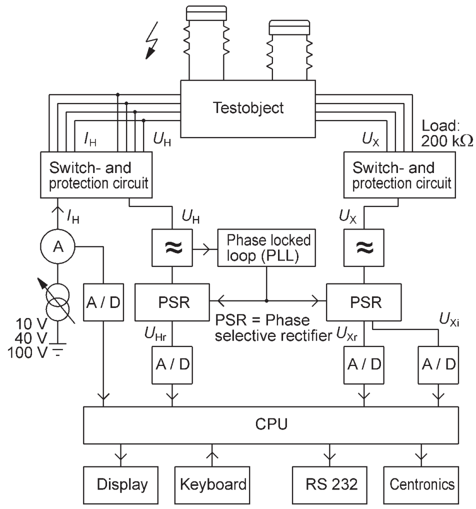



***Figure 4.11:*** *Basic digital ratio bridge circuit, Tettex Typ 2793*

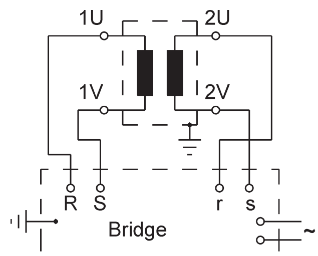



***Figure 4.12:*** *Connection of bridge to single-phase transformer*

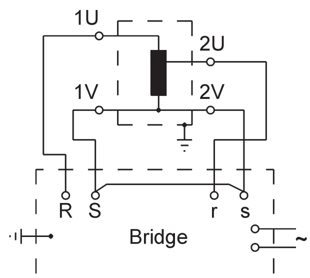



***Figure 4.13:*** *Connection of bridge with single-phase autotransformer*

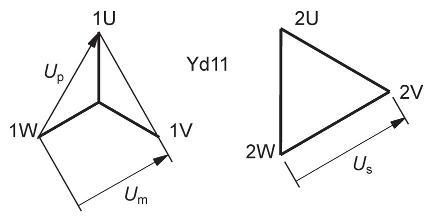



***Figure 4.14:*** *Bridge connection comparing $U_m$ and $U_s$ (same phase), $U_m = 1{,}5 \cdot U_p/\sqrt{3}$*

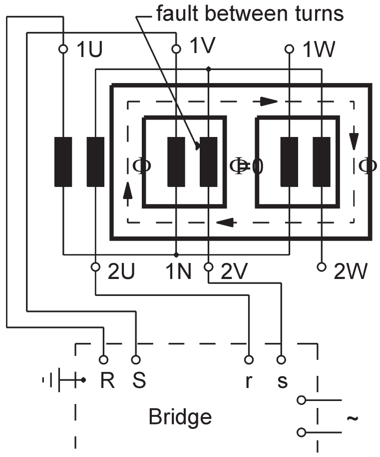



*Figure 4.15:* *Magnetic flux distribution for a test on a Yy transformer with fault between turns*

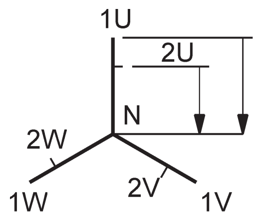



*Figure 4.16:* *Voltage ratio test on three-phase autotransformer with accessible neutral; voltage comparison*

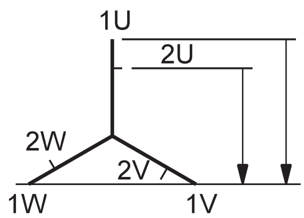



*Figure 4.17:* *Voltage ratio test on three-phase autotransformer with inaccessible neutral; voltage comparison*

A ratio measurement connected as follows:

$$\frac{1U - 1V}{2U - 2V}, \frac{1V - 1W}{2V - 2W}, \frac{1W - 1U}{2W - 2U}$$

could be carried out, but must be avoided because a possible short-circuit between turns cannot be detected, see figure 4.15. If there is a short-circuit in one phase, the magnetic flux circuit can be closed via the free limb, and thus maintain the magnetic balance.

For this vector group the measurement must therefore be carried out as follows:

$$\frac{1U - 1N}{2U - 2N} \text{etc.} \qquad \text{or} \frac{1U - 1V1W}{2U - 2V2W} \text{etc.}$$

If the latter method is used, the bridge can be balanced even if there is a short-circuit between turns. The fault can be detected however, by using an ammeter connected in series.

### 4.5.6 Ratio measurement for three-phase autotransformers

a) Star connection with externally accessible neutral, see figure 4.16.

Correct ratio measurement:

$$\frac{1U - N}{2U - N}, \frac{1V - N}{2V - N}, \frac{1W - N}{2W - N}$$

This measurement:

$$\frac{1U - 1V}{2U - 2V} \text{etc.} \qquad \text{or} \frac{1U - N}{N - 2U} \text{etc.}$$

is not permissible, since a short-circuit would occur between the internally tied terminals S and s of the measuring bridge when using bridge in accordance figure 4.10.

b) Star connection without externally accessible neutral, see figure 4.17.

Correct ratio measurement:

$$\frac{1U - 1V1W}{2U - 1V1W}, \frac{1V - 1U1W}{2V - 1U1W}, \frac{1W - 1U1V}{2W - 1U1V}$$

(1V1W, 1W1U, 1U1V – each galvanically connected)

For this measuring circuit, the required measured/declared voltage ratio to be set on the bridge is:

$$r_{mdecl} = \frac{3 \cdot r_{decl}}{r_{decl} + 2}$$

c) Delta connection, see figure 4.18.

Correct ratio measurement:

$$\frac{1U - 1V}{2U - 1V}, \frac{1V - 1W}{2V - 1W}, \frac{1W - 1U}{2W - 1U}$$

Voltage 2U-1V ($U_x$) is determined from the number of turns and the voltage per turn. If only the name plate data are available, the voltage is calculated as follows:

$$U_{x1,2} = -\frac{p}{2} \pm \sqrt{\left(\frac{p}{2}\right)^2 - q}$$

$$p = |U_s| - |U_p|$$

$$q = |U_p|^2 - 2 \cdot |U_p| \cdot U_s|$$

where:

$U_p$ = primary voltage
$U_s$ = secondary voltage

The largest segment of the winding is always considered as "segment $x$" in the calculation; i.e. if $\varphi > 60°$, the segment between 1U-2U is regarded as $U_x$. The unknown $U_x$ in the above formula is determined from the positive result.

The measured/declared voltage ratio is:

$$r_{mdecl} = \frac{U_p}{U_x}$$

Terminals S and s of the measuring bridge must be connected to the common high voltage terminal.

### 4.5.7 Ratio measurement for transformers having a special vector group

a) Polyphase transformers or rectifier transformers, see figure 4.19.

For a delta / double-star connection the neutral point is brought out for connection of the rectifier cathode terminal. This makes it possible to compare phase voltages. For a star / double-star connection the phase to phase voltages are compared the same as for Yy0 and Yy6. The interphase reactor must be by-passed. A similar method is used for the star / star-terminating connection, see figure 4.20.

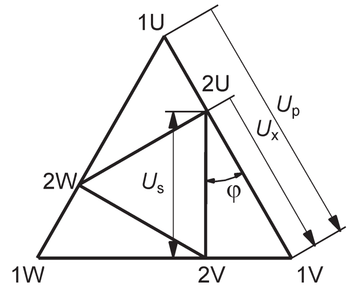



*Figure 4.18:* Voltage ratio test on three-phase autotransformer with delta connection

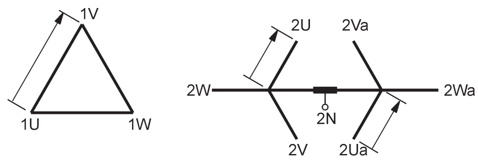



*Figure 4.19:* Voltage ratio test on rectifier transformer with delta-doublestar connection; voltage comparison

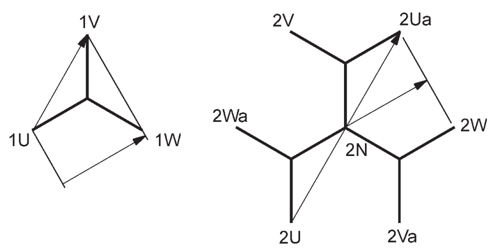



*Figure 4.20:* Voltage ratio test on rectifier transformer with star-terminating connection; voltage comparison

Correct ratio measurement:

$$\frac{1U - 1V}{2U - 2N}\text{etc.} \qquad \text{or } \frac{1U - 1V1W}{2N - 2U_a 2W}\text{etc.}$$

The correct connection for a delta / star terminating connection is:

$$\frac{1U - 1V}{2U - 2V}\text{etc.} \qquad \text{or } \frac{1U - 1V}{2W_a - 2U_a}$$

b) Phase-shifting transformers

Here we are considering phase-shift controlled or quadrature controlled transformers such as phase-shifting rectifier trans-formers. It is not possible to use the bridge method with these types. The ratio measurement is carried out using two voltmeters and the reduced accuracy must be taken into consideration.
If the connections between the common winding and the regulating or shifting windings are accessible the individual winding branches can be measured using the bridge. The phase displacement between the high and low voltage side must be tested for these types, in addition to the previous ratio and polarity tests.

## 4.6 Measuring procedure

### 4.6.1 Ratio measurement using two voltmeters

Refer to Section 4.4, see figure 4.5 for the testing circuit.

If the low voltage side can be measured without using voltage transformers, it is better to feed the high voltage side, since the voltmeter is the only load on the transformer to be tested. Normally a reduced voltage is used for the supply.
The measurement is carried out with a minimum of four voltage values (increasing in steps of 10%). The average value represents the correct measured value and the readings must lie within a range of 1 %. Digital instruments with a sufficiently high resolution must be used. They present practically no load to the transformer because of their high input resistance. The two voltmeters should be read simultaneously. A stable voltage source is mandatory to obtain an accurate measured result.

### 4.6.2 Polarity test using voltmeters

Refer to Section 4.4, see figure 4.8 for the test circuit.

The measured values of the individual voltages are entered on a phasor diagram, from which the correct polarity and vector group can be determined, see figure 4.21. A supply voltage of $100 \cdot \sqrt{3} = 173$ V results in a better presentation. This allows all of the measured voltage values to be entered in a 100 mm radius circle, where 1 V = 1 mm.

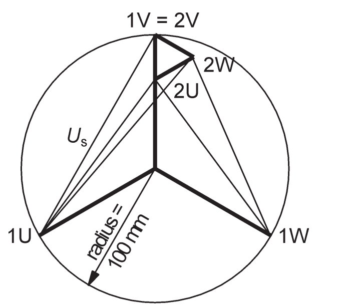



***Figure 4.21:*** *Tree-phase transformer polarity test and connection test using one voltmeter. Graphic display of voltages (Yd 11)* *$U_s = 100 \cdot \sqrt{3} = 173$ V*

Terminal 2V has the same voltage as terminal 1V (2V-1V are galvanically connected) in the example, see figure 4.21, the two points are then identical on the phasor diagram. The points 2U and 2W can be determined by measuring voltages 1U-2U, 1W-2U, and 1U-2W, 1W-2W, from which the transformer vector group can be derived. For high voltage ratios, the phasor diagram for the low voltage would be too small. To improve the accuracy of the readings on the diagram, the low voltage must be increased using vector group 0 type voltage-transformers.

### 4.6.3 Polarity test using DC current

Refer to Section 4.5, see figure 4.9 for the test circuit.

If the polarity is correct a polarized voltmeter deflects on the positive side when the DC current is switched on.

The instrument must be calibrated to be sure which deflection is correct. It is connected to the high voltage terminal in parallel with the transformer under test, see figure 4.9. A series resistor is connected in the circuit to protect the instrument. The direction of the deflection is determined by briefly switching on the DC current. If the instrument is connected to the low voltage terminals, the deflection must be in the same direction when the DC current is switched on, if the polarity of the transformer to be tested is correct.

### 4.6.4 Voltage ratio and polarity check using a ratio bridge

Refer to Section 4.5, see figures 4.10 to 4.20 for the test circuit.

Operation of the bridge varies by manufacturer. In general, the following should be noted:

- connect the terminals of the measuring bridge to the transformer terminals in the correct order
- ensure that no part of the transformer winding is connected to ground, to prevent short-circuits.

## 4.7 Measuring uncertainty

The ratio bridge is very well suited to verify that the voltage ratio meets tolerances according to the Standards (Section 4.1). It is easy to use, normally it requires only a domestic AC supply. It tests the voltage ratio and the polarity simultaneously. It is apparent, however, that despite shielding, external fields can distort the measurement result. Care should be taken to avoid running any high voltage or high current conductors in the vicinity of the bridge. The measuring uncertainty of ratio bridges is approximately ± 0,1%. The uncertainty increases minimally, even if supplementary voltage transformers are required.

When using the two-voltmeter method to determine the voltage ratio, it is not possible to achieve a measuring uncertainty of less than ± 0,5% without considerable extra effort and is therefore not suitable for transformers which must meet the Standards. The voltmeter method is only used when it is not possible to use the bridge or if the tolerances defined above do not need to be maintained.

For preliminary measurements during manufacture without oil and only partially stacked yoke, the error tolerance of ± 0,5% is too great, especially when comparing parallel winding branches. In such cases, the measuring uncertainty of the measuring equipment must be less than the relative deviation of a winding.

# Appendix A 4

# Verification of voltage ratio and vector group or phase displacement

## A 4.1 Determination and localization of errors

### A 4.1.1 Wrong polarity or open circuit

Difficulties to balance the bridge may depend on transformer polarity or an error in voltage ratio. If the polarity test is successful after reversing the supply voltage to the transformer the polarity is incorrect. If not successful an error must be searched for in turns ratio. A further possibility would be an open circuit in the winding connections, such as a bad contact in the tap changer, an interrupted winding, open connection points, etc. It is not possible to balance the bridge if this occurs.

The fault can be immediately detected when using the voltmeter method. If the measured voltage deviates from the rated voltage, a winding fault is indicated. If no voltage can be measured, there is an open circuit. A short-circuit between turns is indicated by increased current consumption, particularly during measurement of no-load loss.

### A 4.1.2 Incorrect voltage ratio

A winding error can be determined from the ratio error or from the voltage difference between the declared and actual value when using the voltmeter method. The faulty phase can be found by testing phase per phase. Using the known calculated winding voltage, the winding fault can be determined as follows:

$$N_f = \frac{U_{act} - U_{decl}}{U_w}$$

where:

$U_{act}$ = measured actual voltage (low voltage)
$U_{decl}$ = declared value (low voltage)
$U_w$ = winding voltage
$N_f$ = winding error

If the winding error is positive, the low voltage has too many turns, or the high voltage too few turns. If the winding error is negative, the low voltage has too few turns, or the high voltage too many turns. The above formula is primarily valid for voltage measurement.

For the test using the measuring bridge the following holds:

$$N_f = \frac{r_{act} - r_N}{r_N}$$

When reading the error directly:

$$N_f = \frac{f \cdot N}{100}$$

where:

$r_{act}$ = actual voltage ratio
$r_N$ = declared voltage ratio
$N$ = number of turns (HV or LV)
$f$ = ratio error in %

For calculation of the ratio error $f$ refer to section 4.4.

Calculation of the winding error can be carried out in the same way for high and low voltage windings, because the source of the error is not yet known. To determine the faulty winding the two suspected windings are compared to a winding which has no faults: e.g. for three-legged types the adjacent winding is used. The winding on the third leg must be shorted, or an auxiliary winding must be used for comparison. Depending on the number of turns in the winding to be tested, the auxiliary winding should have from 10 to 20 turns. The comparison can be made in a similar way when using the voltmeter method.

An apparent shortage of turns can also be caused by a short circuit between turns. This is the easiest to prove by applying rated voltage for 15 to 30 minutes. – Important: for oil-cooled active parts in air, the voltage must be reduced in accordance with the insulation, in order to subsequently check the winding for hot spots. The location of the winding fault can usually be found easily due to significant heating. This method can however, only be recommended for small and mid-sized transformers up to about 10 MVA. For power transformers any faults must be localized by checking the individual winding segments.

If the transformer has series-parallel reconnectable windings, the two winding halves must be exactly symmetrical. A small asymmetry in the number of turns is difficult to detect using ratio measurement. For this reason, no-load losses must be measured for series and parallel connection types. If it is determined that there are significant differences in the losses, an asymmetry in the number of turns must be assumed. To localize the error the separated winding halves on all three limbs must be compared with one another.

# Testing of Power Transformers

## 5. Measuring the short-circuit voltage impedance and the load loss

# 5. Measuring short-circuit voltage / impedance and load loss

## 5.1 References / Standards

- IEC 60076-1 (2000) clause 10.1: "General requirement for routine, type and special tests", clause 10.4: "Measurement of short-circuit impedance and load loss" [1]
- IEC 60076-8 (1997), clause 10: "Guide to the measurement of losses in power transformers" [6]
- IEEE Std C57.12.90-1999, clause 9: "Load losses and impedance voltage" [51]

**Note:**

Measuring the short-circuit voltage, the short-circuit impedance and the load loss are **routine tests** according to IEC Standard [1] and to IEEE Standard [50].

## 5.2 Purpose of the test

Transformer short-circuit voltage and load loss are guaranteed by the manufacturer and are verified for the customer during the acceptance test. Exact knowledge of the load loss is important not only for capitalization of losses but is also important for the safe operation of large power transformers.

A comparison of the calculated and measured values gives an indication about the eddy losses caused by leakage flux in the mechanical parts and the tank wall. Furthermore, it is essential to know the short-circuit voltage and load loss to carry out the temperature rise test, see section 11. For transformers with tapped windings the short-circuit voltage has to be measured in the two extreme tap positions in addition to the principal tap position. Knowledge about short-circuit voltage in extreme tap position is important for parallel operation.

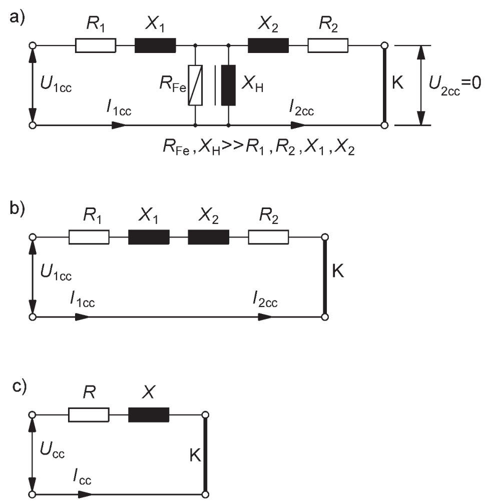
## 5.3 General

The definition of short-circuit voltage is:

> The AC voltage that must be connected to one pair of terminals of a transformer with another pair of terminals shorted, which causes rated current to flow on the two sides of the transformer. The absorbed active power corresponds to the transformer load loss.

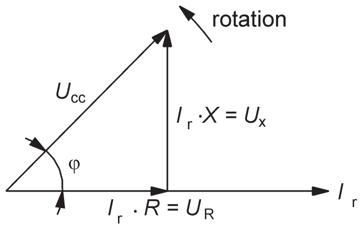
In reality a component of the no-load losses of the transformer is also measured but it can be neglected most of the time, since the short-circuit voltage is minimal compared to the rated voltage. The only exceptions are starting transformers with an air gap, reactor transformers, etc.

The generally applicable short-circuit equivalent schematic can be seen in figure 5.1.




$R_1$ = resistance of winding 1
$R_2$ = resistance of winding 2
$X_1$ = stray resistance of winding 1
$X_2$ = stray resistance of winding 2
$R_{Fe}$ = equivalent resistance of iron
$X_H$ = main reactance
$U_{CC}$ = short-circuit impedance voltage
$I_{CC}$ = short-circuit current
K = short-circuit lead
$R$ = $R_1 + R_2$
$X$ = $X_1 + X_2$

***Figure 5.1:** Short-circuit equivalent diagram*




$U_R$ = resistive voltage drop
$U_X$ = inductive voltage drop
$U_{CC}$ = impedance voltage drop
$I_r$ = rated current

***Figure 5.2:*** *Short-circuit vector diagram*

### 5.3.1 Short-circuit voltage; relative short-circuit voltage

The phasor diagram of the short-circuit equivalent diagram gives the following, according to figure 5.2

$$U_{cc} = \sqrt{U_X{}^2 + U_R{}^2}$$

$$\varepsilon_{cc} = \frac{U_{cc}}{U_r} \cdot 100$$

where:

$U_{cc}$ = short-circuit voltage
$U_R$ = resistive voltage drop
$U_X$ = inductive voltage drop
$\varepsilon_{cc}$ = relative short-circuit voltage in %
$U_r$ = transformer rated voltage

The relative short-circuit voltage is given as a percent of the rated voltage of the energized winding. It is the value which determines the current which flows in the event of a short-circuit during operation:

$$I = \frac{100}{\varepsilon_{cc}} \cdot I_r$$

where:

$I$ = symmetrical short-circuit current
$I_r$ = rated current

### 5.3.2 Interdependence of short-circuit voltage and load current

The short-circuit voltage increases linearly with increasing load current.

$$U_{cc} = U_{ccm} \cdot \frac{I_r}{I_m}$$

where:

$U_{cc}$ = short-circuit voltage at rated current $I_r$
$U_{ccm}$ = short-circuit voltage at $I_m$
$I_m$ = load current during test

### 5.3.3 Interdependence of relative short-circuit voltage (or short-circuit voltage) and winding temperature

This is only significant for transformers < 2 MVA, see clause A 5.1 for the calculation.

### 5.3.4 Interdependence of short-circuit voltage and frequency

The short-circuit voltage is proportional to the frequency, provided that $U_R \ll U_X$.

$$U_{cc} = U_{ccm} \cdot \frac{f_r}{f_m}$$

where:

$f_r$ = rated frequency
$f_m$ = frequency during test

**Short-circuit voltage**

Single-phase two-winding transformers:

$$Z = \frac{U_{cc}}{I_r} \quad [\Omega]$$

$$R = \frac{P_L}{I_r} \quad [\Omega]$$

$$X = \sqrt{Z^2 - R^2} \quad [\Omega]$$

Three-phase two-winding transformers:

| Star connection | Delta connection | |
|---|---|---|
| $Z = \frac{U_{cc}}{I_r \cdot \sqrt{3}}$ | $Z = \frac{U_{cc} \cdot \sqrt{3}}{I_r}$ | [Ω / phase] |
| $R = \frac{P_L}{3 \cdot I_r^2}$ | $R = \frac{P_L}{I_r^2}$ | [Ω / phase] |
| $X = \sqrt{Z^2 - R^2}$ | $X = \sqrt{Z^2 - R^2}$ | [Ω / phase] |

where:

$Z$ = short-circuit impedance
$X$ = short-circuit reactance
$R$ = short-circuit resistance
$I_r$ = rated current
$U_{cc}$ = short-circuit voltage
$P_L$ = load loss

### 5.3.5 Load loss

The load loss represents the total losses developed within the transformer when rated current at rated frequency is applied to the transformer with the winding short-circuited and the winding temperature equal to the reference temperature (75 °C according to IEC or 85 °C according to IEEE). It is made up of the ohmic losses of the windings and internal connections, as well as the stray losses (eddy current losses) caused by leakage fields in the windings and the mechanical parts.

$$P_L = P_j + P_a$$

where:

$P_L$ = load loss at a winding temperature of 75 °C / 85 °C
$P_j$ = ohmic losses at 75 °C / 85 °C
$P_a$ = stray losses at 75 °C / 85 °C

### 5.3.6 Interdependence of load loss and load current

Load loss is proportional to the square of the load current.

$$P_L = P_{Lm} \cdot \left(\frac{I_r}{I_m}\right)^2$$

where:

$P_L$ = load loss at rated current
$P_{Lm}$ = load loss at test current
$I_m$ = test current

### 5.3.7 Separating load loss components when winding resistances are known

The short-circuit voltage and load loss are referred to an average winding temperature of 75 °C (IEC) or 85 °C (IEEE) [1], [51]. However, the winding temperature during the laboratory test is generally significantly lower. To calculate the load loss at a different reference winding temperature, it is necessary to separate the ohmic losses from the stray losses. If the winding resistances are known (see section 3 for measurement), separation is carried out as follows:

$$P_L = P_j + P_a = \Sigma I_r^2\, R + P_a$$
$$P_a = P_L - \Sigma I_r^2\, R$$

where:

$R$ = winding resistance

Load loss separation into its components when winding resistances are not known, see clause A 5.2.

### 5.3.8 Interdependence of load loss and winding temperature

The ohmic component of the load loss increases with increasing winding temperature while the stray losses decrease, see also section 3 for relations between resistance and temperature and example 1 in clause A 5.8.

$$P_{j2} = P_{j1}\frac{C+\Theta_2}{C+\Theta_1} \qquad P_{a2} = P_{a1}\frac{C+\Theta_1}{C+\Theta_2}$$

where:

$P_{j1}$ = ohmic loss at temperature $\Theta_1$
$P_{j2}$ = ohmic loss at temperature $\Theta_2$
$P_{a1}$ = stray loss at temperature $\Theta_1$
$P_{a2}$ = stray loss at temperature $\Theta_2$
$\Theta$ = Temperature in °C
$C$ = Constant which is a function of material type

IEC [1] specifies:

$C$ = 235 for copper
$C$ = 225 for aluminium

IEEE Standard [51] specifies a somewhat different value for copper: $C$ = 234,5

Since the ohmic loss component is much larger than the stray loss, the total load loss increases with increasing winding temperature.

The standards [1], [51] describe in detail the required winding temperature measurement, which must be carried out immediately before taking the load loss measurements.

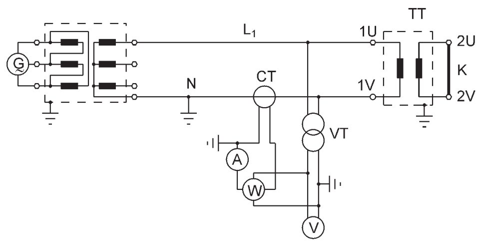
### 5.3.9 Interdependence of load loss and frequency

In general, the ohmic component of load loss is independent of frequency (the influence of the skin effect can be neglected for the frequency range being considered) while the stray losses increase with the frequency.

$$P_L = P_j + P_{am}\cdot\left(\frac{f_r}{f_m}\right)^2 + P_{st}\left(\frac{f_r}{f_m}\right)^{0,8}$$

where:

$P_L$ = load loss at rated frequency $f_r$
$P_{am}$ = stray losses in the windings at test frequency $f_m$
$P_{st}$ = stray losses in structure parts and in tank at test frequency $f_m$




K = short-circuit lead
CW = current transformer
VT = voltage transformer

**Figure 5.3:** *Single-phase transformer connections for load loss and impedance voltage tests.*

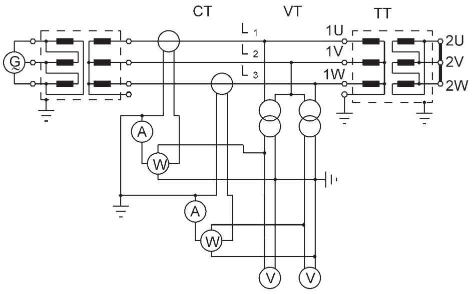



*Figure 5.4:* *Three-phase transformer connections for load loss and impedance voltage tests using two-wattmeter method. This method should not be used according to IEEE standard [51] for three-phase transformers.*

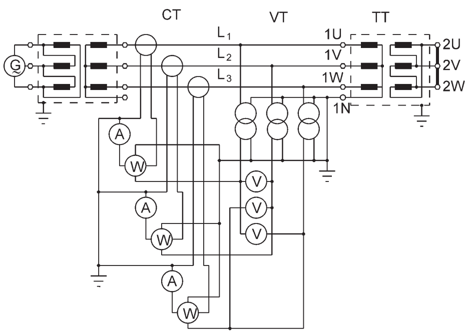



*Figure 5.5:* *Three-phase transformer connections for load loss and impedance voltage tests using three-wattmeter method.*

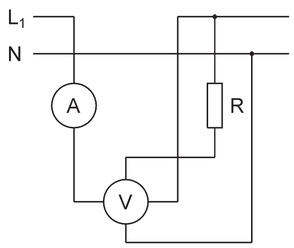



*Figure 5.6:* *Load loss measurement without voltage and current transformer.*

If the rated frequency of the transformer to be tested is not available in the test laboratory when measuring the load loss, the losses can be calculated using the above formula, with the limitation that an additional type test at rated frequency is required to verify the measuring uncertainty.

It follows that the current supply waveform must be sinusoidal and free of harmonics, otherwise the uncertainty of the measured losses will be too high.

## 5.4 Measuring circuit

The measuring circuit for load loss measurements on single-phase transformers is shown in figure 5.3, and for three-phase transformers in figures 5.4 and 5.5. The short-circuit is normally applied on the low voltage side of the transformer. It is more feasible to adapt the test equipment in the test laboratory to the lower current associated with the higher short-circuit voltage at the high-voltage winding.

For loss measurements on three-phase transformers principally two different wattmeter configurations are possible: the three-wattmeter method and the two-wattmeter method, see figures 5.5 and 5.4.

The two methods both require current and voltage transformers.

The power factor for power transformer load loss measurements is about 0,01 to 0,05. This means that even small phase-angle errors in the current and potential transformers require major corrections for errors in the measuring system (IEEE standard [51] allows a maximum ± 5 % error correction).

The two-wattmeter method is less suitable for small power factors because the two wattmeter readings have opposite signs and must be subtracted from one another. As a result, small errors have a greater influence than with the three-wattmeter method. For this reason the two-wattmeter method should be avoided for load loss measurements; nevertheless it is occasionally used for investigation tests in the field (on-side tests), because less instrument transformers are necessary.
It is not permitted by IEEE [51].

If a current carrying neutral is present, or if the power per phase has to be determined for investigation tests, only the three-wattmeter method can be used.

To avoid corrections for instrument transformers, the wattmeter current leads should be, whenever possible, directly connected in the supply circuit and their voltage inputs connected using series resistors, see figure 5.6.

## 5.5 Measuring procedure

Before the actual load loss measurements are taken, the winding resistance measurements (section 3) and the winding temperature measurement must be carried out (compare IEC [1] and IEEE [51] standards).

If there are built-in current transformers, they must be shorted during the test to avoid saturation of their iron cores and overvoltages at the secondary terminals.

The bushing taps must be earthed.

If the transformer under test is equipped with an off-load or on-load tap-changer, the first loss measurement is carried out at the principal tap and subsequently at the highest and lowest taps.

During the test, the current is adjusted steadily upwards from zero to the full measuring current in order to avoid inrush currents. The DC component of the inrush-current can lead to instrument transformer errors, which cannot be corrected (pre-magnetization of the current transformers).

The duration of the test should be as short as possible to avoid any significant heating of the windings.

An approximate value of the time constant for the winding conductor temperature rise above oil can be calculated as:

$$T \cong 160 \cdot \frac{g}{J^2}$$

where:

$T$ = winding time constant in seconds

$g$ = temperature gradient winding conductor to oil (from design calculation)

$J$ = winding current density in A/mm$^2$

Example: $T \cong 160 \cdot \frac{20}{3{,}2^2} \cong 213\text{s} \cong 5{,}2\text{min}$

In general, the measuring time at rated current should be about 30 seconds (rule of thumb).

The measuring current should be as close as possible to the rated current, although IEC specifies that the current should not be below 50% of rated current. In order to ensure that the measured data were properly saved, a second measurement with approximately 10% lower current is recommended. After extra-polating the two points of measurement, the values must agree.

If the supply generator is being driven by an asynchronous or a DC machine, care must be taken to keep the frequency constant (± 0,3 Hz).

The load loss measurement offers the opportunity to measure the ratio of the built-in bushing current transformers by connecting ammeters. Care must be taken to do the check at nominal burden. This is particularly important for current transformers with a rated secondary current of 1 A.

### 5.5.1 Load loss measurement for single-phase transformers

Primarily three-phase generators or matching transformers are used in test laboratories when measuring single-phase transformers. Care must be taken not to measure the capacitive earth current of the free phases with the current transformer (as seen from the supply side), or to connect the current transformer in the energized phase, see figure 5.3.

### 5.5.2 Measuring short-circuit voltage and load loss for three-winding transformers

The short-circuit voltage and load loss for three-winding transformers cannot be determined from one single short-circuit test. They must be calculated using the results of three different short-circuit tests.

The following short-circuit tests must be carried out and the measured quantities: losses and impedances. They have to be adjusted to rated current and reference temperature (75°C or 85°C).

| Measuring arrangements | | | |
|---|---|---|---|
| Test between windings | Winding supplied | Winding Short-circuit | Winding open |
| 1-2 | 1 | 2 | 3 |
| 1-3 | 1 | 3 | 2 |
| 2-3 | 2 | 3 | 1 |

*Legend:* *1 = Winding 1 high-voltage*
*2 = Winding 2 intermediate-voltage*
*3 = Winding 3 low-voltage*

#### Calculation of the equivalent short-circuit voltage per winding

All three measuring results should be referred to a common apparent power (e.g. rated apparent power of the high-voltage winding). The short-circuit voltage is recalculated linearly with the reference power.

$$\varepsilon_{cc\,1} = \frac{\varepsilon_{cc\,12} + \varepsilon_{cc\,13} - \varepsilon_{cc\,23}}{2}$$

$$\varepsilon_{cc\,2} = \frac{\varepsilon_{cc\,12} + \varepsilon_{cc\,23} - \varepsilon_{cc\,13}}{2}$$

$$\varepsilon_{cc\,3} = \frac{\varepsilon_{cc\,23} + \varepsilon_{cc\,13} - \varepsilon_{cc\,12}}{2}$$

Checking the results:

$$\varepsilon_{cc12} = \varepsilon_{cc1} + \varepsilon_{cc2}$$
$$\varepsilon_{cc13} = \varepsilon_{cc1} + \varepsilon_{cc3}$$
$$\varepsilon_{cc32} = \varepsilon_{cc2} + \varepsilon_{cc3}$$

### Calculation of the load loss per winding

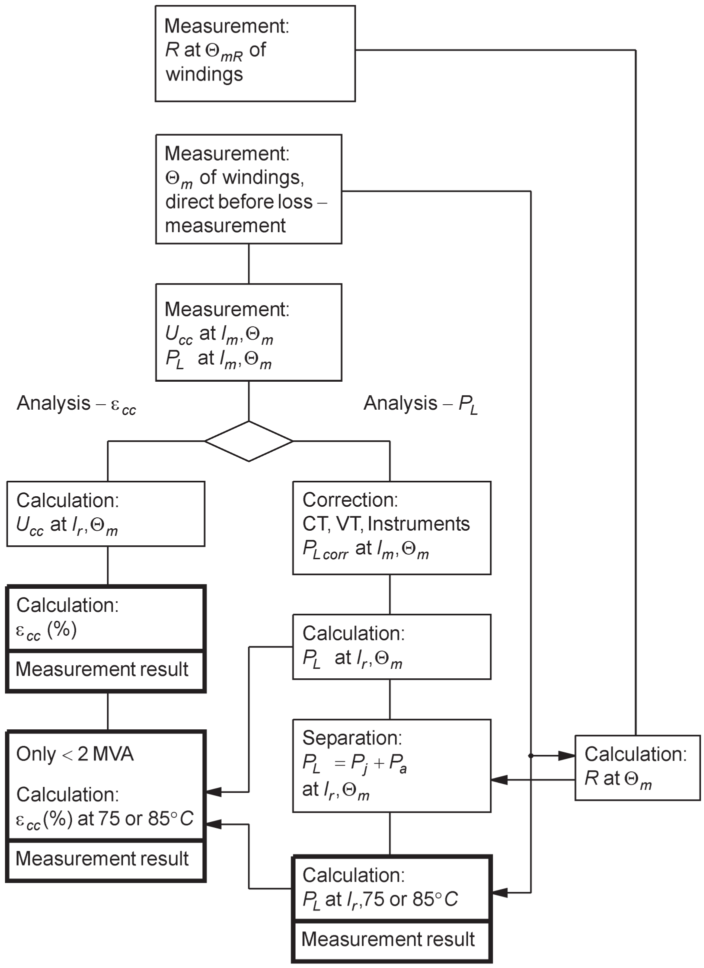
A common reference power must be selected (e.g. rated apparent power of the high-voltage winding). Recalculation gives the load loss as the square of the reference power.

$$P_{L1} = \frac{P_{L12} + P_{L13} - P_{L23}}{2}$$

$$P_{L2} = \frac{P_{L12} + P_{L23} - P_{L13}}{2}$$

$$P_{L3} = \frac{P_{L13} + P_{L23} - P_{L12}}{2}$$

The load loss per winding can now be recalculated to correspond to the operating conditions. They are not always the same as the actual losses during operation because of the differing configurations of leakage flux during the paired measurements and the operating condition with three windings.
For transformers with more than three windings the short-circuit tests should also be carried out in pairs using the same method.




$R$ = winding resistance
$\Theta_{mR}$ = winding temperature at resitance measurement
$\Theta_m$ = winding temperature at loss measurement
$U_{CC}$ = short-circuit impedance voltage
$\varepsilon_{CC}$ = relative impedance voltage in %
$P_L$ = load losses
$P_{Lcorr}$ = corrected load losses
$P_j$ = ohmic losses
$P_a$ = additional losses
$I_m$ = load current measurement
$I_r$ = rated current

***Figure 5.8:*** *Block diagram for calculation of measurement values*

## 5.6 Evaluation of the measuring results

Evaluation of the measuring results is carried out in accordance with the logic diagram in figure 5.8. The required conversion formulae are shown in section 5.3. Section 3 describes the measurement of the winding resistances and the winding temperature.

For instrument error correction and instrument transformer correction, see clause A 5.4 and A 5.5.

## 5.7 Measuring uncertainty

The measuring uncertainty can be examined using Gauss's law.

Example:

For a three-phase transformer: three-wattmeter method with calibrated classic instrument transformers and calibrated digital instruments – considering only the largest influencing factors of the instrumentation (for exactly executed corrections based on available calibration certificates).

a) instrument transformer phase-angle error with a power factor of 0,025; calibration uncertainty ± 1,5 minutes.

   $E = \pm 1{,}5 \cdot 40 \cdot 0{,}0291 = \pm 1{,}75\,\%$ for each phase and transformer

b) wattmeter error; calibration uncertainty at the above power factor ± 0,5 %

c) wattmeter angle error; calibration uncertainty at the above power factor ± 0,5 minutes

   $E = \pm 0{,}5 \cdot 40 \cdot 0{,}0291 = \pm 0{,}58\,\%$ for each wattmeter

This gives a probable variance for the instrumentation of:

$$\lambda = \sqrt{\left(6 \cdot 1{,}75^2\right) + \left(3 \cdot 0{,}5^2\right) + \left(3 \cdot 0{,}58^2\right)} = \pm 4{,}5\,\%$$

The above qualitative observation shows that for load loss measurements, the measuring instruments must be carefully matched to the corresponding test to keep the total measuring uncertainty as small as possible.

By using the best available measuring equipment such as capacitive voltage dividers, zero-flux current transformers, transformer power analyzers etc., the total measuring uncertainty can be reduced to ± 2 % or ± 3 % at power factors of above 0,01.

IEEE limits the permissible uncertainty for loss measurements to be less than 3%.

# Appendix A 5: Measuring the short-circuit voltage impedance and load loss

## A 5.1 Interdependence of relative short-circuit voltage (or short-circuit voltage) and winding temperature

The IEC standards call for the short-circuit voltage and the load loss to be determined at a winding temperature of 75 °C whereas IEEE calls for 85 °C [1], [51]. Short-circuit voltage increases with increasing winding temperature.

$$\varepsilon_{cc} = \sqrt{\varepsilon_X^{\ 2} + \varepsilon_R^{\ 2}}$$

where:

$\varepsilon_{cc}$ = relative short-circuit voltage at $I_r$

$\varepsilon_X$ = relative reactance voltage at $I_r$

$\varepsilon_R$ = relative resistance voltage at $I_r$

**Note:**

Reference winding temperature must be 75 °C or alternatively 85 °C, depending on whether IEC or IEEE is the applicable standard.

$$\varepsilon_{cc} = \sqrt{\varepsilon_{Xm}^{\ 2} + \varepsilon_R^{\ 2}} = \sqrt{\left(\varepsilon_{ccm}^{\ 2} - \varepsilon_{Rm}^{\ 2}\right) + \varepsilon_R^{\ 2}} =$$

$$= \sqrt{\left(\frac{U_{ccm}}{U_r} \cdot 100\right)^2 - \left(\frac{P_{Lm}}{S_r} \cdot 100\right)^2 + \left(\frac{P_L}{S_r} \cdot 100\right)^2}$$

where:

$\varepsilon_{Xm}$ = relative reactance voltage at $I_r$ and the winding temperature during test

$U_{ccm}$ = short-circuit voltage at $I_r$ and the winding temperature during test

$P_{Lm}$ = load loss at $I_r$ and the winding temperature during test

$P_L$ = load loss at $I_r$ and a winding temperature of 75 °C / 85 °C

$S_r$ = rated apparent power

**Note:**

The impedances $\varepsilon_{Xm}$ and $\varepsilon_X$ are identical since the reactance voltage is independent of the temperature.

For large transformers ($S_r \geq 2$ MVA) the calculation is not necessary since $U_X \gg U_R$ (error < 0,5 %).

## A 5.2 Load loss separation when winding resistances are not known

This approximation method is used for transformers where the winding resistances have been estimated, or cannot be determined at all (e.g. for rectifier or arc furnace transformers). It is based on the quadratic frequency dependency of the stray losses.

Two loss measurements are carried out at equal temperature. They are taken at rated frequency and again at a frequency differing by 15 to 20 %. The measurements must be taken at rated current.

$$P_j = \frac{P_{L2} \cdot f_1^2 - P_{L1} \cdot f_2^2}{f_1^2 - f_2^2}$$

$$P_a = P_{L1} - P_j$$

where:

$P_{L1}$ = load loss at rated frequency $f_1$

$P_{L2}$ = load loss at a different frequency $f_2$

Because of the measuring uncertainty, there are limitations to the method.

## A 5.3 Measuring equipment requirements

**IEC 60076-1, clause10.1** [1]

In general, the measuring equipment should have a certified and traceable measuring uncertainty, and be periodically calibrated according to ISO 9001 rules. Specific recommendations for loss measurements are given in IEC 60076-8 [6] (clause 10: Guide to the measurement of losses in power transformers).

**IEEE Std C57.12.90, clause 9** [51]

The supply frequency for the loss measurements should be within ± 0,5 % (0,3 Hz) of rated frequency.

The instrument transformer phase-angle correction is to be carried out at a power factor of ≤ 0,03, a power factor > 0,03 and ≤ 0,10, and a sum of phase-angles > 1 minute; as well as a power factor > 0,10 and a sum of phase-angles > 3 minutes. The maximum correction values cannot exceed ± 5 %, otherwise the measuring equipment must be checked.

The two-wattmeter method should not be used for three-phase transformer load loss measurements. The alternative to the three-wattmeter method is the impedance bridge method.

Modern load loss measuring equipment is equipped with capacitive voltage dividers, zero flux current transformers or alternatively two stage passive current transformers and special power analyzers that are designed for very low power factors. When periodically calibrated, this type of measuring equipment, which has minimum phase-angle errors, provides the best achievable measuring uncertainty.

Classical current and potential transformers should have the smallest possible phase-angle error at the actual burden (± 1 minute) and be loaded between 80 to 120 % of nameplate rating (note the transformer calibration point).

The voltmeters, ammeters and wattmeters used are normally digital instruments with a measuring uncertainty of ± 0,1 % (depending on the measuring range). The performance with respect to power factor and the amount of effort required for the calibration method specified, should be taken into consideration when choosing digital wattmeter (e.g. often only single-phase calibration is possible).

For short measurement duration, a current density of up to 6 A/mm$^2$ is permitted for copper conductors for the connection cables to the transformer to be tested. The voltage measurement should be taken directly at the terminals of the transformer under test, in order to avoid adding the cable losses to the measurement.

The short-circuit connection at the transformer low-voltage winding should be short, and the cross-section large (rule of thumb 1-2 A/mm$^2$). In the event of very high currents, the connecting cables should not be routed too close to metal parts because of the stray losses. If the resistance of the short-circuit connection is large in comparison to the winding resistance, the measured load loss can be corrected in accordance with the following approximate formula:

For copper: $$P = 1{,}96 \cdot \left( \frac{235 + \Theta}{255} \right) \cdot J^2 \cdot m$$

For aluminium: $$P = 11{,}22 \cdot \left( \frac{225 + \Theta}{245} \right) \cdot J^2 \cdot m$$

where:

$P$ = ohmic losses in the short-circuit connection in W

$\Theta$ = temperature of the short-circuit connection in °C

$J$ = current density in A/mm$^2$

$m$ = mass in kg

IEEE Standard does not explicitly permit this type of correction in measured losses.

The supply generator must provide a constant frequency even under load (± 0,3 Hz). If the generator does not have enough power, appropriate reactive power compensation equipment must be provided.

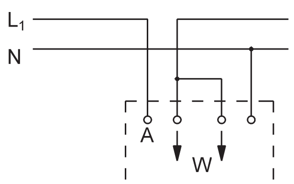



*Figure 5.8:* *Wattmeter connection*

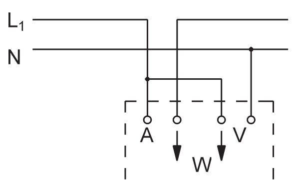



*Figure 5.9:* *Wattmeter connection*

**Matching transformer**

If a testing transformer cannot be avoided to match the generator voltage to the transformer under test, care must be taken not to tie the two neutrals together, see figure 5.5. Because of the differing short-circuit impedances per phase, they can be phase shifted and cause circulating currents.

## A 5.4 Instrument error correction

The correction is made according to a calibration table as well as the power consumption in the instruments:

Voltmeter: $P_i = \frac{U^2}{R_i}$

Ammeter: $P_i = I^2 \cdot R_j$

where:

$P_i$ = instrument power consumption

$R_i$ = instrument internal resistance

Wattmeter:

The loss figure measured by the wattmeter will, to a certain extent, also include the power consumption in the voltage and current measuring circuits. A correction will therefore be necessary if the losses in the instrument circuits are high.

For the connection circuit used in figure 5.8 the following holds:

$P_{corr} = P - P_I$

where:

$P$ = indicated load loss

$P_I$ = current circuit power consumption

For the connection circuit used in figure 5.9 the following holds:

$P_{corr} = P - P_U$

where:

$P_U$ = voltage circuit power consumption

The wattmeter phase-angle correction is carried out in the same way as the instrument transformer phase-angle correction.

## A 5.5 Instrument transformer error correction

- IEC 60076-8 (1997), clause 10: “Guide to the measurement of losses in power transformers” [6]
- IEEE Std C57.12.90-1999, clause 9. “Load losses and impedance voltage” [51]

If current and potential transformers are used, only the instrument transformer ratio error need be considered for the current and voltage measurements. For the wattmeters, the instrument transformer phase-angle error must also be corrected. The measuring error resulting from the phase-angle error is a function of the power-factor of the measuring circuit. This is naturally not the case for the ratio error. The ratio error and the phase-angle error for the applied instrument transformers must be taken from the calibration certificate at the respective measuring point (per phase and at the equivalent measuring circuit burden).

IEEE limits the correction of load loss measurements due to phase angle errors to 5 %.

### A 5.5.1 Measuring inductive single-phase power or three-phase power using the three-wattmeter method

A shorted transformer always represents an inductive load. Figure 5.10 shows the phasor diagram for a single-phase inductive measuring circuit with current and potential transformers, where Index 1 represents the corrected value and Index 2 the uncorrected (measured value). The phase-angles were arbitrarily taken as positive in this diagram (i.e. leading).

For the measuring error:

$$E_\delta = \frac{P_2 - P_1}{P_2} \cdot 100\,\%$$

where:

$E_\delta$ = measuring error caused by the phase-angle in %

$P_1$ = corrected power

$P_2$ = uncorrected power (measured power)

The measuring error is referred to the uncorrected power since it is a known measured value

$$E_\delta = \frac{U_2 \cdot I_2 \cdot \cos(\varphi - \delta) - U_1 \cdot I_1 \cdot \cos\varphi}{U_2 \cdot I_2 \cdot \cos(\varphi - \delta)} \cdot 100$$

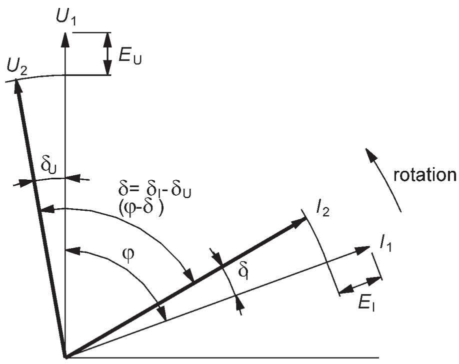
$$= \left[1 - \frac{\cos\varphi}{\cos(\varphi - \delta)}\right] \cdot 100\,\%$$

The phase-shift in an instrument transformer is normally given as an angle error in minutes. On a per-unit basis the angle $\delta$ (minute) of the arc is:

$$\delta = \delta_I - \delta_U = \frac{2 \cdot \pi}{360 \cdot 60} \cdot (\delta_I - \delta_U) = 0{,}000291 \cdot (\delta_I - \delta_U)$$

This can be converted to:

$$E_\delta = +\,0{,}0291 \cdot (\delta_I - \delta_U) \cdot \mathrm{tg}(\varphi - \delta_I + \delta_U) \quad \%$$




Index 1 = corrected value

Index 2 = not corrected value (measured value)

$\delta_U$ = phase angle error of voltage transformer

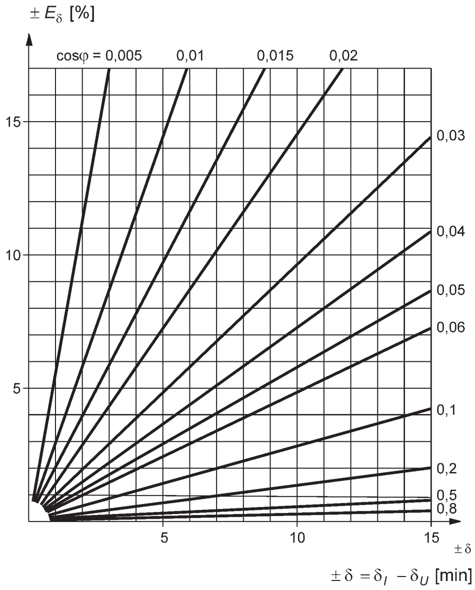
$\delta_I$ = phase angle error of current transformer

$\delta$ = $\delta_I$-$\delta_U$

$E_I$ = ratio error of current transformer

$E_u$ = ratio error of voltage transformer

***Figure 5.10:*** *Vector diagram for a single-phase load measurement connection using voltage and current transformer*




$E_\delta$ = error in measured value
$\delta$ = phase angle error difference ($\delta_I$-$\delta_U$)

***Figure 5.11:*** *Error in measured losses as a function of the difference in phase angle errors for the voltage and current instrument transformers. (The phase angle error is expressed in minutes.)*

The instrument transformer phase-angle errors are less than 1 minute, this gives $\varphi \gg (\delta_I - \delta_U)$;

Therefore, $\mathrm{tg}(\varphi - \delta_I + \delta_U)$ can be used, instead of

$$E_\delta = +\,0{,}0291 \cdot (\delta_I - \delta_U) \cdot \mathrm{tg}\varphi \qquad \%$$

where:

$\delta_I$ = current transformer phase-angle error in minutes

$\delta_U$ = voltage transformer phase-angle error in minutes

Error in measured losses depends on the difference in phase-angle errors for voltage and current transformers and not on the error for the individual instrument transformer, see figure 5.11. It should also be noted that angle errors for instrument transformers are generally expressed in minutes (arc minutes).

The total error caused by the instrument transformers is:

$$E = E_\delta + E_I + E_U \ \%$$

where:

$E_I$ = ratio error for current measuring circuit in %

$E_U$ = ratio error for voltage measuring circuit in %

or

$$E = +\,0{,}0291 \cdot (\delta_I - \delta_U) \cdot \mathrm{tg}\varphi + E_I + E_U \ \%$$

This correction formula is also valid for inductive three-phase power measurements using the three-wattmeter method. Each phase is individually corrected since the power factor, the instrument transformers and the deflections differ.

## A 5.5.2 Measuring inductive three-phase power using the two-wattmeter method

After an appropriate conversion, we arrive at the correction formula for the two wattmeters (i.e. each wattmeter (deflection) must be individually corrected).

### Wattmeter with large deflection

The corresponding instrument transformers have Index 1

$$E = +\,0{,}0291 \cdot (\delta_{I1} - \delta_{U1}) \cdot \mathrm{tg}(\varphi - 30) + E_{I1} + E_{U1} \ \%$$

### Wattmeter with small deflection

The corresponding instrument transformers have Index 2

$$E = +\,0{,}0291 \cdot (\delta_{I2} - \delta_{U2}) \cdot \mathrm{tg}(\varphi + 30) + E_{I2} + E_{U2} \ \%$$

where:

$\delta_{I2}$, $\delta_{U2}$ = phase-angle error in minutes

$E_{I2}$, $E_{U2}$ = relative error in percent where:

$$\cos(\varphi \pm 30) = \frac{P}{U_{LL} \cdot I} \rightarrow \mathrm{tg}(\varphi \pm 30) \quad \text{Note the signs}$$

The sign of the error is the same as the angle error difference when measuring single-phase power. When measuring three-phase power using the two-wattmeter method on the other hand, the sign depends also on the magnitude of the phase-angle.

The corrected load loss is therefore:

$$P_1 = P_2 \cdot \left(1 - \frac{E}{100}\right)$$

where:

$P_1$ = corrected load loss

$P_2$ = uncorrected load loss (measured load loss)

$E$ = error in percent

In general, the following holds: a positive error is subtracted from the measured value, while a negative one is added.

## A 5.6 Measuring the short-circuit voltage for starting transformers having an air gap

For starting transformers having an air gap, the relationship $X_H \gg X_1, X_2, R_1, R_2$ no longer holds, see figure 5.1. It therefore matters from which side the short-circuit voltage is being measured.

Figure 5.12 shows three possibilities for taking the measurements, but only the first two are approximately correct. If exact values are needed, the no-load and load measurements must be carried out from both sides, in order to be able to calculate the individual impedances. To measure the load loss, the measured value must be corrected by the value of the no-load losses.

## A 5.7 Connection for investigation tests

In the case of investigation tests, it may be necessary to measure the load loss of a three-phase transformer phase by phase using a single-phase supply. For star/star or star/delta connected transformers with externally accessible neutral, the measurement is taken from line to neutral.

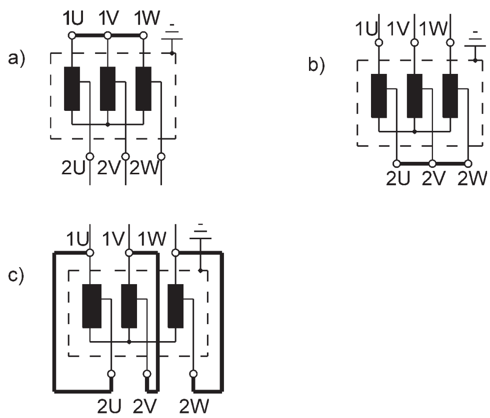



*Figure 5.12:* *Starting transformer with air gap; three possibilities for measuring the impedance voltage*

## A 5.8 Examples

### Example 1

Transformer under test:

Three-phase transformer without regulation, as per IEC.

| | | | |
|---|---|---|---|
| Power: | 55 MVA | Frequency: | 50 Hz |
| Voltages: | 55,0/11,0 kV | Vector group: | Yd5 |
| Currents: | 577/2887 A | Cooling: | ONAN |

The transformer must be out of service for at least three hours, so that there is no temperature gradient between the windings and the oil.

a) Measuring the winding resistances phase to phase

Average winding temperature: $\Theta_{mR}$ = 21,0 °C
HV (1U-1V) Average value: $R_{HV}$ = 0,0913 Ω
LV (2U-2V) Average value: $R_{LV}$ = 3,320 mΩ

b) Measuring the average winding temperature

$\Theta_{m\ top\ oil}$ = 18,0 °C
$\Theta_{m\ bottom\ oil}$ = 16,0 °C

average oil temperature = 17,0 °C
average winding temperature $\Theta_m$ is equal to the average oil temperature

**Note:**

Measurement is done immediately prior to the load loss measurement.

c) Measurement using the three-wattmeter method

Power supply: high-voltage winding
Shorted : low-voltage winding

Measured value for average winding temperature $\Theta_m$ = 17,0 °C

| $U_{av}$ | $I_{L1}$ | $I_{L2}$ | $I_{L3}$ | $I_m$ | $P_{L1}$ | $P_{L2}$ | $P_{L3}$ | $P_L$ |
|---|---|---|---|---|---|---|---|---|
| kV | A | A | A | A | kW | kW | kW | kW |
| 5,60 | 552 | 552 | 552 | 552 | 53,04 | 34,92 | 37,20 | 125,16 |

d) Checking the instrument transformer error

Error according to calibration certificate:

| Phase | Current transformer | | Voltage transformer | |
|---|---|---|---|---|
| | $E_I$ (%) | $\delta_I$ min | $E_U$ % | $\delta_U$ min |
| $L1$ | +0,02 | +2,4 | +0,15 | +2,0 |
| $L2$ | +0,02 | +3,2 | +0,14 | +1,3 |
| $L3$ | +0,02 | +3,1 | +0,15 | +1,0 |

Calculation of the instrument transformer error per phase:

| Phase | Power factor | Error calculation, $E$ % |
|---|---|---|
| $L1$ | 0,0297 | +0,0291(2,4–2,0) 33,6+0,02+0,15 = +0,56 |
| $L2$ | 0,0196 | +0,0291(3,2–1,3) 51,1+0,02+0,14 = +2,99 |
| $L3$ | 0,0208 | +0,0291(3,1–1,0) 47,9+0,02+0,15 = +3,10 |

Corrected values for $P_{L\,corr}$

| $U_{av}$ kV | $I_{L1}$ A | $I_{L2}$ A | $I_{L3}$ A | $I_m$ A | $P_{L1}$ kW | $P_{L2}$ kW | $P_{L3}$ kW | $P_{Lcorr}$ kW |
|---|---|---|---|---|---|---|---|---|
| 5,60 | 552 | 552 | 552 | 552 | 52,74 | 33,88 | 36,05 | 122,67 |

e) conversion of the short-circuit voltage and the load loss to rated current $I_r$

Short-circuit voltage kV

$$U_{CC} = 5{,}60\frac{577}{552} = 5{,}85\,\text{kV}$$

Relative short-circuit voltage %

$$\varepsilon_{CC} = \frac{5{,}85}{55}\cdot 100 = 10{,}64\,\%$$

Load loss:

$$P_L = 122{,}67\cdot\left(\frac{577}{552}\right)^2 = 134{,}03\ \text{kW}$$

at $I_r$ = 577 A $\quad\Theta_m$ = 17,0°C

f) Separation of the load losses

The ohmic loss component is

$$P_{jHV} = 3\cdot I_{ph}^{\ 2}R_{ph} = 3\cdot I_r^{\ 2}R_{ph-ph}\cdot 0{,}5 = 1{,}5\cdot I_r^{\ 2}R_{ph-ph}$$

$$P_{jLV} = 3\cdot I_{ph}^{\ 2}R_{ph} = 3\left(\frac{I_r}{\sqrt{3}}\right)^2 R_{ph-ph}\cdot 1{,}5 = 1{,}5\cdot I_r^{\ 2}R_{ph-ph}$$

HV: $577^2$ · 0,0913 · 1,5 = 45,59 kW
LV: $2887^2$ · 0,003320 ·1,5 = 41,51 kW

$P_j$ at $\Theta_{mR}$ = 21,0 °C = 87,10 kW

Conversion to $\Theta_m$ = 17,0 °C (copper winding) gives:

$$P_j = 87{,}10\cdot\left(\frac{235+17{,}0}{235+21{,}0}\right) = 85{,}74\ \text{kW}$$

at $\Theta_m$ = 17,0 °C

$P_L$ at $I_r$ and 17,0 °C = 134,03 kW
$P_j$ at $I_r$ and 17,0 °C = 85,74 kW

$P_a$ at $I_r$ and 17,0 °C = 48,29 kW

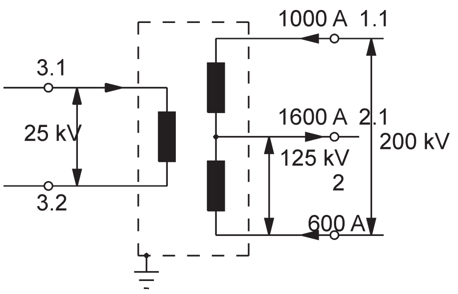



***Figure 5.13:*** *Single-phase autotransformer with a tertiary winding*

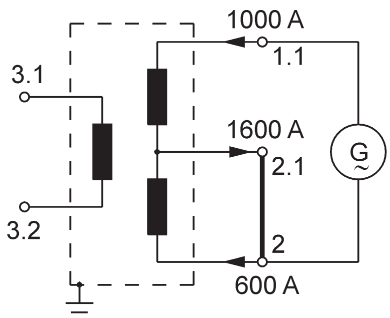



***Figure 5.14:*** *Short-circuit HV/MV*

g) Conversion to 75 °C average winding temperature gives:

$$P_j = 85{,}74 \cdot \left(\frac{235+75}{235+17}\right) = 105{,}47 \text{ kW}$$

$$P_a = 48{,}29 \cdot \left(\frac{235+17}{235+75}\right) = 39{,}26 \text{ kW}$$

$P_L$ at $I_r$ and 75 °C gives:

$$105{,}47 + 85{,}74 = 144{,}73 \text{ kW}$$

## Example 2

Transformer under test:

Single-phase autotransformer with tertiary winding, as per IEC:

$S$ = 200/200/25 MVA
$U$ = 200/125/25 kV
$I$ = 1000/1600/1000 A

Connection: Ia
Frequency: 50 Hz
Cooling: ONAN

$\varepsilon_{cc}$: HV/MV 10 %, HV/LV 35 %, MV/LV 30 %, } base 200 MVA for all values

See figure 5.13 for the schematic transformer equivalent rating:

$$S_e = (U_{HV} - U_{LV}) \cdot I_{HV} = (I_{LV} - I_{HV}) \cdot U_{LV}$$
$$= (1600 - 1000) \cdot 127 = 75 \text{ MVA}$$

Relationship $S_e$ to $S_r = \frac{75}{200} \cdot 100 = 37{,}5\ \%$

Apparent power developed in the short-circuit voltages:

$S_{cc}$ for HV/MV = 0,1 · $S_r$ = 20 MVA
$S_{cc}$ for HV/LV = 0,35 · $S_r$ = 70 MVA
$S_{cc}$ for MV/LV = 0,30 · $S_r$ = 60 MVA

The following connection circuits are possible for measuring load losses for HV/MV:

a) As per figure 5.14:

Measurement: $P_L$ = 600 kW

$$U_{cc} = \frac{S_{cc}}{I} = \frac{20000}{1000} = 20 \text{ kV}$$

$$\varepsilon_{cc} = \frac{20}{200} \cdot 100 = 10\ \%$$

The short-circuit connection must be rated for 1600 A. The measured short-circuit voltage does not need to be recalculated.

b) As per figure 5.15:

Measurement:

$$U_{cc} = \frac{S_{cc}}{I} = \frac{20000}{1000} = 20 \text{ kV}$$

$$\varepsilon_{cc}' = \frac{20}{200-125} \cdot 100 = 26{,}6\,\%$$

$$\varepsilon_{cc} = 26{,}6 \cdot \frac{S_e}{S_r} = 10\,\%$$

The short-circuit connection must be rated for 600 A.
The measured short-circuit voltage needs to be converted.

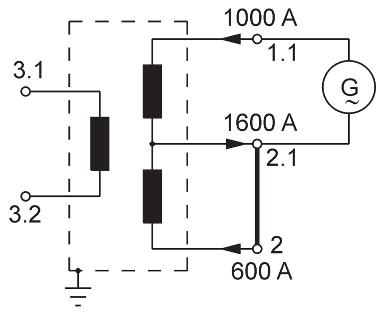



***Figure 5.15:*** *Short-circuit HV/MV*

c) As per figure 5.16:

Measurement:

$$U_{cc} = \frac{20000}{1600} = 12{,}5 \text{ kV}$$

$$\varepsilon_{cc} = \frac{12{,}5}{125} \cdot 100 = 10\ \%$$

The short-circuit connection must be rated for 1000 A and is normally very long because of the distance from the neutral connection point to the high-voltage terminal. The measured short-circuit voltage does not need to be recalculated.

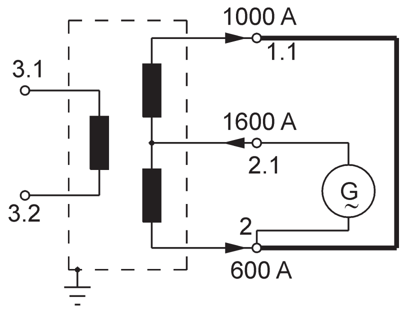



***Figure 5.16:*** *Short-circuit HV/MV*

d) As per figure 5.17:

Measurement:

$$U_{cc} = \frac{20000}{600} = 33{,}3 \text{ kV}$$

$$\varepsilon_{cc}' = \frac{33{,}3}{125} \cdot 100 = 26{,}6\ \%$$

$$\varepsilon_{cc} = 26{,}6 \cdot \frac{S_e}{S_r} = 10\ \%$$

The short-circuit connection must be rated for 1000 A and is shorter than for c). The measured short-circuit voltage needs to be converted.

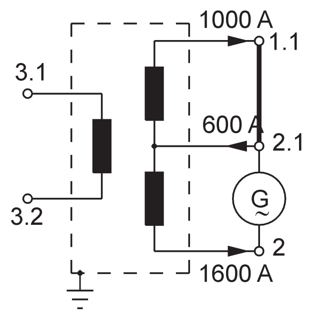



***Figure 5.17:*** *Short-circuit HV/MV*

Load loss measurement for the combination HV/LV, figure 5.18.

Measurement:

$$U_{cc} = \frac{S_{cc}}{I} = \frac{70000}{1000} \cdot \frac{25}{200} = 8{,}75 \text{ kV}$$ referred to 25 MVA

$P_L$ = 80 kW

Referred to 200 MVA: $80 \cdot \left(\frac{200}{25}\right)^2 = 512 \text{ kW}$

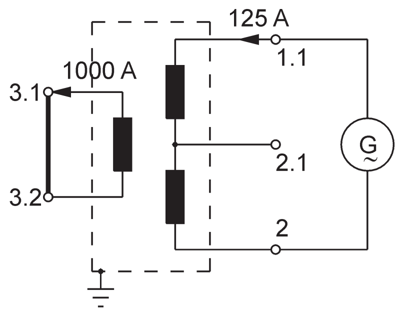



***Figure 5.18:*** *Short-circuit HV/LV*

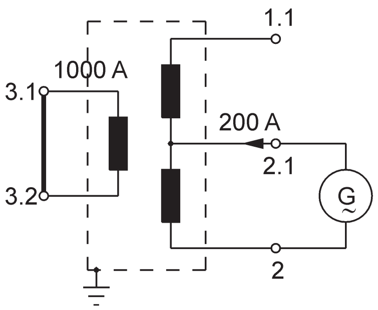



***Figure 5.19:*** *Short-circuit MV/LV*

Load loss measurement for the combination MV/LV, see figure 5.19.

