SIEMENS

Electrical Testing of Power Transformers

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In collaboration with
Siemens Power Transformer Division

SIEMENS

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Foreword

The first considerable long distance transmission of electric energy was performed successfully on the 24th of August 1891, only possible with the help of a transformer, invented by Michail Doliwo-Dobrowolski in Berlin.

Today transformers are indispensable in terms of the usage in high voltage grids and special applications like HVDC transmission or electric arc furnace plants. The complexity of a transformer and its components make it necessary to monitor the manufacturing process and verify the operation without failure, fulfilling the required Standards and customer's expectations.

Therefore this booklet gives an overview about electrical testing of power transformers, combining the knowledge and experience of Siemens' designers, consultants and test field engineers.

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1 Introduction

This booklet is to be understood as a supportive guide, giving a summary about applied electrical measurements. These electrical tests are essential to estimate and verify the specifications and the dielectric strength of the transformer. It also provides the sense of manufacturer's internal quality protection and aspiration of constructing a valuable product. Although some calculations are necessary for preparing and analysing the measurements, we are not considering the matter of scientific approach or any mathematical explanations. The essential content is to inform and give formal explanations by means of basic formulas.

Followed by chapters with descriptions of each measurement, the initial chapters cover the issue of relevant Standards and dielectric integrity in general, simplifying the area of testing high voltage devices, such as power transformers.

Note: All pictured circuits are exemplary and only serve as better understanding. The corresponding measuring circuits for the transformer´s customized vector group will be appended in the last subchapter of each section (where it is useful).

1.1 Power Transformers Dresden

In Dresden, the beginning of transformer manufacturing was in the twenties, when the founder Franz Koch and Kurt Sterzel extended their company "Koch & Sterzel AG", by purchasing former airport grounds and built a factory in Dresden-Kaditz. They developed and produced high-voltage- and instrument transformers, x-ray apparatus and radio devices. After the Second World War, the remaining parts of the "Koch & Sterzel AG" were re-established to the "VEB Transformatoren- und Röntgenwerk (TuR)", which developed to one of the most important export establishments of the former GDR. During the time from 1949 to 1990 the number of employees had been grown to 3500 at this location.

Founder of „Koch & Sterzel AG":
Kurt August Sterzel (1876 – 1960), left
Franz Joseph Koch (1872 – 1941), right

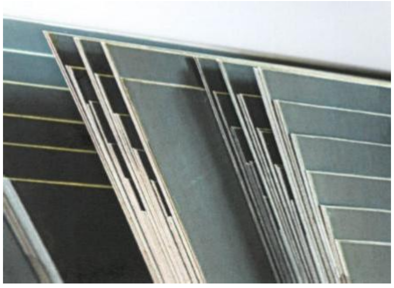
After the fall of the Berlin Wall, the company was privatized and decommissioned, until 1992 Siemens took over the ground partly. Today Siemens employs about 280 co-workers and belongs to the Power Transmission & Distribution Division. As a sheer manufacturer, we are focusing on design and construction as well as testing of Medium Power Transformers (40 to 250 MVA), which are typical applications for network- and generator step-up transformers. They are also widely used for industrial applications (e.g. arc furnace transformer).

Manufacturing ground (1992)

1.2 Transformer components

Core

On the right track right from the start: The iron core and windings influence the subsequent efficiency of a transformer. That's why we design our transformers as core types in which the wound and non-wound limbs of the core are located at the same level and connected by yokes. The choice of sheet metal also greatly effects the quality of the core. At Siemens, we use only high-quality, cold-rolled sheet metal. Depending on your requirements, we may also opt to laser-treat the sheet metal. Using state-of-the-art numerical controls, we cut the sheet metal precisely to the millimeter for step-lap layering. This ensures favorable flux distribution at joints, providing the basis for low losses and minimized noise during no-load operation.



Windings

Transformer windings must be able to withstand high electrical and mechanical loads in daily operation. Our windings made from copper wire definitely pass the test of time. Their high mechanical stability ensures safe operation, no matter what type of winding you need to meet your power and voltage requirements. For the winding we use transposed conductors, consisting of many enamel-insulated, twisted section wires to minimize losses.

Voltage Variation

To adjust the ratio safely and easily to system conditions, Siemens Power Transformers have tapped windings. In this way the ratio of Power Transformers can be changed gradually - either in no-load condition via off-load tap-changers or under load by means of on-load tap-changers.

Tank

Another main component besides the core and the winding is the tank of a Power Transformer: It accomodates the active part and the oil filling. With the final assembly the active part (the core, windings, pressed parts, tap-changer and connecting cables) is installed in the tank and filled with high-grade insulating oil under vacuum. The transformer is then ready for testing.

1.3 Standards and Norms

Every transformer has to comply with national and international standards, which are published by certain institutions. The primary Standards Organizations are the ANSI and the ISO. They specify the respective tests that verify compliance with the requirements. It is important to know that in terms of the electric field, the ANSI has delegated the writing and publication of standards to the IEEE, as similar as the ISO handed over its authority to the IEC. All tests are referred to the IEC and IEEE standards. The German Standards, settled in the VDE, are mentioned as well.

Institution	**International Electrotechnical Commission**	**Institute of Electric and Electronics Engineers**	**Association of electrical engineering & electronics**
Area served	Worldwide	Worldwide	Germany
Headquarter	Geneva	New York	Frankfurt on the Main
specific Standard	IEC 60076-xx	IEEE C57.12.xx	VDE 0532-xx

Table 1.3.1: Applied Standards

Usually those standards are used directly to develop national standards. Which standards are valid in which country can be looked up on the respective websites of IEC and IEEE. The Standards and requirements based on transformers are settled in IEC 60076 and IEEE Std. C57.12 generally.

1.4 Types of tests

It will be distinguished between different types of tests.

- **Routine tests**
  Routine tests are tests required for every single transformer.
  → typical examples: Resistance measurement, Voltage ratio, Loss measurements

- **Type- or design[1] tests**
  Those tests will be conducted on transformers which are representative of other transformers, not covered by routine tests, but needed to withstand the same specified requirements. “Representative” means identical in calculation and construction. Transformers with slight deviations in their characteristics can be considered to be representative as well.
  → typical examples: Temperature rise test, Sound level measurement

- **Special- or other[1] tests**
  Special- or other tests are additional tests different from type- or routine tests. Usually these kinds of tests will be agreed upon the manufacturer and the customer.
  → typical examples: Measurement of zero-sequence impedance, Hot-Spot measurement

[1] Terms used in the IEEE Standards

Note: Certain dielectric tests, such as lightning impulse tests for example, can be routine-, type-, or special tests, depending on the respective standard, the insulation system and the maximum system voltage.

1.5 Test sequences

There are often discussions about how and in which order tests will be conducted. Dielectric tests are generally fixed in IEC and IEEE Standards. Existing Standard recommendations and regulations referred to this issue are following below.

1.5.1 IEC Standard

IEC 60076-3, clause 7.3

"The dielectric tests shall, where applicable and not otherwise agreed upon, be performed in the sequence as given below. This test sequence is in principle obligatory, but allows other agreements between customer and manufacturer."

Recommended test sequence (Dielectric tests only)

- Switching impulse test (SI) for the line terminals
- Lightning impulse test (LI) for the line terminals
- Lightning impulse test (LI) for the neutral
- Separate source AC withstand voltage test (Applied voltage test)
- Short duration induced AC withstand test (ACSD); including PD-measurement
- Long duration induced AC voltage test (ACLD); including PD-measurement

IEC 60076-1, 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. It serves quality control purposes, verifying partial discharge-free operation under operating conditions. There are different categories of windings, which require different test sequences, specified in the referenced IEC Standard (see Table 1.5.1: Separation according to IEC Standard).

Winding category	Highest voltage for equipment U_m [kV]	Tests					
		LI	SI	ACLD	ACSD		AC
					Single-phase (phase-to-earth)	Three-phase (phase-to-phase)	
Uniform insulation	≤ 72,5 72,5 < U_m < 170 170 < U_m < 300 ≥300	T R R R	NA NA R* R	NA S R R	NA NA NA NA	R R S* S	R R R R
Non-uniform insulation	72,5 < U_m < 170 170 < U_m < 300 ≥300	R R R	NA R* R	S R R	R S* S	R S* S	R R R

Table 1.5.1: Separation according to IEC Standard

R – routine test
S – special test
T – type test
NA – not applicable

* If the ASCD test is specified, the SI test is not required.

Repeated dielectric tests

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

1.5.2 IEEE Standard

After IEEE Standards, power transformers are divided into two different classes due to system voltage and transformer type insulation. This separation has an influence on the test sequence and its classification (Routine-, Type- or Other test). For more details the IEEE Standards have to be consulted.

Winding category	Class I		Class II	
	Non-graded isolation	Graded isolation	/	
Highest system voltage U_m [kV]	< 115		≥ 115 < 345	≥ 345

Table 1.5.2: Separation according to IEEE Standard

Recommended test sequence (Dielectric tests only)

- Switching impulse test
- Lightning impulse test on line terminals and on transformer neutral
- Applied voltage test
- Induced voltage test
- PD measurement
- Insulation power factor[2] test
- Insulation resistance test

[2] Term used in IEEE Standard for loss factor (tan δ)

If required, lightning impulse tests shall precede the AC voltage tests. Switching impulse tests, when required, shall also precede the AC voltage tests. For class II power transformers, the final dielectric tests shall be the induced voltage test. This test sequence is a recommendation and not obligatory either.

IEEE Std. C57.12.90, 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."

IEEE Std. C57.12.90, 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."

1.5.3 Siemens recommendation

Based on our own experience and taking into consideration all IEC and IEEE regulations and recommendations, we suggest the following test sequence:

1. Ratio, polarity and phase displacement
2. Resistance measurement
3. Current Transformer tests
4. Dielectric test:
    - Switching impulse test (if required)
    - Lightning impulse test
    - Separate source AC voltage test
    - Measurement of Insulation capacitances & loss factor (tan δ)
    - Insulation resistance measurement
    - Induced voltage test (including Partial discharge measurement)
5. Sound level measurement
6. No-load test (followed by sound level test, if specified)
7. Load loss and impedance
8. Zero-sequence impedance test (if specified)

Different from the common Standards (IEC and IEEE), we treat the Insulation resistance measurement as a routine test, which means every single transformer has to comply with that test additionally.

1.6 Reasons for Transformer failure

It is expected that a transformer will experience and survive a number of short circuits during its service life, but sooner or later one such event will cause slight winding movement, and the ability of the transformer to survive short circuits in future will then be severely reduced. As the transformer ages, its components deteriorate and the probability of a failure increases. There are several reasons for deterioration, summarized in the following.

Paper insulation deterioration

The transformer paper insulation has a limited life, the extent of which depends on thermal, oxidation, and moisture effects. When the paper insulation has reached the end of its expected life, the mechanical strength of the paper is much reduced whereas its electrical strength is still satisfactory. However the reliability of such a transformer is reduced and the mechanical forces of a short circuit or other outside influence may cause a mechanical breakdown of the insulation leading to an electrical failure of the transformer.

Core and winding movements

The core, windings, and turns can move due to short circuit forces, vibration, transport jolts, and loosening of clamping pressure that have accrued during the life of the transformer.

Tap changer

Moving parts in the tap-changer and electrical joints in the tap-changer deteriorate over the years.

Auxiliary components

Auxiliary components such as bushings deteriorate, e.g. bushing gaskets leak causing ingress of moisture and insulation deterioration.

Gaskets

Main gaskets and pipe work gaskets leak allowing ingress of moisture to the transformer and oil leaks from the transformer

Rust

Rust causes deterioration of ferrous materials, especially in high humidity climates.

2 Voltage stresses & dielectric integrity

2.1 General

During their operating time, transformers are exposed to several voltage stresses, which can appear during normal as well as abnormal operation. In general, over-voltages are distinguished into three categories:

- **Lightning over-voltages (A)**
  with a duration in the order of microseconds
- **Switching over-voltages (B)**
  with a duration in the order of a fraction of a second
- **Over-voltages (C)**
  with a duration in the order of seconds to minutes

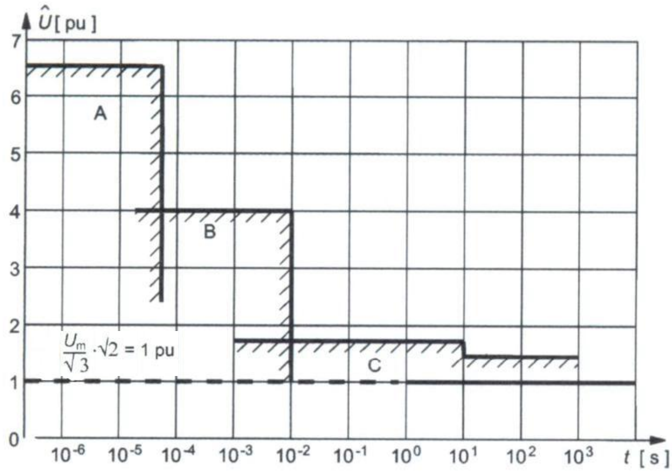


Figure 2.1.1: Types of over-voltages

Dielectric tests are intended to verify transformers integrity in case of over-voltages, as described above. The different groups of over-voltages have also been considered in a test code. The actual test code for a particular object, which is specified by a Standard, depends primarily on the size and rated voltages of the object. Test voltages are primarily sinusoidal AC voltages. DC voltages are usually only relevant for valve transformers, like HVDC transformers. Today´s test programs have their roots in a test code based on short time AC-tests only, at voltages considerably higher than normal operating voltages. Test objects either passed the test or broke down electrically. Later on it was found that other voltage shapes, which includes transient impulse voltages (e.g. switching- or lightning over-voltages), are more suitable to describe the stresses during abnormal conditions like lightning strikes. Through the evolution of electronic diagnostic tools, more tests were added, those like the measurement of partial discharges, which has become indispensable nowadays.

Standard	Section/Clause	Type of test
IEC	60076-3 Power transformers – Part 3: “Insulation levels, dielectric tests and external clearances in air”	Routine tests
IEEE	C57.12.90 Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers, Clause 10: “Dielectric tests”	
	C57.12.00 General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers	

Table 2.1.1: Associated Standards

2.1.1 Lightning over-voltages

Lightning over-voltages are caused by weather-related, atmospheric discharges. The power of the over-voltage in the grid depends on the lightning current and the impedance at the strike location. The typical wave form of a lightning over-voltage can be seen in Figure 2.1.2. This wave is unipolar (only one polarity) and propagates along the line, starting at the location of the voltage strike. It increases to a peak within a few microseconds (wave front, distinctive: high surge) and decays back to zero within about a hundred microseconds (wave tail). By line impedance and corona discharge, the propagating wave becomes deformed and dampened. To preserve from extreme surges entering the object (e.g. a transformer), protection equipment such as surge arresters and spark gaps, either in individually or in combination, are highly recommended. The insertion of those protective devices may conversely cause a steep voltage breakdown, which can be seen as a chopped lightning impulse at the transformer terminal.

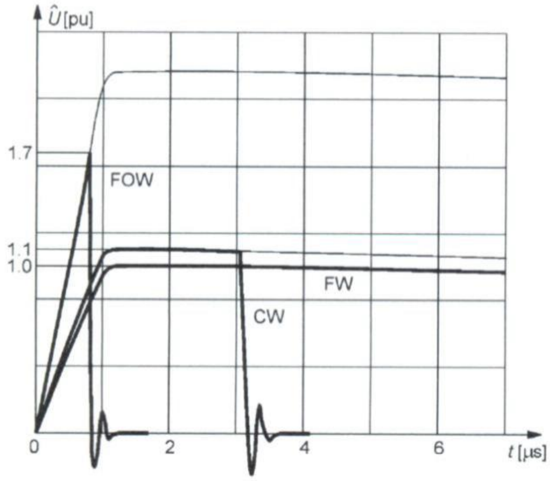


Figure 2.1.2: Lightning over-voltages

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

2.1.2 Switching over-voltages

Switching operations cause transient phenomena, what can lead to over-voltages. Shape, duration and amplitude depending on the grid's configuration and point of switching operation related to sinus wave.

Figure 2.1.3 shows an example of an over-voltage, during a switching operation in an overhead line.

a) configuration of network

b) equivalent diagram

c) oscillogram of switching impulse voltage

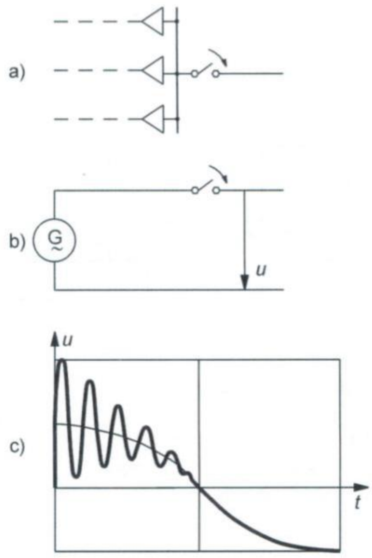


Figure 2.1.3: Switching over-voltages

2.1.3 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 1,7 pu (depending on neutral point configuration)
- Ferro resonance (saw-tooth oscillations)
- Ferranti-effect
- other resonance oscillations

2.2 Transformer's insulation verification

Figure 2.2.1 shows the relationship of the withstand voltage of conductor insulation to earth and the duration of the over-voltage. Curve I and II represent the general behaviour of the major insulation to earth in the area of impulse- and temporary overvoltages. Each area is specified in duration and magnitude.

A: lightning impulse overvoltage

B: switching impulse overvoltage

C: temporary overvoltage

Diagram I: oil insulation

Diagram II: air insulation

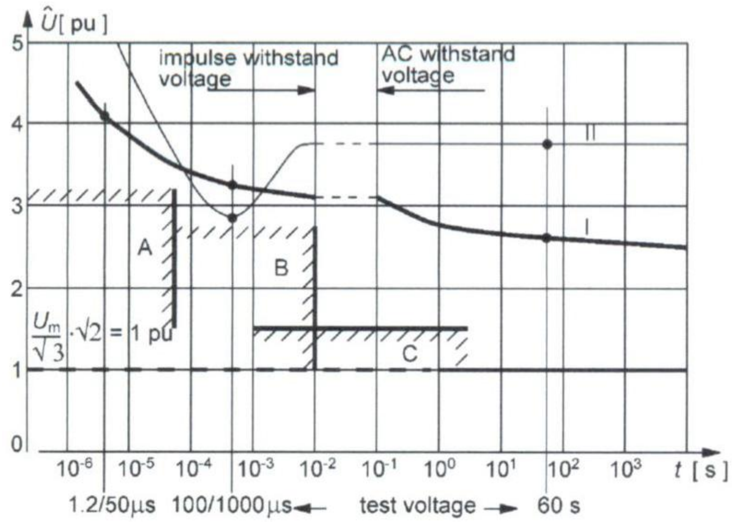


Figure 2.2.1: Insulation levels

For each area (A/B/C) tests are specified, verifying the impulse and AC withstand voltage of the Transformer. The magnitude of the three test voltages depends on the highest voltage for equipment U_m and is defined in IEC and IEEE. For a comparison diagram I & II show the withstand voltage characteristics of oil and air insulated transformers. It should be mentioned that a significant decrease in withstand voltage in the area of switching over-voltages occurs. That is why a switching impulse test is required here in every case, whereas an additional AC voltage test is not necessary. Even though a transformer's durability depends on more factors such as, insulation construction, oil purity, temperature, partial discharge, etc. If the transformer exceeds or runs close to its major insulation level, the operating life time may be decreased.

2.3 Test voltages

2.3.1 Alternating voltages

Regarding the standards, an alternating test voltage may either consist of a voltage electrically energizing a circuit called a separate source, or a voltage across two terminals of a winding, needed to conduct a test called an Induced voltage test. The duration of the alternating test voltage has been traditionally 60 seconds, which is called “one-minute test” at low frequency (close to the rated frequency). For voltages substantially above rated value during an induced voltage test, the core will saturate unless frequency is increased in proportion.

For large high-voltage transformers, the short-time induced voltage test has often been replaced 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 crucially for insulation integrity, while the level of partial discharges is a qualitative measure of the insulation.

2.3.2 Impulse voltages

As seen in section: 2.1, there are actually two different types of transient impulse voltages: The Lightning impulse with a “short” duration and the Switching impulse with a “long” duration. The Lightning impulse is characterized by a steep voltage rise and a fast decay. On the other hand, the switching impulse possesses a longer duration for wave front and –tail. 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 behaviour is similar to that under normal AC voltage and power frequency conditions.

2.4 Electrical test fields

A modern high-voltage test system is mandatory to conduct all common dielectric tests, verifying transformer’s insulation and integrity. It consists of several parts, which are developed and produced by only a handful of manufactures. Due to our vicinity to “HighVolt Prüftechnik Dresden“, specialized in high-voltage test devices, their expertise is very useful in testing of power transformers.

At our grounds we are running two test fields. Because of their spatial dimensions and the installed equipment, they are not convenient for all high-voltage configurations, which depend on size, rated power and voltage of the transformer.

Test field 1 ($U_m \leq 425$ kV)

Test hall

1. Control room

2. Control room

Test field 1 is used as the routine test field for almost every measurement. Because of its larger dimensions (distances to walls etc.), it is allowed to conduct measurements with higher voltages than test field 2.

Test field 2 ($U_m \leq 145$ kV)

Test hall

1. Control room (1)

1. Control room (2)

Test field 2 is feasible for transformer with less rated voltages. Because of small distances to the walls, lightning impulse tests are limited to values where no flash overs will occur.

Digital measuring systems

Digital measuring systems are used for measuring and displaying impulse voltage and current waves as well as AC transients, evaluating impulse parameters for peak voltage, current and time. By means of an analyzing system, test results are stored to a database for evaluation and comparison from different tests. Moreover, in combination with HV components, such as voltage dividers, shunts, chopping gaps or impulse generators, we can control the circuit for easier and faster adjusting for certain test specifications. The measuring systems are integrated in our control rooms (pictured above).

- → Power and instrument transformer controls
- → AC Resonant test system (HighVolt)
- → Impulse voltage test system "MIAS" (HighVolt)

To cover all electric measurements, further devices like AC/DC Peak voltmeter, instrument transformer controls etc. are installed. In fact there are also portable measuring devices (e.g. winding resistance meters, voltage ratio meter, etc.), which are not placed in control rooms.

3 Measurement of winding resistance

3.1 Purpose and Standards

To know a transformer's winding resistance is essential. The value is needed for further calculations and serves a number of functions like:

- Checking the internal winding connections
- Load loss calculations (short-circuit measurement)
- Indirect method, establishing winding temperature and temperature rise within a winding (see section: 14 Temperature rise measurement)
- Verifying electric continuity within in a winding

Standard	Section/Clause	Type of test
IEC	60076-1 Clause 10.2: "Measurement of winding resistance"	Routine test
IEEE	C57.12.90 Clause 5: "Resistance Measurements"	
VDE	0532-76-1	

Table 3.1.1: Associated Standards

3.2 General

Winding resistances are always measured in the unit Ohms [Ω] and is defined as a direct current resistance.

Temperature

It is important to know that the resistivity of the conductor material strongly depends on the temperature. The general statement is with increasing temperature, material's resistivity also rises. For temperatures within the normal operating range the following relation between resistance and temperature is sufficiently accurate:

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

R_1 = resistance at temperature Θ_1
R_2 = resistance at temperature Θ_2
$\Theta_{1,2}$ = temperature in °C
C = constant (function of material type)

Material	IEC [1]	IEEE [51]
Copper	C = 235	C = 234,5
Aluminium	C = 225	C = 225

Table 3.2.1: Material constants

A value of resistance without the respective temperature is not useful, otherwise the resistance will be considered at room temperature. The indirect method of establishing the winding temperature can be achieved by repeating the resistance measurement at a further random temperature.

Winding characteristics at resistance measurement

According to the law of induction, a winding has not only a resistance, but also a large inductance. When a voltage is applied across two terminals (e.g. of a winding), the relationship between voltage and current can be described as:

$$\boxed{u = R \cdot i + L \cdot \frac{\partial i}{\partial t}}$$

u = *applied voltage*
i = *supplied current*
L = *inductance, which is current-dependent*

Readings first may be taken after the current has reached a steady value. Establishing a magnetic field in the winding and switching phenomena influence the resistance value readings (see Figure 3.2.1).

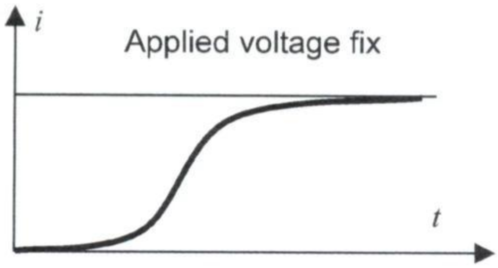


Figure 3.2.1: current properties

3.3 Measuring circuit

There are several methods measuring the winding resistance. The basic methods are the “Kelvin-Bridge” and the “Voltmeter-ammeter Method”. According to IEEE Standard an accuracy of ± 0,5% is required for resistance measurement and ± 1°C for temperature measurements.

Our measuring devices are based on the “Voltmeter-ammeter Method” (see Figure 3.3.1), which is carried out using DC current. The principle is grounded on Ohm’s law, calculating the resistance by the recorded values. The measurement itself is performed using digital meters (see Figure 3.3.2), but can also be performed with conventional analog-meters, which requires simultaneous readings and is not common anymore.

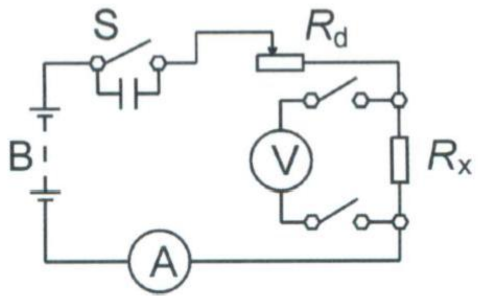


Figure 3.3.1: Principle of voltmeter-ammeter measuring method

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

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

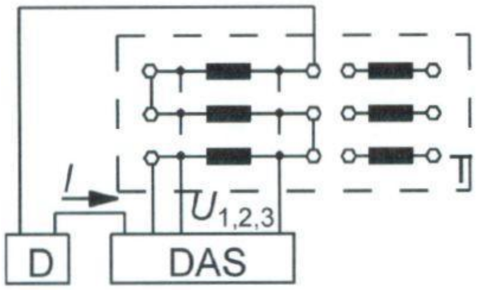


Figure 3.3.2: Measuring circuit (schematic)

D = *DC source*
DAS = *Data Acquisition system*
T = *transformer with the unknown Resistance*

3.4 Measuring procedure

If the transformer is equipped with an off-circuit ratio adjuster or on-load tap changer, the preliminary test of the core-and-coil assembly of this measurement is carried out in all switching and tap changing positions. Whereas in most cases the final measurement of the winding resistance is carried out in the principal tapping position (rated position) and in the tap position with the minimum and maximum number of windings. The winding resistances are always measured between the phases. Depending on the measuring system used, up to four or three windings of the test object connected in series may be measured at the same time. The test is made up by the transformer test system of Tettex Instruments type 2291 or Raytech resistance meter WR50R. Depending on the winding type, phase-to-earth or phase-to-phase resistances are measured.

As noted, the ohmic winding resistances are highly depending on the temperature. For this reason the measurement is effected with a maximum of 10% of the rated current, in order to avoid an unnecessary heat-up of the winding. Additionally the winding temperature is measured, which is implemented by means of a digital thermometer at the bottom of the tank, half way up of the tank's height and on the tank cover. The information obtained are averaged and the results taken to be the mean oil temperature and to be equivalent to the mean winding temperature. An alternative method of test is based on the direct withdrawal of an oil sample and the measurement of its temperature by means of a precision mercury thermometer.

Condition

DC-current value, used for measurement:
Maximum value – 10% of the rated winding current, (IEEE Standard permits 15%)
Minimum value – 1,2 times the magnetizing current crest value

Uncertainty in measurements

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%.

