Transformer Tests

Introduction:

The methods used during tests and measurements of the Power Transformers, test and measurement circuits, calculations and evaluation criteria's are included in this manual. At the end of this manual, The Transformer Factory laboratory hardware and measurement and test equipment are listed.

For insulation levels of transformers, electrical characteristics and evaluation, please refer to national and international standards and customer specifications.

Tests and evaluation definitions are listed below:

Routine Tests :

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1- Measurement of winding resistance

Measurement is made to check transformer windings and terminal connections and also both to use as reference for future measurements and to calculate the load loss values at reference (e.g. 75°C) temperature. Measuring the winding resistance is done by using DC current and is very much dependent on temperature. Temperature correction is made according to the equations below:

$$R_2 = R_1 \cdot \frac{235 + t_2}{235 + t_1}$$ (for copper) $$R_2 = R_1 \cdot \frac{225 \quad t_2}{225 + t_1}$$ (for aluminium)

R_2 : winding resistance at temperature t_2, R_1 : winding resistance at temperature t_1

Because of this, temperatures must be measured when measuring the winding resistances and temperature during measurement should be recorded as well.

Winding resistances are measured between all connection terminals of windings and at all tap positions. During this, winding temperature should also be appropriately measured and recorded.

The measuring current can be obtained either from a battery or from a constant(stable) current source. The measuring current value should be high enough to obtain a correct and precise measurement and small enough not to change the winding temperature. In practice, this value should be larger than $1{,}2 x I_0$ and smaller than $0{,}1 x I_N$, if possible.

A transformer consists of a resistance R and an inductance L connected in serial. If a voltage U is applied to this circuit;

The value of current measurement will be : $i = \frac{U}{R}(1 - e^{-\frac{R}{L}t})$. Here, the time coefficient depends on L/R ratio.

As the measurement current increases, the core will be saturated and inductance will decrease. In this way, the current will reach the saturation value in a shorter time.

After the current is applied to the circuit, it should be waited until the current becomes stationary (complete saturation) before taking measurements, otherwise, there will be measurement errors.

Measuring circuit and performing the measurement

The transformer winding resistances can be measured either by current-voltage method or bridge method. If digital measuring instruments are used, the measurement accuracy will be higher. Measuring by the current-voltage method is shown in figure 1.1

In the current – voltage method, the measuring current passing through the winding also passes through a standard resistor with a known value and the voltage drop values on both resistors (winding resistance and standard resistance) are compared to find the unknown resistance (winding resistance). One should be careful not to keep the voltage measuring voltmeter connected to the circuit to protect it from high voltages which may occur during switching the current circuit on and off.

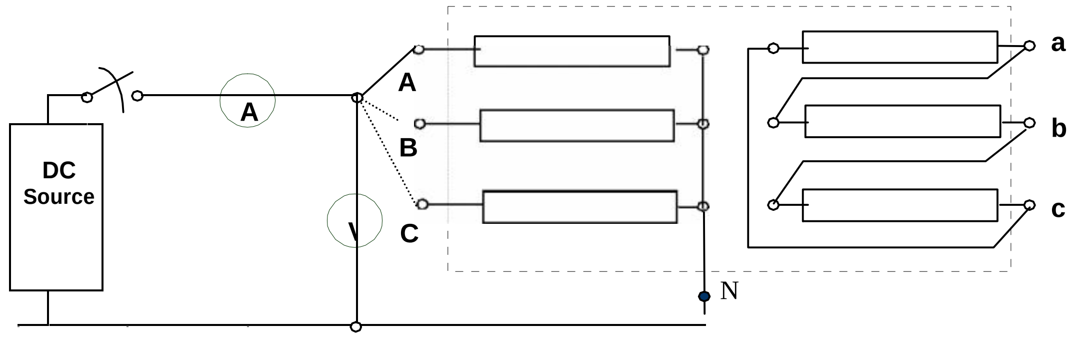


Figure 1.1: Measuring the resistance by Current-Voltage method

The bridge method is based on comparing an unknown (being measured) resistor with a known value resistor. When the currents flowing in the arms are balanced, the current through the galvanometer will be zero. In general, if the small value resistors (e.g. less than ≤1 ohm) are measured with a Kelvin bridge and higher value resistors are measured with a Wheatstone bridge, measurement errors will be minimised.