Measurement:

$$U_{cc} = \frac{S_{cc}}{I} = \frac{60000}{1600} \cdot \frac{25}{200} = 4{,}59 \text{ kV} \quad \text{referred to 25 MVA}$$

$P_L$ = 70 kW

Referred to 200 MVA: $70 \cdot \left(\frac{200}{25}\right)^2 = 448 \text{ kW}$

Calculation of the short-circuit voltage for three-winding operation:

$\varepsilon_{cc}$ referred to 200 MVA, gives: $\varepsilon_{cc12}$ = 10 %
$\varepsilon_{cc13}$ = 35 %
$\varepsilon_{cc23}$ = 30 %

$$\varepsilon_{cc1} = \frac{10+35-30}{2} = 7{,}5 \text{ \%}$$

$$\varepsilon_{cc2} = \frac{10+30-35}{2} = 2{,}5 \text{ \%}$$

$$\varepsilon_{cc3} = \frac{30+35-10}{2} = 27{,}5 \text{ \%}$$

Calculation of the combined three-winding load loss at 200/200/25 MVA:

$P_{L\ (200\ MVA)}$: → $P_{L12}$ = 600 kW
$P_{L13}$ = 512 kW
$P_{L23}$ = 448 kW

For a load of 200 MVA the three losses ($P_{L1}$, $P_{L2}$ and $P_{L3}$) will be:

$$P_{L1} = \frac{600+512-448}{2} = 332 \text{ kW}$$

$$P_{L2} = \frac{600+448-512}{2} = 268 \text{ kW}$$

$$P_{L3} = \frac{512+448-600}{2} = 180 \text{ kW}$$

The actual load (rated value) is only 25 MVA and the loss $P_{L3}$ has to be adjusted accordingly:

$$P_{L3(\text{adj})} = 180 \cdot \left(\frac{25}{200}\right)^2 = 2{,}8 \text{ kW}$$

The combined three-winding load loss at 200/200/25 MVA will then be:

$$P_L = 332 + 268 + 2{,}8 = 602{,}8 \text{ kW}$$

# Testing of Power Transformers

## 6. Measuring the no-load loss and no-load current

# 6. Measuring the no-load loss and no-load current

## 6.1 References / standards

- IEC 60076-1(2000), clause: 10.1: “General requirement for routine, type and special tests”, clause 10.5: “Measurement of no-load loss and current” [1]
- IEC 60076-8 (1997), clause: 10: “Guide to the measurement of losses in power transformers” [6]
- IEEE Std C57.12.90-1999, clause: 8: “No-load losses and excitation current” [51]

**Note:**

Measurement of the no-load loss and no-load current is a **routine test** according to IEC Standard [1] and to IEEE Standard [50].

## 6.2 Purpose of measurement

The no-load loss is developed by the excitation of the transformer and it represents a considerable amount of energy during the life-time of the transformer. In general the actual loss figure has to be guaranteed by the manufacturer and a correct value on the measured no load loss is therefore important.

## 6.3 General

### 6.3.1 The unloaded transformer

An energized but not loaded transformer can be seen as an iron core reactor. The equivalent circuit diagram of this reactor (transformer in no-load operation without a secondary winding) is shown in figure 6.1.

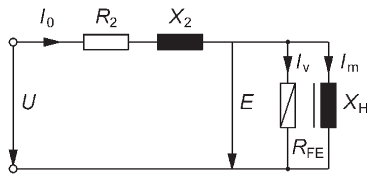
The phasor diagram in figure 6.2 is derived from the equivalent circuit diagram.

The magnetizing characteristic of the iron core displays the well-known loop characteristic or hysteresis curve, see figure 6.3. The area inside this dynamic or AC loop is a measure of the energy required to vary the flux for one cycle, i.e. for one period:

$$P_{Fe} = \frac{E^2}{R_{Fe}}$$

where:

$P_{Fe}$ = magnetizing loss
$E$ = applied voltage
$R_{Fe}$ = equivalent resistance




$R_2$ = winding resistance
$X_2$ = winding self-inductance expressed as a reactance
$R_{Fe}$ = iron equivalent resistance
$X_H$ = magnetising reactance
$I_0$ = no-load current
$E$ = open-circuit voltage

***Figure 6.1:*** *No-load – equivalent diagram*

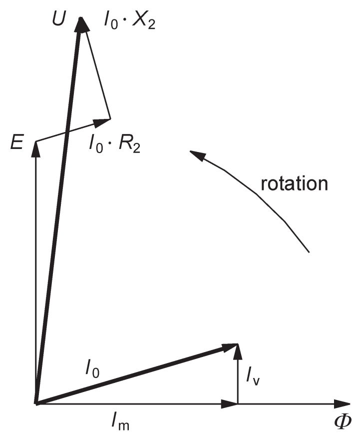
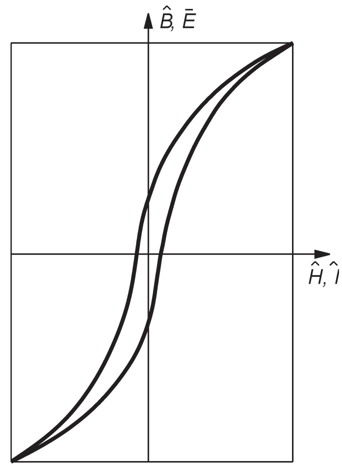



***Figure 6.2:*** *No-load – vector diagram*




$\hat{B}$ = max. magnetic induction
$\hat{H}$ = max. magnetic intensity

***Figure 6.3:*** *Magnetic loop*

Using Faraday's law, the following induction formula can be derived:

$$u = -\frac{\partial \Phi}{\partial t}$$

where:

$u$ = instantaneous value of induced voltage

$\Phi$ = $\hat{\Phi} \cdot \cos\omega t$

**Note:**

Magnetic fluxes and flux densities are generally presented by their peak values, $\Phi_0$ is therefore assigned to the $\hat{\Phi}$-value.

This gives:

$u$ = $\omega \cdot \Phi_0 \cdot \sin \omega t$

Using:

$\hat{\Phi}_H$ = $\hat{B}_{Fe} \cdot A$

$\omega$ = $2\pi f$

where:

$\hat{B}$ = flux density in the core (peak value) in $T$ generally denoted $B$

$A$ = core cross-section area

$\omega$ = angular frequency 1/s

$f$ = power frequency in Hz

This gives:

$u$ = $\omega \hat{B} A N \sin \omega t$

where:

$N$ = number of turns circumferencing the flux $\hat{B} \cdot A$.

The average rectified voltage $\bar{U}$ is then:

$\bar{U}$ = $4{,}0 \cdot f \cdot \hat{B} \cdot A \cdot N$

For its r.m.s.-value the wellknown transformer formula valid for sinusoidal quantities is:

$U_e$ = $4{,}44 \cdot f \cdot \hat{B} \cdot A \cdot N$

where:

$\bar{U}$ = average value of the voltage in volts

$U_e$ = r.m.s.-value of the voltage in volts

### 6.3.2 No-load loss

The no-load loss $P_0$ consists of the following components:
a) Iron losses:

$$P_{Fe} = P_h + P_w = k_h \cdot f \cdot \hat{B}^x + k_w \cdot \delta^2 \cdot f^2 \cdot \hat{B}^2$$

where:

$P_h$ = hysteresis losses
$P_w$ = eddy losses
$k_h, k_w$ = hysteresis and eddy loss coefficient
$\delta$ = sheet thickness
$x$ = exponent - function of induction

b) Dielectric losses:

$$P_c = U^2 \cdot \omega C \cdot \text{tg}\delta$$

c) Winding losses:

$$P_j = I_0^2 \cdot R_2$$

For normal power transformers the dielectric and Joule losses can be neglected as they are several orders of magnitude smaller:

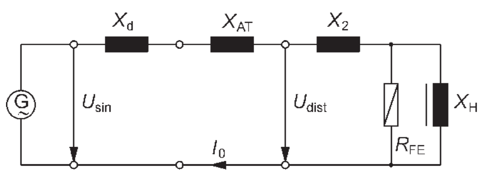
$$P_{Fe} \gg P_c + P_j$$

This means that no-load loss $P_0$ is equal to the iron losses $P_{Fe}$. Exceptions are starting transformers with an air gap or with windings designed for short-time duty.

### 6.3.3 Interdependence of no-load loss and voltage distortion

For no-load measurements in the test laboratory, the voltages at the transformer under test will be distorted due to internal impedance of the voltage source. The voltage distortion is caused by the non-sinusoidal no-load current of the transformer under test, which causes a voltage drop in the internal impedance of the supply, the generator and matching transformer, see figure 6.4.

Normal measuring practice assumes that the hysteresis losses $P_h$ are a function of the peak value of induction and therefore also a function of the average value of the applied voltage. If this voltage is properly set, $P_h$ is not affected by the voltage distortion.




$X_d$ = generator synchronous reactance
$X_{AT}$ = matching transformer short-circuit reactance
$X_2$ = LV winding stray reactance
$R_{FE}$ = iron equivalent resistance
$X_H$ = main resistance
$U_{sin}$ = source voltage without distortion
$U_{dist}$ = voltage with distortion at TT
$I_0$ = no-load current

***Figure 6.4:*** *Transformer connections for no-load loss test: equivalent diagram*

The eddy losses $P_w$ on the other hand are a function of the square of the r.m.s. voltage, the same as the losses in a DC resistance. The r.m.s. value is however affected by the voltage distortion and therefore also the eddy losses.

For sinusoidal voltage waveforms:

peak factor of the voltage $$k_s = \frac{\hat{U}}{U} = \sqrt{2}$$

form-factor of the voltage $$k_f = \frac{U}{\overline{U}} = 1{,}11$$

For a distorted waveform, the form-factor changes as a factor of the sine wave. Peaked waves ($k_f > 1{,}11$) with a higher r.m.s. value at the same average voltage (i.e. at the same maximum induction) lead to higher losses. Shallow waves ($k_f < 1{,}11$) with a smaller r.m.s. value at the same average voltage cause lower losses.

These voltage distortions do not occur during operation because the impedance of the supply system is much smaller than the impedance of the main inductance $X_H$ of the transformer. For this reason, and to be able to compare the losses of different transformers, the no-load losses are guaranteed using a sinusoidal supply. Losses measured with a distorted voltage must be recalculated.

### 6.3.4 Form-factor correction for no-load losses

The following holds for no-load losses measured with a distorted voltage:

$$P_{0m} = P_h + P_w \cdot \left(\frac{k_f}{1{,}11}\right)^2$$

where:

$P_{0m}$ = no-load loss measured with distorted voltage
$P_h$ = hysteresis losses
$P_w$ = eddy losses
$k_f$ = form-factor of voltage

Division by $P_0$ (= losses for a sinusoidal voltage) gives:

$$\frac{P_{0m}}{P_0} = \frac{P_h}{P_0} + \frac{P_w}{P_0} \cdot \left(\frac{k_f}{1{,}11}\right)^2$$

**IEC 60076-1** [1]

Correction formula gives:

$$P_0 = P_{0m} \cdot (1 + d)$$

where:

$$d = \frac{\bar{U} \cdot 1{,}11 - U}{\bar{U} \cdot 1{,}11}$$

A voltage distortion during test ($\bar{U} \cdot 1{,}11 - U$) of up to 3 % is permitted. If the value is larger, the measuring circuit must be checked and improved.

**IEEE Std C57.12.90** [51]

IEEE defines the relative loss components. The no-load loss must be corrected as follows:

$$\frac{P_h}{P_0} = P_1 \quad \text{and} \quad \frac{P_w}{P_0} = P_2$$

it follows that:

$$P_0 = \frac{P_{0m}}{P_1 + P_2 \cdot \left(\frac{U}{\bar{U} \cdot 1{,}11}\right)^2} = \frac{P_{0m}}{P_1 + P_2 \cdot \left(\frac{k_f}{1{,}11}\right)^2} = \frac{P_{0m}}{P_1 + P_2 \cdot k}$$

If the actual per-unit values for $P_1$ and $P_2$ are known, the no-load loss can be calculated for a true sinusoidal waveform. If the values are not known, 0,5 per-unit is used for both quantities (grain oriented core steel quality). If the correction for the measured no-load loss is greater than 5 % by this calculation, the measuring circuit related to the voltage distortion must be checked or improved.

The per-unit values $P_1$ and $P_2$ can also be determined by measurement, see clause A 6.2.

### 6.3.5 Interdependence of no-load loss and iron temperature

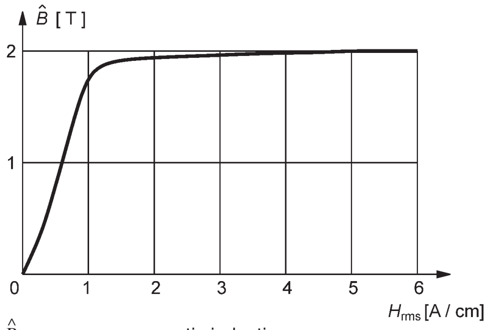
Fundamentally, a no-load loss temperature dependence can be seen only at relatively high temperature variations.

**IEC 60076-1** [1]

The transformer should be tested at the ambient temperature in the test laboratory. Neither a reference temperature nor a correction formula is specified.

**IEEE Std C57.12.90** [51]

The reference temperature for no-load loss is +20 °C – see IEEE Std C57.12.00 clause 5.9.




$\hat{B}$ = max. magnetic induction
$H_{rms}$ = magnetic intensity

***Figure 6.5:*** *Magnetization diagram*

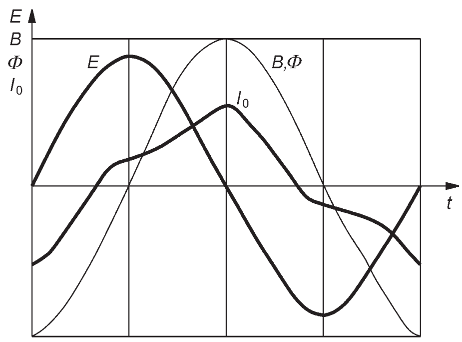
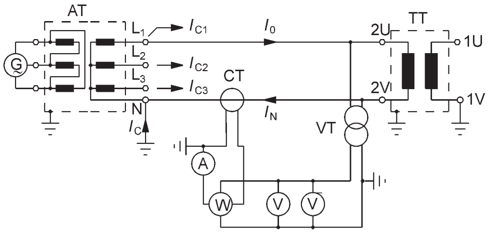



***Figure 6.6:*** *Oscillographic diagram*




| | | |
|---|---|---|
| AT | = | matching transformer |
| TT | = | transformer under test |
| CT | = | current transformer |
| VT | = | voltage transformer |
| V_ | = | r.m.s.-voltmeter |
| V | = | mean values voltmeter |
| $I_0$ | = | no-load current |
| $I_N$ | = | neutral current |
| $I_{C,\,C1...3}$ | = | capacitive currents |

***Figure 6.7:*** *Single-phase transformer connections for no-load loss test; supply with phase-voltage L1-N*

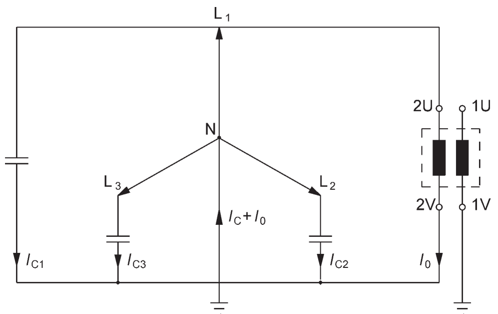



***Figure 6.8:*** *Influence of capacitance currents; supply with phase-voltage L1-N; equivalent diagram of figure 6.7*

Correction of the measured no-load loss is not required if the following conditions are met:

a) The average oil temperature (average iron temperature) is within ±10 °C of the reference temperature

b) The difference between the top and the bottom oil temperatures does not exceed 5 °C.

If the above conditions cannot be met, the measured no-load loss can be referred to the above reference temperature of 20 °C using the following empirical formula:

$$P_0 = P_{0m} \cdot (1 + (\Theta_m - 20) \cdot K)$$

at a reference temperature of 20 °C

where:

$P_0$ = no-load loss at 20 °C and average oil temperature (iron temperature)

$P_{0m}$ = no-load loss at the average oil temperature (iron temperature) during test

$\Theta_m$ = average oil temperature (iron temperature) during test

$K_T$ = empirical coefficient; for grain oriented core quality it is 0,00065 if the actual value is not available

### 6.3.6 No-load current

Because of the non-linear magnetization characteristic, see figure 6.5, of the transformer core and the iron losses corresponding to the area under the loop, see figure 6.3, the resulting no-load current is necessarily distorted when a sinusoidal voltage is applied, see figure 6.6. For smaller power transformers the no-load current is about 1 to 5 % of rated current and for large power transformers 0,1 to 0,3 %.

The no-load current is the r.m.s value of the current measured during the no-load loss test. It is generally expressed in percent of the rated current of the winding which supplies the voltage. For three-phase transformers the value is the average of the three phases.

The current supplied into the transformer is the sum of the current needed for the magnetization of the core and a capacitive current reflecting the capacitance of the windings. For low magnetization the capacitive current may be dominant, especially for high voltage transformers, and as a consequence the no-load current may decrease to a minimum value when increasing the voltage. Once the voltage is above the minimum current value the no-load current will increase.

## 6.4 Measuring circuit

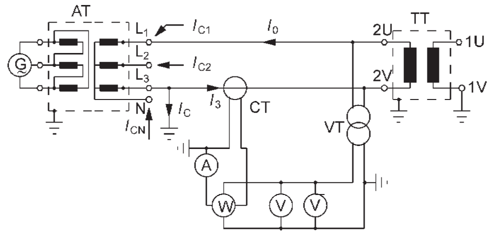
### 6.4.1 Single-phase transformers

The position of the circuit earthing may create an error on the measured no-load loss figure when measuring no-load loss on single-phase transformers. The source of the error is a capacitive earth current caused by parasitic cable capacitances, as well as generator and matching transformer windings. The path to earth for the individual currents is the earthed terminal, see figures 6.7 and 6.9, on the supply-side.

The circuit shown in figure 6.7 and the corresponding equivalent circuit diagram, figure 6.8, show the relationships when using a phase to neutral supply ($L_1$ - $N$). In certain cases the no-load current $I_0$ is affected by the resulting capacitive current $I_c$. Normally the three capacitive currents $I_{c1}, I_{c2}$ and $I_{c3}$ are approximately of the same magnitude and shifted in phase by 120°. In this case the resulting current is zero.

If the supply voltages do not have the same potentials to earth, there will be a residual current $I_c$. This residual current can affect the no-load current, depending on the location of the earth termination. This source of error can be eliminated by placing the earth ahead of the current transformers on the supply-side. For the measuring circuit shown in figure 6.9, the matching transformer supply the transformer under test with line-to-line voltage, phases $L_1$ and $L_3$. The corresponding equivalent circuit diagram, compare figure 6.10, shows the effect of the resulting current $I_c$ on the no-load current $I_0$.

The following guideline is applicable when performing no-load measurements on single-phase transformers having one terminal earthed on the supply side. The current transformer is then to be connected to the non-earthed side. If this is not permitted because of the rated operating voltage of the transformer, it can be connected in the earthed supply cable if the earth is connected ahead of the transformer as viewed from the supply-side.




$I_3$ = resultant current
$I_{C, CN, C1...3}$ = capacitive currents

**Figure 6.9:** *Single-phase transformer connections for no-load loss test; supplied with voltage $L_1$-$L_3$*

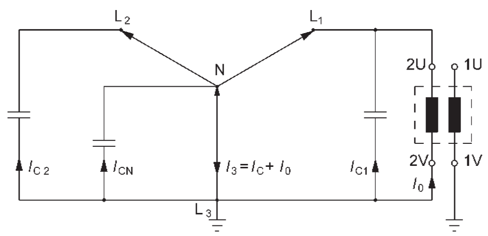



**Figure 6.10:** *Influence of capacitive currents; supplied with voltage $L_1$-$L_3$; equivalent diagram of figure 6.9*

### 6.4.2 Three-phase transformers

When testing no-load losses using a matching transformer, care must be taken in the primary and secondary circuits of the measuring circuit. Figure 6.11 is a single-line diagram of the test circuit and includes a table with the fundamentally allowed connection combinations.

The individual elements of the circuit have the following requirements:

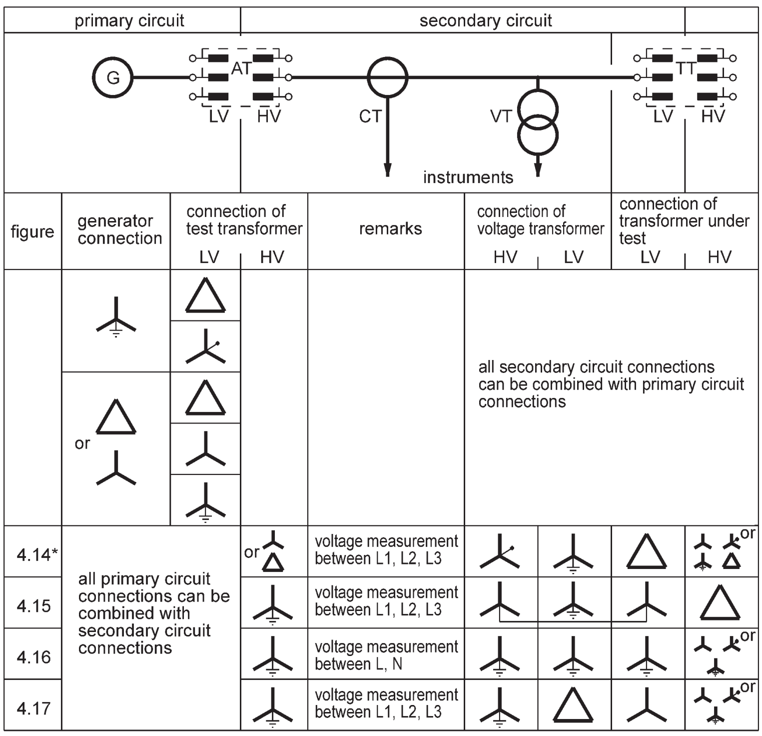
- the generator must maintain a constant frequency with changing load
- the short-circuit impedance of the generator and the matching transformer should be as small as possible

This means that the machine rating compared to the no-load apparent power of the transformer under test should be as large as possible (factor of 5 to 10). Low short-circuit impedances result in small voltage distortions.

When testing three-phase transformers, the voltages induced in the individual windings (phase voltages) must be measured to be able to determine the form factor of the voltage. The line-to-line voltages of star-connected windings are made up of the phase voltages; the form factor for these voltages is different because it cannot include harmonics divisible by three. To achieve the maximum induction the exact measurement of

$$\bar{U} = K \cdot f \cdot \hat{B}$$

is necessary.




AT = matching transformer
TT = transformer under test
HV = high voltage
LV = low voltage
CT = current transformer
VT = voltage transformer

***Figure 6.11:*** *Three-phase transformer connections for no-load loss test; single pole schematical form*

# 6. Measuring the no-load loss and no-load current

The table in figure 6.11 includes the necessary and allowed connection combinations possible for the different connection types and individual circuit elements. Figures 6.12 to 6.15 show the various measuring circuits.

The circuit in figure 6.12 is suitable for all transformers under test, with vector groups Yd, Ynd or Dd. The voltage transformers and wattmeters are connected in star. The voltmeters are connected between two phases and measure the line-to-line voltages which are also the phase voltages for a delta-connected transformer under test.

Figure 6.13 shows the connection for transformers having vector group Dyn. The voltage transformers and wattmeter are connected in star. The voltmeters measure the line-to-line voltages, this is allowed in this case despite the star connection. This is because the third order harmonic currents can flow in the high-voltage winding due to the delta connection. Voltage distortions on the low-voltage winding are thus avoided.

In figure 6.14, for vector groups Yyn and YNyn, the voltmeters must measure the phase voltages.

For the circuit in figure 6.15, vector groups Yy und YNy, the voltage transformers are delta-connected on the secondary side. The voltmeters measure the line-to-line voltages.

### 6.4.3 Measuring equipment specification

For measuring equipment specification, see clause A 6.1.

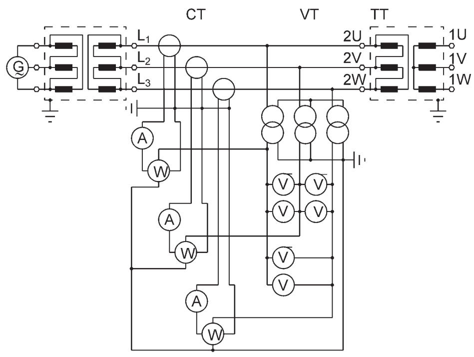



*Figure 6.12:* *Three-phase transformer connections for no-load loss test; for Yd, YNd and Dd*

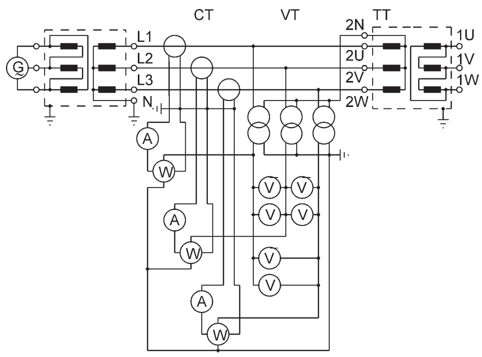



*Figure 6.13:* *Three-phase transformer connections for no-load loss test; for Dyn*

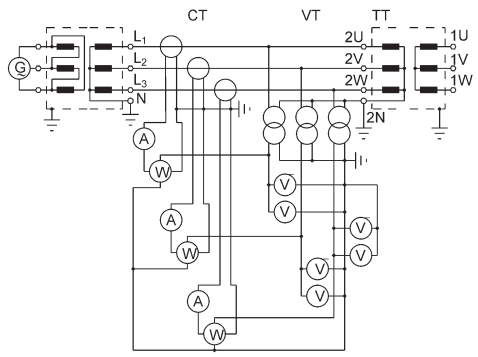



*Figure 6.14:* *Three-phase transformer connections for no-load loss test; for Yyn and YNyn*

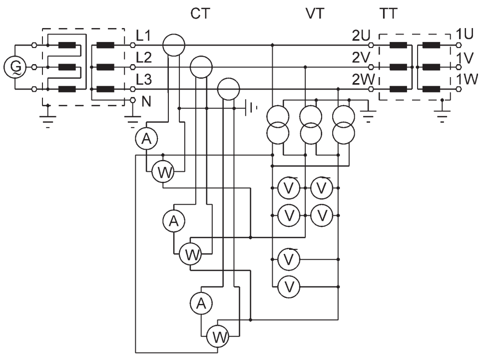



***Figure 6.15:*** *Three-phase transformer connections for no-load loss test; for Yy and YNy*

## 6.5 Measuring procedure

Built-in current transformers must be shorted during the test and condenser bushing taps must be earthed. Furthermore, care must be taken to earth the neutral points with not fully insulated windings as per information in figure 6.11. Before carrying out the no-load loss test, the voltage ratio must be checked. For oil transformers the bushings and Buchholz relay must be vented and the oil level of the transformer (and on-load changer if there is one) must be checked.

Before the loss measurements actually take place the transformer to be tested must be excited by 1,1 to 1,15 times rated voltage. The over-excitation reduces the effects of remanence caused by DC current excitation during resistance measurements or from the switching impulse. The correct no-load loss cannot be seen until there have been several cycles of the magnetizing characteristic. During this process the readings of the ammeters and wattmeter decrease. When the measured figures are steady, the actual loss measurements can start.

Typically, measurements are taken starting at 110 and decreasing to 100, 90 and 80 % of rated voltage. The supply voltage is adjusted using an average reading voltmeter. For three-phase transformers the average of the three voltages is used. If the voltage cannot be set with a precision of about 0,1 % of the guaranteed values, the actual loss figure for a specified voltage is obtained by interpolation.

When testing large three-phase units the three wattmeters will exhibit differing figures. It is even possible for one wattmeter reading to be negative. The actual input power is the sum of the readings of the three wattmeter. The magnetic asymmetry of the iron core causes asymmetrical no-load currents. Depending on the flux density in the core, the phase displacement between current and voltage in one phase is greater than 90° which will be seen as a negative power in one wattmeter [211].

## 6.6 Evaluation of the measuring results

Depending on the type of voltage distortion, the no-load loss compared to the excitation with a sinusoidal waveform can be less or greater. The supply voltage is adjusted using an average-voltage voltmeter and all remaining test values are collected. If corrections are required for instruments and instrument transformer errors (see section 5 clause A 5.5) the measured no-load loss is recalculated for a sinusoidal waveform using the formula

for IEC:

$$P_0 = P_{0m} \cdot \left[ 1 + \left( \frac{\overline{U} \cdot 1{,}11 - U}{\overline{U} \cdot 1{,}11} \right) \right]$$

and for IEEE:

$$P_0 = \frac{P_{0m}}{P_1 + P_2 \cdot \left( \frac{U}{\overline{U} \cdot 1{,}11} \right)^2}$$

In general IEEE requires that the no-load loss shall be referred to an average oil temperature (average iron temperature) of + 20°C, see Section 6.3.2.

The r.m.s value of the current measured during the no-load loss test is the no-load current. It is generally presented as a relative figure to rated current of the winding to be excited. For three-phase transformers the average of the three phases is used.

Correction of the instrument and instrument transformer errors is carried out for the no-load loss measurements (see section 5, appendix A 5). The effect of the instrument transformer error is smaller for no-load loss measurements than for the load measurements, since cos $\varphi_0 = R_{Fe}/Z$ is greater.

## 6.7 Measuring uncertainty

The current and voltage transformers, as well as the instruments must be adequate for the special requirements of no-load loss measurements (i.e. the frequency response must be approximately 1000 Hz to allow the current and voltage distortions to be properly measured).

The following are the target measuring uncertainties:

- stability of the supply frequency:
  ± 0,5 % of rated frequency (a requirement for IEEE)
- voltage measuring system:
  ± 0,1 % for a frequency range of 50 to 1000 Hz
- no-load loss measuring system:
  ≤ 0,5 % for a power factor of 0,5 and a frequency range of 50 to 1000 Hz

Classical current and voltage transformers should have the smallest possible phase-angle and amplitude errors at the actual burden and be loaded between 80 to 120 % of rated value (note the transformer calibration point).

Care must be taken to ensure that the measuring devices have sufficient frequency response. Especially the selection of the measuring ranges, which must include the peak measured values. This is even (and especially) true when choosing modern loss measuring equipment, like capacitive voltage dividers, zero flux current transformers and special power analyzers for transformers.

# Appendix A 6

# Measuring the no-load loss and no-load current

## A 6.1 Measuring equipment specification

Although the power factors for unloaded transformers are generally greater than for load loss measurements, the three-wattmeter method is preferred instead of the two-wattmeter method.

Especially for large three-phase units where significant differences in power input to the individual phases occur due to a non-symmetrical core, the three-wattmeter method should be used so that required instrument error corrections can be applied (see section 5). For small and medium-sized transformers on the other hand, the two-wattmeter method could be an alternative.

### IEC 60076-1 clause 10.1 [1]

In general the measuring equipment should have a certified and traceable measuring uncertainty, and be periodically calibrated according to ISO 9001 rules. Special recommendations for loss measurements are given in IEC 60076-8 [6] (clause 10 "Guide to the measurement of losses in power transformers").

### IEEE Std C57.12.90 clause 8 [51]

The supply frequency for the loss measurements should be within 0,5 % of rated frequency. For three-phase transformers the average of the three voltages is the correct measuring value.

The two-wattmeter method should not be used for three-phase transformer no-load loss measurements.

## A 6.2 Determination of the hysteresis and eddy current loss components

If the values for $P_1$ and $P_2$ (section 6.3.4) are not reliably known for some reason, they can be empirically determined in the test laboratory using two test methods.

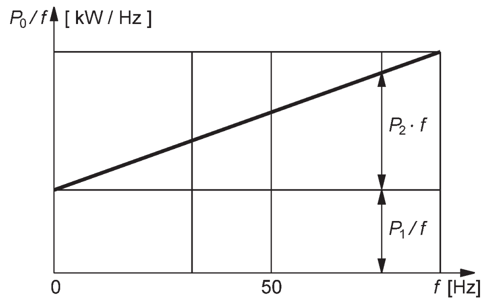
a) Frequency method

This method is based on the relationship:

$$P_0 = P_h + P_w = P_1 \cdot f + P_2 \cdot f^2$$

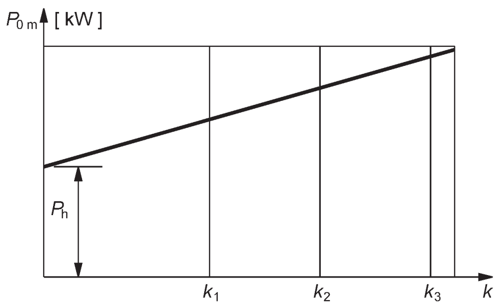
division by $f$ gives:

$$\frac{P_0}{f} = P_1 + P_2 \cdot f \qquad \text{for } \hat{B} = const.$$




$P_0/f$ = $P_1 + P_2 \cdot f$
$P_0$ = no-load losses
$P_1$ = hysteresis losses
$P_2$ = eddy current losses

***Figure 6.16:*** *Separation of no-load losses; frequency method*




$P_{0m}$ = measured no-load losses
$P_h$ = hysteresis losses
$k_{1,2,3}$ = form factors $k = k_f/1{,}11$

***Figure 6.17:*** *Separation of no-load losses; form factor method*

The no-load loss is determined for at least two frequencies with the same induction and non-distorted voltage. The measuring points are entered on a graph after recalculation of the measured figures according to the above formula, see figure 6.15.

The loss component $P_1/f$, is determined by extrapolation to $f = 0$ and further calculation gives the $P_2 \cdot f$ component. The loss components can therefore be determined at any frequency. For this method the waveforms must be purely sinusoidal so that the $P_1$ and $P_2$ components can be determined with sinusoidal excitation. It is therefore not always usable in test laboratories since distortions frequently occur.

b) Form-factor method

The form-factor method does not have the above limitations. On the contrary, it uses the effect of the voltage distortion to determine the components $P_1$ and $P_2$.

Starting with the above formula

$$P_{0m} = P_h + P_w \cdot k \qquad k = \left(\frac{k_f}{1{,}11}\right)^2$$

the no-load loss at the same maximum induction and various $k$-factors are measured by changing the generator and the matching transformer connections and are entered on a graph, see figure 6.17. The hysteresis loss component is obtained when $k = 0$. The remainder makes up the eddy current loss component. The definition of $k_f$ is found in clause 6.3.4.

## A 6.3 Preliminary measurements of the iron core

For new designs, different manufacturing processes or after repair service, preliminary measurements are carried out on the completed iron core (with upper yoke).

A temporary auxiliary winding is mounted on the iron core for this purpose. This winding, which can be made from flexible cable wrapped around the core, must be evenly distributed and cover a minimum of 80 % of the length of the limb so that the induction along the limb length is constant. For three-phase cores the three windings are connected in delta.

The core data, based on the design calculations, or the transformer nameplate data are used to determine the winding requirements. The optimal number of turns and the conductor cross-section (taking into account the over-excitation at e.g.120%) are based on the supply source for the test laboratory, the winding voltage per turn at rated induction or rated voltage, and the no-load apparent power. The auxiliary winding must also be insulated for the maximum expected voltage referred to the core.

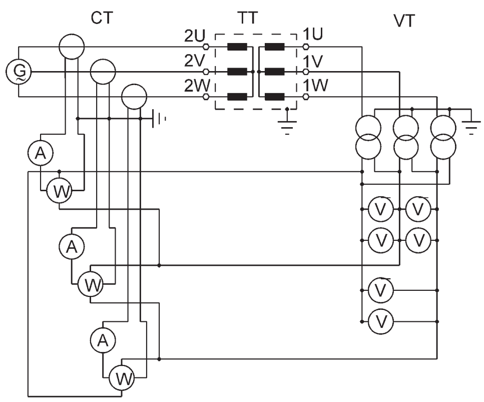



***Figure 6.18:*** *Connections for no-load loss test on three-phase starting transformer with air gap*

By comparing the Epstein values of the steel quality and the iron core measured values, the effects of manufacturing are shown. This gives an indication of the average steel quality for the total quantity of steel used. In addition, a comparison of the measured values of the completed transformer with those of the iron core provides information about the increased loss due to the stacking procedure of the upper yoke, which is performed after winding assembly.

## A 6.4 Special measuring circuits

### A 6.4.1 Starting transformers

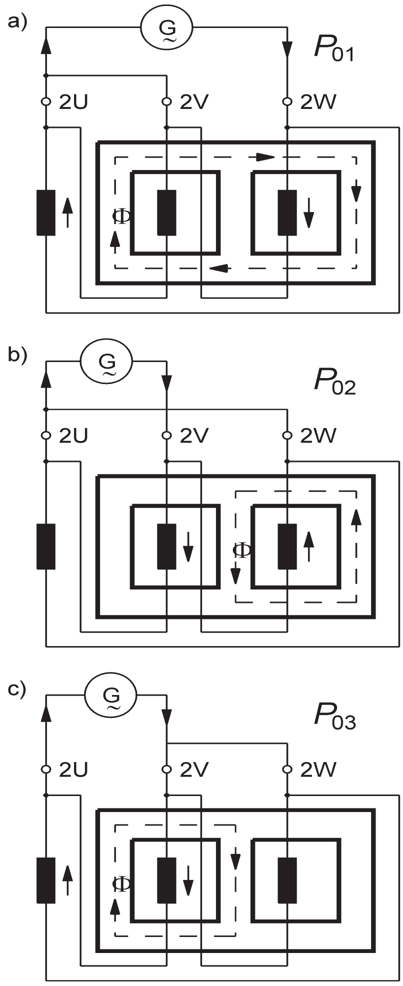
For starting transformers with an air gap, reactor cores with a small air gap, as well as transformers with windings rated for short-time duty, the winding losses caused by no-load currents are no longer negligible. Even the voltage drop, see figure 6.2, is possibly no longer negligible. In such cases the measuring circuit shown in figure 6.18 is used. The currents are measured on the supply side and the voltages determined on the secondary side. To calculate the corresponding voltage the voltage ratio needs to be considered.

### A 6.4.2 Single-phase no-load loss measurement for three-phase transformers

For investigation tests during faults, the determination of no-load losses using single-phase excitation can be useful. Figure 6.19 shows the three connection configurations and the corresponding flux characteristic in the core.

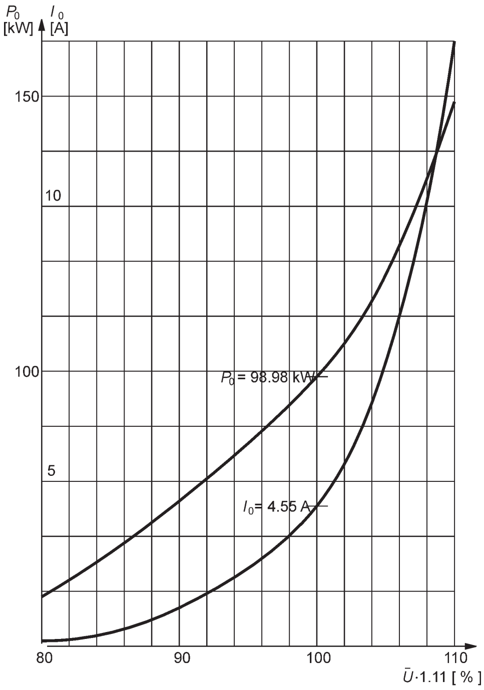
$$P_0' = \frac{P_{01} + P_{02} + P_{03}}{2}$$

This corresponds approximately to the measured no-load loss with three-phase excitation.




$P_{01,02,03}$ = measured values

***Figure 6.19:*** *Connection for single-phase no-load test on three-phase transformers; clarification test*




$P_0 \;=\; f(\bar{U} \cdot 1{,}11)$

$I_0 \;=\; f(\bar{U} \cdot 1{,}11)$

***Figure 6.20:*** *No-load loss and current as a function of voltage mean value*

## A 6.5 Example

Three-phase regulating transformer, as per IEC:

Power: 146,5 / 146,5 / 40 MVA

Frequency: 50 Hz

Voltages: 250 ± 12 x 3,2 / 165 / 24 kV

Vector group: YNyn0d5

Currents: 292 ... 338 ... 402 / 513 / 962 A

The low-voltage winding was fed with 110, 100, 90, and 80 % of rated voltage during the acceptance test. The following values are the measured values at 100 % rated voltage from the test report

| $\bar{U}$·1,11 | $U$* | $I_{L1}$ | $I_{L2}$ | $I_{L3}$ | $I_0$ | $P_{L1}$ | $P_{L2}$ | $P_{L3}$ | $P_{0m}$ | $P_0$ |
|---|---|---|---|---|---|---|---|---|---|---|
| kV | kV | A | A | A | A | kW | kW | kW | kW | kW |
| 24,00 | 24,33 | 5,56 | 4,05 | 3,79 | 4,47 | 43,52 | 42,00 | 14,84 | 100,36 | 98,98 |

*average of the three voltages

The measured values determined in this way for 110, 100, 90, 80 % are entered on a graph and the actual value is derived from it by interpolation, see figure 6.20.

From the graph in figure 6.20, the value $\bar{U} \cdot 1{,}11 = 24$ kV corresponding to 100 % rated voltage is found, $P_0$ = 98,98 kW and $I_0$ = 4,55 A.

The no-load apparent rating power is:

$$S_0 = 4{,}55 \cdot 24 \cdot \sqrt{3} = 189{,}14 \text{ kVA}$$

The relative no-load current is:

$$I_0 = \frac{I_{0m}}{I_{rLV}} \cdot \frac{S_{rLV}}{S_{rHV}} = \frac{4{,}55}{962} \cdot \frac{40}{146{,}5} \cdot 100 = 0{,}129\,\%$$

referred to 146,5 MVA

The power factor is:

$$\cos \varphi_0 = \frac{P_0}{S_0} = \frac{98{,}98}{189{,}14} = 0{,}52$$

# Testing of Power Transformers

## 7. Separate source AC withstand voltage test or Applied-voltage test

# 7. Separate source AC withstand/or Applied-voltage test

## 7.1 References / Standards

- IEC 60076 (2000), clause:11,
  "Separate source AC withstand voltage test" [3]
- IEEE C57.12.90-1999, clause10.6:
  "Applied-voltage tests" [51]
- IEEE C57.12.00-2000, clause 5.10: "Insulation levels" [50]

**Note:**

The separate source AC withstand test or applied-voltage test is a **routine test** according to IEC Standard [1] and to IEEE Standard [50].

## 7.2 Purpose of the test

The purpose of the separate source AC withstand test or applied-voltage test (according to IEEE) is to verify the integrity of the main insulation.

This main insulation does not only mean the insulation system between the two windings (major insulation), but also - more generally - the insulation between the winding and earth (end insulation) and all connections to earth and to each other.

## 7.3 General

A separate AC source is applied to the transformer, hence the name "applied-voltage test". The transformer is not magnetized for this test, as it is for instance during the induced voltage test, see section 8.

Test voltage $U_P$ relates to the insulation level of transformer winding for transformers with uniform insulation. Every part of the winding is exposed to the full test voltage, $U_P$, between the winding and earth.

With non-uniform insulation (graded insulation) the test voltage, $U_P$, refers to insulation requirements of the winding end with the lowest requirements, generally the neutral.

Test voltage $U_P$ in kV r.m.s.-value according to IEC is given in table 2, 3 and 4 of the above- referenced standard [3]; according to IEEE in table 5, 6, 7 and 8 of IEEE C57.12.00-2000 [50].

Test voltage must be adjusted using peak voltmeter $U_{Peak}/\sqrt{2}$.

On repeated tests somewhat reduced test voltages may apply, see section 2.

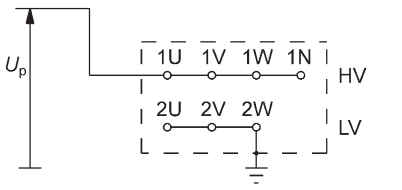
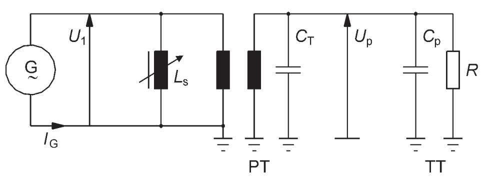
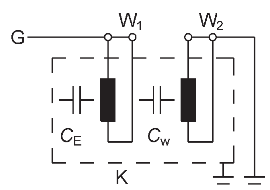



*Figure 7.1:* *Test circuit for the applied-voltage test of a three-phase transformer*




G = voltage source
PT = testing transformer (single phase)
$L_S$ = compensating reactor (constant or variable)
$C_p, R$ = capacitance and resistance of the transformer unit test
$U_1$ = primary voltage
$U_p$ = test voltage
TT = transformer under test

*Figure 7.2:* *Simplified measuring circuit*




$W_1$ = winding under test
$W_2$ = earthed winding
K = transformer tank
$C_E$ = capacitance to earth
$C_W$ = capacitance between windings
G = voltage source

*Figure 7.3:* *The capacitances of the transformer under test for the applied-voltage test*

## 7.4 Principle and measuring circuit

### 7.4.1 Principle

The applied-voltage test is performed at rated frequency as opposed to the higher test frequency necessary for the induced voltage test, see section 8.

The test principle of is shown in figure 7.1:

For the applied-voltage test, the equivalent diagram of the transformer under test is an $R$-$C$ parallel circuit composed of the effective capacitance $C_P$ and the resistor $R$, corresponding to the dielectric losses of the transformer under test. Effective capacitance $C_E$ is defined as the capacitance between the winding under test and earth (including the bushing capacitance) or between the other windings $C_W$ , see figure 7.2 and 7.3.

For calculation of the capacitive load and compensation requirements, see clause A 7.

### 7.4.2 Measuring circuit

The test laboratory measuring circuit is shown in figure 7.4.

For the measuring equipment requirements, see clause A 7.2.

## 7.5 Measuring procedure

### 7.5.1 Preparations

Before an applied-voltage test starts, it must be ensured that the whole winding insulation level is designed for the test voltage $U_P$ (transformer with uniform insulation). For transformers with non-uniform (graded) insulation, the applied-voltage test can only be carried out at a test voltage level conforming to the insulation of the transformer neutral.

The Buchholz-relay and all bushings must be degassed before the test; any surge arresters and bushing arcing horns must be removed. The secondary windings of current transformers must be short-circuited and earthed.

Electrodes such as spheres or similar protection shields mounted on the outer terminal of the bushing are permitted because they increase the external electric strength, whereas the applied-voltage test verifies the internal electric strength. Smooth external electrodes are absolutely necessary if partial discharge measurements are performed together with the applied-voltage tests e.g. for series regulating transformers, see section 9.

To avoid dangerous over-voltages a sphere-gap may be connected in the supply circuit or between the high-voltage terminal and earth. The protection sphere-gap has to be adjusted to produce a flashover at about 50% of the test voltage. When it has been confirmed that there is no risk of self-excitation, the gap can be removed, see clause A 7.1.

In general the test must be conducted at ambient temperature, but at least at 10 °C [3].

The test voltage is applied directly (via $R_D$) to the bushings of the transformer windings under test. All other windings and the tank must be earthed, see figure 7.1.

#### Compensation adjustment (if applicable)

The voltage is increased to about 25 % of the test voltage magnitude, while the variable reactor is adjusted for minimum inductance. The reactor inductance is then increased until the primary current $I_G$ reaches its minimum value.

### 7.5.2 Application of the test voltage; duration of test; test frequency

The voltage should be raised rapidly from 25% or less to the test voltage $U_P$ but remain consistent with measurement requirements. IEEE standard cites 15 seconds. At the end of the test the voltage should be reduced rapidly (i.e. in about 5 seconds [51]).

The test duration is 60 seconds.

The test frequency is the normal power frequency. IEC allows frequencies of not less than 80 % of rated frequency [3]. A test frequency of 50 Hz is usually accepted for transformers for railway applications with a rated frequency of 16,7 Hz.

### 7.5.3 Interpretation of the test

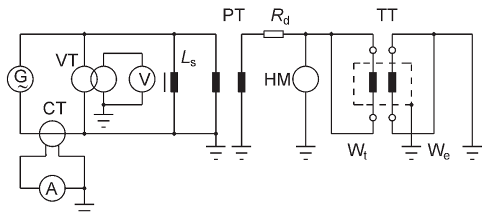
The test is successful if the test voltage does not collapse [3] or if there are no other fault indications such as smoke, bubbles and thumps or a sudden test circuit current increase [51].

If the transformer fails to meet the test requirements and the fault is in a bushing, the bushing may be replaced by a temporary bushing and the test continued. This is also valid when the specified bushing is not PD-free [3].

## 7.6 Measuring Uncertainty

The test voltage can be adjusted with an accuracy of about 1 % when capacitive or mixed dividers connected with AC measuring equipment, or potential transformers are used.

If sphere gaps are used for the measurement, an accuracy of not more than 3% can be expected. Correction of the voltage drop across the protective resistance $R_S$ of the sphere gaps is normally not necessary at power frequencies, see section 8.




G = variable voltage source
$L_S$ = compensating reactor (constant or variable)
PT = testing transformer (single phase)
HM = HV measurment equipment
TT = transformer under test
VT = voltage transformer with voltmeter to verify the primary voltage $U_1$
CT = current transformer with ammeter to measure the generator current $I_G$
$R_d$ = damping resistor
$W_1$ = tested winding
$W_E$ = earthed winding

*Figure 7.4: Measuring circuit for the applied-voltage test*

# Appendix A 7
# Applied-voltage test

## A 7.1 Calculation of the capacitive load compensation requirements

### A 7.1.1 Capacitive load

The additional capacitances (potential divider, capacitance of the testing transformer, etc.) need to be considered when calculating the capacitive load for the applied voltage test.

The (capacitive) power $S_{cap}$ required to perform the test is given by the following equation:

$$S_{cap} = U^2_p \cdot \omega\, C_{total}$$

where:

$C_{total}$ = the total capacitance.

### A 7.1.2 Compensation requirement

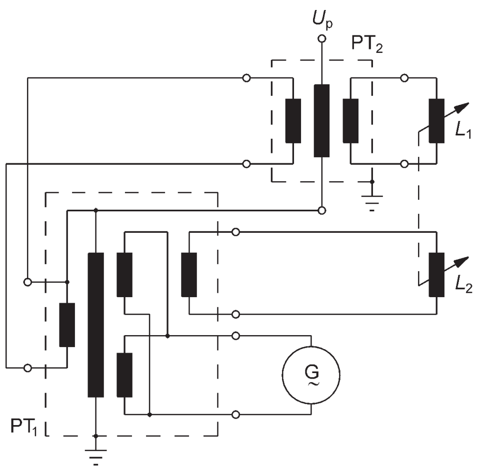
The active component of the required power, composed of the dielectric losses of the transformer under test and the losses in the testing transformer, can be neglected. The load will therefore be practically capacitive.

For this reason (similar to the induced voltage test) there is a real risk of self-excitation of the synchronous supply generator. It is normally necessary to compensate the capacitive current to avoid problems in this regard. This is of course not necessary for test laboratories connected directly to the grid via a regulating transformer.

Compensation is normally applied on the primary side of the testing transformer. This has the advantage that reactor $L_S$ must only be insulated for primary voltage $U_1$ and any adjustment required can be performed easily during the test.

Theoretically the compensation could also be done on the high voltage side of the testing transformer, but adjustable HV reactors may not be available especially for high test voltages.

Finally, another method is to apply the compensation via auxiliary windings of the testing transformer, see figure 7.5.




PT$_1$ = testing transformer in cascade, stage 1
PT$_2$ = testing transformer in cascade, stage 2
L$_{1,2}$ = variable reactors
G = voltage source
$U_p$ = test voltage

***Figure 7.5:*** *Testing transformer with auxiliary windings*

## A 7.2 General requirements for the measuring equipment

### Voltage source

A single-phase AC source having an industrial power frequency is required for the applied voltage test. The voltage should be adjusted continuously (without steps, if possible).

Usually three-phase generators (connected in single phase) or sliding transformers, which must be adapted to the measuring circuit with regard to voltage and power used.

The waveform requirements (sinusoidal characteristics) are specified in IEC 60060-1 [21].

### A 7.2.2 Testing transformer

The testing transformer is normally a single-phase unit (mostly in cascade) and one winding end of the HV- or of the LV-winding is usually earthed.

The rating of the testing transformer depends on load. Its rating is several hundred kVA for power transformers testing. The short circuit impedance of the testing transformer should be as low as possible to reduce the negative voltage-drop $\Delta U$ caused by the capacitive load to a minimum.

$$\Delta U = I_2 \cdot Z_k$$

where:

$I_2$ = load current in the measuring circuit

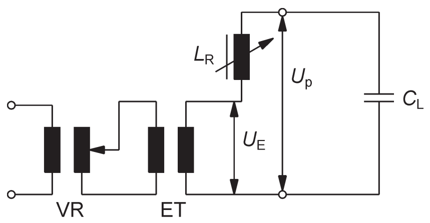
$Z_k$ = short-circuit impedance of the testing transformer

Series Resonant Systems [200] are used in some test laboratories instead of classical testing transformers. These systems were developed especially for the testing HV power cables, transformers, bushings and HV capacitors. This is shown in figure 7.6.

Voltage regulator VR supplies a variable voltage to an exciter transformer ET. The exciter transformer excites the resonant circuit, consisting of the variable HV reactor $L_R$ and the load capacitance $C_L$.

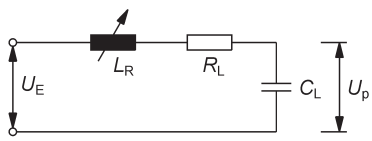
Although capacitance $C_L$ consists mainly of the capacitance of the transformer under test, it also includes the stray capacitance of the circuit and the capacitance of the HV divider, etc. The inductance of the HV reactor can be varied by adjusting the air gap in the core.

For the system to be in resonance, the HV reactor must be adjusted so that its impedance is equal to the impedance of the load capacitance $C_L$ at power frequency, see also figure 7.7.




$L_R$ = variable HV reactor
$C_L$ = load capacitance (transformer under test)
$U_E$ = exciting voltage
$U_p$ = test voltage
VR = voltage regulator
ET = exciter transformer

**Figure 7.6:** *Basics of a series resonant system*




$R_L$ = losses in the HV reactor
$L_R$ = HV reactor
$C_L$ = load capacitance
$U_E$ = exciting voltage
$U_p$ = test voltage

**Figure 7.7:** *Simplified diagram for series resonant system*

When $C_L$ is of the low loss type, as it is for transformers in the applied voltage test, the relative gain in voltage ($Q$ factor) of the resonant circuit can be calculated as follows:

$$Q = \frac{\omega L_R}{R_L} = \frac{1}{\omega C_L \cdot R_L}$$

where:

$L_R$ = inductance of variable HV reactor
$R_L$ = ohmic resistance of the HV reactor
$C_L$ = load capacitance

A typical value for $Q$ is between 30 and 100. This means that an exciting voltage $U_E$ of 1 - 3% of the test voltage $U_P$ is sufficient to keep the circuit resonant. Therefore, a resonant system with an output of 600 kV will need an exciting voltage of 6 - 20 kV.

## A 7.2.3 High voltage measurement equipment

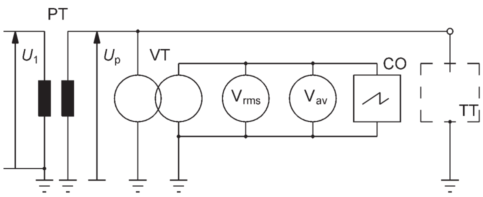
Due to the capacitive loading of the testing transformer by the transformer under test, the load current produces a voltage increase (negative voltage-drop) which can be significant, depending on the short-circuit impedance of the testing transformer. This phenomenon is especially important for the higher harmonics, which could cause additional voltage distortion.

Measurement of the test voltage $U_P$ should always be carried out on the HV side. In practice, different measuring methods are used:

### a) Measurement with a voltage transformer

This measurement is especially suited for voltage measurements up to 70 kV. Calibration of the measuring circuit is unnecessary when calibrated voltage transformers are used, see figure 7.8.

For this measuring circuit, the test voltage is monitored using the r.m.s.-voltmeter. The waveform of the test voltage $U_P$ can either be monitored by an oscilloscope or the form factor can be determined by measuring the average value of the voltage.

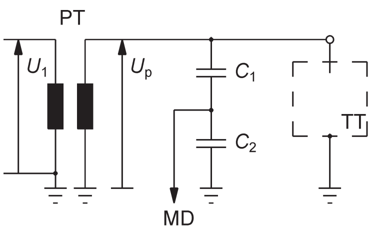



$V_{rms}$ = rms voltage voltmeter
$V_{av}$ = average voltage voltmeter
CO = oscilloscope
$U_p$ = test voltage
VT = voltage transformer
PT = testing transformer
TT = transformer under test

***Figure 7.8:*** *Measurement of the test voltage with a voltage transformer*

### b) Measurement using an HV potential divider with an AC measuring device

This method is well proven and can be used up to the highest test voltages. It allows direct readings of the crest value (peak value) and the r.m.s-value of the test voltage. Another advantage of this method is its high measuring accuracy, see figure 7.9. The measured test voltage is reduced by a capacitive or mixed divider and connected to the LV-measuring equipment.




$C_1$ = HV capacitor
$C_2$ = measuring capacitor
PT = testing transformer
TT = transformer under test
MD = measuring device

***Figure 7.9:*** *Measurement of the test voltage with a potential divider*

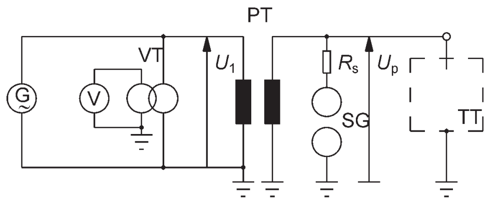
When a calibrated potential divider is used, the measurement is performed as previously described (measurement with a voltage transformer). The test voltage value can be read directly from the measuring instrument. The waveform can be checked using an oscilloscope or by comparing the readings of the two voltmeters ($U_{peak} / \sqrt{2}$ and $U_{r.m.s}$). The test voltage should primarily be adjusted using the peak-voltmeter ($U_{peak} / \sqrt{2}$)

#### c) Measurement with sphere-gaps

Although this method of measurement has a lot of disadvantages compared with the others described above, it is still occasionally required, see figure 7.10.

This method allows only an indirect measurement. This means that before each test the whole installation is calibrated using sphere gaps. During the test itself, measurement of $U_P$ is not possible.

The protective resistors $R_S$ is required to limit the arc-current of the sphere-gap. Its rating is about 1 Ω/V , see also section 10, clause A10.5 "Measurement of impulse voltages".




$R_S$ = protective resistor
SG = sphere gap
VT = voltage transformer
TT = transformer under test

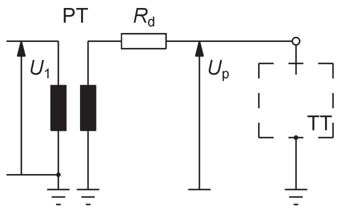
***Figure 7.10:*** *Measurement with sphere gaps*

### A 7.2.4 Damping resistor $R_D$

The damping resistor $R_D$ protects the voltage supply from overvoltages due to a possible flashover in the secondary circuit, at the sphere gaps or at the transformer under test. Its resistance should be as low as possible [21]. According to our experience the damping resistor should be designed so that, in the event of a short-circuit at the transformer under test:

- the voltage-drop across will not exceed 15 % of the test voltage $U_P$
- no flash-over across $R_D$ will occur and
- it will not be thermally overloaded by the short-circuit current, see figure 7.11.

For testing transformers with a relatively high short-circuit impedance and for series resonant testing systems, use of a damping resistor is not necessary.




$R_d$ = damping resistor

***Figure 7.11:*** *Damping resistance in the secondary circuit*

### A 7.2.5 Voltage transformer UW for measurement of the primary voltage $U_1$

The required primary voltage $U_1$ can be approximately calculated using the voltage ratio $r$ (turns-ratio) of the testing transformer:

$$U_1 = \frac{U_P}{r}$$

This value may only be used for checking the test voltage, as the voltage at the transformer under test does not correspond exactly to the voltage ratio (turns-ratio) $r$ (due to voltage increase caused by capacitive load, harmonics, etc.).

# Testing of Power Transformers

## 8. Induced voltage tests

# 8. Induced voltage tests

## 8.1 References / Standards:

- IEC 60076 (2000), clause 7.3 “Dielectric tests”, clause 12, “Induced AC voltage tests (ACSD, ACLD)” [3]
- IEEE C57.12.00-2000, clause 5.10 “Insulation levels” [50]
- IEEE C57.12.90-1999, clause 10.7 and 10.8 “Induced voltage tests” [51]

**Note:**

The induced voltage test is a **routine test** according to IEC Standard [1] and to IEEE Standard [50]; for details, see section 2: “Dielectric integrity” and section 8.3.

## 8.2 Purpose of the test

The induced voltage test is intended to verify the AC withstand strength of each line terminal and its connected winding(s) to earth and other windings; it also verifies the withstand strength between phases and along the winding(s) under test (turn-to-turn insulation).

## 8.3 General

There are some essential differences between induced voltage tests according to IEC and those specified in IEEE. They are discussed in the following paragraphs.

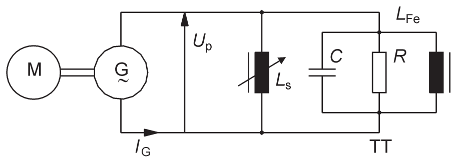
**IEC Standard** [3]

The IEC Standard distinguishes principally between:

- “Short duration AC” (ACSD) and “Long duration AC” (ACLD) tests
- Tests on transformers with uniform or with non-uniform insulation
- Tests on transformers with $U_m$-levels below or above 72,5 kV

Table 1 (columns 3, 4 and 5) of section 2.6.1 specifies the different types of individual tests to be carried out. There are 3 different types of test: routine test, type test and special test. In specific cases, depending on the highest voltage for equipment, a specific test is not applicable and must not be carried out.

The Standard specifies that simultaneous partial discharge measurements (PD) are required, section 9; exception: transformers with $U_m$ less or equal 72,5 kV.




| | | |
|---|---|---|
| M | = | motor drive |
| G | = | medium frequency generator (normally with variable frequency) |
| $L_S$ | = | compensating reactor (possibly variable) |
| TT | = | transformer under test |
| $C$ | = | equivalent capacitance of the TT |
| $R$ | = | active resistance of the TT |
| $L_{Fe}$ | = | no-load inductance of the TT |
| $U_p$ | = | test voltage |
| $I_G$ | = | generator current |

***Figure 8.1:*** *Simplified test circuit*

IEC 60076-3 [3] tables 2, 3 and 4, specify the test levels for a winding identified by the highest voltage for equipment, $U_m$. For transformers with uniform insulation, the voltage across an untapped winding should as a rule be as close as possible to twice the rated voltage [3].

For the value of test voltage for repeated dielectric tests, see section 2.6.3.

**IEEE Standards** [50], [51]

IEEE distinguishes between Class I (69 kV and below) and Class II (115 kV and higher) transformers. For Class II transformers, a long duration test ("one hour level") in combination with a partial discharge measurement is always required.

The test values for IEEE are given in table 5 and 7 for Class I transformers and in table 6 for Class II transformers. They are always based on BIL figures. [50].

## 8.4 Principle and test circuit

### 8.4.1 Principle

Since the test voltage $U_P$ for the induced voltage test is often higher than twice the rated voltage, the test frequency must be at least doubled to avoid over-excitation of the iron core.

$$U = k \cdot f \cdot \hat{B} \qquad \text{(See section 6)}$$

The principle of the induced voltage test is shown in figure 8.1.

# 8. Induced voltage tests

Calculation of the load in this test, including an example and compensation requirements are given in clause A 8.1.

For measuring equipment requirements, see clause A 8.2.

**Table 1: Summary:**
**Induced voltage test for three- and single-phase transformers according to IEC [3] and IEEE Standards [51]**

| **Category of winding** | **Highest voltage for equipment $U_m$ [kV]** | **Three-phase transformers** | | | **Single-ph. transf.** | |
|---|---|---|---|---|---|---|
| | | ACLD | ACSD | | ACLD | ACSD |
| | | | Single-phase phase-to-earth test | Three-phase phase-to-phase test | | Single-phase phase-to-earth test |
| **Induced voltage test according IEC [3]** | | | | | | |
| **Uniform insulation** | < 72,5 | | | o | | o |
| | 72,5< $U_m$< 170 | | | **PD** | | **PD** |
| | 170< $U_m$< 300 | **PD** | | | **PD** | |
| | > 300 | **PD** | | | **PD** | |
| **Non-uniform insulation** | 72,5< $U_m$< 170 | | **PD** | **PD** | | **PD** |
| | 170< $U_m$< 300 | **PD** | | | **PD** | |
| | > 300 | **PD** | | | **PD** | |
| Test connection | Figure | 8.7 | 8.6 | 8.7 | 8.8 | 8.8 |
| **Induced voltage test according IEEE [51]** | | | | | | |
| **Class I** Non-graded insulation | < 115 | | | o | | o |
| **Class I** Graded insulation | | | o | o | | o |
| **Class II** | 115 and above | **PD** | | | **PD** | |
| Test connection | Figure | 8.7 | 8.6 | 8.7 | 8.8 | 8.8 |

Symbols: o Routine test without PD measurement
PD Routine test with PD measurement

## 8.5 Measuring procedure

### 8.5.1 Preparations for the test

The test should only be conducted, if sufficient time has passed between the time of impregnation of the windings and the time of the test. This “standing-time” depends on the rated voltage of the transformer and is about 3 days for a 220 kV transformer and 5 days for a 400 kV transformer.

The Buchholz relay and all bushings must be degassed before the test; any surge arresters and bushing arcing horns must be removed. The secondary windings of the bushing current transformers must be short-circuited and earthed.

Electrodes, such as spheres or similar protection shields mounted on the bushing heads are recommended, because they increase the external electric strength considerably, especially for high test voltages. These electrodes or spheres at all bushings (including earthed bushings) are mandatory, for partial discharge measurements in combination with the induced voltage test (e.g. ACLD-test according to IEC [3] or induced voltage tests for Class II transformers according to IEEE [51]), see section 9.