Interpretation of the measured values

As pictured in Table 3.4.1, the resistance might have two different values, depends on the inner circuitry of the transformer (star- or delta connection). This has to be considered when calculating the phase resistance R_{ph}, which is the required value.

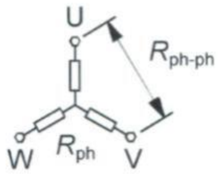
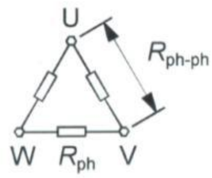
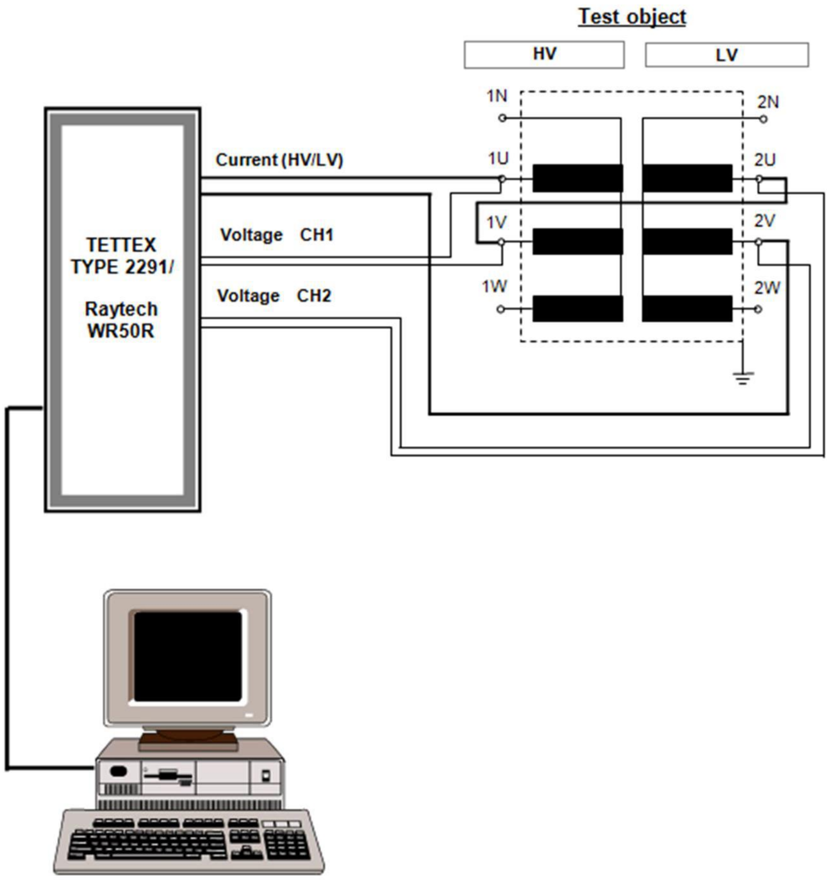
	Star connection 	**Delta connection** 
Phase resistance	$R_{ph} = {}^{1}/_{2} \cdot R_{ph-ph}$	$R_{ph} = {}^{3}/_{2} \cdot R_{ph-ph}$
Line resistance	$R_{ph-ph} = 2 \cdot R_{ph}$	$R_{ph-ph} = {}^{2}/_{3} \cdot R_{ph}$

Table 3.4.1: Difference between Star- and Delta - connection

3.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

TETTEX 2291	Raytech WR50R
	

→ High current micro-ohmmeter

Measuring range:	*2mΩ…20kΩ*
Accuracy:	*± (0,05% of rdg. +0,05 of scale)*

→ Resistance measurement of high inductivities

Measuring range:	*0,5µΩ…1kΩ*	*1mΩ…0,1MΩ*
Accuracy:	*± (0,1% of rdg. + 2 digits)*	*± (0,5% of rdg +. 3 digits)*

4 Voltage ratio & verification of vector group or phase displacement

4.1 *Purpose and Standards*

The voltage ratio and the phase displacement are principally of interest when it comes up to parallel operation with two or more transformers.

Standard	Section/Clause	Type of test
IEC	60076-1 Clause 6: “Connection and voltage displacement symbols for three-phase transformers” Clause 10.3: “Measurement of voltage ratio and check of phase displacement”	Routine test
IEEE	C57.12.90 Clause 6: “Polarity and phase relation test” Clause 7: “Ratio tests”	
VDE	0532-76-1	

Table 4.1.1: Associated Standards

4.2 *General*

Voltage ratio

The voltage ratio is considered to be the ratio between the no-load voltages of HV- and LV-side. Vector groups and their characteristics are only defined for poly-phase transformers. They can be connected in star-, delta- or zigzag-connection, depending on the requirement. The phase displacement between the windings can only be influenced within 30° - steps from 0° to 330°, which depends on the connection method. Transformers parallel operation needs a similar no-load ratio and the same vector group. Otherwise circulating currents would occur between the parallel transformers, what have to be avoided.

The term “voltage ratio” is defined as:

$$\boxed{r = \frac{N_p}{N_s} = \frac{U_p}{U_s}}$$

N = *number of turns*
U = *open-circuit voltage*
p = *primary side*
s = *secondary side*

Vector groups

The most common vector groups according to IEC 60076-1 (Figure 4.2.1).

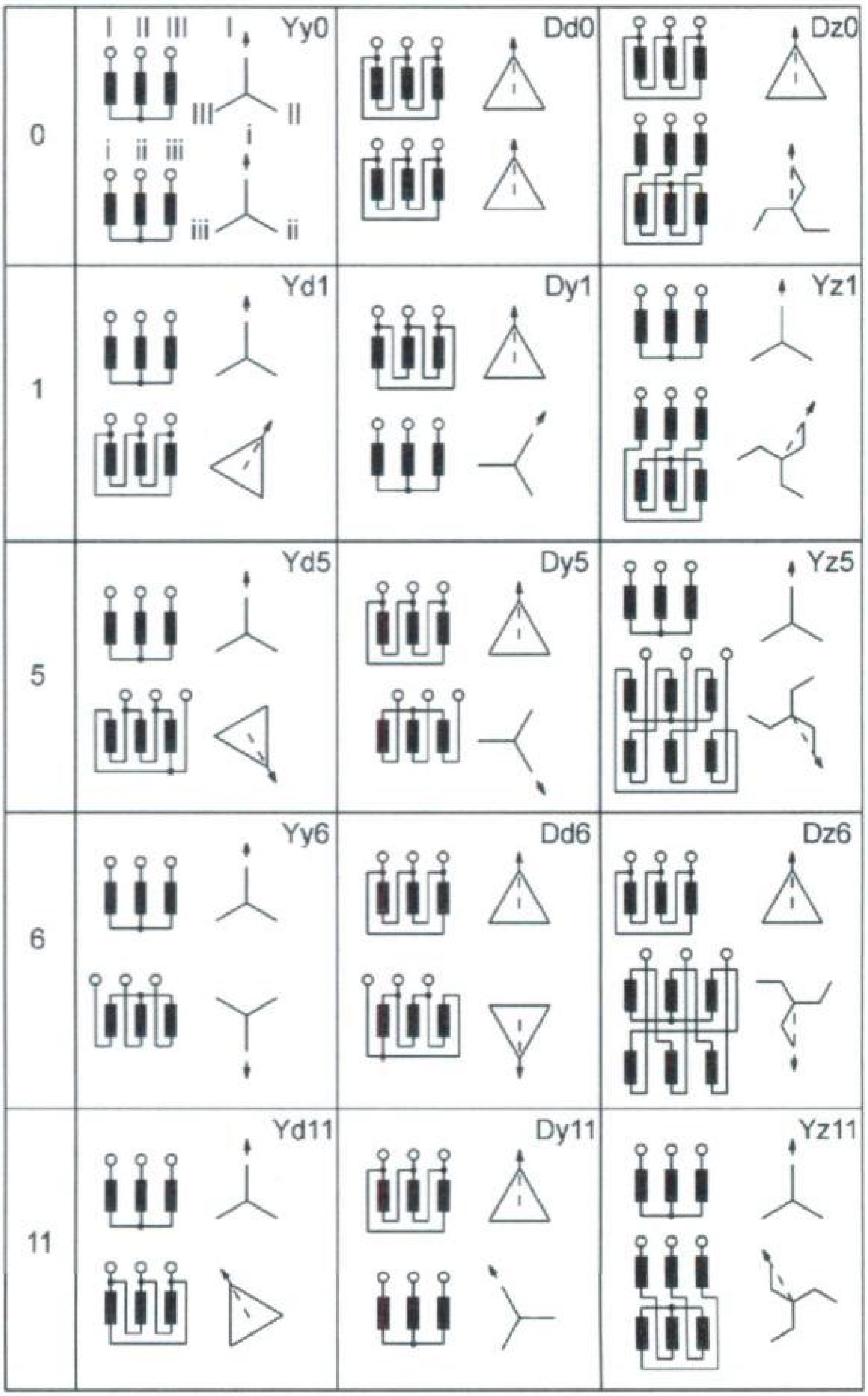


Figure 4.2.1: Common connections (IEC 60076-1)

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. Thereby one hour is equal to 30° phase displacement.
For a zig-zag 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.

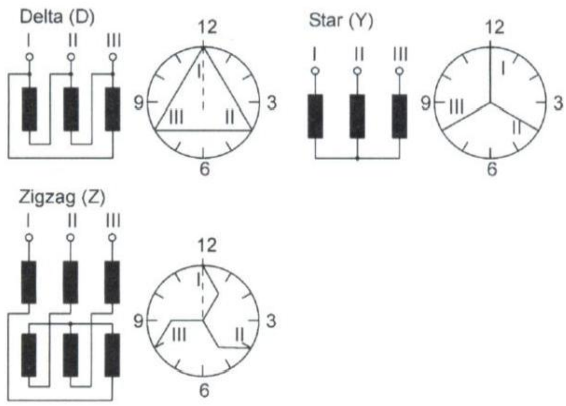


Figure 4.2.2: Illustration of clock-number

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. If there is a neutral, it is defined by the letter "N" (high voltage winding) or "n" (low voltage winding); e.g. Dyn11.

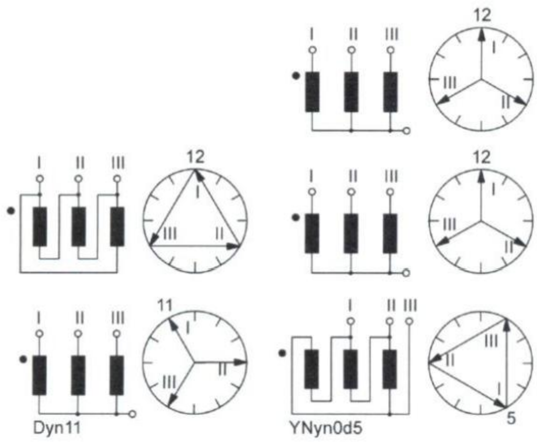


Figure 4.2.3: Examples of clock numbers

IEEE Standard

Vector groups according to IEEE Std. C57.12.90 are essentially the same as the IEC vector groups. The designation of the terminals is H1, H2 and H3 for the high voltage side and X1, X2 and X3 for the low voltage side.

4.3 Voltage ratio measurement

Measuring Circuit

In our test field the digital measuring instruments are comparing the voltage ratios of two windings (Voltmeter-method). The principle measuring circuit is shown in Figure 4.3.1, which is the same for all transformer vector groups. 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.

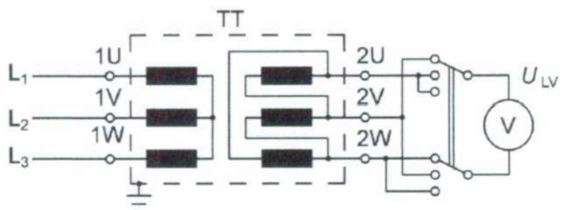


Figure 4.3.1: Principle Voltmeter-method measuring circuit

Procedure

As a condition, the distribution of magnetic flux in the core has to be the same. This means that only windings, winding segments and winding combinations which have the same magnetic flux, can be compared with one another. Normally a reduced voltage is used for the supply. The measurement is carried out with a minimum of three 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 are required. They have practically no load to the transformer because of their high input resistance. A stable voltage source is mandatory to obtain an accurate measured result.

4.4 Vector group verification

Measuring circuit

Determining the vector group is only valid for three phase transformers. This can be applied by connecting a terminal from the low voltage side to a terminal on the high voltage side (see bold lined path in Figure 4.4.1). The terminals 1V and 2V are then galvanically connected, having the same potential. If 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.

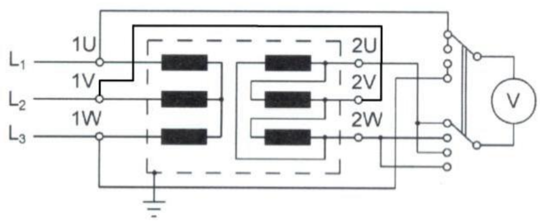


Figure 4.4.1: Principal measuring circuit for verification of the vector group

The measured values of the individual voltages are entered on a phasor diagram, from which the correct polarity and vector group can be determined. In this example terminal 2V has the same voltage as terminal 1V. 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.

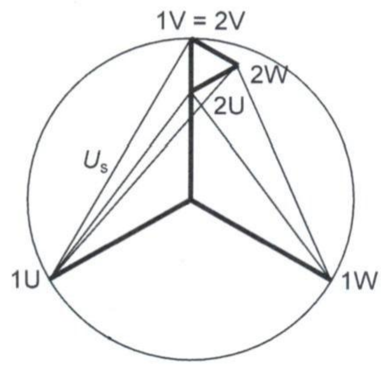


Figure 4.4.2: Graphic display of voltages

Procedure

The measuring instruments, which are the same for voltage ratio, energize the transformer with a symmetric 3-phase voltage supply and conducts the procedure (described above) automatically, creating a chart as a printout, by which the respective vector group is determined (example in Figure 4.4.3). Generally both measurement (voltage ratio & voltage group) can be conducted by the “Tettex 2793a” or “Raytech TR-Spy Mark III”.

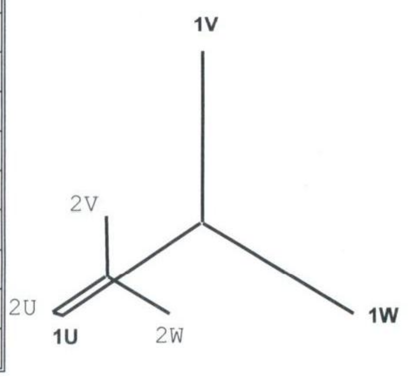
TRANSFORMER-No. : Annex 1 : 1 / 2

CHECKING OF THE VECTOR GROUP BY VOLTMETER METHOD **HV / LV**

Phase 1U on HV-side and phase 2U on LV-side are connected together. The transformer is energized by a symmetric 3-phase 380 V. Voltages of the terminals are measured and vector group symbol is determinated by following chart (tap **11**).

HV-side Main voltage		LV-side Main voltage		Voltage between HV and LV terminals	
Terminals	**U [V]**	**Terminals**	**U [V]**	**Terminals**	**U [V]**
1U-1V	380	2U-2V	53,2	1V-2V	329
1V-1W	381	2V-2W	52,0	1V-2W	358
1W-1U	381	2W-2U	53,3	1W-2V	358
				1W-2W	329

Vector group symbol	Voltage relationship between terminals
0	1W2W<1V2W=1W2V>1W2W<1U1V
1	1W2W<1V2W>1W2V=1W2W<1U1V
2	1W2W<1V2W>1W2V<1W2W<1U1V
3	1W2W<1V2W>1W2V<1W2W≥1U1V
4	1W2W<1V2W>1W2V<1W2W>1U1V
5	1W2W=1V2W>1W2V<1W2W>1U1V
6	1W2W>1V2W=1W2V<1W2W>1U1V
7	1W2W>1V2W<1W2V=1W2W>1U1V
8	1W2W>1V2W<1W2V>1W2W>1U1V
9	1W2W>1V2W<1W2V>1W2W≥1U1V
10	1W2W>1V2W<1W2V>1W2W<1U1V
11	1W2W=1V2W<1W2V>1W2W<1U1V



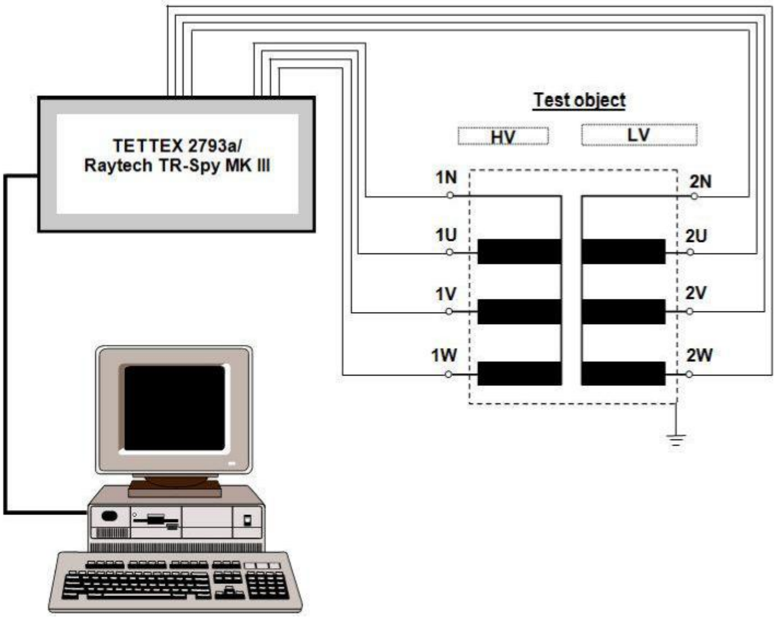
The vector group symbol is ___________

30.01.2013 Sign. :

Figure 4.4.3: Example for measuring results of transformer´s vector group (Yy0)

4.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

TETTEX 2793a

→ voltage ratio, vector group (3-phase)

Measuring range: 0.8:1…13,000:1

Accuracy:	10V	40V	100V
0.8…100	*±0.05%*	*±0.05%*	*±0.05%*
101…1000	*±0.1%*	*±0.05%*	*±0.05%*
1001…1500	*±0.12%*	*±0.05%*	*±0.05%*
1501…2000	*±0.14%*	*±0.08%*	*±0.08%*

Raytech TR-Spy Mark III

→ voltage ratio, vector group (3-phase)

Measuring range: 0.8:1…13,000:1

Accuracy:	10V	40V	100V
0.8:1…2000:1	*±0.15%*	*±0.08%*	*±0.08%*
2001:1…4001:1	*±0.22%*	*±0.1%*	*±0.1%*
4001:1…13000:1	*±0.5%*	*±0.3%*	*±0.3%*

5 Short-circuit voltage & load loss

5.1 Purpose and Standards

Knowing the exact load loss and short-circuit voltage is interesting, not only for the operating costs It is important to know in case of large power transformers (non-permissible temperature rise, see section: 14. Temperature rise measurement). Moreover it gives an indication about the eddy-losses caused by leakage fluxes in mechanical parts like the tank wall, by comparing the calculated and measured values

For transformers with tapped windings the short-circuit voltage has to be measured in the principal tap position and the two extreme tap position additionally.

Standard	Section/Clause	Type of test
IEC	60076-1 Clause 10.1: “General requirement for routine, type and special tests” Clause 10.4: “Measurement of short-circuit impedance and load loss”	Routine test
	60076-8 Clause 10: “Guide to the measurement of losses in power transformers”	
IEEE	C57.12.90 Clause 9: “Load losses and impedance voltage”	
VDE	0532-76-1	

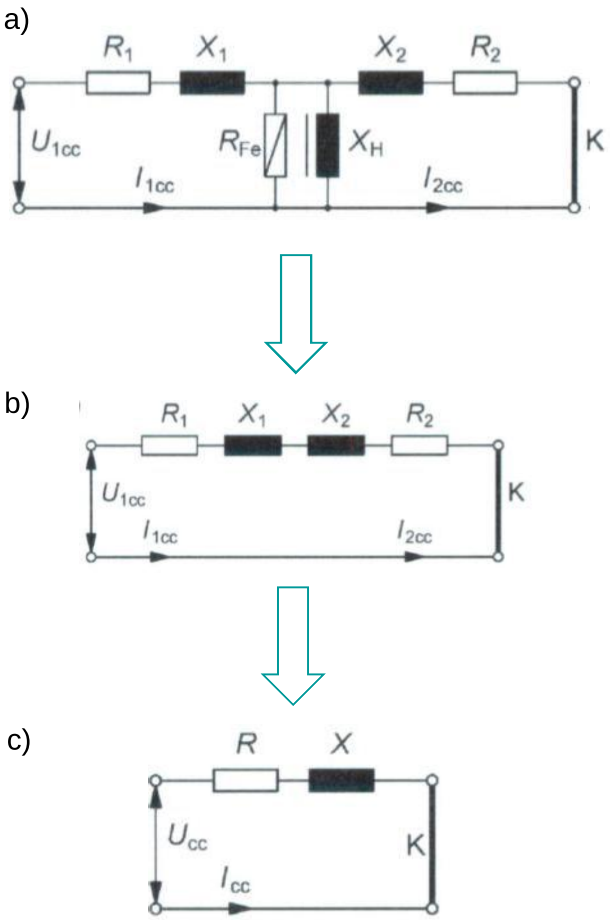
Table 5.1.1: Associated Standards

5.2 General

The generally applicable short-circuit equivalent schematic can be seen in Figure 5.2.1.

The definition of short-circuit voltage and load loss:

> An AC voltage is connected to one winding system of a transformer with the opposite winding system short-circuited. When rated current flows in the short-circuited winding system, the appearing voltage between the terminals is the short-circuit voltage. The absorbed active power corresponds to the transformer load loss.



R_1 = *winding resistance* 1
R_2 = *winding resistance* 2
X_1 = *winding stray resistance 1*
X_2 = *winding stray resistance 2*
R_{Fe} = *represent iron losses*
X_h = *main reactance*
K = *short − circuit lead*

Because of the short-circuit, the iron losses and the main reactance don't have to be considered.

R = $R_1 + R_2$
R_2 = $X_1 + X_2$
U_{cc} = *short − circuit voltage*
I_{cc} = *short − circuit current*

Figure 5.2.1: Scheme for short-circuit

A component of the transformer's no-load losses ($R_{Fe} + X_H$) will also be measured. It can be neglected, since the short-circuit voltage is minimal compared to the rated voltage (exceptions are starting transformers with an air gap, reactor transformers, etc.). The manufacturer ensures all data about short-circuit voltage and load loss.

Short-circuit voltage

According to Figure 5.2.1 c) the short-circuit voltage can be determined as follows:

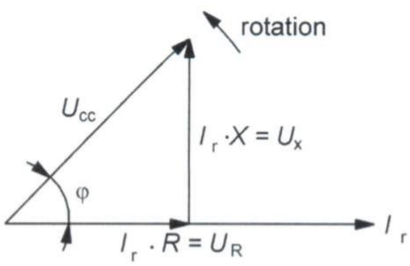


Figure 5.2.2: Short-circuit vector diagram

U_{cc} = *short − circuit voltage* (*voltage drop over impedance*)
U_R = *resistive voltage drop*
U_X = *inductive voltage drop*
ε_{cc} = *relative short − circuit voltage*
U_r = *transformer rated voltage*

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

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

ε_{cc} describes the relative short-circuit voltage. It is given as a percent of the rated voltage. With this value it can be determined which current flows in case of a short-circuit during operation.

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

I_r = *rated current*
I = *short – circuit current*

For power transformers a small value of relative short-circuit is requested unlike furnace arc transformers which have higher relative short-circuit values.

Load loss

The total losses occurring within the transformer when rated current and frequency is applied are represented in the load loss. 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. The load loss is referenced to the winding temperature (75°C according to IEC and 85°C according to IEEE).

$$P_L = P_j + P_a$$

P_L = *load loss*
P_j = *ohmic losses*
P_a = *stray losses*

5.3 Measuring circuit

Figure 5.3.2 and Figure 5.3.1 showing the measuring circuit for load loss measurements on single-phase and three-phase transformers. Usually the short-circuit is applied on the low voltage side of the transformer, because it is more practicable to adapt the test equipment in the test field.

In case of testing three-phase transformers there are principally two different wattmeter configurations possible: the two- and the three-wattmeter method. The three-wattmeter method is preferred, because it more accurate and allows to determine the power per phase (for investigation tests).

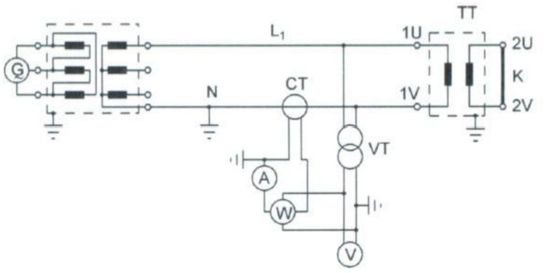


Figure 5.3.2: Measuring circuit for single-phase transformers

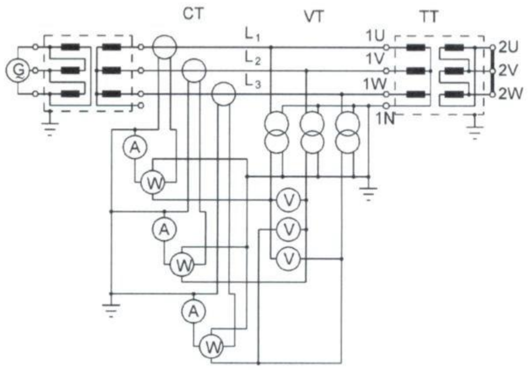


Figure 5.3.1: Three-wattmeter method for three-phase transformers

5.4 Measuring procedure

Winding resistance and winding temperature measurements must be carried out before the actual load loss measurement. If there are built-in current transformers, they must be shorted during the test to avoid saturation of their iron cores and prevent over-voltages at their secondary terminals. The bushing taps must be earthed. If the transformer is equipped with an 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 full measuring current) in order to avoid inrush currents. Its DC component 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 avoiding any significant heating in the windings. Therefore the measuring time at rated current should be about 30 seconds (rule of thumb).

Moreover 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. To confirm the measured results a second measurement with approximately 10% lower current, is recommended. The values should be agreed by extrapolating the two points.

Procedure for three-winding transformers

For three-winding transformers (e.g. additional stabilizing winding) the short-circuit and load loss cannot be determined by a single short-circuit test. They have to be calculated within three different short-circuit tests, allocating the results to every single winding. The following short-circuit tests must be carried out. Losses and impedances 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

Table 5.4.1

Legend:
1 – High-voltage winding
2 – Intermediate-voltage winding
3 – Low-voltage winding

Calculation of the equivalent short-circuit voltage per winding

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

$$\varepsilon_{cc1} = \frac{\varepsilon_{cc12} + \varepsilon_{cc13} - \varepsilon_{cc23}}{2}$$

$$\varepsilon_{cc2} = \frac{\varepsilon_{cc12} + \varepsilon_{cc23} - \varepsilon_{cc13}}{2}$$

$$\varepsilon_{cc3} = \frac{\varepsilon_{cc23} + \varepsilon_{cc13} - \varepsilon_{cc13}}{2}$$

Checking the results:

$$\varepsilon_{cc12} = \varepsilon_{cc1} + \varepsilon_{cc2}$$

$$\varepsilon_{cc13} = \varepsilon_{cc1} + \varepsilon_{cc3}$$

$$\varepsilon_{cc32} = \varepsilon_{cc3} + \varepsilon_{cc2}$$

Calculation of the load loss per winding

Once more a common reference power must be selected (e.g. rated apparent power of the high-voltage winding). The load loss per winding can be recalculated to correspond to the operating conditions. The load losses per winding are not always the same as the actual losses during operation because of the differing configurations of leakage flux during operating conditions with three windings.