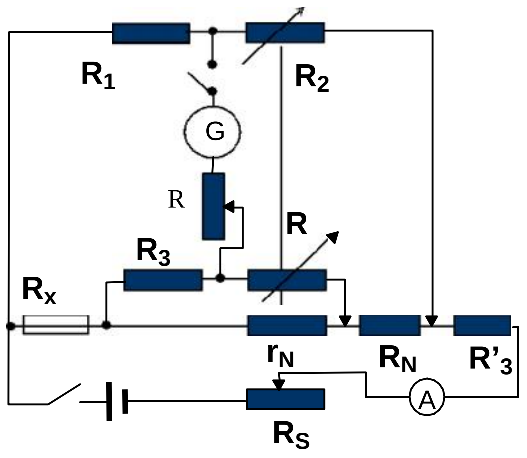


Figure 1.2: Kelvin bridge

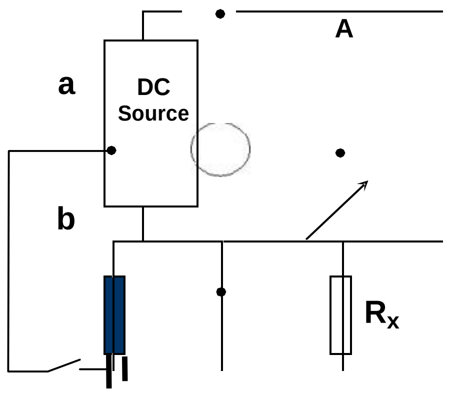


Figure 1.3: Wheatstone bridge

The resistance measured with the Kelvin Bridge;

$$R_x = R_N \cdot \frac{R_1}{R_2} \qquad (R_1 = R_3 \text{ ve } R_2 = R_4)$$

The resistance measured with the Wheatstone Bridge;

$$R_X = R \frac{a}{b}$$

2- Measurement of voltage ratio and check of phase displacement

The no-load voltage ratio between two windings of a transformer is called turn ratio.
The aim of measurement is; confirming the no-load voltage ratio given in the customer order specifications, determining the conditions of both the windings and the connections and examining the problems (if any)
The measurements are made at all tap positions and all phases.

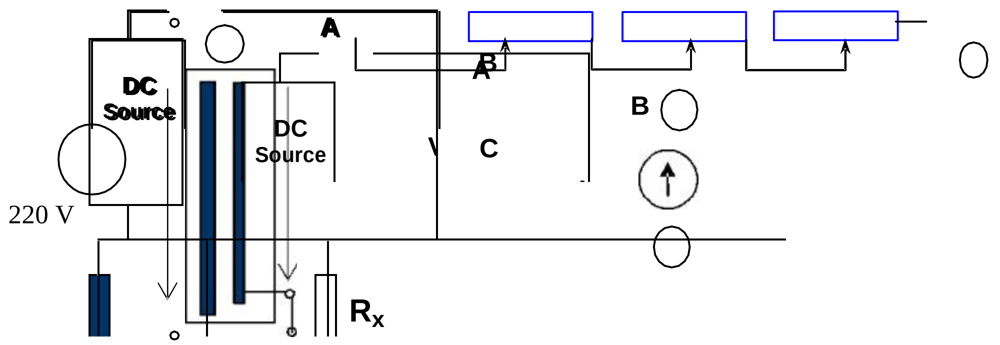
Measurement circuit and performing the measurement

2.1 Turn Ratio Measurement

The turn ratio measurement can be made using two different methods;

a. Bridge method
b. By measuring the voltage ratios of the windings

a). Measurement of turn ratio is based on, applying a phase voltage to one of the windings using a bridge (equipment) and measuring the ratio of the induced voltage at the bridge. The measurements are repeated in all phases and at all tap positions, sequentially. During measurement, only turn ratio between the winding couples which have the same magnetic flux can be measured, which means the turn ratio between the winding couples which have the parallel vectors in the vector diagram can be measured. (fig 2.1, 2.2, 2.3). In general, the measuring voltage is 220 V a.c. 50 Hz. However, equipments which have other voltage levels can also be used. The accuracy of the measuring instrument is ≤ ±0,1%.