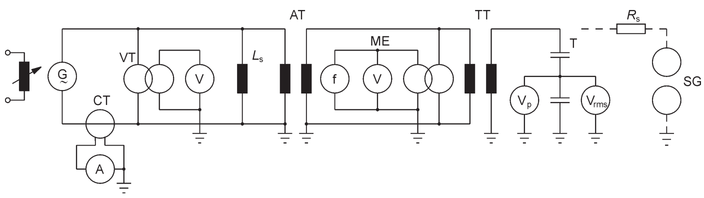
### 8.5.2 Practical test connections

The measuring procedure for the induced voltage test depends on various parameters, as given in table 1.

The test connections depend strongly on the transformer design. To avoid discussions and misunderstandings concerning the test connections for the final test, it is therefore recommended that they are clearly stated in the contract between the customer and the manufacturer.

The following rule should be observed for tests on transformers, which have a tapped winding:

The test voltage is determined by the winding with the highest $U_m$. If the ratio between windings is variable because of tappings, the taps should be used to adjust the test voltage for the winding with the lower $U_m$ as closely as possible to the appropriate value [3].




G = medium frequency generator (possibly with variable frequency)
$L_S$ = compensating reactor (possibly variable)
AT = testing transformer
ME = voltage and frequency measurement equipment
T = capacitive or mixed potential divider for the HV measurement with voltmeter
SG = sphere-gap with protective resistor
TT = transformer under test
CT = current transformer and ammeter for measuring
VT = voltage transformer and voltmeter for measuring the generator voltage
$V_p$ = peak / $\sqrt{2}$ – voltmeter

***Figure 8.2:*** *Basic test circuit for the induced voltage test*

### 8.5.3 Important remarks concerning the IEC test practice [3]

a) All three-phase transformers with uniform insulation should be ACSD tested using a symmetrical three-phase power supply (phase-to-phase test). If the transformer has a neutral, it should be earthed during the test.

b) PD-measurements are mandatory for transformers with $U_m$ > 72,5 kV during induced voltage tests, for $U_m \leq$ 72,5 kV PD measurements are generally not required, see section 9.

c) For transformers with $U_m$ >72,5 kV, where a phase-to-phase ACSD test is performed with a PD-measurement, the voltage-time sequence should be in accordance with figure 8.3, see also section 9.

d) ACSD tests for transformers where the HV windings have non-uniform insulation, the voltages are phase-to-earth voltages.

e) ACSD tests for transformers with non-uniformly insulated HV windings:

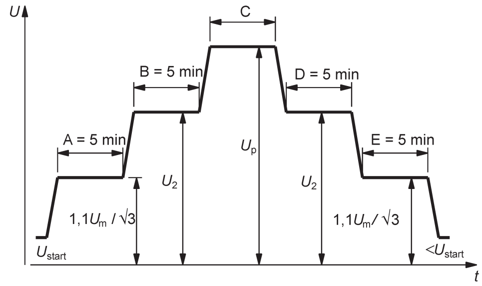
Two sets of ACSD tests are required for three-phase transformers: namely:

- A phase-to-earth test at the rated withstand voltages between phase and earth according to tables 2, 3 and 4 of IEC 60076-3 [3] with partial discharge measurement. These tests are performed as (three) single-phase tests. Test connections according to figure 8.6.
- A phase-to-phase test with earthed neutral at the rated voltages between phases according to tables 2, 3 and 4 of IEC 60076-3 [3]. It is performed as a three-phase test, as described in c) above. Test connections are according to figure 8.7.

For single-phase transformers only a phase-to-earth test is required.

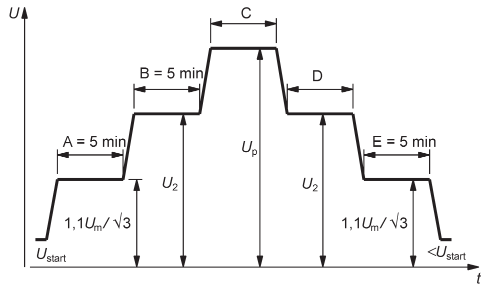
f) ACLD test with non-uniform and/or uniform insulation of HV windings:

- The test should be performed with the same connection configuration as in operation; this means symmetrical three-phase connection for three-phase transformers.
- The time sequence should be in accordance with figure 8.7, see also section 9.



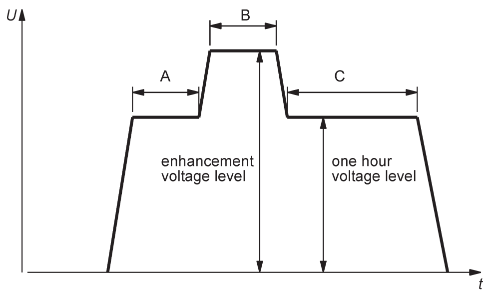

$C$ = test time according to clause 8.5.8
$U_2$ = 1,3 $U_m$ (phase to phase)
= 1,3 $U_m$ / √3 (phase to earth)

***Figure 8.3:*** *Voltage-time sequence for the ACSD test*




$C$ = test time according to clause 8.5.8
D = 60 min for $U_m$ > 300 kV or 30 min for $U_m$ <300 kV
$U_2$ = 1,5 $U_m$/ √3 (phase to earth)
$U_D$ = 1,7 $U_m$/ √3 (phase to earth)

***Figure 8.4:*** *Voltage-time sequence for the ACLD test*




A = time needed for PD measurement
B = 7200 cycles
C = 60 minutes

***Figure 8.5:*** *Time sequence for the induced voltage test for Class II transformers*

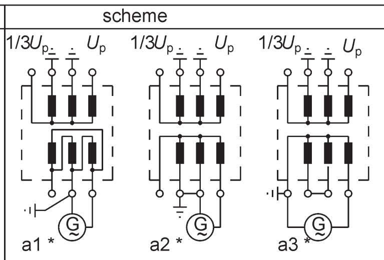
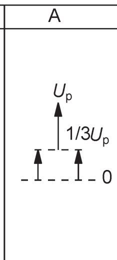
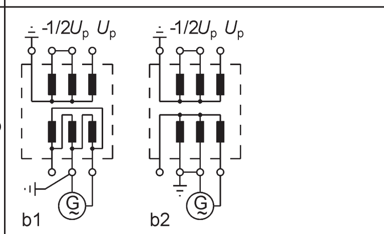
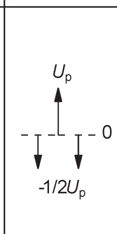
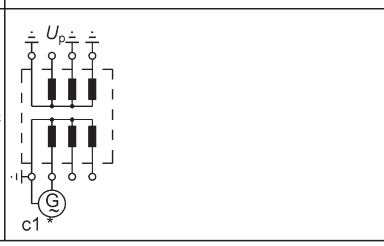
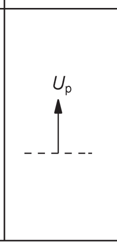
### 8.5.4 Important remarks concerning IEEE test practice [50],[51]

a) Class I transformers (HV ≤ 69 kV)

- A voltage to earth (not necessarily to the neutral) should be developed at each terminal in accordance with column 6 of table 5 of IEEE Std C57.12.00 [50]. This can either be done using an applied voltage test (see section 7) for non-graded (uniformly) insulated windings or by using a single-phase induced voltage test for graded (non-uniformly) insulated windings.
- A phase-to-phase voltage should be developed between the line terminals of each three-phase winding in accordance with column 6 of table 5, or column 2 of table 7 of IEEE Std C57.12.00 [50].

b) Class II transformers (HV ≥ 115 kV)

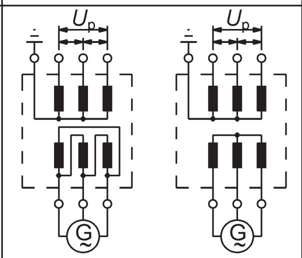
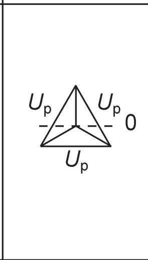
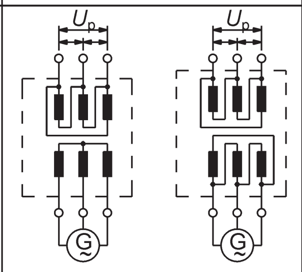
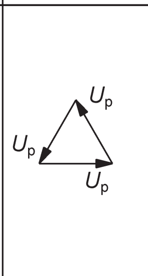
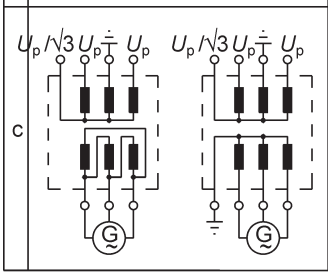
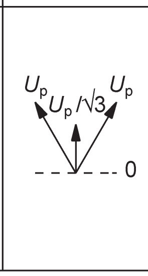
- The test should be performed with the transformer connected and excited as it will be in service. This means a three-phase transformer will be tested with a symmetrical three-phase supply and with a earthed neutral (if present).
- The test sequence is shown in figure 8.5.
- For the partial discharge measurement, see section 9.

| | scheme | A | B | C | D |
|---|---|---|---|---|---|
| a |  |  | $U_p$ | 1/3$U_p$ | 3 |
| b |  |  | 3/2$U_p$ | 0 | 3 |
| c |  |  | $U_p$ | 0 | 3 |

A = phasor diagram
B = voltage between phases
C = voltage at HV neutral
D = number of tests

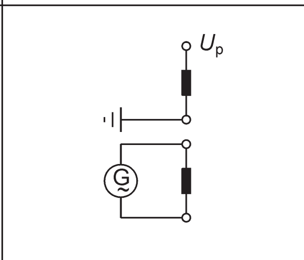
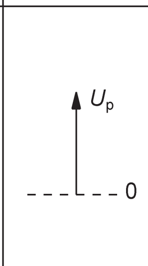
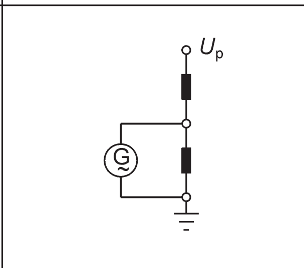
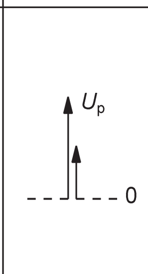
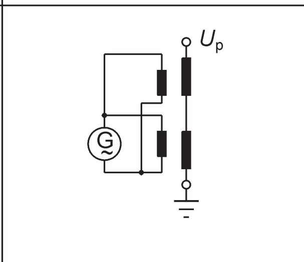
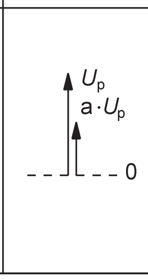
Note1: Connections a1, a2 and a3 may be used only when the neutral is designed to withstand at least $^1/_3$ of the voltage
Note 2: Only a1 is possible for transformers with 5 limb core or for shell-type transformers
Note 3: Connections b are used for ACLD test according IEC [3], if performed phase-by-phase in single-phase connection
Note 4: Connection c is only possible when the transformer has a no wound limb for the magnetic return path for the flux in the tested limb (five limb core); if there is a delta-connected winding, it has to be open during the test

***Figure 8.6:*** *Examples of test connections for single-phase tests of three phase transformers to avoid excessive overvoltages between line terminals [3], ]100]*

| | scheme | A | B | C | D |
|---|---|---|---|---|---|
| a |  |  | $U_p$ | 0 | 1 |
| b |  |  | $U_p$ | - | 1 |
| c |  |  | $U_p$ | $U_p/\sqrt{3}$ | - |

A = phasor diagramm
B = voltage between phases
C = voltage at HV neutral
D = number of tests

***Figure 8.7:*** *Examples of test connections for three-phase tests [100]*

| | scheme | A | B | C | D |
|---|---|---|---|---|---|
| a |  |  | $U_p$ | 0 | 1 |
| b |  |  | $U_p\,(1\text{-}(N_2\,/\,N_1 + N_2\,))$ | $U_p \cdot N_2\,/\,N_1 + N_2$ | 1 |
| c |  |  | $U_p\,(1\text{-}a)$ | $a \cdot U_p$ | 1 |

A = phasor diagramm
B = voltage between phases
C = voltage at HV neutral
D = number of tests
$N_1$ = number of windings HV
$N_2$ = number of windings LV

***Figure 8.8:*** *Examples of test connections of single-phase transformers [3], [100]*

### 8.5.5 Examples of test connections for single-phase tests on three-phase transformers [100]

All test connections marked with * in figure 8.6 and 8.7 are recommended by IEC [3], clause 12.3 and 12.4, but other test connections are also possible [100].

### 8.5.6 Compensation adjustment (if applicable)

The compensation is adjusted either by varying the frequency or inductance of the additional reactor. This is done in order to reduce generator current $I_G$ to a minimum value.

To avoid dangerous over-voltages due to self-excitation phenomena, see clause A 8.1, a sphere-gap may be connected in the supply circuit or between the HV terminal and earth. The protection-gap must be adjusted to produce flashover at about 50% of the test voltage. When it has been confirmed that there is no risk of self-excitation, the gap may be removed.

### 8.5.7 Calibration of the test voltage

If the potential divider is removed during the test with the full test voltage, the voltage at the transformer under test has to be adjusted using the voltmeter on the LV side. This voltmeter is calibrated for example at 50%, 60% and 80% of the test voltage using the potential divider.

$$U_P = \frac{\hat{U}}{\sqrt{2}} = f(U_{LV})$$

The calibration graph is a straight line starting at the source of the co-ordinate system. Calibration with the sphere-gaps is done in the same way.

### 8.5.8 Duration of the test

At full test voltage, the test time should be 60 seconds for any test frequency up to and including twice rated frequency. When the test frequency exceeds twice the rated frequency, the test time $t$ in seconds is:

$$t = 120 \cdot \frac{f_r}{f_P}$$

where:

$t$ = duration of the test in seconds

$f_r$ = rated frequency of the transformer

$f_P$ = test frequency

The duration should not be less than 15 seconds, independent of the test frequency

The test sequence for an induced voltage test in combination with partial discharge measurements (ACSD, ACLD according to IEC [3]) is given in figure 8.3 and 8.4 or for Class II transformers according to IEEE [51] in figure 8.5 and also in section 9 “Partial discharge measurement”.

### 8.5.9 Interpretation of the test

The test is successful if the test voltage does not collapse.

For transformers subjected to partial discharge measurements, the criteria for the success of the test are further discussed in section 9.

## 8.6 Measuring uncertainty

The test voltage can be adjusted with an accuracy of about 1 %, when capacitive or mixed dividers connected with an AC measuring equipment or potential transformers are used.

If sphere-gaps are used for the measurement, an accuracy of not more than 3 % can be expected.

For the higher test frequencies used for induced voltage tests, a correction of the voltage drop across the protective resistance $R_S$ of the sphere-gaps is necessary, see clause A 8.3.

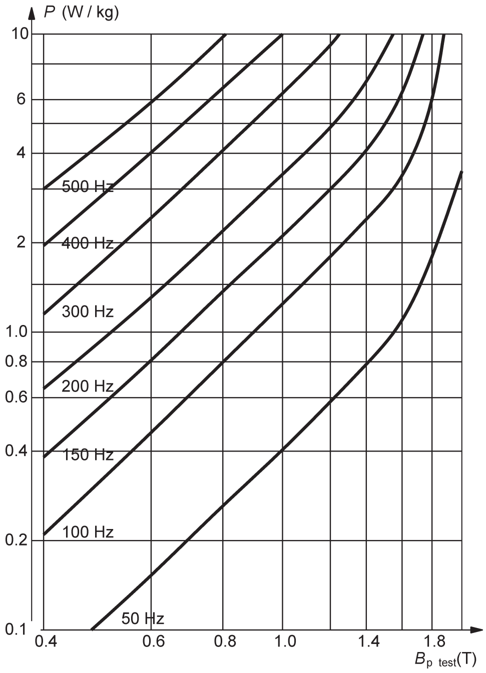



***Figure 8.9:*** *Specific iron losses as a function of induction and test frequency*

# Appendix A 8:

# Induced voltage test

## A 8.1 Calculation of the load for the induced voltage test

The principle of the induced voltage test is shown in figure 8.1, section 8.4.1. In reality the test-circuit is more complicated than shown in this figure, because the leakage reactance of the transformers (testing transformer and the transformer under test) and the reactance of the generator have been omitted for better understanding. The circuit is a current resonance circuit, where the transformer under test is represented as $C$, $R$ and $L_{Fe}$ in parallel connection.

The load impedance of the generator is therefore an $R$-$L$-$C$ parallel oscillation circuit, where $L$ is the parallel inductance $L_{Fe}$ and $L_S$, see figure 8.1. If the damping is sufficiently low, which is normal for transformers during the induced voltage test, the resonant frequency $\omega_R$ of the circuit becomes:

$$\omega_R = \frac{1}{\sqrt{LC}}$$

Generator current $I_G$ reaches its minimum value when the measuring frequency $\omega$ is equal to the resonant frequency $\omega_R$. This is achieved either by varying the frequency of the generator or by varying the inductance of the additional reactor $L_S$.

For stability reasons, the equivalent impedance of the whole circuit should always be inductive.

Without an additional reactor this requirement is nearly impossible for modern power transformers, when tested at double or more than the rated frequency, as shown in the following example.

### Example

For a single-phase transformer rated 105 MVA; 50 Hz; 420/√3/15,75 kV:

- Induction at rated voltage: $\hat{B}_r$ = 1,77 T
- Mass of the magnetic circuit = 44000 kg
- Capacitance $C_E$ between HV and earth ≈ 8000 pF
- Test voltage (ACSD-test) $U_P$ = 630 kV
- Test frequency = 10 Hz

$$\frac{U_P}{U_r} = \frac{630}{420/\sqrt{3}} = 2{,}6 \text{ times } U_r$$

$$\frac{f_P}{f_r} = \frac{150}{50} = 3 \text{ times } f_r$$

$$B_{test} = \frac{2{,}6}{3} \cdot \hat{B}_r = 0{,}87 \hat{B}_r = 1{,}53 \text{ T}$$

Calculation of the active power to be supplied by the generator:

With a test induction of 1,53 T and a test frequency of 150 Hz, figure 8.9 gives specific losses of about 5 W/kg, from which the active load $P_W$ can be calculated:

$P_W$ = 5 · 44 000 = 220 000 W → 220 kW

The reactive power $S_M$ to magnetise the transformer under test can be calculated in the same way. According to figure 8.10 the specific apparent power at 1,53 T and 150 Hz is about 7 VA/kg:

$S_M$ = 7 · 44 000 = 308 000 VA → 308 kVA

The purely inductive component $S_{ind}$ can be calculated by vectorial subtraction of $S_M$ and $P_W$:

$$S_{ind} = \sqrt{\left(S_M^2 - S_W^2\right)} = \sqrt{\left(308^2 - 220^2\right)} = 216 \text{ kvar}$$

The capacitive power $S_{cap}$ can be estimated using the approximate formula for classical two-windings transformers, as:

$$S_{cap} = -\frac{U^2 \cdot \omega C_E}{3}$$

where:

$S_{cap}$ = capacitive power in var
$U$ = highest voltage difference for the capacitance HV – earth in V
$C_E$ = capacitance in F

In this case:

$U$ = 630 – 2,6 · 15,75 = 589 kV

$$S_{cap} = -\frac{589000^2 \cdot 2\pi \cdot 150 \cdot 10^{-12}}{3} = -871000 \text{ var} \rightarrow -871 \text{ kvar}$$

It should be noted that the approximate formula for the capacitive power gives values, which are too low for polyphase transformers and transformers with interleaved windings.

This means that the transformer under test, even at low test frequencies, such as 150 Hz represents a high capacitive load. The use of higher test frequencies would further increase the ratio $S_{cap}/S_{ind}$. The capacitive power would increase linearly with the test frequency, while the inductive magnetising power would be significantly reduced.

Using the values from the above example, but with a test frequency of 200 Hz:

$S_{cap}$ = – 1160 kvar $S_{ind}$ = 140 kvar

It is therefore highly recommended, even in test installations with variable frequency, to use an additional reactor right from the beginning to avoid undesirable self-exciting phenomena, see also A 7.1. It could have significant consequences for the transformer under test.

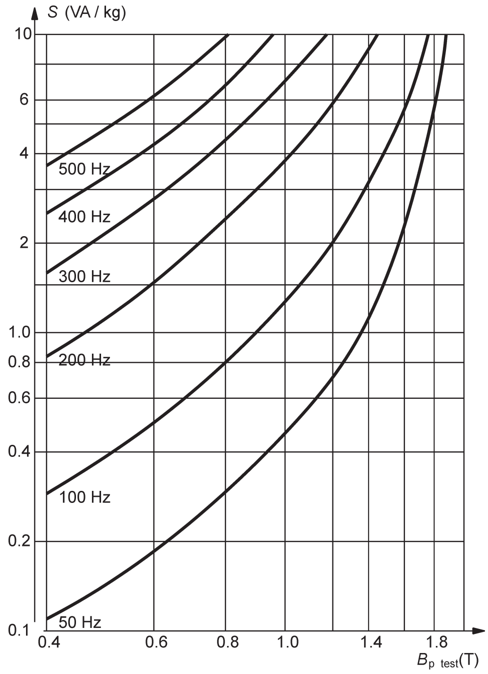



***Figure 8.10:*** *The specific magnetizing apparent power in function of the induction and test frequency*

Some test laboratories optimise the test circuit using specially developed computer programs. These programs calculate each component of the test circuit, voltage and current to reduce unpleasant surprises when conducting the induced voltage test.

## A 8.2 General requirements for the measuring equipment

(See figure 8.2)

### Voltage source G

For the induced voltage test a variable medium frequency generator is generally used with single- or three-phase configuration and a frequency range of about 50 - 400 Hz.

### Reactor

In general, the compensation is done on the LV side of the testing transformer. Theoretically, it could also be made on the high voltage side or at the tertiary of the testing transformer. Requirements for a low partial discharge level of the whole test installation, compensation near the generator is often the best alternative.

### Testing transformer

Testing transformer AT is required to adjust the generator voltage to the LV voltage of the transformer under test. If this transformer has other windings, which are unused for the test, they must be earthed at one winding end.

### Voltage- and frequency measuring equipment ME

The voltage is measured on the LV side of the transformer under test using a potential transformer and a voltmeter. The test voltage is normally adjusted with this voltmeter. The required voltage can be approximately calculated with the ratio $r$ of the transformer under test.

$$U_1 \cong \frac{U_P}{r}$$

where:

$U_1$ = primary voltage (LV) of the transformer under test
$U_P$ = test voltage
$r$ = ratio of the transformer under test

For the example in clause A 8.1 with $U_P$ = 630 kV

$$r = \frac{420/\sqrt{3}}{15{,}75} = 15{,}4$$

$$U_1 \cong \frac{630}{15{,}4} \cong 41\ \text{kV}$$

This value should only be used for checking. The voltmeter reading on the primary side has to be calibrated at the HV measuring equipment (for instance capacitive divider).

Due to the negative voltage drop $\Delta U = I_{cap} \cdot Z_K$ (result of the capacitive current Icap at the leakage impedance $Z_K$), the voltage ratio $U_p/U_1$ does not correspond exactly to the no-load voltage ratio r; i.e. if the transformer under test were supplied with $U_1 = U_p/r$, it would be tested with too high voltage.

The test frequency has to be checked simultaneously, as the test duration is directly dependent on the frequency.

### Capacitive- or mixed potential divider with AC measuring device T

This method is well proven and can be used up to the highest test voltages. It allows direct readings of the crest value (peak value) and the r.m.s.-value of the test voltage.

Instead of a free-standing capacitive divider the bushing measuring tap can be used as input signal to the voltage measurement equipment. It is however important to calibrate the signal from the bushing measuring tap before each test.

### Measurement with sphere-gaps SG

Although this method of measurement has many disadvantages compared with the others described above, it is still in use if no adequate equipment is available.

This method only allows an indirect measurement. This means that before each test the whole installation is calibrated. During the test itself, the measurement of $U_P$ is not possible. The protective resistor $R_S$ is required to limit the arc-current of the sphere gap. Its rating is about 1 Ω/V, see section 7, clause A 7.2.

## A 8.3 Correction of the voltage drop across the protective resistance of sphere-gaps

$$I = U_{SG} \cdot \omega C$$

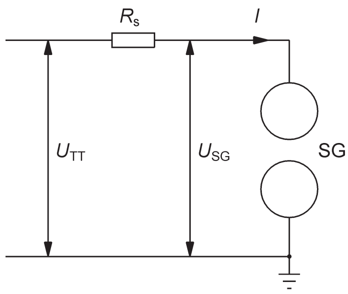
$$U_R = I \cdot R_S = U_{SG} \cdot \omega C \cdot R_S$$

$$U_{TT} = \sqrt{\left(U_{SG}^2 + U_R^2\right)} = U_{SG} \cdot \sqrt{\left(1 + \omega^2 C^2 R_S^2\right)}$$

For a test frequency of 250 Hz, a sphere-gap capacitance of 200 pF and a protective resistance of 1 MΩ, the voltage at the transformer under test becomes:

$$U_{TT} = U_{SG} \cdot 1{,}05$$

Without correction, the voltage at the transformer under test would be 5 % too high.




$R_S$ = protective resistor
SG = sphere-gap
$U_{SG}$ = voltage across the sphere-gap
$U_{TT}$ = voltage at the transformer under test

***Figure 8.11:*** *Fault correction of a sphere-gap*

# Testing of Power Transformers

## 9. Partial Discharge Measurements

# 9. Partial Discharge Measurements

## 9.1 References / Standards:

- IEC 60076-3 (2000), Annex A "Application guide for partial discharge measurements during a.c. withstand voltage test on transformers according to 12.2, 12.3, and 12.4" [3]
- IEC 60270 (2000) "Partial discharge measurements" [26]
- IEEE C57.12.90-1999, clause 10.8 and 10.9 "Induced voltage tests" [51]

**Note:**

The partial discharge measurement is a **routine test** for transformers where $U_m$ > 72,5 kV according to IEC [3] or $U_m$ ≥115 kV according to IEEE [50];

## 9.2 Purpose of measurement

A partial discharge measurement (PD-measurement) is a non-destructive tool used to establish the condition of a transformer insulation system. The goal of partial discharge measurement is to certify that no harmful PD-sources exist. A PD-measurement makes it possible to detect and localize areas within the transformer which are exposed to elevated dielectric stresses, i.e. stresses which in the long run can be harmful to safe transformer operation.

Partial discharge measurements are explicitly specified in standards or in customer specifications. They are to be carried out in conjunction with dielectric tests in high voltage laboratories using AC-voltage in the power frequency range.

For HVDC transformers PD measurements are also carried out on dielectric tests with DC-voltages.

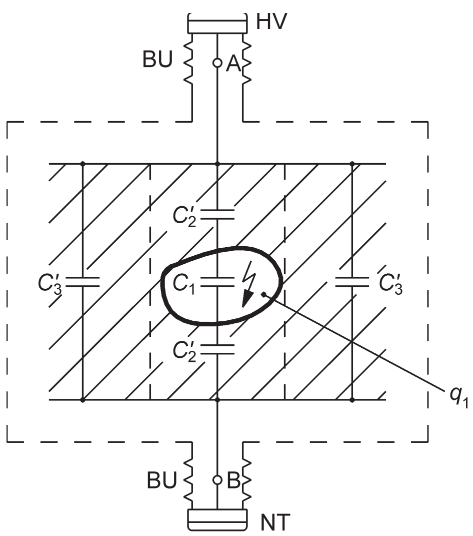
For on-site PD measurements (for example on repaired transformers) other types of PD-free excitation may also be carried out [221].

Partial discharge measurement should generally be the last dielectric test conducted on the transformer.

## 9.3 General

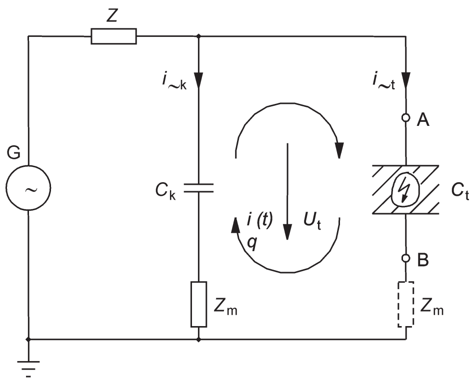
Partial discharge is a partial voltage breakdown within a series of insulating elements between two electrodes of different potential, (capacitances $C'_2$ and $C'_3$, see figure 9.1). During a typical PD measurement, the magnitude of the detectable value of partial discharge activity is recorded as a function of the applied voltage.

A partial discharge can be interpreted as the rapid movement of an electric charge from one position to another. For very fast changes, or during the first instant after charge movement, the individual insulation links in a series of connected links between two line terminals can be regarded as a number of series-connected capacitors.




BU = bushing
HV = high voltage
NT = neutral terminal
$C_{1,2,3}$ = active part of transformer (including oil)
$C_1$ = weak region
$C_t$ = test object capacitance ($C'_2$ and $C'_3$)

***Figure 9.1:*** *Schematic representation of a part of the transformer insulation.*




$C_t$ = test object capacitance
$C_k$ = coupling capacitor
G = voltage source
$i\ (t)$ = PD current pulses
$i_{\sim k,\sim t}$ = displacement currents
$Z$ = voltage source connectors
$q$ = transferred charge
$U_t$ = voltage at parallel-connected capacitors
$Z_m$ = measuring impedance

***Figure 9.2:*** *Equivalent circuit for PD measurement*

If the two line terminals are connected together via an external capacitor $C_k$, see figure 9.2, the charge movements within the series-connected insulation links (capacitances $C'_2$ and $C'_3$, see figure 9.1) will also be reflected in the charge of external capacitor $C_k$. The charge movements can be detected as circulating current impulses $i(t)$ in the parallel-connected capacitors $C_k$ and $C_t$, see figure 9.2.

Two requirements must be fulfilled to initiate a partial discharge (i.e. electric breakdown) within the weak region of an extended insulating system:

- Local electric field stress $E$ in the weak region must be greater than the inception electric field of the PD source
- Free electrons must be available to initiate the electric breakdown, see clause A 9.1.

Excessive stress in the weak region can result from design flaws, contamination or deviation from permissible tolerances in the manufacturing process, insulating material flaws, etc. Another possibility is hidden damage to the insulation caused by preceding tests.

## 9.4. Principle of PD measurement

All PD measuring methods are based on the detection of PD current impulses $i(t)$ circulating in the parallel-connected capacitors $C_k$ (coupling capacitor) and $C_t$ (test object capacitance) via measurimg impedence $Z_m$.

The basic equivalent circuit for PD measurements is presented in figure 9.2 [212].

The measuring impedence $Z_m$ can either be connected in series with coupling capacitor $C_k$ or with the test object capacitance $C_t$.

As discussed in section 9.3 “General”, PD current impulses are generated by charge transfers between parallel-connected capacitor $C_k$ (coupling capacitor) and $C_t$ (test object capacitance).

Present IEC and IEEE Standards have both established rules for measuring and evaluating electric signals caused by partial discharges together with specifications on permissible magnitude.

The IEC approach to the processing of the recorded electric signal is different from the IEEE approach. IEC transforms the signal to an apparent electric charge generally measured in picocoulombs (pC), while IEEE transforms the signal to a Radio Interference Voltage RIV, generally measured in microvolts (µV).

The use of the RIV-method for PD-signal detection will be abandoned, although the IEEE standard has not yet been officially approved. The detection of apparent charge in pC is the preferred method now in use in IEEE Std C57.113 [56].

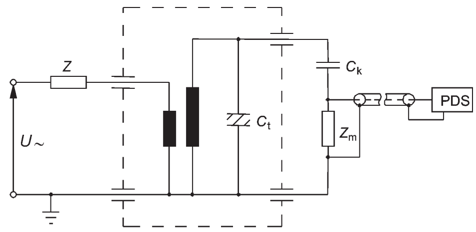
For the detection of apparent charge the integration of the PD-current impulses $i(t)$ is required.

Integration of the PD current impulses can be performed either in the time domain (digital oscilloscope) or in the frequency domain (band-pass filter). Most PD systems available on the market perform a "quasi-integration" of the PD current impulses in the frequency domain using a "wide-band" or "narrow-band" filter, see clause A 9.2.

**Note:**

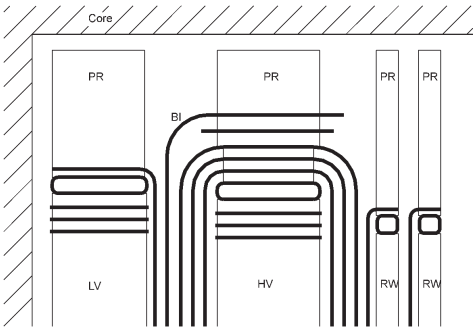
For short duration currents (ns-range) the test voltage source is practically decoupled from the PD measuring circuit (parallel connection of $C_k$ and $C_t$) by the inductive impedance $Z$ (step-up transformer connections).

For the HV-components without any bushing an external coupling capacitor $C_k$ must be connected in parallel with the test object $C_t$, see figure 9.3.



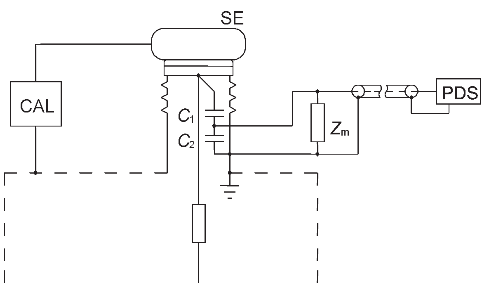

PDS = PD system
$C_k$ = coupling capacitor
$C_t$ = test object capacitance
$Z$ = voltage source connection
$Z_m$ = measuring impedance

***Figure 9.3:*** *Test circuit for measurement without capacitive tap*




PR = press ring
BI = barrier insulation
LV = low voltage
HV = high voltage
RW = regulation winding

***Figure 9.4:*** *Transformer insulating system; Barrier system with shielding rings and angle rings towards yoke*




$C_1$ = $C_k$ = coupling capacitor
SE = shielding electrode
PDS = PD system
CAL = calibrator
$C_2$ = capacitive tap
$Z_m$ = measuring impedance

***Figure 9.5a:*** *Calibration circuit for PD measurement on transformers; bushings with capacitive tap*

## 9.5 PD measurement on transformers

Circulating PD current impulses – generated by an external PD source (in the test circuit) or by an internal PD source (in the insulating system of the transformer) – can only be measured at the transformer bushings. Bushing capacitance $C_1$, see figure 9.5a, represents the coupling capacitor $C_k$, which is connected in parallel with capacitance $C_t$ (test object = total capacitance of the transformer insulating system). An example of a typical transformer insulating system is shown in figure 9.4.

For power transformers the measuring impedance is generally connected between the bushing measuring tap and earth, i.e. in parallel with capacitance $C_2$, see figure 9.5a.

For bushings without a capacitive tap an external coupling capacitance $C_k$ must be connected in parallel with the bushing, see figure 9.5b.

There are some essential differences between the two Standards (IEC and IEEE) regarding the evaluation of the PD current impulses.

### 9.5.1 IEC Standard [3]

According to IEC, PD measurements are conducted by measuring the "apparent charge, $q$". In this context the apparent charge is obtained by integrating the PD current impulse using "wide band" or "narrow band" filter, see clause A 9.2.

The PD measuring system is connected via a coaxial cable to measuring impedance $Z_m$, see figure 9.5.

The apparent charge $q$, measured in picocoulombs (pC), corresponds to the charge transferred during the $\Delta U$ voltage drop compensation process at one of the parallel-connected capacitances $C_t$ (transformer insulation) and bushing capacitance $C_1$ or coupling capacitance $C_k$, see figure 9.2 and 9.5.

This voltage drop $\Delta U$ may be caused either in the test object (internal partial discharge in the bushing or in the transformer insulating system) or in the test circuit (external partial discharge). If PD activity is detected during the test, the PD source must be investigated, see section 9.7.

The magnitude of measurable apparent charge $q_m$ in pC must be defined by the calibrating procedure for each test circuit.

#### Calibration

Calibration of the PD test circuit is performed using a battery-operated calibrator. The calibrator consists of a square-wave generator with adjustable amplitude $U_0$ connected in series with a small capacitor $C_0$ ($C_0$ should be less than 10 % of $C_k$). For PD measurements on transformers, the calibrator is connected across the bushing, or across the coupling capacitor connected in parallel with the bushing, see figure 9.5. Calibration must be performed separately for each bushing.

Under the assumption that $C_0 << C_k$, the injected impulse from the square-wave generator corresponds to the charge $q_0$, which is set to pre-defined values (100 pC, 1000 pC etc.) by the adjusting the amplitude $U_0$. IEC 60270 recommends that the rise time of the injected impulse should be ≤ 60ns, amplitude $U_0$ between 2V and 50 V, selectable polarity, and the repetition rate 100 Hz.

$$q_0 = U_0 \cdot C_0$$

where:

- $q_0$ = injected charge
- $U_0$ = adjustable voltage of the square-wave generator
- $C_0$ = calibrator capacitance

The measuring circuit, consisting of the test capacitance $C_t$ of the test object, coupling capacitor $C_k$, measuring impedance $Z_m$, coaxial cable and measuring system, is now calibrated, see figure 9.5. During the PD test the measuring system values are read directly in pC. This pC reading is only valid for the specific calibrated bushing.

### 9.5.2 IEEE Standard [50], [51]

For routine PD measurements, IEEE Standards require the measurement of "RIV" (RIV = Radio Interference Voltage). RIV is determined in µV (interference voltage). A "narrow band" filter performs quasi-integration of PD current impulses with quasi-peak detection at center frequencies between 0,85 MHz and 1,15 MHz. The narrow-band pass filter is applied to allow suppression of external noise in non-shielded laboratories by varying the center frequency of the filter. The measuring system is called a RIV-meter or a radio-noise-meter.

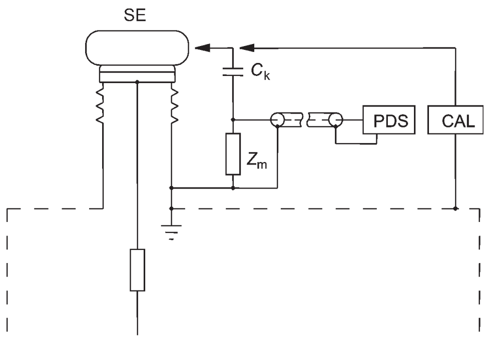
The RIV in µV depends on both, on the transferred charge and on the repetition rate of the PD impulses (number of PD impulses per second). This is why it is not possible to directly convert measured RIV values in µV into values of apparent charge in pC, see clause A 9.2.

The transferred charge (measured in µV) is the result of a compensation process of the voltage drop $\Delta U$ at one of the parallel-connected capacitances $C_t$ (transformer insulation) and bushing capacitance $C_1 = C_k$ or coupling capacitor $C_k$, see figure 9.5.

#### Calibration

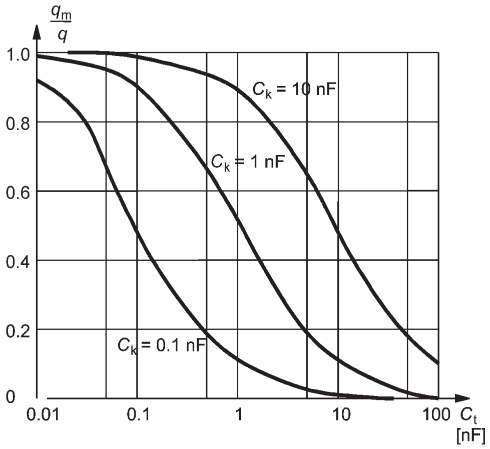
The PD test circuit is calibrated in the same way as the one for measuring apparent charge in pC, see figure 9.5. Assuming that $C_0 << C_k$, the applied sinusoidal voltage corresponds exactly to the values defined by the adjustable amplitude of $U_0$ in µV (100 µV, 1000 µV etc...).

During the PD test the measuring system values are read directly in µV. This µV reading is only valid for the specific calibrated bushing.




PDS = PD system
CAL = calibrator
$C_k$ = coupling capacitor
$Z_m$ = measuring impedance
SE = shielding electrode

***Figure 9.5b:*** *Calibration circuit for PD measurement on transformers; bushings without capacitive tap*




$q$ = apparent charge

$q_m$ = measurable charge

$$\frac{q_m}{q} = \frac{C_k}{C_t + C_k}$$

***Figure 9.6:*** *Influence of coupling capacitor $C_k$ on the measuring sensitivity $\frac{q_m}{q}$*

According to IEEE Standard C57.12.90 [51] PD activity within the transformer may be measured in terms of apparent charge (picocoulomb). This approach should normally provide several advantages, including less attenuation of signal.

### 9.5.3 Sensitivity of the PD measurement

The true charge $q_1$ released during an internal electric breakdown in a weak region in the transformer insulation is not measurable, see figure 9.1. Only the charge transfer between the capacitance of the weak region $C_1$ and capacitances of the insulating system ($C'_2$ and $C'_3$ in figure 9.1) is detectable at the bushing ($C_k$). Capacitances $C'_2$ and $C'_3$ (winding and transformer insulating system) are directly connected to this bushing. The relationship between true charge $q_1$, apparent charge $q$ and measurable charge $q_m$ is discussed in clause A 9.3.

The sensitivity of the PD measurement (i.e. the measurable apparent charge $q_m$ in pC or interference voltage in µV) is strongly dependent on the components in the test circuit; especially on the ratio of the test capacitance $C_t$ (insulating system of the transformer) and coupling capacitor $C_k$ (capacitance of the bushing). The influence of the coupling capacitor value on the sensitivity of the PD circuit is shown in figure 9.6 [212]. This shows that calibration must be repeated if major changes are made to the test circuit (connection of new coupling capacitor, etc.).

For an extended insulating system such as that of a transformer, the calibration described above is only valid for PD defects that are close to the bushing.

The real PD impulse currents – especially those generated by internal PD sources hidden deep within the insulating system – are heavily attenuated by the RLCM network of the transformer [214]. (RLCM stands for resistances, inductances, capacitances and mutual inductances.) Such "slow" PD impulses are only detectable at the bushings and may not always be correctly measured by the applied PD system, see clause A 9.2.

The amplitude of apparent charge $q_m$ is therefore not always a meaningful criterion to decide if the PD source is dangerous to the insulating system. A procedure for investigating the internal PD source is described in section 9.7.

**Note 1:**

Normally $Z_m$ and the measuring system must be matched to correctly quasi-integrate the PD current impulses. Mixing measuring impedances $Z_m$ and detection systems of different manufacturers is not recommended.

**Note 2:**

For delivery tests it is only specified to measure on bushings for $U_m$> 72,5 kV (IEC) or on bushings $U_m$>115 kV (IEEE).

# 9. Partial Discharge Measurements

It is recommended that all bushings of the transformer under test should be equipped with measuring impedances $Z_m$ to ensure that PD activity can be detected simultaneously. If PD activity is detected in the test circuit, identification and localization of the PD source is then much faster, see section 9.9.

To avoid external discharge (corona) in the PD measuring circuit all transformer bushing tops should be covered with shielding electrodes (including earthed bushings), see figure 9.5. Shielding electrodes should also be used for all sharp metallic parts on top of the transformer and in the voltage source connections, see clause A 9.8. The voltage source in the HV laboratory must be PD-free. All objects in the test field close to the transformer under test must be earthed. Typical external noise sources are discussed in clause A 9.4.

## 9.6 PD measuring procedure

The procedure for PD measurement is basically defined by the induced voltage test procedure shown in section 8, Table 1. There are some differences between PD measuring procedures according to IEC and those specified in the IEEE Standards. Sometimes the customer specifies a special PD procedure according to his experience and to the recommendations of the national technical committee.

### 9.6.1 IEC Standard [3]

According to the IEC Standards PD measurements shall be carried out in conjunction with induced voltage test on all transformers with highest voltage for equipment ($U_m$) above a certain level. The PD measurement is mandatory for long duration induced voltage test (ACLD) as well as for short duration induced voltage test (ACSD). Time sequences for ACSD and ACLD are given in section 8, figures 8.3 and 8.4.

PD activity should be checked at all bushings where the system voltage is higher than 72,5 kV. PD activity is measured in pC. Any wide-band pass filter or narrow-band pass filter can be used as a PD measuring system, see clause A 9.2.

The first PD measurement (values of apparent charge in pC) should be made at a low test-voltage level (ca. 10% $U_r$). This value serves as a reference for the background noise level in HV laboratory. According to the IEC Standards, the background noise level must be lower than half of the required pC value of apparent charge for the specific transformer. In a shielded HV laboratory, the background noise level is sufficiently low.

The following PD measurements should be made at each test voltage level indicated in figures 8.3 and 8.4 (parts A, B, D, E) with the exception of the enhancement level (part C). All measured pC values at all bushings of the transformer should be documented (see example Table 1).

**Table 1:** Documentation of the PD results

| Bushing Voltage | HV pC | LV pC | NT pC | Notes |
|---|---|---|---|---|
| Calibration | 100 $k_c$ = | 100 $k_c$ = | 100 $k_c$ = | |
| 10% | | | | |
| A | | | | |
| B | | | | |
| C | – | – | – | Enhancement |
| D | | | | |
| E | | | | |

$k_c$ = calibrating factor (amplification of the PD system)

During the long duration test (part D in figure 8.4), the PD activity should be checked at least every 5 minutes at each bushing. The best way to check PD activity in the transformer insulating system is to apply a multi-channel PD measuring system capable of detecting PD activity at all bushings simultaneously (8-channel PD system). A detailed description of the PD measuring system (ICMsys8) used in ABB HV laboratories is given in clause A 9.5.

#### Acceptance criteria for PD test

The PD test is considered successful if no continuous PD activity greater than the specified apparent charge amplitude in pC is detected at any bushing, and if there is no rising trend in the apparent charge amplitude during the long duration test. The recommended acceptable values of apparent charge given in the IEC Standards are:

- 300 pC at 130% $U_m$
- 500 pC at 150% $U_m$
- the level of continuous PD-activity does not exceed 100 pC at 1.1 $U_m$

where:

$U_m$ = highest voltage for equipment according to IEC or in other words highest r.m.s phase-to-phase voltage for which the transformer winding is designed.

### 9.6.2 IEEE Standards [50], [51]

According to the IEEE Standards, the PD measurement should be performed at the “one-hour level” of the test voltage (defined by the customer), before the enhancement level and during the one-hour test after the enhancement test voltage, see figure 8.5 in section 8. The duration for part A must be sufficiently long to initiate possible PD activity in the oil-impregnated transformer insulating system (minimum 10 minutes). The physics of PD activity in oil-impregnated insulating systems is discussed in clause A 9.1.

PD activity should be checked at all bushings where the system voltage is ≥ 115 kV. PD activity is measured in µV. A narrow-band pass filter should be used as a PD measuring system. The recommended center frequency for the narrow-band pass system is 1 MHz. If there is high background noise, the center frequency can be varied between 0,85 MHz and 1,15 MHz.

The first PD measurement (RIV values in µV) should be performed at a low test voltage level (about 10% $U_r$). This value serves as a reference for the background noise level in the HV laboratory. According to the Standards, the background noise level must be lower than half of the required µV value for the specific transformer. In a shielded HV laboratory the background noise level is less than a few µV.

The following PD measurements should be performed at each test voltage level indicated in figure 8.5 (parts A, C) of section 8 with the exception of the enhancement level (part B).

All measured µV values at all bushings of the transformer should be documented, see example Table 2.

During the one-hour test (part C in figure 8.5), the PD activity at each bushing should be checked at least every 5 minutes.

**Acceptance criteria for PD test**

The PD test is considered successful if no continuous PD activity greater than the specified RIV level in µV is detected at any bushing, and if there is no rising trend of RIV during the long duration test. According to the IEEE Standard the PD test was successful if the following conditions were met:

- The magnitude of the PD level did not exceed 100 µV
- The PD level increase during one hour of test did not exceed 30 µV
- The PD level during the one-hour test did not exhibit any steadily rising trend, and no sudden, sustained increase in levels occurred during the last 20 minutes of the test.

## 9.7 Procedure for Investigation of PD sources

If PD activity that exceeds the customer requirements or our internal quality rules is detected, the type of the PD source and its location (external or internal in the insulating system) must be investigated. The procedure for investigating the PD source should generally be adapted to the behavior of the registered PD activity.

### 9.7.1 Investigation of external PD sources

The first step is to exclude all possible external PD sources. Typical external PD sources are, see also clause A 9.4:

- Conducting particles on the bushing surface
- Non-shielded sharp points on the transformer or in the test circuit
- Bad connections on shielding electrodes
- Unearthed metallic objects close to the transformer
- Noise or internal PD from the voltage source

Electric discharges in air (corona) generated by sharp electrodes (tip-point electrode) are easy to detect using a portable ultrasonic detector (corona gun), see figure 9.7.

A PD problem in the voltage source can easily be checked by separately measuring the voltage source.

**Table 2:** Documentation of the PD results

| Bushing<br>Voltage | HV<br>µC | LV<br>µC | NT<br>µC | Notes |
|---|---|---|---|---|
| Calibration | 100<br>$k_c$ = | 100<br>$k_c$ = | 100<br>$k_c$ = | |
| 10% | | | | |
| A | | | | |
| B | – | – | – | Enhancement |
| C | | | | |

$k_c$ = calibrating factor (amplification of the PD system)

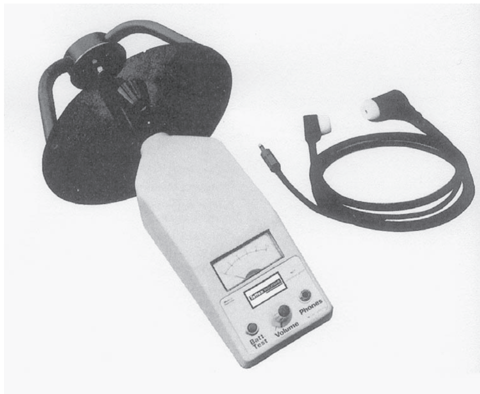


*Figure 9.7: Ultrasonic detector for external PD in the test circuit*

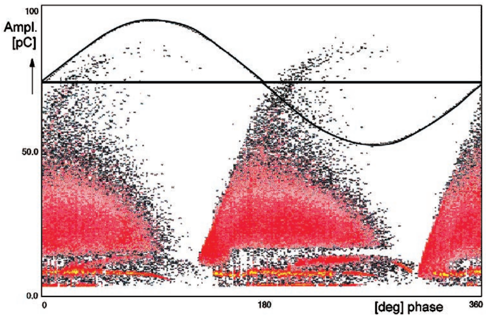



*Figure 9.8a:* *Registration of PD impulses (bubbles and surface discharge); advanced PD system (statistical analysis of PD impulses)*

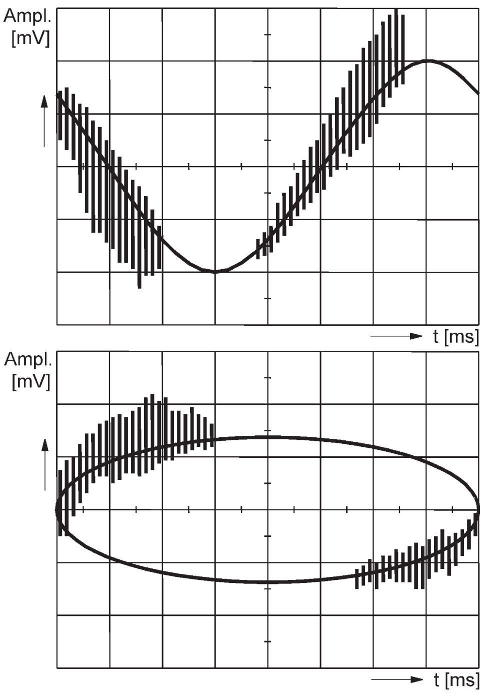



*Figure 9.8b:* *Registration of PD impulses (bubbles and surface discharge); conventional PD system one cycle only*

### 9.7.2 Investigation of the type of PD source

A PD source type is defined by its specific statistical behaviour (PD pattern). The statistical behaviour of the PD source is mainly influenced by the availability of starting electrons, which trigger an electric discharge in the weak region in the transformer insulating system, see physics of discharge processes in clause A 9.1. The availability of starting electrons is strongly dependent on the PD source itself (conducting or non-conducting material) and on the position of the PD source with respect to the metallic electrode. As a result, five typical PD patterns representing the physical processes of the PD sources exist (for a visual interpretation, see Table 3).

These typical PD patterns are based on physical electric discharge processes in the weak region, see clause A 9.1, and can theoretically be detected in any insulating system (if the measuring circuit is sufficiently sensitive). PD patterns (statistical analysis of the PD signals) are not influenced by the structure of the insulating system [213].

**Note:**

The structure of extended insulating systems, like those of a transformer, heavily attenuate the amplitude of the original internal PD current impulses, but do not change their statistical behavior.

An advanced PD system **P**hase **R**esolving **P**artial **D**ischarge **A**nalyser = PRPDA-system is used to record a PD pattern [215]. The advanced PD system, see clause A 9.5, performs a statistical analysis of the recorded PD data. At the specific test voltage, the PD activity is saved as a function of the phase position and of the amplitude of apparent charge during a preset time (two dimensional multi-channel analyser). The results are finally presented as a two dimensional PD pattern, see figure 9.8a. The third dimension (color) indicates the total number of PD impulses collected during the preset measuring time. For the statistical analysis of a PD-source a minimum of 3000 cycles are needed (for 50 Hz the preset measuring time must be 60 seconds).

Figure 9.8b shows the well-known presentation of PD impulses during one cycle, recorded using a conventional PD system.

To investigate the PD source, the first PD pattern should be recorded under the following test conditions [216]:

- Inception voltage of the PD source
- Extinction voltage of the PD source
- 10 % above the inception voltage

Further test conditions for the investigation of the PD-source are dependent on the results of the analysis of the PD-pattern.

Analysis of the PD pattern is based on comparing the recorded real PD pattern with the typical PD pattern types presented in Table 3: (Figure 9.9)

**Table 3: Typical PD sources in the transformer insulating system**

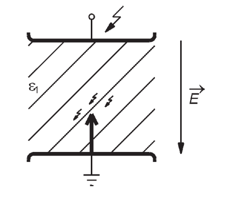
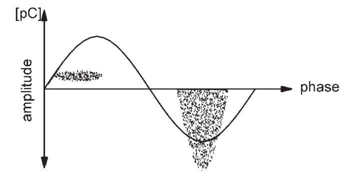
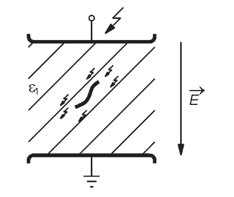
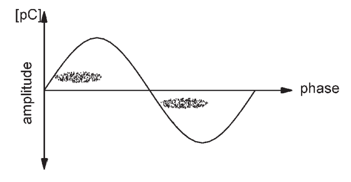
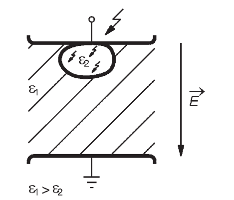
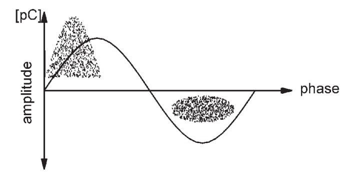
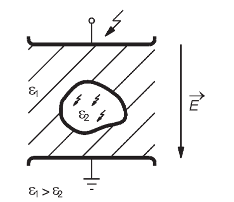
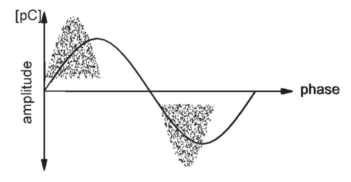
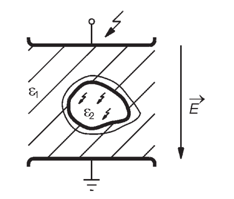
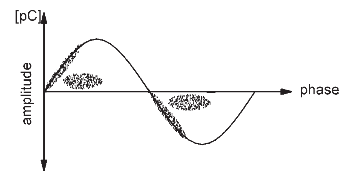
| PD source description | Schematic drawing of the PD source | Typical PD pattern |
|---|---|---|
| Conducting material (tip electrode) with direct contact to metallic electrode |  | PD pattern type 1  |
| Conducting material without any contact to metallic electrode |  | PD pattern type 2  |
| Non-conducting material (cavity) with direct contact to metallic electrode |  | PD pattern type 3  |
| Non-conducting material (cavity) without any contact to metallic electrode |  | PD pattern type 4  |
| Non-conducting material (cavity) without any contact to metallic electrode with changing surface due to the partial discharge |  | PD pattern type 5  |

***Figure 9.9:*** *Typical PD pattern*

In reality, the five typical PD patterns appear in many variations. Due to the continuous change of both the surrounding area at the location of the PD source and of the PD source itself (due to the electric discharge), there are only a few PD patterns that exhibit constant behavior during the test.

Basic PD pattern characteristics that should be analyzed are [216]:

- Phase position of the PD signals
- Symmetry of the PD signals during the positive and negative sine wave
- Number of PD signals per cycle
- Reproducibility of the PD pattern

Interpretation and screening of the correct type of PD pattern from the real PD pattern results, requires experience and a strong interpolation capability. If PD defects are superimposed, a comparison with the typical types of PD patterns and finding the correct type of PD pattern becomes much more difficult.

An overview of the typical PD sources in the transformer insulating system together with their typical PD pattern and their typical behavior during the test is presented in Table 4.

If there is a clear indication of internal PD activity in the transformer insulating system, localization of the PD source must follow, see sections 9.8 and 9.9.

**Table 4: Typical PD sources in the transformer insulating system (Figures 9.10a, b, c)**

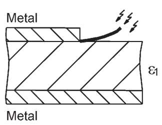
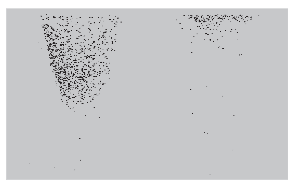
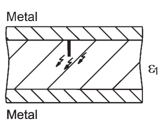
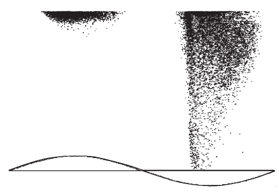
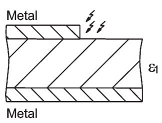
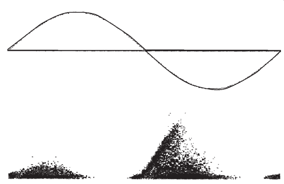
| PD defect description | Schematic drawing of PD defect | Measured PD pattern: Tip electrode in oil | Typical behavior during the test | Recommended procedure |
|---|---|---|---|---|
| Tip electrode in oil |  |  | Delay in inception<br>Change of PD pattern | Conditioning of the tip electrode by long duration test<br>Attention: may cause an electrical breakdown |
| Tip electrode in solid insulating material |  |  | Change of PD pattern<br>Carbonized tracks may be generated<br>**PD pattern type 5** | Long duration test by observation of the PD pattern behavior<br>Attention: breakdown may occur |
| Tip electrode on the surface of solid insulating material |  |  | Change of PD pattern<br>Surface discharge<br>**PD pattern type 5**<br>Carbonized tracks may be generated | Long duration test by observation of the PD pattern behavior<br>Attention: breakdown may occur |

***Figure 9.10a:*** *Typical PD defects in the transformer insulation;*
***conducting material = PD pattern type 1***

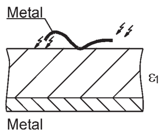
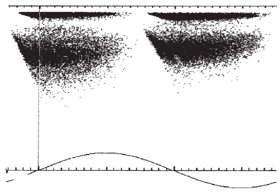
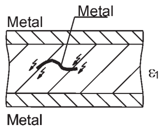
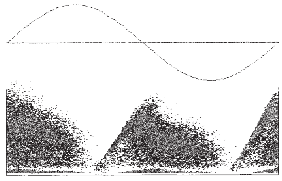
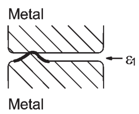
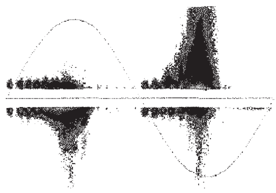
| PD defect description | Schematic drawing of PD defect | Measured PD pattern | Typical behavior during the test | Recommended procedure |
|---|---|---|---|---|
| Conducting particle in oil |  |  | Delay in inception<br>Change of PD pattern<br>**PD pattern type 5** | Conditioning of the tip electrode by long duration test<br>Attention: may cause an electrical breakdown |
| Conducting particle in insulating material |  |  | Change of PD pattern<br>Carbonized tracks may be generated<br>**PD pattern type 5** | Lond duration test by observation of the PD pattern behavior<br>Attention breakdown may occur |
| Bad contact |  |  | No PD at higher test voltage level<br>**PD pattern type 5** | Long duration test by observation of the PD pattern behavior |

***Figure 9.10b:*** *Typical PD defects in the transformer insulation;*
***conducting material = PD pattern type 2***

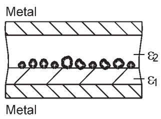
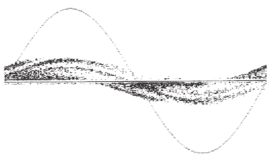
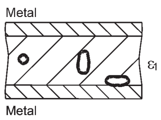
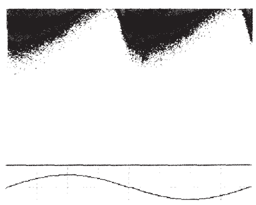
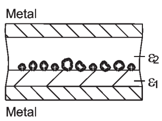
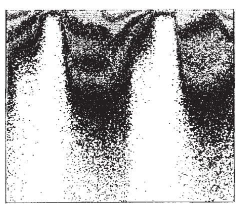
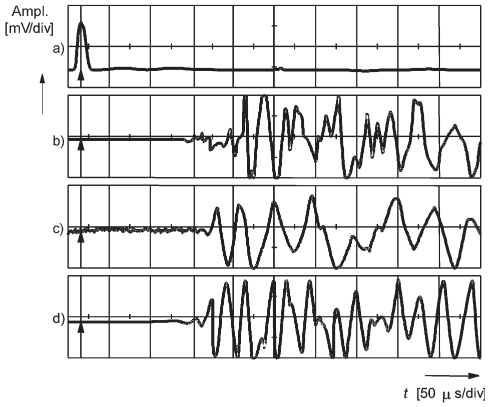
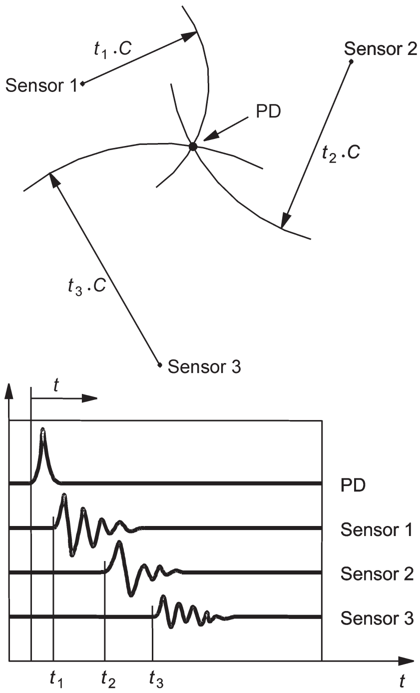
| PD defect description | Schematic drawing of PD defect | Measured PD pattern | Typical behavior during the test | Recommended procedure |
|---|---|---|---|---|
| Bubbles in oil |  |  | Possible change of PD pattern | Longer standing time<br>Long duration test<br>Degassing of oil<br>Refilling of the transformer under vacuum |
| Bubbles in solid insulation material (paper, pressbord, glue) |  |  | Change of PD pattern<br>Carbonized tracks may be generated | Long duration test by observation of the PD pattern behavior<br>Attention: breakdown may occur |
| Bubbles due to the humidity of the insulating system (local humidity) |  |  | Very high amplitudes of apparent charge | Re-drying the transformer |

***Figure 9.10c:*** *Typical PD defects in the transformer insulation;* ***bubbles = PD pattern type 3 and 4***




a) = electric PD signal [0,50 V/div]
b) = acoustic PD signal [20 mV/div], sensor 1
c) = acoustic PD signal [10 mV/div], sensor 2
d) = acoustic PD signal [50 mV/div], sensor 3

***Figure 9.11:*** *Detection of acoustic PD signals*




$C$ = velocity of acoustic wave
$t_1, t_2, t_3$ = time of signal arrival at the sensor

***Figure 9.12:*** *Location of PD source using triangulation method*

## 9.8 Detection of acoustic PD signals

An acoustic PD signal is a mechanical vibration in the elastic medium (acoustic wave). Means to locate PD sources that are generated by the electric discharge in the weak region using acoustic wave analysis (acoustic emission) are based on time delay measurements between the electric PD signal (oscilloscope trigger) and acoustic signals detected by a minimum of three acoustic sensors positioned along the transformer tank wall. The theory of the propagation of acoustic waves in the transformer insulating system and an advanced acoustic system are discussed in clause A 9.6 [217].

Piezoelectric transducers (crystal) with a resonance frequency between 60 - 150 kHz are normally used as acoustic sensors. A four-channel digital oscilloscope is needed to analyze acoustic PD signals. A typical result of detecting acoustic PD signals correlated with an electric PD signal is shown in figure 9.11.

The location of the PD source in the insulating system is calculated from the time delay between the electric and acoustic PD signals using the triangulation method, see figure 9.12 [217]. The velocity of acoustic waves in oil is around 1400 m/s. This method is theoretically only applicable for “direct waves” i.e. acoustic waves propagating through the oil only.

Acoustic wave propagation in the transformer, see clause A 9.6, is heavily influenced by the complicated structure of the insulating system (winding barriers, core, tank walls). In a complicated structure the acoustic signal emitted by the PD source changes along its propagation path. Both the amplitude (attenuation) and the signal shape (absorption, dispersion) are influenced. It must therefore be possible to distinguish between direct-propagated and wall-propagated waves when analyzing the time difference between electric and acoustic PD signals for the purpose of localization, see figure 9.12. This information is theoretically hidden in the wave-front of the acoustic signal detected by a sensor on the tank wall, see figure 9.13.

### 9.8.1 Sensitivity of the measurement

Localizing PD defects that emit the acoustic wave directly into oil, similar to a metallic particle lying on the surface, can easily be detected (amplitude of apparent charge > 100 pC).

PD defects hidden in the solid insulation, similar to a metallic particle in the insulation, are quite difficult to detect (amplitude of apparent charge >1000 pC), due to the different propagation velocities in different materials and due to the reflection phenomena of acoustic waves in the extended insulating system of the transformer, see clause A 9.6.

PD defects in the main insulation of the transformer are the most difficult to detect due to the transformer board barriers and outer winding, see figure 9.4.

Acoustic waves caused by PD defects in the core are very difficult to analyze and may give very misleading results.

**Note:**

Detection of acoustic PD signals should be performed at a test voltage level close to the inception voltage of the PD source to achieve a reliable correlation between electric and acoustic PD signals. At higher test voltages the number of PD impulses per cycle usually increases and is likely to initiate additional PD sources.