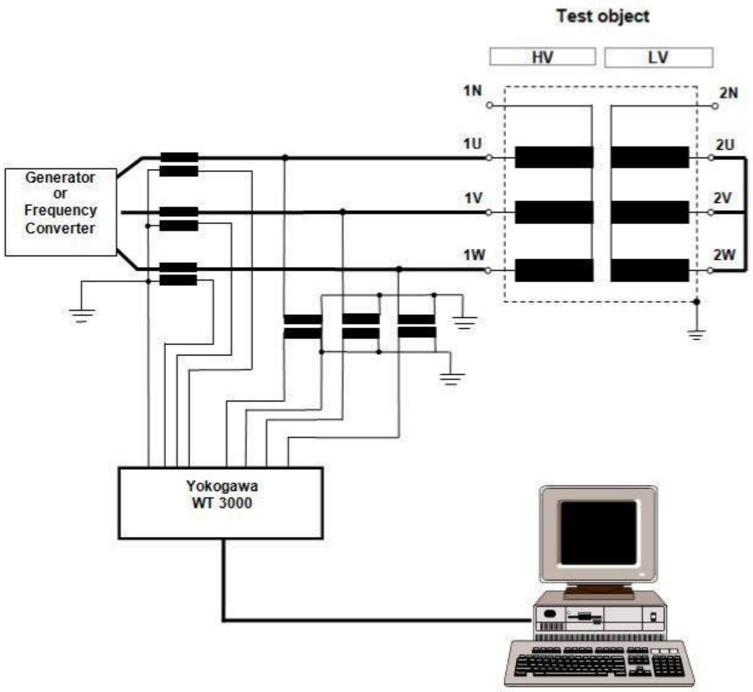
$$P_1 = \frac{P_{12} + P_{13} - P_{23}}{2}$$

$$P_2 = \frac{P_{12} + P_{23} - P_{13}}{2}$$

$$P_3 = \frac{P_{13} + P_{23} - P_{12}}{2}$$

5.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

Yokogawa WT3000

→ Digital Precision Power Analyzer

Accuracy:	*0,01% of basic readings 0,02% of power readings*
Bandwidths:	*DC and 0,1Hz-1MHz*
Direct inputs:	*up to 30 A/1000 V*

Rack

→ contains Power Analyzer, Votlage- and Current transducer controls

Tettex TMS-PT-581

→ Voltage transducer

Output voltage:	*100 V*
Measuring range:	*0,5, 1, 2, 5, 10, 20, 50, 100, 200, 400, 800 kV*
Overall accuracy:	*0,04 % (5-800 kV)* *0,1% (1-2 kV)* *0,15% (0,2-0,5 kV)*

Tettex TMS-CT-582

→ Current transducer

	Test field 1	Test field 2
Output current:	*1 A*	*1 A*
Measuring range:	*1, 2, 10, 20, 40, 100, 500, 1000, 2000, 4000A*	*1, 2, 5, 10, 20, 50, 100, 500, 1000, 2000 A*
Overall accuracy:	*0,005% (40-4000 A)* *0,01% (10-20 A)* *0,03% (4 A)* *0,05% (2 A)*	*0,005% (20-2000 A)* *0,01% (5-10 A)* *0,03% (2 A)* *0,05% (1 A)*

6 Measuring the no-load loss & no-load current

6.1 *Purpose and Standards*

The no-load loss is a very important value, representing a considerable amount of energy during the life-time of the transformer. The no-load losses are caused by the no-load current which is necessary to excite the transformers core. The actual loss figure has to be guaranteed and depends on the sheet material of the core and its manufacturing process.

Standard	Section/Clause	Type of test
IEC	60076-1 Clause 10.1: "General requirement for routine, type and special tests" Clause 10.5: "Measurement of no-load loss and current"	Routine test
	60076-8 Clause 10: "Guide to the measurement of losses in power transformers"	
IEEE	C57.12.90 Clause 8: "No-load losses and excitation current"	
VDE	0532-76-1	

Table 6.1.1: Associated Standards

6.2 *General*

Unloaded Transformer

An energized but not loaded transformer can be seen as an iron core reactor. The equivalent diagram for this case is shown in Figure 6.2.1. The secondary winding can be neglected, because there is no current flow.

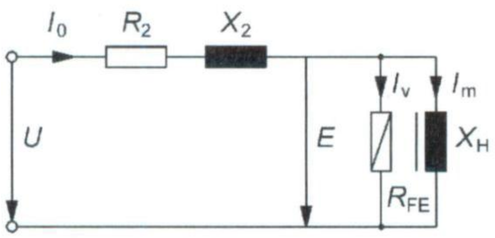


Figure 6.2.1: No-load equivalent diagram

R_2 = *winding resistance*
X_2 = *winding reactance*
R_{Fe} = *iron equivalent resistance*
X_h = *magnetising reactance*
I_0 = *no − load current*
E = *open − circuit voltage*

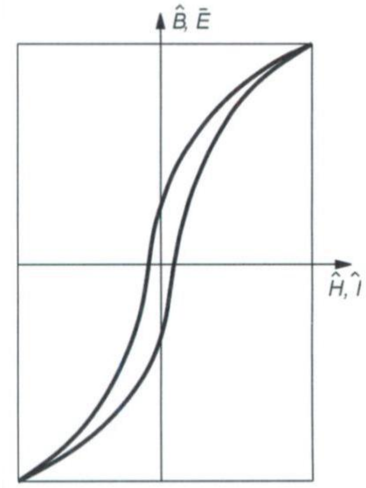


Figure 6.2.2: Magnetic loop

The magnetizing characteristic of the iron core is pictured by the hysteresis curve (Figure 6.2.2). The area inside this dynamic loop is a measure of the energy required to change the flux for on cycle (one period). The smaller the area, the less energy is required.

B = *magnetic induction*
H = *magnetic intensity*
P_{Fe} = *magnetizing losses*
U = *applied voltage*

$$\boxed{P_{Fe} = \frac{U^2}{R_{Fe}}}$$

No-load current

The no-load current express the sum of the current needed for the magnetization of the core and a capacitive current reflecting the capacitances between the windings. Because of the non-linear magnetization characteristic of the iron core, the corresponding no-load current is naturally distorted when a sinusoidal voltage is applied (see Figure 6.2.3). The measured no-load current is as RMS value. It is generally expressed in percentage of the rated current and is about 1 to 5 % for small power transformers and 0,1 to 0,3% for large power transformers. For three-phase transformers the value is the average of the three windings.

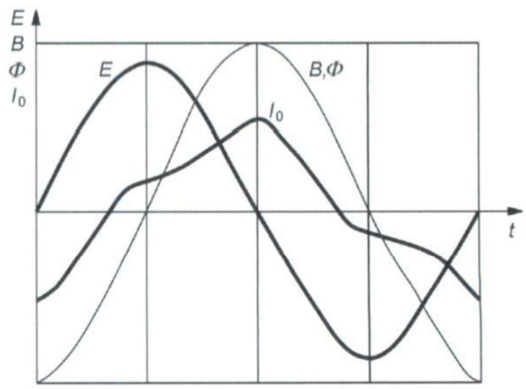


Figure 6.2.3: No-load current I_0

No-load loss

The no-load loss of a transformer consists of several components:

a) Iron losses $\quad P_{Fe} = P_h + P_w$

(P_h = hysteresis losses; P_w = eddy losses)

b) Dielectric losses $\quad P_c = U^2 \cdot \omega C \cdot tg(\delta)$

c) Winding losses $\quad P_j = I_0{}^2 \cdot R_2$

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

SIEMENS

Usually dielectric and winding losses are negligible, because for power transformer they are several orders of magnitude smaller. That means that the no-load losses P_0 are equal to the iron losses P_{Fe}, which consist of hysteresis losses (depending on sheet metal of the core) and eddy losses (depending on sheet thickness). There're exceptions like starting transformers with an air gap.

Relationship between no-load loss and voltage distortion

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 (generator/matching transformer).
Hysteresis losses P_h depending on the average value of applied voltage. If this voltage is properly set, P_h is not affected by voltage distortion. The eddy losses P_W on the other hand are a function of the square of the RMS voltage, the same as the losses in a DC resistance. However, the RMS value is affected by the voltage distortion, which includes the eddy losses.

Those voltage distortions do not occur during operation because the impedance of the supply system is much smaller than the transformers main inductance X_h. Comparing the losses of different transformers, the no-load losses are guaranteed using a sinusoidal supply. Losses measured with distorted voltage must be recalculated.

Relationship between no-load loss and iron temperature

No-load loss temperature dependence can be seen only at relatively high temperature variations. That is why transformers should be tested at the ambient temperature in the test field (about 20°C, according to IEC/IEEE). Corrections of the measured no-load losses are not required, if the following conditions are hold:

a) The average oil 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:

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

$$\begin{aligned} P_0 &= no-load\ loss\ at\ 20°C\ oil\ temperature \\ P_{0m} &= no-load\ loss\ at\ average \\ &\quad\ oil\ temperature\ during\ test \\ \Theta_{m_{Fe}} &= average\ oil\ temperature\ during\ test \\ K_T &= empirical\ coefficient \end{aligned}$$

6.3 *Measuring circuit*

Single-phase transformer

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 and generator and matching transformer windings. 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, which 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 (seen from the supply side, see Figure 6.3.1).

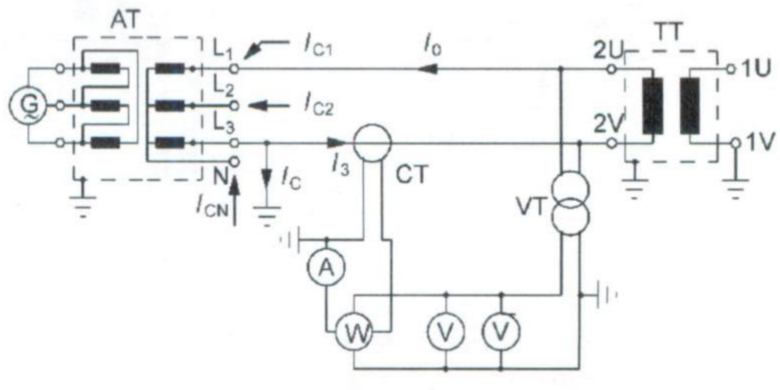


Figure 6.3.1: Influence of capacitive currents

I_3 = *resultant current*
I_C = *capacitive currents*
I_0 = *no − load current*
AT = *matching transformer*

Three-phase transformer

When testing three-phase transformers, the voltages induced in the individual windings (phase voltages) must be measured to determine the form factor of the voltage. The form factor for star-connected windings is different, because it cannot include harmonics divisible by three. The individual elements of the measuring circuit should fulfil 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

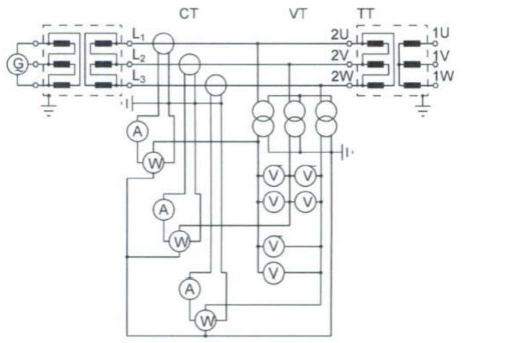
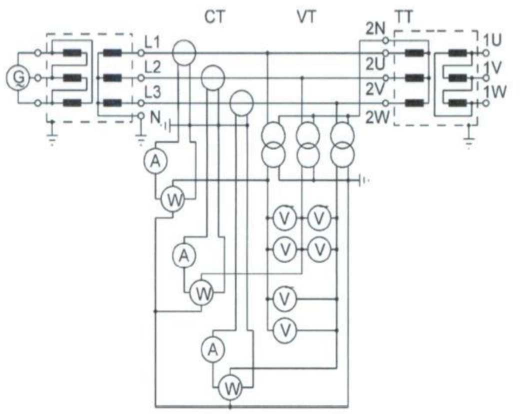
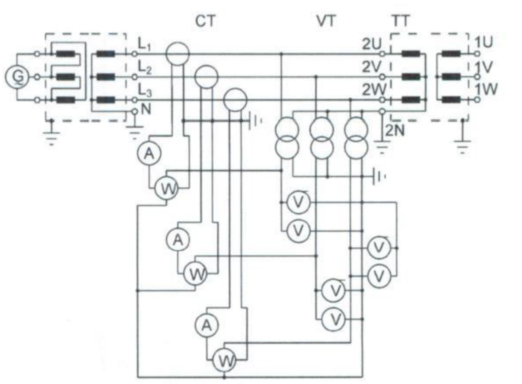
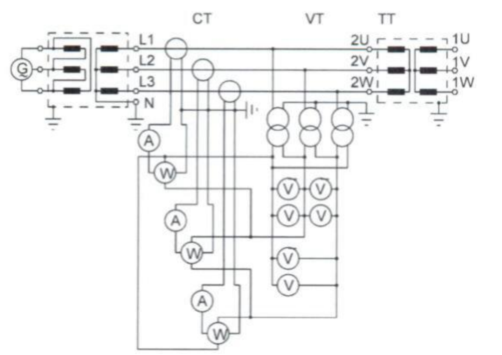
Vector groups	Remarks	Measuring circuit
Yd YNd Dd	▪ Voltage transformers and wattmeters are connected in star ▪ Voltmeters are connected between two phases and measure the line-to-line voltages, which are also the phase voltages for a delta-connected transformer under test.	
Dyn	▪ Voltage transformers and wattmeters are connected in star ▪ Voltmeters measure the line-to-line voltages (allowed, because third order harmonic currents can flow in the high-voltage winding due to the delta connection → voltage distortions on the low-voltage winding are avoided)	
Yyn YNyn	▪ Voltmeters must measure the phase voltages	
Yy YNy	▪ Voltage transformers are delta-connected on the secondary ▪ Voltmeters measure the line-to-line voltages	

Table 6.3.1: Measuring circuits

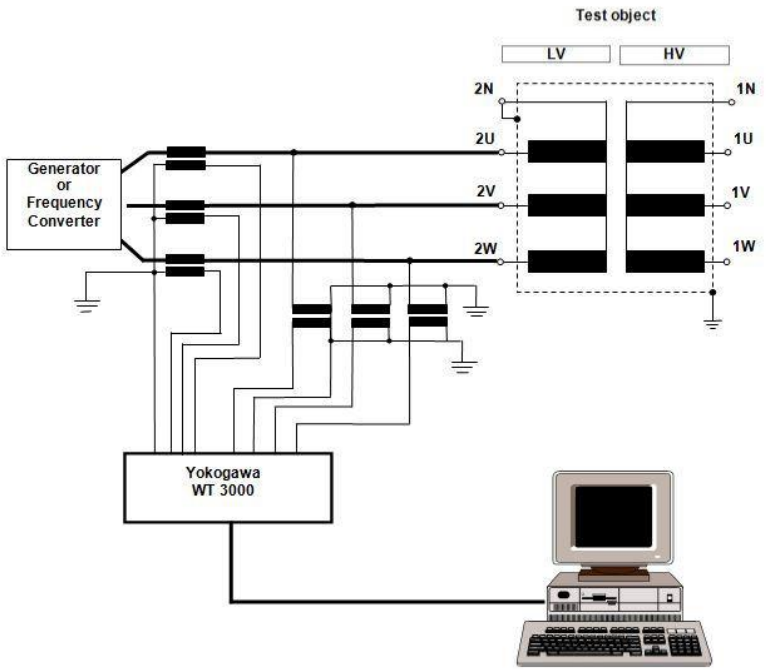
6.4 Measuring procedure

Because there are lower voltages required, the no-load measurement is carried out on the low-voltage side of the transformer under test. Built-in current transformers must be shorted during the test and condenser bushing taps must be earthed. 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 must be checked. Before the actual loss measurements take place the transformer must be excited by 1,1 to 1,15 times rated voltage. The over-excitation reduces the effects of remanence caused by direct current excitation during resistance measurement or from the Switching impulse test. Until the measured figures are not steady, the actual loss measurement cannot start.

Typically, measurements are taken starting at 110 and decreasing to 100, 90 and 80% of rated voltage. When testing large three-phase units the three watt-meters may show differing figures. It is even possible for one wattmeter reading to be negative. 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. After all, the actual input power is the sum of the readings of three watt-meters. The measuring instrument “Yokogawa WT3000” does this automatically, since it has more than three input channels.

6.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

Yokogawa WT3000
→ Digital Precision Power Analyzer

Accuracy:	*0,01% of basic readings* *0,02% of power readings*
Bandwidths:	*DC and 0,1Hz-1MHz*
Direct inputs:	*up to 30 A/1000 V*

Rack
→ contains Power Analyzer, Votlage- and Current transducer controls

Tettex TMS-PT-581
→ Voltage transducer

Output voltage:	*100 V*
Measuring range:	*0,5, 1, 2, 5, 10, 20, 50, 100, 200, 400, 800 kV*
Overall accuracy:	*0,04 % (5-800 kV)* *0,1% (1-2 kV)* *0,15% (0,2-0,5 kV)*

Tettex TMS-CT-582
→ Current transducer

	Test field 1	Test field 2
Output current:	*2, 4, 8 A*	*2, 4, 8 A*
Measuring range:	*1, 2, 10, 20, 40, 100, 500, 1000, 2000, 4000A*	*1, 2, 5, 10, 20, 50, 100, 500, 1000, 2000 A*
Overall accuracy:	*0,005% (40-4000 A)* *0,01% (10-20 A)* *0,03% (4 A)* *0,05% (2 A)*	*0,005% (20-2000 A)* *0,01% (5-10 A)* *0,03% (2 A)* *0,05% (1 A)*

7 Separate source AC withstand voltage test (Applied voltage test)

7.1 Purpose and Standards

The test is designed to check the main insulation of the transformer. This main insulation is generally understood as the insulation system between two windings (major insulation), but also the insulation between the winding and earth (end insulation) and all connections to earth.

Standard	Section/Clause	Type of test
IEC	60076-3 Clause 11: “Separate source AC withstand voltage test”	Routine test
IEEE	C57.12.90 Clause 10.6: “Applied voltage tests”	
	C57.12.00 Clause 5.10: “Insulation levels”	
VDE	0532-76-3	

Tabelle 7.1.1: Associated Standards

7.2 General

In this test a separate AC source is applied to the transformer (“applied-voltage test”). For transformers with uniform insulation every part of the winding is exposed to the test voltage U_p, which relates to the insulation level of the transformer between the windings and earth. In case of transformers with graded insulation between their windings, the test voltage must be adjusted to the lowest insulation requirements (usually the winding end or neutral).

7.3 Measuring circuit

The principle test circuit is shown in Figure 7.3.1. The equivalent diagram of the transformer under test is an R-C parallel circuit consisting of the effective capacitance C_P, representing the capacitance between the winding under test and earth (including the bushing capacitance) or between the other windings, and the resistor R, representing the insulation (Figure 7.3.2). The used principle measuring circuit in test laboratory is shown in Figure 7.3.3.

G = *variable voltage source*
U_P = *test voltage*
W_1 = *tested winding*
W_e = *earthed winding*
C_E = *capacitance to earth*
C_W = *capacitance between windings*
K = *transformer tank*
L_S = *compensating reactor*
TT = *transformer under test*
PT = *testing transformer*
HM = *HV measurement equipment*
VT = *voltage transformer with voltmeter to verify the primary voltage*
CT = *current transformer with ammeter to measure the generator current*
R_d = *damping resistor*

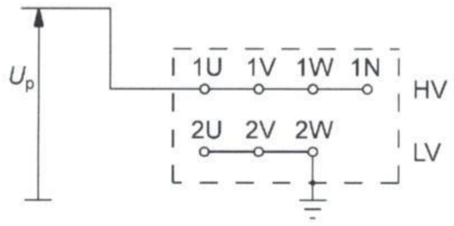


Figure 7.3.1: Test connection for a three-phase transformer

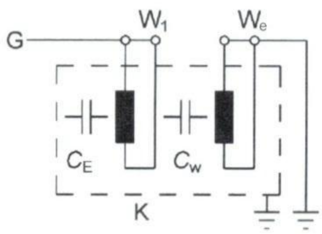


Figure 7.3.2: Capacitances of the transformer

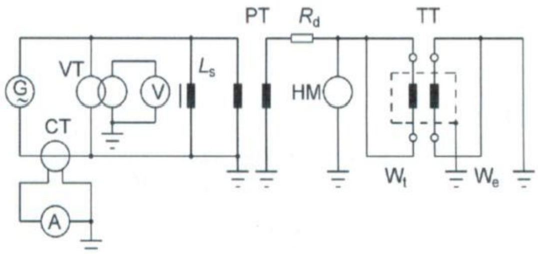


Figure 7.3.3: Measuring circuit

7.4 *Measuring procedure*

Before the test can be carried out, it must be ensured that the whole winding insulation is calculated properly for the test voltage. Care must be taken for transformers with graded insulation (non-uniform), where the voltage level must be adjusted to the insulation of the transformer neutral. In this case each phase will be tested individually, see test connections in Induced voltage tests for non-uniform transformers

The Buchholz-relay and all bushings must be degassed before the test; any surge arresters and bushings arcing horns must be removed. 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. Generally the test must be carried out at ambient temperature (at least 10°C). During the test, the voltage is applied directly to the bushings of the transformer windings by a single-phase source. All other windings and the tank must be earthed (see Figure 7.3.1).

Voltage, frequency and duration

The test voltage U_p is a RMS value [kV] and represent the withstand voltage of the insulation (given in the IEC 60076-3, clause 7). It depends on the respective highest voltage for equipment U_m. The table below shows an extract for some values. The applied test voltage should be raised rapidly from 25% or less to the test voltage U_p and remain constant for 60 seconds. At the end of the test the voltage should be reduced rapidly (in about 5 seconds). The test frequency should be the rated frequency. The measured values may be read directly by means of a capacitive voltage divider and an AC peak voltmeter. This method is characterized by a high accuracy, achieving precise measurements.

Highest voltage for equipment U_m [kV]	Rated separate source AC withstand voltage [kV]
…	…
52	95
60	115
72,5	140
100	185
123	230
145	275
170	325
…	…

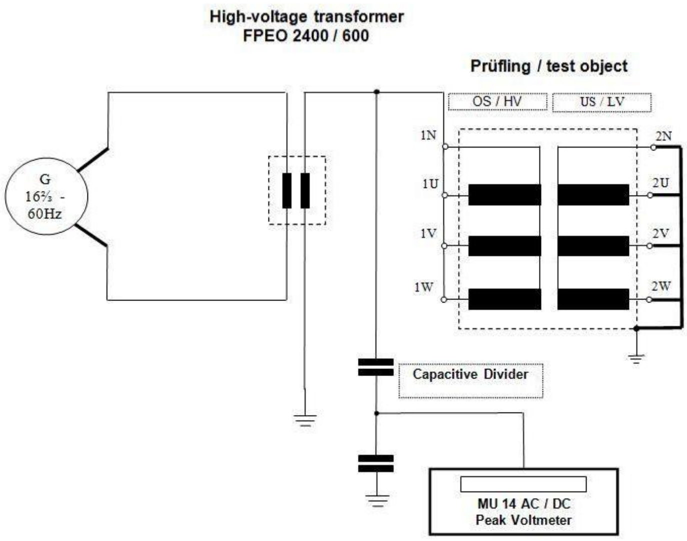
Table 7.4.1: Rated withstand voltages for transformer windings

Acceptance criteria

The test is successful if the test voltage does not collapse or if there is no indication of other faults (smoke, bubbles, sudden current increase).

7.5 Appendix: Measure arrangement of customized vector group

Test circuit 1 ($U_m \geq 230$ kV)



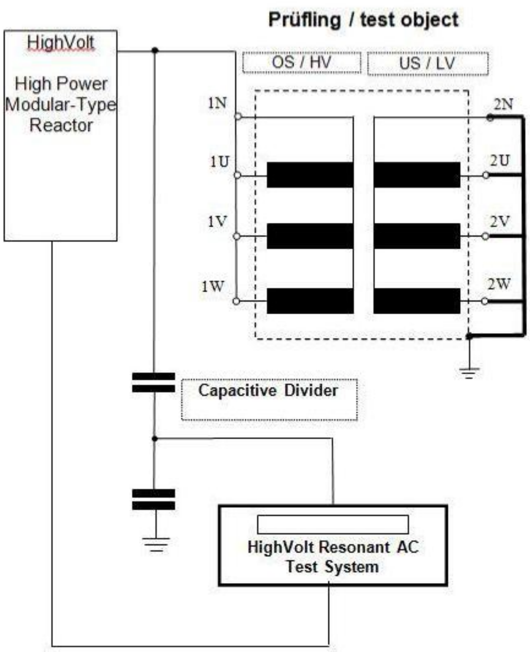
Measuring instruments

FPEO 2400/ 600 (HV-Transformer)

MU 14 (AC/DC Peak Voltmeter)

Measuring quantities:	$\hat{U}$; $\hat{U}/\sqrt{2}$; RMS -value
Accuracy:	max. ±0.5%

Test circuit 2 ($U_m \leq 375$ kV)



Measuring instruments

Reactor

Rated Power:	1750 kVar
Inductance:	235 H

Resonant AC test system

8 Switching impulse test & Lightning impulse test

8.1 Purpose and Standards

The purpose of the test is to verify the integrity of the insulation for transient voltages, which are caused by atmospheric phenomena (lightning strikes), switching operations or network flaws.

Standard	Section/Clause	Type of test
IEC	60060-1 High-voltage test techniques – Part 1: "General definitions and test requirements"	Routine tests LI for U_m > 72,5 kV SI for U_m > 300 kV for the rest: Special tests
	60060-2 High-voltage test techniques – Part 2: "Measuring systems"	
	60060-3 High voltage test techniques – Part 3: "Definitions and requirements for on-site tests"	
	60076-3 Power Transformers – Part 3: "Insulation levels, dielectric tests and external clearances in air"	
	60076-4 "Guide to lightning impulse and switching impulse testing of power transformers and reactors"	
IEEE	C57.12.90 Clause 10: "Dielectric tests"	Routine tests LI for U_m > 115 kV SI for U_m > 345 kV for the rest: Other tests
	C57.98 "Guide to impulse testing techniques, interpretation of oscillograms and failure detection criteria"	
VDE	0532-76-3 0532-76-4	acc. to IEC

Table 8.1.1: Associated Standards

8.2 General

Because impulse tests always mean high dielectric stresses for the insulation system, it is possible that hidden damages occur, which will be identified during the voltage insulation tests. That is why, if not otherwise specified, the impulse test (SI and LI) precede the insulation tests (applied voltage test and induced voltage test in combination with PD measurements).

Impulse shapes

Switching impulses as well as lightning impulses have standardized wave shapes. The following table shows the essential differences.

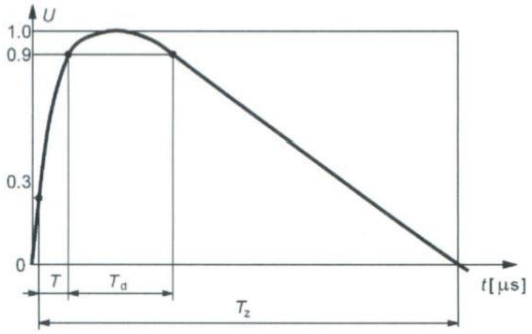
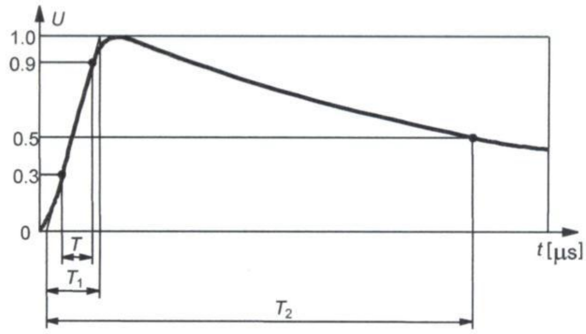
Switching impulse (SI)	Lightning impulse (LI)
	
Front: T_1 : 100 µs Tail: T_2 : 1000 µs T_d: 200 µs[1] Polarity: negative[2]	Front: T_1: 1,2 µs (± 30%) = 1,67 · T Tail: T_2: 50 µs (± 20%) Polarity: negative[2]
→ one characteristic wave form	→ Three different wave shapes a) full wave (pictured above) b) tail chopped wave c) front chopped wave (only required by IEEE Std.) → chopped waves • peak should be 10% higher full wave value • chopping after T_C = 2 – 6 µs • overshoot U_s not higher than 30% of test amplitude
<u>Test sequence (acc. IEC)</u> → impulse at about 60% of the specified insulation level → three impulses at the specified insulation level Consider: It may force the core into saturation, because switching impulse represents a time integral of the applied voltage to the transformer.	<u>Test sequence (acc. IEC)</u> → one reduced level full impulse (calibration) → one full level full impulse → one reduced level chopped impulses (if requested) → two full level chopped impulses (if requested) → two full level full impulses (Chopped wave should have an amplitude of 110% of full wave amplitude)

Table 8.2.1: Characteristics of Switching- and Lightning impulse

[1] time above 90% of peak voltage
[2] for oil insulated transformers

To prevent flashovers on the air-side of the transformer bushings, the polarity of the impulse voltages is generally negative. Because of their unusual aperiodic waveform transient voltages cannot be generated perfectly. Therefore the definition of rise time needs additional specification: A straight line from the bottom to the peak, passing through the voltage values 0,3 and 0,9 times the crest value, gives the rise time (see figures in Table 8.2.1; SI and LI). The rise time T_1 is then 1,67 times the time between these two voltage values.