(1) Transformer under test

(2) Transformer with adjustable range (standard)

(3) Zero position indicator

U_1 Applied voltage to the bridge and HV winding (220 V, 50 Hz)

U_2 Induced voltage at the LV winding

Figure 1-1: Bridge connection for measuring the turn ratio

Theoretical turn ratio = HV winding voltage / LV winding voltage

The theoretical no-load turn ratio of the transformer is adjusted on the equipment by an adjustable transformer, it is changed until a balance occurs on the % error indicator. The value read on this error indicator shows the deviaton of the transformer from real turn ratio as % .

$$\text{Deviation} = \frac{(\text{measured turn ratio}) - (\text{expected turn ratio}}{)\ \text{expected turn ratio}} \cdot \%100$$

b). The voltages at the winding couples to be measured, can be measured at the same time and the ratio can be determined, or digital instruments which are manufactured for this purpose can be used in the voltage ratio measurement method. By using such instruments, in addition to measuring the turn ratio, also determining the connection group (with three phase measuring instrument) and measuring the currents during measurement are also possible. The method of comparing the vector couple voltages also allows measuring the angle (phase slip) between vectors at the same time

The no-load deviation of the turn ratios should be ≤ % 0,5 .

2.2 Determining the Connection Group

Depending on the type of the transformer, the input and output windings of a multi-phase transformer are connected either as star (*Y*) or delta (*D*) or zigzag (*Z*). The phase angle between the high voltage and the low voltage windings varies between *0°* and *360°* .

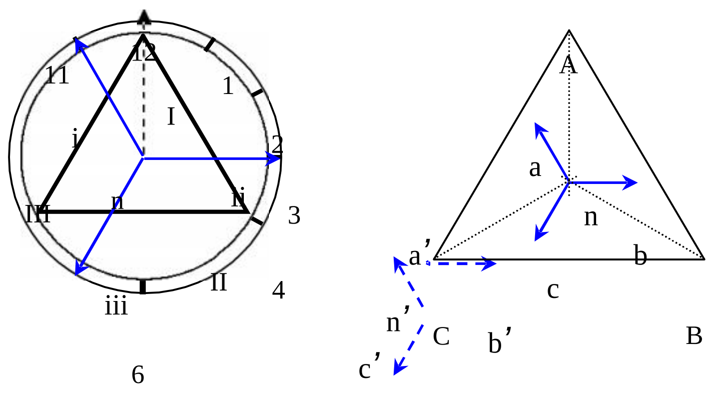
Representing as vectors, the HV winding is represented as *12 (0*) hour and the other windings of the connection group are represented by other numbers of the clock in reference to the real or virtual point. For example, in *Dyn 11* connection group the HV winding is delta and the LV winding is star and there is a phase difference of 330° (11x30°) between two windings. While the HV end shows *12 (0)*, the LV end shows 11 o'clock *(after 330°).*

Determining the connection group is valid only in three phase transformers. The high voltage winding is shown first (as reference) and the other windings follow it.

If the vector directions of the connection are correct, the bridge can be balanced.

Also, checking the connection group or polarity is possible by using a voltmeter. Direct current or alternating current can be used for this check.

The connections about the alternating current method are detailed in standards. An example of this method is shown on a vector diagram below.



The order of the measurements:

1)- *3 phase voltage is applied to ABC phases*
2)- *voltage between phases (e.g. AC) is measured*
3)- *A short circuit is made between C and n*
4)- *voltage between B and b′ is measured*
5)- *voltage between A and c′ is measured*

Figure 1-2: Connection group representation and measuring

As seen from the vector diagram, in order to be Dyn 11 group , A.c′ > AB > B.b′ correlation has to realized. Taking the other phases as reference for starting, same principles can be used and also for determining the other connection groups, same principles will be helpful.