In case of unidentified PD activity, a detailed and in depth investigation of the PD source should follow. A minimum of one day is required for the PD measurements and an additional day to analyze the results, see section 9.9.

## 9.9 Detailed investigation of the PD source

Detailed investigation of the PD source goes beyond the requirements specified in the IEC and IEEE standards. This procedure is adapted to the behavior of the PD source. The goal of the investigation is to find the PD source as quickly as possible [216], [219].

Detailed investigation of the PD source requires the following commercially available equipment:

**High frequency current transformer:** High frequency current transformers (HF CT, 100 kHz - 30 MHz) must be used as a measuring impedance $Z_m$ to detect the real PD current impulses. HF CTs are connected to each bushing of the transformer (multi-terminal measurement).

**Spectrum analyzer:** A spectrum analyzer is used both to analyze PD current impulses in the frequency domain for localization of the PD sources and to detect PD signals as a variable band-pass filter (quasi-integration of PD current impulses) as the front-end of the advanced PD-system.

**Advanced PD-system:** For example ICM system or ICMsys8 is used to record and analyze the statistical behaviour of the PD signals for investigation of the type of the PD source (PD-pattern).

**Digital oscilloscope:** A digital oscilloscope is used as a control device for the digitized signals and as an analyzing device for time resolved signals when localizing the PD activity.

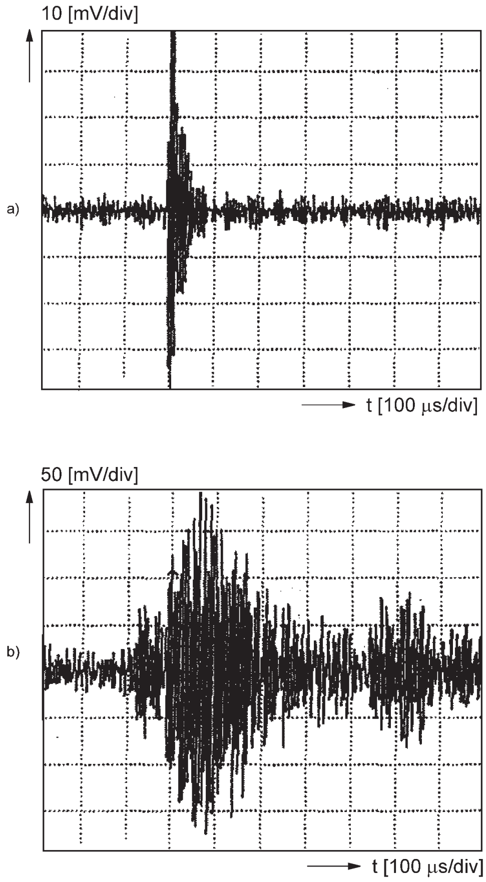



*Figure 9.13:* *Analysis of acoustic waves of PD sources*
*a) Detection of direct acoustic wave (through the oil)*
*b) Detection of reflected acoustic wave or wave propagated through different media*

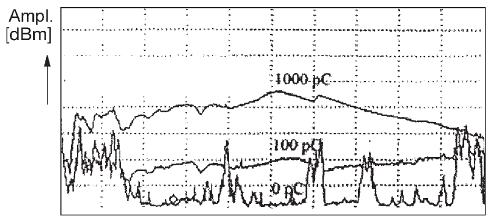



*Figure 9.14a:* *Characterization of the transformer; calibration in the frequency domain*

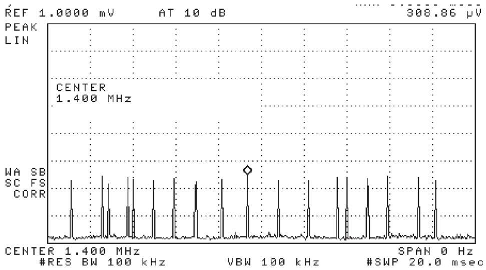



***Figure 9.14b:*** *Characteristics of the transformer, calibration in pC (spectrum analyzer as a band pass filter)*

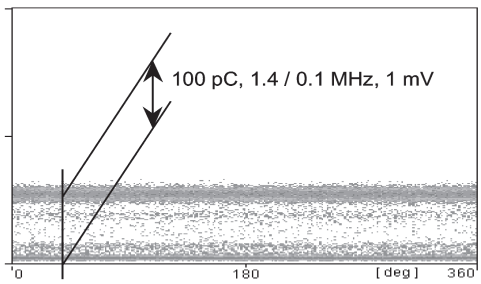



***Figure 9.14 c:*** *Characteristics of the transformer, calibration in pC (ICM record of calibrating impulse)*

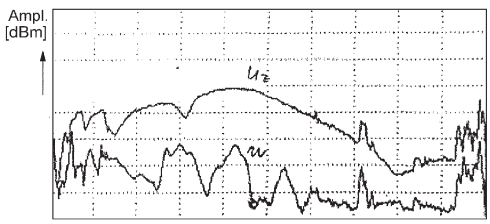



***Figure 9.14d:*** *Characteristics of the transformer; cross coupling in the frequency domain*

### 9.9.1 Investigation and localization of the PD-source

The investigation of the PD source should be performed in the following sequence:

- analysis of the frequency spectrum of the PD current impulses
- analysis of the PD pattern (statistical analysis of the PD signals)
- efforts to locate the PD source using analysis of electric PD signals in the frequency domain
- efforts to locate the PD source using analysis of electric PD signals in the time domain

These steps above should be repeated at the following test voltage levels:

- at the inception voltage of the PD source
- at the extinction voltage of the PD source
- at different test voltage levels up to the required test voltage level
- as a function of the time of the applied voltage

The analysis of the results is mainly based on comparing the real PD signal behavior with the characteristic behavior of the specific insulating system. The characteristic behavior of the insulating system of the transformer under test must be defined by a special “calibrating procedure”.

An example of the characteristics of a transformer using a conventional calibrator for PD measurements is shown in figure 9.14:

- frequency spectra at each bushing (spectrum analyzer works in full span, see figure 9.14a).
- sensitivity (in pC) of the measuring circuit at each bushing (spectrum analyzer works in span zero), see figure 9.14 b (band pass filter).
- registration of the sensitivity in pC at each bushing with ICM-system (video out signal from the spectrum analyzer), see figure 9.14 c (PD-pattern).
- cross-coupling of calibrating signals in the frequency domain, see figure 9.14 d (localization of PD-source).
- cross-coupling of calibrating signals in the time domain, see figure 9.14 e (localization of PD-source).

For the cross-coupling characteristics of the insulating system, a calibrating signal of 1000 pC is usually injected at one specific bushing and the response is measured at all other bushings (multi-terminal method). This procedure is repeated for each bushing (time needed for a three-phase transformer is about 6 hours).

### Localization

Localization of the PD sources is based on the following theory:

Electric PD signals (PD current impulses) propagate from the PD source through the RLCM network of the transformer, see clause A 9.7. The response of this network to excitation by a PD current impulse at any location in the insulating system can only be detected at the bushings. The measured real PD current impulses at the bushings are compared with the characteristic values obtained during the calibrating procedure described above, both in the frequency domain and the time domain, see figure 9.14. The theory of propagation of electric PD signals through the transformer RLCM network is discussed in clause A 9.7.

### Analysis of PD current impulses in the frequency domain

[216], [219]

In order to define the background noise condition of the entire test circuit (background frequency spectrum) the first data registration when taking the PD measurement is performed using a spectrum analyzer at about 10 % $U_r$ at all bushings. The background frequency spectra serve as the basis for unambiguous identification of repeated PD activity detected at the specific bushing.

For each subsequent test voltage level, frequency spectra are checked and compared with the background frequency spectrum at each bushing. Any PD activity in the test circuit generates a change in the background frequency spectrum (visual interpretation).

PD signals close to the bushing generate a frequency spectrum similar to the calibrating signal, see figure 9.15 (1U).

PD signals transferred to the bushing via the RLCM network of the transformer insulating system generate a spectrum with defined resonances, see figure 9.15 (1V).

The basic frequency spectra characteristics that should be analyzed are:

- Amplitude of the power spectrum in dBm
- Frequency range of the power spectrum
- Typical resonances
- Reproducibility of power spectra

Comparison of the PD signal frequency spectra with the results of the characterization of the transformer gives the first indication of the location of the PD source.

**Note:**

Analysis of the PD signals in frequency domain can only be performed for repetitive PD signals. Sporadic PD signals can only be registered with a peak detector (conventional or advanced PD measuring systems).

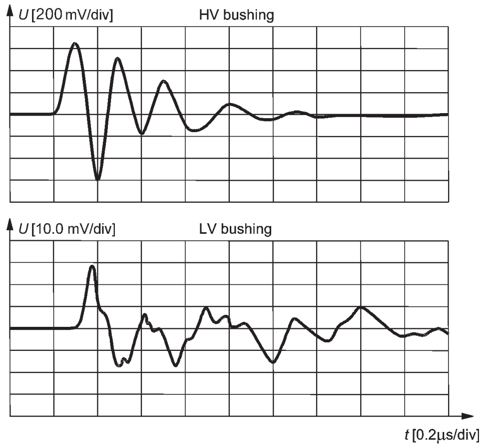
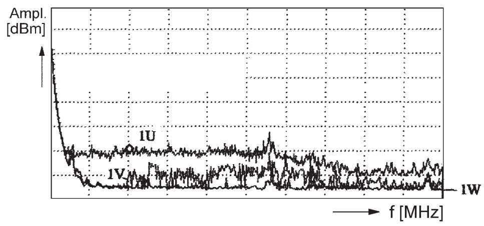
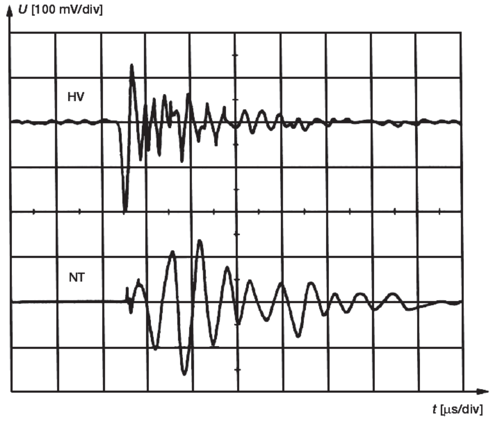



***Figure 9.14e:*** *Characteristics of the transformer; cross-coupling in the time domain*




1U = PD source close to the bushing
1V = PD signal coupled from the phase $U$
1W = background noise

***Figure 9.15:*** *Real PD signal in the frequency domain detected at different bushings*




HV = PD source close to the HV bushing
NT = PD signal coupled to the neutral terminal

***Figure 9.16:*** *Real PD signal in the time domain*

**Analysis of PD currents in the time domain** [214]

Besides analyzing the PD signals in the frequency domain (spectrum analyzer), the PD current impulses are also analyzed in the time domain (oscilloscope). The highest PD current amplitude is used as a trigger signal for the oscilloscope (channel, HV) and the response of the RLCM network at all other bushings is usually systematically analyzed at the second channel (NT), see figure 9.16. Additional simultaneous recording of four specific channels may be used to confirm previous results.

Recorded PD current signals in the time domain are again compared with the calibrating signals (visual interpretation).

PD signals close to the bushing generate a time-resolved signal similar to the calibrating signal, see figure 9.16 (HV).

PD signals transferred to the bushing via the RLCM network of the transformer insulating system generate a time-resolved signal that is comparable with the response of a RLC filter, see figure 9.16 (NT).

Basic time-resolved PD signal characteristics that should be analyzed are:

- Maximum amplitude of the PD current signal in mV
- Rise-time of the PD current signal
- PD current signal oscillations
- Reproducibility of the PD current signals

A comparison of the PD signals recorded in the time domain with the results of the characterization of the transformer gives the second indication of the location of the PD source.

**Note:**

In the event of superimposed PD sources, it is possible to distinguish between two different PD current signals by varying the trigger level.

While attempting to localize the PD source, the type of the PD activity (PD pattern) is continuously analyzed in the same way as described in section 9.7

### 9.9.2 Final analysis of the results

All results recorded during the detailed investigation of the PD source under different test conditions must be analyzed (an experienced person takes at least 4 hours) before making any decisions regarding the next steps in the investigation procedure. In depth analysis of all results will reliably identify the type of PD source (PD pattern), give information about the location of the PD defect and provide a basic idea of how dangerous the PD source is for the transformer insulating system.

# 9. Partial Discharge Measurements

The behavior of the PD source during the investigation procedure allows us to distinguish between dangerous PD sources and non-dangerous PD sources. The amplitude of the apparent charge is not always a meaningful criterion for this decision, see clause A 9.3.

Dangerous PD sources for the transformer insulating system are:

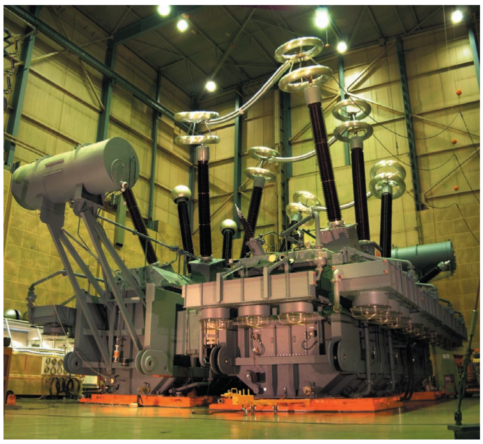
- PD source with inception voltage below 100 % $U_r$
- PD source with extinction voltage below 100 % $U_r$
- PD source hidden in the solid insulation
- PD source with continuous change in PD pattern
- PD source where the amplitude of the apparent charge increases with the time of applied voltage
- PD source where the number of PD signals per cycle increases with the time of applied voltage

Less dangerous PD sources for the transformer insulating system are:

- PD source with inception voltage above the protection level (external surge arresters) in the supply
- PD source with extinction voltage above 100 % $U_r$
- Gas bubbles in the oil
- PD source with a constant PD pattern
- PD source where the number of PD signals per cycle decreases with the time of applied voltage

Successful resolution of the PD problem can be finally reached by discussing the results with the design engineers to mutually find the real cause of the PD source. Depending on the results of the discussion, the next steps in the procedure may be:

- Additional calibration
- Additional investigation of the PD source in HV laboratory
- Conditioning the PD source
- Re-drying the transformer insulation
- Modifying the identified weak region (cause of PD defect)
- Disassembling the transformer



*Set-up for three-phase induced test including partial discharge measurement.*

## 9.10 Measuring uncertainty

The calibrated values for measurement of apparent charge in pC and of RIV-values in µV are only valid for PD defects close to the bushings. For all PD defects far from the bushing, the uncertainty may be more than 50 %, see clause A 9.3.

Since the resonance phenomena of the PD detection circuit (bushing, measuring impedance, measuring cable and band pass filter of the PD measuring system) are not known, the RIV system may deliver confusing results if the center frequency of the narrow band-pass filter (usually 1 MHz) is the same as the resonance frequency of the specific PD detection circuit, see clause A 9.2.

Exact conversion of the measured interference voltage in µV to a corresponding apparent charge is only possible in certain cases, see clause A 9.2.

# Appendix A 9

# Partial Discharge Measurement

## A 9.1 Physics of partial discharge

Partial discharge (PD) is an electric breakdown in the weak region of an extended insulating system, see figure 9.17.

An electric breakdown of the insulating material between two electrodes means generally that the distance between them has been bridged by electric charges (high ohm resistance has changed to low ohm resistance). Electric breakdown occurs if the following conditions are fulfilled:

- local electric field $E$ in kV/mm is greater than the breakdown field strength $E_b$ in kV/mm of the specific insulating material (different values for different insulating materials)
- starting electrons are available

For a homogeneous electric field (main insulation between the windings; see figure 9.17) the breakdown field strength $E_b$ is defined as:

$$E_b = \frac{V_b}{d}$$

where:

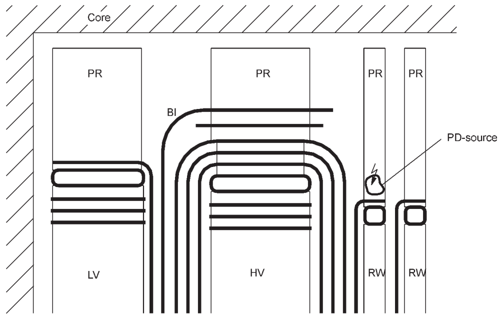
$E_b$ = breakdown field strength in kV/mm
$V_b$ = breakdown voltage in kV
$d$ = distance between two electrodes in mm

**Note:**

There are many places in the transformer insulating system, where the electric field is non-homogeneous, see figure 9.17. At these locations, the calculated homogeneous electric field must be multiplied by the electrode shape factor to estimate the maximum electric field. When designing a transformer, the maximum electric field strength of critical locations must be calculated using a field program.

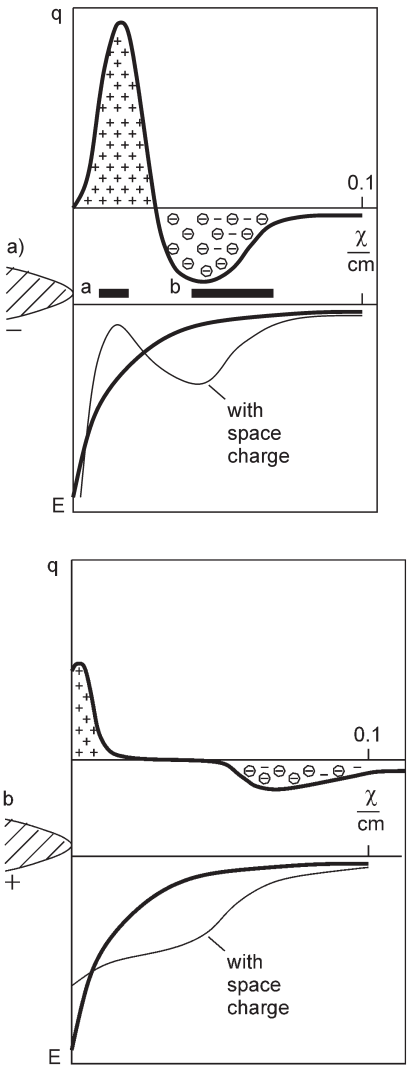
The following physical mechanisms describe the electric breakdown between two electrodes [111] and [220]:

- generation of primary electrons to start the electric breakdown
- charge multiplication and transport phenomena to bridge the distance between electrodes
- charge storage phenomena to support the next electric breakdown (memory effect of the PD source)




PR = press ring
BI = barrier insulation
LV = low voltage
HV = high voltage
RW = regulation winding

***Figure 9.17:*** *PD source in insulating system of the transformer*




$E$ = electrical field [kV/cm]
$x$ = distance between the electrodes [cm]

***Figure 9.18:*** *Charge distribution (upper graph) and electric field distribution (lower graph) for negative tip electrode (upper figure, a) and positive tip electrode (lower figure b).*

### Generation of primary electrons

Generation of primary electrons depends on:

- maximum electric field $E_{max}$
- electrode material (conducting, non-conducting)
- electrode shape (homogeneous or non-homogeneous electric field)
- electrode surface condition (uncovered, or covered with insulating material)
- smoothness of the surface (micro-tip electrodes)

The best condition for generating starting electrons occurs for an uncovered metallic tip electrode as shown in figure 9.18. Starting electrons are generated by field emission from the surface if the magnitude of the local electric field E exceeds the field emission values of the specific material. PD activity appears as soon as the local inception electric field is reached.

The most difficult location for generating a starting electron is a weak region without contact to the metallic electrodes, as shown in figure 9.19. In this situation the starting electrons are generated by radioactive ionization (cosmic, X-ray, etc.). Due to the lack of starting electrons, there is a delay before the PD-activity starts (up to several minutes), even if the local electric field exceeds the inception value.

**Note:**

For PD sources in the transformer insulating system the electrode material can be either an interface between different insulating materials (for example, solid insulation with a gas bubble) or a conducting material (for example copper covered with paper insulation).

### Charge multiplication and transportation

Charge multiplication and transport processes, see figure 9.20, are based on an avalanche mechanism described by the equation:

$$n = n_0 e^{\alpha d}$$

where:

$n$ = number of electrons at distance $d$
$d$ = distance between electrodes
$n_0$ = number of available starting electrons
$e^{\alpha d}$ = electron avalanche

An electron avalanche can only cause an electric breakdown (bridging of the distance between electrodes) if the following condition is fulfilled:

$$e^{\alpha d} \approx 10^7$$

where:

$\alpha$ = factor which is a function of the local electric field $E$
$d$ = distance between the electrodes

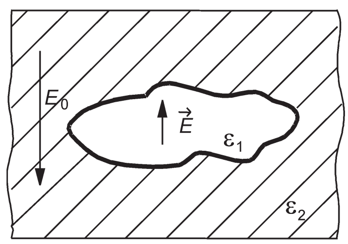
Both physical processes described above take time to develop (breakdown delay), see figure 9.21. During this time the applied voltage (i.e. the local electric field) must be constant.

The limiting parameters for PD activity in the weak region of the insulating system are:

- local electric field $E$ exceeds the design rating ($\alpha$-factor)
- size of the weak region (bubble) is sufficient (distance between electrodes in the weak region)
- duration of the applied voltage (local electric field) is long enough to develop the discharge processes

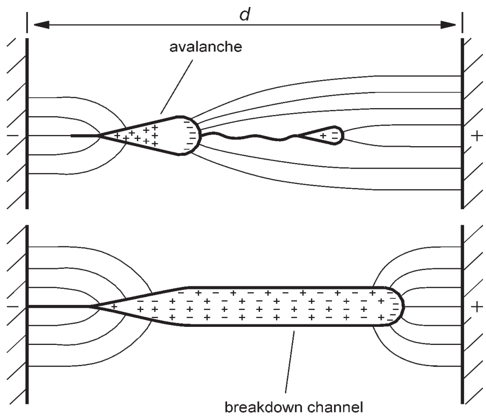
**Note:**

In order to detect dangerous PD sources in the insulating system of the transformer, the test voltage must be applied long enough to fulfill the requirement for the described breakdown process.



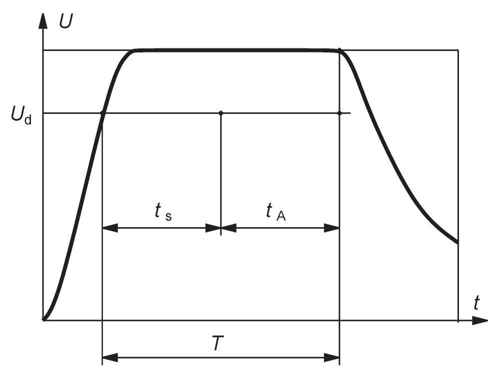

$\vec{E}$ = local electric field
$E_0$ = electric field
$\varepsilon$ = dielectric permitivity of the material

***Figure 9.19:** PD defect without metallic electrodes*



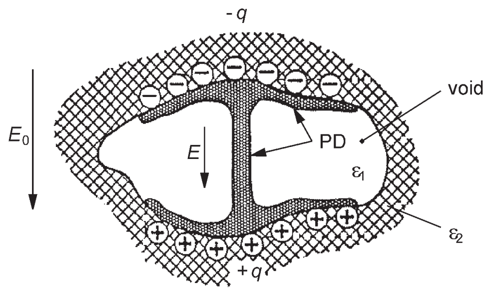

$d$ = distance between electrodes

***Figure 9.20:** Development of electric breakdown*



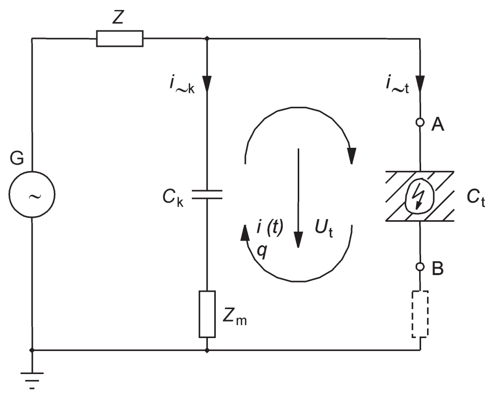

$T$ = total time delay
$t_S$ = starting electrons
$t_A$ = avalanches
$U_d$ = statistical voltage breakdown

***Figure 9.21:** Time delay of electric breakdown*




$q$ = charge
$E$ = local electric field
$PD$ = partial discharge
$E_0$ = electric field
$\varepsilon_1, \varepsilon_2$ = dielectric permittivity of the molecules

***Figure 9.22:*** *Schematic presentation of charge storage*




$C_t$ = test object capacitance
$C_K$ = coupling capacitance
G = voltage source
$i\,(t)$ = PD current impulses
$i_{\sim k,\sim t}$ = displacement currents
$Z$ = voltage source connection
$q$ = transferred charge
$U_t$ = voltage at parallel-connected capacitor

***Figure 9.23:*** *Equivalent circuit for PD measurement*

### Charge storage

Charge storage mechanisms are important for the weak regions with no contact to conducting electrodes (bubbles in insulating system), see figure 9.22. Charge storage and de-trapping mechanisms strongly influence successive electric breakdowns in the weak region. The repetition rate of the PD impulses and the type of PD-pattern (PD-type pattern type 5 in Table 3) are permanently changing. The physical phenomena caused by the charge storage mechanism can be observed by the recorded PD patterns during a long duration test (several hours at a constant value of the test voltage). An increasing repetition rate in the PD impulses indicates continuous damage to the insulating system in the vicinity of the PD source.

**Note:**

This short introduction into the physics of partial discharge has shown that electric breakdown in insulating materials is strongly influenced by the statistical behavior of the discharge mechanisms. To interpret PD results, it is necessary not only to consider the amplitude of the apparent charge, but also to analyze the statistical behavior of the PD source. Statistical analysis of PD activity is performed using an advanced PD-system (Phase Resolving Partial Discharge Analyser, see clause A 9.5).

## A 9.2 Principle of quasi-integration

A PD signal is always detected as a current impulse $i(t)$ via a measuring impedence $Z_m$ [212], see figure 9.23.

International standards (IEC 60270) [26] require that apparent charge should be measured:

$$q = \int i(t)dt$$

where:

$q$ = apparent charge in pC
$i(t)$ = PD current signal

Integration of the PD current impulses can be performed either in the time domain (digital oscilloscope) or in the frequency domain (band-pass filter). Most PD systems available on the market, perform a “quasi-integration” of the PD current impulses in the frequency domain using a “wide-band” or “narrow-band” filter.

The following assumption is made when non-periodic PD current impulses in the frequency domain are integrated using a band-pass filter, see figure 9.24 [109]:

$$q = F(0) = F(f)$$

where:

$q$ = apparent charge
$F(0)$ = amplitude frequency spectrum at frequency $f$ = 0 Hz
$F(f)$ = amplitude frequency spectrum at frequency $f$ Hz

The limiting frequency for constant spectral amplitude density, i.e. for a correct integration of the PD impulses in the frequency domain, depends on the pulse shape of the PD impulse as shown in figure 9.24 [109].

For a PD impulse with rise-time $T_1$ = 1 µs and half-value time $T_2$ = 5 µs, the limiting frequency for $F(f) = F(0)$ is about 5 kHz. For PD systems that are based on "quasi-integration" of the PD impulses, the lower cut-off frequency $f_1$ should therefore be sufficiently low (kHz range), otherwise correct measurements are not possible.

A "wide-band" PD measuring system consists of a band-pass filter with lower and upper cut-off frequencies $f_1$ and $f_2$, see figure 9.25 [212]. Recommended values in IEC 60270 [26] are for $f_1$ = 50 kHz and for $f_2$ = 150 - 400 kHz.

The amplitude $s_{max}$ of the wide-band filter response to excitation by a PD current impulse is proportional to the apparent charge $q$ if the center frequency $f_0$ of the filter corresponds to the frequency range of the current impulse where $F(f) = F(0)$, see figure 9.24.

Typical wide band filter response is presented in figure 9.26 [109]. For the amplitude is valid:

$$s_{max} \sim F(0) \quad = \quad q$$

where:

| | | |
|---|---|---|
| $s_{max}$ | = | amplitude of filter response |
| $q$ | = | apparent charge |
| $F(0)$ | = | amplitude frequency spectrum at the frequency $f$ = 0 Hz |

For the center frequency is valid:

$$f_0 = \frac{f_1 + f_2}{2}$$

where:

$f_0$ = center frequency of the band-pass filter

$f_1$ = lower cut-off frequency of the band-pass filter

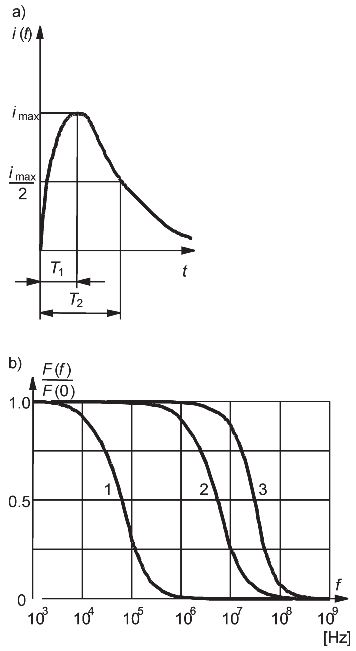
$f_2$ = upper cut-off frequency of the band-pass filter

Advantages of a wide-band PD system:

- distinguish positive and negative polarity of PD current impulses
- high resolution capacity for repetitive PD impulses, with typical filter response duration $\tau$' between 2 µs and 5 µs a PD impulse repetition frequency of 100 kHz can still be resolved

Disadvantage of the wide-band PD system:

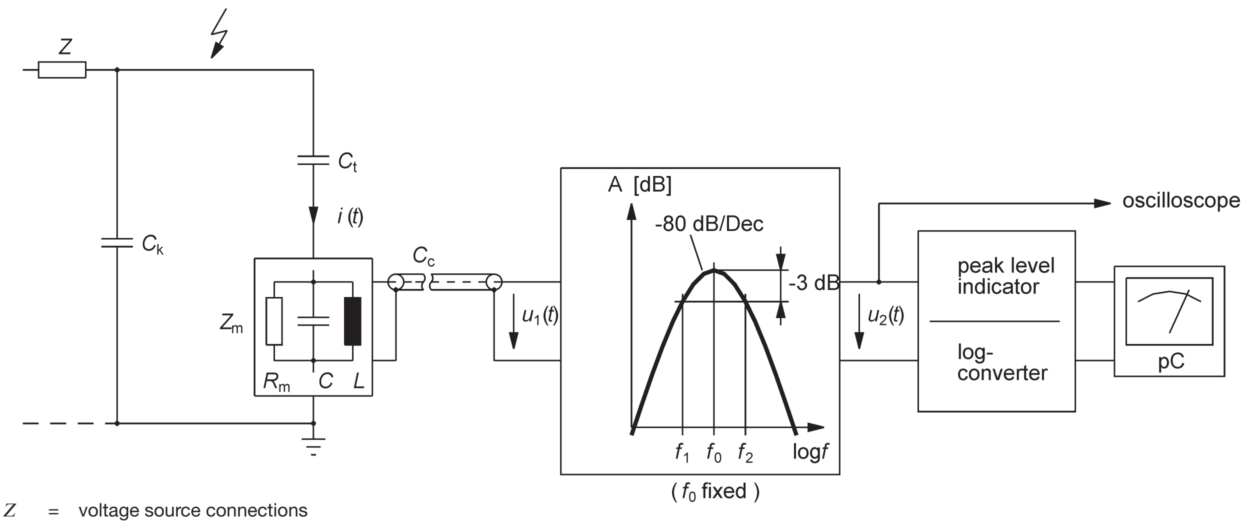
- sensitive to external noise (not suitable for unshielded HV laboratories)




a) Idealized PD current impulse
$i(t)$ = PD pulses
$T_1$ = time to maximum $I_{max}$
$T_2$ = half-value time

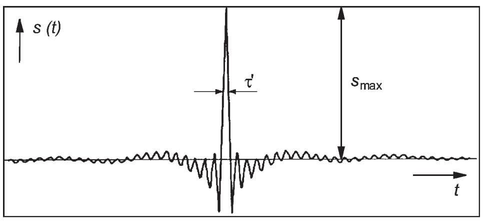
b) Normalized spectral amplitude density
1 = $T_1/T_2$ = 1µs / 5 µs
2 = $T_1/5T_2$ = 5 ns / 50 ns
3 = $T_1/5T_2$ = 5 ns / 15 ns
$F(0)$ = amplitude frequency spectrum at the frequency f = 0 Hz
$F(f)$ = amplitude frequency spectrum at frequency f Hz

***Figure 9.24:*** *Quasi-integration of PD impulses*




$Z$ = voltage source connections
$C_k$ = coupling capacitor
$C_t$ = test objekt capacitance
$Z_m$ = measuring impedance (R, L, C-type)
$C_c$ = capacitance of the measuring cable
$i(t)$ = PD-current impulse
$u_1(t)$ = response of the measuring impedance $Z_m$
$u_2(t)$ = response of the band pass filter
$f_1$ = lower cut off frequency of the band pass filter
$f_2$ = upper cut off frequency of the band pass filter
$f_0$ = center frequency of the band pass filter

***Figure 9.25:*** *Wide-band pass filter*




$s_{max}$ = maximum amplitude ~$q$
$\tau'$ = impulse duration (response of the filter)

***Figure 9.26:*** *Typical response of the wide-band pass filter*

A "narrow-band" PD measuring system, see figure 9.27 [212], consists of a band-pass filter with variable center frequency $f_0$ and narrow bandwidth $\Delta f$ (between 3 kHz and 30 kHz). Values accepted by IEEE C57.12.90.1999 [51] are:

- center frequency $f_0$ between 0,85 MHz and 1,15 MHz (recommended 1 MHz)
- bandwidth $\Delta f$ between 3 kHz and 10 kHz (9 kHz recommended)

The amplitude $s_{max}$, see figure 9.28, of the narrow-band filter response to excitation by a PD current impulse is proportional to the apparent charge $q$ if the variable center frequency $f_0$ of the filter corresponds to the frequency range of the current impulse where $F(f) = F(0)$, see figure 9.24.

Typical narrow-band filter response is presented in figure 9.28 [109].

Advantage of the narrow-band PD system:

- Less sensitive to external PD sources (successfully used in unshielded HV laboratories)

Disadvantages of the narrow-band PD system:

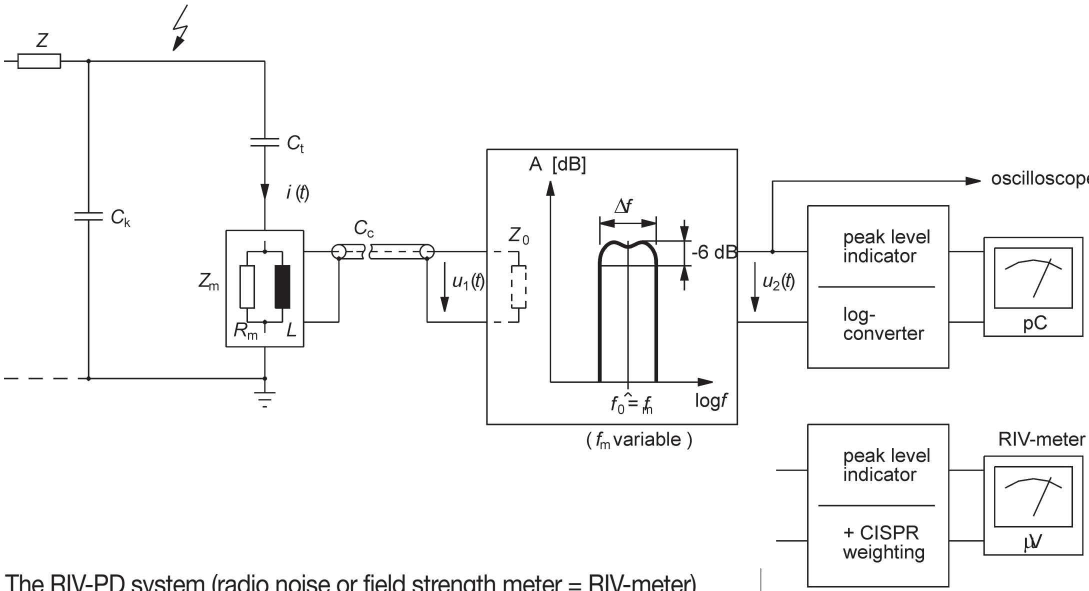
- not possible to distinguish the polarity of the PD impulses (signal oscillation with the center frequency $f_0$)
- low resolution capacity for repetitive PD impulses, with typical filter response duration $\tau' \sim 200\mu s$ a PD impulse repetition frequency of 4 kHz can only be resolved

The response duration of a narrow-band filter to the PD current impulse input can be estimated as:

$$\tau' \approx \frac{2}{\Delta f}$$

where:

$\tau'$ = impulse duration (response of the filter)
$\Delta f$ = bandwidth of the filter




The RIV-PD system (radio noise or field strength meter = RIV-meter) recommended by IEEE Standard C57.12.90.-1999 [51] is a narrow-band pass filter, which includes the CISPR weighting circuit (non-linear psophometric curve, see figure 9.29) to quantify the magnitudes of the repeated impulses. The readings on this type of instrument depend not only on the amplitude of apparent charge but also on the repetition rate of the PD impulses.

For a given constant PD impulse amplitude with a variable repetition rate, the reading on the RIV-meter with the CISPR-weighting circuit will increase linearly with an increasing repetition rate up to $n = 100$ impulses per second, see figure 9.29 [109]. For a pulse repetition rate higher than 4000 per second, which corresponds to a narrow-band filter pulse resolution time of $\tau = 220$ µs with $\Delta f = 10$ kHz, the reading becomes useless.

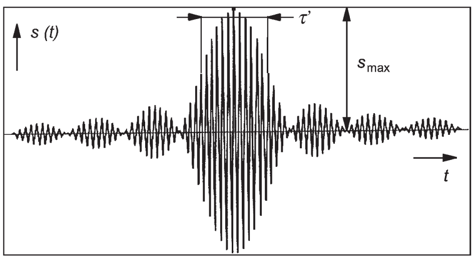
Because of the CISPR weighting circuit, there is no relationship between the pC and the µV-reading. Only if equally large impulses occur on the positive and the negative halfcycles a conversion can be made. With a repetition rate of twice a cycle ($n = 100$ in a 50 Hz-system) and a measuring impedance of 60 Ω the relationship 1µV = 2,6 PC holds.

**Note:**

For PD sources in the transformer insulating system far from the bushings (for example in the main insulation), the PD current impulses are heavily attenuated by the RLCM-network of the transformer. Such attenuated PD impulses may be outside the range of the PD system if the lower cut-off frequency $f_1$ of the wide-band filter (recommended 50 kHz) or the center frequency of the narrow-band filter $f_0$ (recommended 1 MHz) are higher than the limiting frequency of the attenuated PD-impulses $F(f) = F(0)$, see figure 9.24. In this case the “quasi-integration” is not correct and the amplitude of apparent charge no longer corresponds to $s_{max}$.

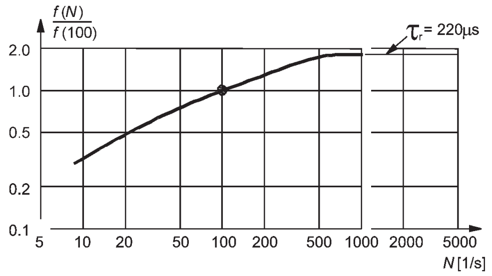
$Z$ = voltage source connections
$C_k$ = coupling capacitor
$C_t$ = test objekt capacitance
$Z_m$ = measuring impedance (R, L-type)
$C_c$ = capacitance of the measuring cable
$i(t)$ = PD-current impulse
$u_1(t)$ = response of the measuring impedance $Z_m$
$u_2(t)$ = response of the band pass filter
$f_0$ = center frequency of the band pass filter = $f_m$ (variable)

***Figure 9.27:** Narrow-band pass filter*




$s_{max}$ = maximum amplitude ~$q$
$\tau'$ = impulse duration (response of the filter)

***Figure 9.28:** Typical response of the narrow-band pass filter*




$f(N)$ = variation of meter reading [µV]
$N$ = pulse repetition rate

***Figure 9.29:*** *CISPR weighting characteristic for periodic pulse sequence with constant amplitude*

## A 9.3 True charge, apparent charge and measurable charge

A partial discharge can be interpreted as a rapid movement of an electric charge from one position to another. For very fast changes, or during the first instant after charge movement, the individual insulation links in a series of connected links between two line terminals can be regarded as a number of series-connected capacitors.

If the two line terminals are connected together via an external capacitance $C_k$ the charge movements within the series-connected insulation links (capacitances) will also be reflected in the charge of external capacitance $C_k$. The charge movements can be detected as circulating current impulses in the equivalent circuit, via measuring impedance $Z_m$, see figure 9.23.

In figure 9.30 a schematic drawing of the PD source (capacitance $C_1$) in the insulating system (capacitances $C'_2$ and $C'_3$) and the corresponding equivalent circuit are presented [212].

If the PD source is assumed to be a small cavity in the solid insulation, the following ratio exists between the capacitances

$$C_t \approx C'_3 \gg C_1 \gg C'_2$$

The electric breakdown in the cavity (capacitance $C_1$) is represented by the spark gap $F$ and resistance $R_1$.

The electric breakdown in the cavity generates a PD current $i_1(t)$, which is a local current and cannot be measured at the bushings.

Voltage drop $\Delta U_1$ across the cavity is caused by discharge current $i_1(t)$ and releases a charge $\Delta q_1$ = true charge.

$$\Delta q_1 = \Delta U_1\, C_1$$

The discharge of $C_1$ causes a rapid charge transfer in capacitances $C'_2$ and $C'_3$. This charge transfer causes a measurable voltage drop $\Delta U_t$ at the test object capacitance $C_t$ (at the winding bushing connection).

$$\Delta U_t = \Delta U_1 \frac{C'_2}{C'_3 + C'_2}$$

$$C_t = C'_3 + \frac{C_1 C'_2}{C_1 + C'_2}$$

Assuming:

$$C_t \approx C'_3 \gg C_1 \gg C'_2$$

The theoretically measurable charge $q_t$ is:

$$q_t \approx q_3$$

$$q_3 = \Delta U_3\, C_t$$

$$\Delta U_t \approx \Delta U_3$$

$$q_3 = \Delta U_1 \frac{C'_2}{C'_3 + C'_2}\left(C'_3 + \frac{C_1 C'_2}{C_1 + C'_2}\right)$$

$$\Delta U_1 = \frac{\Delta q_1}{C_1}$$

$$q_3 \approx \frac{\Delta q_1}{C_1}\frac{C'_2}{C'_3}C'_3$$

$$q_3 \approx \Delta q_1 \frac{C'_2}{C_1} = q_t$$

In an extended insulating system the $\Delta U_t$ values are in the millivolt-range, while the magnitude of $\Delta U_1$ (at the PD source) may be in the kilovolt-range. The theoretically measurable charge $q_t$ is linked to true charge $q_1$ via capacitances $C_1$ and $C'_2$ and is defined as apparent charge. Because the location of the PD source is not known, capacitances $C_1$ and $C'_2$ cannot be estimated. The apparent charge (theoretically measurable charge $q_t$ at the bushing) can therefore not be derived from the true charge $q_1$ at the location of the PD source.

### Sensitivity of the measurement:

In any PD test circuit, the real measurable charge $q_m$ (integral of the circulating PD current $i(t)$), is dependent on the ratio of coupling capacitance $C_k$ to test object capacitance $C_t$, see figure 9.31.

The charge transfer processes between capacitances $C_t$ and $C_k$ cause a residual voltage drop $\Delta U_{res}$. If there is PD activity in the test object ($C_t$), the real measurable charge $q_m$ released by coupling capacitance $C_k$ is estimated as:

$$q_m = C_k \cdot \Delta U_{res}$$

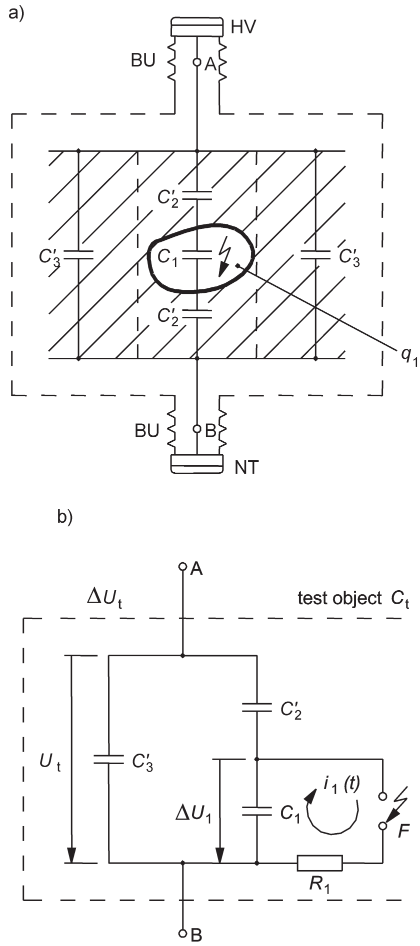
Apparent charge $q_t$ is:

$$q_t = C_t \Delta U_t = (C_t + C_k)\, \Delta U_{res}$$

The ratio of the real measurable charge $q_m$ and apparent charge $q_t$ (theoretically measurable charge) is defined as:

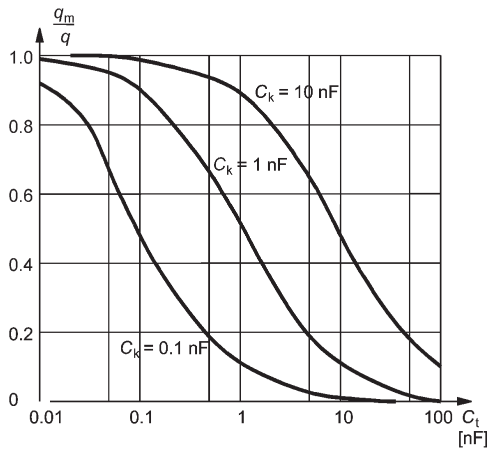
$$\frac{q_m}{q_t} = \frac{C_k}{C_t + C_k}$$

To improve PD measurement sensitivity, a sufficiently large coupling capacitance $C_k$ should be installed, see figure 9.31 [212]. In power transformer PD circuits the coupling capacitance value is determined by the type of bushing (from 200 to 600 pF). The sensitivity of each PD circuit is defined by the calibration procedure.




BU = bushing
HV = high voltage
NT = neutral terminal
$C_1$ = weak region
$C_t$ = test object capacitances ($C'_2$ and $C'_3$)
$U_t$ = test voltage
$F$ = simulation of the PD-source
$R_1$ = damping resistance
$\Delta U_1$ = internal voltage drop caused by PD
$\Delta U_t$ = voltage drop measurable at the bushing
$i_1(t)$ = local PD-current impulse

***Figure 9.30:*** *Detectable PD signals*
*a) schematic representation of a part of the transformer insulation*
*b) equivalent circuit for PD defect in insulating system*




$q$ = apparent charge

$q_m$ = measurable charge

$$\frac{q_m}{q} = \frac{C_k}{C_t + C_k}$$

***Figure 9.31:*** *Influence of coupling capacitor* $C_k$ *on the measuring sensitivity* $\frac{q_m}{q}$

The maximum sensitivity for detection of a compensating PD current-impulse $i(t)$ is reached for $C_k \gg C_t$ ($C_k$ = 100 $C_t$, see figure 9.31). As the value of coupling capacitance $C_k$ decreases, the sensitivity of the PD circuit is reduced due to the lower compensating current $i(t)$.

The minimum coupling capacitance of any PD test circuit is the stray capacitance $C_s$ of the HV potential electrodes to ground. A PD circuit using $C_s$ as a coupling capacitance has a very low sensitivity because $C_s \ll C_t$.

Theoretically a RIV-system without CISPR weighting circuit delivers the same amplitude of measurable charge $q_m$ as a narrow-band filter ("quasi-integration" of circulating PD current $i(t)$), except that the reading is calibrated in microvolt.

For any RIV-system with a weighting circuit, no conversion is possible between pC and µV.

## A 9.4 Typical external noise sources

A sensitive PD system connected to an extended test circuit for PD measurements on HV transformers is able to detect all high frequency impulses in the test circuit. The PD system cannot distinguish between the real PD impulse and external noise. If PD activity is detected, the possibility of an external source must be investigated.

An overview of external PD sources is given in figure 9.32 [212].

### Low voltage power supply (1, 2, 11)

Noise such as thyristor pulses or harmonics from the low voltage power supply, may especially influence a sensitive PD system which is directly connected to the power line. If these are present, a low-pass filter or insulating transformer should be used.

Due to the filtering effect of the step-up transformer (3) and of the HV filter (4) in the connection to the test object, the noise from the low-voltage power line is usually sufficiently suppressed. If there is a noise problem, a second step-up transformer may be used as an additional filter or a PD system with a narrow-band filter could be used ($f_0$ > 1 MHz).

### High voltage source (3)

An HV source must generally be PD-free. If there is a problem, the coupling capacitor $C_k$ can be connected directly to the source (without the test object) to easily check the HV source.

### HV filter (4)

In difficult cases, a PD-free HV filter (low pass) must sometimes be used.

### Connections in the test circuit and electrodes (5)

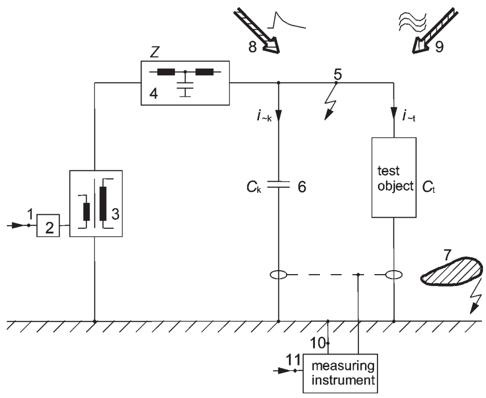
All bushing tops (even earthed bushings) and sharp metallic parts on top of the transformer (especially close to the bushings) should be shielded; see clause A 9.8. All connections should be PD-free (sufficient radius). All measuring impedances $Z_m$ must have a good connection to earth. If there is a problem an ultrasonic detector (corona gun) may be used to detect an external PD source. The PD type can be determined from the statistical analysis of the PD signals (typical PD-pattern, see Table 3).

### Coupling capacitor (6)

The coupling capacitor must be PD-free. If there is a problem, the coupling capacitor must be measured separately.

### Conductive objects close to the transformer under test (7)

Unearthed conductive objects close to the transformer under test are charged to a high potential due to the electric field. If the breakdown field value is reached, a pulse-like discharge occurs. These PD impulses are coupled to the PD test circuit and detected at the measuring impedances, and normally exhibit a very high apparent charge amplitude. This PD source can be recognized by comparing it with typical PD patterns, by visual observation in the laboratory, or by using an ultrasonic detector.




1,2 = low voltage power supply
3 = high voltage source
4 = HV-filter
5 = connections and electrodes
6 = $C_k$ = coupling capacitor
7 = conducting object
8 = pulse shaped interferences
9 = harmonic interferences
10 = interference currents in the earthing system
11 = low voltage power supply

***Figure 9.32:*** *Typical noise sources (see text for explanation)*

**Interference in non-shielded laboratories (8,9)**

Pulse-shaped interferences (switching phenomena) or harmonic interferences (radio transmitters) heavily influence the sensitivity of the PD system. In these cases a narrow-band filter with variable center frequency should be used, see clause A 9.2, to suppress the ambient interference. The best way to suppress the effect of such external interferences is to apply an advanced PD system, which uses a spectrum analyzer as a front-end, see clause 9.9. Repetitive external sources like thyristor pulses can be “gated out”. A gating function is available on several PD systems. The final possibility for suppressing these electromagnetic waves is the construction of a shielded HV laboratory (Faraday cage).

**Note:**

Measuring impedance $Z_m$ (lower cut-off frequency at 10 kHz) normally suppresses the power frequency displacement currents at capacitances $C_k$ and $C_t$. If the power frequency current limit for the specific impedance $Z_m$ is exceeded, suppression of power frequency current is lost. Before applying a test voltage, the maximum power frequency current in the test circuit, which is dependent on capacitances $C_k$ and $C_t$ in the test circuit, should be calculated. The maximum power frequency current in the capacitance is defined by:

$$i_{ac} = U_{test} \; j\omega C$$

## A 9.5 Advanced PD system

The ICMsys8, (manufactured by Power Diagnostix Systems GmbH, Germany) is a specially designed modern PD system to meet the requirements of partial discharge measurements on power transformers. The ICMsys8 uses wide-band filters for both digital data acquisition and further data processing of conventionally detected PD signals, see clause A 9.2.

True parallel acquisition of PD impulse currents on eight channels is achieved by using eight individual amplifiers (wide-band filters) connected to eight measuring impedances at the bushings via eight pre-amplifiers. The PD activity is detected simultaneously on all eight channels and processed in the controller unit, see figure 9.33a. PD readings can be weighted according to IEC in pC or according to IEEE in µV (analog interface for RIV-meter). Typical result of the ICMsys8 is shown in figure 9.33b.

In addition to PD signal detection, the ICMsys8 offers eight independent channels for voltage measurements via a separate tap at each measuring impedance $Z_m$.

Besides conventional PD signal detection of the apparent charge values, the ICMsys8 is capable of performing a statistical analysis of the detected PD activity (i.e. phase-resolving partial discharge analysis (PD pattern) at the specific channel, see figure 9.33b.

The principle of a Phase-Resolving Partial Discharge Analyzer (PRPDA-system, ICM systems) is shown in figure 9.34 [215].

A PRPDA-system produces a two or three-dimensional PD pattern (phase angle, discharge magnitude and number of events are obtained; see figure 9.35). For two-dimensional PD patterns the third dimension (number of counts per channel) is indicated by the color code.

PD pattern reflects the sum of all PD impulses collected during a specific measuring time (for example, a preset time of 60 seconds corresponds to 3000 cycles for a 50 Hz test voltage power frequency).

PD pattern can be regarded as a fingerprint of the partial discharge activity of a specific defect in the test object.

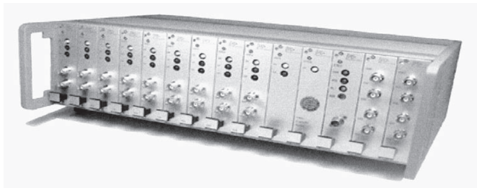


***Figure 9.33a:*** *Advanced PD system ICMsys8*

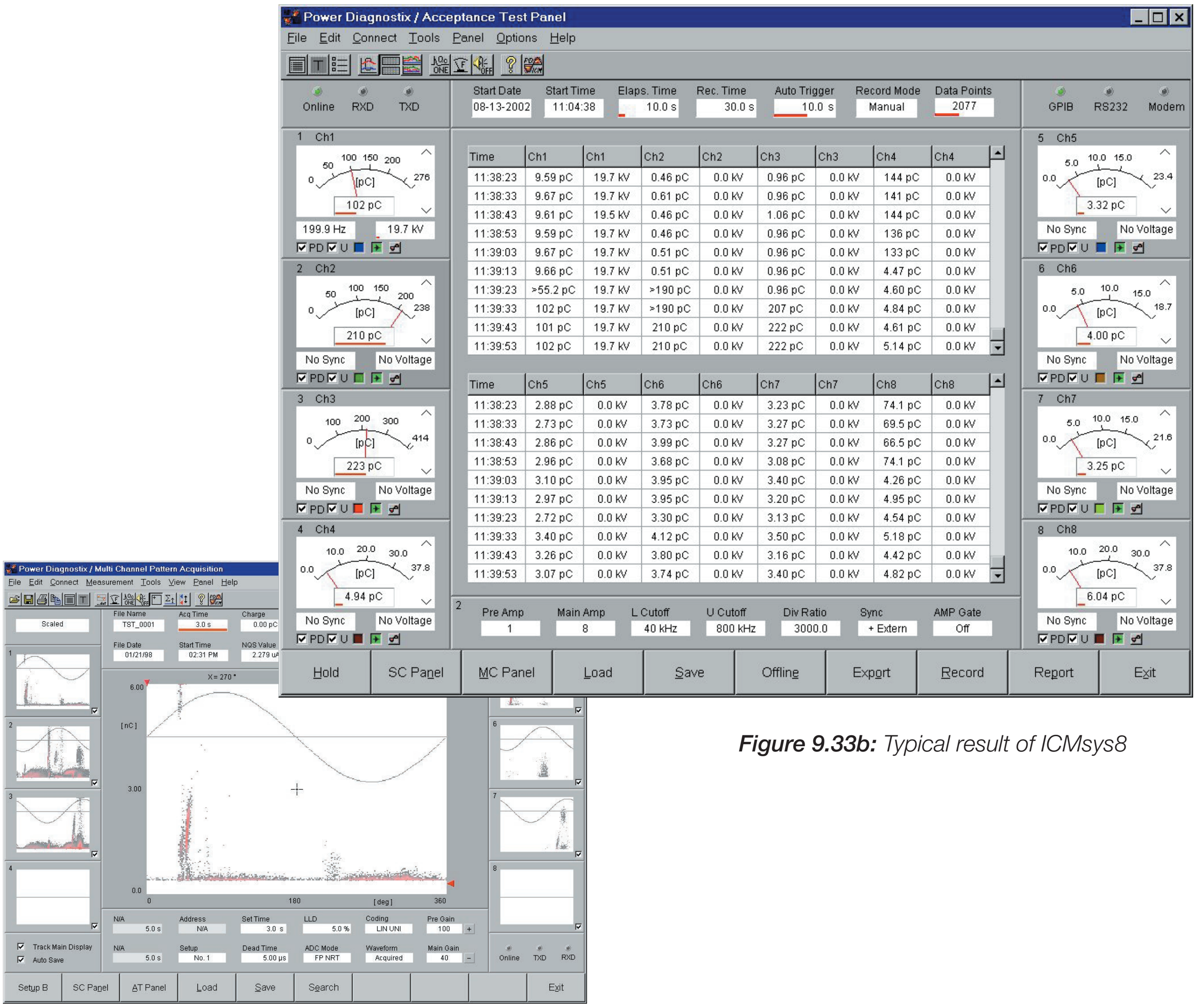



***Figure 9.33b:*** *Typical result of ICMsys8*

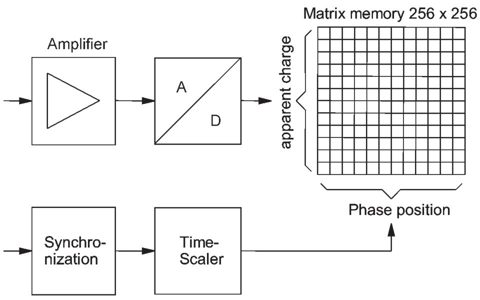



***Figure 9.34:*** *Principle Phase-Resolving Partial Discharge Analyser (PRPDA-system)*

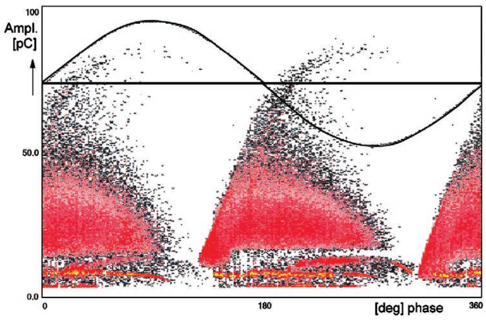



***Figure 9.35:*** *Registration of PD impulses (bubbles and surface discharge); advanced PD system (statistical analysis of PD impulses)*

Both the phase resolution and the amplitude resolution are 8-bit (256 channels for the phase and 256 levels for the amplitude of the apparent charge).

The main difference between a conventional and a modern digital PD system is the ability to perform a statistical analysis of the detected PD current impulses (PD pattern). A conventional PD system delivers phase-resolved information about the PD activity for only one cycle, see figure 9.8b.

A phase-resolving partial discharge analysis is important for identification of the type of PD source for the following reasons:

- PD patterns identify a specific type of PD source (image of the physical process; see Tables 3 and 4 and clause A 9.1)
- PD patterns are not influenced by the signal transfer function of the extended insulating system (statistical behavior does not change)
- PD patterns can be used to distinguish between superimposed PD defects on the basis of different statistical behavior

## A 9.6 Detection of acoustic PD signals

An acoustic PD signal is a mechanical vibration characterized by its frequency $f$.

Theoretically, the PD source acts as a point source of acoustic waves. The intensity of the emitted acoustic waves is proportional to the energy released during the discharge.

$$\Delta W_1 = q_1 \ \Delta U_1$$

where:

$\Delta W_1$ = locally released energy

$q_1$ = local charge

$\Delta U_1$ = local voltage drop

Acoustic wave propagation occurs only if the wavelength $\lambda$ is small compared with the length of the propagation path.

In a specific medium the wavelength is given by:

$$\lambda = \frac{v}{f}$$

where:

$\lambda$ = wavelength

$v$ = sound velocity in a specific medium (1400 m/s in oil)

$f$ = frequency of mechanical vibration (acoustic wave)

Oil would be a perfect medium for the propagation of acoustic waves, with no attenuation or dispersion occurring. In the transformers, acoustic waves propagation is heavily influenced by the complicated structure of the insulating system (winding barriers, core, and tank walls). In a complicated structure, both the amplitude (attenuation) and the signal-shape (absorption, dispersion) of the acoustic signal emitted by a PD source change along its propagation path [217].

Besides the absorption and dispersion phenomena, the multitude of wave types complicate the analysis of acoustic PD signals detected in a multi-material structure.  Two types of waves must generally be considered for the analysis of acoustic signals, see figure 9.36.

- transversal waves; attenuation is dependent on wall thickness
- longitudinal waves; higher velocity than transversal waves (approximately a factor of two)

Possible propagation paths of acoustic waves from a PD source to the transformer tank wall are shown schematically in figure 9.37. The two waves (superimposed) are created at an interface, either by incidence or reflection, see figure 9.37. An acoustic sensor positioned at a defined location on the tank wall detects both, directly propagated waves and wall-propagated waves. The two wave types have different propagation velocities.

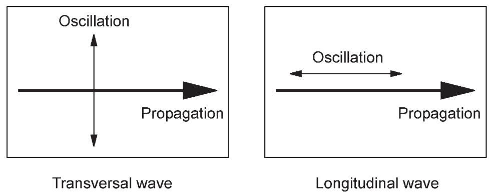
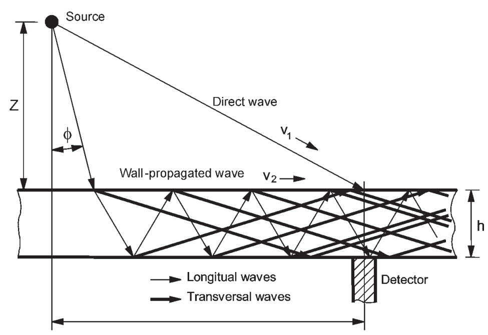



***Figure 9.36:*** *Schematic presentation of two types of acoustic waves*




$v_1$ = velocity of direct wave

$v_2$ = velocity of wall wave

$\Phi$ = incident angle

$Z$ = distance of the PD-source to the wall

$h$ = thickness of the wall

***Figure 9.37:*** *Possible acoustic waves at the sensor*

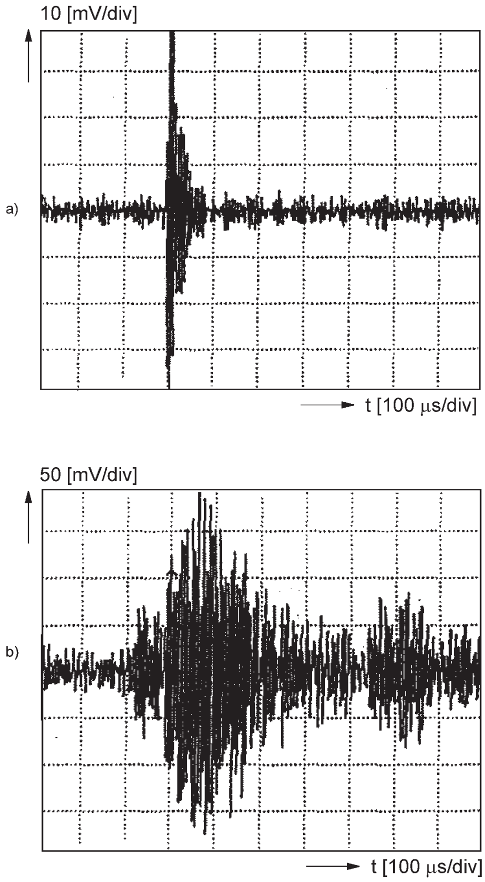



***Figure 9.38:*** *Analysis of acoustic waves of PD sources*
*a) Detection of direct (through the oil) acoustic wave*
*b) Detection of reflected acoustic wave or wave propagated through different media*

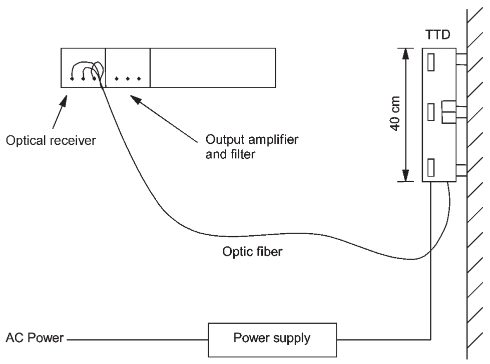



***Figure 9.39a:*** *Main components of the TTD-system*

In order to localize the PD sources by analyzing the time difference between the electric and acoustic PD signals, there must be a possibility to distinguish between directly propagated and wall-propagated waves. This information is theoretically hidden in the wave front of the acoustic signal that is detected at the sensor on the tank wall, see figure 9.38.

**Note:**

The fastest propagation path is not the direct path, but the path with an incident angle $\Phi$, see figure 9.37:

$$\sin \Phi = \frac{v_1}{v_2}$$

where:

$v_1$ = velocity in medium 1 (for example in oil)

$v_2$ = velocity in medium 2 (for example in the tank wall)

**Advanced detection system:**
**Three-Transducer Detector (TTD)**

A minimum of three acoustic sensors (piezoelectric transducers) and a four-channel digital oscilloscope are theoretically required to localize PD sources using the time difference between electric and acoustic signals. An advanced detection system, **T**hree-**T**ransducer **D**etector (TTD) is used in ABB factories, see figure 9.39 [218].

**Note:**

This system is not manufactured any more, but is still in use.

The three transducers (piezoelectric crystals) are placed close to one another (equilateral triangle with $L$ = 0,15m) so that the propagation path of the acoustic waves from the PD source is nearly the same. TTD defines its own $x$, $y$ and $z$ co-ordinate system (normalized vectors). The normalized co-ordinates ($x, y, z$) give the direction to the source and depend only on time differences in the TTD system, see figure 9.39c. It is assumed that the distance between the transducers $L$ is considerably less than the distance $d$ of the TTD-sensors to the PD-source when deriving the localization formulas, see figure 9.39c.

A typical result obtained by the TTD-system is shown in figure 9.40.