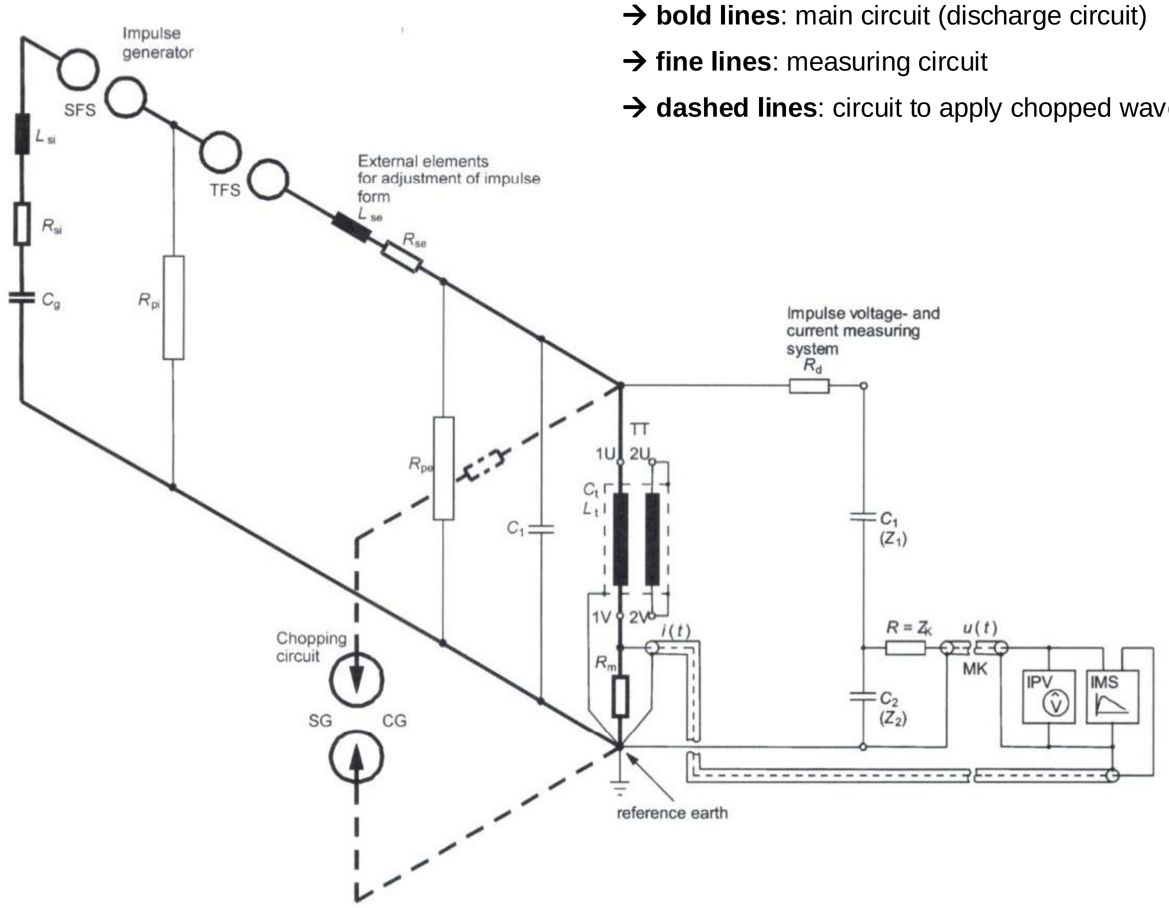
8.3 Measuring circuit

The following figure shows the impulse test circuit with all its components. It is illustrated in three ways to make out the different parts of the circuit:

→ **bold lines**: main circuit (discharge circuit)

→ **fine lines**: measuring circuit

→ **dashed lines**: circuit to apply chopped wave



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 disharge resistor*

L_{se} = *external stray inductance*

R_{se} = *external damping resistor*

R_{pe} = *external disharge 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*

MK = *coaxial measuring cable*

IPV = *impulse peak voltmeter*

IMS = *impulse measuring circuit*

The configuration of the test connection should be selected so that it corresponds with conditions under operation. So there are lots of test configurations possible. Only single-phase impulses are considered occurring most of all in the grid. Therefore non-tested winding terminals have to be earthed. Figure 8.3.1 shows the most common test connections. The impulse test sequence is applied to each of the line terminal. Other line terminals (three-phase transformers) shall be earthed directly or through a low impedance.

According to IEC Standard, transformers with tapped windings are tested with the two extreme- and the principal tapping position (one tapping for each of the three individual phases of a three-phase transformer), unless nothing else has been agreed. If the tapping range is 5% or less only the principal has to be tested.

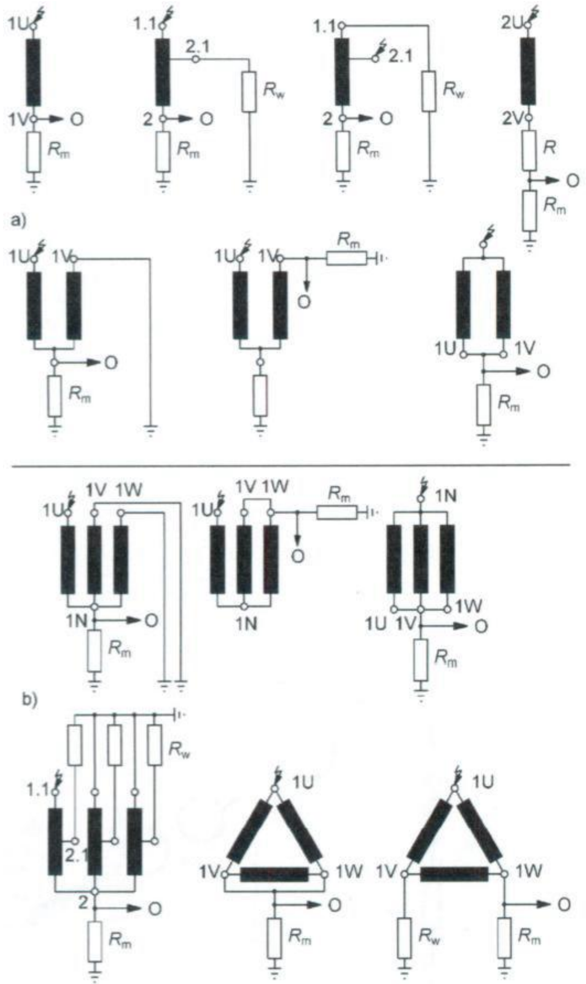


Figure 8.3.1: Common test connections

R_W = *resistor with value equal to line wave impedance*
R_m = *measuring shunt*
R = *series resistor*
O = *oscillograph*

8.4 Measuring procedure

Preparation

Before conducting the impulse tests (Lightning- and Switching impulse), the transformer will be checked for the following points:

- standing time
- confirming measurement of voltage ratio, polarity and winding resistance
- oil level and quality
- vent the Buchholz relay and porcelain bushings
- short-circuit and earth any built-in transformers
- earth the capacitive bushing taps
- check on-load or off-load tap changer positions

Steps

The actual impulse tests:

- calibrating and verifying the impulse voltage waveform
- applying the impulse voltage to the transformer under test (see test sequence)
- verifying that the transformer under test had withstood the stresses without damage (by comparing oscillographic recordings)

Acceptance criteria

The switching and lightning impulse tests are successfully if the recordings of the oscillographics do not show any changes (close similarity in wave form; between calibrated voltage and applied test voltage). If the waveforms are deviated from each other, the reasons have to be determined.

8.5 Test equipment for high-voltage tests

In this section the most important components of our high-voltage test field are introduced. They are mandatory to simulate Switching- and Lighting impulse voltages.

Impulse voltage generator

An Impulse voltage generator is an electrical apparatus which produces very short high-voltage surges. They are used to test the strength of electric power equipment against lightning and switching surges. The main components are capacitors, which are separated in stages, connected in series by spark gaps. By charging the stages with positive or negative DC voltage, the charging voltages totalize to the required impulse voltage. Additionally the waveform of the impulse (front/tail) can be adjusted by the contained resistors. The applicable impulse voltages of Impulse Generator in Test field 2 are limited, because of the close distance to the wall.

Test field 1

IG 300/2000G

Number of stages:	n	= 10
Capacitance per stage:	C_S	= 1500 nF
Charging voltage per stage:	U_I	= 190 kV
Total charging voltage:	U_Σ	= 1900 kV
Total charging energy:		≤ 300 kJ
Lightning impulse voltage: (permitted)	U_P	= 1675 kV
Switching impulse voltage: (permitted)	U_P	= 1100 kV

Test field 2

IG 120/1600G

Number of stages:	n	= 10 (extended)
Capacitance per stage:	C_S	= 1500 nF
Charging voltage per stage:	U_I	= 190 kV
Total charging voltage:	U_Σ	= 1900 kV
Total cha ging energy:		≤ 150 kJ
Lightning impulse voltage: (permitted)	U_P	= 650 kV
Switching impulse voltage: (permitted)	U_P	= 350 kV

Multiple chopping gap

To simulate impulse voltage with chopped waveforms, the applied voltage has to be reduced to zero within a certain time (µs). Therefore a multiple chopping gap is necessary to force voltage collapses within the applied impulse voltage. The chopping can be realized at the front or at the tail of the impulse wave.

AFC 890/1800

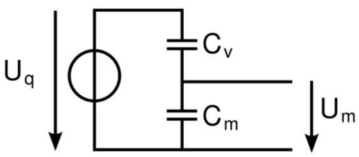
Number of stages:	n = 9
Gap range/stage	5…120 mm
Operating range/stage:	n · (60…200)kV
Chopping voltage:	540…1800kV
Chopping time:	2…6µs (±50ns)
Capacitance/stage:	9 nF

AFC 200/1200

Number of stages:	n = 6
Gap range/stage	5…120mm
Operating range/st ge:	n · (60…200)kV
Chopping voltage:	360…1200kV
Chopping time:	2…6µs (±50ns)
Capacitance/stage:	8 nF

Capacitive voltage divider

Voltage dividers are useful for measuring high voltages, which cannot be handled by the measuring system. Similar to an potential divider with ohmic resistors, two capacitances are connected in series, where one serves as measuring capacitance C_m with a considerably larger capacitances referred to C_v. By means with the common formula for voltage dividers, the voltage can be reduced to a harmless dimension for the corresponding measuring equipment.



$$U_m = U_q \cdot \frac{C_v}{C_v + C_m}$$

SMCF 1000/1600

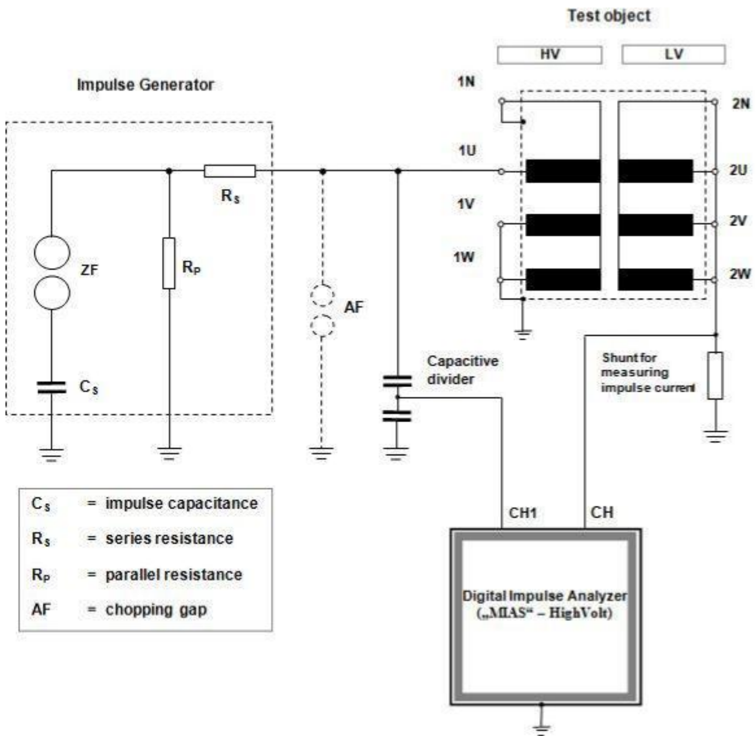
Rated voltage:	2000kV
Number of divider stages:	4 (400-800-1600-2000 kV)
Capacitance of voltage divider:	1 nF

SMCF 1333/1200

Rated voltage:	1200 kV
Number of divider stages:	5 (200-400-600-800-1200 kV)
Capacitance of voltage divider:	1,333 nF

8.6 Appendix: Measure arrangement of customized vector group

Test circuit



8.7 Transferred overvoltage

Lightning and Switching surges can be transferred from one voltage level to another through transformer couplings. A distribution system, which may not be directly exposed to the overvoltages of atmospheric origin, but is connected to a utility system through a transformer of high turns ratio will be exposed to overvoltages on the secondary side due to overvoltages on the primary windings. The resulting stresses on the distribution system may exceed the basic insulation levels (BIL). The inspection of transferred overvoltages is only justified for large generator step-up transformers, which have a large voltage ratio and high-voltage network transformers with a low-voltage tertiary winding.

Standard	Section/Clause	Type of test
IEC	60076-3 Annex B “Overvoltage transferred from high-voltage winding to a low voltage winding”	Special test
VDE	0532-76-3	

Table 8.7.1: Associated Standards

The issue of transferred overvoltage is also treated from a system viewpoint in IEC 60071-2 Annex A.

Procedure

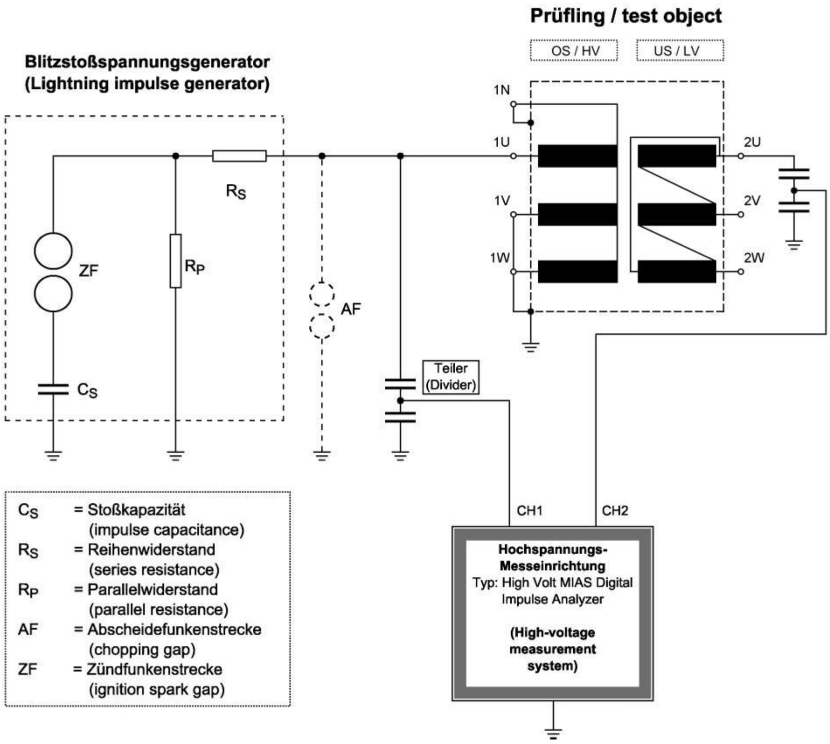
When the low-voltage winding cannot be subjected to lightning over-voltages from the low-voltage system, this winding may be impulse tested with surges transferred from the high-voltage winding. This method is also be preferred when the design is such that an impulse directly applied to the low-voltage winding could result in unrealistic stressing of higher voltage windings, particularly when there is a large tapping winding physically neighbouring to the low-voltage winding.

With the transferred surge method, the tests on the low-voltage winding are carried out by applying the impulses, at lower impulse levels (approximately 25% of original impulse level) to the neighbouring higher voltage winding. The line terminals of the low-voltage winding are connected to earth through resistances of such value that the amplitude of transferred impulse voltage between line terminals and earth, or between different line terminals or across a phase winding, should be as high as possible but not exceeding the rated impulse withstand voltage. The magnitude of the applied impulses shall not exceed the impulse level of the winding to which the impulses are applied.

This method is also applicable, as a special procedure, with low voltages (usually 100V). Therefore a mini impulse generator with integrated chopping gap and adjustable impedances is needed.

Mini impulse generator

Test circuit



The impulse voltage will be applied on each high-voltage terminal (except neutral). The transferred overvoltage will be measured on each low-voltage terminal separately, which means that nine measurements have to be taken in total. The acceptance criteria are the same as for the standard impulse voltages.

High-voltage terminal (impulse applied)	Low-voltage terminal (transferred overvoltage)
1U	2U
	2V
	2W
1V	2U
	2V
	2W
1W	2U
	2V
	2W

9 Partial Discharge Measurement

9.1 Purpose and Standards

A partial discharge measurement is another important way to verify the transformers insulation system, ensuring that no harmful PD sources exist. The purpose of a PD-measurement is to detect and localize areas where partial discharges are about to occur, typically cavities or conducting particles inside the insulating material. Those areas are exposed to higher dielectric stresses, which in the long run can be very harmful to transformers insulation (e.g. electric breakdown). So usually PD-measurements are carried out in conjunction with dielectric tests (Induced voltage test).

Standard	Section/Clause	Type of test
IEC	60076-3 Annex A "Application guide for partial discharge measurements during AC withstand voltage test on transformers according to 12.2, 12.3 and 12.4"	Routine test for U_m > 72,5 kV
	60270 "Partial discharge measurements"	
IEEE	C57.12.90 Clause 10.8/10.9: "Induced voltage tests"	Routine test for U_m ≥ 115 kV
VDE	0532-76-3	Routine test

Table 9.1.1: Associated Standards

Because the partial discharge measurement and the induced voltage test are carried out simultaneously, the corresponding measuring circuit of the customized vector group is consolidated in the next section ("Induced voltage test", see 10.5 Appendix: Measure arrangement of customized vector group).

9.2 General

A partial discharge is a partial voltage breakdown within a series of insulating elements between two electrodes (of different potentials). It can be interpreted as an electric charge from one position to another. For very fast changes the individual insulation links between two line terminals can be regarded as a number of series connected capacitors, where is a potential source for discharges (Figure 9.2.1 and Figure 9.2.3). The excessive stress in these “weak” spots can result from design- or insulating material flaws or deviations in the manufacturing process. A damage to the insulation caused by previous tests is also possibie.

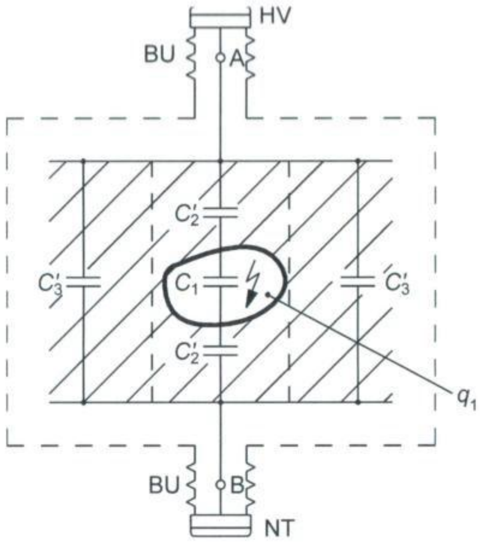


Figure 9.2.1: Schematic representation of a part of the transformer insulation

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 9.2.2 and Figure 9.2.3 are showing the RLC-network of a transformer as an example, illustrating the complexity of possible spots where partial discharges may occur.

HV = *high voltage winding*
LV = *low voltage winding*
RW = *regulating winding*
NT = *neutral terminal*

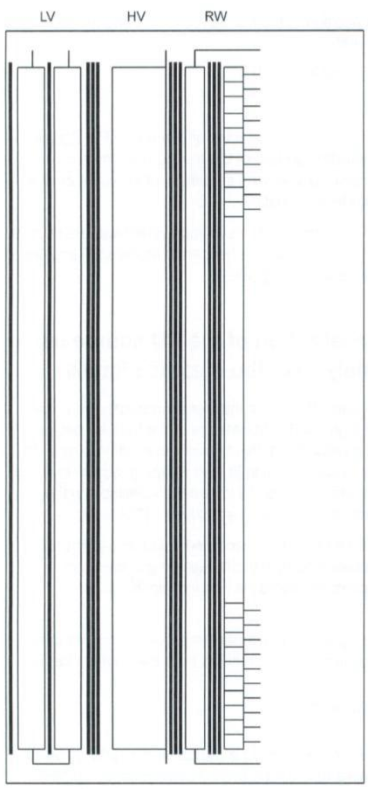


Figure 9.2.2: Winding and insulation system

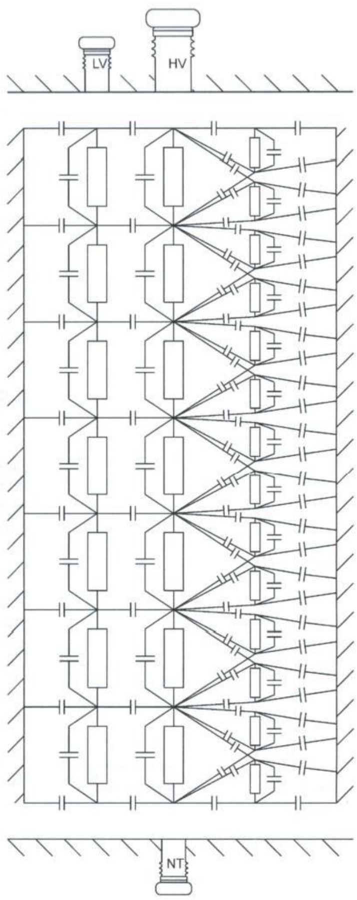


Figure 9.2.3: Equivalent circuit

9.3 Measuring circuit

If the two line terminals are connected together via an external capacitors C_k (Figure 9.3.1), a charge within the series connected capacitances (inside the insulation, Figure 9.2.1) will also be reflected in the charge of external capacitor C_k. Under the assumption that C_t << C_k, potential discharges only occur inside the transformers insulation system (represented by C_t). Then the charge movements can be detected as circulating current impulses i(t). All PD measuring methods are based on this principle. Therefore the basic equivalent circuit for PD measurements is presented Figure 9.3.1.

The preferred method is to transform the signal to an apparent electric charge, measured in picocoulombs (pC) which requires an integration of the PD current impulse i(t).

$$Q(t) = Q(t_0) + \int i(t)\,dt$$

Q(t) = *electric charge depending on point of time*
$Q(t_0)$ = *electric charge at the beginning*

Worth mentioning is the different approach of PD measuring by the IEEE, transforming the signal to a Radio Interference Voltage (RIV), generally measured in microvolts (µV). Most PD systems available on the market perform a “quasi-integration” of the PD current impulses in the frequency domain using wide-band filter.

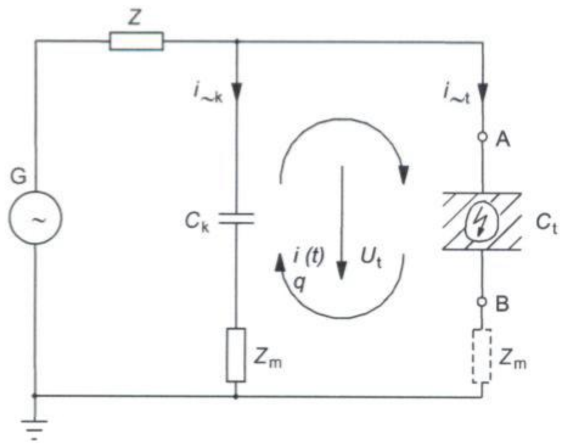


Figure 9.3.1: Equivalent circuit for PD measurement

G	=	*voltage source*
Z	=	*voltage source connectors*
C_t	=	*test object capacitance*
C_k	=	*coupling capacitor*
Z_m	=	*measuring impedance*
i(t)	=	*PD current impulse*
$i_{\sim k,\sim t}$	=	*displaced currents*
q	=	*transferred charge*
U_t	=	*voltage at parallel connected capacitors*

PD measurements on transformers can only be conducted on their bushings. For power transformers the measuring impedance is generally connected between the bushing measuring-tap and earth (parallel with C_2).

C_1	=	*coupling capacitor* (= C_k)
C_2	=	*capacitive tap*
CAL	=	*calibrator*
SE	=	*shielding electrode*
PDS	=	*PD measuring system*
Z_m	=	*measuring impedance*

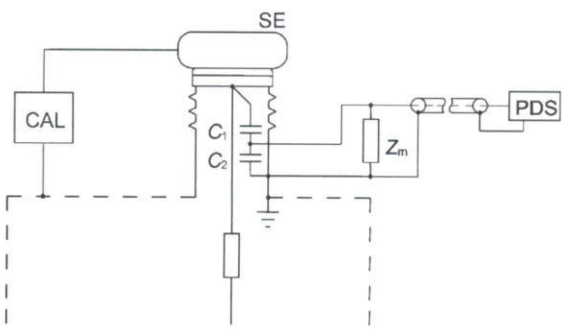


Figure 9.3.2: Calibration circuit for PD measurement (bushings with capacitive tap)

For bushings without a capacitive tap, external coupling capacitances ([C_k] picturedi in 10.5) must be connected in parallel with the bushing (compare Figure 9.3.2 and Figure 9.3.3). To avoid external discharge (corona) in the PD measuring circuit all transformer bushing tops should be covered with shielding electrodes (including earthed bushings).

C_k = *coupling capacitor* (= C_k)
SE = *capacitive tap*
PDS = *PD measuring system*
CAL = *calibrator*
Z_m = *measuring impedance*

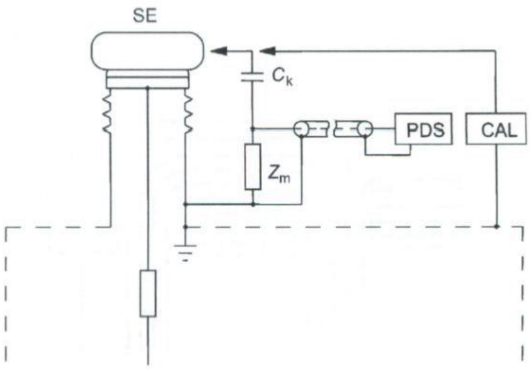


Figure 9.3.3: Calibration circuit for PD measurement (bushings without capacitive tap)

9.4 Measuring procedure

Although there are some differences between the IEC and IEEE Standard, the PD measurement is basically integrated in the Induced voltage tests (see section: 10 Induced voltage tests). Considering the IEC Standard, PD measurement is mandatory for long- and short duration induced voltage tests (ACLD and ACSD). The time sequences are shown in Figure 10.4.1 and Figure 10.4.2, according to IEC. PD activity will be checked on all bushings where the system voltage is higher than U_m > 72,5kV. The measurements (in pC) are carried out at each voltage level, except the enhanced level (part C) and should be documented.