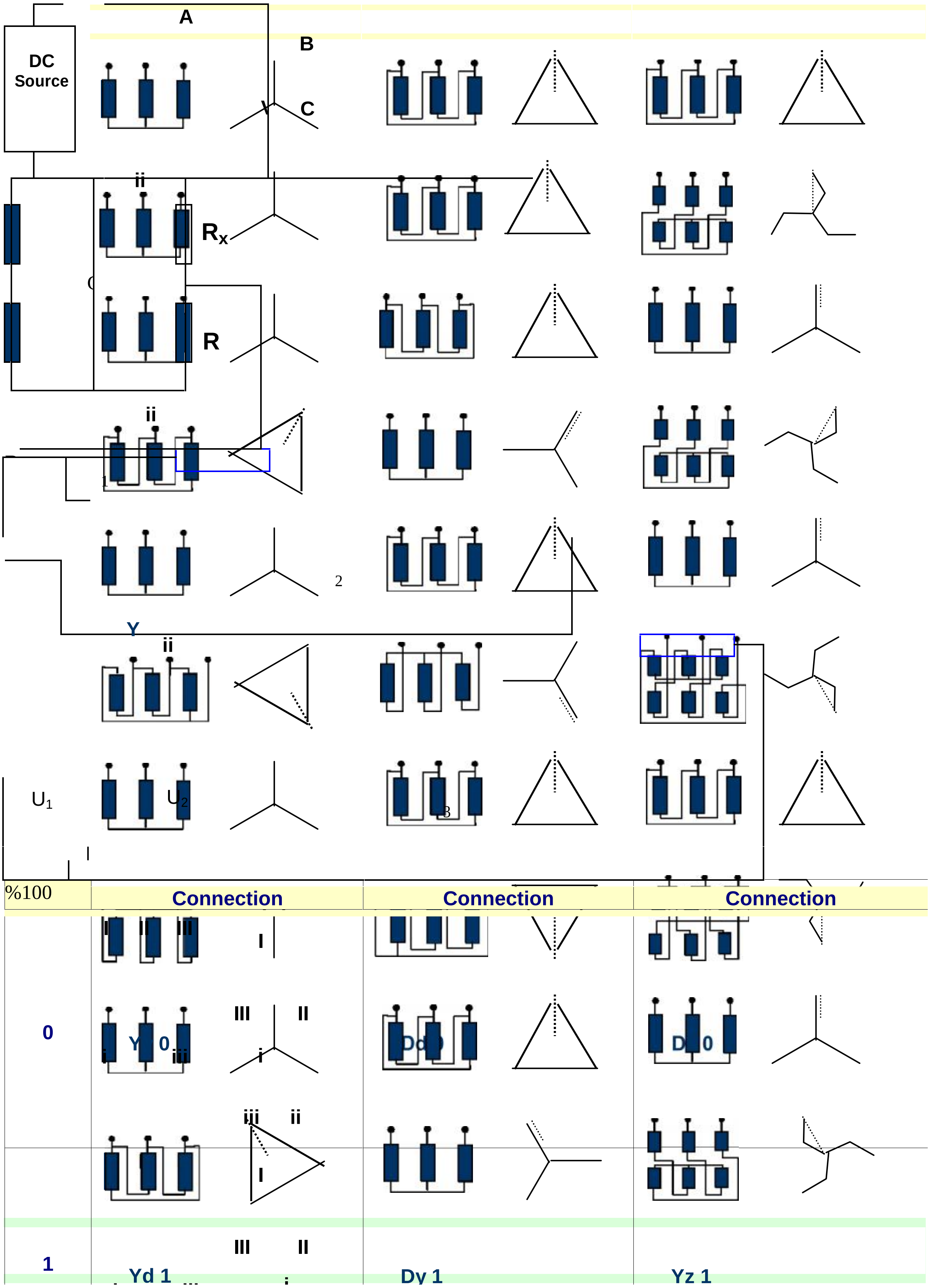


Figure 2.3: Some of the connection groups according to IEC 60076-1 standard

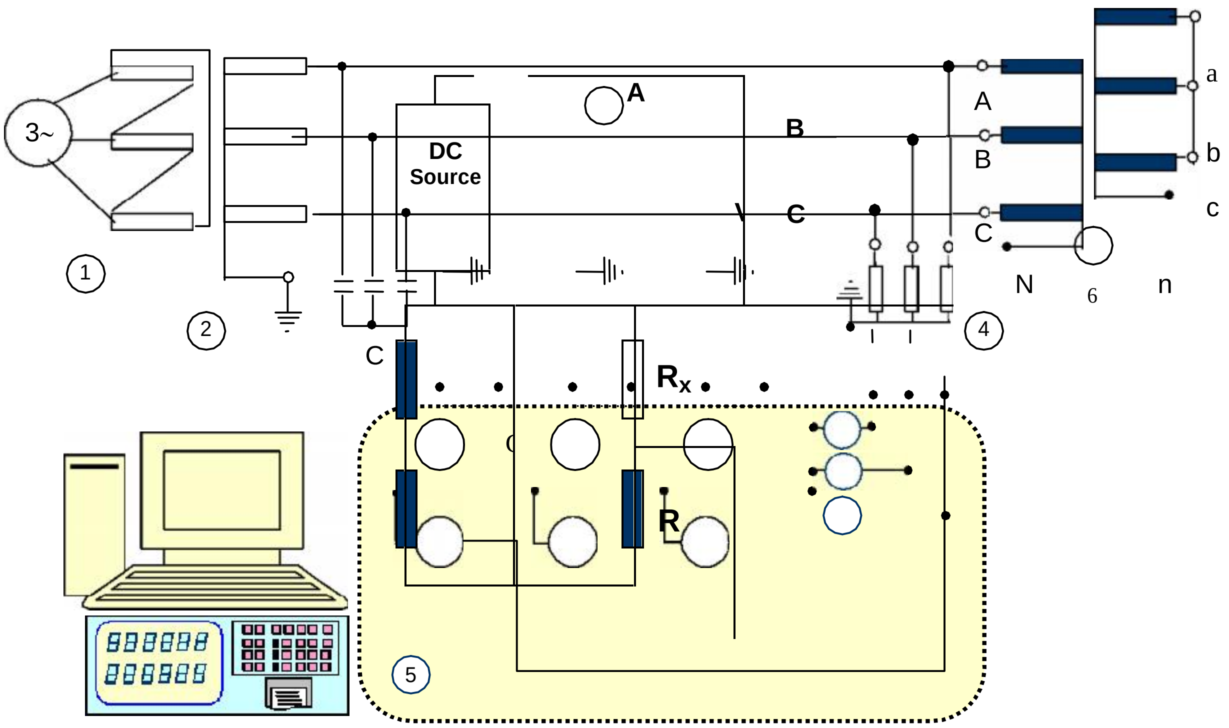
3- Measurement of short-circuit impedance and load loss

The short-circuit loss and the short-circuit voltage show the performance of the transformer. These values are recorded and guaranteed to the customer and important for operational economy. The short-circuit voltage is an important criteria especially during parallel operations of the transformers. The short-circuit loss is a data which is also used in the heat test.

Short-circuit voltage; is the voltage applied to the primary winding and causes the rated current to flow in the winding couples while one of the winding couples is short circuited. The active loss measured during this, is called short-circuit loss. If the adjusting range is more than 5%, in addition to the rated value, the losses are repeated for the maximum and minimum values.

The short-circuit loss is composed of; “Joule “ losses (direct current/DC losses) which is formed by the load current in the winding and the additional losses (alternating current/AC losses) in the windings, core pressing arrangements, tank walls and magnetic screening (if any) by the leakage (scatter) fluxes.

Measuring circuit and performing the measurement:



1- Power supply
2- Supply (intermediate) Transformer
3- Current Transformers
4- Voltage Transformers
5- Power Analyser
6- Transformer under test
C- Compensation Capacitor groups

Figure 3.1: Short-circuit losses measurement connection diagram

In general, the HV windings of the transformer are supplied while the LV windings are short-circuited. During measurement, the current has to be at the value of I_N or close to this value as far as possible. The voltage, current and short-circuit losses of each phase should be measured during measurement.