The procedure for localizing the PD source using the TTD results is given in the following and will be explained further using an example:

- a decision is made whether a “direct wave” or a “wall wave” was detected by analyzing the shape of the detected signal
- the “apparent velocity”, $v_{app}$ is calculated by approximate expression to distinguish between direct wave and wall wave

$$v_{app} = \frac{L}{\sqrt{\frac{2}{3}\left[(t_1 - t_2)^2 + (t_2 - t_3)^2 + (t_1 - t_3)^2\right]}}$$

where:

$L$ = distance between transducers

$t_1, t_2, t_3$ = time difference between electric and acoustic signals for the three transducers

- the apparent velocity $v_{app}$ is compared with sound velocities in materials relevant for the transformer insulating system, see Table 5.
- a decision is made about the type of wave (direct or wall wave)
- the co-ordinates x, y, z of the PD source are calculated using TTD software for the specific wave (direct or wall wave)

**Table 5:** Example of sound velocities

| Material | Velocity [m/s] | Density [kg/m³] |
|---|---|---|
| Oil | 1400 | 950 |
| Pressboard | 2000<br>parallel to fiber | 1250 |
| Pressboard | 3500<br>perpendicular to fiber | 1250 |
| Steel, plate | 3200<br>transversal wave | 7900 |
| Steel, plate | 5200<br>longitudinal wave | 7900 |

There are three different conditions for the calculated apparent velocity $v_{app}$.

$v_{app} > v_{transversal}$ -> direct incident wave with shallow angle

$v_{app} \approx v_{transversal}$ -> transversal wave

$v_{app} < v_{transversal}$ -> should not happen (possibly in thin walls)

**Note:**

Apparent velocity $v_{app}$ is always higher than $v_{oil}$ (1400 m/s).

**Example**

Calculation of the PD source location using the results presented in figure 9.40.

- the shape of the detected acoustic signal indicates a wall wave (superimposed longitudinal and transversal waves)
- apparent velocity $v_{app}$ = 3417 m/s for a longitudinal wave, calculated values for a longitudinal wave ($t_{1L}$ ~ 336 µs, $t_{2L}$ ~ 363 µs, $t_{3L}$ ~ 320 µs) do not clearly indicate a longitudinal wave

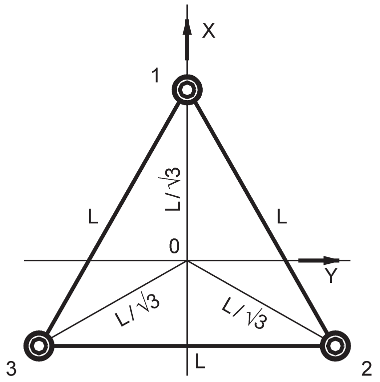



***Figure 9.39 b:*** *Geometric design*

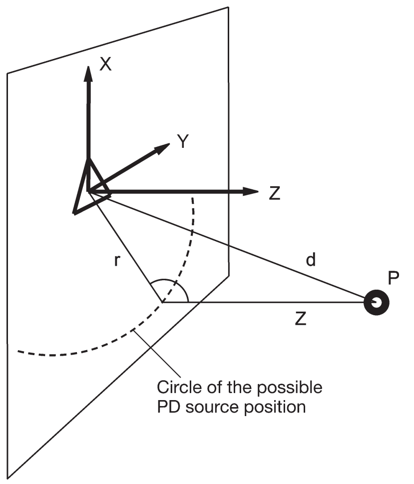



***Figure 9.39 c:*** *Normalized co-ordinates*

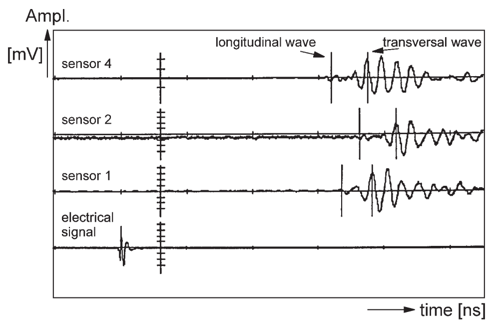



***Figure 9.40:*** *Typical TTD system result*

- apparent velocity $v_{app}$ = 3236 m/s for a transversal wave, calculated values for a transversal wave ($t_{1T}$ ~ 382 µs, $t_{2T}$ ~ 418 µs, $t_{3T}$ ~ 375 µs) indicate a wall wave (3200 m/s = velocity of transversal wave for steel plate)
- calculated position of the PD source for wall wave (TTD software)

  $x$ = +0,19, $y$ = -0,52, $z$ =+0,34 m

**Note:**

Due to the different paths of electric and acoustic PD signals through the insulating system of the transformer, there is no simple relationship between the amplitude of apparent charge and the amplitude of acoustic waves.

Knowledge of the transformer insulating system and experience in the analysis of the results are needed to localize PD sources by analyzing acoustic PD signals.

## A 9.7 Localization of the PD source using analysis of the electric signals

Electric PD signals (PD current impulses) propagate from the PD source through the RLCM-network of the transformer, see figure 9.42. The response of this network to excitation by a PD current impulse at any location in the insulating system can only be detected at the bushings. All information available in the detected signal must therefore be analyzed. [214, 219]

All signals in the time domain (recorded using an oscilloscope) and in the frequency domain (recorded using a spectrum analyzer) are generally linked via Fourier transformation, see figure 9.41. [121]

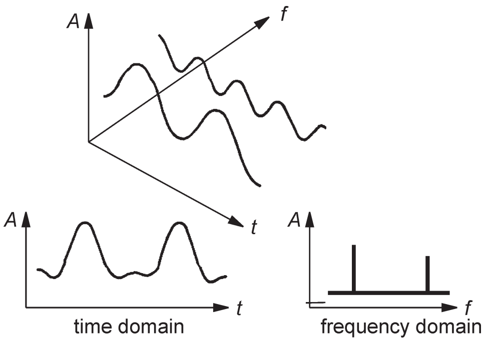



***Figure 9.41:*** *Signal presentation in time domain and frequency domain*

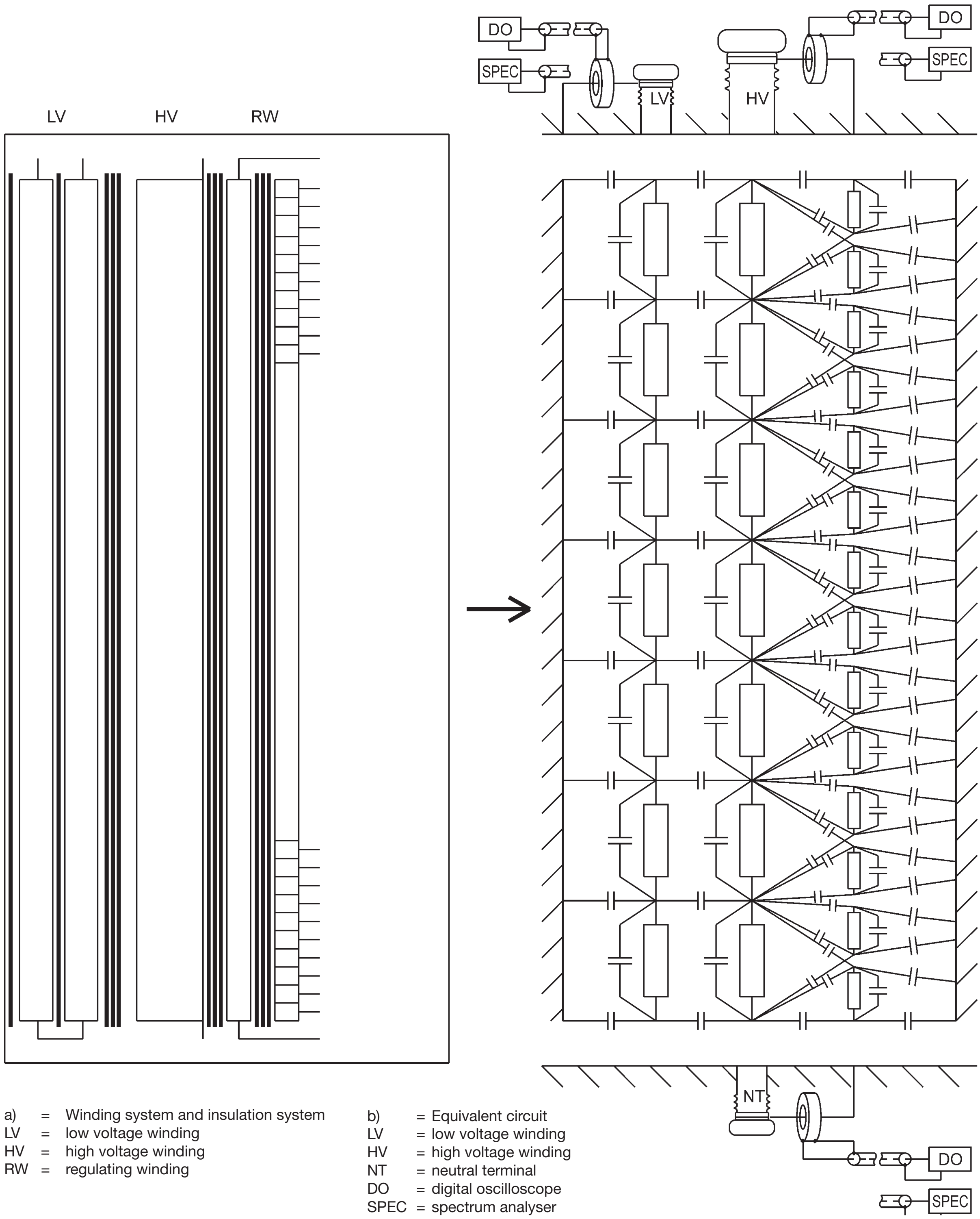
For a given non-periodic PD current impulse $i(t)$, the complex frequency spectrum $I(j\omega)$ is obtained from the Fourier integral:

$$I(j\omega) = \int_{-\infty}^{+\infty} i(t)\, e^{-j\omega t}\, dt$$

Allthough the PD current signal is the same, the data recorded in the time domain and in the frequency domain contain different information, which is important for localization of the PD source.

Theoretically a specific response of the RLCM network exists for any type of PD pulse and for any location of the PD source in the insulating system, and may be detected at the transformer bushings.

A time consuming characterization of the transformer RLCM network is generally necessary to be able to analyze real PD signals in the time and frequency domains. A calibrating signal (usually 1000 pC) is injected at one specific bushing and cross-couplings are successively recorded at all other bushings. This procedure is repeated for each bushing, see clause 9.9.




a) = Winding system and insulation system
LV = low voltage winding
HV = high voltage winding
RW = regulating winding

b) = Equivalent circuit
LV = low voltage winding
HV = high voltage winding
NT = neutral terminal
DO = digital oscilloscope
SPEC = spectrum analyser

***Figure 9.42:*** *RLC network of the transformer*

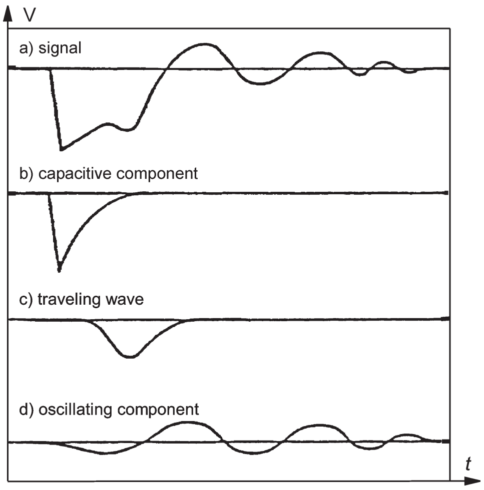
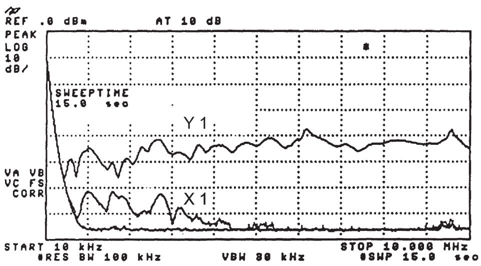



*Figure 9.43:* *PD signal analysis in time domain*




$Y_1$ = close to the measuring top
$X_1$ = coupling via RLCM network

*Figure 9.44:* *PD signal analysis in frequency domain*

## A 9.7.1 Analysis of PD signals in the time domain [214]

The PD current impulse in the time domain detected at the bushing can be characterized by three components, see figure 9.43:

- capacitive component caused by transmission through the capacitive ladder network
- traveling wave component caused by electromagnetic wave transmission
- oscillating component determined by the resonance frequency of the LC-circuit

Basic time-resolved PD signal characteristics that should be analyzed are:

- Maximum amplitude of the PD current signal (mV)
- Rise-time of the PD current signal
- Oscillations of the PD current signal
- Reproducibility of PD current signals

An indication about the location of the PD source is given by comparing the recorded PD signals in the time domain with the results of the characterization of the transformer.

## A 9.7.2 Analysis of PD signals in the frequency domain [216]

The PD current impulse in frequency domain detected at the bushing can be characterized by two typical frequency spectra, see figure 9.44:

- typical frequency spectrum generated by very fast PD signals (close to the measuring tap)
- typical frequency spectrum generated by attenuated PD signals (inside the insulating system)

Basic frequency spectra features that should be analyzed are:

- Amplitude of the power spectrum (dBm)
- Frequency range of the power spectrum
- Typical resonances
- Reproducibility of power spectra

The indication about the location of the PD source is found by comparing the PD signal frequency spectra with the results of the characterization of the transformer.

**Note:**

All the theoretical components of the signals in the frequency domain as well as in the time domain are strongly dependent on the design of the transformer (size, type of windings), on the true location of the PD defect with respect to the terminal where the PD signal was detected and on the original shape of the PD signal (discharge in gas, oil, or solid material).

Knowledge of the transformer insulating system and experience in the analysis of the results are required to localize PD sources using the analysis of the electric PD signals.

## A 9.8 Corona shielding

External discharge (corona) can be prevented by shielding. A guideline for shielding is given in figure 9.45. The graph shows permissible voltage on the shield without giving rise to corona.

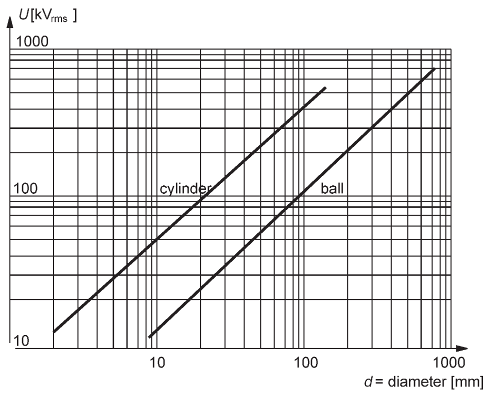



***Figure 9.45:*** *Shielding dimensions to eliminate corona*

# Testing of Power Transformers

## 10. Lightning impulse and switching impulse test

# 10. Lightning impulse and switching impulse test

## 10.1 References / Standards

- IEC 60060-1(1989), High-voltage test techniques – Part 1: “General definitions and test requirements” [21]
- IEC 60060-2 (1994), High-voltage test techniques – Part 2: “Measuring systems” [22]
- IEC 60060-3 (w.i.p.*), High-voltage test techniques – Part 3: “Definitions and requirements for on-site tests” [23]
- IEC 60076-3 (2000), Power Transformers – Part 3: “Insulation levels, dielectric tests and external clearances in air” [3]
- IEC 60076-4 (2002), “Guide to lightning impulse and switching impulse testing of power transformers and reactors” [4]
- IEEE Std C57.12.90-1999, clause 10: “Dielectric tests” [51]
- IEEE Std C57.98-1993, “Guide to impulse testing techniques, interpretation of oscillograms and failure detection criteria” [58]

* work in progress

Although the two main standards [3], [51] are harmonized today; there are several differences, especially in the way insulation criteria and requirements are specified. IEC specifies the ratings **L**ightning **I**mpulse Withstand Level, (abbreviated LI) and **S**witching **I**mpulse Withstand Level (abbreviated SI) for impulse withstand.
IEEE specifies the rating **B**asic lightning **I**mpulse insulation **L**evel (abbreviated BIL) and BSL (**B**asic **S**witching impulse insulation **L**evel).

IEC allows free selection of standardized values for LI and SI, while a given BIL value specifies the lightning impulse as well as the switching impulse insulation requirements.

**Note:**

The lightning impulse test is a **routine test** for transformers where $U_m$ > 72,5 kV according to IEC [3] or ≥115 kV according to IEEE [50]; the switching impulse test is a **routine test** for transformers where $U_m$ > 300 kV according to [3] or 345 kV and above according to [50]. For any other value of $U_m$, these tests are considered to be design tests or special (“other”) tests, see section 2, tables 1 and 2.

## 10.2 Purpose of the test

The purpose of the test is to verify the insulation integrity for transient voltages, caused either by atmospheric phenomena (lightning), network disturbances or switching operations.

## 10.3 General

When the Standards and/or a customer specification request an impulse test, the following tests may apply:

- the lightning impulse test at one or all terminals
- the switching impulse test at the terminal with the highest rated voltage

If not otherwise specified, the impulse tests precede the voltage insulation test at power frequency (induced voltage test and separate source test). The IEC requires that a switching impulse test precede any of the lightning impulse tests.

A transformer is generally considered to have passed an impulse test when there is a close similarity between the traces for a calibration impulse and those of the impulses at specified voltage levels. Because the impulse tests precede all other dielectric tests at power frequency, it is also possible to later identify non-conformances or hidden damage caused by the impulse tests.

Lightning impulses as well as switching impulses have standardized shapes that are specified in the applicable Standards, see section 10.4. A switching impulse has only one characteristic, identified as a normal full wave. A lightning impulse on the other hand may have three different shapes:

- Full wave
- Chopped wave on the tail
- Front chopped wave (front-of-wave)

In a full wave the applied voltage has a monotonous decay to zero after the voltage crest has been reached. In a chopped wave the applied voltage is short-circuited to zero voltage after a pre-set time.

The polarity of the impulse voltages is generally negative to prevent flashovers on the air-side of the transformer bushings or any other external flashovers.

**Test sequence**

If not otherwise specified by the customer the test sequence for an impulse test should be:

- Switching impulse test, if applicable
- Lightning impulse test

### 10.3.1 Lightning impulse test

The test sequence depends on the test code, IEC [3] or IEEE [51], and customer requirements. Generally the test sequence starts with reduced level impulses and ends with full wave test impulses at specified amplitude.

IEC specifies:

- One reduced level full impulse (calibration impulse)
- One full level full impulse (LI)
- One or more reduced level chopped impulse(s) (only if specially requested)
- Two full level chopped impulses (LIC), only if specifically requested
- Two full level full impulses (LI)

If not otherwise requested, IEC [3] test requirements specify that the chopped wave should have an amplitude of 110 % of the LI value.

IEEE specifies:

- One reduced full wave impulse (calibration impulse)
- Two front-of-wave impulses at specified amplitude (only if specifically requested)
- Two chopped wave impulses at specified amplitude
- One full wave impulse at rated amplitude (BIL)

The chopped wave should be at 110 % of the BIL value and the front-of-wave should have an amplitude according to table 5 of [50] (only for Class I transformers).

The chopped wave calibration impulse for the applicable wave shape may immediately precede the chopped wave test itself, and it need not be carried out as the initial part of the test sequence.

The integrity of the transformer is confirmed when there is a close similarity between the voltage traces for the applied calibration impulse voltage and all of the applied full test voltages.

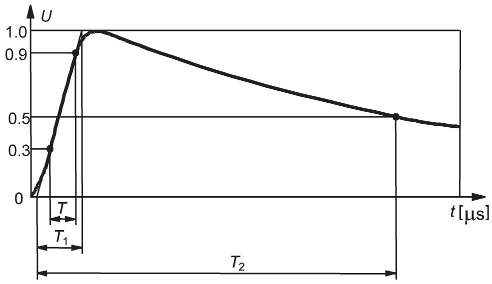
### 10.3.2 Switching impulse test

The switching impulse test generally consists of:

- A calibration impulse at about 60 % of the specified insulation level
- Two [51] or three [3] impulses at the specified insulation level

Insulation integrity is verified when there is no voltage breakdown during the test.

To the transformer, the switching impulse represents a time integral of the applied voltage. It may force the transformer core into saturation and in a saturated condition the impedance will drop to such a low value that the applied voltage can no longer be maintained. It is therefore important that the transformer has a remanence condition opposite to the flux generated by the applied impulse. This is normally achieved by applying a number of switching impulses of opposite polarity (positive) and reduced voltage prior to each test impulse.




$T_1$ = 1,67 · $T$ = 1,2 μs ± 30 % – front
$T_2$ = 50 μs ± 20 % – tail

***Figure 10.1:*** *Lightning impulse full wave; IEC and IEEE*

## 10.4 Impulse shape

### 10.4.1 Lightning impulse

The basic impulse is used to verify the lightning withstand voltage in accordance with IEC 60076-3 [3] and IEEE Std C57.12.90 [51].

The waveform of the impulse is aperiodic as shown in figure 10.1. It has a specified rise time of 1,2 μs and duration of 50 μs to half value. The specified shape is the same for both IEC and IEEE.

The waveform is characterised by:

front: $T_1$ = 1,2 μs, tolerance ± 30 % (0,84 to 1,56 μs)

tail: $T_2$ = 50 μs, tolerance ± 20 % (40 to 60 μs)

polarity: negative (for oil insulated transformers)

Because impulse generating circuits are not perfect, the definitions of rise time as well as crest value need additional clarification. The slope of a straight line passing through the voltage values 0,3 and 0,9 times the crest value gives the rise time. The rise time will then be 1,67 times the time between these two voltage values.

See clause A 10.1 for a definition and assessment of crest value.

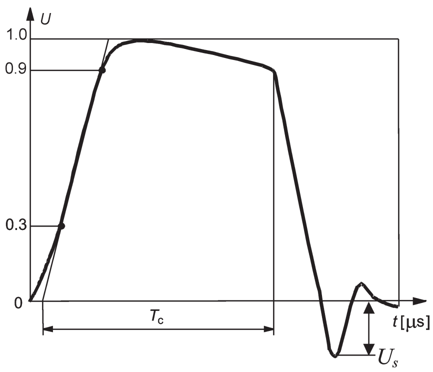
### 10.4.2 Impulse voltage wave shape, chopped on the tail

IEC states:

The chopped wave peak should be 10% higher than the full wave. The time to chopping is $T_c$ = 2 to 6 μs, see figure 10.2. Triggered chopping equipment is preferred but untriggered spark gaps are permitted, see clause A 10.2. The overshoot $U_s$ of the test amplitude after the first zero crossing should not be more than 30 % of the test amplitude.

IEEE states:

The lightning impulse chopped on the tail shall always be carried out together with the lightning impulse full wave test. The test voltage and the time to chopping are defined in table 5.6 (IEEE C57.12.00) [50] and lie approximately 10 % above the full wave values, see figure 10.1. The overshoot $U_s$ may not exceed 30 % of the test amplitude.

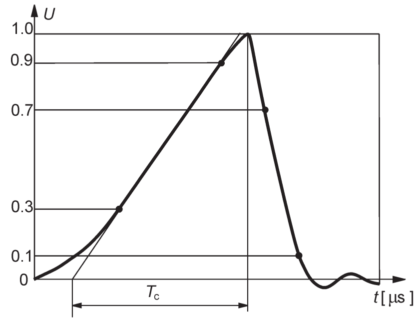



$T_C$ = 2…6 μs – time to chopping

***Figure 10.2:*** *Wave chopped on the tail; IEC and IEEE*

### 10.4.3 Impulse voltage wave shape, chopped on the front (front-of-wave)

The front-of-wave chopped impulse wave test is only required by IEEE and only after special agreements.
The test voltage and the time to chopping for BIL ≤ 350 kV are defined in table 5 (IEEE C57.12.00) [50], see figure 10.3.
The overshoot may not exceed 30 %, see clause A 10.2.




$T_C$ = time to chopping (IEEC C57.12.00 table 5)

***Figure 10.3:*** *Front chopped wave (front-of-wave); IEEE*

### 10.4.4 Switching impulse wave form

The following aperiodic waveform is used to verify transformer switching impulse withstand voltage, in accordance with IEC and IEEE, see figure 10.4:

The impulse waveform is characterised by:

Front: $T_1 \geq 100$ µs $\Rightarrow T_1 = 1{,}67 \cdot T$
90% value: $T_d \geq 200$ µs
$U = 0$: $T_z \geq 500$ better $\geq 1000$ µs (IEC)
$T_z \geq 1000$ µs (IEEE)
$T_z$ = time to first zero crossing

The front time $T_1$ should be selected to ensure that a linear voltage distribution takes place across the winding.

Polarity:

- negative (oil insulated equipment) per IEC [3]
- positive* or negative or both per IEEE [51]

* Negative polarity is recommended to avoid external flash-over.

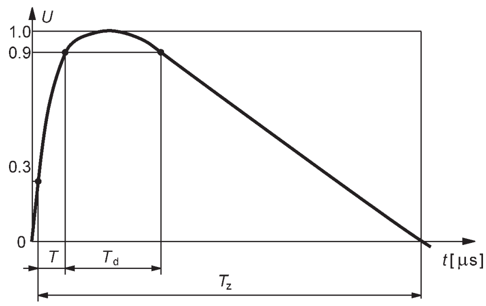
For theoretical considerations concerning the time to the first zero-crossing $T_z$, see clause A 10.10.

For generation of switching impulse voltages, see clause A 10.2. The rise time $T$, for switching impulse is defined in a similar way as the lightning impulse

$T_1 = 1{,}67 \cdot T$

where:

$T$ = the time between 30 % and 90 % of the test voltage on voltage rise.




$T_1$ = front
$T_d$ = time above 90 %
$T_z$ = time to the first zero cross

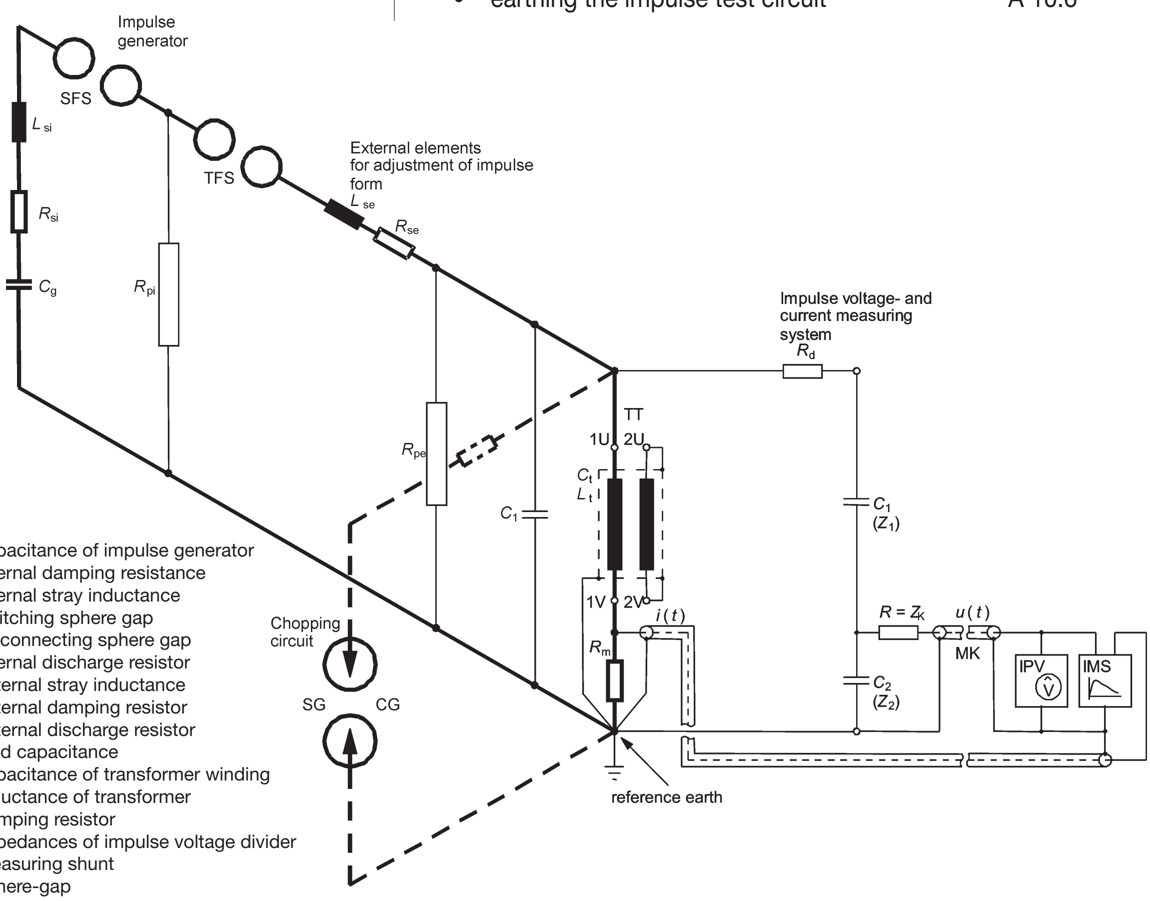
***Figure 10.4:*** *Switching impulse wave; IEC and IEEE*

## 10.5 Test connections

### 10.5.1 General

Figure 10.5 shows the impulse test circuit and its components. The individual components are described in the appendix in the following clauses:

- impulse generator — A 10.2
- pre-calculation of the impulse test parameters — A 10.3
- impulse voltage measurement — A 10.4
- impulse current measurement — A 10.5
- sphere-gap — A 12.4
- chopping gap — A 10.2
- earthing the impulse test circuit — A 10.6




$C_g$ = capacitance of impulse generator
$R_{si}$ = internal damping resistance
$L_{si}$ = internal stray inductance
SFS = switching sphere gap
TFS = disconnecting sphere gap
$R_{pi}$ = internal discharge resistor
$L_{se}$ = external stray inductance
$R_{se}$ = external damping resistor
$R_{pe}$ = external discharge resistor
$C_1$ = load capacitance
$C_t$ = capacitance of transformer winding
$L_t$ = inductance of transformer
$R_d$ = damping resistor
$Z_{1,2}$ = impedances of impulse voltage divider
$R_m$ = measuring shunt
SG = sphere-gap
CG = chopping gap

***Figure 10.5:*** *Basic layout of impulse test and impulse measuring circuit; connection of test object for lightning impulse test*

The overall impulse circuit can be split into three individual circuits:

- main circuit (main discharge circuit) – shown bold in figure 10.5
- voltage measuring circuit – shown with fine lines in figure 10.5
- the chopping circuit for the chopped waves and front of waves (shown with a bold dashed line in figure 10.5). It also includes the sphere-gaps to calibrate the impulse voltage measuring equipment, if required.

Switching impulse test is principally the same. Only the resistance and capacitance values are different.

It is important to keep the impulse voltage and current measuring systems away from the high current loops – shown bold in the above diagram.

## 10.5.2 Lightning impulse

The configuration of the test connections has a significant influence on the transformer lightning impulse test:

- on the stress of the transformer under test itself
- on the ease of detecting a failure or localization of a defect
- on the achievable impulse voltage wave shape and definition of the parameters for the impulse test circuit.

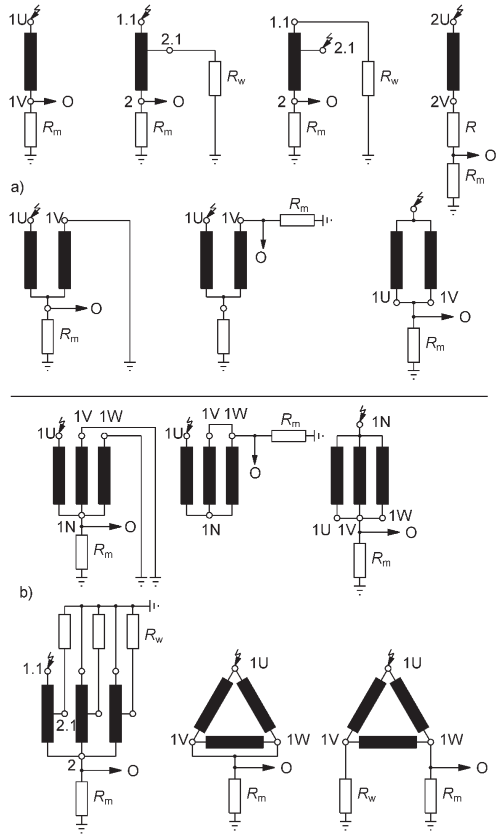
In general, the test connection configuration should be selected so that it corresponds to the operational condition. Only a single-phase lightning impulse (which occurs most frequently during operation) is considered. Figure 10.6 shows the most usable circuits for the lightning impulse test (only the winding current measurement is shown in this diagram; for other methods, see clause A 10.5).

In principle, non-tested winding terminals must be solidly earthed. Exceptions include autotransformers (≤ 400 Ω) [3]. For other exceptions (e.g. to increase the specified half-time) see clause A 10.1 and clause A 10.3.

Non-tested windings are short-circuited and solidly earthed. If the specified half-time of the tail cannot be achieved, the winding may be earthed via resistors, see clause A 10.1.

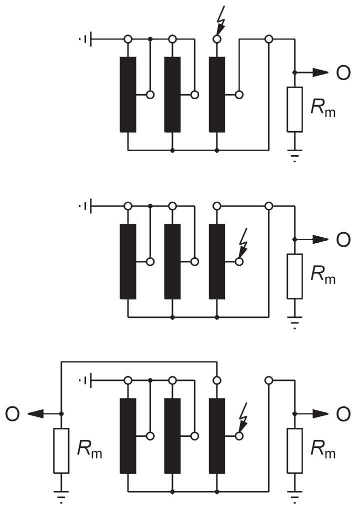
IEC states that the neutral must be solidly earthed or earthed via a low impedance shunt.

If the regulating system is a plus / minus or a coarse / fine regulating system, the fine tap position depends on the rotation direction of the selector (as required by the design). It is therefore connected to either the coarse tap input or output for the on-load-tap changer center tap position, depending on which way the selector was turned, see figure 10.7.



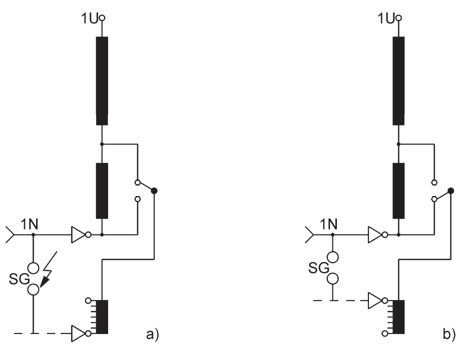

$R_m$ = measuring shunt
$R_W$ = resistor with value equal to line wave impedance
$R$ = series resistor
O = oscillograph

***Figure 10.6a:*** *Usual winding connections for lightning impulse test; single-phase and three-phase transformers*




$R_m$ = measuring shunt
O = oscillograph

***Figure 10.6b:*** *Usual winding connections for lightning impulse test; auto-transformers*




a) = direction from minimum to maximum
b) = direction from maximum to minimum
SG = protection gap

***Figure 10.7:*** *Connection of coarse and fine regulating winding*

The voltage distribution within the winding can be significantly uneven and for one of the two circuits, see figure 10.7, could lead to a flashover at one of the on-load tap changer selector switch protective gaps. This can be seen in the test oscilloscope recordings and must be appropriately analysed.

If the neutral point is tested directly, see figure 10.6 b, all three line terminals must be earthed. In this case increased tolerances must be accepted, see clause A 10.1.

**Tap position**

The two Standards IEC [3] and IEEE [51] have different rules for selection of tap positions.

IEC states:

Unless impulse testing on a particular tapping has been agreed to, the two extreme tappings and the principal tapping shall be used; one tapping for each of the three individual phases of a three-phase transformer or the three single-phase transformers designed to form a three-phase bank. When the tapping range is 5 % or less only the principal tap shall be selected. For an impulse test on the neutral, see IEC 60076-3 [3], clause 7.4.3.

IEEE states:

The impulse shall be applied for a tap position giving minimum electric turns within the winding to be impulse tested. This shall be interpreted as disconnected tapping ranges, corresponding to minimum tap position for linear and coarse-fine regulating arrangements and a tap position where no part of the tapping range carries current in a boost-buck arrangement.

**Impulse test on the neutral terminal**

When the neutral terminal of a winding has a rated impulse withstand voltage, it may be verified by a test using.

a) indirect application:

Test impulses are applied to any of the line terminals or to all three line terminals of a three-phase winding connected together. The neutral terminal is connected to earth through an impedance or left open. When a standard lightning impulse is applied to the line terminal, the voltage amplitude developed at the neutral shall be equal to the rated impulse level of the neutral terminal. For this test the resulting wave shape is not specified [3].

b) direct application:

Test impulses are applied directly to the neutral with all line terminals earthed, see figure 10.6 b. When this method is used a front time of up to 13 µs [3] or 10 µs [51] is allowed.

IEEE only permits direct application alternative.

### 10.5.3 Switching impulse

The transformer winding configuration corresponds to that of the induced voltage test, see section 8.

For single-phase transformer configuration see figure 10.8 a.

The voltage distribution across the winding is linear, the same as for the induced voltage test. A voltage corresponding to the voltage ratio is induced in the windings not being tested. Tests on more than one winding per phase are therefore superfluous.

For the switching impulse test the transformer should generally be connected as in normal operation; i.e. neutral earthed and all other terminals left open or alternatively connected to a voltage measuring device.

The impulse is generally applied to the terminal with the highest rated voltage for each phase. This test should be performed directly whenever possible; i.e. apply the test voltage at the HV terminals. Only in exceptional cases it may be applied to a terminal with a voltage less than the highest rated voltage. In such cases the applied voltage should be adjusted to reach the specified test voltage at the terminal with the highest voltage.

In three-phase transformers may it be advisable to short-circuit the two non-tested high voltage terminals to each other to ensure equal induced voltages on the non-tested phases.

The voltage induced in terminals other than that at the applied terminal are theoretically proportional to the turns ratio, but oscillations may change the voltage and it should be checked at reduced voltage.

IEC requires three-phase transformers to be connected in star (Figure 10.8 b); the neutral is solidly earthed, so that there is a voltage between phases of 1,5 times the test voltage.

IEEE C57.98 figures 36 and 37 show alternative connections for the various vector groups, e.g. figure 10.8 c.

IEEE treats the switching impulse as a phase to earth test.

**Tap position**

In general there is no requirement for the tap position to be used during a switching surge test. One exception is when two or more windings have switching surge test requirements. In such a case the tap position should be selected to give an induced voltage in the non-tested winding close to its specified test level.

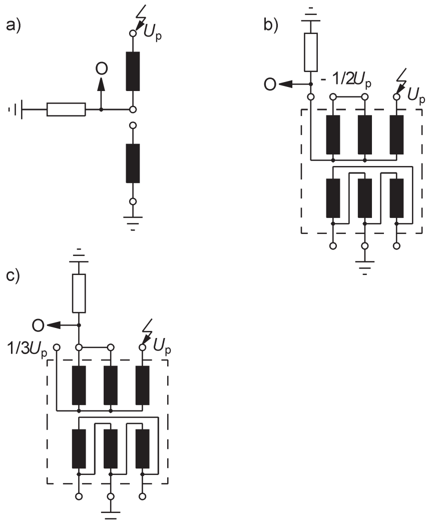
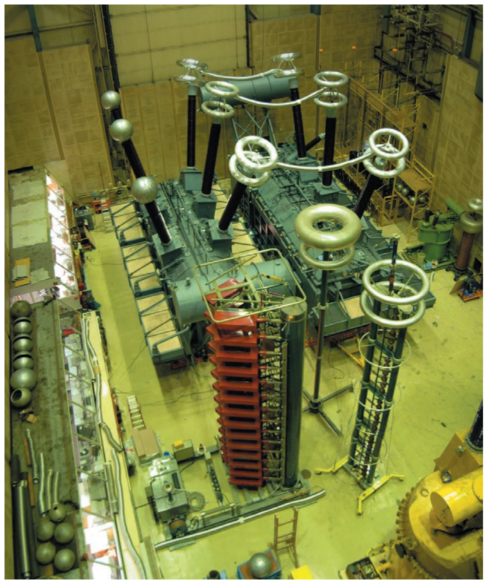



**Figure 10.8 :** *Usual winding connections for switching impulse test*



*800 MVA phase-shifting transformer under preparation for impluse test*

### 10.5.4 Direct or indirect impulse

In general the impulse is applied to the terminal to be tested and the impulse is denoted as a direct impulse. This applies to the switching as well as lightning impulse.

On transformers with non-uniform insulation the winding end with the lower insulation requirements may be tested using an indirect method. This means that the tested terminal is connected to earth via a resistor and the impulse is applied to the terminal with the higher insulation level, see clause 10.5.2.

The resistor, impulse amplitude and impulse shape are adjusted to reach the specified insulation requirements across the resistor, while the amplitude of the applied impulse does not exceed a specified upper limit (generally less than 80 % of the insulation requirements of the terminal receiving the impulse).

## 10.6 Test procedure / recordings

### 10.6.1 Checks preceding impulse tests

The following checks should be carried out at the transformer under test immediately before the lightning impulse test:

- check duration of the minimal transformer "standing time"
- measure the voltage ratio, the polarity and the winding resistances (sections 4 and 3)
- check transformer oil quality
- vent the Buchholz relay and the porcelain bushings
- short-circuit and earth any built-in bushing current transformers present
- earth the capacitive bushing taps
- check the oil level in the transformer and in the OLTC (if present).
- check on-load or off-load tap changer positions

### 10.6.2 Lightning impulse test

Selection of the impulse test circuit parameters follows, clause A 10.3.

The actual lightning impulse test consists of the following steps:

- verifying the impulse voltage waveform, see figure 10.1 to 10.3
- applying the impulse voltage to the transformer under test
- verifying that the transformer under test has withstood the stresses without damage (compare the digital or oscillographic recordings)

For the order in which to apply the test voltages (test sequence), see section 10.3.1.

## Recordings

### General

The impulse voltage and the impulse response current can be recorded in either oscillographic or digital form. Digital recording instruments are recommended.

Digital processing that includes transfer function analysis is often used as an additional tool for failure analysis (see IEC 60076-4 [4] clause 10 and figure B17).

IEC requires:

The lightning impulse voltage wave and at least one other characteristic (generally impulse current) shall be recorded using a measuring system, see clause A 10.5. All impulses > 50 % (IEC) [3] shall be recorded.

Impulse current is normally the more sensitive parameter for failure detection. Oscilloscope readings are therefore the main criteria for assessing the test results.

It is useful to have simultaneously captured oscilloscope recordings with different time scales to help identify failures.

IEEE requires:

In addition to the impulse voltage also the winding current or the neutral point current shall be recorded. All impulses > 40 % shall be recorded [51].

Additional observations during test such as other current measuring methods, microphones (acoustic recordings), etc. can be used to assess the test results or to defect localization.

Guidelines for the time scale during the lightning impulse test (FW = full wave, CW = lightning impulse chopped wave):

| | | Analog [µs] | Digital [µs] |
|---|---|---|---|
| FW | Voltage | 50 – 100 | (100 -) 150 |
| | Current | 50 – 100 | (100 -) 150 |
| CW | Voltage | 10 | 10-25 |
| | Current | 10 – 25 | (10 -) 25 |

### 10.6.3 Switching impulse test

In order to avoid an external flashover, it is recommended to conduct the test using negative polarity. A positive polarity switching impulse test (permitted by IEEE) has stricter requirements with respect to the dimensional considerations of the test laboratory. Larger external clearances in air between energized parts and earth must be used compared with those required for the lightning impulse test. Figure 10.41 in clause A 10.11 shows mean values for the 50 % flashover-voltage for lightning and switching impulses with negative and positive polarity.

The test itself is normally conducted using the direct method i.e. direct application of the impulse voltage waves at the high voltage winding, see section 10.5.4. The impulse withstand voltage must be verified in the winding with the highest voltage rating.

Both the winding impulse current and the impulse voltage characteristic can be used to assess the results.

The actual switching impulse test is conducted as follows:

- verify the impulse voltage waveform, see figure 10.4
- apply the impulse voltage to the transformer under test
- verify that the transformer under test has withstood the stresses without damage (compare the oscilloscope recordings)

For the order in which to apply the test voltages (test sequence), see section 10.3.1.

In order to achieve the specified time to zero crossing $T_z$, the required iron core pre-magnetization must be developed by applying impulses of opposite polarity at 25 to 50 % of rated voltage immediately before the 100 % full waves are applied.

Because of the iron core saturation caused by the test, clear audible noises, which should not be identified as defects can be heard within the tank (magnetostriction).

## Recordings

#### General

The switching impulse voltage recording and the switching impulse response current recording can be either analog or digital. Digital recording instruments are recommended.

Digital processing which includes transfer function analysis is often used as an additional tool for failure analysis (see IEC 60076-4 [4] clause 10 and figure B17).

IEC and IEEE require only that the switching impulse voltage wave be recorded. An additional characteristic (e.g. winding current) can be used to assess the outcome of the test.

Other test observations, such as other current measuring methods, acoustic recordings, etc. can provide additional information in the event of non-conformance.

Guidelines for time scaling: 1000 to 2500 µs for impulse voltage and current.

For digital recordings a sampling rate of approximately 10 MHz is sufficient.

## 10.7 Assessing the test results and failure detection

### 10.7.1 Lightning impulse test

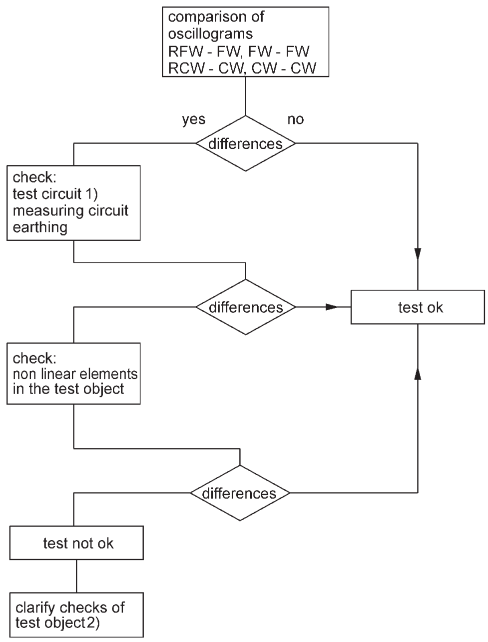
To satisfy the test criteria, the recordings (digital or oscillographic) for RFW and FW or RCW and CW, as well as FW or CW are compared. The current characteristic is normally the more sensitive parameter for failure detection. If the recordings do not show any changes, the transformer has passed the lightning impulse test.

If deviations in the waveform are observed, the causes must be determined. This assumes a good deal of testing experience. The relatively complicated configuration of the impulse test circuit where high frequency processes can occur may lead to a diverse range of possible failure causes. The logic diagram in figure 10.9 gives a point of reference to locate failures, but necessarily includes only basic directions.

Typical oscilloscope recordings are shown in IEC 60076-4 [4] and IEEE C57.98. [55].

### 10.7.2 Switching impulse test

To satisfy the test criteria, the impulse voltage and impulse current recordings (digital or oscillographic) for RFW and FW are compared, and FW are compared among each other. If the recordings do not show any changes, the transformer has passed the switching impulse test. It should be noted however, that the time to the first zero crossing cannot be kept constant because of the voltage related saturation effects in the iron core.




1) = for example – check ignition of impulse generator
2) = connection of windings – figure 2.45

***Figure 10.9:*** *Failure detection for impulse test*

For other non-conformances, mostly high frequency type deviations, the cause must be investigated. Because of the relatively complicated configuration of the impulse test circuit, various causes other than the transformer under test itself are possible. The logic diagram shown in figure 2.46 for determining failures during the lightning impulse test can in principle also be used here.

Voltage breakdowns within the transformer under test are generally easy to detect.

Because of the linear impulse voltage distribution across the winding, breakdowns generally occur in the form of short-circuits between the windings or parts of windings, or flashovers from winding to earth. These types of non-conformances can be clearly distinguished by observing the differences in the recordings. Typical test oscilloscope recordings are shown in IEC 60076-4 [4] and IEEE C57.98 [55].

## 10.8 Calibration - impulse measuring system / measuring uncertainty

Calibration is described in the Standards as follows:

- IEC 60060-1, High-voltage test techniques – Part 1: General definitions and test requirements [21]
- IEC 60060-2, High-voltage test techniques – Part 2: Measuring systems [22]
- IEC 1083-1, Digital recorders for measurements in high-voltage impulse tests – Part 1: Requirements for digital recorders [32]
- IEC 1083-2, Digital recorders for measurements in high-voltage impulse tests – Part 2: Evaluation of software used for the determination of the parameters of impulse waveforms [33]
- IEEE Std 4, Standard Techniques for High Voltage Testing [53]

A reference system within the test laboratory is generally the best solution for calibration of the impulse measuring system, see also clauses A 10.6 and A 10.7.

## Appendix A 10:

## Lightning and switching impulse testing

### A 10.1 Waveshape and its assessment

The amplitude of possible oscillations on the crest of the voltage near the front should not exceed 5% of the peak value according to IEC 60060-1 [21] and IEEE Std 4 [53] (IEC allows 10 % under certain special conditions as described below). Figures 10.10 and 10.11 show the standard test voltage peak wave value.

The tolerances defined above for the front and tail times cannot always be maintained.

#### Increasing the front time tolerance (> ± 30 %)

The front time is determined principally by series resistance $R_s$ and the effective capacitance of the transformer under test $C_t$, see clause A 10.3. If the capacitance $C_t$ is large, resistance $R_s$ must be reduced to achieve the specified front time. This occasionally causes oscillations on the crest of the voltage, whose amplitude exceeds the permitted 5 %.

A compromise is then required. In such cases, the oscillations on the crest of the voltage can increase to maximum 10 % (per IEC) while maintaining the front time tolerance. Above this value, allowance is made for a longer front.

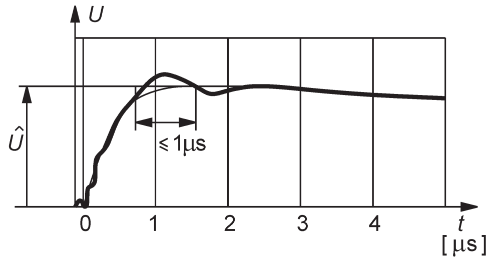
When using a direct impulse for testing the neutral point, a longer front is unavoidable. IEC allows up to 13 µs and IEEE up to 10 µs. In operation no transient coming from over-head lines will strike the neutral directly and the transferred surge will therefore always have a long front.

#### Increasing the tail half-time duration tolerance (> ± 20 %)

When impulse testing the low-voltage winding on large power transformers, the tail time (40 to 60 µs) cannot always be achieved using typical impulse circuit components because of the low inductance, see clause A 10.3.

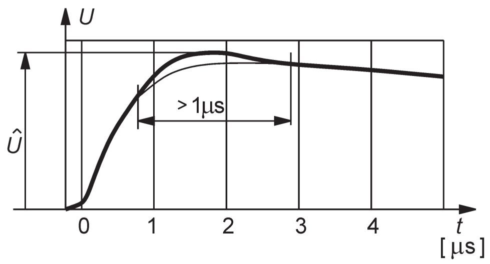
Special circuits are required and in certain circumstances compromises must be made:

- adding resistors connected to earth in the windings, which are not being tested. Normally non-tested windings are shorted and solidly earthed.



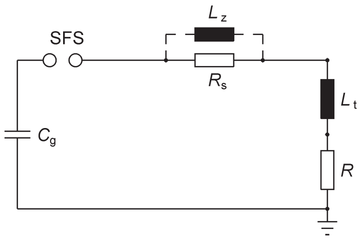

$\hat{U}$ = governing peak voltage for lightning impulse test

***Figure 10.10:*** *Impulse voltage oscillogram with overshoot*



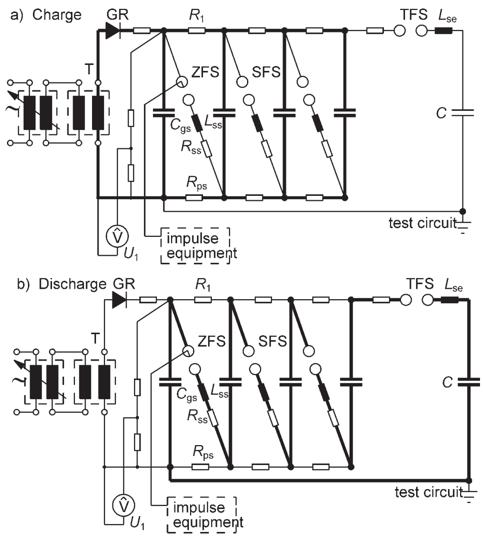

$\hat{U}$ = governing peak voltage for lightning impulse test

***Figure 10.11:*** *Impulse voltage oscillogram with overshoot*




$L_2$ = additional inductor
$R$ = resistor in series or with winding

*Figure 10.12: Impulse circuit equivalent diagram, windings with low inductivity $L_t$ < 20 mH*




T = high voltage transformer
GR = rectifier
$R_1$ = charge resistors
$U_1$ = charge voltage per stage
$C_{gs}$ = capacitance per stage
$R_{ss}$ = damping resistance per stage
$R_{ps}$ = discharge resistance per stage
$L_{ss}$ = stray inductance per stage
ZFS = ignition sphere gap
SFS = switching sphere gap per stage
TFS = disconnecting sphere gap
$L_{se}$ = external stray inductance
$C$ = test object load capacitance

*Figure 10.13: Impulse generator (Marx circuit); a) charge b) discharge*

IEC states:

- the maximum voltage occurring at the non-tested terminals must not exceed 75 % of the test voltage for a star-connection and 50 % for a delta-connection.
- The earthing resistor should not be larger than 400 Ω.

IEEE states:

- the maximum voltage occurring at the non-tested terminals should not exceed 80 % BIL.
- Earthing resistors:

  Nominal system voltage ≤ 345, 500, 765 kV - corresponding resistors ≤ 450, ≤ 350, ≤ 300 Ω.

- adding resistors in series with the tested winding, see figure 10.12. The major insulation (to earth) is being tested in this circuit, but the stress on the winding insulation is minimal.

IEC fundamentally permits a resistor in series with the tested winding.

In such cases, IEEE specifies a minimum impulse generator capacitance of 0,011 µF. If this capacitance is achieved a shorter wave is accepted:

- increasing the total inductance using an additional inductor in parallel with series resistance $R_s$, see figure 2.41.

The tail of the impulse voltage will generally give rise to an overshoot of opposite polarity. The impulse will usually act as a highly dampened oscillating voltage. Only in some exceptional cases does it have a true aperiodic characteristic. The amplitude of the overshoot must not exceed 50 % of the crest value of the impulse voltage [4].

## A 10.2 Generation of high impulse voltages

Impulse generators are used to produce high lightning and switching over-voltages for testing power transformers.

In principal a generator is made up of a number of capacitors, $C_{gs}$, which are charged in parallel and discharged in series. The discharge voltage peak (ideal value) will then be the sum of the final charging voltages on each of the capacitors.

The generator is called a Marx generator. It was first designed in 1923 by Professor Erwin Marx, Braunschweig Germany.

The individual capacitors are charged to a given voltage, generally in the range of 0 to 200 kV. When the ignition gap ZFS ignites all the other gaps, SFS follows. The total output voltage is the sum of the charging voltages on the individual capacitors.

The test circuit is connected through a disconnecting sphere-gap TFS. It closes the main discharge circuit shown in bold in figure 10.13 b. Activation of ignition sphere gap ZFS and therefore triggering of the impulse generator, can occur in various ways. These include increasing charging voltage $U_1$ until it reaches the ZFS flashover voltage, reducing the ZFS clearance at constant charging voltage or triggering by means of an impulse device.

Figure 10.14 shows the equivalent circuit diagram of the impulse generator with a load, $C$ (transformer under test), at the instant of discharge.

The generated impulse voltage waveform is primarily determined by the damping resistance $R_s$ (affects the front time), discharge resistance $R_p$ (affects the tail halftime) and the resulting impulse test circuit leakage inductance $L_s$ (undesirable, superimposed high frequency oscillations), provided that $R_s \ll R_p$ and $C \ll C_g$, which is true for most test configurations,

The following holds for the impulse voltage:

$$U(t) \approx U_1 \cdot \frac{e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}}}{1 - \frac{1}{\tau_2}}$$

where:

$\tau_1$ = front time constant

$\tau_2$ = tail time constant

$$\tau_1 = R_s \cdot \frac{C \cdot C_g}{C + C_g} \approx R_s \cdot C$$

$$\tau_2 = R_p \cdot (C_g + C) \approx R_p \cdot C_g$$

In order to avoid superimposed high frequency oscillations, the impulse test circuit must have an aperiodic damping. This is achieved when the following requirement is met:

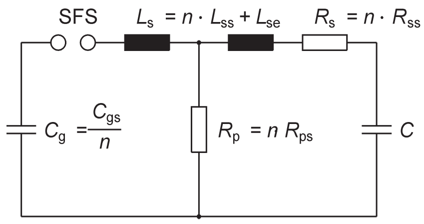
$$R_s \geq \sqrt{\frac{C + C_g}{C \cdot C_g} \cdot L_s}$$

Inductance $L_s$ is comprised of the damping resistance inductances, the interconnections among the capacitors, the stage component connections (about 5 µH per stage) and the external supply connection inductance $L_{se}$ (about 1 µH per meter). The resistance inductance can be considerably reduced with a parallel connection and bifilar winding.

The impulse test circuit parameters are determined by the following approximation for the lightning impulse wave,1,2/50 µs:

front time $T_1 \approx 3 \cdot R_s \cdot \frac{C \cdot C_g}{C + C_g}$

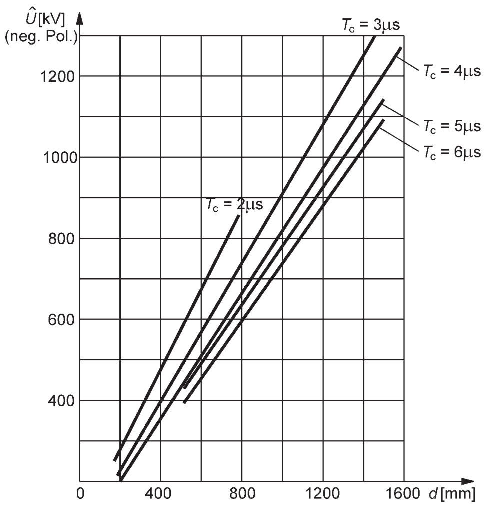
tail halftime $T_2 \approx 0{,}72 \cdot R_p \cdot (C + C_g)$




$C_g$ = total impulse capacitance
$n$ = number of stages
$R_p$ = total discharge resistance
$R_s$ = total series resistance (damping resistance)
$L_s$ = total inductivity of impulse circuit

***Figure 10.14:*** *Equivalent diagram of impulse generator; discharge*

*Impulse test generator and voltage divider.*




Gap form: 12 / 12 mm square
Diagrams for 760 Torr, 20 °C, 11 g/m³
Impulse wave: 1,2 / 50 µs, negative polarity
$T_C$ = time to chopping, figure 10.2
$d$ = gap distance
$\hat{U}$ = peak value of impulse voltage wave

***Figure 10.15:*** *Breakdown voltage of rod-rod gap for negative polarity as a function of gap distance*

Calculation of the impulse test circuit parameters in advance is more complicated, when testing power transformers. As can be seen from the equivalent circuit diagram, there is a highly variable inductance (function of the transformer under test) connected in parallel with the effective capacitance $C$ of the transformer under test, see clause A 10.3.

Impulse generators are manufactured based on a unit construction system (building block system). Assembly of the individual components such as capacitors, ignition sphere gaps and resistors takes place in accordance with the required isolation clearances, one above the other.

The system for generating the DC voltage (to about 200 kV) consists of a regulating and high-voltage transformer, which charges the capacitances through a rectifier. Commutation of the rectifier makes generation of positive or negative impulses possible. The size of the impulse generator is generally described by its impulse energy in Ws:

$$E = \frac{1}{2} \cdot n \cdot C_{gs} \cdot U_1^{\;2} \qquad [\text{ Ws}]$$

Typical impulse generators used for impulse testing power trans-formers have an impulse energy of approximately 100 - 500 kWs with a maximum impulse voltage of up to 10 MV.

### A10.2.1 Generation of chopped lightning impulses

The simplest and least expensive means for generating chopped lightning impulse voltages is the uncontrolled rod-rod gap, see figures 10.2 and 10.3. It is normally connected directly to the transformer bushings so that the flashover gap is parallel to the bushing axis and symmetrical halfway up the bushing. The minimum bushing clearance must be maintained, depending on the voltage (0,3 to 2,5 m). The gap distance is determined as a function of the voltage and (minimum) time to flashover, (2 to 6 µs as per IEC) using characteristic curves.

Figure 10.15 shows the curve for lighting impulse waves chopped on the tail with negative polarity (wave form 1,2/50 µs; minimum time to flashover, $T_c$ = 2 to 6 µs).

It should be noted that due to its discharge mechanism the un-controlled rod-rod gap exhibits a comparatively large variation in the time to flashover, especially for impulse voltages below 200 kV. Different chopping times lead to current and voltage courses, which are no longer identical (after chopping). This makes possible non-conformances difficult to detect. Since the tolerance on the chopping time for impulse waves chopped on the tail is relatively large (2 to 6 µs as per IEC). Therefore, no absolute equality of the oscilloscope recordings is required after chopping.

This makes the rod-rod gap method well-suited.

For front-of-wave chopped waves (figure 10.3) the conditions are still less favorable due to the variation of the chopping time. It affects the voltage amplitude, contrary to situation with the wave chopped on the tail. The test is not required for IEC and for IEEE only when specifically agreed upon. It is not possible to provide generally accepted characteristics with sufficient accuracy.

Controlled spark-gaps can reduce the disadvantages described above to a certain extent.

Trigatrons and multiple sphere gaps are used for this purpose. With these devices a high chopping steepness and chopping time tolerance of approximately ± 0,1 µs can be achieved. Chopping the front with short chopping times of ≤ 0,5 µs is not straightforward and assumes a good deal of testing experience.

### A 10.2.2 Generation of switching impulse voltages

Two methods are primarily used to generate the switching impulse voltage:

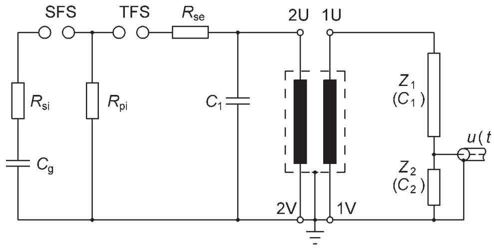
- The common method is to generate the impulse voltage using a conventional impulse generator and apply the voltage to the high voltage winding, see figure 10.13. The impulse test circuit basically corresponds to the one for the lightning impulse test - see section 10.5.1.
- The second method is to discharge a capacitor through the low voltage winding. This can sometimes be done using a typical impulse generator. The impulse capacity should be somewhere between 1 and 2 µF, to avoid high voltage peaks at the beginning of the impulse voltage wave. The impulse test circuit is shown in figure 10.16.

The series resistance values must be greater and the discharge resistor must be removed or increased, compared with the lightning impulse test.

## A 10.3 Pre-calculation of impulse waveform

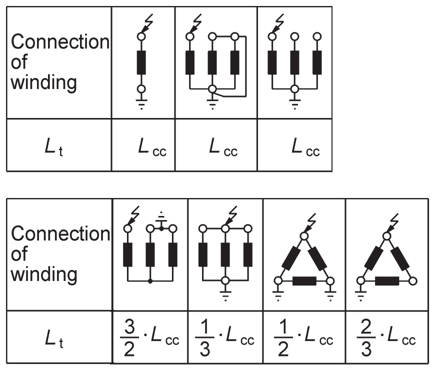
Calculating the individual impulse circuit parameters in advance to produce the specified impulse voltage waveform occurs in practice by comparing it with similar, already tested objects. The corrections required in the majority of cases are then carried out with a reduced voltage (< 50 % of the test voltage) using the impulse voltage test system. This can consume a considerable amount of time. By using an impulse signal generator, an exact and quicker pre-determination can be achieved, since the parameters can be reproduced at a lower impulse voltage (approximately 200 to 800 V peak value). Computer programs support the empirical values and permit sufficiently precise calculations with a minimum of effort.

The following formulae should be regarded as guides for estimating the parameters. They do not allow exact specification of the impulse circuit components.



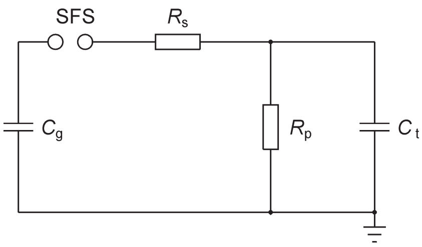

$C_g$ = capacitance of impulse generator
$R_{si}$ = internal damping resistance
SFS = switching sphere
TFS = disconnecting sphere
$R_{pi}$ = internal discharge resistance
$R_{se}$ = external damping resistor
$C_1$ = load
$C_t$ = capacitance of transformer
$L_t$ = inductivity of transformer
$Z_{1,2}$ = impedances of impulse voltage divider

***Figure 10.16:** Basic layout of switching impulse test; method: discharge a capacitor to low-voltage winding*



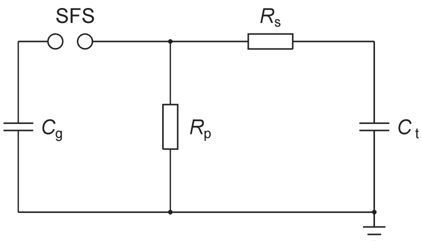

$L_{cc}$ = short-circuit inductivity
= $(U^2_{ph} / \omega \cdot S_N) \cdot (\varepsilon_{cc} / 100)$
$\varepsilon_{cc}$ = relative short-circuit voltage
$U_{ph}$ = Voltage line to earth
$S_N$ = nominal transformer power per phase

***Figure 10.17:** Inductance $L_t$ of transformer winding; windings not under test short-circuited*




$C_g$ = impulse generator capacitance
SFS = switching sphere
$R_s$ = damping resistance
$R_p$ = parallel resistance (discharge resistance)
$C_1$ = transformer load capacity

***Figure 10.18:*** *Impulse circuit equivalent diagram; windings with high inductance $L_t$ > 100 mH.*




$C_g$ = impulse generator capacitance
SFS = switching sphere
$R_s$ = damping resistance
$L_1$ = transformer inductance

***Figure 10.19:*** *Impulse circuit equivalent diagram; windings with high inductance $L_t$ > 100 mH.*

## A 10.3.1 Impulse test circuit parameters for the lightning impulse test (1,2 / 50 µs)

There is a fundamental distinction made between an impulse on windings with high inductance ($L_t$ > 100 mH) and low inductance ($L_t$ < 20 mH). Transformer winding inductance $L_t$ can be estimated for typical test circuit connections, see figure 10.17.