Acceptance criteria

The PD test is considered successful if no partial discharges 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, according to 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

If the PD activity cannot comply with the requirements, the type and the location (external or internal insulation system) of the PD source has to be detected. In
Table 9.4.1 typical PD sources are shown, which is just for a better visualization. Those PD pattern can be regarded as a fingerprint of the partial discharge activity of a specific defect in the transformers insulation system. For getting more details about the subject of PD source investigation, professional literature has to be consulted.

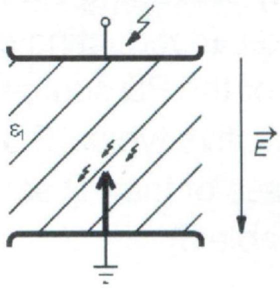
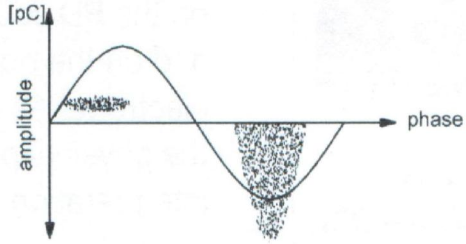
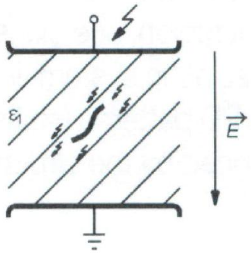
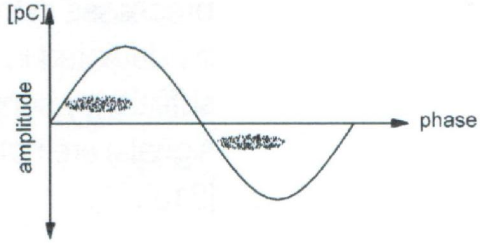
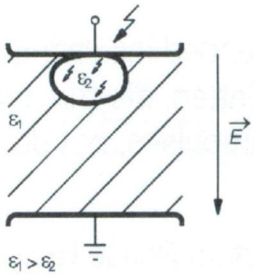
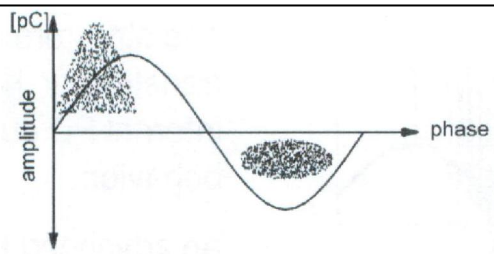
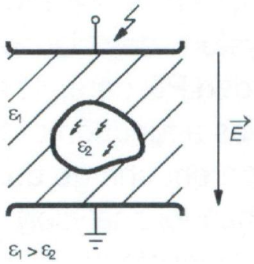
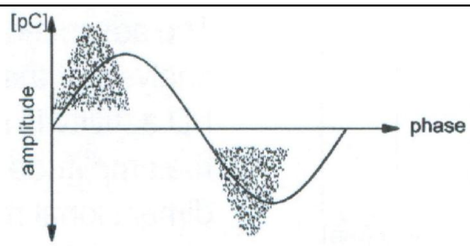
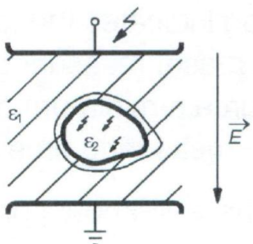
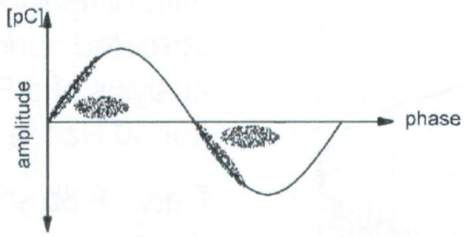
PD source	Schematic drawing of the PD source	Typical PD pattern
Conducting material (tip electrode) with direct contact to metallic electrode		
Conducting material without any contact to metallic electrode		
Non-conducting material (cavity) with direct contact to metallic electrode		
Non-conducting material (cavity) without any contact to metallic electrode		
Non-conducting material (cavity) without any contact to metallic electrode with changing surface due to the partial discharge		

Table 9.4.1: Typical PD sources in the transformer insulation

10 Induced voltage tests

10.1 Purpose and Standards

The induced voltage test verifies the AC withstand strength of each line terminal and its connected windings to earth and to other windings, but also between phases and along the winding (turn-to-turn insulation).

<table>
<tr><th>Standard</th><th>Section/Clause</th><th>Type of test</th></tr>
<tr><td>IEC</td><td>60076-3
Clause 7.3: “Dielectric tests”
Clause 12: “Induced AC voltage tests (ACSD, ACLD)”</td><td rowspan="4">Routine test</td></tr>
<tr><td rowspan="2">IEEE</td><td>C57.12.90
Clause 10.7/10.8: “Induced voltage tests”</td></tr>
<tr><td>C57.12.00
Clause 5.10: “Insulation levels”</td></tr>
<tr><td>VDE</td><td>0532-76-3</td></tr>
</table>

Table 10.1.1: Associated Standards

10.2 General

The testvoltages U_p of this measurement are nearly the same as for the Applied Voltage Test (see section 7). The difference is the measuring procedure and the possibility to conduct a Partial Discharge Measurement (during the whole test duration), which can indicate insulation faults before an electric breakdown occur. There are essential differences between the IEC and IEEE understanding of induced voltage tests. Generally IEC distinguishes between:

- Short- and Long duration AC tests (ACSD/ACLD)
- Uniform- and non-uniform (graded) insulation
- Highest voltage levels

Note: Partial discharge measurements (PD; see section: 9 Partial Discharge Measurement) has to be conducted simultaneously, except for transformers with U_m < 72,5kV.

IEEE distinguishes only between class I (U_m< 115kV) and class II (U_m≥ 115kV) transformers. For class II transformers a long duration test in combination with a PD measurement is always required. Table 10.2.1 gives an overview about the separation, according to IEC and IEEE Standards.

Category of winding	Highest voltage for equipment U_m [kV]	Three-phase			Single-phase	
		ACLD	ACSD		ACLD	ACSD
			Phase-to-earth test	Phase-to-phase test		Phase-to-earth test
According IEC						
Uniform insulation	< 72,5			X		X
	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	
According IEEE						
Class I Non-graded insulation	< 115			X		X
Class I Graded insulation			X	X		X
Class II	≥ 115	PD			PD	

Table 10.2.1: Induced voltage tests for three- and single-phase transformers

X : Routine test without PD measurement
PD : Routine test with PD measurement

10.3 Measuring circuit

The principle of the induced voltage test is shown in Figure 10.3.1. In reality the test-circuit is more complicated than shown in this figure, because the leakage reactance of the transformer and the generator have been omitted for better understanding. The load impedance of the generator is a current resonance circuit (R-C-L). The generator current reaches its minimum value when the test frequency f is equal to the resonant frequency f_R. Because the test voltage U_p is normally higher than twice the rated voltage, the test frequency has to be adjusted (double test voltage means double frequency) to avoid over-excitations in the iron core (see formula; k = variable depending on transformer design). To keep the generator current as low as possible the variable reactor can influence the resonance circuit and its resonant frequency.

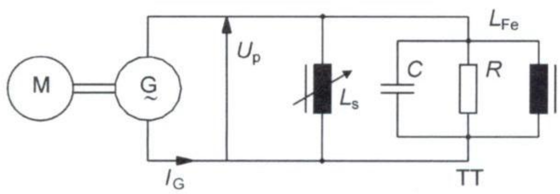


Figure 10.2.1: Simplified test circuit

U_p = *test voltage*
L_S = *compensating reactor (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*
I_G = *generator current*

$$U = k \cdot f \cdot \hat{B} \quad \rightarrow \quad \hat{B} = \frac{U}{k \cdot f}$$

10.4 Measuring procedure

Preparations

The actual test should not be carried out until the impregnation of the windings has been completed. The necessarily “standing-time” depends on the rated voltage of the transformer (e.g. about 3 days for a 220 kV transformer).

The Buchholz-relay and all bushings must be degassed before the test; any surge arresters and bushings arcing horns must be removed. Unlike in the applied voltage test: Electrodes, such as spheres or similar protection shields mounted on the outer terminal of the bushing are highly recommended, especially for high voltage tests. These electrodes are mandatory for partial discharge measurements in combination with the induced voltage test.

Test voltage U_p

The test voltage depends on the highest voltage for equipment U_m and can be looked up in the Standards. Generally these are the same values used in the separate source AC withstand voltage test (except ACLD) and is about twice the rated voltage.

Test duration at full test voltage U_p

The test time should not exceed 60 seconds (at full test voltage U_p), but not less than 15 seconds (independent of the test frequency). If the test frequency is adjusted and is higher than twice the rated frequency, the test time will be decreased after the following formula:

$$\boxed{t = 120 \cdot \frac{f_r}{f_p}}$$

$t \;=\; test\ duration\ in\ seconds$ (C)

$f_r \;=\; rated\ frequency\ of\ the\ transformer$

$f_p \;=\; test\ frequency$

Test sequence (according IEC)

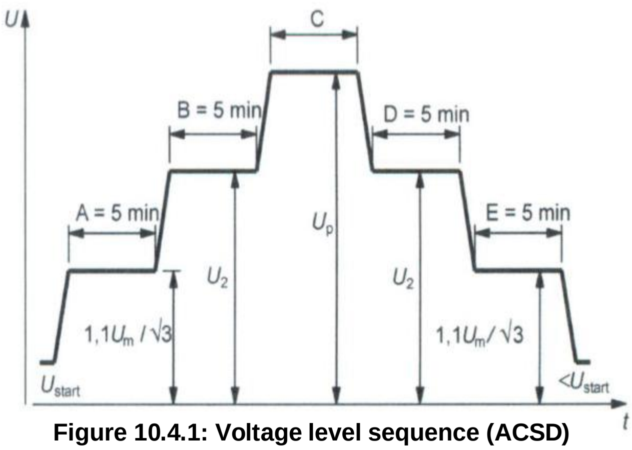


Figure 10.4.1: Voltage level sequence (ACSD)

Short duration AC withstand voltage test (ACSD)

$$U_2 = 1{,}3 \cdot U_m\ (phase-to-phase)$$

$$= 1{,}3 \cdot \frac{U_m}{\sqrt{3}}\ (phase-to-earth)$$

$$U_p = see\ IEC\ 60076-3,\ clause\ 7$$

$$C = for\ test\ duration\ see\ above$$

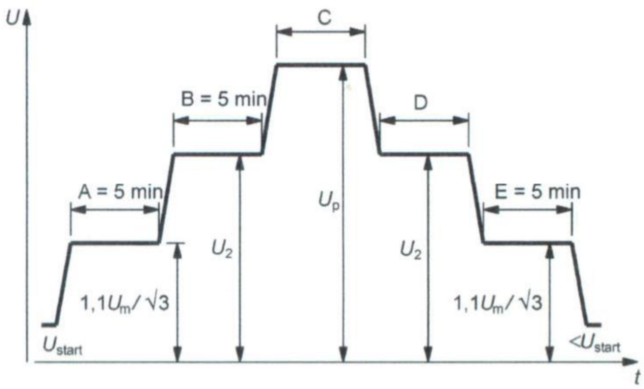


Figure 10.4.2: Voltage level sequence (ACLD)

Long-duration AC withstand voltage test (ACLD)

$$U_2 = 1{,}5 \cdot \frac{U_m}{\sqrt{3}} \; (phase - to - earth)$$

$$U_p = 1{,}7 \cdot \frac{U_m}{\sqrt{3}} \; (phase - to - earth)$$

$$C = for\ test\ duration\ see\ above$$

$$D = \begin{cases} 30\,\text{min}\ for\ \ U_m < 300kV \\ 60\,\text{min}\ for\ \ U_m > 300kV \end{cases}$$

Test sequence (according IEEE)

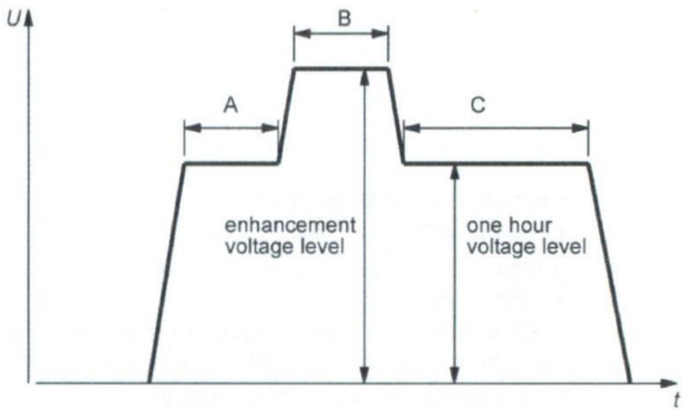


Figure 10.4.3: Test sequence for class II transformer

Long-duration AC withstand voltage test (ACLD)

ACLD tests always in combination with PD measurement, Table 10.2.1.

A = time for PD measurement
B = 7200 cycles (ca. 2min for 50Hz)
C = 60 minutes

The voltage shall first be raised to the 1h level and held for a minimum of 1 min or until a stable partial discharge level is obtained to verify that there are no indications of partial discharges (voltage level of A and C are the same). The level of partial discharges shall be recorded just before raising the voltage to the enhancement level (B), which is held for 7200 cycles. Then the voltage shall be reduced directly to the 1h level (C). Partial discharge measurements shall be made at 5 min intervals.

Acceptance criteria

The test is successful if the test voltage does not collapse. In combination with PD measurements the criteria for success of the test are further explained in section: 9 Partial Discharge Measurement.

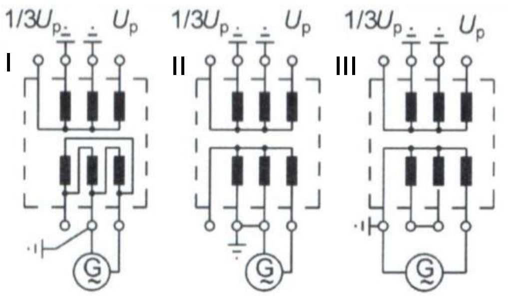
Transformers with non-uniform insulated HV windings

Induced AC voltage tests for non-uniform insulated HV windings are treated separately, settled in IEC 60076-3, clause 12.3. On single-phase transformers, only a phase-to-earth test is required. For three-phase transformers, two sets of ACSD tests have to be carried out:

- phase-to-earth test at rated withstand voltages + PD measurement (performed as (three) single-phase tests, see Table 10.4.1)

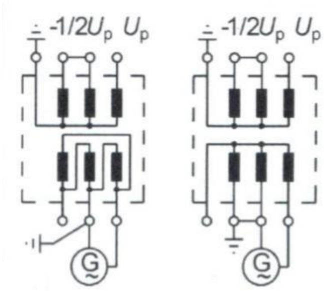
- phase-to-phase test with earthed neutral at rated voltage (performed as three-phase test)

In case of ACLD tests, single-phase connection (phase-to-phase) are possible as well, but are not obligatory. Recommended test connections which avoid excessive overvoltage between line terminals are shown below. Other separate windings shall generally be earthed at the neutral if they are star-connected and at one of the terminals if they are delta-connected. Depending on the low-voltage winding, three different generator connections are possible.

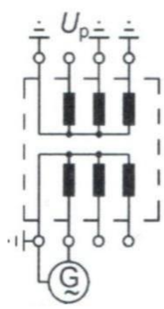


→ This test connection can be used when the neutral is designed to withstand at least one-third of the voltage

→ Test connection I is only possible for transformers with 5 limb core or shell-type transformers



→ Test connections for ACLD test, if performed phase-to-phase in single-phase connection

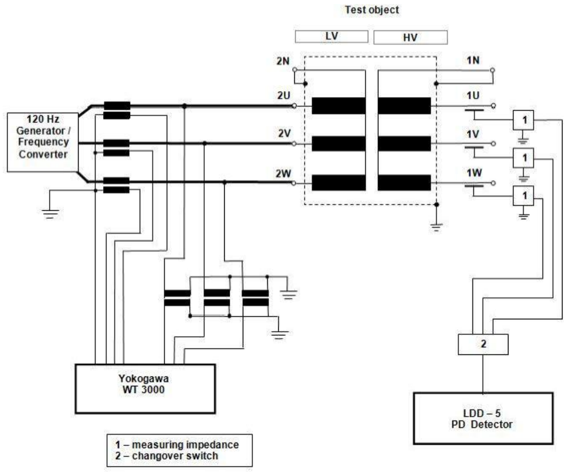


→ only possible when the transformer has a no wound limb for the magnetic return path for the flux in the tested limb (five limb core)

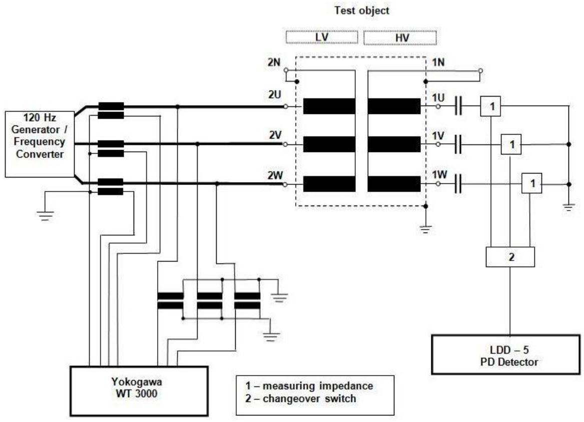
Table 10.4.1: Single-phase test connections for Induced voltage AC test

10.5 Appendix: Measure arrangement of customized vector group

Test circuit 1 (with capacitive tap)



Test circuit 2 (without capacitive tap)



Measuring instruments

Lemke LDD-5

→ **Partial Discharge Detector**

detectable apparent charge:	*0,1pC-25µC (extendable)*
measuring range:	*5, 20, 100, 500 pC*
Accuracy:	*± 10 % of readings*

Omicron CPL 542 & MPP600

→ measuring impedance (CPL 542) + battery pack (MPP600)

Omicron CAL542

→ **Charge calibrator**

→ complies with all parts of IEC 60270

→ fed a defined impulse charge into the measuring circuit. The partial discharge detection system is then calibrated to this value

WMC 0,8/150

rated voltage:	150 kV
rated capacitance:	0,8 µC

WCF 1,25/200

→ **Coupling capacitances**

→ necessary for bushings without capacitive taps

rated voltage:	200 kV
rated capacitance:	1,25 µC

Note: The power analyser “Yokogawa WT3000” is used additionally, observing applied voltage and current

11 Insulation resistance measurement

11.1 Purpose and Standards

The insulation resistance test (also commonly known as a “Megger test”) is a spot insulation test which uses an applied DC voltage and is performed to determine the insulation resistance from a winding to earth or between individual windings. This value is important to know, when assessing the transformers insulation condition. The measured insulation resistance is to be understood as a reference value used for comparison in measurements made at a later stage. In our test field the Insulation resistance measurement is treated as a routine test, different from the applied Standards.

Standard	Section/Clause	Type of test
IEC	60076-1 Power transformers – Part 1: “General”	Routine test U_m > 72,5 kV Special test U_m < 72,5 kV
IEEE	C57.12.90 Clause 10.11 “Insulation resistance tests”	Routine test for class II transformers Other test for class I transformers

Table 11.1.1: Associated Standards

11.2 General

Although there are more sophisticated measuring methods, like the FDS measurement (section: 20 FDS measurement for moisture estimation), the advantage of this method is the very easy procedure. The value the insulation resistance is generally measured in megohms (MΩ), which depends strongly on transformers design, temperature, dryness and cleanliness (especially bushings). Considering those factors can help to explain and find existing insulation uncertainties. It has to be noted that insulation measurement varies with the applied voltage. To compare measurements with each other, the applied voltage should always be the

11.3 Measuring circuit

The measuring circuit is quite similar to that of the applied voltage test. All terminals of one winding system (e.g. HV side) must be connected with each other. The megohm - meter used for this test has an integrated DC power supply, which generates a voltage of 5kV. In case of arc furnace transformers the low-voltage side is usually not designed for 5kV. The voltage has to be adjusted to avoid flashovers in this case.

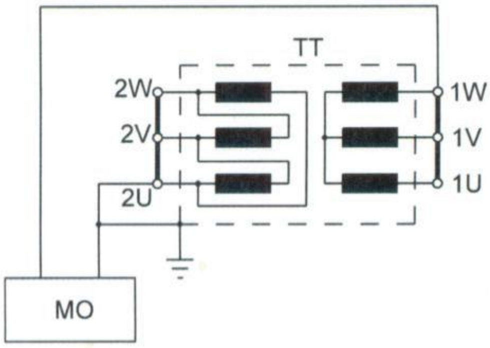


Figure 11.3.1: Principal measuring circuit (MO = megohm-meter)

11.4 Measuring procedure

In accordance with the IEC Standard, the duration for the measurement is 1 minute. The readings take place after 15 seconds (R_{15}) and 60 seconds (R_{60}). The ratio of R_{60}/R_{15} is a criteria for the insulation condition and should be in the range of 1,3 – 3.

The IEEE defines the measurement with a third reading of the resistance after 600 seconds (R_{600}). With that value the “Polarisation Index (PI)” can be determined, which serves as an evaluation of the insulation as well. PI values < 1 stand for unsatisfactory condition, whereas PI values > 2 indicate a really good condition.

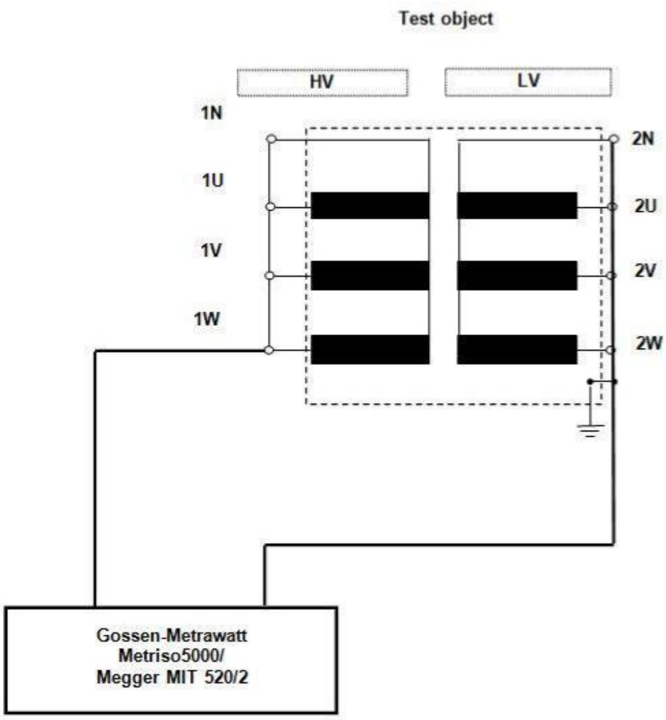
Polarisation Index:

$$PI = \frac{R_{600}}{R_{60}}$$

The number of measurements increases with the presents of a tertiary winding, because more combinations of connections are possible. The temperature of the transformer should be close to the reference temperature of 20°C.

11.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

Gossen-Metrawatt Metriso5000

→ Digital High-Voltage Insulation Tester

Accuracy: *± (10% of readings + 8 digits)*

Measuring range: *0,4 MΩ - 1 TΩ*

Test voltages: *100V, 250V, 0,5kV, 1kV, 1,5kV, 2kV, 2,5kV, 5kV*

Megger MIT520/2

→ Insulation Resistance Tester

Accuracy:

	5kV	2,5kV	1kV	500V
±5%	1TΩ	500 GΩ	200 GΩ	100G Ω
±20%	10TΩ	5 TΩ	2 TΩ	1 TΩ

Measuring range: *10 kΩ…15 TΩ*

Test voltages: *250V, 500V, 1kV, 2,5kV, 5kV,*

12 Test on tap-changers & auxiliary equipment

12.1 Purpose and Standards

Although all on-load tap-changers are tested individually during the manufacturing process, it is necessary to check the correct operation in combination with the fully assembled transformer, verifying a proper performance without failure during operation.

Standard	Section/Clause	Type of test
IEC	60076-1 Clause 10.8: “Test on on-load tap-changers”	Routine tests
	60076-3 Clause 10: “Insulation of auxiliary wiring”	
IEEE	C57.12.00 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”	Routine tests for class II transformers Other tests for class I transformers
VDE	0532-76-1	acc. to IEC

Table 12.1.1: Associated Standards

12.2 Tests on Tap-changers

Specified by the IEC Standards, the following tests for tap-changers have to be conducted:

Un-energized transformer	Energized transformer
1 complete cycle of operation with 85% of rated voltage	1 complete cycle of the tapping range at no-load at rated voltage and frequency
8 complete cycles of operation at rated voltage (one cycle is defined as going from one end to the other and back again of the whole tapping range)	10 switching operations across the range of ± 2 stages on either side of the principal tapping. The switching operations are carried out, if possible, at rated current in the winding with taps with one winding short-circuited

Table 12.2.1: Test procedure (acc. IEC)

The test circuits with rated voltage is similar to that for measurement of no-load loss (see section: 6 Measuring the no-load loss & no-load current) and the test circuit for the operation test with rated current is similar to that for measurement of load loss (see section: 5 Short-circuit voltage & load loss). The tap-changer should be observed and checked for any abnormal activities during the test.

12.3 Tests on Auxiliary equipment

In addition to the on-load tap-changer test, the auxiliary equipment have to be tested. Therefore all wirings for auxiliary power and control circuits are subjected to an AC separate source test (2kV RMS to earth for 1 minute, acc. IEC). The IEEE Standard specifies an AC applied voltage test at 1,5kV RMS for the auxiliary equipment, excluding current transformer circuits, which are tested at 2,5kV RMS. If 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. This test will be carried out with the high-voltage testing unit “Schleich GLP1-g”. The test is successful when voltage breakdowns occur.

IEC	IEEE	
2kV RMS to earth for 1 minute	Auxiliary equipment: 1,5kV RMS to earth (AC applied voltage test)	Current transformers: 2,5kV RMS to earth for current transformers

Schleich GLP1-g

→ manual adjustable AC high-voltage source

→ arc detection

Measuring range: 0…6000V

Accuracy: ± (2% of rdg + 0,1mA)

13 Check of built-in current transformers

13.1 Purpose and Standards

Current transformers, together with voltage transformers (VT), are known as instrument transformers. They are used for measuring alternating currents and voltages, operating on the same principle of common transformers. Because measuring and recording instruments are really sensitive, they are not allowed to be exposed to high currents. Therefor the current transformer produces a reduced current accurately proportional to the current in the circuit, which can be conveniently connected to measuring system. Additionally current transformers isolate the measuring instruments and protect them from over-voltage in the monitored circuit.

Standard	Section/Clause	Type of test
IEC	60044-1 Instrument transformers - Part 1: Current transformers	Routine test
IEEE	C57.13 "…current and inductively coupled voltage transformers used in measurement of electricity and the control of equipment associated with the generation, transmission, and distribution of alternating current."	Routine test

Table 13.1.1: Associated Standards

13.2 General

Like any other transformer, a current transformer has a primary winding, a magnetic core, and a secondary winding. The alternating current flowing in the primary produces an alternating magnetic field in the core, which then induces an alternating current in the secondary winding circuit. An essential objective of current transformer design is to ensure that the primary and secondary circuits are efficiently coupled, so that the secondary current bears an accurate relationship to the primary current. The most common design of CT consists of a length of wire wrapped many times around a silicon steel ring passed 'around' the circuit being measured. The CT's primary circuit therefore consists of a single 'turn' of conductor, with a secondary of many tens or hundreds of turns.