In cases where the power supply is not sufficient enough to supply the measurement circuit, compensation to meet the reactive power has to be made using capacitors.

Before beginnig to measure, the transformer winding/oil temperature has to be stabilised and the winding/oil temperature and winding resistances have to be measured.

In order to avoid increasing the winding temperature by the applied current, the measurement has to be completed in a short time and the measuring current has to be kept between 25%...100% of the rated current. In this way, the measurement errors due to winding temperature increase will be minimised.

The losses have to be corrected based on reference temperature (e.g. 75°C) stated in the standards and evaluated. The short-circuit voltage U_{km} and losses (P_{km}) which are found at the temperature which the measurement was made, have to be corrected according to this reference temperature.

The direct-current/DC losses on the winding resistances, while the resistance values are R_{YG} and R_{AG} (phase to phase measured resistances) are as follows ;

Direct-current loss = at measuring temperature t_m $P_{DC} = 1,5.(I_1^2.R_{YG} + I_2^2.R_{AG})$.

AC / Additional losses = at measuring temperature t_m $P_{ac} = P_{km} - P_{dc}$.

Losses at reference (75°C) temperature:

$$P_k = P_{DC} \cdot \frac{t_R + 75°C}{t_R + t_m} + P_{AC} \cdot \frac{t_R + t_m}{t_R + 75}$$

t_R : 235 °C for Copper (acc. to IEC)
225 °C for Aluminium (acc. to IEC)

Short-circuit voltage :

At measuring temperature (t_m) $u_{km} = 100 \cdot \frac{U_{km}}{U_N}$ [%]

$u_{RM} = 100 \cdot \frac{P_{km}}{S_N}$ [%] "ohmic/DC " component, $u_{xm} = \sqrt{u^2_{km} - u^2_{RM}}$ [%] "inductive /AC" component

At reference (75°C) temperature: $u_R = 100 \cdot \frac{P_k}{S_N}$ [%] $u_k = \sqrt{u^2_R + u^2_{xm}}$ [%]

The short-sircuit losses and short-circuit voltage measurements, calculations and corrections have to made at rated, maximum and minimum ranges.

Since the circuit forming the measurement in high power transformers and reactors are inductive, the power factor (Cos φ) will be very small (Cos φ: 0,01 ...... 0,003, or angle = 1°..... 10 minutes). For this reason, the errors in measurement current and voltage transformers will be very high. In this case, the measurement results have to be corrected by a multiplier.

Measuring circuit and error correction equations :

$$P_{kd} = P_{km} \cdot \left(1 - \frac{E(\%)}{100}\right)$$

P_{kd} : Corrected loss

P_{km} : Loss read at the Wattmeter

E (%) : Total error

$E(\%) = E_{\delta}(\%) + E_i(\%) + E_u(\%)$

$E_{\delta}(\%)$: Measurement error

$E_i(\%)$: Current transformer turn ratio error

$E_u(\%)$: Voltage transformer turn ratio error

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

Here $\delta = \delta_i - \delta_u$.

δ_i : Current transformer phase error

δ_u : Voltage transformer phase error

When the measurement transformer phase errors are stated in minutes;

$$E_{\delta}(\%) = + 0{,}0291 . (\delta_i - \delta_u). \text{tg}\, \varphi \quad .$$

If the measurement current is different than rated current " I_N ", the short-circuit voltage and short-circuit losses for the rated current value are calculated as follows;

$$U_k = U_{km} \cdot \frac{I_N}{I_m} \qquad P_k = P_{km} \cdot \left(\frac{I_N}{I_m}\right)^2$$

U_{km} : Measured short-circuit voltage

P_{km} : Measured short-circuit losses

U_K : Short-circuit voltage at the rated current

I_m : Measured test current

P_k : Short-circuit losses at the rated current

When the transformer short-circuit losses and the voltage are measured at a frequency which is different than the rated frequency, correction has to be made to according to below equations:

Short-circuit voltage : $U_k = U_{km} \cdot \frac{f_N}{f_m}$ Short-circuit loss : $P_k = P_{DC} + P_{AC} \cdot \left(\frac{f_N}{f_m}\right)^2$