### Impulse for windings with high inductance

Figures 10.18 and 10.19 show the basic equivalent circuit diagram of the impulse circuit. They are distinguished by the arrangement of parallel resistance $R_p$.

For front time $T_1$ (figure 10.1) the following holds (reference to figure 10.18):

$$T_1 \approx 3 \cdot \frac{R_s \cdot R_p}{R_s + R_p} \cdot \frac{C_g \cdot C}{C_g + C}$$

where:

$C = C_t + C_l + C_1$ total capacitance, see figure 10.5

$C_t = C_B + \sqrt{C_w \cdot C_e}$

$C_B$ = bushing capacitance

$C_w$ = winding series capacitance

$C_e$ = winding capacitance to earth

Alternatively as per figure 10.19:

$$T_1 \approx 3 \cdot R_s \cdot \frac{C_g \cdot C}{C_g + C}$$

For tail time $T_2$ the following holds, see figure 10.1:

circuit as per figure 10.19

$$T_2 \approx 0{,}7 \cdot (R_s + R_p) \cdot (C_g + C)$$

$$C_t = C_B + C_e$$

where:

$C_e$ = part of the winding capacitance to earth dependent on the voltage distribution circuit as per figure 10.19

$$T_2 \approx 0{,}7 \cdot R_p \cdot (C_g + C)$$

for $R_p \gg R_s$ and $C_g \gg C$ the following holds:

$$T_1 \approx 3 \cdot R_{ss} \cdot C$$

$$T_2 \approx 0{,}7 \cdot R_p \cdot C_g$$

For windings with an inductance of approximately 20 to 100 mH, the above formula for $T_2$ is not sufficiently accurate and $R_p$ must be increased by a factor of 2 to 10.

### Impulse for windings with low inductance ($L_t$ < 20 mH)

Figure 10.20 shows the equivalent circuit diagram for the impulse circuit. The same formulae as used for windings with high inductance are valid for front time $T_1$.

For the tail time $T_2$ the following considerations apply: the impulse voltage waveform has an oscillating or exponential form which is a function of damping coefficient $k$.

$$k = \frac{R_s}{2 \cdot \sqrt{\frac{L_t}{C_g}}}$$

If $k \geq 1$, the waveform becomes exponential. This damping is normally not possible because the front time $T_1$ becomes too long. For sub-critical damping where $k < 1$ the waveform begins to oscillate. The overshoot should be limited to 50 % of the test voltage as per IEC. For this situation, if the damping coefficient $k$ = 0,25, then $T_2$ is

$$T_2 \approx \sqrt{0{,}5 \cdot L_t \cdot C_g}$$

Earthing non-tested windings via resistors increases the equivalent winding inductance. The voltage developed across the resistor must, however, be less than 75% of the test voltage.

The minimum impulse generator capacity is:

$$C_g \approx 2 \cdot \frac{T_2^{\,2}}{L_t}$$

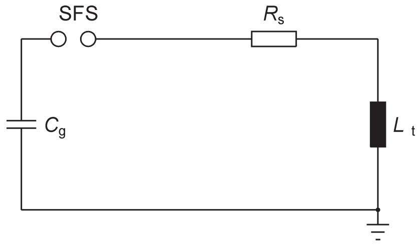
If the generator capacity is too small, series resistance $R_s$ can be reduced.

The discharge time for the impulse circuit is:

$$\tau = \frac{L_t}{R_s}$$

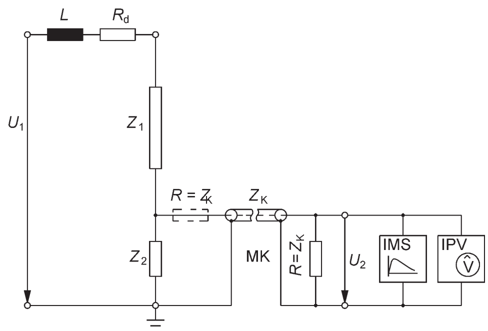
The overshoots on the front caused by the reduction of $R_s$ must be damped with an additional capacitance $C_l$ If the objective is still not achieved (i.e. reaching the specified tail $T_2$ = 50 µs ± 20 %), a resistor can be connected in series with the tested winding, see figure 10.12. It should be noted that with this connection the major insulation is being tested, but the stress on the winding insulation is minimal.

Another method to increase the total inductance is to connect an inductance in parallel with resistor $R_s$, see figure 10.12.




$C_g$ = impulse generator capacitance
SFS = switching sphere
$R_s$ = damping resistance
$L_1$ = transformer inductance

***Figure 10.20:*** *Impulse circuit equivalent diagram; windings with low inductance $L_t$ <20 mH*




$Z_1$ = voltage divider primary impedance
$Z_2$ = voltage divider secondary impedance
$L$ = conductor stray inductivity
$R_d$ = damping resistor
$R$ = terminating resistor
MK = coaxial measuring cable
$Z_K$ = measuring cable wave impedance
IMS = impulse measuring system
IPV = impulse peak voltmeter

***Figure 10.21:*** *Impulse voltage measuring equipment*

## A 10.4 Test circuit parameters for switching impulse test

The wave form for the switching impulse test is defined in figure 10.4.

The following holds for the front time:

$$T_1 \approx k \cdot R_s \cdot C \quad 5 \leq k \leq 10$$

Considerations for the tail time:

Transformer windings that are not being tested are generally left open, in contrast to the lightning impulse test. The core is therefore magnetized. Because the core has been magnetized in the opposite direction (at opposite polarity) at reduced impulse voltage, the tail can be adjusted to the specified values. Discharge resistances $R_p$ are not normally used, since the high resistance impulse generator charging resistors $R_1$ (10 to 25 kΩ per stage) act as discharge resistances, see figure 10.13.

## A 10.5 Measuring high impulse voltages

### A 10.5.1 General

The impulse voltage measuring equipment should reproduce the amplitude and the shape of the impulse wave at a significantly reduced voltage level as accurately as possible.

Essential components of a measuring system are shown in figure 2.16:

- supply connections
- voltage dividers
- measuring cables with coaxial type terminal resistance
- impulse measuring system (oscilloscope) and impulse peak voltmeter

In the first stage, the impulse wave is reduced to a level (a few hundred volts) which can be measured by the impulse measuring system and impulse peak voltmeter. A voltage divider is used for this purpose. It consists of a primary impedance leg $Z_1$ and a secondary impedance leg $Z_2$, and can be composed of resistances, capacitances, or a combination of the two. The ratio of the divider is defined by the two impedances $Z_1$ and $Z_2$.

The voltage $U_2(t)$ appearing at the secondary impedance $Z_2$ of the voltage divider is fed to the impulse measuring system or the impulse voltmeter by a low-loss coaxial cable equipped with a terminal resistance. The measuring cable shield is earthed at the voltage divider, see figure 10.21.

The impulse waveform required for the test assessment is recorded with an impulse measuring system; an oscilloscope or a digital recording system. The amplitude of the applied test voltage is measured using the impulse peak voltmeter.

The high-voltage interconnection between the transformer under test and the voltage divider should be as short as possible since its inductance (approximately 1 µH per meter) can significantly influence the test equipment transmission characteristics at the high frequencies which occur.

It is sometimes necessary to connect a low inductance resistor $R_d$ of several hundred ohms between the transformer under test and the voltage divider to dampen the series oscillation circuit consisting of the supply connection inductance and the divider capacitance (primary impedance of the voltage divider).

## A 10.5.2 Impulse voltage divider

The impulse voltage divider shall provide a voltage as undistorted as possible. It shall be independent of frequency, voltage amplitude, polarity, temperature changes and external influences. Various voltage divider designs can be used depending on the required impulse voltage wave shape; i.e. lightning impulse full wave, impulse wave chopped on the tail, impulse wave chopped on the front or switching impulse wave.

The following dividers are frequently used in test laboratories in addition to special designs:

- resistor dividers
- controlled resistor dividers
- capacitance dividers (damped and undamped)
- combined resistor – capacitance dividers

### Resistance impulse voltage divider

It comprises a series connection of a high-voltage resistor $R_1$ and a low voltage resistor $R_2$, see figure 10.22.

The ratio of the divider is:

$$r = \frac{R_d + R_1 + \left(\frac{R_2 \cdot R}{R_2 + R}\right)}{\left(\frac{R_2 \cdot R}{R_2 + R}\right)}$$

where:

$R_d$= damping resistor

$R$ = measuring cable with a terminal resistance, e.g. 75 Ω

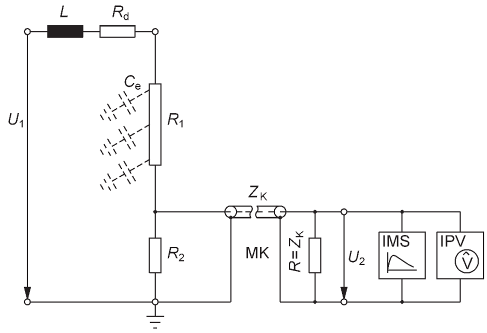
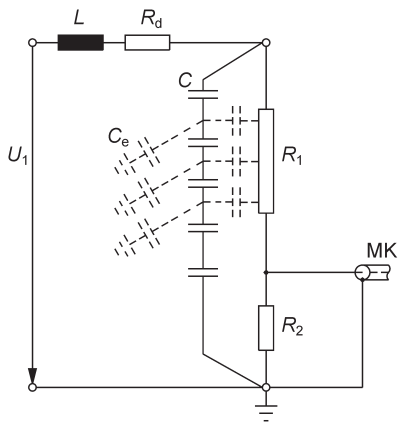
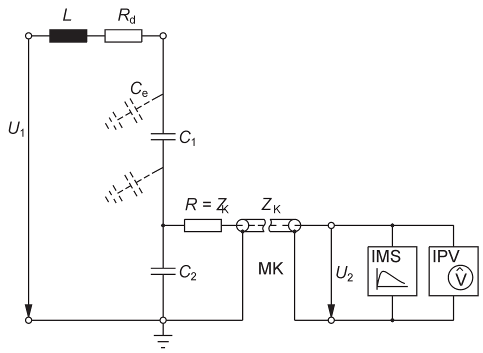



**Figure 10.22:** *Resistive impulse voltage divider $C_e$ = stray capacitance other symbol definitions: refer to figure 10.21*



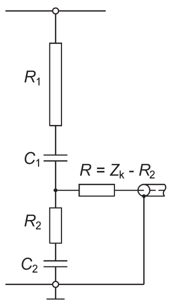

$L$ = stray inductance of conductor
$R_d$ = damping resistor
MK = coaxial measuring cable
$R_1$ = voltage divider primary resistance
$R_2$ = voltage divider secondary resistance
$C_e$ = stray capacitance

**Figure 10.23:** *Controlled resistive impulse voltage divider $C$ = control capacitance*




$C_1$ = primary capacitance of voltage divider
$C_2$ = secondary capacitance of voltage divider
$L$ = stray inductance of conductor
$R_d$ = damping resistor
$R$ = terminating resistor
MK = coaxial measuring cable
$Z_k$ = wave impedance of measuring cable
IMS = impulse measuring system
IPV = impulse peak voltmeter

***Figure 10.24:*** *Capacitive impulse voltage divider*




$R_1$ = primary resistance of voltage divider
$R_2$ = secondary resistance of voltage divider
$C_1$ = primary capacitance of voltage divider
$C_2$ = secondary capacitance of voltage divider
$L$ = stray inductance of conductor
$R_d$ = damping resistor
$R$ = terminating resistor

***Figure 10.25:*** *Damped-capacitive impulse voltage divider*

The high-voltage resistor $R_1$ is affected by stray capacitances $C_e$, which will lead to an unequal and non-linear frequency dependent voltage distribution across the divider for steep impulse voltages. The deviation increases, as the relationship of the series capacitance to stray capacitance $C_e$ becomes smaller. The high frequency components of the voltage waves are damped. This causes a flattening of the measuring signal.
The rise and response times are relatively large. This divider may not be used for very high frequency processes (front-of-wave chopped waveforms).

The frequency dependency and therefore the response time can be significantly improved by reducing the value of the high-voltage resistor $R_1$ to a few kilo-ohms. Because of the high energy consumption and its influence on the wave tail halftime value, it is only used for front-of-wave chopped impulse waves.

### The controlled resistance impulse voltage divider

A quasi linear impulse voltage distribution is achieved along the resistive divider by capacitive control and can be used for all types of impulse voltage tests because of the relatively short response time, see figure 10.23.

### The capacitive impulse voltage divider

A voltage divider is formed by connecting an HV capacitance $C_1$ in series with an LV capacitance $C_2$, see figure 10.24.

The measuring equipment used for the impulse test is primarily a pure capacitive impulse voltage divider (figure 10.24) or a damped capacitive impulse voltage divider (figure 10.25). Resistance impulse voltage dividers would affect the waveform and possibly become thermally overloaded.

The divider ratio is frequency independent and is:

$$r = \frac{C_2 + C_1}{C_1}$$

In some cases stray capacitances can cause a change in the divider ratio depending on the actual position in the test hall.

This capacitive impulse voltage divider shall not be used for very high frequency processes (front-of-wave chopped waveforms). The supply cable inductance and the divider capacitance form an oscillation circuit, which must be dampened by a resistor $R_d$, causing an increase in the response time. In addition the high-voltage capacitances are affected by an inductance which can lead to travelling wave phenomena because of the low internal damping. These drawbacks can be sufficiently eliminated by even distribution of the damping resistors within the voltage divider, see figure 10.25. At high frequencies the ohmic resistance remains effective and at low frequencies the capacitive component behaves as a high resistance. The response time is relatively short.
This divider is therefore suitable for fast and slow processes.

### The combined ohmic-capacitive impulse voltage divider

The drawbacks discussed for the pure resistance divider led to the development of the combined ohmic-capacitive voltage divider, see figure 10.26. When correctly compensated the divider ratio is the same as for the resistance divider. A quasi-linear and frequency independent voltage divider is constructed by connecting capacitances in parallel with the resistances and therefore a relatively short response time is achieved. The divider behaves as a capacitance for fast processes. This divider is suitable for all types of impulse tests.

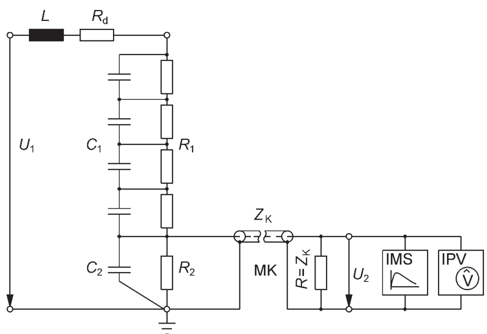
### Coaxial measuring cables

The coaxial measuring cable MK (high frequency cable) which transmits the measured signal is directly connected to the impulse measuring system or the impulse peak voltmeter (both have a high resistance input). The arriving impulse wave (measuring signal) would double in amplitude due to reflection if no further measures were taken at the end of the measuring cable. A terminal resistor will prevent amplitude doubling when its resistance $R$, is equal to the surge impedance of the cable $Z_k$ (e.g. 75 Ω), The surge impedance of an ideal cable is:

$$Z_k = \sqrt{\frac{L_k}{C_k}}$$

For resistance and combined impulse voltage dividers, the terminal resistance is connected (for measuring systems) at the end of the cable, figure 10.22, 10.23, and 10.26. For capacitive impulse voltage dividers this is not possible since the secondary capacitor $C_2$ would be discharged with time constant

$$\tau = C_2 \cdot R$$




$C_1$ = primary capacitance of voltage divider
$C_2$ = secondary capacitance of voltage divider
$R_1$ = primary resistance of voltage divider
$R_2$ = secondary resistance of voltage divider
$L$ = stray inductance of conductor
$R_d$ = damping resistor
$R$ = terminating resistor
MK = coaxial measuring cable
$Z_k$ = wave impedance of measuring cable
IMS = impulse measuring system
IPV = impulse peak voltmeter

***Figure 10.26:*** *Ohmic-capacitive mixed impulse voltage divider*

The resistor is connected to the beginning of the measuring cable (divider side) in the measuring cable lead, see figure 10.24. The arriving impulse wave (measuring signal) is first divided in half by $R$ and $Z_k$

$$r = \frac{R + Z_k}{Z_k} = \frac{75 + 75}{75} = 2$$

It is reflected back to its original amplitude at the cable end (for measuring systems). For dampened capacitance dividers, the connection is the same except for terminal resistance, see figure 10.25.

$$R = Z_k - R_2$$

Any additional measuring errors caused by the measuring cable are determined by the response time of the total impulse voltage measuring equipment.

### A 10.5.3 Impulse measuring system and impulse peak voltmeter

A high precision analog or digital recording of the development of the impulse voltage wave and the impulse current wave, using at least a two-channel impulse measuring system, is required to assess power transformer impulse voltage tests.

#### Typical characteristics of an analog impulse measuring system

The amplitude of the applied test voltage is measured using an impulse peak voltmeter.

- cathode-ray oscilloscope: two channel with a printing speed of approximately 7000 km/s
- vertical deviation: deviation coefficient 140 to 900 V/cm
- horizontal deviation: linear or logarithmic
  deviation in steps of 1,0 to 5000 µs
  time marker interval 0,1 to 500 µs
- triggering: internal or external using Trigatron or antenna
- vertical deviation: attenuation divider steps 1 to 6,4
- inputs: maximum peak voltage approximately 1500 $V_p$
- shielding: impulse oscilloscopes are usually exposed to strong electromagnetic fields. They must be specially shielded from internal and external high frequency stray flux

### Typical characteristics of a digital impulse measuring system, including the digital impulse peak voltmeter

Analog part:

- input channels: up to 4
- input impedance: 2 MΩ, 50 pF
- input divider: 1:200
- input voltage: 100 to 1950 V peak-to-peak
- bandwidth: 50 MHz

Digital part:

- AD converter: 12 bit, up to 120 MS/s, up to 128 k (12 bit) data point memory
- data processing: PC

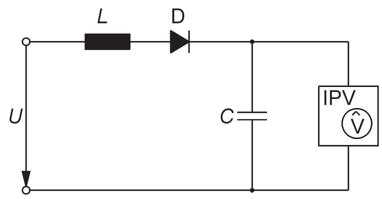
## A 10.5.4 Analog impulse peak voltmeter

The analog peak impulse voltmeter measures the peak value of the impulse voltage. One principle consists of charging a measuring capacitance through a diode with a high blocking resistance and measuring the voltage across the capacitor using a high resistance voltmeter, see figure 10.27. The uncertainty of the measured impulse voltage (lightning impulse and chopped impulse) is ± 1 %.

## A 10.5.5 Transmission characteristics of impulse voltage measuring equipment

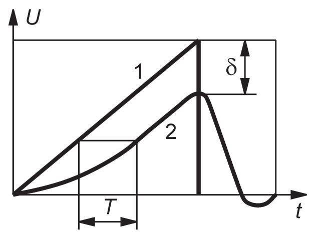
The transmission characteristics of the entire impulse voltage measuring equipment must be calibrated at regular intervals for quality assurance purposes and in order to ensure a reliable impulse measuring methodology, see figure 10.21. The empirical determination of the transmission error is described in detail in IEC 60060 [21], [22]. The following description is limited to an overview.

Figures 10.28 and 10.29 show a typical transmission error. The transmission error is defined by the response time of the impulse voltage measuring equipment. It causes a more or less incorrect timing analysis of the oscilloscope recordings for all impulse types, see figure 10.29, and in addition an incorrect amplitude determination or measurement for front-of-wave chopped impulse waves, see figure 10.28. The maximum allowable response time $T$ specified by IEC [21] for lightning impulses waves and impulse waves chopped on the peak or on the tail.



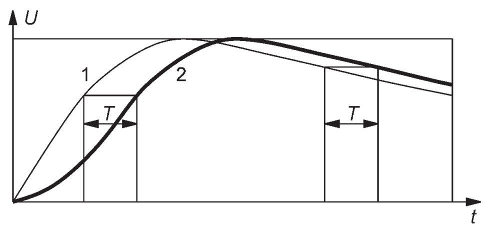

D = diode
IPV = impulse peak voltmeter
$L$ = inductance

*Figure 10.27: Impulse voltmeter equivalent diagram*



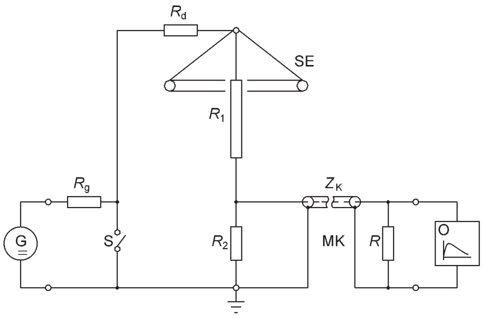

$T$ = response time
1 = impulse voltage
2 = measuring signal
$\delta$ = amplitude failure

*Figure 10.28: Typical transfer failure of an impulse measuring system; chopped wave*



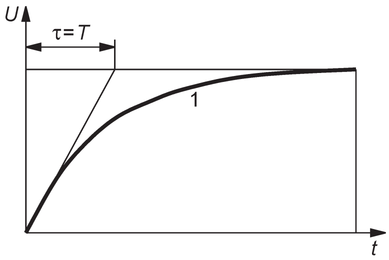

$T$ = response time
1 = impulse voltage
2 = measuring signal

*Figure 10.29: Typical transfer failure of an impulse measuring system*




G = DC source
S = mercury switch
SE = control electrode
O = oscillograph

***Figure 10.30:*** *Response time measurement*




$\tau$ = response time
1 = response of a divider

***Figure 10.31:*** *Typical response time oscillogram*

The response time measurement is normally carried out using the step voltage method, and it is important to calibrate the measuring equipment in the same configuration as it will later be used with the transformer under test (i.e. the supply connections, voltage dividers and measuring cables should not change). Figure 10.30 shows the measuring circuit. A step voltage (a steep voltage step of approximately 1 ns) of several hundred volts is applied at the high voltage part of the divider and the response is measured at the low voltage part using an oscilloscope, see figure 10.31.

The time constant $\tau$ is defined as the response time $T$. Figures 10.28 and 10.29 show the effect of the response time on the time axis of the wave. The step voltage is generated using an impulse generator or by shorting a DC voltage using a fast closing relay. The secondary voltage at the divider is very small, which means that high quality amplifiers are needed. The impulse oscilloscope is not suitable for this purpose.

A correction is required for the effect of the vertical supply connection in the test configuration shown in figure 10.30:

$$T = T_m + \tau_v \cdot \left(1 - \frac{Z}{R}\right)$$

$$\tau_v = \frac{h}{c}$$

where:

$\tau_v$ = travel time along the vertical supply connection

$h$ = length of the supply connection in m

$c$ = speed of light 300 m/µs

$R$ = resistance between the divider top and bottom (infinite for capacitive dividers)

$Z$ = vertical supply connection impedance

This gives:

$$Z \approx 60 \cdot ln\left(\frac{4 \cdot h}{d}\right)$$

where:

$d$ = supply conductor diameter in m

## A 10.6 Calibrating the impulse voltage divider ratio

Periodic calibration of the divider ratio is a pre-requisite for a flawless impulse test.

Various methods are used:

- calculating the divider ratio based on measured divider component impedances.
- simultaneous voltage measurement on the high and low-voltage side of the divider.
- checking the divider against a calibration divider

The measurements can be carried out with AC or DC for resistance dividers. AC is used for measuring capacitive dividers and the divider ratio is checked at several frequencies (e.g. 50 Hz and 1 kHz). For capacitive and combined dividers it is necessary to test the divider ratio in the respective measuring arrangement since stray capacitances can have a significant effect.

## A 10.7 Use of a Sphere-gap for checking the scale factor of an impulse peak voltmeter

The use of a sphere-gap for checking the scale factor has a lot of disadvantages, especially concerning its uncertainty, but it is still required occasionally, see figure 10.32.

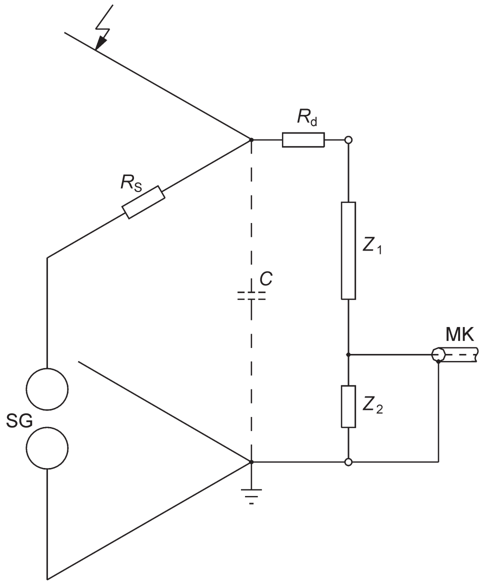
The uncertainty is in the order of ± 3 % (note: the 3 % is however valid for the entire impulse voltage measuring equipment). Calibration is done by direct measurement of the high voltage using the sphere gap (SG) and simultaneous recording (analog or digital) the impulse voltage peak voltmeter.

The amount of effort required to prepare the sphere for high voltages and the time for the calibration itself are significant, which is why comparison with calibrated impulse measuring systems is the primary methodology used. In special cases however, the sphere gap is used.

The divider ratio is then:

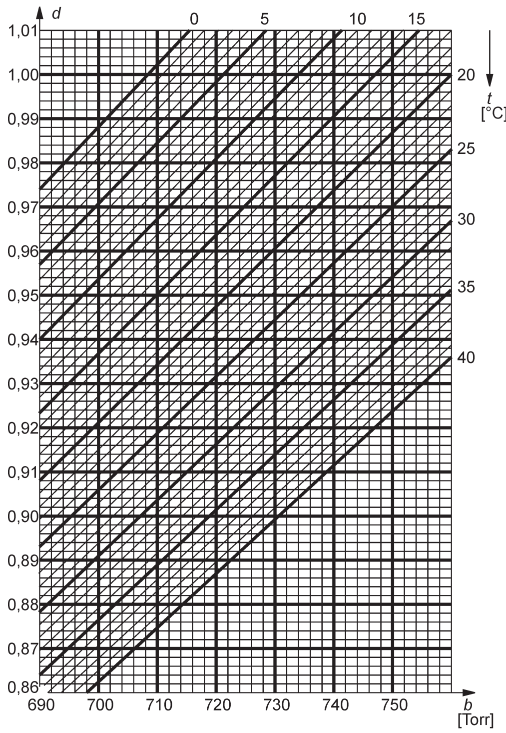
$$r = \frac{U_1}{U_2}$$

Measuring high voltage using sphere gaps is described in detail in IEC 60052 [35]. It is based on established calibration tables, which give 50 % - flashover voltages (peak values) for the respective sphere clearances and diameters. The calibration tables are based on a relative air density of $b$ = 760 torr and $t$ = 20 °C ($k$ = 1). A conversion is necessary for other atmospheric conditions:




SG = sphere-gap
$R_S$ = damping resistor for gap (< 500 W)
C = load capacitance

**Figure 10.32:** *Impulse measuring system calibration using a sphere gap*




$d$ = correction factor
$b$ = air pressure in Torr (mmHg); 760 Torr = 1013 mbar
$t$ = ambient temperature

**Figure 10.34:** *Diagram for determination of correction factor $d$*

$$U = k \cdot U_T$$

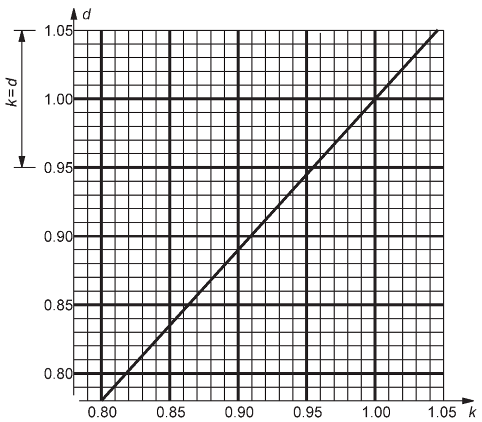
where:

$$d = \frac{b}{760} \cdot \frac{273 + 20}{273 + t}$$

$U$ = actual 50 % - flashover voltage

| SG-distance [mm] | Sphere gap (SG)-diameter [mm] 250 | | 500 | | 750 | | 1000 | | 1500 | | 2000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Δ | ∇ | Δ | ∇ | Δ | ∇ | Δ | ∇ | Δ | ∇ | Δ | ∇ |
| 15 | 45,5 | 45,5 | | | | | | | | | | |
| 20 | 59,0 | 59,0 | | | | | | | | | | |
| 35 | 99,0 | 99,0 | 99,0 | 99,0 | 99,0 | 99,0 | | | | | | |
| 55 | 149 | 151 | 151 | 151 | 151 | 151 | 151 | 151 | | | | |
| 80 | 206 | 211 | 214 | 214 | 215 | 215 | 215 | 215 | 215 | 215 | | |
| 120 | | | 309 | 311 | 315 | 315 | 318 | 318 | 318 | 318 | 318 | 318 |
| 160 | | | 392 | 402 | 410 | 411 | 414 | 414 | 414 | 414 | 414 | 414 |
| 200 | | | 460 | 480 | 492 | 505 | 510 | 510 | 510 | 510 | 510 | 510 |
| 280 | | | | | 635 | 660 | 675 | 685 | 700 | 700 | 705 | 705 |
| 320 | | | | | 695 | 725 | 745 | 760 | 790 | 790 | 795 | 795 |
| 400 | | | | | | | 875 | 900 | 955 | 965 | 975 | 980 |
| 600 | | | | | | | | | 1280 | 1310 | 1340 | 1380 |
| 800 | | | | | | | | | | | 1600 | 1690 |

***Figure 10.33:*** *Peak value of 50% breakdown voltage as a function of sphere-gap diameter and distance (IEC 60052)*
*Δ = AC-voltage – peak value, lightning impulse and switching impulse – negative polarity, DC-voltage – negative and positive polarity*
*∇ = lightning impulse and switching impulse – positive polarity*




$d$ = correction-faktor – figure 10.34
$k$ = total correction-factor

***Figure 10.35:*** *Diagram for determination of total correction factor $k$*

Figure 10.33 shows an excerpt from an IEC 60052 [35] calibration table. The total correction factor k is determined using figures 10.34 and 10.35.

The influence of humidity is neglected for the measurement using the sphere-gap (quasi-homogeneous field). The sphere-gap is a peak-value measuring device. Care should be taken to ensure that the flashovers occur at the peak value (check using an oscilloscope). This is why high frequency oscillations near the peak value must be eliminated.

In principle, calibration can take place with or without the transformer under test $C$, see figure 10.32:

Calibration with the transformer under test has the advantage, that the impulse circuit connections, with the exception of the removal of the SG, remain unchanged for the actual test. The disadvantage is that the voltage waveform with the transformer under test connected can sometimes have high frequency oscillations, which cause the calibration uncertainty to increase. Also, because the calibration can only be carried out with reduced voltage (50 to 70% of the test voltage), any non-linearity, which may exist in the measuring equipment cannot be detected.

Calibration without the test transformer can be carried out at full test voltage. By appropriately selecting the impulse test circuit parameters, the waveform can be better adjusted to the specifications. This however, requires additional time. Any poorly dimensioned isolation distances in the total test equipment arrangement (without the transformer under test) can already be determined during calibration.

The actual process is described in the following example:

test voltage: 1050 $kV_p$
calibration without the test object and negative polarity;

sphere diameter: 2000 mm

nearest table value: 975 $kV_p$ for sphere gap 400 mm (from figure 10.33)

atmospheric conditions:

$b$ = 740 Torr

$t$ = 25 °C

$d$ = 0,957 from figure 10.34

$k$ = 0,961 from figure 10.35

$U$ = 0,961 · 975 = 937 $kV_p$

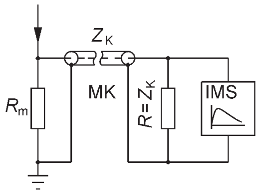
First the voltage is increased in steps until a flashover occurs. After 3 to 5 further flashovers have occurred (burning of any dust on the spheres) the voltage is decreased in steps until no further flashovers occur. The 50 % - flashover voltage is determined by applying further impulses with alternating higher and lower voltage. If the display on the impulse peak voltmeter at this voltage is for example 925 $kV_p$, a divider ratio of

$$r = \frac{937}{925} = 1{,}013$$

results. The required voltmeter deflection for a test voltage of 1050 $kV_p$ is then

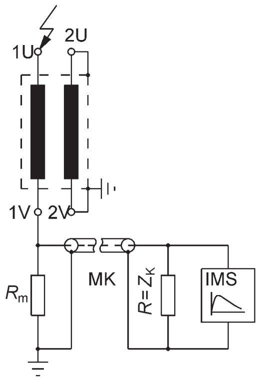
$$\alpha = \frac{1050}{1{,}013} = 1037 \quad kV_p$$

Before starting the calibration, the measuring equipment must have reached thermal stability and the internal device calibrations must have been carried out. If the measuring equipment is independent of polarity, calibration at one polarity suffices. If the measuring equipment is also frequency independent, the lightning impulse calibration is also valid for the switching impulse wave, as it is for the tail or front-of-wave chopped wave.



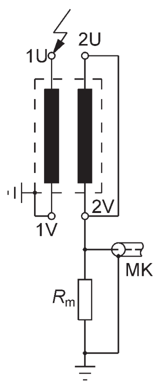

$R_m$ = measuring resistor (shunt)
IMS = impulse measuring system
$Z_k$ = wave impedance of measuring cable
$R$ = terminating resistor
MK = coaxial measuring cable

***Figure 10.36:** Impulse current measuring equipment*




$R_m$ = measuring resistor (shunt)
IMS = impulse measuring system
$Z_k$ = wave impedance of measuring cable
$R$ = terminating resistor
MK = coaxial measuring cable

***Figure 10.37:** Measurement of winding impulse current*




$R_m$ = measuring resistor (shunt)
IMS = impulse measuring system
$Z_k$ = wave impedance of measuring cable
$R$ = terminating resistor
MK = coaxial measuring cable

***Figure 10.38:** Measurements of capacitively transferred impulse current*

## A 10.8 Measuring the impulse current

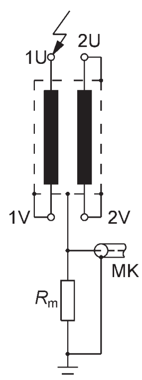
The current response is recorded with an oscilloscope in addition to the voltage response during power transformer impulse voltage tests. This is done to detect or to localize non-conformities.
The most useable method is based on measuring the voltage drop across a measuring resistor $R_m$ (shunt) which is connected in the relevant circuit.

The measurement signal is fed to the impulse measuring system using a coaxial measuring cable (similar to the impulse voltage measurement), see figure 10.36.

A true recording of the current response requires measuring equipment, which is nearly frequency independent and has a short time constant. The measuring shunt should be independent of the current and voltage amplitude, and have high thermal capacity, low inductance and low capacitance. When selecting the measuring shunt, care must be taken to avoid flashovers in the measuring cables or elsewhere in the measuring circuit. A sphere-gap is used as a rough over-voltage protection device. The active part of the shunt must be shielded to avoid stray electromagnetic field influences (metal housing). Shunts in the range of 0,1 to 20 Ω are used for testing power transformers. Figures 10.37 to 10.39 show the various impulse current measuring methods:

- measuring the current flowing through the tested winding - winding current or neutral current, see figure 10.37
- measuring the capacitive current transmitted on a non-tested, short-circuited winding, see figure 10.38
- measuring the current flowing to earth from the tank - tank current, see figure 10.39. The tank must be isolated from earth for this measurement.

Several methods can be used at the same time for trouble-shooting failure locations.




$R_m$ = measuring resistor (shunt)
IMS = impulse measuring system
$Z_k$ = wave impedance of measuring cable
$R$ = terminating resistor
MK = coaxial measuring cable

***Figure 10.39:** Tank impulse current measurement*

## A 10.9 Earthing the impulse circuit

The impulse currents in the main circuit have large amplitudes and steep edges. The interconnection conductors between individual elements have an inductance of approximately 1 µH per meter. They represent a significant impedance during the high frequency impulse processes, which can lead to large voltage drops or potential differences. The following example is used to illustrate this.

A 3 m long earth connection has an inductance of approximately 3 µH. If a current with a peak value of 4000 A and a rise time of 4000 A/µs flows through this inductance a rough estimate of the voltage drop is:

$$\Delta U = -L \cdot \frac{di}{dt} = 3 \cdot 10^{-6} \cdot 4000 \cdot 10^{6} = 12 \text{ kV} \qquad \text{(peak value)}$$

These conditions are particularly unfavourable for front and tail chopped impulses. High earth potential differences can lead to oscilloscope faults, measuring uncertainties and faults in the low voltage distribution network as well as safety risks for operating personnel. In general, the following basic rules must be observed when designing the earthing of impulse test laboratories, see figure 10.40:

- low inductance interconnections
- high as possible capacitance $C_e$ to keep voltage $U_e$ low

$$U_e = \frac{C_s}{C_s + C_e} \cdot U$$

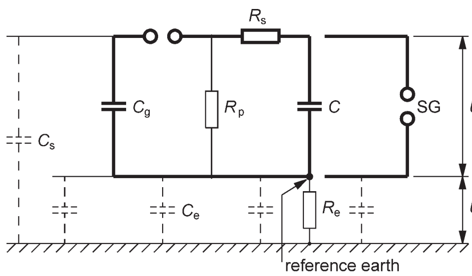
where:

$C_s$ = stray capacitance
$C_e$ = total capacitance of the impulse earthing system to actual earth

- low earth resistance $R_e$

These requirements are more or less fulfilled by using metallic lattice embedded in the test laboratory floor or similar earthing surfaces with several earth terminals. The metallic lattice has several connection points distributed across the test laboratory floor, to which the individual impulse circuit components are connected, using wide copper straps as short as possible.

The most suitable impulse circuit earthing depends on the relevant testing conditions (type of test, dimensions of the test area, design of the transformer under test and the test equipment, etc.). This requires different earthing configurations from case to case. A prerequisite is a correct understanding of the processes in the earthing system, which were only touched upon here.




$C_s$ = stray capacitance
$C_e$ = capacitance to earth
$R_e$ = resistance to earth
$U$ = impulse voltage
$U_e$ = different voltage between reference- and real earth

**Figure 10.40:** *Impulse circuit earthing*

## A 10.10 Switching impulse wave form

The switching impulse is applied across one of the windings and all other windings are open-circuited.

The time integral of the applied voltage will give rise to a variation of the flux in the core. As the applied voltage is unipolar of comparatively long duration and high amplitude the core may go into saturation. It can be seen when the core goes into saturation as a substantial drop in impedance for the applied voltage and a high current will be needed to maintain the voltage.

A high current through the transformer will drain the capacitors in the impulse generator and the supply voltage goes quickly towards zero.

For the calculation of the maximum time to zero voltage, $T_s$ the following consideration can be done.

The voltage from the impulse generator is in a first approximation constant as long as there is no current, non-saturated condition and after saturation it drops instantly to zero. This gives:

$$T_s = k\frac{\Phi_s - \Phi_0}{u}$$

where:

$T_s$ = time to reach saturation

$\Phi_s$ = saturation flux

$\Phi_0$ = remanence flux (the flux in the core just prior to the impulse)

$k$ = constant

The remanence flux, $\Phi_0$ may vary somewhere in the range $\pm 0{,}9\,\Phi_s$ depending on the flux in the core just prior to the disconnection of a previous voltage source.

In order to reach a sufficiently long period to saturation the remanence flux should have an opposite polarity as compared to the flux generated by the voltage time integral.

One way to build a remanence of opposite polarity is the application of a number of switching impulses of positive polarity in between each of the specified test impulses, which are assumed to have negative polarity. The impulses to push the remanence into an opposite polarity should have an amplitude of about the same as the calibration impulses in order not to create any dielectric stress in the transformer.

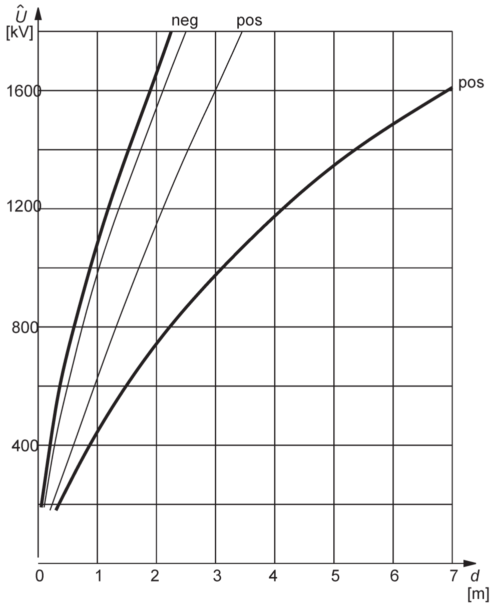
## A 10.11 Air withstand

Figure 10.41 shows the difference of the 50% flash-over voltage for clearances in air in air for lightning- and switching impulse voltages for negative and positive polarity.

## A 10.12 Impulse voltage stress on power transformers

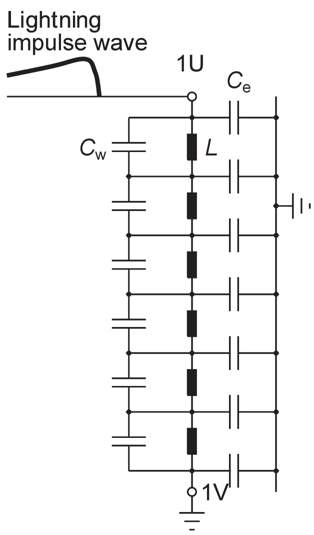
The main difference between a lightning impulse stress on a transformer winding and the stress due to the applied voltage test and induced voltage test (sections 7 and 8) is in the voltage distribution across the winding. For the AC test and the switching impulse test the voltage distribution is approximately linear.

Figure 10.42 shows the arrival of a lightning impulse full wave (1,2 / 50 µs) at a transformer winding.



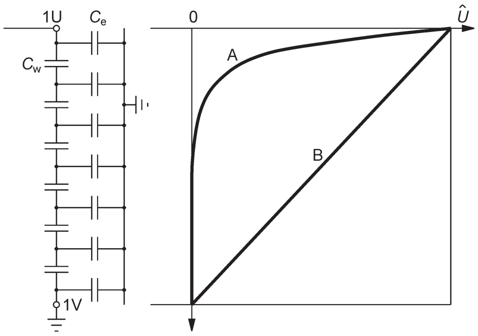

**—** = switching impulse 120 / 4000 µs
— = lightning impulse 1,2 / 50 µs
Diagrams for 760 Torr, 20 °C, 11 g/m³
$d$ = distance
$\hat{U}$ = impulse peak voltage

***Figure 10.41:*** *50% breakdown voltage for rod-plate electrodes in air as a function of distance*



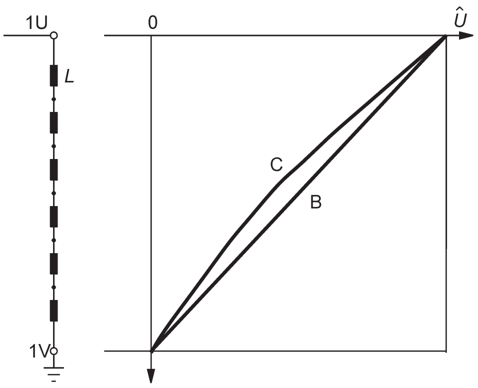

$C_e$ = capacitance to earth
$C_w$ = capacitance to winding
$L$ = inductance of winding

***Figure 10.42:*** *Equivalent diagram of winding*



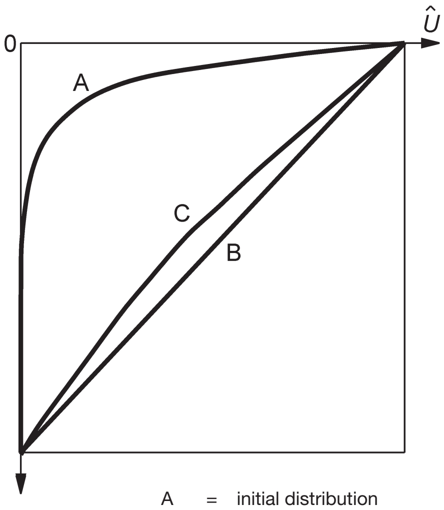

A = initial distribution
B = linear distribution

***Figure 10.43:*** *Winding equivalent diagram for initial distribution*




B = linear distribution
C = final distribution

***Figure 10.44:*** *Winding equivalent diagram for final distribution*




A = initial distribution
B = linear distribution
C = final distribution

***Figure 10.45:*** *Lightning impulse voltage distribution along the winding*

Note that the equivalent circuit diagram of the winding is a rough approximation only. The various frequency spectra of the wave front and tail must be regarded separately. On arrival of the steep wave front at the transformer inductance and capacitance network, the current is low due to the inductance. The main current component flows through capacitances $C_w$ and $C_e$. The steeper the front, the larger this component becomes. The winding behaves approximately like capacitors in series and in parallel. The voltage distribution is determined by capacitances $C_w$ and $C_e$ and is identified as the initial (impulse) distribution in figure 10.43.

The capacitance to earth component $C_e$ has an unfavourable influence on the initial (impulse) distribution.

transmission factor $\alpha \approx \sqrt{\frac{C_e}{C_w}}$

The larger the capacitance to earth $C_e$, the larger are the voltage differences and therefore the voltage stress on the end turns of the winding, see figure 10.43, curve A.

After the front has passed the tail of the impulse wave (50 µs) determines the voltage distribution. This state is defined as the final (impulse) distribution. The current flowing through the capacitances becomes small. The main impulse current flows as a conductor current through the winding and is now primarily responsible for the voltage distribution, see figure 10.44.

The transition from the initial to the final (impulse) distribution results in transient phenomena in the winding, see figure 10.45.

The less the initial distribution deviates from the final distribution, the smaller they are. The voltage distribution for all impulse tests types is calculated using computers or is measured using impulse signal generators and oscilloscopes on the active part of the transformer, see figure 10.46.

The following is a summary of the above explanation for winding stress during the lightning impulse test:

The full wave stresses the winding insulation on arrival of the front. The stress level increases with front steepness and decreases with the degree of entry. The major insulation is stressed during the tail of the wave; i.e. the insulation from the tested winding to all earthed parts (iron frame, tank, other earthed windings), as well as the insulation across the winding.

The lightning impulse wave chopped on the tail stresses mainly the winding insulation and primarily the winding end turns because of the steep voltage collapse (approximately 0,2 µs). The stress increases with increasing steepness of the voltage wave collapse. Flashovers near the transformer terminals are the most dangerous because the shorter the distance, the lower is the damping and the steeper is the voltage collapse.

The chopped front-of-wave stresses mainly the same winding parts as the impulse wave chopped on the tail. The test voltage peak value is nevertheless significantly higher and the duration of the stress much shorter.

The same insulation components are stressed for the switching impulse test as for the induced voltage test (section 8).

### A 10.12.1 Impulse voltage transferred to adjacent windings and winding segments

Because of capacitive coupling to the non-tested windings, a similar initial (impulse) distribution occurs in these windings due to the charging of the tested winding. The subsequent transient phenomena are magnetically transmitted to the individual windings.

The capacitive voltages transmitted are however rather small due to the capacitive voltage distribution between the windings and the capacitance to earth.

The magnetically transmitted voltages (transient phenomena) corresponding to the voltage ratio can be significantly higher. Figure 10.47 shows an example of the initial (impulse) distribution of a regulating winding connected in series with the basic winding (additive connection). The impulse voltages transmitted to other winding parts or to the non-tested windings are a function of the respective capacitive / inductive coupling, or the winding configuration (e.g. additive or subtractive connection of regulating windings).

If a resistor is connected across the non-tested winding (representing cables, transmission lines and electric machines), the magnetically transmitted voltages are greatly reduced.

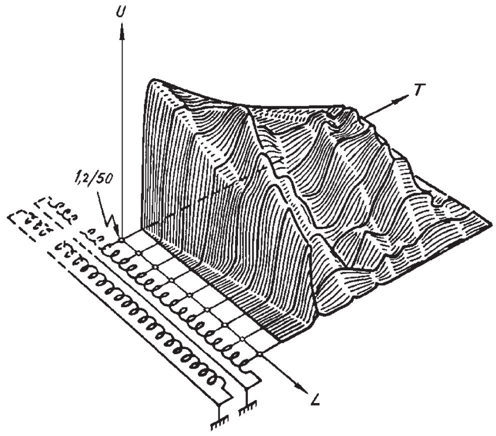
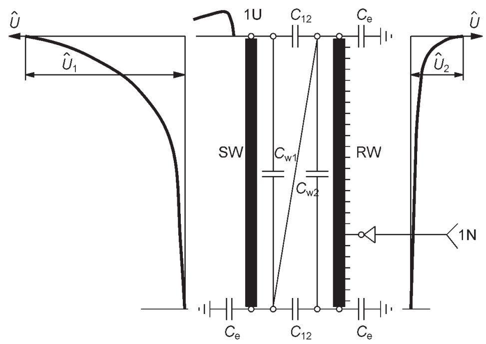



***Figure 10.46:*** *The distribution across winding as a function of time*




SW = basic winding
RW = regulating winding
$C_{12}$ = capacitance between windings
$C_{w1,2}$ = capacitance of winding
$C_e$ = capacitance to earth

***Figure 10.47:*** *Lightning impulse – initial distribution across basic and regulating windings*

# Testing of Power Transformers

## 11. Temperature rise test

# 11. Temperature rise test

## 11.1 References / Standards

- IEC 60076-2 (1993), clause 5 “Test of temperature rise“ [2]
- IEC 60354 (1991) “Loading guide for oil immersed power transformers“ [11]
- IEEE Std C57.12.00-2000, clause 5.11 “Temperature rise and loading conditions“ [50]
- IEEE Std C57.12.90-1999, clause 11 “Temperature rise“ [51]

**Note:**

The temperature rise test is a **type test** as defined by IEC or **design test** in the IEEE context. The test is also called a heat-run test.

## 11.2 Purpose of the test

The purpose of the temperature rise test is to verify guaranteed temperature rises for oil and windings. It may also be used to establish possible hot-spots (inside and outside the windings), especially for transformers with high stray fields (for instance, power transformers > 300 ... 500 MVA or auto-transformers).

Knowledge of the measured average- and top oil temperature rise and of the winding-oil gradient is even more important today than in the past, in view of future upgrade and overload considerations.

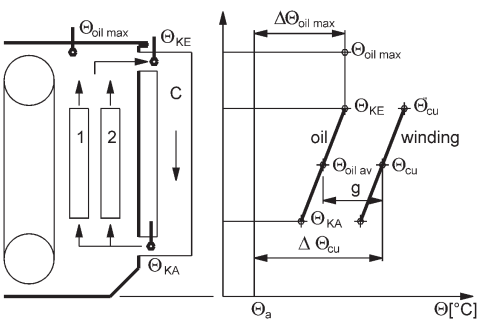
## 11.3 Temperature / temperature rise

Maintaining permissible temperatures in a transformer is considered vital for a long and reliable service. IEC and IEEE Standards therefore specify temperature limits, which must be complied with.

In order to allow uniform comparison between different transformer concepts and suppliers, the Standards specify permissible temperature rises above the temperature of the cooling medium. Ambient temperatures are also outlined in the Standards and it is the responsibility of the customer to make necessary adjustments.

There is a slight difference between the IEC and IEEE Standards regarding the relationship between power ratings and specified temperature rises. IEC states that for a specified value of power rating the specified temperature rises must not be exceeded. IEEE on the other hand, regards power rating as the load which corresponds to the specified temperature rises.

For definitions of temperature / temperature rise, see clause A 11.1.




$\Theta_{oil\ max}$ = top oil temperature (under the cover)
$\Delta\Theta_{oil\ max}$ = top oil temperature rise (guarantee value) $\Delta\Theta_{oil\ max} = \Theta_{oil\ max} - \Theta_a$
$\Theta_a$ = ambient temperature, or water inlet temperature for water-cooled transformers
$\Theta_{Cu}$ = average winding temperature
$\Delta\Theta_{Cu}$ = average winding temperature rise (guarantee value)
$\Theta_{KE}$ = oil temperature (cooler inlet)
$\Theta_{KA}$ = oil temperature (cooler outlet)
$\Theta_{oil\ av}$ = calculated average oil temperature
$\Theta''_{Cu}$ = maximal winding temperature; Attention: this is normally not the winding hot-spot
C = cooler
1,2 = transformer windings
$g$ = temperature gradient winding-oil

***Figure 11.1:*** *Simplified temperature distribution in a transformer [2], [11]*

## 11.4 Temperature measurements

Oil temperature can be directly measured using a temperature sensor in direct or indirect contact with the oil.

The winding temperature must be measured indirectly using the winding resistance. The winding resistance is measured before the test when the entire transformer is in thermal equilibrium, generally in connection with the common measurement of resistance.
The resistance is measured once again immediately following the completion of the current injection during the temperature rise test. The difference in resistance values will then reflect the difference in winding temperature before and after the test.

The temperature measurements using sensors directly attached to the winding are not considered in the Standards. Generally such measuring devices rely on fiber optics and are primarily used for development work.

## 11.5 Principle and test methods

### 11.5.1 Principle

A simplified temperature distribution model is shown in figure 11.1. The simplifications made are mainly:

a. the oil temperature inside and along the windings increases linearly from bottom to top

b. the winding temperature has a linear increase from bottom to top and a constant difference $g$ to adjacent oil.

Only the temperatures $\Theta_{oil\text{-}max}$ , $\Theta_{KE}$ and $\Theta_{KA}$ can be measured directly in a temperature rise test. The winding temperatures $\Theta_{Cu}$ are determined indirectly by calculation (resistance measurement).

### 11.5.2 Test methods [2], [51]

Theoretically there are several methods for performing temperature rise tests. However, for practical reasons, the short-circuit method prevails in reality.

Other methods like the back-to-back method and temperature measurements during normal operation are discussed in more detail in clause A 11.2

### 11.5.3 Short-circuit method

The test is carried out for each pair of windings.
For a two-winding transformer only one test is needed.

One of the winding systems is short-circuited for this test, see figure 11.2. The transformer is subjected to the calculated total losses, which were previously obtained, by two separate determinations of losses; namely, the load loss at reference temperature and no-load loss (see section 5 and 6).

The test is carried out in two steps:

- total loss injection, to get the top-oil temperature rise
- rated current injection, to find the average winding temperature rise

The supply voltage for this test is about the same as the short-circuit voltage. This means there are practically no losses in the iron core (see section 5) However, total losses are required to obtain the correct top-oil temperature rise; therefore, the no-load losses must be simulated in the windings by injecting a current slightly higher than rated current.

$$I_G = k \cdot I_r$$

$$U_G = k \cdot U_{SC}$$

where:

$$k = \sqrt{\frac{P_L + P_0}{P_0}}$$

$P_L$ = load loss at rated current and reference temperature
$P_0$ = no load loss at rated voltage
$I_G$ = supply current
$I_r$ = transformer rated current
$U_{cc}$ = short-circuit voltage
$U_G$ = supply voltage

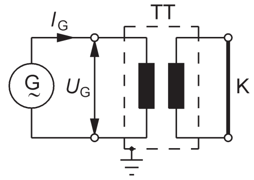
The apparent power required for the test is therefore:

$$S_G = k^2 \cdot S_r \cdot \left(\frac{\varepsilon_{cc}}{100}\right)$$

where:

$S_r$ = rated power
$\varepsilon_{cc}$ = short-circuit impedance in %

The generator has to deliver at least the active power $P_L + P_0$. The reactive power can be compensated if possible by using banks of capacitors. This is what is done in most laboratories.




G = voltage source
K = short-circuit lead
$I_G$ = supply current
$U_G$ = supply voltage
TT = transformer under test

***Figure 11.2:*** *Connection diagram for the short-circuit method*

## 11.6 Measurement circuit and procedure

### 11.6.1 Preparations before the test

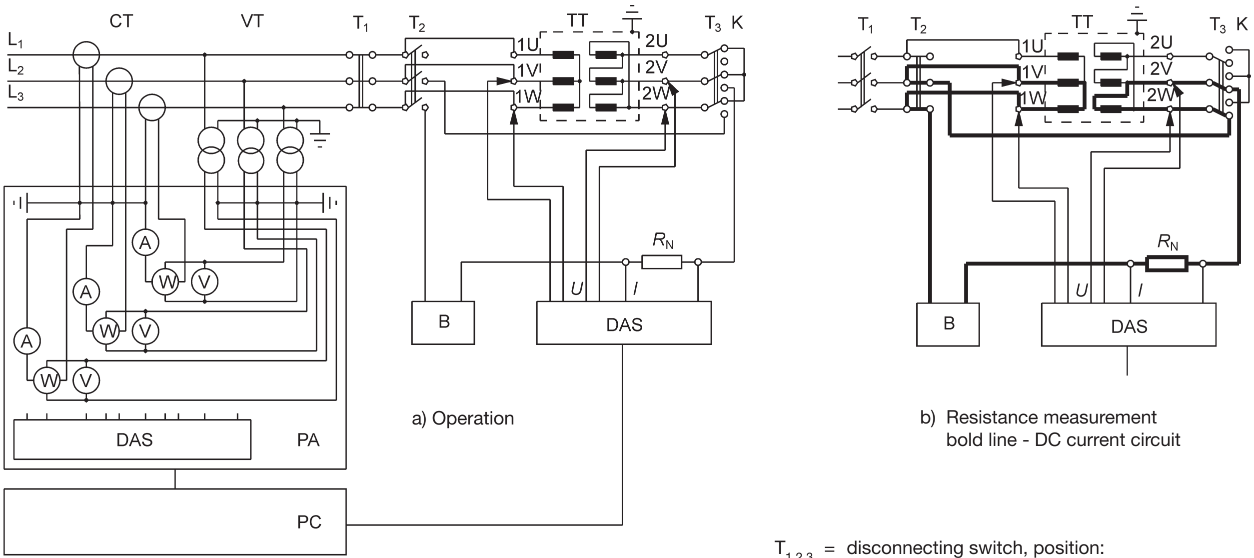
The transformer must be located in the test laboratory in such a manner that objects or walls situated near the cooling air inlet or outlet will not affect the cooling. The room should be as free from drafts as possible [51].

The transformer must be equipped with its protective devices (e.g. Buchholz relay) [2].

To protect the test staff from electric accidents, the voltage supply must be connected to the transformer in such a way that temperature readings on coolers and on the transformer tank can be taken without danger. The cables used should have a sufficient cross section and cables with soldered lugs should be avoided.

To guarantee optimal test laboratory utilization, it is important to know the temperature rise test duration. A method to determine the thermal time-constant is given in clause A 11.3.

Measuring circuit basics for the temperature rise test is shown in figure 11.3.




$T_{1,2,3}$ = disconnecting switch, position:
a) for operation and
b) for resistance measurement
PA = power analyser for U, I, and loss measurement
DAS = data aquisition system
PC = personal computer
$R_x$ = resistance of the transformer under test
TT = transformer under test
$B$ = DC source
$R_d$ = regulating resistor
VT = voltage transformer
CT = current transformer
K = short-circuit bus bar

*Figure 11.3: Basic measuring circuit for the temperature rise test*

The main measuring circuit and the circuit for measurement of losses, voltages and currents is principally identical to the one used for the measurement of load losses (see section 5). The only difference is that there are two supplementary disconnecting switches ($T_1$ and $T_2$ in figure 11.3) to connect the DC resistance measuring equipment to the transformer under test as quickly as possible after shutting down the test power.

It should be noted that also two independent DC sources which can be used, one for the HV windings, the other for LV windings.

For temperature rises on large power transformers with high nominal currents on the LV side, suitable disconnecting switches are often not available. In such cases the short-circuit connection is normally made with high current bus bars, which can be opened quickly after shutting down, one possibility is to use screw clamps.

All resistance measuring methods – described in section 3 (resistance measurement) – can be used or a combination of two different methods.

The same is valid for the DC source as outlined in the same chapter. It is imperative to drive the core into saturation as quickly as possible, especially for temperature rise tests, in order to stabilize the DC measuring current.

A cold resistance measurement has to be performed before the test, in exactly the same measuring configuration as the one used for the warm resistance measurement.

A particular recommendation for large transformers is to perform a gas-in-oil analysis (DGA) *before* and *after* the test to detect possible local overheating which will not show up as abnormal temperature rise values during the test [2], [201], see clause A 11.9, example 2.

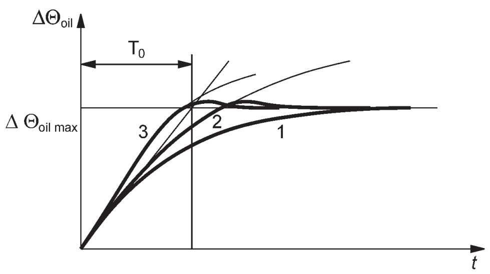
### 11.6.2 Measurement of the cooling air temperature

#### General

According to standards [2], [51] the temperature of the cooling air must be measured with at least 3 sensors (thermocouples or thermometers), protected from turbulence (drafts) and from radiant heat emitted by the transformer under test.

The sensors should be placed in oil-filled containers with about the same time constant as the transformer under test.

The IEEE standard [51] gives exact rules for the time constant of these containers, to avoid measurement errors due to abrupt variations of cooling-air temperature. Cylindrical containers with an oil volume of about 1 to 2 $dm^3$ comply well with the above requirements. The temperature readings must either be taken at regular intervals, or automatically by a continuous recording.




1 = normal test with total losses, coolers in operation, steady after 3-4 $T_0$
2 = test with total losses, but started with reduced cooling
3 = test started with higher losses
$T_0$ = time constant of the transformer with all coolers in operation

***Figure 11.4:*** *Temperature rise test started with higher losses or a reduced cooling system*

#### Natural air cooling (ON or AN)

The air temperature must be measured with at least 3 sensors distributed around the tank, they must be situated halfway up the tank or cooling surface and placed at a distance of 1 to 2 m away.

#### Forced air cooling (AF or AF)

A similar procedure is used, but the sensors must be placed so as to record the true temperature of the air drawn into the coolers or fans.

#### Cooling water temperature measurement

The reference water temperature is measured in a pocket (well) at the intake of the cooler (incoming water). Temperature readings should also be taken of the outgoing water and rate of water flow.

### 11.6.3 Oil temperature rise measurement

Measuring the oil temperature rise is the first step for temperature rise tests conducted using the short-circuit method. To establish the top oil temperature rise $\Theta_{oil\text{-}max}$ and the average oil temperature rise $\Theta_{oil\text{-}av}$ the transformer is subjected to the sum of the previously measured load- and no-load losses (see section 5 and 6).

For transformers with tapped windings the losses are different for different tappings. In this case IEC Standard 60076-2, clause 4.2 [2] and IEEE Std C57.12.90, clause 11 [51] state that the temperature rise test should be carried out at the maximum current tapping, which is normally the tapping with the highest load losses.

The test with total loss injection continues until a steady-state oil temperature rise is established. The test is terminated when the rate of change of top-oil temperature rise has fallen below 1 K per hour and has remained there for a period of 3 hours [2]. IEEE [51] specifies that the top-oil temperature must not vary more than 2,5% or 1 K, whichever is greater, during a consecutive 3 hour period [51].

IEC Standard 60076-2, annex C [2] gives a method for the extra-polation of measured values to steady state, see clause A 11.4.

In order to reduce the time required for the temperature rise test, it is possible to start the test with higher losses or with reduced cooling, see figure 11.4. However, a certain level of experience is necessary to choose the correct duration under these conditions, since extrapolation according to figure 11.10 in clause A 11.4 is not possible.

### 11.6.4 Definition of the average oil temperature

The average oil temperature $\Theta_{oil\text{-}av}$ must be taken to be equal to the top-oil temperature $\Theta_{oil\text{-}max}$ minus half the difference in the temperature of the oil at the top $\Theta_{KE}$ and the bottom of the cooling means $\Theta_{KA}$ [51]. Alternatively it is the average of the top oil temperature $\Theta_{oil\text{-}max}$ and the bottom oil temperature $\Theta_{KA}$ (temperature of the oil returning from the cooling equipment to the tank) [2].

According to IEC [2]:

$$\Theta_{oil\text{-}av} = {}^{1}/_{2}\,(\Theta_{oil\text{-}max} + \Theta_{KA})$$

According to IEEE [51]:

$$\Theta_{oil\text{-}av} = \Theta_{oil\text{-}max} - {}^{1}/_{2}\,(\Theta_{KE} - \Theta_{KA})$$

The average oil temperature rise is therefore:

$$\Delta\Theta_{oil\text{-}av} = \Theta_{oil\text{-}av} - \Theta_{a}$$

The top oil temperature should always be measured with thermocouples or thermometers in one or more oil-filled pockets (wells) in the cover.

The measurement of the oil temperatures at top and bottom of the coolers ($\Theta_{KE}$ and $\Theta_{KA}$ in figure 11.1) is more complicated, especially for transformers with ON cooling and radiators. Normally they have no pockets. In this case, the temperatures have to be determined by measuring the surface temperature using thermocouples, see clause A 11.5. Even when the thermocouples are carefully mounted a relatively high measuring error must be accepted (thermal conductivity).

The top-oil temperature measured in an oil-filled pocket on the cover $\Theta_{oil\text{-}max}$ can therefore be several degrees higher than the temperature $\Theta_{KE}$ measured at the surface. This does not affect the measuring accuracy of $\Theta_{oil\text{-}av}$ according to [51], because $\Theta_{KA}$ is determined with the same measuring error. This means that the difference $\Theta_{KE}$ - $\Theta_{KA}$, and therefore $\Theta_{oil\text{-}av}$, remains correct.

For transformers with separate coolers (e.g. for OFAF- or OFWF-cooling) measurement of $\Theta_{KE}$ and $\Theta_{KA}$ is easier. Normally they have thermometer pockets to measure the incoming and outgoing oil. If the power necessary to perform the temperature rise test (see section 11.5.3) is not available; the test may be performed at reduced power. The result of $\Delta\Theta_{oil\text{-}max.M}$ must be corrected according to the following equation:

$$\Delta\Theta_{oil-maxN} = \Delta\Theta_{oil-\max M}\left(\frac{P_{tot}}{P_{M}}\right)^{x}$$

where:

$\Delta\Theta_{oil\text{-}max.N}$ = top-oil rise at total losses $P_{tot}$

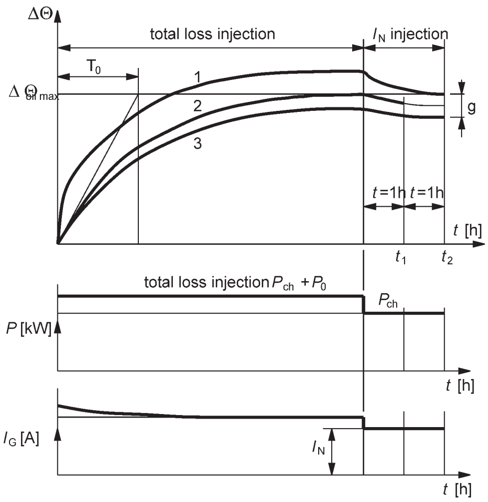
$\Delta\Theta_{oil\text{-}max.M}$ = top-oil rise at reduced losses $P_{M}$

$x$ = exponent as specified in table

This is valid within a range of ± 20% of the power target value [2], [51].