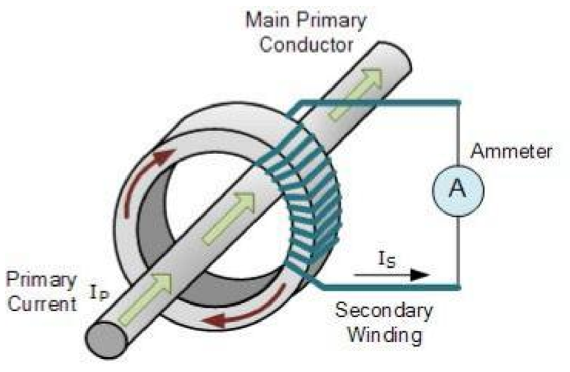


Figure 13.2.1: Principle of a current transformer

13.3 Measuring procedure

The portable Omicron CT-Analyzer performs excitation, ratio and polarity tests on current transformers using the voltage-comparison method. Current transformers can be tested in their equipment configuration, such as being mounted in transformers, oil circuit breakers or switchgear. It is necessary for the equipment to be totally isolated from the electrical system prior to testing.

Polarity Test

Connected to the high voltage winding, the method is used will be conducted by switching on a DC current source briefly. The polarity can be checked on a polarized voltmeter, connected to secondary winding (low voltage side). The voltmeter must be calibrated to be sure that the deflection is correct. Usually a series resistor is applied in the circuit to protect the instrument. If the polarity of the transformer is correct, the deflection must be in the same direction when the DC current is switched on.

Saturation Test

Measuring the excitation voltage and excitation current that results as the voltage applied to the CT under test increased. As the CT under test begins to saturate, a large increase in current will be detected for a small increase in voltage. With this test the magnetization curve and magnetization characteristics will be confirmed. Saturation test shall be conducted before ratio test and after polarity test, since residual magnetism left in the core due to DC test (polarity, resistance), which leads additional error in ratio test.

Ratio Test

The ratio test is performed by comparing a voltage applied to the secondary winding to the resulting voltage produced on the primary winding. For example, if 1 volt per turn is applied to the secondary winding, the voltage present on the primary winding would be 1 volt. More specifically, if 120V were applied to the secondary of a 600/5 current transformer (120:1 ratio), 1V should be present on the primary winding.

13.4 Measuring circuit

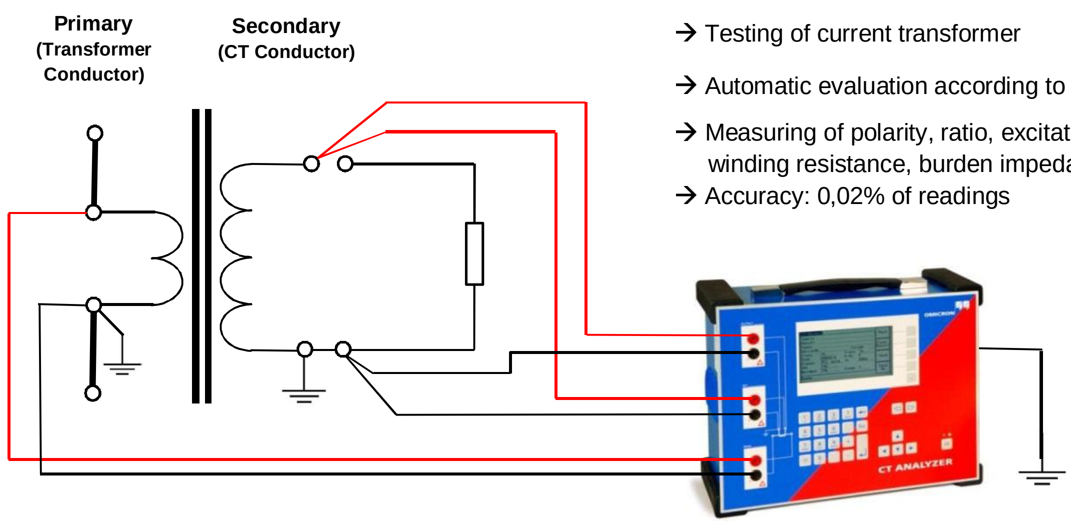
Omicron CT-Analyzer

→ Testing of current transformer

→ Automatic evaluation according to IEC & IEEE

→ Measuring of polarity, ratio, excitation/saturation, winding resistance, burden impedance

→ Accuracy: 0,02% of readings



14 Temperature rise measurement

14.1 Purpose and Standards

The rate of aging or decomposition depends strongly on the temperature the insulation material is exposed to. At a temperature of 100°C is already a noticeable degree of decomposition. 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. As a result, the Standards have not only established the highest permissible temperature values for the windings and oil, but also rules for permissible overloads, including their influence on life expectancy. Defined by IEC, the term temperature rise is the difference between the temperature of the average winding temperature and the temperature of the external cooling medium. It confirms the guaranteed temperature rises of oil and windings. It is also useful for detecting possible hot-spots in- and outside the winding. Measuring the average- and top oil temperature rise, as well as knowing the winding-oil gradient, may be really important in terms of future upgrades (overload considerations).

<table>
<tr><th>Standard</th><th>Section/Clause</th><th>Type of test</th></tr>
<tr><td rowspan="2">IEC</td><td>60076-2
Clause 5: “Test of temperature rise”</td><td rowspan="5">Type- or design test</td></tr>
<tr><td>60354
“Loading guide for oil immersed power transformers”</td></tr>
<tr><td rowspan="2">IEEE</td><td>C57.12.90
Clause 11: “Temperature rise”</td></tr>
<tr><td>C57.12.00
Clause 5.11: “Temperature rise and loading conditions”</td></tr>
<tr><td>VDE</td><td>0532-76-2</td></tr>
</table>

Table 14.1.1: Associated Standard

14.2 General

The temperature inside the transformer has to comply with certain temperature limits, specified by IEC and IEEE Standards. Those limits are necessary to guarantee a long and reliable service of the transformer. To compare between different transformer concepts and suppliers properly, the permissible temperature rise above the cooling medium (winding-oil gradient), as well as the ambient temperature, have to be regarded.

Cooling methods and Identification symbols (according IEC)

Generally the cooling methods are specified in the IEC Standards as a test code (see Table 14.2.1). The cooling system which is applied, influences the temperature rise but may be also the sound emission. In the end it depends on the area of application.

First letter *Internal cooling medium (in contact with windings)*		**Second letter** *Circulation mechanism for int. cooling medium*		**Third letter** *External cooling medium*		**Fourth Letter** *Circulation mechanism for ext. cooling medium*	
O	mineral oil or synthetic insulating liquid with fire point ≤ 300°C	**N**	natural convection flow through cooling equipment and in windings	**A**	air	**N**	natural convection
K	insulating liquid with fire point ≥ 300°C	**F**	forced circulation through cooling equipment and natural convention flow in the windings	**W**	water	**F**	forced convection → fans (air) → pumps (water)
L	insulating liquid with no measurable fire point	**D**	forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings				

Table 14.2.1: Identification symbols (acc. IEC)

A common example:

- ONAN/ONAF
  The transformer has a set of fans which may be put into service if required at high loading. The insulating liquid circulation is by thermosiphon-effect only, in both cases.

Measuring principle

During the temperature rise test only $\Theta_{oil,max}$, Θ_{KE} and Θ_{KA} can be measured directly. The winding temperature Θ_{Cu} will be determined indirectly by calculation (resistance measurement). Measuring the winding temperature, using sensors directly attached to the winding are carried out with fiber optics and useful, detecting possible hot-spots and predict transformer´s operational life span. A simplified temperature distribution model is shown in Figure 14.2.1.

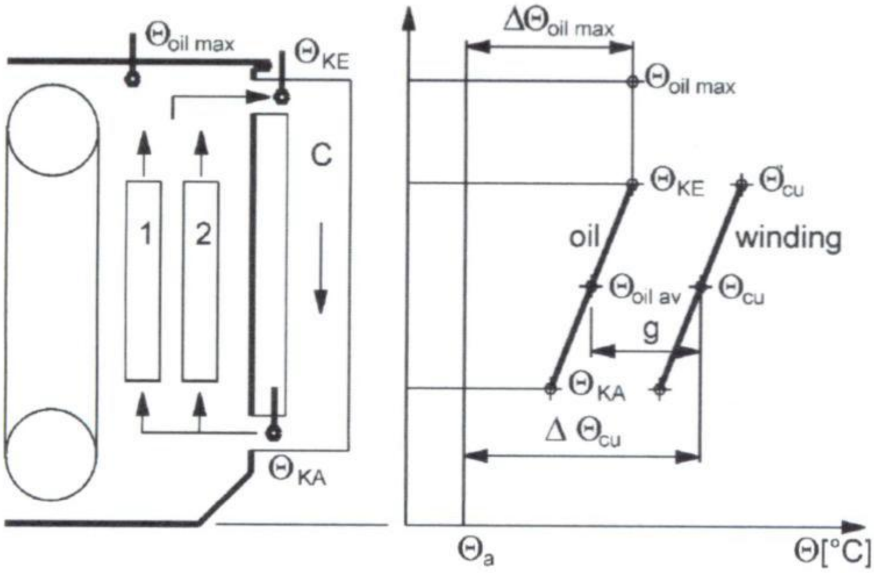


Figure 14.2.1: Simplified illustration of temperature distribution

$\Theta_{oil\ max}$	=	*top oil temperature (under the cover)*	Θ_{Cu}	=	*average winding temeperature*
			Θ_{KE}	=	*exit temperature from cooler*
Θ_a	=	*ambient temperature*	Θ_{KA}	=	*input temperature to cooler*
$\Delta\Theta_{Cu}$	=	*average winding temeperature rise (guarantee value)*	$\Theta_{oil\ av}$	=	*average oil temperature (calculated)*
			C	=	*cooling unit*
$\Delta\Theta_{oil\ max}$	=	*top oil temperature rise (guarantee value)*	1, 2	=	*transformer windings*
			g	=	*temperature gradient winding – oil*

→ $\Delta\Theta_{oil\ max} = \Theta_{oil\ max} - \Theta_a$

14.3 Measuring procedure

Short-circuit method

There are several methods to determine the temperature rise. Because of practical reasons the short-circuit method has been established for the determination of steady-state temperature rises. As seen in Figure 14.3.1 the principle of short-circuit connection is applied. During this test the transformer is not subjected to rated voltage and rated current simultaneously, but to the calculated total losses, previously obtained by two separate determinations of losses, namely load loss at reference temperature and no-load loss.

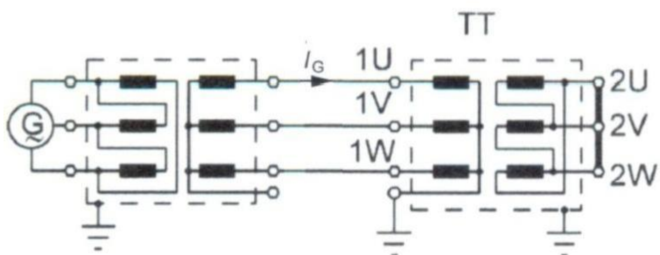


Figure 14.3.1: Principal test connection (three-phase) with matching transformer

The supply voltage is about the same as the short-circuit voltage, which means there are no losses in the iron core practically. But to obtain the correct top-oil temperature rise, the total losses are required. That's why the no-load losses must be simulated in the windings by injecting a current slightly higher than rated current.

$$\boldsymbol{I_G = k \cdot I_r}$$

$$\boldsymbol{k = \sqrt{\frac{P_L + P_0}{P_L}}}$$

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*

The power required for the test is therefore:

$$\boldsymbol{S_G = k^2 \cdot S_r \cdot \left(\frac{\varepsilon_{cc}}{100}\right)}$$

S_r = *rated power*
ε_{cc} = *short − circuit voltage in* %

Preparations

The transformer has to be placed that the cooling system (inlet and outlet) will not be affected by any objects in the test field. Besides protective devices like the Buchholz relay must be equipped. Any indication from these devices during the test shall be noted and investigated. All cold resistance measurements have to be performed before the test, in exactly the same measuring configuration as the one used for the warm resistance measurement.

Procedure

The purpose of the short circuit-method is to establish several values:

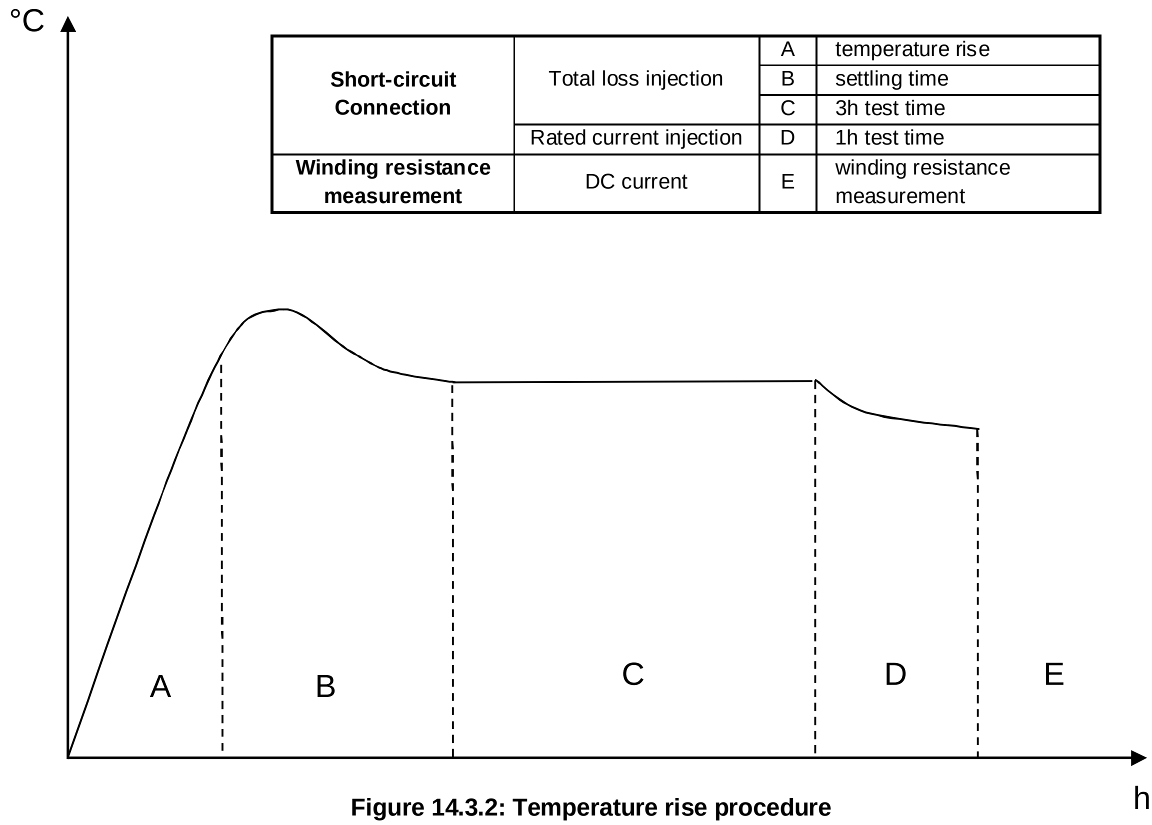
- top oil temperature ($\Delta\Theta_{oil\ max}$)
- average oil temperature rise ($\Delta\Theta_{oil\ av}$)

→in a steady-state of total loss injection

- average winding temperature rise ($\Delta\Theta_{Cu}$)
- top oil temperature rise ($\Delta\Theta_{oil\ max}$)
- hot-spot winding temperature rise ($\Delta\Theta_h$)

→ at rated current

Additionally to the short-circuit method, a winding resistance measurement will be carried out before the temperature rise test (reference values: R_1 and Θ_1) and after disconnection of power supply. To get correct values for the winding resistance after shutdown, the winding temperature variation have to be extrapolated backwards in time to the instant of shutdown. Therefore the resistance measurement should be conducted as soon as possible after short-circuit method was applied.



Short-circuit Connection	Total loss injection	A	temperature rise
		B	settling time
		C	3h test time
	Rated current injection	D	1h test time
Winding resistance measurement	DC current	E	winding resistance measurement

Figure 14.3.2: Temperature rise procedure

As seen in Figure 14.3.2 the whole measurement is divided in several steps. Unless otherwise specified, the temperature rise test is conducted with the transformer connected on the maximum current tapping.

a) Total loss injection

- test current corresponds to the total losses of the transformer (above rated current to the extent necessary for producing an additional amount of loss equal to the no-load loss at rated voltage)
- top-oil temperature and cooling medium temperature are monitored
- test will be continued until steady-state liquid temperature rise are established, which is terminated when the rate of change of the top-oil temperature rise has fallen below 1K per hour
- readings will be taken at regular intervals (readings during the last hour is taken as the result of the test)

b) Rated current injection

- test current reduced without a break to rated current, which condition
- during testing time (1h), continuous temperature records of top-oil, winding hot-spot (if measured) and external cooling medium will be taken at least every 5min

c) Winding resistance measurement

- cooling devices maintained to the same condition as during the current injection
- measurement starts after power supply and short-circuit connections have been removed; DC current sources will be connected to the windings (short break)
- fast decreasing of winding temperature and its resistance after shutdown
- measured resistance values have to be corrected backwards

Acceptance criteria

IEC specifies the maximum permitted ambient temperature with 40°C, and the corresponding permitted temperature rise of the winding with 65 K. The maximum average winding temperature is therefore: 65 + 40 = 105°C.

14.4 Measuring circuit

(1) Measuring circuit for temperature rise

The main measuring circuit and the circuit for measurement of losses, voltages and currents is principally the same for the measurement of load losses (section: 5 Short-circuit voltage & load loss).

PA = $power\ analyzer\ for\ U, I$ $and\ loss\ measurement$

CT/VT = $current/voltage\ transformer$

DAS = $data\ aquisition\ system$

TT = $transformer\ under\ test$

DAS = $data\ aquisition\ system$

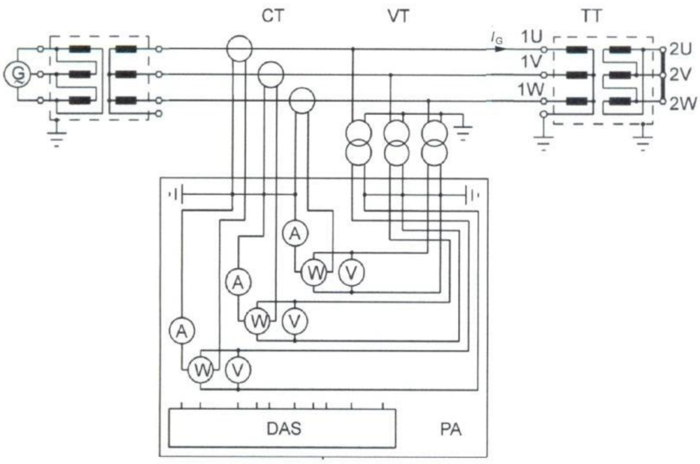


Figure 14.4.1: Principle test circuit for temperature rise

(2) Measuring circuit for determination of winding resistance after shutdown

The winding temperature must be determined indirectly, measuring the winding resistance. It is measured before the test and once again immediately after the completion of the current injection (several values needed for extrapolation of winding temperature to the instant of shutdown). The windings will be connected to separate DC circuits. Care has to be taken that the readings are correct, because direct current needs to stabilize to a steady state (inductive voltage drop in the winding). A total duration of 20 min for the measurement is appropriate for the determination of the cooling down curve.

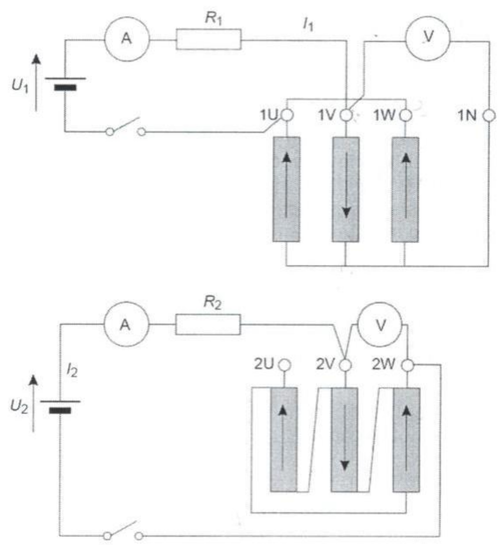
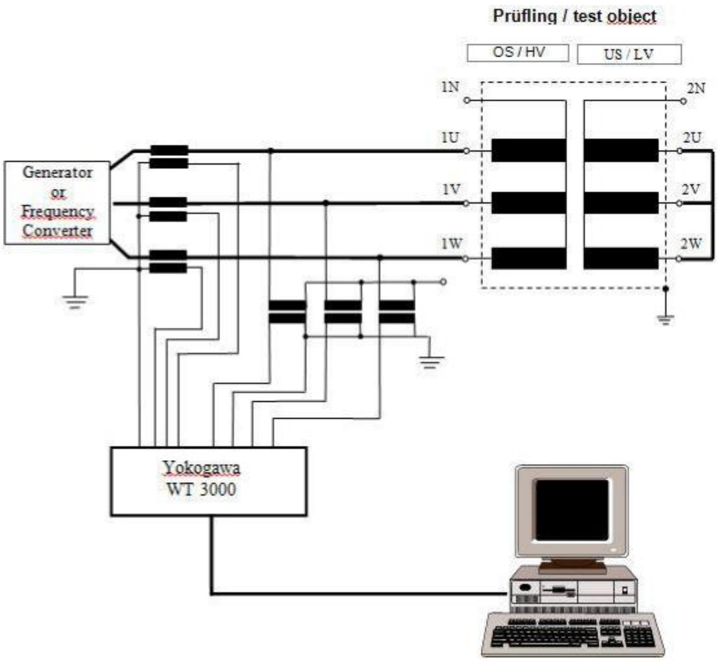


Figure 14.4.2: Test circuit for winding resistance (different from figure: windings connected in series for simultaneous measurement)

14.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

Yokogawa MV100/MV1000

→ data acquisition recorder/system (for thermal sensors)
→ 12 channels (MV100)/ 24 channels (MV1000)
→ data collection over Ethernet network
→ external storage media (floppy disk, zip disk, ATA flash memory)

MV 100 built-in control room

LumaSHIELD (Luma Sense)

→ Fiber Optic Winding Hot Spot Temperature Monitor/Controller

Accuracy: ± 0,8°C (total accuracy, includes signal conditioner and sensor errors)

Resolution: 0,1°C

The arrangement is similar to the short-circuit voltage & load loss measurement. The respective measuring equipment (power analyzer: Yokogawa WT3000, instrument transformers), which is needed for power observation, has been illustrated before.

14.6 Hot-spot measurement

The hot-spot temperature (Θ_h) is the hottest temperature of winding conductors in contact with solid insulation or insulating liquid. The hot-spot winding temperature rise ($\Delta\Theta_h$) is the difference between hot-spot winding temperature and the external cooling medium temperature. It can be determined through calculation based on the result of the temperature rise test (at rated power <20MVA) or by direct measurement, as a special test and by agreement between manufacturer and purchaser (at rated power >20MVA). Usually we are only considering the direct measuring method.

Standard	Section/Clause	Type of test
IEC	60076-2 clause 7.10: "Determination of the hot-spot winding temperature"	Special
VDE	0532-76-2	

Table 14.6.1: Associated Standards

Direct measurement during the temperature rise test

A number of thermal sensors (optical fibre sensors) will be mounted inside the windings in position where it is supposed the hot-spots are located. Usually hot-spots emerge at the top of the windings. When more than one sensor is used on the same winding, the maximum reading shall be taken as the hot-spot winding temperature. The hot-spot winding temperature rise ($\Delta\Theta_h$) is then obtained by:

$$\boxed{\Delta\Theta_h = \Theta_h + \Delta\Theta_{of} - \Theta_a}$$

Θ_h = $hot-spot\ temperature\ reading\ at\ shutdown$

$\Delta\Theta_{of}$ = $fall\ of\ the\ top-oil\ temperature\ during\ 1h\ test\ at\ rated\ current$

Θ_a = $ambient\ temperature\ at\ the\ end\ of\ the\ total\ loss\ period$

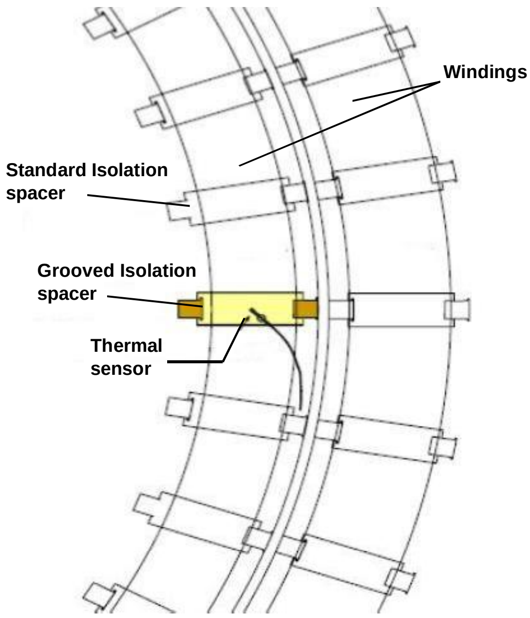


Figure 14.6.1: Mounting of thermal sensors

Dissolved gas-in-oil-analysis

For large mineral oil-immersed power transformers, in which additional flux effects are potential risk factors, a chromatographic analysis of dissolved gas-in-oil may allow the detection of possible local overheating. Therefore the gas-in-oil analysis gives another opportunity of hot-spot indication and is a routine test for transformers with U_m > 72,5kV (IEC 60072-2, Appendix D), conducted by intern or extern laboratory.

15 Measurement of cooling losses

15.1 General

The value of cooling losses will be determined to get a completion of the overall losses of the transformer (additionally to winding and core losses). The cooling losses are defined as the power which is taken by the installed cooling system (fans, liquid pump motor). These losses will be measured by means of the power analyser “Yokogowa WT3000”.

15.2 Measuring circuit and instruments

Figure 15.2.1 shows a simplified extract of the electric cabinet’ circuit layout (only essential parts). Generally the electric cabinet is a box for electrical or electronic equipment to mount switches, knobs and displays, to control and monitor auxiliary equipment (e.g. fans, liquid pumps, sensors) of the transformer. Moreover it has an important function in preventing electrical shock to equipment users and protects the contents from the environment. In the figure below only fans are pictured exemplary and for better comprehension.

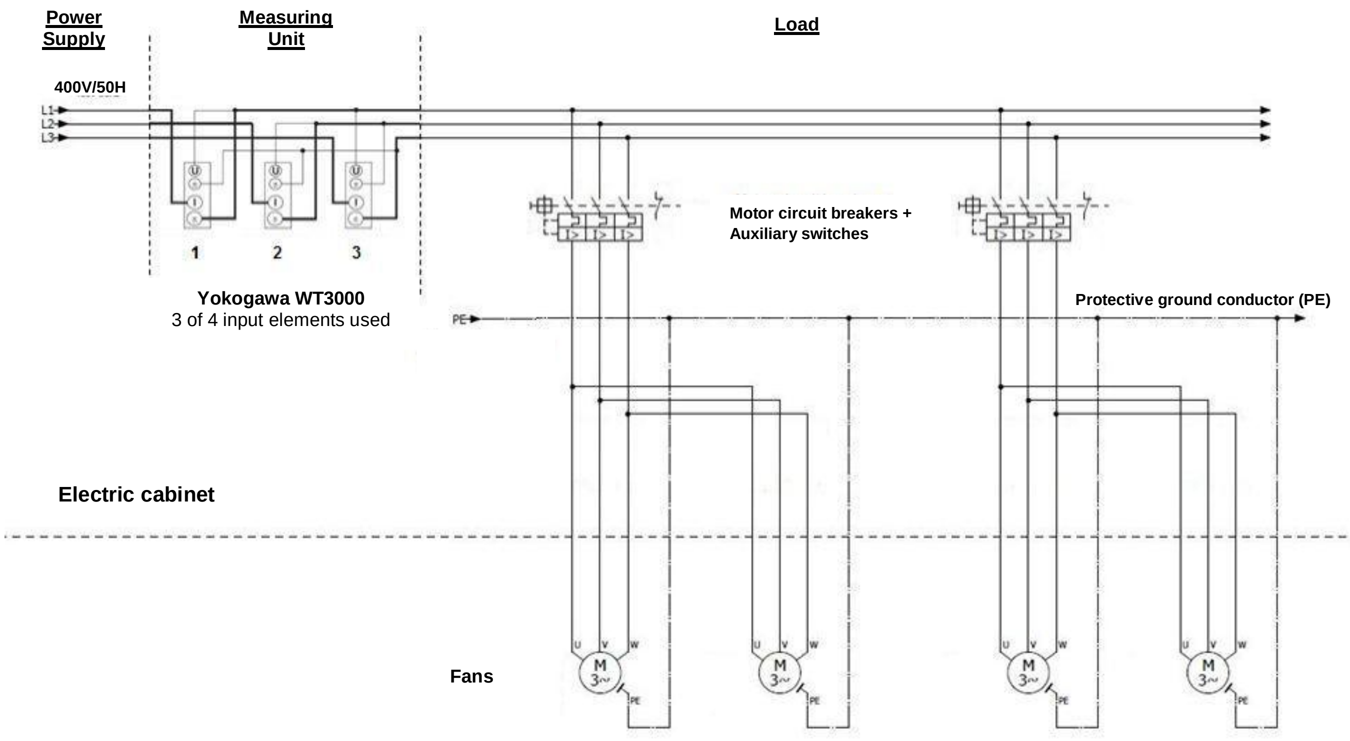
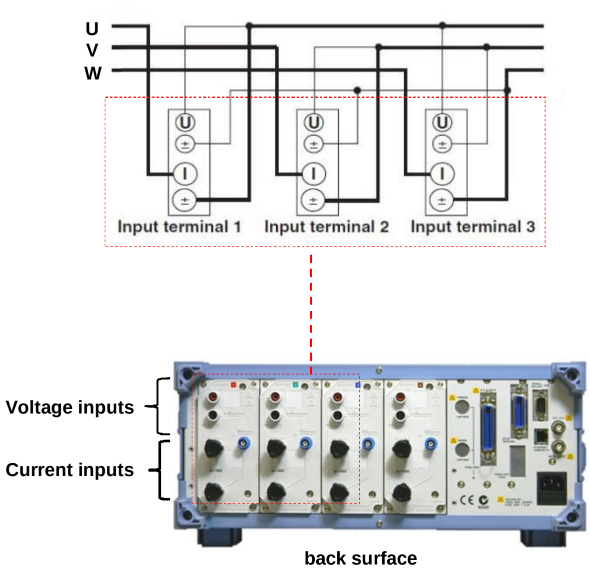
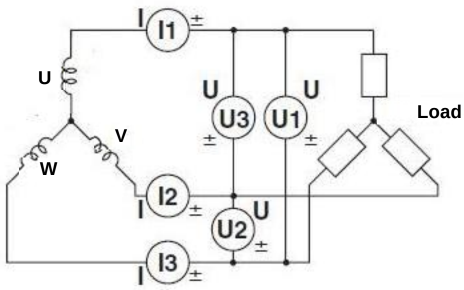


Figure 15.2.1: Example of measuring configuration for cooling losses

The power, which is taken by fans and liquid pump motors, is measured with the digital precision power analyzer “Yokogawa WT3000”. It is switched in between power supply and load and is not part of the actual circuit layout. Because there is a three-phase power supply different measuring configurations are feasible. An appropriate setup is the three-wire system, measuring three voltages and three currents (one for each phase), illustrated below.





Yokogawa WT3000

→ Digital Precision Power Analyzer

→ 4 Input terminals available

Accuracy:	*0,01% of basic readings*
	0,02% of basic power readings
Direct Current Input:	*up to 30 A*
Direct Voltage Input:	*up to 1000 V*

16 Sound level measurement

16.1 Purpose and Standards

Today sound emissions, caused by electric installations such as transformers, have to be considered, especially in populated areas. To protect from these noise inconveniences, electric components are required to operate within specified noise limits. For this reason knowledge about sound emissions from the transformer is really important.

Standard	Section/Clause	Type of test
IEC	60076-10 Part 10: "Determination of sound levels" Part 10-1: Draft: "Determination of transformer and reactor sound levels" – User Guide	Special- or other test
IEEE	C57.12.90 Clause 13: "Audible sound emissions"	
VDE	0532-76-10	

Table 16.1.1: Associated Standard

16.2 General

Operating transformers generate sound, or more correctly noise. Sources of a transformers sound are:

No-load sound (noise from the core)

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 as mechanical vibrations to the tank walls and radiated to open air. The 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. For example in a 50 Hz system, the audible sound consists of the harmonics: 100 Hz, 200 Hz, 300 Hz etc.

Load sound (noise from the windings)

Due to its magnetic forces load current generates vibrations in the winding, tank wall and magnetic shields. The load sound power is strongly dependent on the load current. Depending on the type of cooling, pump and fan noises are added.

16.3 Measuring circuit

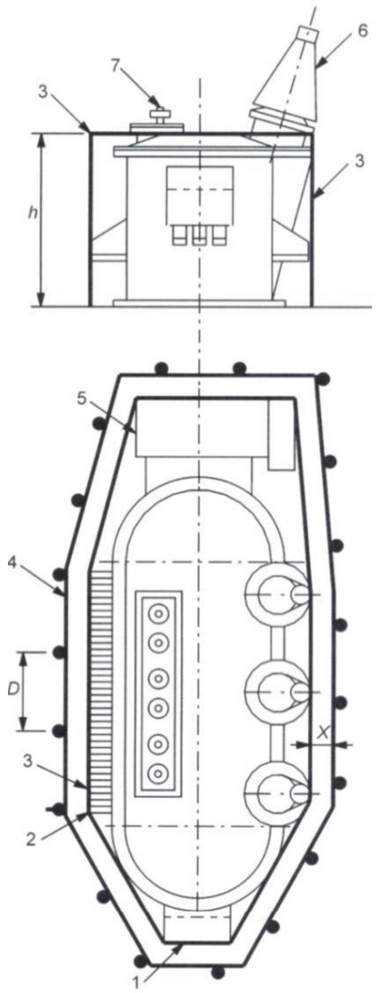
According to IEC, the transformer has to be energized during the test. The condition of “energized” will be agreed between manufacturer and customer. It means either no-load or load condition in the following permissible combinations:

(1) Transformer energized; cooling equipment and any pumps out of service
(2) Transformer energized; cooling equipment and any pumps in service
(3) Transformer energized: cooling equipment out of service, pumps in service
(4) Transformer not energized: cooling equipment and any pumps in service

The measuring circuit for load noise measurement is the same for load loss measurement (see section: 5 Short-circuit voltage & load loss), just like the circuit for no-load noise measurement is similar to no-load loss measurement (section: 6 Measuring the no-load loss & no-load current). To get the total sound level, load- and no-load noises have to be sum up.

Measuring points (acc. IEC)

The position of the microphones has to be at the prescribed contour (Figure 16.3.1), with equally distance to each other (not more than 1 m apart). In case of a detached cooling system, which is placed more than 2 meter away from the transformer, the Sound level of the cooling system has to be measured separately.



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 16.3.1: Typical microphone positions

Natural air cooling (e.g. ONAN)

→ Contour must be spaced 30 cm from the principal radiating surface

Forced air cooling (e.g. ONAF)

→ Contour must be spaced 2 m from the principal radiating surface

Tank height < 2,5 m	Tank height ≥ 2,5m
Measurements carried out at half the tank height	Measurements carried out at 1/3 and 2/3 of the tank height

16.4 *Measuring procedure*

Test conditions

During the entire measurement the excitation voltage should be sinusoidal and keep its rated magnitude and frequency. It is 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. Moreover the transformer under test should be placed as far as possible from reflecting walls, especially parallel to walls, or other equipment to minimize reflections.

Calibration

The measuring equipment has to be checked with a calibrator before and after the test. The test instruments are not allowed to differ more than 0,3dB (acc. IEC) or 1dB (acc. IEEE).

Test sequence

The A-weighted sound pressure level of the background will be measured right away before and after the actual transformers sound level test (A-weighted means all hearable frequencies for humans; 20Hz - 20kHz). The positions of the microphones are therefore the same as for the actual sound level measurement. The background level is the arithmetic average of these measuring points, if the variation is 5dB or less (acc. IEC) or 3dB or less (acc. IEEE). Otherwise a certain formula will be used to get the average background sound level. The actual sound measurement will be conducted similar to background noise level with transformer permissible conditions (see 16.3).

Acceptance criteria

The sound level measurement is valid if the difference between the first and second background measurement is below 3dB (acc. IEC).

Measuring instruments

Typ B&K 2260

→ Measuring device

- linear operating range: 80dB adjustable to give full-scale readings from 80dB to 130dB in 10dB steps
- max. peak level: 3dB above full scale reading
- 6.3 Hz - 20 kHz frequency range in real-time 1/3-octave bands

Typ B&K 4189

→ Microphone

- wide dynamic ranges: from 14.2dB(A) to 146dB and 20dB(A) to 162 dB (3% distortion limit)
- very wide operating temperature range and low ambient-temperature coefficient

Typ B&K 4231

→ Sound level calibrator

- calibration accuracy ±0.2dB
- conforms IEC Standard

17 Measurement of zero-sequence impedance

17.1 Purpose and Standards

It is usual in performing system design calculations, particularly those involving unbalanced loadings and for system earth fault conditions, to use the principle of symmetrical components. This system is described in positive, negative and zero-sequence impedance values to the components of the electrical system. For a three-phase transformer, the positive and negative sequence impedance values are identical to that value described above, but the zero-sequence impedance varies considerably according to the construction of the transformer.

Standard	Section/Clause	Type of test
IEC	60076-1 Clause 10.7 “Measurement of the zero-sequence impedance(s) on three-phase transformers”	Special- or other test
IEEE	C57.12.90 Clause 9.5 “Zero-phase-sequence impedance”	
VDE	0532-76-1	

Table 17.1.1: Associated Standards

17.2 General

Calculations in a symmetrical three-phase system are only possible as far as the values of the phases are simply shifted by 120° and have the same magnitude. Otherwise each phase has to be considered and calculated separately, which is relevant in case of single short-circuits for instance (impedances differ from those in a symmetrical network). Generally it is necessary to convert the given unbalanced three-phase system into a balanced three-phase system. It will be distinguished in:

Phase system	Rotation order
Positive-sequence Z_+	U-V-W
Negative-sequence Z_-	U-W-V
Zero-sequence $\boldsymbol{Z_0}$	All phases in same direction

Table 17.2.1: Phase systems

Corresponding with voltage- and current components, the transformers positive- and negative-sequence impedances are the same, whereas the zero-sequence impedance can differ significantly, depending on winding connection and design. An example for an unbalanced three-phase system consisting of positive-, negative- and zero-sequence system is shown in Figure 17.2.1.

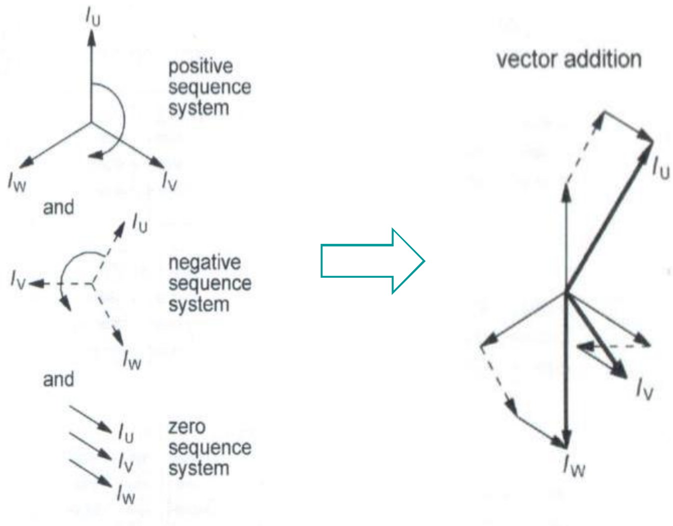


Figure 17.2.1: Unbalanced three-phase system

Zero-sequence impedance

After definition the zero-sequence impedance is the impedance measured between phase terminal (three phases connected) and neutral, which is only possible in star- or zig-zag- connected windings. The zero-sequence impedance, attributed to each phase, is three times the measured value.

$$\boxed{Z_0 = 3 \cdot \frac{U}{I}}$$

U = rated voltage (phase − to − neutral)
I = current in the neutral

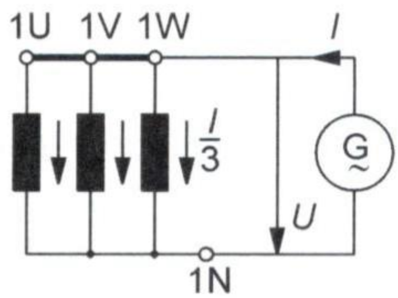


Figure 17.2.2: Zero-sequence impedance

Normally it is given as a percentage value of the basic impedance Z_b, which can be calculated as follows:

$$\boxed{z_0 = \frac{Z_0}{Z_b} \cdot 100}$$

$$Z_b = \frac{{U_r}^2}{S_r}$$

U_r = rated voltage (phase − to − neutral)
S_r = rated power

17.3 Measuring circuit

It should be noted that the directly measured impedances are not used. For further calculation equivalent zero-sequence circuits are more preferred. The equivalent circuits and principal test connections for different neutral- and network conditions are shown in Figure 17.4.1 respectively.

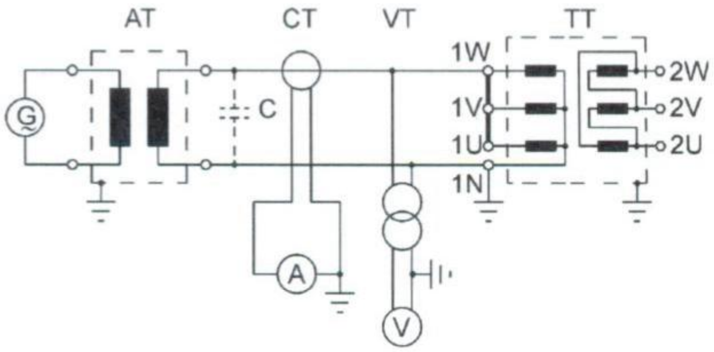


Figure 17.3.1: Principle measuring circuit

TT	=	*transformer under test*	*AT*	=	*matching transformer*
CT	=	*current transformer with ammeter*	*C*	=	*bank of capacitors (eventually necessary for the compensation of the reactive power)*
VT	=	*voltage transformer with voltmeter*			

17.4 Measuring procedure

The measurement must be carried out at rated frequency and always with the active part in the tank, because of its high influence on the zero-sequence impedance. The zero-sequence flux may cause excessive heating in metallic structural parts such as tank, cover or clamping construction. That's why the measuring current must not be higher than 30% of nominal current I_r. Currents up to nominal current are only permitted for a very short time. The applied voltage must not exceed the phase-to-neutral voltage, which occurs during normal operation.

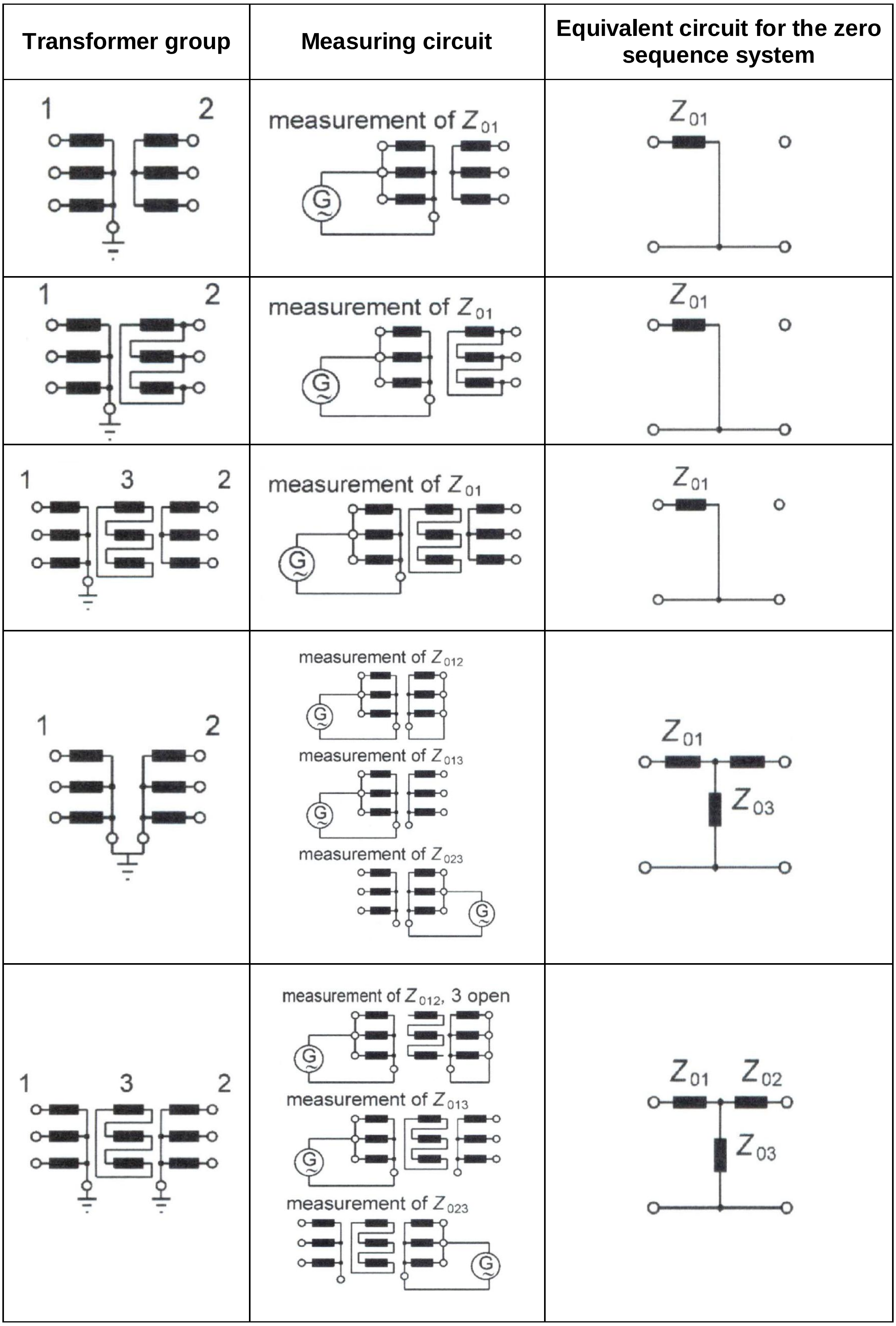
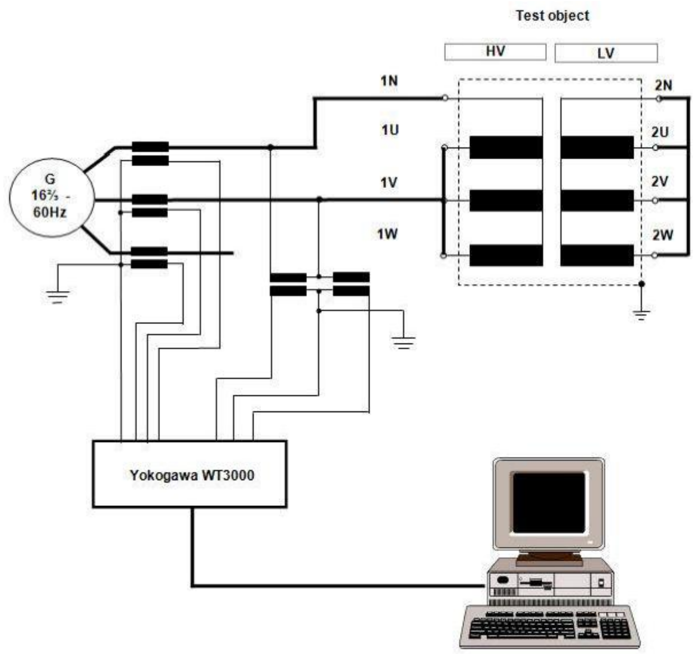


Figure 17.4.1: Examples of test connections for zero sequence impedance measurement

17.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

Yokogawa WT3000
→ Digital Precision Power Analyzer

Accuracy:	*0,01% of basic readings* *0,02% of power readings*
Bandwidths:	*DC and 0,1Hz-1MHz*
Direct inputs:	*up to 30 A/1000 V*

Rack
→ contains Power Analyzer, Votlage- and Current transducer controls

Tettex TMS-PT-581
→ Voltage transducer

Output voltage:	*100 V*
Measuring range:	*0,5, 1, 2, 5, 10, 20, 50, 100, 200, 400, 800 kV*
Overall accuracy:	*0,04 % (5-800 kV)* *0,1% (1-2 kV)* *0,15% (0,2-0,5 kV)*

Tettex TMS-CT-582
→ Current transducer

	Test field 1	Test field 2
Output current:	*1 A*	*1 A*
Measuring range:	*1, 2,10, 20, 40, 100, 500, 1000, 2000, 4000A*	*1, 2, 5, 10, 20, 50, 100, 500, 1000, 2000 A*
Overall accuracy:	*0,005% (40-4000 A)* *0,01% (10-20 A)* *0,03% (4 A)* *0,05% (2 A)*	*0,005% (20-2000 A)* *0,01% (5-10 A)* *0,03% (2 A)* *0,05% (1 A)*

18 Measurement of the harmonics of the no-load current

18.1 Purpose and Standards

Generally it is of interest to keep the amount of harmonics as low as possible. For modern power transformers the harmonic content of the no-load current is actually of little interest, because the no-load current is only about 0,1 – 0,5 % of the rated current, which does not affect the grid effectively enough. It could be interesting in case of old transformers. It has to be noted that there are no applicable Standards according this measurement.

18.2 General

Although a sinusoidal voltage is applied at the transformers terminals, a non-sinusoidal magnetizing current occurs, caused by the non-linear relationship between magnetizing force H and the flux density B (see Figure 6.2.2: Magnetic loop). As seen in Figure 18.2.1 the magnetizing current, as well as the harmonic oscillations (Figure 18.2.2), depends on the applied voltage, which represent the flux density B. The more voltage is applied, the odd-numbered harmonics of the current increase as well, whereas the fundamental harmonic decreases.

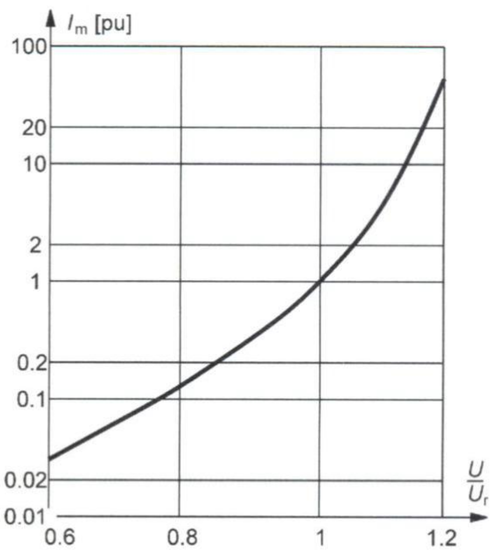


Figure 18.2.1: Magnetizing current

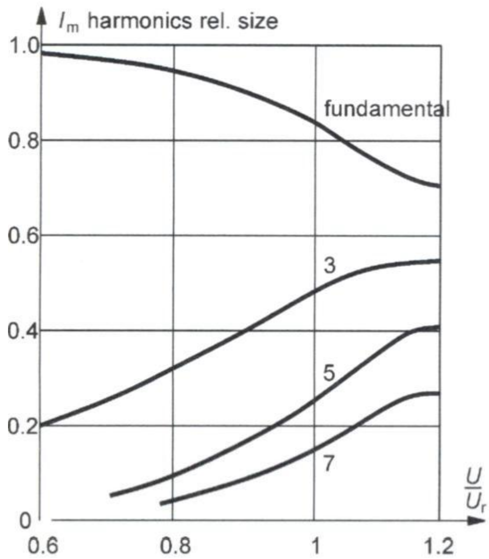


Figure 18.2.2: Harmonics of the magnetizing current

18.3 Measuring circuit

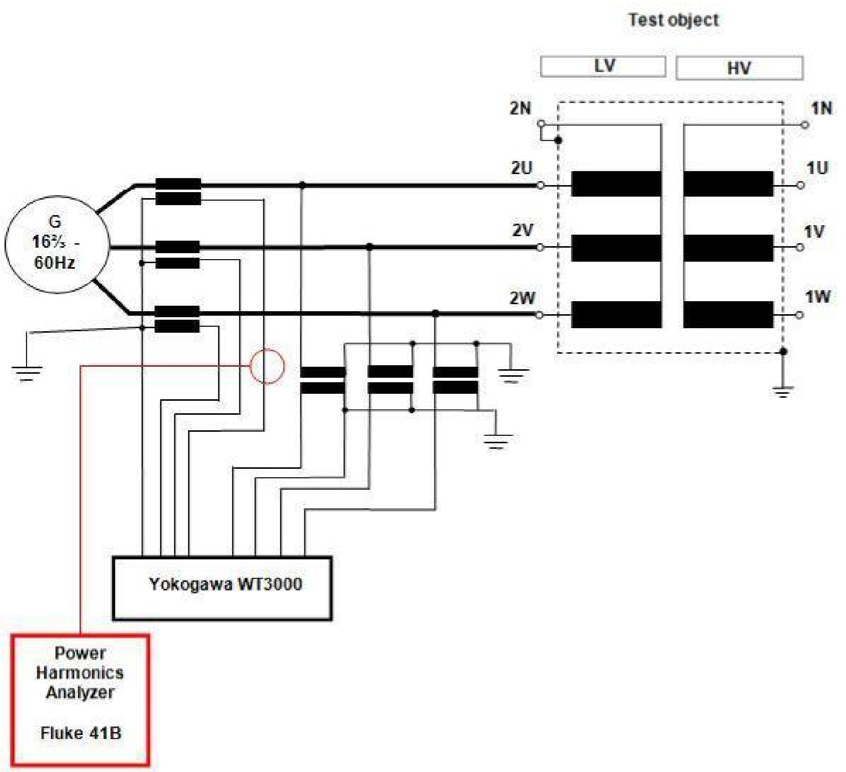
Additionally to the measuring circuit, which is exactly the same as for the measurement of no-load losses and no-load current (see sections: 5 and 6), a harmonic-analyzer (Fluke 41B) is used in one of the ammeter circuits. The possibility of voltage distortion should be excluded. Therefore the generators and matching transformers have to be large enough, obtaining a linear magnetizing characteristic and a voltage free of distortion.

18.4 Measuring procedure

The measuring is conducted at 90%, 100% and 110% of the transformers rated voltage for each of the three phases. The voltage is increased gradually from zero to the full values. Switching on directly would create transient inrushes including DC components, which could saturate the iron core and increase the measuring uncertainty.

18.5 Appendix: Measure arrangement of customized vector group

Test circuit



Measuring instruments

Fluke 41B

→ Powermeter/ Power harmonics analyzer

Accuracy[1]:

Fundamental to 13th Harmonic (ampere):
±(3% of rdg + 3 digits)

13th to 31st Harmonic (ampere):
13th: ±(3% of rdg + 3 digits)…31st: ±(8% of rdg + 3 digits

Fundamental (phase):
± 2 degrees

2nd to 31st Harmonic (phase):
2nd: ± 5 degrees…31st: ± 20 degrees

[1] referred to harmonics measurement

19 Frequency response analysis measurement (FRA)

19.1 Purpose and Standards

Frequency response analysis is a major advance in transformer and reactor condition analysis, allowing you to “see” inside transformers without costly de-tanking. Since the FRA test is used to detect mechanical movement or damage in a transformer, it is most appropriately used after some event or condition that has the possibility of causing mechanical movement or electrical damage to the transformer assembly (e.g. earth quake). Some of the typical scenarios where FRA - measurements may be used include:

- Factory short-circuit testing
- Installation or relocation
- After a significant through-fault event
- As part of routine diagnostic measurement protocol
- After a transformer alarm (i.e. sudden pressure, gas detector, Buchholz)
- After a major change in on-line diagnostic condition
  (i.e. a sudden increase in combustible gas, etc.)
- After a change in electrical test conditions (i.e. a change in winding capacitance)

Standard	Section/Clause	Type of test
IEC	60076-18 “…when a frequency response measurement is required either on-site or in the factory either when the test object is new or at a later stage. This standard is applicable to power transformers, reactors, phase shifting transformers and similar equipment”	Special test
IEEE	C57.149 “Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers”	
VDE	0532-76-18	

Table 19.1.1: Associated Standard

19.2 General

The most common cause of failure in the 20-400 MVA transformer group is general ageing of insulating material. It is therefore desirable to periodically check the mechanical condition of transformers during their service life, particularly for older units and after significant short-circuit events, to provide an early warning of impending failure. Such a capability is perhaps just as important as the ability to diagnose suspected short-circuit failures.