**Exponent $x$**

| Cooling | IEC [2] | IEEE [51] |
|---|---|---|
| ONAN | 0,9 | 0,8 |
| ONAF | 0,9 | 0,9 |
| OFAF | 1,0 | 1,0 |
| ODAF | 1,0 | 1,0 |




$T_0$ = time constant of the transformer
$t_1$ = moment of measurement of HV- and LV resistance measurement
$t_2$ = moment of resistance measurement of the second winding in case of separate resistance measurement
$g$ = temperature gradient winding-oil
1 = winding rise
2 = top oil rise
3 = average oil rise

***Figure 11.5:*** *Temperature development during test*

### 11.6.5 Measurement of average winding temperature rise

The measurement of the average winding temperature rise is the second step when conducting temperature rise tests made using the short-circuit method. After the top-oil temperature rise $\Delta\Theta_{oil\text{-}max}$ has been established, the test must immediately continue with test current $I_G$ reduced to rated current $I_r$ (see figure 11.5).
A resistance measurement performed immediately after the first step would necessarily result in too high winding temperatures.

This condition is maintained for 1 hour. This is enough time to subsequently measure the correct winding temperature rise, as the thermal time-constant of the windings is generally in the range 3 to 20 minutes. If the transformer design is known, the time constant for copper windings $\tau_w$ can be calculated according to the following equation:

$$\tau_W \approx 160 \frac{g}{J^2} \quad [s]$$

where:

$\tau_w$ = winding time constant in seconds
$J$ = current density in A/mm²
$g$ = winding-oil gradient in K

For the first step of the test (the measurement of the oil temperature rise) it makes no difference with which frequency the total losses are produced in the transformer. This is not the case for the second step. Here, the injected current must be at rated frequency, only then will the correct eddy losses occur in the windings. If injection at nominal frequency is not possible, see clause A 11.6.

The resistance measurement is conducted as follows:

- Immediately after disconnecting the test power supply (at nominal current) and removing the short-circuit connection, a DC measuring circuit is connected across the windings to be measured (possibly HV- and LV windings together or one winding after the other with a 1 hour period in between).

  Because the winding temperature and its resistance after shutdown vary with time, the measured resistance values have to be corrected backwards in time to the instant of shutdown.

- During shutdown for OFAF-cooled transformers resistance measurements, IEC Standard [2] proposes keeping both pumps and fans operating, while IEEE Standard [50] proposes shutting off the fans, and shutting off the oil pumps, or leaving them running.

- The standard method for making this correction is by a resistance measurement as a function of time [2], [51]. An alternative method is given in IEEE Std C57.12.90 [51], which uses correction factors to obtain the correct resistance at the instant of shutdown, see clause A 11.7.

The first resistance readings must be taken as soon as the inductive effect has subsided (see section 3), but not later than 4 minutes after shutdown. To check the complete decay of the inductive effect, voltage measurements may be performed on non-used windings. The resistance/time data must be measured over a period of about 10 to 20 minutes.

Measuring the resistance as a function of time using the ammeter-voltmeter method (including Data Acquisition Systems) is normally not difficult. The bridge method on the other hand requires a certain level of experience, because the resistance changes continuously. A proposed method is to adjust the decade resistor and to measure the time to zero deflection of the galvanometer. In any case, the bridge method is only conditionally recommended for resistance measurement of temperature rise.

Nowadays resistance measurements for temperature rise tests are primarily performed using Data Acquisition Systems, which allow automatic extrapolation of the resistance/time data and calculation of winding temperature, see figure 11.13.

If a Data Acquisition System is not available, the resistance/time data must be plotted on suitable coordinate paper and the resulting curve extrapolated to obtain the resistance at the instant of shutdown ($t$ = zero). The extrapolation is usually made using linear co-ordinates, see figure 11.6.

Figure 11.6 shows that the correct average oil temperature close to the windings can be determined by using the asymptote of the resistance/time function; this is especially important for multi-winding transformers, see clause A 11.9, example 3.

Normally the average winding temperature is calculated as follows:

$\Theta_{oil\text{-}av} = \Theta_{oil\text{-}max} - 0{,}5\ (\Theta_{KE} - \Theta_{KA})$ (IEEE) or

$\Theta_{oil\text{-}av} = \Theta_{oil\text{-}max} - 0{,}5\ (\Theta_{oil\text{-}max} + \Theta_{KA})$ (IEC)

The average winding temperature $\Theta_{Cu}$ for copper windings is calculated using:

$$\Theta'_{Cu} = \frac{R_W}{R_C}\left(235^* + \Theta_C\right) - 235^*$$

where:

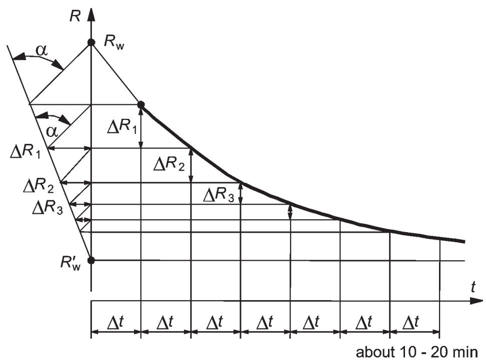
$\Theta'_{Cu}$ = winding temperature (warm)

$R_W$ = active resistance at temperature $\Theta_W$ (warm)

$R_C$ = active resistance at temperature $\Theta_C$ (cold)

* 234,5 according to IEEE Standards

For aluminum windings a value of 225 must be used instead of 235 (234,5).




$R_w$ = extrapolated hot resistance of the winding at the instance of shutdown

$R'_w$ = resistance value, corresponding to the average oil temperature close to the winding

***Figure 11.6:*** *Extrapolation of the resistance/time function (linear coordinates)*

Since oil temperature decreases during the 1-hour energisation at rated current, the winding temperature calculated using the above formula has to be corrected, see figure 11.5.

First, the winding-oil gradient $g$ during operation at $I_r$ is determined:

$$g = \Theta'_{Cu} - \Theta_{oil\text{-}av(Ir)}$$

and is added to the average oil temperature rise $\Theta_{oil\text{-}av(Ptot)}$ measured in the first step of the test with total loss injection.

$$\Delta\Theta_{Cu} = \Theta_{oil\text{-}av(Ptot)} + g$$

The average winding temperature rise $\Delta\Theta_{Cu}$, calculated in this way, corresponds well to the real temperature rise. For an explanation, see clause A 11.8.

If the specified value of current has not been obtained during the test, the results should be corrected according the following relation:

$$g_r = g_M \left( \frac{I_r}{I_t} \right)^y$$

where:

$I_r$ = rated current

$I_t$ = test current

$g_r$ = gradient winding - oil at rated current

$g_M$ = measured gradient winding - oil at the test current

$y$ = exponent [2], [51]
1,6 for ON and OF cooling
2,0 for OD cooling

This equation is valid within a range of ±10 % of the target current value [2], [51].

If it is not possible to use the resistance method to obtain winding temperature rise, (for instance for transformers with extremely low resistance), other methods may be used.

This is occasionally done for measuring the LV resistance for large rectifier- and arc-furnace transformers by using built-in fiber-optical sensors.

## 11.7 Hot spot temperatures

### 11.7.1 Winding hot-spot [2], [11]

As mentioned in section 11.5.1, the winding temperature at the top of the winding does not correspond to the real winding hot-spot. This is due to the influence of the increased stray loss caused by the horizontal component of stray flux. To account for this non-linearity, the winding-oil gradient $g$ at the top of the winding has to be multiplied by the factor $H$. This $H$-factor may vary from 1,1 to 1,5, depending on transformer size, short-circuit impedance and winding design.

$$\Delta\Theta_{Hot\text{-}spot} = \Delta\Theta_{oil\text{-}max} + g \cdot H$$

where:

$H$ = 1,1 for distribution transformers, and
1,3 for medium and large power transformers

IEC 60076-2 [2] does not directly specify permissible hot-spot temperature values, while Loading guide IEC 60354 [11] is based on a winding hot-spot rise of 78 K. The hot-spot temperature rise is defined in IEEE Std C57.12.00 [50] at 80 °C.

### 11.7.2 External Hot-spots

A check for possible external local hot-spots should be carried out, especially for large power transformers or transformers with extremely high nominal currents (rectifier- or arc-furnace transformers). Particular attention should be paid to all transformer parts which are exposed to high stray fields, or which are situated near high-current bushings. This is normally done using infrared cameras [2].

## 11.8 Practical examples and analysis of the measured values

Examples for a two-winding transformer, multi-winding transformer (three-winding transformer) and a combination of main- and regulating transformers are given in clause A 11.9.

## 11.9 Measuring uncertainty

The measuring error when measuring the winding temperature consists of different individual errors such as:

- the measurement of the maximum and average oil temperature
- the ambient air temperature (e.g. radiation from the transformer) or water temperature
- the measurement of resistance, etc.

The measuring error for a resistance value of, for example, 0,05 %, which is rather low for an extrapolated warm-resistance, results in a measuring uncertainty of about ± 1,5 K (at a winding temperature of 70 °C).

A total measuring error of about ± 2-3 K must be taken into account.

# Appendix A 11
# Temperature rise test

## A 11.1 Definitions, temperature and temperature-rise

### A 11.1.1 Temperature and life-time expectations

Cellulose is the base for most of the insulation materials used in transformer design (paper, transformer board, etc.).
The rate of aging or decomposition of the insulation material increases with increasing temperature. Already at a temperature of 100°C is a noticeable degree of decomposition. The adviseable permissable temperature is generally based on a figure of 100°C or slightly above for an acceptable life expectancy.

According to Montsinger's law, on which different loading guides are based, the aging rate doubles with each temperature increase of about 6 K in the range from 80°C to 140°C. [11]

As a result of this aging, the Standards ([2], [50]) have not only established the highest permissible temperature values for the windings and the oil, but also rules for permissible overloads, including their influence on life expectancy (life-reduction) [11], [52].

### A 11.1.2 Temperature-rise

Temperature is a quantitative measure of thermal energy contained in an object; the higher the thermal energy, the higher the temperature. Temperature is measured in Kelvin, which is abbreviated K.

Traditionally there are also a couple of additional temperature scales in use, e.g. degrees Celsius, abbreviated °C and degrees Fahrenheit, abbreviated °F. By definition, 273,15 K equals 0°C and a difference in degrees Celsius, °C, is the same as a difference in Kelvin, K.

Temperature-rise is always defined as the difference between the temperature of an object and the temperature of the corresponding cooling medium (e.g.: oil, air or water).

In this manual we will use degrees Celsius for absolute temperature and Kelvin for temperature difference. It should be noted that IEEE uses degrees Celsius for temperature difference as well as absolute temperature. Symbols for temperature are:

- Absolute temperature: $\Theta$ or T
- Temperature difference: $\Delta\Theta$ or T

**Example:**

According to IEC [2], the maximum permitted ambient temperature is specified as 40°C, and the corresponding permitted temperature rise of the winding as 65 K.

The average winding temperature is therefore: 65 + 40 = 105 °C.

## A 11.2 Other test methods for temperature rise test

### A 11.2.1 "Back-to-back" method

For this test method two similar transformers must be available, see figure 11.7. One is the transformer under test, the other is connected in parallel and excited at the rated voltage of the transformer under test. The rated current is made to flow in the transformer under test by using differing voltage ratios or an injected voltage [2], [15].

The iron core of the transformer under test is thereby excited as it is during normal operation and has nominal flux density. This is why this method is normally used for dry-type transformers as required by the standards [15].

The generator needs only to supply the sum of the total losses $P_L + P_0$ of the two transformers as well as the reactive power to energize the two transformers.

The current $I$ which can be reached in per cent of rated current $I_N$ of the transformer under test can be calculated using the following equation:

$$I = 100 \cdot \frac{\Delta U}{\left(u_{TT} + u_r \frac{S_{TT}}{S_r}\right)}$$

where:

$\Delta U$ = relative difference in no-load voltages of the two transformers

$\Delta U$ = $(1 - U_{TT}/U_T)$ in p.u.

$U_{TT}$ = (no-load) rated voltage of the transformer under test TT

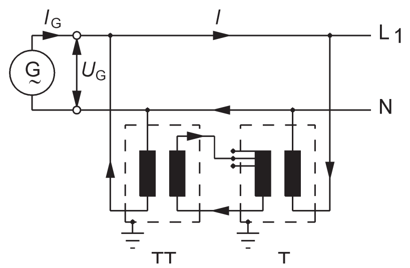
$U_r$ = (no-load) rated voltage of the transformer T

$u_{TT}$ = short-circuit impedance of the transformer under test TT

$u_T$ = short-circuit impedance of the transformer T

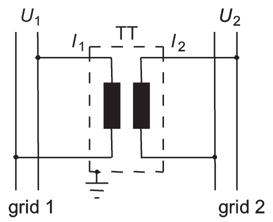
$S_{TT}$ = nominal rating of the transformer under test TT

$S_r$ = nominal rating of the transformer T




$I_G$ = supply current
$U_G$ = supply voltage
$I$ = nominal current of the transformer under test
TT = transformer under test
T = transformer, similar to TT

***Figure 11.7:*** *Test connections for a temperature rise test with "back to back" method*




$U_1, U_2$ = voltage of grid 1 and 2
$I_1, I_2$ = current in grid 1 and 2

***Figure 11.8:*** *Measuring circuit for temperature rise test during operation*

### A 11.2.2 Temperature rise test during operation

This method cannot be recommended (especially for large power transformers) as load- and voltage variations during the test may influence the measuring results. In addition, the resistance measurement to determine winding temperature is rather complicated.

Figure 11.8 shows the principal measuring circuit for a temperature rise test during operation.

## A 11.3 Estimating the duration of the temperature rise test [2]

#### Calculation of the thermal time-constant of the transformer under test

IEC 60076-2, clause C1 gives a formula for the thermal time-constant $\tau_0$ of the transformer, based on information usually available on the transformer rating plate:

$$\tau_0 = \frac{5m_T + 15m_O}{P_{tot}} \cdot \left( \frac{\Delta\Theta_{oil-\max}}{60} \right)$$

where:

$\tau_0$ = thermal time-constant of the transformer in hours
$m_T$ = total mass of the transformer without oil in tons
$m_O$ = total mass of oil minus oil in conservator in tons
$P_{tot}$ = total transformer losses in kW
$\Delta\Theta_{oil-max}$ = estimated ultimate top-oil rise, normally somewhat below 60 K

#### Example:

For a 20 MVA transformer ONAN:

$m_T$ = 32 t, $m_O$ = 7 t

$P_{tot}$ = 110 kW, $\Delta\Theta_{oil-max}$ = 54 K

$$\tau_0 = \frac{5 \cdot 32 + 15 \cdot 7}{110} \cdot \left( \frac{54}{60} \right) = 2{,}2 \text{ h}$$

The thermal time-constant is generally in the order of 1-5h. It is shorter for large, compact, forced-cooled transformers, and longer for naturally cooled transformers.

The time to obtain the ultimate oil temperature rise of a transformer is about four times the thermal time-constant $\tau_0$, corresponding to about 98,5% of its final temperature; the time spent to perform the whole test is therefore about four times $\tau_0$ plus 1 hour.

## A 11.4 Graphical extrapolation to ultimate temperature rise [2]

## A 11.5 Oil temperature measurement by measuring the surface temperature [51]

The preferred method for measuring the surface temperature is to use a thermocouple. As it is normally not possible to solder the thermocouple directly to the surface, the thermocouple should be soldered to a thin metal plate or foil of about 25 x 25 mm (1 in$^2$). The plate must be held firmly and snugly against the tank surface and the paint should preferably be removed behind the plate. The thermocouple must also be thoroughly thermally insulated from its surrounding medium.

## A 11.6 Correction of the injected current with non-nominal frequency

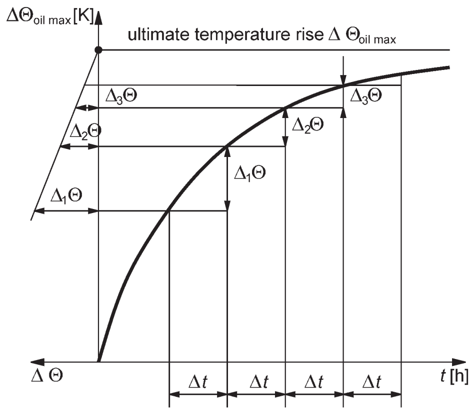
If current injection at nominal frequency is not possible it is necessary to correct the current using the following relationship:

$$I_{fM} = I_{fr}\sqrt{\frac{P_j + P_a\left(\frac{f_r}{f_M}\right)^2}{P_j + P_a}}$$

where:

- $I_{fM}$ = injected current for the temperature rise test performed at frequency $f_M$
- $I_{fr}$ = rated current
- $f_r$ = rated frequency
- $f_M$ = power frequency for measurement
- $P_{DC}$ = $I^2R$ ohmic loss (see section 5)
- $P_{sp}$ = eddy losses (see section 5)

For a 60 Hz transformer tested at 50 Hz and a normal relationship between $P_a/P_j$, the injected current has to be increased by about 3-4 % to simulate the correct losses during 60 Hz operation.




$\Delta t$ = time interval between readings
$\Delta\Theta_{1,2,3}$ = three successive temperature rise readings time interval between them

***Figure 11.9:*** *Graphical extrapolation of measured temperature rises to ultimate temperature rise*

## A 11.7 Correction factors according to IEEE Std C57.12.90 [51]

### A 11.7.1 Specific winding losses >15 W/kg, but < 66 W/kg

If the winding load loss does not exceed 66 W/kg (30 W/lb) for copper or 132 W/kg (60 W/lb) for aluminum, correction factors must be used as defined in the following. Note that the losses ($I^2R$-losses + eddy losses) per winding must be calculated at rated winding temperature rise (65 K) plus 20 °C (i.e. 85 °C) divided by the mass of the corresponding winding.

The temperature correction to the instant of shutdown must be an added number of degrees Kelvin equal to the factor given in the table below, multiplied by the specific losses in W/kg.

For copper windings
the correction factors are:

| Time after shutdown [min] | Correction factor |
|---|---|
| 1 | 0,09 |
| 1,5 | 0,12 |
| 2 | 0,15 |
| 3 | 0,20 |
| 4 | 0,23 |

**Example:**

For a transformer winding with 25 W/kg losses at 85 °C, a first reading taken after 1,5 minutes, and a measured winding temperature rise of 61 K, the correction factor is 0,12 (see table).

Correction: 25 · 0,12 = 3 K

The winding temperature rise at the instant of shutdown is:
61 + 3 = 64 K

### A 11.7.2 Specific losses < 15 W/kg

A correction of 1 K/minute must be used.

## A 11.8 Conformance of the measured average winding temperature rise with the real winding temperature rise in operation

$$\Delta\Theta_{Cu} = \Theta_{oil\text{-}av(Ptot)} + g$$

The average winding temperature rise $\Delta\Theta_{Cu}$, calculated in this way corresponds well to the real temperature rise because:

- the oil temperature is measured correctly. It is irrelevant for the transformer, where - locally - the total losses occur:
- in operation: no-load loss $P_0$ in the iron core, load loss $P_L$ in windings and tank, etc.
- during test: there is no loss in the core, but the sum of $P_0$ and $P_L$ occurs in the windings, tank etc.
- The winding-oil gradient $g$, determined at $I_r$ - injection is identical to that in operation

Therefore, the sum of the average oil temperature rise for injection with total losses $\Theta_{oil\text{-}av(Ptot)}$ plus the gradient $g$ gives the correct winding temperature rise $\Delta\Theta_{Cu}$.

## A 11.9 Practical examples and analysis of the measured values

### A 11.9.1: Example 1: Two-winding transformer

Conventional graphical extrapolation for the winding resistance

For a three-phase transformer rated:

75 MVA

132 ± 8 x 1,65 / 66 kV; Ynd11, ONAN-cooling with separate radiator battery; $\varepsilon_{cc}$ = 9,4 %;

$P_0$ = 53,5 kW, $P_L$ = 256,5 kW (at pos. 118 / 66 kV)

Required power:

$$S = k^2 \cdot S_r \cdot \left(\frac{\varepsilon_{cc}}{100}\right) = 1{,}10^2 \cdot 75 \cdot \left(\frac{9{,}4}{100}\right) = 8{,}52 \text{ MVA}$$

$$k = \sqrt{\frac{P_L + P_0}{P_L}} = \sqrt{\frac{256{,}5 + 53{,}5}{256{,}5}} = 1{,}10$$

$I_G = k \cdot I_r = 1{,}10 \cdot 656 = 722$ A (supply on LV)

For a given loss, the current required at the beginning of the test, when the transformer is still cold, is 5-8% higher than the current at the end of the test. This is caused by the change in winding resistance as a function of temperature.

This is shown in the following table. The current at $t$ = zero is 764 A instead of the above calculated value of 722 A; also the supply power $S$ is correspondingly higher (9,59 MVA instead of 8,52 MVA)

The power supply is on the LV side and HV is short-circuited.

#### Cold resistance measurement before the test

$R_C$ = 547,8 mΩ at 18,5 °C (HV)

$R_C$ = 117,9 mΩ at 18,5 °C (LV)

### Measurement of the oil temperature rise (first step of the test)

Total loss injection: $P_{tot} = P_0 + P_L$ = 53,5 + 256,5 = 310 kW

| $t$ h | $U_g$ V | $I_g$ A 1) | $P_{tot}$ kW 2) | $\Theta_a$ °C 3) | $\Theta_{oil\text{-}max}$ °C | $\Theta_{KE}$ °C 4) | $\Theta_{KA}$ °C 4) | $\Theta_{oil\text{-}av}$ °C 5) | $\Delta\Theta_{oil\text{-}max}$ K 6) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 7250 | 764 | 310 | 19,5 | 20,5 | 20,0 | 18,0 | | 1,0 |
| 1 | 6980 | 736 | 310 | 19,3 | 43,2 | 43,0 | 31,0 | | 23,9 |
| 2 | 6890 | 725 | 310 | 20,3 | 53,7 | 53,5 | 41,2 | | 33,4 |
| I | I | I | I | I | I | I | I | | I |
| 9 | 6810 | 717 | 310 | 22,2 | 69,5 | 69,5 | 56,4 | | 47,3 |
| $9^{30}$ | 6800 | 717 | 310 | 22,2 | 69,5 | 69,5 | 56,7 | | 47,3 |
| 10 | 6800 | 716 | 310 | 22,2 | 69,5 | 69,5 | 56,7 | 63,1 | 47,3 |

1) *average of 3 amperemeters*
2) *sum of 3 wattmeters*
3) *average of 4 thermocouples*
4) *average of 2 thermocouples*

5) $\Theta_{oil\text{-}av} = \frac{1}{2}(\Theta_{oil\text{-}max} + \Theta_{KA})$
6) $\Delta\Theta_{oil\text{-}max} = \Theta_{oil\text{-}max} - \Theta_a$
$\Delta\Theta_{oil\text{-}max}$ = *47,3 K (guarantee value 60 K)*
$\Delta\Theta_{oil\text{-}av(Ptot)} = \frac{1}{2}(69{,}5 + 56{,}7) - 22{,}2 = 40{,}9$ K

### Measurement of winding temperature rise (second step of the test)

Rated current injection: $I_r = I_G$ = 656 A

| $t$ h | $U_g$ V | $I_g$ A 1) | $P_{tot}$ kW 2) | $\Theta_a$ °C 3) | $\Theta_{oil\text{-}max}$ °C | $\Theta_{KE}$ °C 4) | $\Theta_{KA}$ °C 4) | $\Theta_{oil\text{-}av}$ °C 5) | $\Delta\Theta_{oil\text{-}max}$ K 6) |
|---|---|---|---|---|---|---|---|---|---|
| $10^{30}$ | 6200 | 656 | 254 | 22,3 | 69,0 | 69,0 | 56,0 | | 46,7 |
| 11 | 6200 | 656 | 254 | 22,3 | 68,5 | 68,5 | 55,5 | 62,0 | 46,2 |
| $\Theta_{oil\text{-}av(Ir)}$ = 62,0°C | | | | | | | | | |

1) *average of 3 amperemeters*
2) *sum of 3 wattmeters*
3) *average of 4 thermocouples*
4) *average of 2 thermocouples*
5) $\Theta_{oil\text{-}av} = \frac{1}{2}(\Theta_{oil\text{-}max} + \Theta_{KA})$
6) $\Delta\Theta_{oil\text{-}max} = \Theta_{oil\text{-}max} - \Theta_a$

After 1 hour of operation at rated current, a resistance measurement is carried out on both windings:

**Example: HV winding**

| *t* [min] | $R_{HV}$ [mΩ] |
|---|---|
| $1^{30}$ | 681,3 |
| 2 | 679,0 |
| $2^{30}$ | 677,3 |
| 3 | 674,3 |
| $3^{30}$ | 674,0 |
| 4 | 671,5 |
| 5 | 668,1 |
| 6 | 664,2 |
| 8 | 658,6 |
| 10 | 655,2 |

For extrapolation of the resistance / time function, see figure 11.10.

The extrapolated resistance value is 689,4 mΩ

With the measured cold resistance:

$R_C$ = 547,5 mΩ at 18,5 °C:

$$\Theta'_{CuHV} = \frac{689,6}{547,5}(235+18,5) - 235 = 84,3\ °C$$

$$g_{HV} = \Theta_{Cu} - \Theta_{oil\text{-}av(Ir)} = 84,3 - 22,3\ K$$

The corrected temperature rise of the HV winding is therefore:

$$\Delta\Theta_{CuHV} = g_{HV} + \Delta\Theta_{oil\text{-}av(Ptot)} = 22,3 + 40,9 = 63,2\ K$$
(guarantee value = 65 K)

Similarly for the LV windings:

$R_w$ = 148,4 mΩ

$R_C$ = 117,9 mΩ at 18,5 °C

$$\Theta'_{CuLV} = \frac{148,4}{117,9}(235+18,5) - 235 = 84,1\ °C$$

$$g_{LV} = \Theta'_{CuLV} - \Theta_{oil\text{-}av(Ir)} = 84,1 - 62,0 = 22,1\ K$$

$$\Delta\Theta_{CuLV} = g_{LV} + \Delta\Theta_{oil\text{-}av(Ptot)} = 22,1 + 40,9 = 63,0\ K$$
(guarantee value= 65 K)

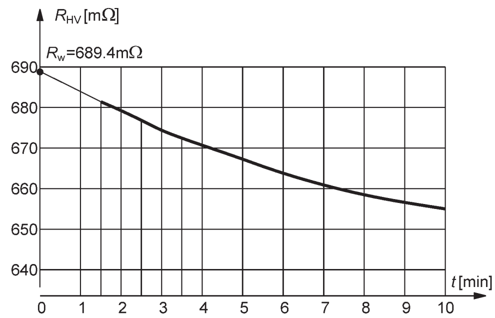



***Figure 11.10:*** *Extrapolation of the resistance/time function for the HV winding of a 75 MVA transformer*

Resistance measurement with a Data Acquisition System (Power analyzer) (example HV winding: 1U-1V):

| $t$ [min] | $R_{HV}$ [mΩ] |
|---|---|
| 2 | 805,710 |
| 3 | 798,990 |
| 4 | 793,500 |
| 5 | 788,800 |
| 6 | 784,720 |
| 7 | 781,070 |
| 8 | 777,890 |
| 9 | 775,060 |
| 10 | 772,500 |
| 11 | 770,240 |
| 12 | 768,280 |
| 13 | 766,450 |
| 14 | 764,770 |
| 15 | 763,330 |
| 16 | 762,010 |
| 17 | 760,840 |
| 18 | 759,780 |
| 19 | 758,810 |
| 20 | 757,950 |

Computer aided extrapolation of the resistance-time data, see figure 11.11.

## A 11.9.2 Example 2: two-windings generator transformer

Rating 500 MVA ODWF cooling, resistance measurement with Data Acquisition System and computer aided extrapolation.

The power supply is on the HV side and LV is short-circuited.

### Cold resistance measurement before the test

$R_C$ = 680,3 mΩ at 21,7 °C (HV)
$R_C$ = 0,8814 mΩ at 21,7 °C (LV)

### Measurement of the oil temperature rise (first step of the test)

Total loss injection:

$$P_{tot} = P_0 + P_L = 157 + 1198 = 1355 \text{ kW}$$

At a steady state, after about 5 hours:

$\Theta_{water}$ = 9,5 °C (cooler inlet)

$\Theta_{oil\text{-}max}$ = 51,3 °C

$\Delta\Theta_{oil\text{-}max}$ = 51,3 - 9,5 = 41,8 K (guarantee value 60 K)

$\Theta_{oil\text{-}av(Ptot)} = {}^1/_2\,(51,3 + 41,8) = 46,6$ °C

$\Delta\Theta_{oil\text{-}av}$ = 46,6 - 9,5 = 37,1 K

### Measurement of the winding temperature (second step)

Rated current injection:

$$I_r = 704 \text{ A}$$

After 1 hour of operation at rated current, the following temperatures were measured:

$\Theta_{water}$ = 9,5 °C (cooler inlet)

$\Theta_{oil\text{-}max}$ = 50,4 °C

$\Delta\Theta_{oil\text{-}max}$ = 50,4 - 9,5 = 40,9 K (guarantee 60 K)

$\Theta_{oil\text{-}av(Ir)} = {}^1/_2\,(50,4 + 41) = 45,7$ °C

$\Delta\Theta_{oil\text{-}av}$ = 45,7 - 9,5 = 36,2 K

The extrapolated resistance value is 821,479 mΩ

With the measured cold resistance $R_C$ = 680,3 mΩ at 21,7 °C:

$$\Theta'_{CuHV} = \frac{821{,}479}{680{,}3}(235 + 21{,}7) - 235 = 75{,}0\,°C$$

$$g_{HV} = \Theta'_{Cu} - \Theta_{oil\text{-}av(Ir)} = 75{,}0 - 45{,}7 = 29{,}3\ K$$

The corrected temperature rise of the HV winding is therefore:

$$\Delta\Theta_{cuHV} = g_{HV} + \Delta\Theta_{oil\text{-}av(Ptot)} = 29{,}3 + 37{,}1 = 66{,}4\ K$$
(guarantee value: 70 K)

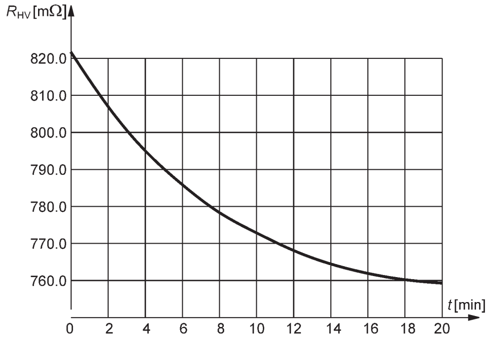



***Figure 11.11:*** *Extrapolation of the resistance/time data with a computer program for the HV winding of a 500 MVA transformer*

**Gas-in oil analysis before and after the temperature rise test**

| Dissolved gases | Typical values* [ppm] | Before test [ppm] | After test [ppm] |
|---|---|---|---|
| $H_2$ | 15 | 3,2 | 3,3 |
| $CH_4$ | 5 | 0,4 | 0,4 |
| $C_2H_6$ | 5 | 0,1 | 0,1 |
| $C_2H_4$ | 2 | 0,2 | 0,2 |
| $C_2H_2$ | 1 | 0,2 | 0,1 |
| CO | 80 | 19 | 27 |
| $CO_2$ | 200 | 56 | 46 |

** according to IEC 61181 [34]*

### Result

The measured values after the temperature rise test are normal, according to IEC 61181 [34]

### A 11.9.3 Example 3: Multi-winding transformer (three-winding transformer)

For a three-phase transformer rated
146,5/146,5/40 MVA, 50 Hz,
250 ±12 x 3,3/165/22,4 kV; YNyn0d5
OFAF cooling, $P_0$ = 110,5 kW;

#### Oil temperature rise measurement (first step)

losses to inject:

$$P_{total} = P_0 + P_{L(146,5/146,5/40\ \mathrm{MVA})}$$

For determination of the losses at 146,5/146,5/40 MVA, see section 5.

$$\left.\begin{aligned} P_{L12} &= 414\ \mathrm{kW} \\ P_{L13} &= 1065\ \mathrm{kW} \\ P_{L23} &= 781\ \mathrm{kW} \end{aligned}\right\} \text{base 146,5 MVA}$$

$$P_{L1} = {}^1/_2\,(419 + 1065 - 781) = 351{,}5\ \mathrm{kW}$$
$$P_{L2} = {}^1/_2\,(419 + 781 - 1065) = 67{,}5\ \mathrm{kW}$$
$$P_{L3} = {}^1/_2\,(1065 + 781 - 419) = 713{,}5\ \mathrm{kW}$$

$$\begin{aligned} P_{L(146,5/146,5/40\ \mathrm{MVA})} &= P_{L1} + P_{L2} + (40/146{,}5)^2 \cdot P_{L3} \\ &= 351{,}5 + 67{,}5 + (40/146{,}5)^2 \cdot 713{,}5 \\ &= 472{,}2\ \mathrm{kW} \end{aligned}$$

The power supply is at the MV terminals (165 kV), HV is short-circuited, and LV is open.

At steady state, after about 8 hours:

$$\Theta_a = 27{,}0\ °\mathrm{C}$$

$$\Theta_{oil\text{-}max} = 68{,}0\ °\mathrm{C}$$

$$\Delta\Theta_{oil\text{-}max} = 68{,}0 - 27{,}0 = 41\ \mathrm{K}$$ (guar. value 60 K)

$$\Theta_{oil\text{-}av(Ptot)} = {}^1/_2\,(68{,}0 + 61{,}5) = 64{,}8\ °\mathrm{C}$$

$$\Delta\Theta_{oil\text{-}av(Ptot)} = 64{,}8 - 27{,}0 = 37{,}8\ \mathrm{K}$$

#### HV and MV winding temperature measurement (second step)

Rated current injection in MV-winding:

$I_r$ = 513 A

After 1 hour of operation at rated current, the following temperatures were measured:

$$\Theta_a = 26{,}3\ °\mathrm{C}$$

$$\Theta_{oil\text{-}max} = 64{,}5\ °\mathrm{C}$$

$$\Delta\Theta_{oil\text{-}max} = 64{,}5 - 26{,}3 = 38{,}2\ \mathrm{K}$$

$$\Theta_{oil\text{-}av(In)} = {}^1/_2\,(64{,}5 + 58{,}0) = 61{,}3\ °\mathrm{C}$$

$$\Delta\Theta_{oil\text{-}av(Ir)} = 61{,}3 - 26{,}3 = 35{,}0\ \mathrm{K}$$

For the resistance measurement (for example HV), extrapolation is as before; calculating the winding temperature $\Theta'_{CuHV} = 86{,}9\,°C$

$(R_C = 341{,}5\ m\Omega$ at $21\ °C)$

$g_{HV} = 869 - 61{,}3 = 25{,}6\ K$

$\Theta_{CuHV} = g + \Theta_{oil\text{-}av(Ptot)} = 25{,}6 + 37{,}8 = 63{,}4\ K$

The MV resistance measurement is analogous;

### LV winding temperature measurement (third step)

Nominal current is injected at the MV terminals (based on 40 MVA), LV is short-circuited and HV is open:

$I_{r(40MVA)} = 513 \cdot (40/146{,}5) = 140\ A$

After 2 hours of operation at 140 A, the following temperatures were measured:

$\Theta_a = 22{,}3\,°C$

$\Theta_{oil\text{-}max} = 49{,}0\,°C$

$\Delta\Theta_{oil\text{-}max} = 49{,}0 - 22{,}3 = 26{,}7\ K$

$\Theta_{oil\text{-}av(Ir)} = {}^1/_2\,(49{,}0 + 45{,}0) = 47{,}0\,°C$

$\Delta\Theta_{oil\text{-}av(Ir)} = 47{,}0 - 22{,}3 = 24{,}7\ K$

For the resistance measurement of LV, the extrapolation is as before ($R_W$= 20,24 mΩ); calculating the winding temperature:

$\Theta'_{CuLV} = 66{,}1\,°C \quad (R_C = 17{,}21\ m\Omega$ at $21\,°C)$

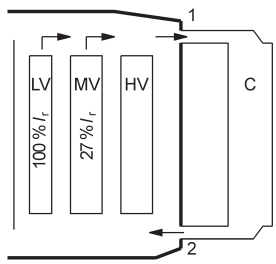
$g_{LV} = 66{,}1 - 47{,}0 = 19{,}1\ K$

$\Theta_{CuHV} = g + \Theta_{oil\text{-}av(Ptot)} = 19{,}1 + 37{,}8 = 56{,}9\ K$

A check of the gradient $g_{LV}$ is recommended, as the average oil temperature $\Theta_{oil\text{-}av(In)}$ measured after 2 hours at nominal current in the LV winding is not representative of the average oil temperature close to the LV-winding, see figure 11.12.

A mixed temperature is measured at the oil inlet and outlet, because the LV winding is 100 % loaded LV and the MV winding is only 27 % loaded, which can result in an unrealistic average oil temperature close to the LV winding.

IEC Standard [2] proposes another way to obtain a fairly correct average oil temperature close to the LV winding by using the so-called “extrapolated mean oil” method. Hereby it is supposed, that the average oil close of the winding corresponds to the extrapolated resistance $R'_w$. The resistance $R'_w$ shall be determined as shown in figure 11.13.




1 = oil inlet
2 = oil outlet
C = cooler

*Figure 11.12: Cooling conditions in a three-winding transformer during the temperature rise test (measurement of the winding)*

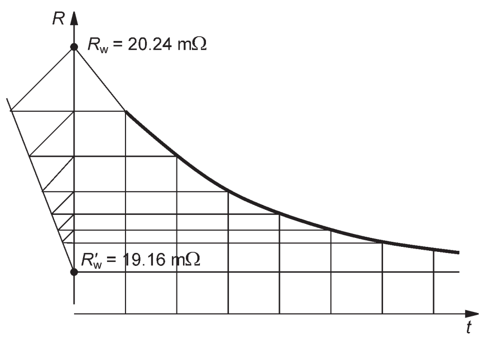



*Figure 11.13: Extrapolation of the resistance/time function and determination of $R'_w$ for LV winding of a three-winding transformer*

$R'_W = 19{,}16\ \text{m}\Omega$

$$\Theta_{oil} = \frac{19{,}16}{17{,}21}(235+21) - 235 = 50{,}0\ °C$$

$g_{LV} = 66{,}1 - 50 = 16{,}1\ K$ (instead of 19,1, determined earlier)

Both winding-oil gradients $g_{LV}$, calculated using different methods, correspond rather well. In case of doubt, the gradient $g$, calculated using $R'_W$ should be used.

The winding temperature rise is then:

$$\Theta_{CuHV} = g + \Theta_{oil\text{-}av(Ptot)} = 16{,}1(19{,}1) + 37{,}8 = 53{,}9\ (56{,}9)\ K$$

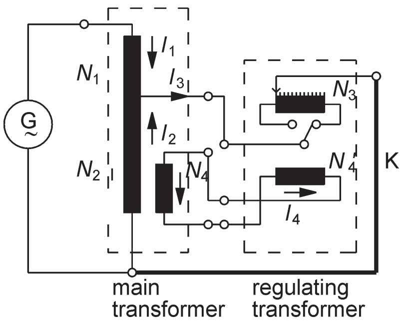
### A11.9.4 Example 4: Transformer consisting of main- and regulating transformer

Connection diagram, see figure 11.14.

$$I_4 = I_1 \frac{N_3}{N_4'}$$

Although two different transformers are considered, it is often necessary to perform the temperature rise test using the combination main- / regulating transformer, especially if the temperature rise test is to be done at the minimal tapping position of the regulating transformer.

A problem arises in determining the winding temperature rise of the common winding $N_2$ of the main (auto) transformer, as its rated current depends strongly on the tap position of the on-load tap changer. If the test would be performed separately, the HV-winding of the main transformer would be overloaded beyond the permissible limits (depending on the regulating range of the regulating transformer).




K = short-circuit lead
$I_{1,2,3,4}$ = nominal current of different windings
$N_{1,2,3,4}$ = number of turns of the different windings
$I_2 = I_3 - I_1$
$I_4 = I_3 \cdot N_3 / N'_4$

*Figure 11.14: Connection diagram of the temperature rise test for the combination main- and regulating temperature*

#### Usually the following tests are required

a) the sum of losses in the main transformer(oil temperature rise of the main transformer). If the relationship $P_L/P_0$ is the same for the main- and the regulating transformer, the correct oil temperature rise for the regulating transformer may also be obtained.

b) the sum of the losses in the regulating transformer (oil temperature rise of the regulating transformer). May not be necessary, see a)

c) the main transformer nominal current (winding $N_1$ and $N_2$) and nominal current of (winding $N_3$ and $N'_4$)

d) LV nominal current (winding $N_4$), as the ratings for $N_4$ and $N'_4$ are usually equal.

# Testing of Power Transformers

## 12. Measurement of zero-sequence impedance(s) on three-phase transformers

# 12. Measurement of zero-sequence impedance(s)

## 12.1 References / Standards

- IEC 60076-1 (2000), clause 10.7
  "Measurement of the zero-sequence impedance(s) on three-phase transformers" [1]
- IEEE Std C57.12.90-1999, clause 9.5
  "Zero-phase-sequence impedance" [51]

**NOTE:**

The measurement of the zero-sequence impedances is considered a **special test** in IEC 60076-1[1] or an **"other" test,** in IEEE Std.C5712.00 [50].

## 12.2 Purpose of measurement

Modern technique in the calculation of system fault conditions demands not only the knowledge of symmetrical components, but also the phase sequence impedances of the individual components, for instance for transformers

## 12.3 General

Any process in three-phase symmetrically loaded network calculations (currents, voltages, etc) can be analysed for one phase only since the values of the other phases are simply shifted by 120° and have the same magnitude. This is also valid for three-phase short-circuits.

For an unbalanced three-phase system, for instance due to a single-phase ground fault, each phase has to be considered and calculated separately since the impedances are different from those in a symmetrical network. This requires the knowledge of the theory of symmetrical components [106], [107], [108] and the phase sequence characteristics of the individual part of the system.

By using this method it is possible to convert any given three-phase system with unbalanced phases to three-phase balanced systems, known as:

- Positive-sequence phase system (rotation order UVW)
- Negative-sequence phase system (rotation order UWV)
- Zero-sequence phase system (three single-phase phases in same direction)

An example of an unbalanced three-phase system, see clause A 13.1.

The symmetrical voltage- and current components in each of these three systems are combined with three corresponding impedances: namely, the positive-sequence impedance, the negative-sequence impedance and the zero-sequence impedance.

For transformers the positive sequence impedence $Z_+$ and the negative impedance $Z_-$ are in general equal. They are also equal to the normal short-circuit impedance, see section 5.

However, the zero-sequence impedance $Z_0$ can differ significantly from the positive sequence impedance, depending on the winding connection and the design (core construction) of the transformer.

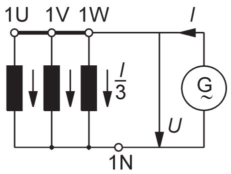



***Figure 12.1:*** *Definition of zero-sequence impedance*

## 12.4 Definition of the zero-sequence impedance

The zero-sequence impedence is the impedence measured between phase terminal and neutral when the three-phase terminals are connected together. The zero-sequence impedence can only develop in star-connected or zig-zag connected windings in three-phase transformers. The zero-sequence impedence to be attributed to each individual phase is three times the measured value.

$$Z_O = 3 \cdot \frac{U}{I}$$

where:

$U_p$ = rated voltage (phase to neutral)

$I$ = current in the neutral

The zero-sequence impedance is normally given as a percent of the base impedance $Z_b$ of the transformer, as is also the case for the normal short-circuit impedance (positive-sequence short-circuit impedance). The base impedance can be deduced as:

$$Z_b = \frac{U_r^2}{S_r} \quad \text{ohm}$$

where:

$S_r$ = rated power

$U_r$ = rated phase-to-phase voltage

The relative zero sequence impedance can be written as:

$$z_0 = \frac{Z_0}{Z_b} \cdot 100 \quad \text{or alt.} \quad z_0 \frac{S_r}{U_r^2} \cdot 100$$

The zero-sequence impedance has two components as does any impedance: the zero-sequence resistance $R_0$ and the zero-sequence reactance $X_0$. In practice, since $R_0 \ll X_0$, the resistive part can be neglected; in other words: the zero-sequence impedance is equal to the zero-sequence reactance.

# 12. Measurement of zero-sequence impedance(s)

For the practical application of the symmetric component method, the directly measured impedances are not used. Instead, those of the equivalent circuit are used, the same as for "normal" short-circuit impedances [106], [107], [108], [204], see figure12.3.

As mentioned above, the zero-sequence impedance depends on the winding connection and the core construction of the transformer.

The different types of zero-sequence impedances are shown in clause A 12.2; the influence of winding connection and design on zero-sequence impedance are in clause A12.3.

## 12.5 Measuring procedure

The general test circuit is shown in figure 12.2; the measurement must be performed at rated frequency [1], [51].

The principal test connections for zero-sequence impedance measurements for different neutral- and network conditions, including the corresponding equivalent circuit for the zero sequence system are given in figure 12.3.

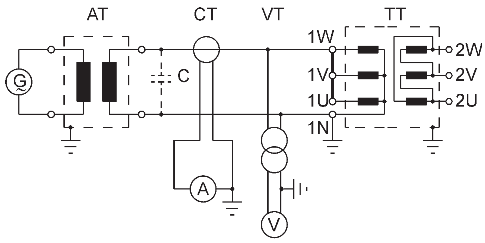
The measurement must always be done with the active part in the tank, because of its  high influence on the zero-sequence impedance ("reactor type"); see example 1 in clause A 12.4.1.

Under conditions where the winding balancing ampere-turns are missing, the relationship between voltage and current is generally non-linear ("reactor type"). In this case several measurements at different values of current may give useful information.

It should also be noted that the zero-sequence flux may cause excessive heating in metallic structural parts such as tank, cover, clamping construction. For this reason the measuring current must not be higher than 30 % of the nominal current $I_r$. Currents up to nominal current are only permitted for a very short time (a few seconds). The applied voltage must not exceed the phase-to-neutral voltage which occurs during normal operation.

For transformers with balanced ampere-turns ("short-circuit type"), the measuring current may be as high as the nominal current. A 13.6  Examples and interpretation.

Applicable examples of zero-sequence measurement for a star-star transformer without delta tertiary ("reactor type") and for a star-delta transformer ("short-circuit type") can be seen in clause A 12.4.




G = voltage source (single-phase)
C = bank of capacitors (eventually necessary for the compensation of the reactive power, can also be placed near the generator terminals)
CT = current transformer
VT = voltage transformer
TT = transformer under test

***Figure 12.2:*** *General measuring circuit for zero sequence impedance measurement; star-star connection for example*

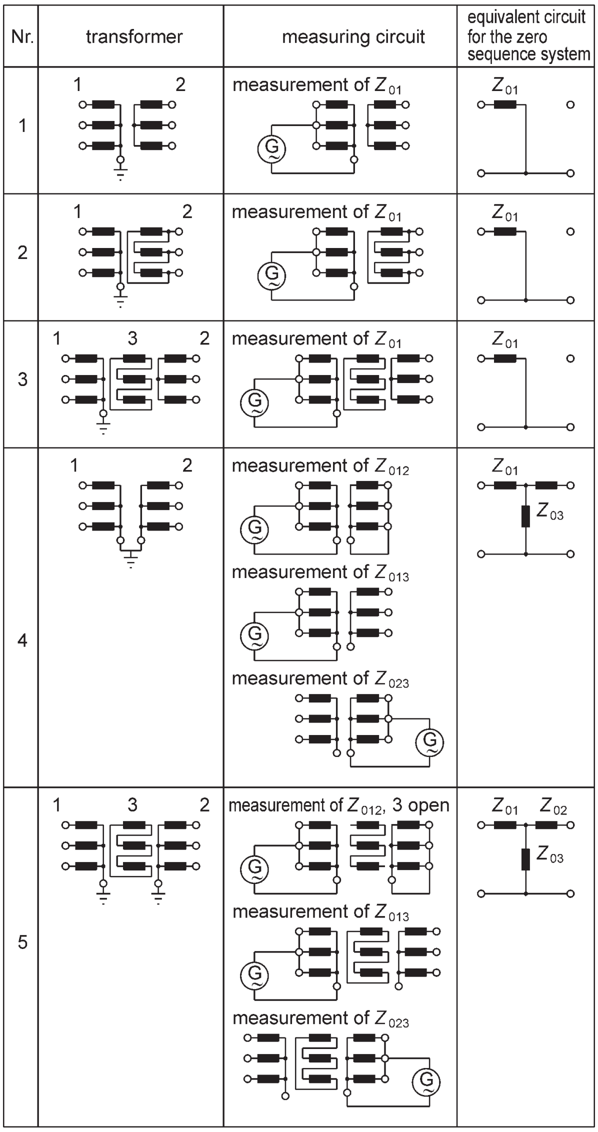



***Figure 12.3 a:*** *Test connections for zero sequence impedance measurement*

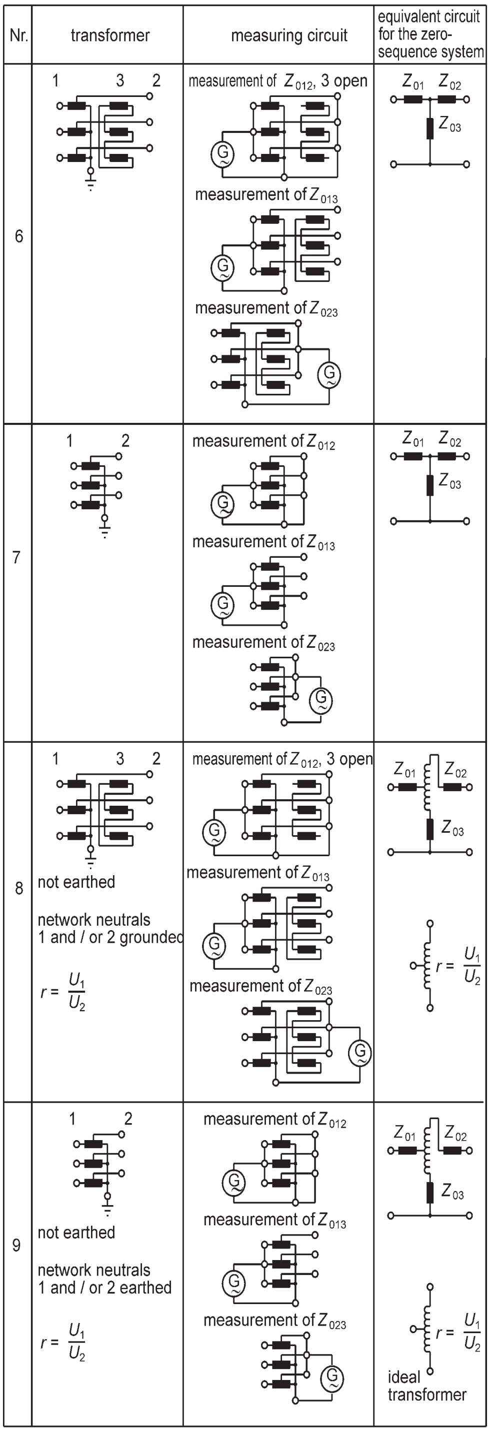



Figure 12.3b - Principal test connections for zero-sequence impedance measurement for different neutral and network conditions with the corresponding equivalent circuit

***Figure 12.3 b:*** *Test connections for zero sequence impedance measurement, continued*

# Appendix A 12

# Measurement of the zero-sequence impedance of three phase transformers

## A 12.1 Example for an unbalanced three-phase system

Figure12.4 shows an example of the composition of the currents in an unbalanced three-phase system comprised of the components of the positive-sequence-, the negative-sequence and the zero-sequence system.

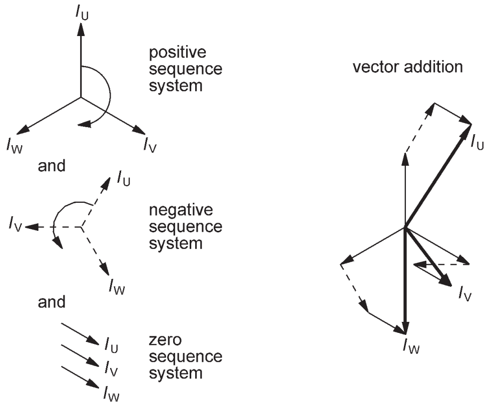



*Figure 12.4:* *Example for an unbalanced three-phase system*

## A 12.2 Types of zero-sequence impedance

The zero-sequence impedance can be measured either as:

- an open circuit zero-sequence impedance (all other winding terminals open), see figure12.5. or
- a short-circuit zero-sequence impedance (terminals of at least one other winding system are short-circuited), see figure 12.6.

A zero-sequence current can circulate in the winding of a transformer with a delta winding, thus balancing the ampere-turns fed into a star connected winding. As seen from the star winding, the delta winding is equivalent to a short-circuited winding for the zero sequence current, see figure 12.7.

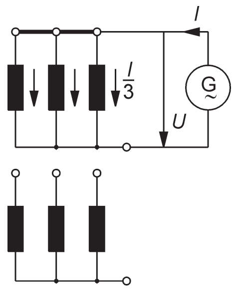



*Figure 12.5:* *Open circuit zero-sequence impendance of a star-star connected transformer*

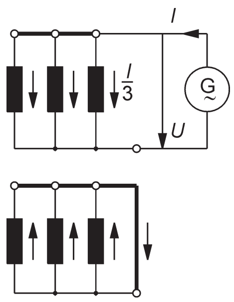



*Figure 12.6:* *Short-circuit zero-sequence impendance of a star-star connected transformer*

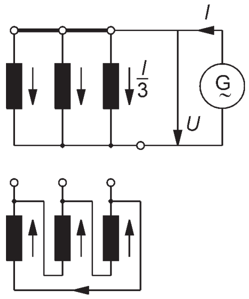
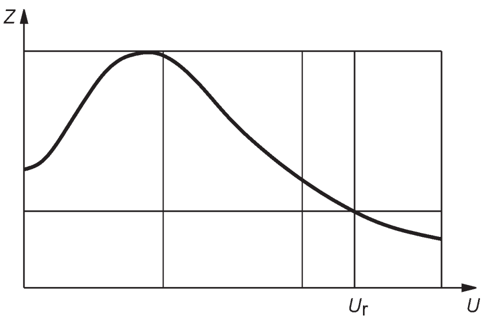
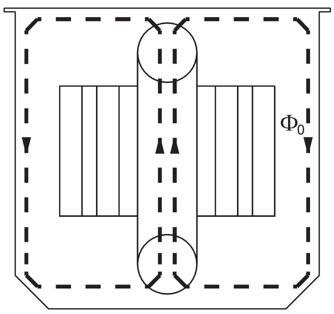



*Figure 12.7:* *Zero-sequence impendance of a star-delta transformer*




$U_r$ = rated voltage

*Figure 12.8:* *Zero-sequence impendance of a star-delta transformer*




$\Phi_0$ = zero-sequence flux; same direction in all three phases

*Figure 12.9:* *Zero-sequence flux in connection with transformer in star-star connection*

Physically, three different types of zero-sequence impedances exist:

a) "no-load type"

The zero-sequence impedance $Z_0$ corresponds to the impedance of a closed magnetic circuit, such as an unloaded transformer. The magnetizing flux circulates almost exclusively in the magnetic circuit and the magnetizing current is minimal (in the order of about 0,1 - 1% $I_r$), $Z_0$ is correspondingly high ($10^4$ – $10^5$) and depends strongly on the supply voltage, see figure 12.8.

b) "reactor type"

The zero-sequence impedance $Z_0$ is similar to the characteristic of an open magnetic circuit, (e.g., like an iron core with air gaps. The magnetizing flux circulates only partly in the iron; its return path is in air. The current input is therefore correspondingly higher. The relative zero-sequence impedance $z_0$ is in the order of about 100%. $Z_0$ is more or less constant as a function of the supply voltage, see example in A 13.4, because the magnetic resistance of the whole circuit depends almost exclusively on the air gaps, and the saturation of the core is insignificant.

c) "short-circuit type"

The zero-sequence impedance is similar to the impedance of a shorted transformer in short-circuit; $z_0$ is in the order of about 10% and is independent of the supply voltage.

## A 12.3 Influence of winding connection and transformer design

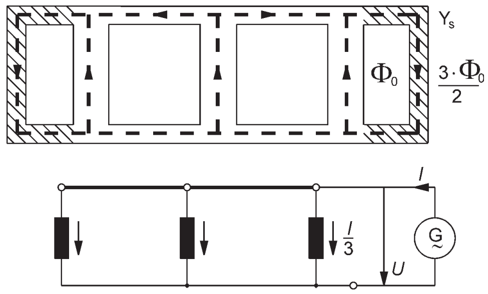
### A 12.3.1 Star-star connection, three-limbed core (core-type transformer)

The magnetizing flux is equal and simultaneous in the three limbs. It must therefore have its return path outside the core via the tank or the magnetic shielding ("reactor type"). There is no ampere-turn balance in the windings. The balancing current in the tank; see figure 12.9. The open circuit zero-sequence impedance $Z_0$ is about 5 to 10 times higher than the short-circuit impedance $Z_1$.

### A 12.3.2 Star-star connection, five-limbed core (core-type transformer)

Normally five-limbed core transformers have a tertiary delta stabilizing winding. When measuring the zero-sequence impedance a balancing current can flow in the tertiary winding (“short-circuit type”). The open circuit zero sequence impedance therefore corresponds to the short-circuit impedance between the fed winding and the tertiary.

In case a tertiary winding does not exist or would – for instance – be open, the value of the zero-sequence impedance depends strongly on the exciting voltage, see figure 12.10. For an exciting voltage up to about 30% of the phase voltage, the open circuit zero sequence impedance is as high as the magnetising impedance. For higher voltages the side limbs and yokes approach full saturation; the open circuit zero-sequence impedance is then similar to A 12.3.1 (“reactor type”).




$\Phi_0$ = zero-sequence flux
$Y_s$ = side yoke

***Figure 12.10:*** *Zero-sequence flux in a three-phase transformer limb core*

### A 12.3.3 Star-delta connection, three-limbed core (core-type transformer)

As shown in figure 12.7, the ampere-turns are completely balanced (“short-circuit type”); the only difference to a three-phase short-circuit impedance measurement is that the stray fluxes in the three phases have the same direction and not a 120° shift. The open circuit zero- sequence impedance $Z_0$ is generally slightly less than the short-circuit impedance $Z_1$, and is about 0,8 - 1,0 $Z_1$.

### A 12.3.4 Star-delta connection, five-limbed core (core-type transformer)

These are similar to A 12.3.3 (“short-circuit type”). As the side limbs are an ideal path for the zero-sequence flux, the open circuit zero-sequence impedance $Z_0$ is identical to the short-circuit impedance $Z_1$.

### A 12.3.5 Three-phase bank of single-phase transformers, star-delta connection (core-type transformers)

These are similar to a three-phase transformer in star-delta connection; the ampere-turns are balanced (“short-circuit type”), see figure 12.11. The zero-sequence impedance is identical to the short-circuit impedance.

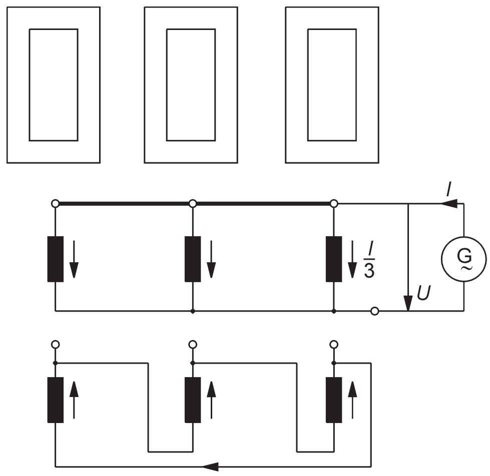



***Figure 12.11:*** *Zero-sequence flux in a three-phase bank single-phase transformer*

### A 12.3.6 Three-phase bank of single-phase transformers, star-star connection (core type transformers)

Three-phase banks in star-star or auto-connection normally have a tertiary delta stabilizing winding. The zero-sequence impedance is therefore identical to the short-circuit impedance between the fed winding and the tertiary (“short-circuit type”).

In the case of an open or non-existing tertiary winding, the transformer behavior is the same as for no-load operation without ampere-turns balancing (“no-load type”). The zero-sequence impedance is equal to the no-load impedance; i.e $z_0 \approx 10^4$ - $10^5$.

### A 12.3.7 Star-delta connection (shell-type transformer)

Similar to the five-limbed core transformer in star-delta connection, the zero-sequence flux will have its return path via the yokes (“short-circuit type”); the open circuit zero-sequence impedance $Z_0$ is therefore identical to the short-circuit impedance $Z_1$.

### A 12.3.8 Star-star connection (shell-type transformer)

Star-star connected shell-type transformers normally have a tertiary delta stabilizing winding; in this case the transformers behave like a transformer in star-delta connection (“short-circuit type”).

In case a tertiary winding does not exist, the open circuit zero-sequence impedance depends strongly on the exciting voltage.

For the zero-sequence impedance measurement, the flux in the cores and the intermediate yokes is the same. If the zero-sequence voltage proves to be higher than half the nominal phase voltage, the intermediate yokes are saturated and unable to conduct the zero-sequence flux. The transformer behavior is similar to that described under A 12.3.2 for a five-limbed core transformer without tertiary (“reactor type”).

It should be pointed out that the zero-sequence current is not equal in the three-phases; higher values are always measured in the medium-limb; with a distribution about 0,3 :0,4 :0,3.

## A 12.4 Examples and interpretation

### A 12.4.1 Three-phase transformer in star-star connection without tertiary ("reactor type")

Three-phase transformer rated 100 MVA, 259,05 ± 15 % / 55 kV, 50 Hz, (tank without magnetic shielding); YNyn0 connection, transformer neutrals in accordance with figure 12.3a, No. 4.

- Measurement of $z_{012}$ "Short-circuit zero-sequence impedance"

| $U$ [V] | $I$ [A] | $Z_0$ [Ω] | $z_{012}$ [%] |
|---|---|---|---|
| 5208 | 223 | 70,1 | 10,45 |
| 4680 | 200 | 70,1 | 10,45 |
| 4240 | 180 | 70,6 | 10,52 |
| 3192 | 135 | 70,9 | 10,57 |
| 2160 | 90 | 72,0 | 10,73 |
| 1100 | 45 | 73,4 | 10,94 |

$$Z_O = 3 \cdot \frac{U}{I}$$

At $I_r$ = 222,9 A → $z_{012}$ = 10,45 %

- Measurement of $z_{013}$ "open circuit zero-sequence impedance"

| $U$ [V] | $I$ [A] | $Z_0$ [Ω] | $z_{013}$ [%] |
|---|---|---|---|
| 9320 | 75 | 372 | 55,43 |
| 7680 | 60 | 384 | 57,22 |
| 5960 | 45 | 398 | 59,31 |
| 4120 | 30 | 412 | 61,39 |
| 2168 | 15 | 433 | 64,52 |
| 1168 | 8 | 437 | 65,12 |

$z_{013}$ at 0,3 $I_r$ (74,3 A) = 55,4 %

- Measurement of $Z_{023}$ "open circuit zero-sequence impedance"

| $U$ [V] | $I$ [A] | $Z_0$ [Ω] | $z_{023}$ [%] |
|---|---|---|---|
| 3212 | 480 | 20,1 | 66,44 |
| 2580 | 380 | 20,4 | 67,44 |
| 1960 | 280 | 21,0 | 69,42 |
| 1444 | 200 | 21,6 | 71,57 |
| 730 | 96 | 22,8 | 75,37 |
| 389 | 50 | 23,4 | 77,36 |

$z_{023}$ at 0,3 $I_N$ (350 A) = 69 %

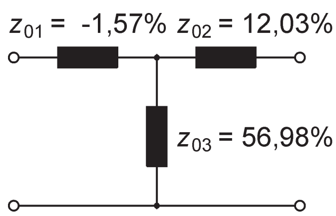



*Figure 12.12: Equivalent circuit in the zero-sequence system of a 100 MVA star-star transformer*

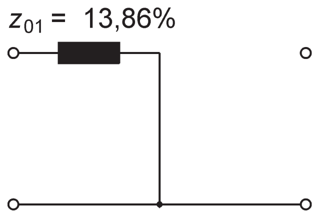



*Figure 12.13:* *Equivalent circuit in the zero-sequence system of a 465 MVA star-delta transformer*

For the equivalent circuit in a zero-sequence system, see figure12.12.

$Z_{012}$ = 10,45 %
$Z_{013}$ = 55,40 %
$Z_{023}$ = 69,00 %

134,85 %

134,85 / 2 = 67,43 %

$z_{01}$ = 67,43 - 69,0 = -1,57 %
$z_{02}$ = 67,43 - 55,4 = 12,03 %
$z_{03}$ = 67,43 -10,45 = 56,98 %

For the impedance calculation, see section 5.

The zero-sequence impedances for the same transformer were measured once outside the tank and once again in the tank equipped with magnetic shielding:

- Measured zero-sequence impedances outside the tank:
  $Z_{012}$ = 11,5 % measured with $I_r$ at the neutral
  $Z_{013}$ = 97,0% measured with 0,3 $I_r$ at the neutral
  $Z_{023}$ = 109,0 % measured with 0,3 $I_r$ at the neutral
- Measured zero-sequence impedances in the tank, with magnetic shielding:
  $Z_{012}$ = 12,1 % measured with $I_r$ at the neutral
  $Z_{013}$ = 109,0 % measured with 0,3 $I_r$ at the neutral
  $Z_{023}$ = 116,0 % measured with 0,3 $I_r$ at the neutral
- For comparison, short-circuit impedance:
  $\varepsilon_{cc}$ = 12,8 % at $I_r$

## A 12.4.2 Three-phase transformer in star-delta connection (“short-circuit type”)

Three-phase transformer rated 465 MVA, 410 /21 kV, 50 Hz, Ynd11 connection, transformer neutral in accordance with figure 12.3a, No. 2.

See figure 12.13

| $U$ [V] | $I$ [A] | $Z_0$ [Ω] | $z_{01}$ [%] |
|---|---|---|---|
| 1042 | 62,4 | 50,07 | 13,86 |

for comparison, short-circuit impedance:
$\varepsilon_{cc}$ = 14,1 % at $I_r$

# Testing of Power Transformers

## 13. Short-circuit withstand test

# 13. Short-circuit withstand test

## 13.1 References / Standards

- IEC 60076-5 (2000), Power transformers - Part 5: “Ability to withstand short-circuit” [5]
- IEEE Std C57.12.00-2000: “IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating” [50]
- IEEE Std.C57.12.90 - 1999, “IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers” clause 12 “Short-circuit tests” [51]

**Note:**
The short-circuit withstand test is a **special test** or an **“other” test**, both according to IEC 60076-1 [1] and - 5 [5] and IEEE Std.C5712.00 [50].

## 13.2 Purpose of the test

The short-circuit test is carried out to verify the integrity for stresses, primarily mechanical, developed when a short-circuit current flows through the transformer.

## 13.3 General

The short-circuit withstand test is the only test in this booklet which is *not* performed in the manufacturer‘s test laboratory. There is a need for a high test field power, especially for large units with ratings of 100 MVA and above. The tests can only be performed at a few powerful test stations, such as those operated by KEMA (Netherlands), EdF (France), CESI (Italy) or IREQ (Canada).

Short-circuit tests are expensive. Not only is the cost of the test itself high, but also activities such as transport to and from the factory, local installation at the test laboratory and again at the factory, untanking and inspection, repetition of dielectric tests, etc. For this reason the IEC Standard also permits demonstration of the short-circuit ability using calculation and design considerations [5].

The choice of demonstration methods to be used is subject to agreement between the purchaser and the manufacturer prior to placing the order as it is for all special tests [1], [5].

Applicable Standards subdivide transformers into categories, according to their rated power:

According to IEC 60076-5 [5]:

- Category I: up to 2500 kVA
- Category II: 2501 - 100 000 kVA
- Category III: above 100 000 kVA

According to IEEE Std C57.12.90 [51]

- Category I: up to 500 kVA
- Category II: 501 - 5 000 kVA
- Category III: 5001 - 30 000 kVA
- Category IV: above 30 000 kVA

## 13.4 Test conditions, testing techniques and test connections

### 13.4.1 Test conditions

The tests must be carried out on a new transformer ready for service; protection accessories such as the Buchholz relay and pressure relief device must be mounted.

Routine tests must be conducted on the transformer prior to the short-circuit test (with the exception of the lightning impulse test, if applicable).

If windings have tappings, the reactance and resistance must be measured for the tapping positions at which the short-circuit test will be carried out [5].

### 13.4.2 Testing techniques

There are basically two different techniques for carrying out a short-circuit withstand test; namely:

- with a post-established short-circuit

  (closing a breaker at the faulted terminals to apply a short-circuit to the energized transformer)

- with a pre-established short-circuit

  (closing a breaker at the source terminals to apply energy to the short-circuited transformer)

The post-established short-circuit method should be used as far as possible, since it more closely represents the typical condition during faults.

For advantages and disadvantages of the two methods, see clause A 13.4 and [105].

### 13.4.3 Test connections

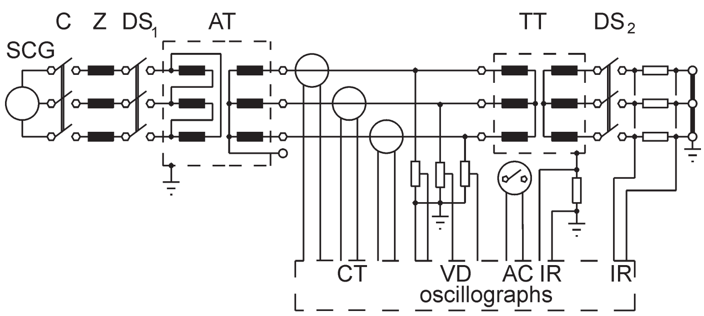
Figure 13.1 shows the basic test circuit for a short-circuit test (two-winding transformer, three-phase power supply).

Depending on the method chosen, either $DS_1$ or $DS_2$ is used to establish the short-circuit.

A three-phase supply should be used for three-phase transformers, as far as possible. The above standards give examples for single-phase arrangements simulating the three-phase test, see clause A 13.2.

For transformers with more than two windings or for auto-transformers, it should be pointed out that a given fault type and location will not produce the maximum fault current in more than one winding. It will therefore be necessary to perform tests with different connections to fully evaluate the capability of all windings [51].

The test connections, the current values, the sequence and the number of tests are always subject to agreement between the manufacturer and the purchaser. [5]




SCG = short-circuit generator
C = synchronized energizing circuit-breaker
Z = adjustable reactors
$DS_{1,2}$ = synchronized making switch
AT = testing transformer
TT = transformer under test
CT = current transformers
VD = voltage driver
IR = measuring shunts
AC = alarm-and trip contacts

***Figure 13.1:*** *Basic test circuit for a short-circuit test*

### 13.4.4 Test requirements

**Test current: (two-winding transformer)**

**Symmetrical short-circuit current**

Clause A 13.3 gives the calculation of the r.m.s. value of symmetrical short-circuit current according to IEC 60076-5 [5], clause 4; the same calculation is shown in IEEE Std C57.12.00 [50].

As can be seen in clauses A 13.3 and A 13.4 of the appendix, the effect of the short-circuit impedance of the system must always be taken into consideration, with the following exceptions:

- according to IEC [5], transformers ≤ 2,5 MVA (IEC-Category I), if the system impedance is equal to or less than 5 % of the transformer impedance.
- according to IEEE [51], all transformers ≤ 5 MVA (IEEE-Category I and II)

Unless otherwise specified, the system short-circuit apparent power to be used according to IEC is indicated in table 2 of IEC 60076-5 [5], and according to IEEE in table 16 of IEEE Std C57.12.00 [50].

#### Asymmetric test current peak $\hat{\imath}$

The test must be performed with the current having maximum asymmetry with respect to the phase under test.

Amplitude $\hat{\imath}$ of the first peak of the asymmetrical test current is calculated as follows:

$$\hat{\imath} = I \cdot k\sqrt{2}$$

The factor $k\sqrt{2}$, or peak factor, depends on the ratio $X/R$:

where:

$X$ = sum of the reactances of the transformer and the system

$R$ = sum of the resistances of the transformer and the system.

For power transformers the order is 2,55 - 2,80. The well-known value of 2,55 corresponds to a $X/R$- ratio of 14. The exact values for $k\sqrt{2}$ are given in table 4 of IEC Standard 60076-5 [5], and in table 15 of IEEE Std C57.12.00 [50].

#### Tolerances

If the duration of the short-circuit current is sufficiently long, the asymmetrical current with initial peak amplitude $\hat{\imath}$ will change to symmetrical current $I$.

- The peak value of the current $\hat{\imath}$ maximum deviation of 5 %
- The symmetrical current $I$ maximum deviation of 10 % according to IEC [5], and 5 % according to IEEE [51]

#### Test frequency [5]

In principle the frequency of the test supply has to be the rated frequency. For exceptions see IEC 60076-5 [5], clause 4.2.5.3.

### 13.4.5 Testing procedure

The moment of switching-in is adjusted by means of a synchronous switch to obtain the maximum asymmetrical current wave in the phase under test. In order to obtain the maximum asymmetry of the current in one of the phase windings, switching-in must occur at the moment the voltage applied to this winding passes through zero [5].

#### Calibration [51]

Calibration tests should be conducted to establish the required source voltage or switch closing times at voltage levels not greater than 50 % of the value that would produce the required symmetrical short-circuit current.

**Voltage limits** [5], [51]

If the post-established short-circuit method is used, the voltage must not exceed 1,15 times (according to IEEE 1,10 times) the rated voltage of the winding.

**Current and voltage measurements**

Oscillographic recordings must be taken in order to check the value of the asymmetrical test current $\hat{\imath}$ and of the symmetrical short-circuit current.

The primary currents are measured using special current transformers, which are able to transmit transient phenomena without distortion. The secondary currents – at the earthed and short-circuited side of the transformer under test – are measured by means of special shunts, while the voltage at the transformer under test is determined using $RC$ potential dividers, see figure 13.1.

**Tapping position; number of tests; test duration**

**According to IEC 60076-5 [5]:**

For categories I and II:

IEC specifies three asymmetrical shots per phase. This means a total of 9 for a three-phase transformer. For tapped windings, one shot in the position corresponding to the highest voltage ratio, one shot on the principal tapping and one shot in the position corresponding to the lowest voltage ratio are specified. Each shot must have a duration of 0,5 seconds and 0,25 seconds for transformers in categories I and II respectively.

For category III - transformers, IEC 60076-5 [5] proposes conducting the test with a duration of 0,25 seconds as for transformers in categories I and II,  but after agreement between manufacturer and purchaser concerning the number of tests and the position of the tap changer.

**According to IEEE Std C57.12.90 [51], [50]:**

IEEE specifies six shots per phase, four of which are with symmetrical current and two with the asymmetrical peak. The duration of the shots for all categories is 0,25 seconds for the asymmetrical current test, and for the symmetrical current test in category IV. For categories II and III, the symmetrical current test is to have a duration of 1 second and 0,5 seconds respectively.

For transformers with tapped windings, at least one test satisfying the asymmetrical current requirements shall be made on that tap position where calculation predicts  the most severe mechanical stresses.

### 13.4.6 Detection of faults and evaluation of test results [5], [51], [105]

The detection of faults and evaluation of the test results are primarily based on current and voltage oscillographic recordings, combined with additional measurements and tests. Finally, a visual inspection is conducted on the transformer active part removed from the tank.

The following conditions must be met to prove satisfactory performance:

- no abrupt changes or anomalies in the voltage and short-circuit current oscillographic recordings
- no abnormal phenomena observed during the test, nor any gas in the gas- and oil- activated relay(s)
- the difference between the short-circuit impedance (per phase) measured before and after the test is < 2 % for circular concentric coils or < 7,5 % for non-circular concentric coils
- < 1 % for category IV transformers according to IEEE Std C57.12.00
- a successful repetition of dielectric tests
- the difference between the no-load current measured before and after the test < 5 % [5]
- additional measurements, such as low-voltage recurrent surge oscillographic recordings, see appendix, clause A 13.5, analysis of winding frequency response spectrum, transfer function analysis (FRA), etc. do not show abnormalities
- no abnormalities in gas-in-oil analysis (DGA) before and after test [5]
- the out-of-tank inspection does not reveal any defects such as displacements, deformation of windings, etc.
- no traces of electric discharge

# Appendix A 13:
# Short-circuit withstand test

## A 13.1 The difference between post-established and pre-established short- circuit [105]

The *pre-established* short-circuit method works well when the secondary winding (short- circuited) is an inner winding of a concentric winding, core-type transformer. During the short-circuit, the core flux is very low, because the closest winding to the core is being short-circuited and no change in flux occurs.

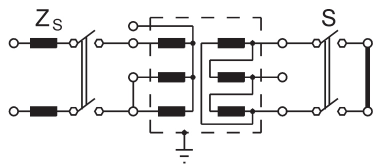
However, if the primary is an inner winding and the short-circuited winding is an outer one, the magnetic flux is forced to re-close inwards, resulting in a high inrush current to magnetize the core. This current is superimposed on the short-circuit current, which produces increased dynamic stresses [105].

The difficulty of uncontrolled magnetization of the core is avoided by using the *post-established* short-circuit method. This method is therefore preferred.

## A 13.2 Examples for single-phase test connections simulating the three-phase test

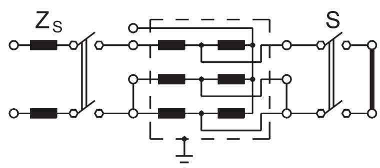
Figure 13.2 shows possible single-phase test connections for simulating a three-phase test for a star-delta transformer. Figure 13.3 shows those for a star-star autotransformer [5].

For star-connected windings with non-uniform insulation, it is necessary to check whether or not the insulation of the neutral is sufficient for single-phase testing.




$Z_S$ = test system impedance
S = synchronous switch for post-established short-circuit or rigid bar for pre-established short-circuit

***Figure 13.2:*** *Single-phase test connection simulating a three-phase test for a star-delta transformer*




$Z_S$ = test system impedance
S = synchronous switch for post-established short-circuit or rigid bar for pre-established short-circuit

***Figure 13.3:*** *Single-phase test connection simulating a three-phase test for a star-star autotransformer*

## A 13.3 The calculation of the symmetrical short-circuit current according to IEC 60076-5 [5]

For three-phase transformers with two separate windings, the r.m.s.-value of the symmetrical short-circuit current $I$ is: [5]

$$I = \frac{U}{\sqrt{3}\left(Z_t + Z_S\right)}$$

$$Z_S = \frac{U_S^2}{S} \qquad [\Omega/\text{phase}]$$

where:

$Z_S$ = short-circuit impedance of the system
$U_S$ = is the rated voltage of the system in kV
$S$ = is the short-circuit apparent power of the system, in MVA

$U$ and $Z_t$ are defined as follows:

$U$ is the rated voltage of the winding under consideration, or the tapping voltage, if the test is being performed for a tapping other than the principal tapping.

$Z_t$ is the short-circuit impedance of the transformer referred to the winding under consideration; it is calculated as follows:

$$Z_t = \frac{z_t \cdot U_r^2}{100 \cdot S_r}$$

where:

$z_t$ = is the measured short-circuit impedance referred to the winding under consideration in %
$S_r$ = is the rated power of the transformer in MVA

## A 13.4 The calculation of the symmetrical short-circuit current $I_{SC}$ according to IEEE Std C57.12.00 [50]

$$I_{SC} = \frac{I_r}{Z_T + Z_S}$$

where:

$I_{SC}$ = symmetrical short-circuit current

$I_r$ = rated current at the given tap connection

$Z_T$ = transformer impedance [pu], based on using $I_r$ as power base

$Z_S$ = system impedance [pu], based on using $I_r$ as the power base

$$I = \frac{I_{SC}}{I_r}$$

$I$ = symmetrical short-circuit current in multiples of normal base current

## A 13.5 Low-voltage recurrent-surge oscilloscope method

LV impulse measurements are performed as an additional diagnostic test in order to detect shifting and/or deformations of the transformer due to short-circuit forces.

**Principle:**

A recurrent surge generator applies a voltage pulse to one or more terminals of the transformer and the current response at the same or other terminals is recorded; see figure 13.4.

Normally a reference set of three oscilloscope readings is taken (one for each phase) prior to the test. After the test a new set of records is taken, see figure 13.5.

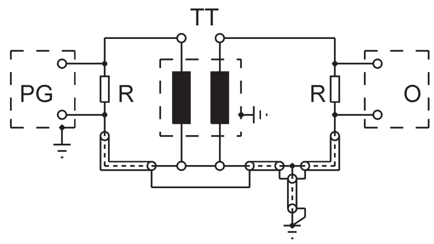



***Figure 13.4:*** *Schematic diagram of the recurrent-surge oscillographic method*

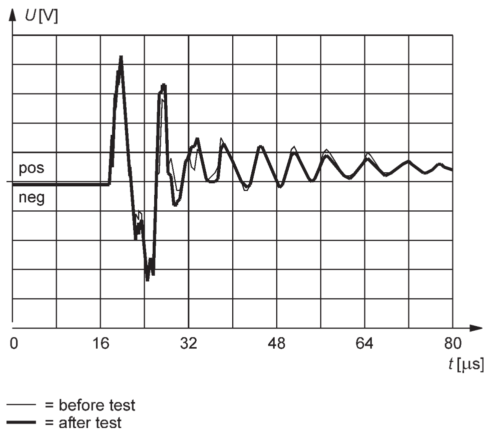



***Figure 13.5:*** *Comparison of the record taken after short-circuit test with reference prior the short-circuit test; three-phase transformer 50 MVA; phase 1*

# Testing of Power Transformers

## 14. Sound level measurement

# 14. Sound level measurement

## 14.1 References / Standards

- IEC 60076-10 (2001) Power transformers - Part 10: "Determination of sound levels" [7]
- IEC 60076-10 Power transformers - Part 10-1: Draft: "Determination of transformer and reactor sound levels" - User Guide [30]
- IEEE Std C57.12.90 - 1999, clause 13: "Audible sound emissions" [51]

**Note:**

The sound level measurement is a **special test** according to IEC 60076-1 [1] and a **design test** or an **"other" test** according IEEE Std C57.12.00 [50].

## 14.2 Purpose of measurement

As electric installations are installed ever closer to densely populated areas, there is increased concern about sound and emissions from transformers.

Operating transformers generate sound, or more correctly noise, whereby noise is defined as unwanted sound. To protect the population from noise inconveniences, rules and regulations exist in most countries requiring electric components – e.g. transformers – to operate within specified noise limits.

For this reason knowledge of the audible sound emissions from a transformer is highly important.

For a detailed evaluation and a study of sound reduction – either with passive elements like walls or active methods like active noise cancellation – a narrow band measurement [7], [51] is a must.

## 14.3 **General** [7], [51], [106]

It should be pointed out that noise is a subjective phenomenon involving the diversity of human nature. For information about human sound perception, see clause A 14.1.

Contrary to the majority of other tests described in this test book, the corresponding standards (see clause 14.1) specify exactly how to perform this test and give additional information; specially IEC 60076-10 [7], in an extensive 35 page pamphlet.

It is not the intention of this booklet to repeat the contents of the standards, but to summarize the most important items and to give some additional information based on our experience.

### 14.3.1 Sources of transformer sound

**No-load sound** (noise from the core)

Transformer no-load sound is caused by magnetostriction (elastic length variations of iron core parts) generated during the magnetizing process. The oscillations are transferred by the oil and the mechanical supports as mechanical vibrations to the tank walls and radiated to open air. The vibration amplitude depends on the flux density in the core and the magnetic properties of the core steel.

The frequency spectrum of the audible sound consists mainly of twice the rated frequency and its even multiples; in a 50 Hz power system, the audible sound consists of the harmonics 100 Hz, 200 Hz, 300 Hz, 400 Hz, etc.

Depending on the type of cooling, pump and fan noises are added (noise from fans).

Normally only no-load sound levels are measured.

**Load sound** (noise from the windings)

Due to its magnetic forces load current generates vibrations in the winding, tank wall and magnetic shields. In the case of modern transformers (low induction), this noise may be louder than the no-load sound.

The load sound power is strongly dependent on the load current, see clause A 14.2.

Measurements of load sound are mentioned in the IEC Standards, but not in the IEEE Standards.

### 14.3.2 Addition of no-load and load-sound

See clause A 14.3.

### 14.3.3 Definitions of important terms

For definitions of sound pressure, sound power and sound intensity, prescribed contour and background level, see clause A 14.4.

## 14.4 Measurement and measuring circuit

Sound level is measured as sound pressure level or as normal sound intensity level, which is only specified in IEC [7]: Normally, “conventional” A-weighted sound pressure level measurements are carried out.

Sound intensity level measurements are used in special cases, where a plurality of sound sources are present which would make difficult or even impossible a conventional measurement. For instance if the difference in the specified sound level and the background is less than 3 dB [30], [7]. They will not be treated here. (see IEC 60076-10, clause 12 [7] and IEC 60076-10-1 Draft: User guide [30] in clause 5.3).

According to IEC [7], the test object must be energized as agreed by the manufacturer and the purchaser. The word “energized” means either no-load or load condition; the permissible combinations are:

- transformer energized, cooling equipment and any pumps out of service
- transformer energized, cooling equipment and any pumps in service
- transformer energized, cooling equipment out of service, pumps in service
- transformer not energized, cooling equipment and any pumps in service

IEEE [51] states that the cooling equipment shall be operated as appropriate for the rating being tested.

For the measurement of the no-load noise (sound pressure level according to IEC and to IEEE or sound intensity level measurement according IEC), the measuring circuit is similar to that for no-load loss measurement; the voltage must be adjusted with average voltmeters (see section 6).

For the measurement of load-noise according to IEC [7], the measuring circuit is similar to that for load-loss measurement (see section 5). To obtain the total sound level, the load-noise has to be added to the no-load sound using the equations given in clause A 14.3.

For the position of the microphones, see section 3.5.5 and IEC [7], IEEE [51].

## 14.5 Measuring procedure

### 14.5.1 Important general remark

When performing this test, contrary to other tests, it is unavoidable that test laboratory staff work close to the transformer under test.

Therefore, every possible precaution must be taken to ensure that personnel or microphones do not come too close to high voltage parts. It is recommended that one person be dedicated to safety procedures during the measurements. In order to maintain safety clearances, measuring points may need to be modified.

### 14.5.2 Test environment

The transformer under test must be placed as far as possible from reflecting walls or other equipment to minimize reflections and standing waves. Locating the transformer tank walls parallel to the walls of the test laboratory or other objects should be avoided.

The transformer must be installed on its original wheels or skids. If the wheels cannot be installed, the supports have to be attached to the wheel installation points; the distance to the floor (or to a possible transport platform) must not be less than in normal operation.

### 14.5.3 Test conditions

If a matching transformer is used to adjust the voltage between the generator and transformer under test, and this transformer is also situated in the test laboratory, an appropriate test connection should be chosen for this transformer to achieve a low induction and, consequently, a low noise level.

It is important that the excitation voltage is sinusoidal and kept at nominal magnitude and rated frequency during the entire measurement (or the load current at load sound level measurements).

It is also important to allow enough time for any DC magnetization to decay before starting the test, because the remaining DC flux causes odd harmonics in the sound spectrum and increases the total sound level by several dB. The time may be about 10 - 20 minutes for medium size power transformers and for a large five limb power transformer it may take several hours.

### 14.5.4 Measurement points and instruments

#### According to IEC 60076-10 [7],[30]

Natural air cooling (or forced air cooling out of service):

– Prescribed contour must be spaced 0,3 m from the principal radiating surface.

Forced air cooling:

– Prescribed contour must be spaced 2 m from the principal radiating surface.

  For transformer tank height < 2,5 m:
  measurements must be conducted at half the tank height.

  For transformer tank height ≥ 2,5 m:
  measurements must be conducted at 1/3 and 2/3 of the tank height.

The microphone positions has to be on the prescribed contour, approximately equally spaced and not more than 1 m apart; (see IEC 60076-10, figure 1 - 5 [7]) and figure 14.1.

The measurement must be made by using a type 1 sound level meter complying with IEC 60651 [31] and calibrated in accordance with clause 5.2 of ISO 3746 [70].

# 14. Sound level measurement

### According to IEEE Std C57.12.90 [51]

Natural cooling:

– Measuring surface must be spaced 0,3 m (1 ft) from the reference sound producing surface.

Forced cooling:

– Measuring surface must be spaced 2 m (6 ft) from any position of the radiators, cooler, or cooling tubes cooled by forced air (see IEEE Std C57.12.90, figure 29)

For transformer tank height < 2,4 m (7,2 ft) : measurements must be conducted at half the tank height.

For transformer tank height ≥ 2,4m (7,2 ft): measurements must be conducted at 1/3 and 2/3 of the tank height.

The microphone positions have to be on the measuring surface (prescribed contour) approximately spaced and not more than 1 m apart (see IEEE Std C57.12.90, figure 29 [51])

The measurement must be made with instrumentation that meets the requirements of ANSI S1.4-1983 [59] for Type 1 meters.

### Calibration

The measuring equipment has to be checked with a calibrator immediately before and after the measurements. If the deviation is more than 0,3 dB according to IEC [7] or 1 dB according to IEEE [51], the measurements must be declared invalid.

### Corrections due to undesired sound reflections (only IEC [7])

IEC 60076-10 defines an environmental correction factor $K$, which takes into consideration undesired reflections, see clause A 14.5.

IEEE Std C57.12.90 [51] does not permit any environmental corrections. It is stated that no acoustic reflecting surface must exist 3 m from the microphone other than the floor.

### Measurement of the background noise level

The A-weighted sound pressure level of the background must be measured immediately before the measurements on the transformer under test. The height(s) of the microphone(s) has to be the same as for the transformer measurement. The background measurements must be taken at points of the prescribed contour.

The background level is the arithmetic average of these measurements, if the variation of the measured background levels is 5 dB or less (according to IEC [7]) or 3dB (according to IEEE [51]).

Otherwise the following equation must be used:

$$L_{bg} = 10 \cdot \log_{10}\left(\frac{1}{M}\sum_{i=1}^{M} 10^{0,1 L_{bgi}}\right)$$

where:

$L_{bg}$ = average background sound pressure level

$M$ = number of background measuring points, between 1 and 10, according to IEC [7], clause 11.2 or at least 4, according IEEE [51]

$L_{bgi}$ = measured background sound pressure level at measuring point $i$

### Test sequence

Immediately after the background measurements, the A-weighted sound pressure level measurements must be carried out for each measuring position. The fast response indication of the meter must be used to identify and avoid measurement errors due to transient background noise.

The uncorrected average A-weighted sound pressure level $\overline{L_{pA0}}$ must be calculated from the measured sound pressure levels $L_{pAi}$.

If the range of these measured values $L_{pAi}$ does not exceed 5 dB (or 3 dB according to IEEE [51]) a simple arithmetical average may be used. Otherwise the following equation is valid:

$$\overline{L}_{pA0} = 10 \cdot \log_{10}\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0,1 L_{pAi}}\right)$$

where:

$L_{pA0}$ = uncorrected average sound pressure level

$N$ = number of measuring points

$L_{pAi}$ = measured sound pressure level at measuring point $i$

After the measurement, a second background measurement must be carried out.

IEC 60076-10 [7] states that the test is valid, if the difference between initial and final background level is below 3 dB. For more details see clause 11.3 of [7], which also discusses the validity of tests with a difference between the specified sound level and the background of less than 8 dB.

The corrected average A-weighted sound pressure level $\overline{L_{pA}}$ must be calculated using the following equation:

$$\overline{L_{pA}} = 10 \cdot \log_{10}\left(10^{0,1\overline{L_{pA0}}} - 10^{0,1\overline{L_{bgA}}}\right) - K$$

IEEE Std C5712.90 [51] does not allow any environmental correction factor, but specifies correction factors if the difference between the combined transformer plus ambient sound pressure level and the ambient sound levels is equal to or less than 10 but more than 5 dB; see table 8 in clause 13.3.1 of IEEE Standard [51].

### Calculation of sound power level

Sometimes the sound power level for a transformer is the guarantee value; it can be calculated from the corrected average sound pressure level $\overline{L_{pA}}$ using the following equation:

$$L_{wA} = \overline{L_{pA}} + 10 \cdot \log_{10} \frac{S}{S_0}$$

where

$S$ = the measurement surface in m$^2$, calculated according to the formulas given in clause A 14.5.

For an example, see clause A 14.6.

### Far-field calculations and measurements

For far-field calculations, see clause A 14.7.

There are customers who require compliance with specific noise levels at the boundary of the installation or site.

When performing field sound level measurements, attention should be paid to different influencing parameters such as: load power factor, load current, operating voltage possible load current and voltage harmonics, DC magnetization etc. etc.

The background level is not easy to control, even if these measurements are carried out at night with only little traffic noise and other noise emissions due to meteorological conditions like wind or rain, noises of animals, birds or insects.

## 14.6 Measuring uncertainties

If the measuring equipment is treated correctly according to the standards, the measuring uncertainty should be less than 1 dB.

But the following parameters may strongly influence the measuring uncertainty:

- voltage adjustment: 1 % voltage variation results in an error of 0,5 dB for inductions of about 1,6 T, 1 dB for inductions of around 1,8 T
- frequency adjustment: 1 Hz variation leads to 0,4 dB error
- harmonics in the excitation voltage
- possible remaining DC magnetization in the core (up to 3 dB if starting the test too early)
- error in measuring distances
- distance too small between tank bottom and floor (sound increase up to 4 dB)
- reflection from test field wall (especially important for measurement according to the IEEE standard, which does not allow any environmental correction)
- too small a difference between background level and transformer sound

# Appendix A 14: Sound level measurement

## A 14.1 Human perception of sound [106]

Human perception is more logarithmic than proportional. A tenfold increase in sound intensity is perceived as a twofold increase. It is also frequency dependent, with a pronounced maximum at about 1000 Hz. Frequencies below and above the 1000 Hz level are perceived as being less loud than those having the same sound pressure level as the 1000 Hz wave.

In order to facilitate the handling of the wide range in numerical value of sound intensity, the absolute value is replaced by its logarithm. The logarithm (base $\log_{10}$) is generally called Bel or decibel (one tenth the figure in Bel), abbreviated as [dB]. The most frequently used weighting rule is denoted as dB(A). The dB(A) weighting is adjusted to 40 dB, i.e. at a level of a typical background noise. It has zero relative reduction at 1000 Hz and about 20 dB reduction at 100 Hz, taking into account the fact that human perception depends on noise level as well as on frequency.

## A 14.2 Estimating load-sound power level, and the influence of the load [7]

In order to decide whether a load-sound measurement will be significant, the magnitude of load-sound power level can be roughly estimated using the following equation:

$$L_{WA,IN} \approx 39 + 18 \cdot \log_{10} \frac{S_r}{S_p}$$

where:

$L_{WA,IN}$ = the A-weighted sound power level of the transformer at rated current

$S_r$ = the rated power in MVA

$S_p$ = the reference power (1 MVA)

An example for a transformer rated 250 MVA is:

$$L_{WA,IN} \approx 39 + 18 \log_{10} 250 \approx 82 \text{ dB}$$

If $L_{WA,IN}$ is found to be 8 dB or more below the guaranteed sound power level, load-sound measurements are not appropriate.

If the measurement can only be performed at a reduced current $I_R$, the sound power level at rated current $I_r$ must be calculated by adding

$$40 \cdot \log_{10} \frac{I_r}{I_R}$$

## A 14.3 Addition of no-load sound and load sound [7]

According to IEC 60076-10 [7], the two sound levels can be measured separately and added by calculation in order to provide the total sound power level during operation.

$$L_{WASN} = 10 \cdot \log_{10}(10^{0.1 L_{WAUN}} + 10^{0.1 L_{WAIN}})$$

where:

$L_{WASN}$ = the A-weighted sound power level of the transformer at sinusoidal rated voltage and sinusoidal rated current

$L_{WAUN}$ = the A-weighted sound power level of the transformer at sinusoidal rated voltage and no-load

$L_{WAIN}$ = the A-weighted sound power level of the transformer at sinusoidal impedance voltage and rated current (one winding short-circuited)

## A 14.4 Definitions [7]

### Sound pressure

#### Sound pressure $p$

Fluctuating pressure superimposed on the static pressure by the presence of sound; it is expressed in Pascal [Pa] .

#### Sound pressure level $L_p$

Ten times the logarithm (base 10) of the ratio of the square of the sound pressure to the square of the reference sound pressure $p_0$, where $p_0 = 20 \cdot 10^{-6}$ Pa; it is measured in decibel [dB].

$$L_p = 10 \cdot \log_{10} \frac{p^2}{p_0^2}$$

### Sound power

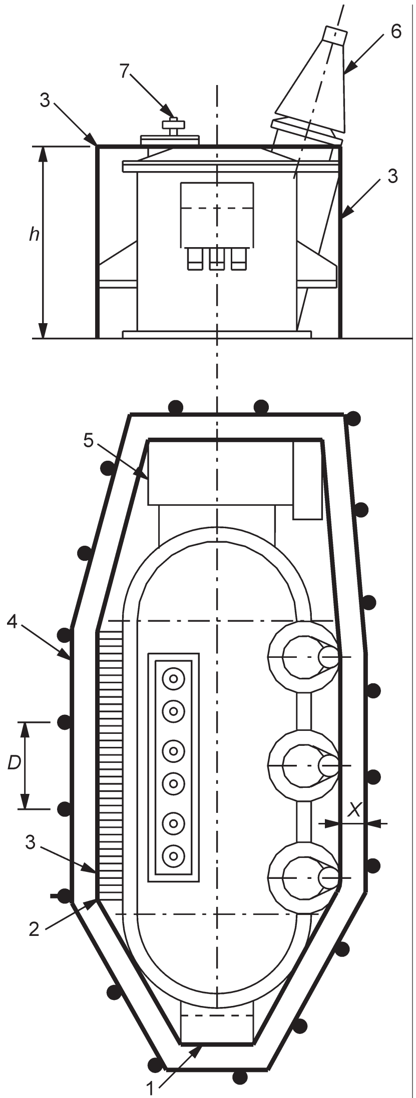
#### Sound power $W$

The rate at which airborne sound energy is radiated by a source; it is expressed in watts, W.

#### Sound power level $L_W$

Ten times the logarithm (base 10) of the ratio of a given sound power to the reference sound power $W_0 = 1 \cdot 10^{-12}$ W; it is expressed in decibels dB.

$$L_W = 10 \cdot \log_{10} \frac{W}{W_0}$$




1 = tertiary bushings
2 = stiffeners and jacking lug
3 = principal radiating surface
4 = prescribed contour
5 = on-load tap changer
6 = HV bushing
7 = LV bushing
$D$ = microphone spacing
$h$ = height of the tank
$X$ = measurement distance

***Figure 14.1:*** *Typical microphone positions for sound measurement on transformers excluding cooling equipment; compare IEC 60076-10 (2001), Figure 1*

## A 14.4.3 Sound intensity (only defined in IEC [7])

### Sound intensity $I$

is a vector quantity describing the amount and the direction of the net flow of sound energy at a given position; its unit is W/m$^2$.

### Normal sound intensity $I_N$

Component of sound intensity in the direction normal to a measuring surface.

### Normal sound intensity level $L_I$

Ten times the logarithm (base $\log_{10}$) of the ratio of the normal sound intensity to the reference sound intensity $I_0 = 1 \cdot 10^{-12}$ watt; it is expressed in decibels [dB].

$$L_I = 10 \cdot \log_{10} \frac{|I_N|}{I_0}$$

## Prescribed contour

A horizontal line on which the measuring positions are located, spaced at a definite horizontal distance (measuring distance) from the principal radiating surface, see figure 14.1.

## Background noise

A-weighted sound pressure level with the test object inoperative.

## A 14.5 The calculation of the environmental correction factor $K$ [51]

Correction factor $K$

$$K = 10 \cdot \log_{10}\left(1 + \frac{4}{A/S}\right)$$

where:

$S$ = is the area of the measuring surface in square metres according to the following equations:

$$S = \begin{cases} 1{,}25 \cdot h \cdot l_m, & x = 0{,}3 \text{ m} \\ (h+2) \cdot l_m, & x = 2 \text{ m} \end{cases}$$

where:

$S$ = the area of the measuring surface in $m^2$

$A$ = intermediate factor

$\alpha$ = average acoustic absorption coefficient, (see IEC 60076-10, table 1)

$S_v$ = the total surface area of the test room in $m^2$

$x$ = the distance between microphone and measuring object (transformer) in m

$h$ = the height of transformer tank in m

$l_m$ = the length of prescribed contour of measuring points in m

The average acoustic absorption coefficient $\alpha$ is between 0,5 (for rooms with a large amount of acoustic material on the ceiling and walls) and 0,05 (for rooms with walls made of concrete, brick etc.).

For a test laboratory to be satisfactory, $A/S$ must be ≤ 1. This will give a value for the environmental correction factor $K$ of ≤ 7 dB.

For very large rooms and work spaces, which are not totally enclosed, the value of $K$ approaches 0 dB.

**For example:**

For a transformer rated 450 MVA:

$H$ = 4,3 m

$S$ = 409,5 $m^2$

Measured in a test laboratory with a surface $S_V$ of 2710 $m^2$ and an absorption coefficient $\alpha$ of 0,25.

$A$ = 0,25 · 2710 = 677,5 $m^2$

The correction factor $K$ is:

$$K = 10 \log_{10}\left(1 + \frac{4}{677{,}5/409{,}5}\right) = 5{,}3 \text{ dB}$$

## A 14.6 The calculation of sound power level, example

For a transformer rated 450 MVA, OFAF cooling,

$H$ = 4,3 m, $l_m$ = 65 m:

Corrected average sound pressure level: 64,5 dB

Calculating according to IEC [7]:

$$S = (h + 2) \cdot l_m = (4{,}3 + 2) \cdot 65 = 409{,}5\ \text{m}^2$$

$$L_{wA} = \overline{L_{pA}} + 10 \cdot \log_{10} \frac{S}{S_0} =$$

$$= 64{,}5 + 10 \cdot \log_{10} 409{,}5 = 90{,}5\ \text{dB}$$

Calculation according to IEEE [51]:

$$S = 1{,}25 \cdot H \cdot l_m = 1{,}25 \cdot 4{,}3 \cdot 65 = 349\ \text{m}^2$$

$$L_{wA} = \overline{L_{pA}} + 10 \cdot \log_{10} \frac{S}{S_0} =$$

$$64{,}5 + 10 \cdot \log_{10} 349 = 90{,}0\ \text{dB}$$

## A 14.7 Far-field calculations

As an approximate calculation, the A-weighted sound pressure level $L_{PAR}$ at a distance of $R$ meters from the center of the transformer may be calculated using the following equation:

$$L_{pAR} = L_{WA} - 10 \log_{10} \frac{S_h}{S_0}$$

where:

$S_h = 2\pi \cdot R^2$ for $R > 30$ m

$L_{WA} =$ the A-weighted sound power level

**For example:**

For a transformer having a sound power level of 87 dB at a distance of 300 m

$$S_h = 2\pi \cdot 300^2 = 565487 \text{ m}^2$$

$$L_{pA300} = 85 - 10 \cdot \log_{10} 565487 = 29{,}5 \text{ dB}$$

# Testing of Power Transformers

## 15. Test on on-load tap-changers and other auxiliary equipment

# 15. Test on on-load tap-changers and other auxiliary equipment

## 15.1 References / Standards

- IEC 60076-1 (2000), Power transformers - Part 1, clause 10.8: “Test on on-load tap-changers” [1]
- IEC 60076-3 (2000), Power transformers - Part 3, clause 10: “Insulation of auxiliary wiring” [3]
- IEEE Std. C57.12.00 (2000), table 19 and clause 8.2.3: “Dielectric test for low voltage control wiring, associated control equipment and current transformer secondary circuits, on Class II power transformers”

**Note:**

These tests are **routine tests** according to IEC [1], [3]; the dielectric test on auxiliary equipment is a **routine test** for Class II transformers according to IEEE [50] and an **“other” test** for less than Class II transformers.

## 15.2 The purpose of the test / General

Although each on-load tap-changer is subjected to routine tests in the manufacturer’s test laboratory according to the corresponding Standard [9], it is necessary to check correct operation of the fully assembled on-load tap-changer at the transformer.

All other control equipment, in conjunction with this test, must be tested to verify the proper operation of the supervisory system.

## 15.3 Test procedure [1] / Test circuit

With the on-load tap changer fully assembled on the transformer the following operations must be carried out without any failures (only for transformers specified according to IEC Standards):

### 15.3.1 Un-energized transformer

– 8 complete cycles of operation with the rated auxiliary voltage. (One cycle of operation is defined as going from one end of the tapping range to the other, and back again).

– One complete cycle of operation with the auxiliary voltage reduced to 85 % of its rated value.

### 15.3.2 Energized transformer

- One complete cycle of operation at no load, at the transformer rated voltage and frequency.
- 10 tap-changer operations across the range of two steps on each side where a coarse or reversing change-over selector operates, or otherwise from the center tap with one winding short-circuited and, as far as practicable, at the rated current of the tapped winding.

The test circuit for the operation test with rated voltage at no-load is similar to that for measurement of no-load loss (see section 6) and the test circuit for the operation test with rated current is similar to that for measurement of load-loss (see section 5).

Observation of tap-changer operations while the transformer is energized and listening for any abnormal sounds is recommended.

## 15.4 Testing auxiliary equipment [3],[50]

All wiring for auxiliary power and control circuitry must be subjected to an AC separate source test of 2 kV r.m.s to earth for 1 minute [3]. IEEE Std C57.12.00 [50] specifies an AC applied voltage test at 1,5 kV r.m.s, for the auxiliary equipment, excluding current transformer circuits, which are tested at 2,5 kV r.m.s.

As some of the auxiliary devices (e.g. motors and other apparatus) have a lower test voltage than specified for the wiring alone, they have to be disconnected before the test of the circuits [3].

# Testing of Power Transformers

## 16. Measurements of the harmonics of the no-load current

# 16. Measurements of the harmonics of the no-load current

## 16.1 References / Standards

- IEC 60076-1 (2000) Power transformers-Part 1 General [1]

  **Note:**

  This test is a **special test** according to IEC Standard [1]; it is not mentioned in IEEE Standards [50], [51].

## 16.2 The purpose of measurement

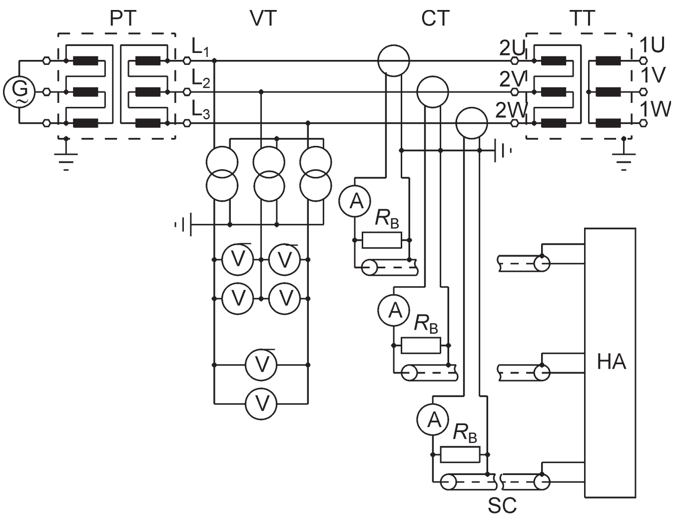
Applying a sinusoidal voltage to a transformer results in a non-sinusoidal magnetizing current due to the non-linear relationship between magnetizing force $H$ and flux density $B$ (magnetizing curve).

Considering the very low no-load currents of modern power transformers of about 0,1 - 0,5 % of nominal current the knowledge of the harmonic content of the no-load current is of little interest.

It could be occasionally interesting for customers to know the harmonic content of old transformers in their grid in order to adjust transformer protection relays, especially if conventional electro-mechanical relays are still used.

## 16.3 General

No-load current depends strongly on the flux density of a transformer as can be seen in figure 16.2 of clause A 16.1 in the appendix, also the harmonic content increases with increasing flux density, see figure 16.3




G = generator
PT = testing transformer
VT = voltage transformer
CT = current transformer
V, V = voltmeters (r.m.s. and average)
A = ammeter
TT = transformer under test
$R_B$ = measuring resistor
HA = harmonic-analyser
SC = shielded connection

***Figure 16.1:*** *Measuring circuit for the analysis of no-load current harmonics*

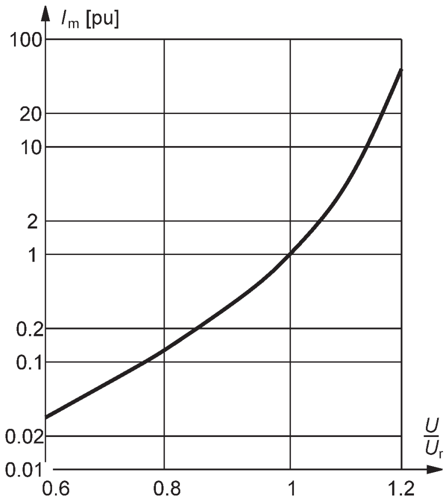



*Figure 16.2:* *Magnetizing current in per unit versus flux density*

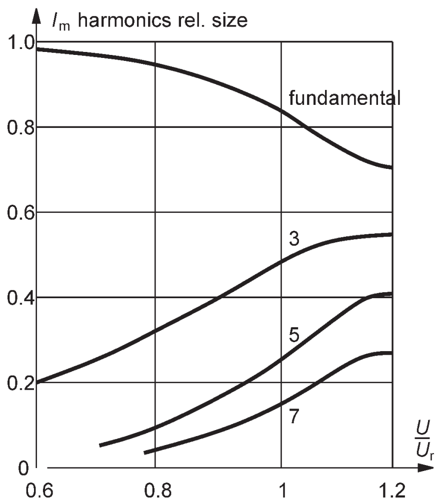



*Figure 16.3:* *Harmonic content as a function of flux density*

## 16.4 The measuring circuit [100]

The measuring circuit is exactly the same as for the measurement of no-load losses and no-load current (see section 6) performed with a power analyzer.

It is also the same as for the no-load measurement carried out with conventional instruments; the only difference is that a harmonic-analyzer is used in addition to one of the ammeters, see figure16.1.

The problem of voltage distortion is very important for this test, (see section 6). The harmonic content should be analyzed by applying a sinusoidal voltage. To obtain linear magnetizing characteristics it is therefore important to choose the generator and matching transformer connections appropriately. Generators and matching transformers used should be as large as possible.

## 16.5 The measuring procedure

The voltage required for the measurement is adjusted using an average-voltage voltmeter. Normally, measurements are carried out at 90 %, 100 % and 110 % of the transformer rated voltage. The voltage is increased gradually from zero to full voltage. Switching-on directly would create transient inrush phenomena including DC components. These DC components could saturate the iron core of the voltage-transformer and increase the measuring uncertainty. For the same reason the measuring voltage should be reduced gradually instead of being shut off.

## 16.6 Examples

Examples of an analysis of no-load current harmonics are shown in clause A 16.2.

# Appendix A 16:

# The measurement of the harmonics of the no-load current

## A 16.1 The relationship between flux density, no-load current and harmonic content. [106]

Magnetizing current is highly dependent on flux density, see figure 16.2.

The content of harmonics also depends on flux density. Generally it can be stated that the higher the flux density, the higher will be the harmonic content. The most important harmonics are the 3rd, 5th and 7th, see figure 16.3.

## A 16.2 Example

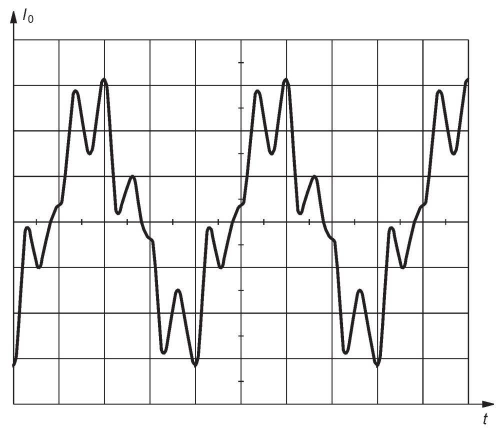
**Example 1**

Generator-Transformer 465 MVA, 50 Hz, 410 / 21 kV, 655 / 12784 A, YNd1; five-limbed core;

Figure 16.4 shows the no-load current wave form measured at phase U on the LV-side of the transformer; figure 16.5 shows the harmonic analysis.

Analysis:

| Order | Attenuation [dB] | Percent of fundamental |
|---|---|---|
| 1 | 0 | 100 |
| 3 | -18,6 | 11,8 |
| 5 | -11,8 | 25,7 |
| 7 | -11,6 | 26,3 |
| 9 | -32,6 | 2,3 |
| 11 | -29,7 | 3,3 |
| 13 | -30,5 | 3,0 |
| 15 | -50,4 | 0,3 |
| 17 | -45,0 | 0,6 |
| 19 | -35,7 | 1,6 |




$I_0$ = 8,5 A *(phase U)* – 0,07 %

***Figure 16.4:*** *No-load current waveform at 100% of rated voltage*

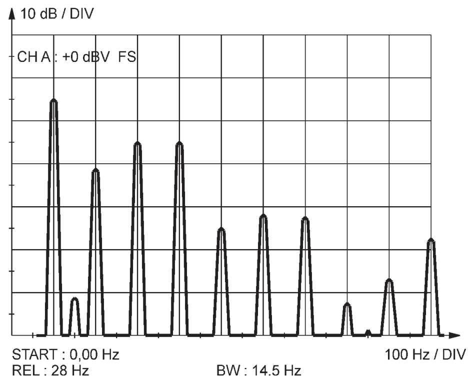



***Figure 16.5:*** *No-load current harmonic analysis at 100% of rated voltage*

### Example 2

Measurement of the harmonics in the no-load current (and source voltage) of a three-phase transformer 100 MVA, 60 Hz, performed with a power analyzer at 110 % of rated voltage:

Power supply at LV side 2U, 2V and 2W

| No-load current | | | | | | |
|---|---|---|---|---|---|---|
| Harmonic order | Amplitude [%] and phase angle [°] | | | | | |
| | 2U | | 2V | | 2W | |
| 1 | 100 | 0 | 100 | 0 | 100 | 0 |
| 3 | 37 | 179 | 83 | 83 | 5,81 | 55 |
| 5 | 50,6 | 64 | 144 | 144 | 60,5 | 130 |
| 7 | 40,1 | 116 | 43 | 43 | 44,7 | 74 |
| 9 | 7,7 | 120 | 167 | 167 | 0,45 | 0 |
| 11 | 13,2 | 2 | 61 | 61 | 14,7 | 33 |

| Source voltage | | | | | | |
|---|---|---|---|---|---|---|
| Harmonic order | Amplitude [%] and phase angle [°] | | | | | |
| | 2U | | 2V | | 2W | |
| 1 | 100 | 0 | 100 | 0 | 100 | 0 |
| 3 | 0,11 | 0 | 0,11 | 0 | 0,04 | 0 |
| 5 | 1,45 | 179 | 0,15 | 177 | 1,37 | 179 |
| 7 | 0,43 | 172 | 0,42 | 179 | 0,49 | 172 |
| 9 | 0,07 | 0 | 0,07 | 0 | 0,02 | 0 |
| 11 | 0,15 | 0 | 0,14 | 5 | 0,17 | 4 |

# Testing of Power Transformers

## 17. Measurement of insulation resistance

# 17. Measurement of insulation resistance

## 17.1 References / Standards

- IEC 60076-1 (2000), clause10.1.3: Power transformers-Part 1 “General” [1]
- IEEE Std 57.12.90-1999, clause: 10.11 “Insulation resistance tests” [51]

  **NOTE:**

  This test is a **special test** according to IEC Standard [1] but a **routine test** for Class II transformers according to IEEE [50], or an **“other” test** for Class I transformers. This is also valid for the insulation resistance test between core and earth.

## 17.2 The purpose of the measurement

Insulation resistance tests - Megger tests - are performed to determine the insulation resistance from individual windings to earth or between individual windings. Knowledge of the insulation resistance is of value when evaluating the condition of the transformer insulation.

Nowadays different sophisticated methods are in use to assess the quality of the insulation system, such as low frequency dielectric spectroscopy measurements (FDS), time domain polarization /depolarization current measurements (PDC) and return voltage polarization spectra (RVM) [207].

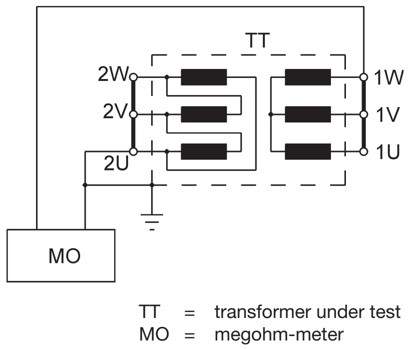



***Figure 17.1:*** *Principal measuring circuit for the insulation resistance measurement*

## 17.3 General

Insulation resistance is commonly measured in megohms, (MΩ).

It should be stated, that variations in insulation resistance can be caused by numerous factors including: design, temperature, dryness, and cleanliness of parts, especially of bushings. When insulation resistance falls below specified value, it can often be brought back to the required value by cleaning and drying.

Insulation resistance varies with the applied voltage. Any measurement comparisons should always be carried out at the same voltage.

IEEE Std C57.12.00 [50] also specifies the insulation resistance measurement between core and earth. It shall be measured after complete assembly of the transformer at a level of at least 0,5 kV DC for a duration of 1 minute.

## 17.4 The measuring circuit / The measuring procedure [51]

The measuring circuit is very similar to that of the applied voltage test (section 7). The test must be conducted with all terminals of each winding system connected together, e.g. high voltage to low voltage and earth and low voltage to high voltage and earth. Figure 17.1 shows the measuring circuit for a two-winding transformer.

Normally megohm-meters with integrated DC power supply are used for insulation resistance measurement. Megohm-meters are commonly available with nominal voltages of 0,5 kV, 1 kV, 2,5 kV and 5 kV DC.

The measurement duration should be 1 minute. Usually readings are taken after 15 and 60 seconds. The relationship between the measured values after 60 seconds (*R60*) and those measured after 15 seconds (*R15*) is about 1,3 - 3; it is a criteria for the insulation condition.

The temperature of the transformer under test must be noted; it should be near to reference temperature of 20°C.

With the same measuring circuit also the Polarization Index *PI* can be determined. The *PI* test takes the ratio of the values at 10 and 1 minutes - this is the Polarization Index, see example 2 in A 17. The value of *PI* can give a rough guide to the insulation condition:

*PI* values > 2 stand for good insulation conditions, *PI* values < 1 for unsatisfactory conditions.

An example for the measurement of the insulation resistance on a two-winding transformer is given in clause A 17.

## Appendix A 17:

## The measurement of insulation resistance

### Example 1

Three-phase transformer 465 MVA, 50 Hz, 410 / 21 kV

Megohm-meter: CHAUVIN ARNOUX Type ISOL 5002
Test voltage: 5 kV DC
Transformer temperature: 24,5 °C

| | HV to LV and earth | LV to HV and earth |
|---|---|---|
| $R15$ [MΩ] | 2000 | 1000 |
| $R60$ [MΩ] | 3000 | 1500 |
| $R60/R15$ | 1,5 | 1,5 |

### Example 2

Measurement of the Polarization Index $PI$

Single-phase autotransformer 500:3 MVA with tertiary:

400/√3 / 170/√3 / 30,8 kV, 50 Hz
Test voltage: 5 kV DC
Transformer temperature: 28,0 °C

| Time [min] | HV to LV tank earthed | LV to tank HV earthed |
|---|---|---|
| | [GΩ] | [GΩ] |
| 1 | 8,0 | 10,0 |
| 2 | 12,0 | 13,0 |
| 3 | 15,0 | 15,0 |
| 4 | 18,0 | 17,0 |
| 5 | 20,0 | 19,0 |
| 6 | 22,0 | 21,0 |
| 7 | 24,0 | 23,0 |
| 8 | 26,0 | 24,0 |
| 9 | 28,0 | 25,0 |
| 10 | 29,0 | 25,0 |
| $T_{10}/T_1=PI$ | 3,62 | 2,5 |

# Testing of Power Transformers

## 18. Measurement of dissipation factor (tanδ) of the insulation system capacitances

# 18. Measurement of dissipation factor

## 18.1 References / Standards

- IEC 60076-1 (2000), clause 10.1.3: Power transformers- Part 1: General, “Measurement of the dissipation factor (tan $\delta$) of the insulation resistance capacitances” [1]
- IEEE Std 57.12.90-1999, clause 10.10 “Insulation power-factor tests” [51]

  **NOTE:**

  This test is a **special test** according to IEC Standard [1] but a **routine test** for Class II transformers according to IEEE [50], and an **“other” test** for Class I transformers.

## 18.2 The purpose of the measurement

The insulation power-factor test, similar to the insulation resistance test, allows certain conclusions to be drawn concerning the condition of the transformer insulation.

The significance of the power factor figure is still a matter of opinion. Experience has shown, however, that the power-factor is helpful in assessing the probable condition of the insulation when good judgment is used [51].

## 18.3 General

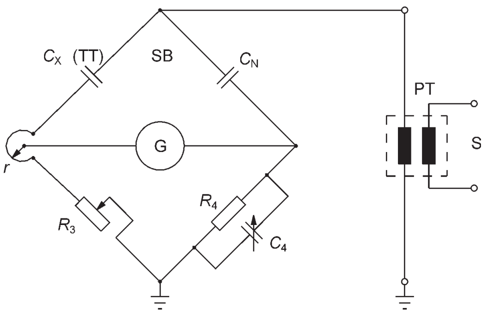
IEC defines the power factor as the ratio between the absorbed active power to the absolute value of the reactive power. This corresponds to tan $\delta$.

IEEE [51], on the other hand defines the insulation power-factor as the ratio of the power dissipated in the insulation in watts, to the product of the effective voltage and current in volt-amperes (corresponding to the *apparent power*) when tested using a sinusoidal voltage. Insulation power-factor is usually expressed in percent [51].

Measurement of power-factor values in the factory is useful for comparison with field power-factor measurements and assessing the probable condition of the insulation.

It has not been feasible to establish standard power-factor values for the following reasons:

- there is little or no relationship between power-factor and the ability of the transformer to withstand the prescribed dielectric tests
- the variation of power-factor with temperature is substantial and erratic
- the various liquids and insulation materials used in transformers result in large variations in insulation power factors [51]




SB = Schering-Bridge
$C_X$ = unknown capacitance (TT-transformer under test)
$C_N$ = standard capacitor
G = galvanometer
$R_{3,4}, r$ = Schering-Bridge resistors
$C_4$ = adjustable capacitor of the Schering-Bridge
$S$ = voltage source
PT = power supply

***Figure 18.1a:*** *Measuring circuit for the measurement of power factor and winding capacitances*

## 18.4 The measuring circuit / The measuring procedure [51]

Insulation power factor may be measured by special bridge circuits or by the so-called volt-ampere-watt method, known as the "Doble test".

### 18.4.1 Measurement using a bridge

The method is based on comparing the capacitance $C_X$ (transformer under test) with a well-known capacitance $C_N$ (standard capacitor).

#### Conventional Schering-Bridge

Figure 18.1a shows the measuring circuit for the insulation power-factor measurement of a two-winding transformer using a conventional Schering-bridge.

#### Instrumentation

The Schering-Bridge test circuit consists of three main parts:

- The unknown capacitance $C_X$, which represents the transformer under test whose power-factor (or $\tan\delta$) and capacitance are to be measured.
- The standard capacitor $C_N$, which must be a HV capacitor with very low dielectric losses. Normally its capacitance is between 100 pF and 10 nF.
- The Schering-Bridge casing contains resistors $R_3$, $R_4$ and $r$, adjustable capacitor $C_4$ and galvanometer G.

In order to reduce the influence of external disturbances, coaxial cables must be used for the connection between $C_X$ (the transformer under test) to the bridge and also between standard capacitance $C_N$ and the bridge.

When the bridge is balanced, the unknown capacitance $C_X$ and $\tan\delta$ can be calculated using the following equations:

$$C_X = \frac{C_N \cdot R_4}{R_3 + r}$$

$$\tan\delta = C_4 \cdot \omega \cdot R_4$$

where

$$\omega = 2\pi f$$

In most bridges the following resistance values are used for $R_4$, to simplify the calculation: $100/\pi$, $1000/\pi$ or $10000/\pi$ etc. in ohms.

# 18. Measurement of dissipation factor

For a 50 Hz measurement, with $R_4 = 1000/\pi$ and $C_4$ in nF, the insulation power-factor tan$\delta$ will be:

$$\tan\delta = 2\pi 50 \cdot C_4 \frac{100}{\pi} \cdot 10^{-9} \cdot 10^{-2} = 0{,}01 C_4 \;[\%]$$

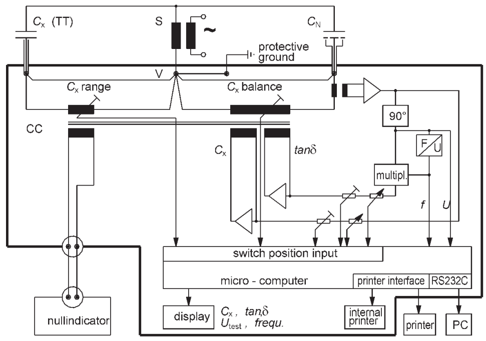
For an example see clause A 18.1.

**A modern tan$\delta$ bridge with current comparator and microprocessor** [208]

This bridge uses basically the same measuring principle as described above. Figure 18.1 b shows the measuring circuit for dissipation factor and capacitance measurement with a modern tan δ measuring bridge with incorporated microprocessor.

The currents are balanced in a comparator (more-winding differential transformer) and quadrature current is injected to balance the losses.

For the unknown capacitance $C_x$, the standard capacitor $C_N$ and the connections between transformer and bridge are the same as mentioned above for the conventional Schering Bridge.




$C_x$ = transformer under test (TT)
$C_N$ = standard capacitor
S = voltage source
CC = current comparator

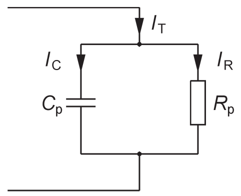
***Figure 18.1b:*** *Block diagram for tan$\delta$ and capacitance measurement with a Tettex Bridge Type 2809*

## 18.4.2 "Doble test" (Volt-ampere-watt method) [209], [210]

The "Doble test" is based on measuring AC charging current in mA or µA, AC dielectric loss in W and capacitance in pF of an insulation specimen (transformer under test). This percent power factor is calculated from the charging current and the recorded loss figure in watts.

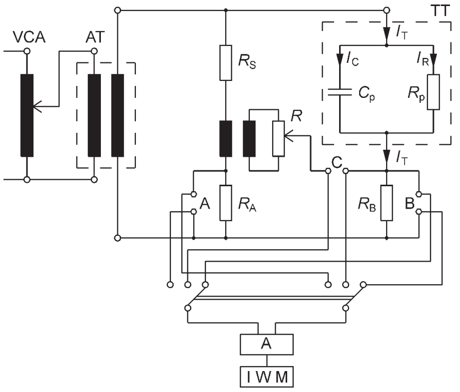
The "Doble test" set has a special measuring circuit in which the total current $I_T$ of the transformer under test, represented as a parallel capacitor/resistor network, see figure 18.2, is first indicated on the meter. Then the balancing network is switched into the measuring circuit and the capacitive component $I_c$ of the transformer under test is balanced out, leaving the in-phase component $I_R$ of the current indicated on the meter.

Figure 18.3 shows the simplified measuring circuit of the "Doble"-Insulation Analyzer.




$I_T$ = specimen total current
$I_C$ = capacitive or quadrature component of the total current
$I_R$ = resistive or in-phase (loss) component of the total current
$C_p$ = equivalent parallel capacitance of the insulation specimen (TT)
$R_p$ = equivalent parallel resistance of the insulation specimen (TT)

***Figure 18.2:*** *Simplified equivalent circuit of transformer under test (TT) as parallel capacitor / resistance network*




A = amplifier
I W M = measuring instrument - mA, W
VCA = voltage-control autotransformer
AT = high-voltage step up transformer
$R_S$ = high ohmic standard resistor
$I_{T,R,C}$ = see figure 18.2
TT = transformer under test

***Figure 18.3:*** *Doble test simplified schematic diagram (test set) Amplifier at*
*Pos A: check for full-scale readings*
*Pos B: measurement of* $I_T$
*Pos C: measurement of* $I_R$ *(after partial balance)*

Measuring procedure [51]:

Before the test all windings must be short-circuited.

The test voltage should not exceed half of the low-frequency test voltage given in IEEE Std C57.12.00 [50] for any part of the winding or 10 kV, whichever is lower.

The Doble Insulation Analyzers normally have a built-in power supply (test voltage 10 kV AC).

The insulation power-factor tests must be conducted from windings to earth and between windings. For a conventional two-winding transformer the following tests are required (Method I, test without guard circuit):

- HV to LV and earth
- LV to HV and earth
- HV and LV to earth

For measurement according to Method II (test with guard circuit) and for three-winding transformers see IEEE Std C57.12.90, clause 10.10.4 , table 4 [51].

The Doble equipment can be used to measure the following modes:

- GND (ground mode)
- GRD (guard mode)
- UST (ungrounded specimen test)

For details, see clause A 18.2.

When the insulation power-factor is measured at an insulation temperature (average oil temperature) above or below the reference temperature of 20°C, it must be corrected in accordance with clause A 18.2.

Note that temperature correction factors for the insulation power factor depend upon the insulating materials and their structure, moisture content, etc. The values given in appendix A 18 are based on IEEE [51], and are typical and satisfactory for practical purposes.

# Appendix A 18:

# The measurement of insulation power-factor

## A 18.1 Examples:

### A 18.1.1 The measurement using a conventional Schering Bridge

For a single-phase auto-transformer rated:

500/3 MVA, 50 Hz
400/√3 / 176,2/√3 / 30,8 kV:

Measurement between HV (power supply) and LV and tank:
supply voltage: 10 kV

$C_N$ = 100,5 pF

temperature : 30 °C
correction factor $K$: 1,25, see table in clause A 18.2.

$R_3 = 13{,}54\ \Omega$, $R_4 = 1000/\pi\ \ \Omega$

$C_4 = 29{,}7$ nF

$\tan\delta$ at 30 °C = $0{,}01\ C_4 = 0{,}297\,\%$ or

$\tan\delta$ at 20 °C = $0{,}297 / 1{,}25 = 0{,}237\,\%$

### A 18.1.2 The measurement using the Doble Insulation Analyzer [209]

For a three-phase transformer the field measurement can be as follows:

Transformer rating:

33,3 MVA, 60 Hz

138 / 13,8 kV Dy

Transformer oil temperature: 50 °C

Over-all test: 10 kV AC

a) HV energized / LV earthed

Measured values: 33,6 mA
1,92 W

Power factor $PF$:

$$PF = \frac{1{,}92}{10\,000 \cdot 0{,}0336} = 0{,}0057 = 0{,}57\%$$

Correction factor for 50 °C → 1,95

$$PF_{corr} = \frac{0{,}57}{1{,}95} = 0{,}29\%$$

b) HV energized / LV guarded

Measured values: 15,3 mA
1,12 W

Power factor $PF$:

$$PF = \frac{1{,}12}{10\,000 \cdot 0{,}0153} = 0{,}0073 = 0{,}73\%$$

correction factor for 50 °C → 1,95

$$PF_{corr} = \frac{0{,}73}{1{,}95} = 0{,}37\,\%$$

For this transformer no UST-test was carried out.

An analogous procedure was performed with LV energized / HV grounded (earthed) or guarded.

## A 18.2 Test modes used for Doble Insulating Analyzers [209]

**GND (ground mode)**

Measures total apparent and active losses (mVA and W) through the insulation between the HV probe and ground (earth) as well as through the insulation between HV probe and LV lead(s).

**GRD (guard mode)**

Measures apparent and active losses (mVA and W) through the insulation between HV and ground (earth); leakage through the insulation between the HV probe and the LV lead(s) bypasses the meter!

**UST (ungrounded specimen test)**

Measures apparent and active losses (mVA and W) through the insulation between HV probe and the LV lead(s); leakage through the insulation between the HV probe and ground (earth) lead bypasses the meter!

## A 18.3 Temperature correction factors according to IEEE Std C57.12.90 [51]

*(based on insulating systems using mineral oil)*

$$F_{p20} = \frac{F_{pT}}{K}$$

where:

$F_{p20}$ = power factor corrected to 20 °C
$F_{pT}$ = power factor measured at $T$
$T$ = test temperature
$K$ = correction factor

| Test temperature $T$ [°C] | Correction factor $K$ |
|---|---|
| 10 | 0,80 |
| 15 | 0,90 |
| 20 | 1,00 |
| 25 | 1,12 |
| 30 | 1,25 |
| 35 | 1,40 |
| 40 | 1,55 |
| 45 | 1,75 |
| 50 | 1,95 |
| 55 | 2,18 |
| 60 | 2,42 |
| 65 | 2,70 |
| 70 | 3,00 |

# Testing of Power Transformers

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# Testing of Power Transformers

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