Conventional condition monitoring techniques such as dissolved gas analysis (DGA) are unlikely to detect such damage until it develops into a dielectric or thermal fault, so a specialist technique is clearly required for the monitoring and assessment of mechanical condition. Thus the most important monitoring technique is one that can give the information about insulating condition for ageing or insulating deterioration products.

Resonance circuits

The image on the right-hand side shows the complex electrical relationship which exists between the transformer's windings, its core, the tank, the oil, the insulation, and the tank wall. At the first approximation a transformer windings can be represented by a complex ladder network with series inductance and capacitance as well as the parallel capacitance to ground. These circumstances lead to Resonance circuits (RLC - circuits), Series- as well as Parallel resonance circuits with resonant properties.

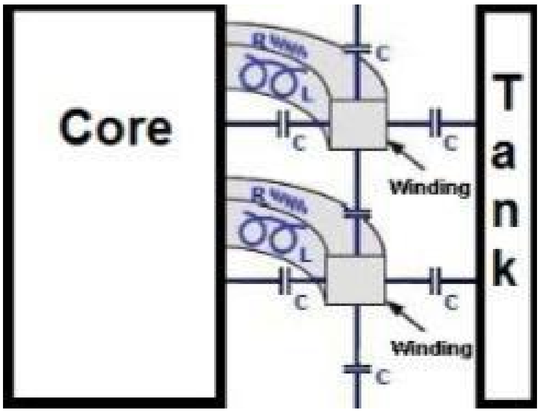


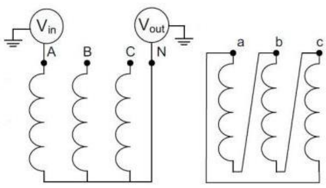
Figure 19.2.1: Illustration of resonance circuits inside the transformer

The transfer function of such networks, calculated by the FRA – measurement, shows a number of poles at the resonance frequency of the local L and C circuits. A breakdown between the turns or coils of the transformer under test corresponds to a short circuit of one or more of these local LC - networks. This will result in shifting the resonant pole to another frequency or the creation of a new pole, which can be interpreted as an indication of failure in transformer's structure.

19.3 Measuring circuit

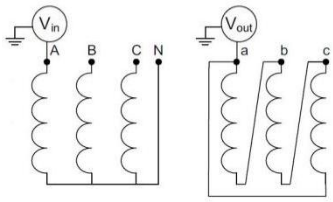
Generally there are four different measuring configurations, which are explained briefly in the following. The measurements are conducted on each of the transformer HV-windings (A,B,C) with the principle tapping position.

- **End-to-end measurement**
  A frequency response measurement made on a single coil (phase winding) with the source lead (V_{in}) connected to one end and the response lead (V_{out}) connected to the other end.



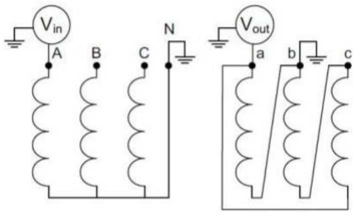
End-to-end (YNd1)

- **Capacitive inter-winding measurement**
  A frequency response measurement made on two neighbouring coils (windings of the same phase) with the source lead (V_{in}) connected to one end of a winding, the response lead (V_{out}) connected to one end of another winding and with the other winding ends floating.



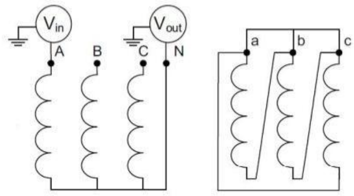
Capacitive inter-winding (YNd1)

- **Inductive inter-winding measurement**
  A frequency response measurement made on two neighbouring coils (windings of the same phase) with the source lead (V_{in}) connected to one end of the higher voltage winding, the response lead (V_{out}) connected to one end of the other winding and with the other ends of both windings grounded.



Inductive inter-winding (YNd1)

- **End-to-end short-circuit measurement**
  A frequency response measurement made on a single coil (phase winding) with the source and lead (V_{in}) connected to one end, the response lead (V_{out}) connected to the other end. Another windings of the same phase are short-circuited.



End-to-end short-circuit (YNd1)

19.4 Measuring procedure

The Frequency Response Analysis is a test measurement made to the winding structures of a power transformer, performed by an instrument injecting a voltage signal into the top of the selected winding structure and measuring the voltage signal appearing at the bottom of the same or neighbouring selected winding structure, calculating the transfer function. This is performed for each winding structure of the transformer. Values of impedance and phase angle are measured over the given frequency range and are available as logarithmic graphs, for each of the tested winding structures. This graph is a representation of the frequency response of the windings at different frequencies (example in Figure 19.4.1).

Any transformer under test should be completely isolated from any high-voltage source or power system source. The transformer tank should be grounded. Two of the bushings will be used. The measurement (most accepted: End-to-end measurement) will be conducted for all windings in maximum tapping position. The stabilizing winding (if existing) remains and will not be earthed.

Frequency range

The test is made over the entire frequency range up to 2 MHz, so as to be able to diagnose problems in the core, clamping structure, windings and interconnections. Successive frequency measurements are equally spaced so as to obtain adequate resolution in the higher frequencies so as to give unambiguous diagnosis. The highest measuring frequency depends on the highest voltage level of the transformer. For an example of a Frequency resonance analysis for one winding see the following figure.

U_m > 72,5 kV at least 1 MHz
U_m < 72,5 kV at least 2 MHz

Measuring instrument

TETTEX FRA 5310

→ Frequency Response Analyser

Accuracy:	*± 0,1dB*
Frequency Range:	*10Hz – 10MHz*
Sweep Mode:	*Logarithmic or Linear*

	effective in determination of following conditions
Low Frequency Range (0 – 50 kHz)	▪ Core problems within the transformer ▪ Presence of shorted turns.
Medium Frequency Range (50 – 500 kHz)	▪ Axial collapse ▪ Localized winding movement ▪ Winding asymmetry
High Frequency Range (500 – 2000 kHz)	▪ Movement of main and tap winding leads ▪ LTC and DETC connections

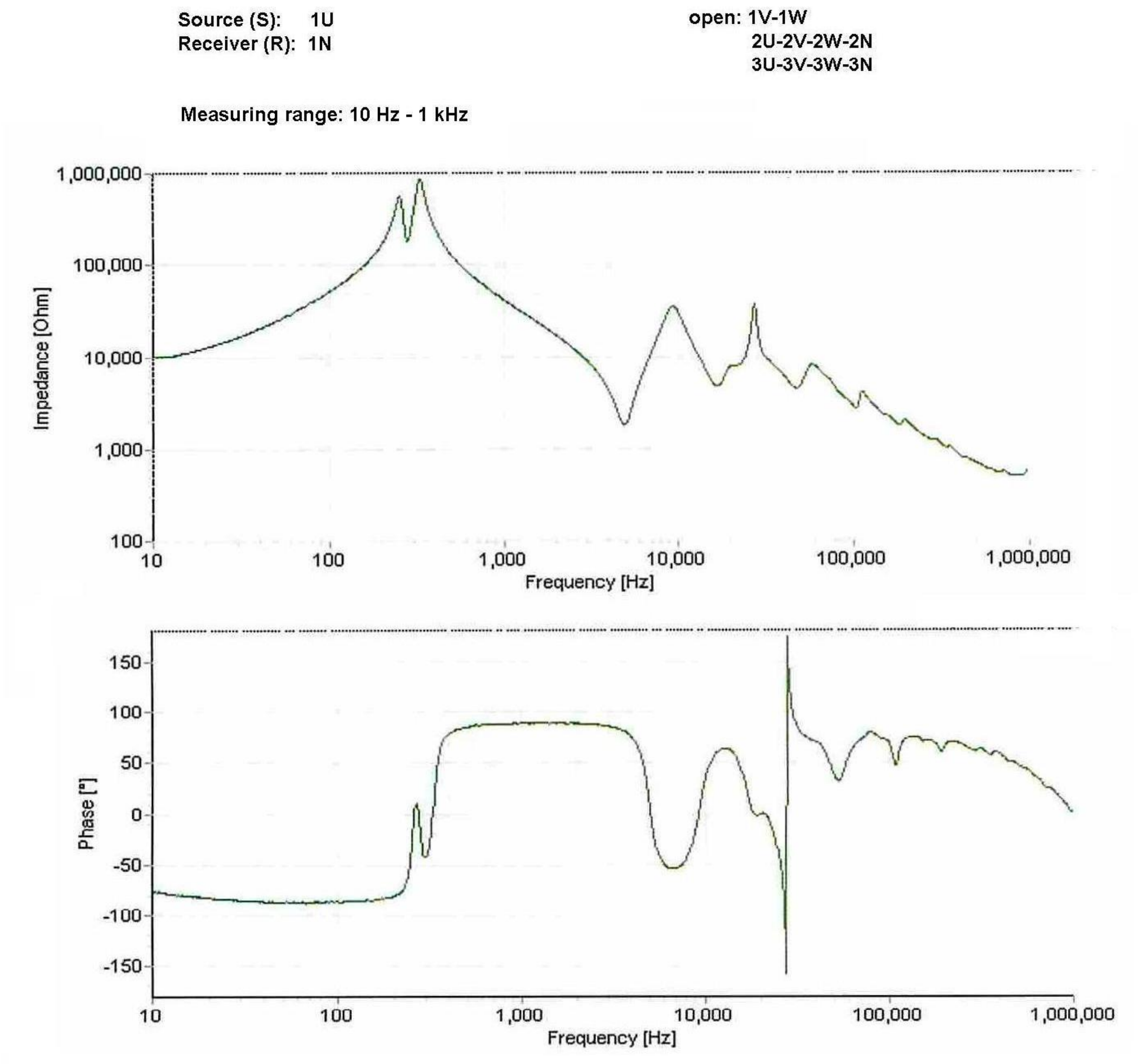


Figure 19.4.1: Example of a Frequency resonance analysis

20 FDS measurement for moisture estimation

20.1 Purpose and Standards

Traditional oil sampling methods requires the use of an equilibrium diagram for evaluating moisture in transformers and can result in errors in the assessment. The application of conventional equilibrium charts causes inaccurate results due to the uncertainties during the sampling and water-in-oil measurement. Together with very long time constants for equilibrium processes, it leads to a very poor accuracy. The dielectric response method, in contrast, is a very reliable method providing a high degree of accuracy in assessing the moisture content in the paper insulation.

Moisture in the solid part of power transformer insulation (paper, pressboard) is one of the most critical condition parameters. Water enters transformers from the atmosphere (breathing, leaky seals) and during installation and repair. Aging of the oil-paper insulation also increases the moisture level. Typically, the solid part of the insulation structures holds most part of the water, i.e. 2000 times more than the oil. Measurement of the water content in oil-paper insulation is therefore a helpful tool for making an assessment of the ageing of the cellulose and a key factor to ensure transformer's reliability and longevity.

Standard	Section/Clause	Type of test
IEC	<u>60422</u> "…supervision and maintenance of the quality of the insulating oil in electrical equipment."	Special test
	<u>60296</u> "It applies to oil intended for use in transformers, switchgear and similar electrical equipment in which oil is required for insulation and heat transfer."	

Table 20.1.1: Associated Standards

20.2 General

Today transformers are not automatically replaced, if they have reached the end of their life span, but left in service as long as possible. In contradiction to the past, power transformers are operated nowadays at or above rated power. This accelerates the ageing process of the inner insulation, particularly of the insulation paper, which cannot be easily replaced.

Moisture entering in oil-paper insulations can cause dangerous effects:

- Decreases the dielectric withstand strength
- Accelerates cellulose aging (the so-called: de-polymerization)
- Causes the emission of gas bubbles at high temperatures and may lead to a sudden electrical breakdown.

It is important to have reliable tools for measuring the water content in the oilpaper insulation. This way unexpected breakdowns can be avoided and the maintenance, repair or replacement can be scheduled in time. Those faults are often indicated by the oil analysis, which is a proven and meaningful tool. Dielectric spectroscopy methods are used to determine the moisture in the solid insulation of power transformers.

1. **Polarisation and depolarisation current (PDC)**
   → Dielectric spectroscopy in the time domain.

2. **Frequency domain spectroscopy (FDS)**
   → Measurement of the capacitance and the dissipation factor over a wide frequency range (µHz to kHz)

Although the results of PDC and FDS methods are comparable and can be transformed from the time domain into the frequency domain and reversely, both methods have advantages and disadvantages. A new approach combines both methods. The FDS measurement is replaced by the PDC method in the low frequency range and the results are transformed into the frequency domain, whereas the FDS is used for higher frequencies, which can be done rather quickly.

The measuring instrument OMICRON Dirana makes use of this principle and shortens the measurement time to a minimum. Two input channels for simultaneous measurement of two insulation gaps make it even faster. The software takes also the conductivity of the oil into account. This makes the results for aged transformers much more reliable compared to the standard model curves which were used in the past. The analysis of the gas in oil is a well-proven method of analysis but must be complemented by efforts to locate any faults. This way important maintenance can be performed in time to avoid a sudden total failure. The fault location can be successfully performed using modern type test equipment for resistance, winding ratio, short circuit impedance, capacitances and dissipation factor (tan δ), FRA and PD measurements.

20.3 Measuring circuit

The dielectric response is measured by a three-terminal measurement that includes the output voltage (Power output), the measurement current (CH A) and a guard (CH B) to prevent disturbances due to current paths caused by dirty bushings or electromagnetic fields and to short-circuit the winding-capacitance, which is necessary for the return-voltage-analysis. During the test the tank is generally earthed.

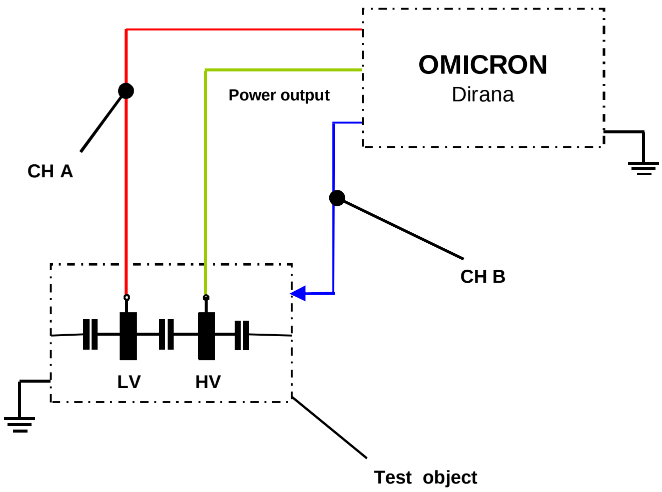


Figure 20.2.1: Principle measuring circuit

Measuring instrument

OMICRON Dirana

→ FDS/PDC Dielectric Response Analyzer

Measuring range:	*10 µHz...5kHz*
Measuring voltage/current:	*200* V_{peak} */ 50* mA_{peak}
Measuring time:	*2mHz…1kHz: approx. 15min*
	100µHz…1kHz: < 3h
	10µHz…1kHz: < 6h

20.4 Measuring procedure

The OMICRON instrument derives the moisture content in paper or pressboard from properties such as polarization current, complex capacitance, and dissipation factor. Each of these parameters is strongly affected by moisture.

The dissipation factor plotted against frequency shows a typical S-shaped curve (see example in Figure 20.4.1). With increasing moisture content, temperature or aging the curve shifts towards the higher frequencies. Moisture influences the low and the high frequency areas. The linear, middle section of the curve with the steep gradient reflects oil conductivity.

This moisture determination is based on a comparison of the transformers dielectric response to a modeled dielectric response. A fitted algorithm compares the measured data with the model data and calculates the geometry data, the moisture content as well as the oil conductivity. Only the oil temperature needs to be entered.

Measurement steps

For e.g. a two-winding transformer which has been disconnected from the network:

- Apply the test voltage to the HV windings
- Current measurement via LV windings
- Connect the guard to the bushing flange (ground)

Unlike the conventional equilibrium method, the measurement can be taken right away. There is no requirement to allow the transformer to cool, or wait until moisture equilibrium between paper and oil has been reached.

Assessing the results

The IEC Standard categorizes moisture saturation of more than 6 % as “moderately wet“, which is equivalent to a moisture content of approximately 2.2 %. At this level the dangerous effects caused by water can affect the insulation. Based upon this, corrective action should be taken for e.g., a drying process.

Moisture content relates water mass to the material mass, whereas moisture saturation relates water mass to the maximum water mass a material can adsorb.

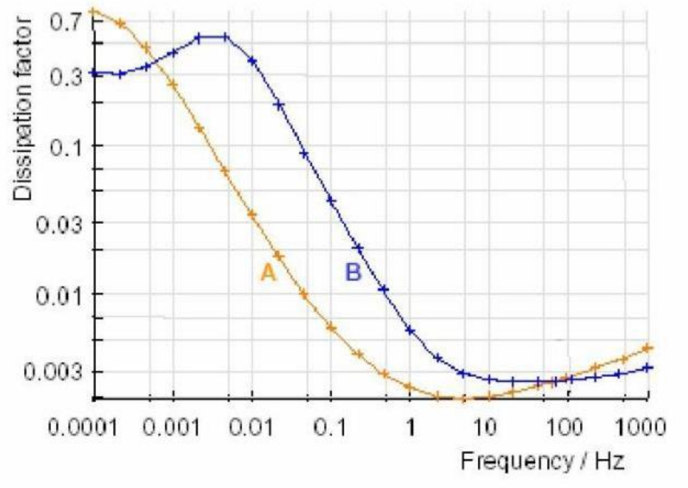


Figure 20.4.1: Example of a moisture measurement (curve B with increased moisture)

21 Measurement of insulation capacitances & loss factor (tan δ)

21.1 Purpose and Standards

Similar to the Insulation resistance measurement, the determination of the loss factor (tan δ) allows certain conclusions about the condition of the transformer insulation and serves as a reference value for later measurements, especially for comparisons during operation at later stage.

Standard	Section/Clause	Type of test
IEC	60076-1 Clause 10.1.3: Power transformers – Part 1: General, "Measurement of the dissipation factor (tan δ) of the insulation resistance capacitances"	Routine test U_m > 72,5 kV Special test U_m ≤ 72,5 kV
IEEE	C57.12.90 Clause 10.10 "Insulation power-factor tests"	Routine test for class II transformers Other test for class I transformers

Table 21.1.1: Associated Standards

21.2 General

These special tests include the determination of the winding capacitance with respect to ground and also the loss factor. The loss factor is defined (by IEC; also known as power factor in IEEE Standards) as the ratio between the absorbed active power and the absolute value of the reactive power, which corresponds to tan δ. In the ideal insulator, the angle would be 90°C as it is purely capacitive and non-conducting. However in real insulators, there will be some leakage current and resistive losses through the dielectric. There is no relationship between the loss factor and the transformers withstand (dielectric test). Moreover its dependence on temperature is substantial and erratic. The various insulation materials and liquids used in the transformer result in large variations of loss factor as well. That`s why it indicates to information about the condition of the oil.

21.3 Measuring circuit

The loss factor will be generally measured in special bridge circuits, based on comparing the capacitance and balancing them. The measuring instrument Tettex MiDAS 2880 does this automatically. External influences must be reduced by a coaxial cable. In the figures below examples of the measuring circuit are given.

Tettex MiDAS 2880

→ Mobile Insulation Diagnosis & Analysing System

Accuracy: (Dissipation Factor)	*± 0,5% of readings ± 0,01% of resolution*
Accuracy: (Capacitance)	*± 0,3% of readings ± 0,3 pF*

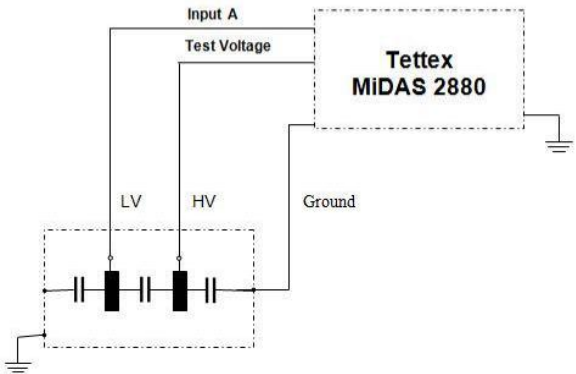


Figure 21.3.2: Test connection for HV side against tank and LV side

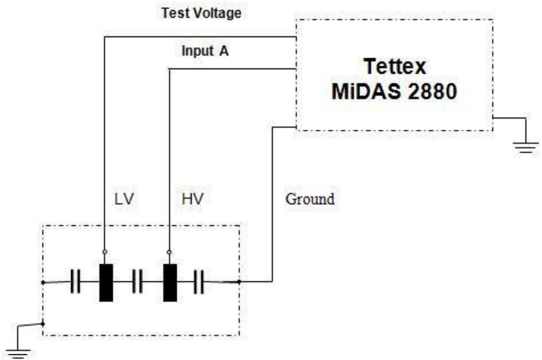


Figure 21.3.1: Test connection for LV side against tank and HV side

21.4 Measuring procedure

A 10kV voltage at 50Hz is applied to the test object. Depending on the number of windings and whether there exists a stabilizing winding, the number of measurements will differ. Usually measurements will be taken of:

- low-voltage side against the tank and high-voltage side
- high-voltage side against the tank and low-voltage side
- low-voltage and high-voltage sides against the tank

The winding of the test object that is not measured and the tank are in each case grounded via the measuring equipment. If a stabilizing winding exist more measuring combinations are applicable. The gathered values are relevant for later measurement as reference values.

22 Measurement of excitation current with 400V

22.1 General

This test will be performed with portable instruments (common digital multimeter), carried out at the jobsite before the transformer will be connected to the power supply. The excitation current, measured with a 400V supply in the field, allows an evaluation of the transformer's condition and serves as a final check. Because the value is already known before dispatch, possible rough damage (internal winding/core faults) caused by shipping can be detected quickly this way. That's why the measured excitation current, which has a fixed value, is also understood as a "fingerprint" for the respective transformer.

Note: Usually known as "no-load measurement", the gathered results can be used to obtained further basic parameters like transformer turns ratio or polarity.

22.2 Measuring procedure

The excitation current is the current flowing into the high voltage winding with the low voltage side open. This current should be proportional to the no-load acceptance test, regarding the use of test voltages different from nominal values. Therefor an alternating voltage of 400V will be applied to the high voltage winding of the transformer in each of its phases (low voltage side open).

Care have to be taken that the core is fully unsaturated before the measuring the excitation current. Otherwise a distorted value will be measured, leading to false conclusion about transformer's condition. To avoid saturation of the core, a slightly higher voltage than system voltage will be applied to the transformer terminals and will be then reduced to zero. The core should be free of any residual magnetism after that.

23 Calibration of the Winding Temperature Indicator (WTI)

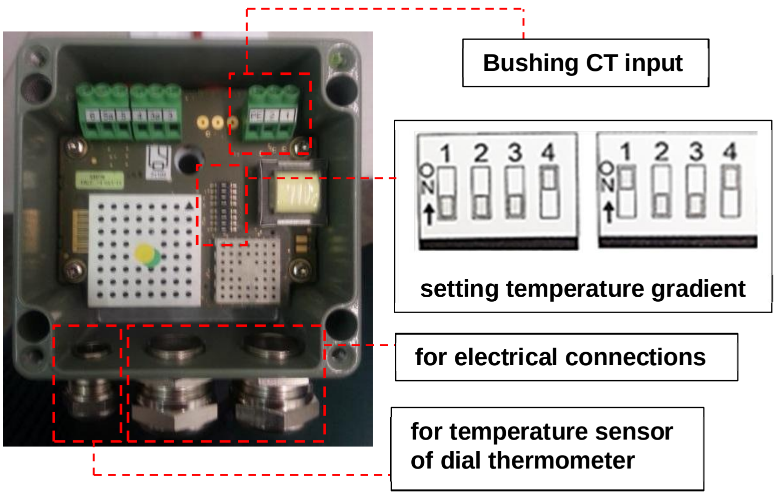
23.1 General

The Winding Temperature Indicator (WTI) is supposed to indicate the hottest spot in the winding. An alternative are fiber optic temperature sensors can be imbedded directly into the winding (14.6 Hot-spot measurement) and are more accurate, which may be worth it, since exact values for hot-spot temperatures are essential when higher loading is required. They can be used as monitoring device or turn on additional cooling or activate alarms, as top oil thermometers do.

MESSKO pointer thermometer

The WTI, also known as transformer temperature transmitter, can only be used in conjunction with a pointer thermometer, which is used to present the hot-spot temperature in the transformer. The measured value is captured by a liquid filled temperature sensor and is then transmitted via a spiral spring which is linked with zero backlashes to a pointer spindle.
The temperature transmitter heats the sensors of the pointer thermometer by simulating the winding temperature. The temperature gradient between the winding and the coolant is dependent on the current in the winding of the transformer. To this winding current the secondary current of the bushing current transformer is proportional, which is used to supply the heating resistor of the temperature transmitter. This causes an increase corresponding to the transformer loads in the actually measured oil temperature. When it comes up to monitoring issues, the measured value can also be transferred to a digital display, via an installed Pt100 resistor. The temperature gradient at rated load, which is a known data from the temperature rise test, have to be set by DIP switches and calibrated before putting into operation.

MESSKO Transformer temperature transmitter (WTI)



Inside temperature transmitter

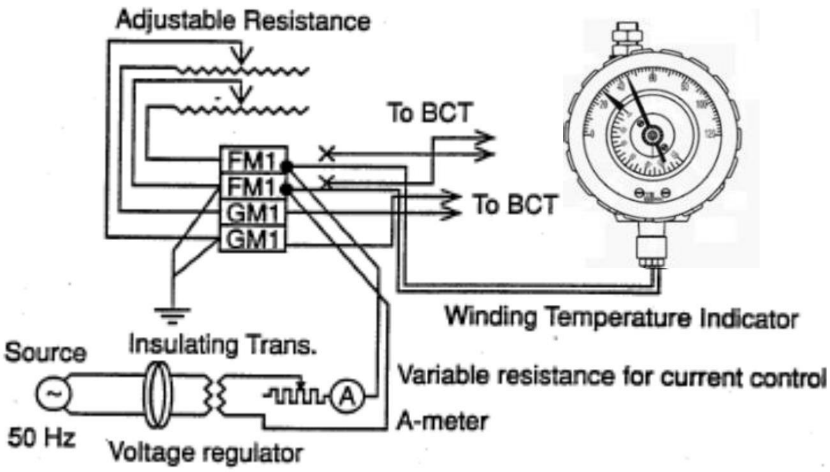
23.2 Calibration

As mentioned, the adjustment value for the calibration is calculated by means of the temperature rise gradient and the bushing current transformer's rated current, which are known data of the transformer at rated power. By injecting the rated CT current and by means of a specific curve (thermal replica or formula) of the heating resistance, the Winding temperature indicator can be calibrated before installation.

Steps

- connect current supply
- inject a current corresponding to the rated power (regard BCT ratio) of the transformer (usually about 2 A)
- maintain the current for a couple of minutes and check the rise of the indicator
- temperature rise gradient has to correspond to rated current of bushing CT (see specific curve)

Variable current source for calibration



Connection diagram for calibration