Here :

U_{km} : short-circuit voltage at f_m measured frequency

P_{ac} : additional losses at f_m measured frequency

U_k : short-circuit voltage at f_N rated frquency

P_k : short-circuit losses at f_N rated frequency

4- Measurement of no-load loss and current

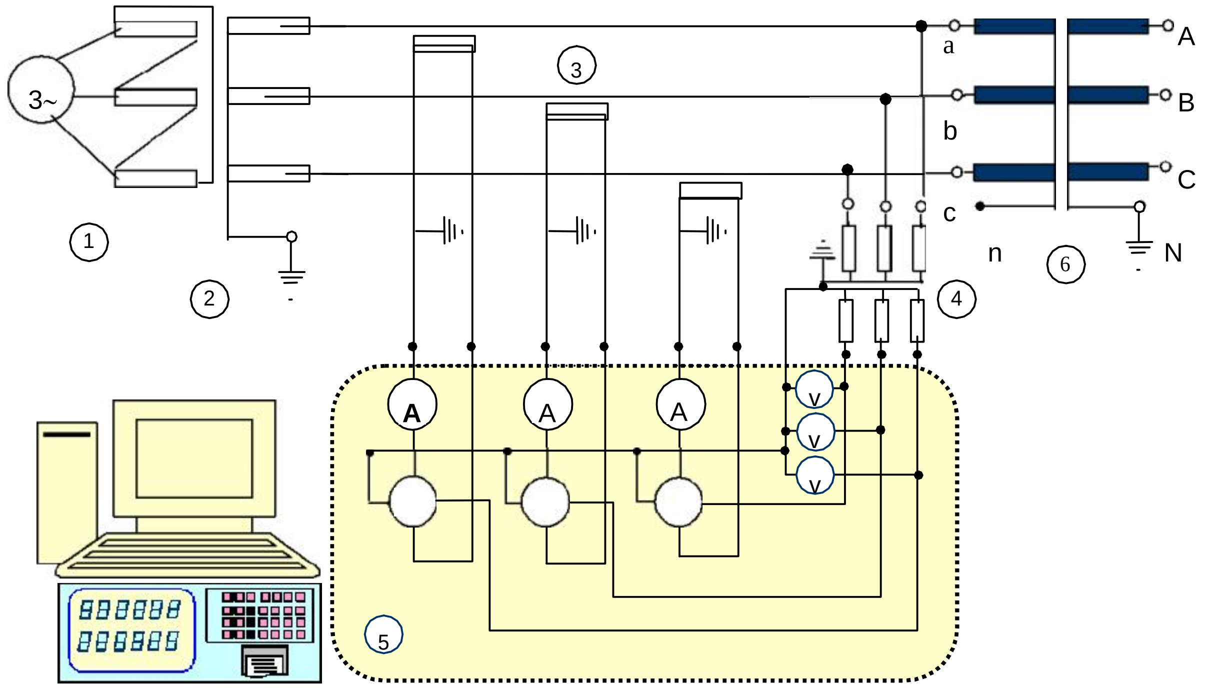
The no-load losses are very much related to the operational performance of a transformer. As long as the transformer is operated, these losses occur. For this reason, no-load losses are very important for operational economy. No-load losses are also used in the heating test.

The no-load loss and current measurements of a transformer are made while one of the windings (usually the HV winding) is kept open and the other winding is supplied at the rated voltage and frequency. During this test the no-load current (Io) and the no-load losses (Po) are measured. The measured losses depend heavily on the applied voltage waveform and frequency. For this reason, the waveform of the voltage should be very sinusoidal and at rated frequency. Normally, the measurements are made while the supply voltage is increased at equal intervals from 90% to 115% of the transformer rated voltage (U_N) and this way the values at the rated voltage can also be found.

No-load losses and currents:

The no-load losses of a transformer are grouped in three main topics; iron losses at the core of the transformer, dielectric losses at the insulating material and the copper losses due to no-load current. The last two of them are very small in value and can be ignored. So, only the iron losses are considered in determining the no-load losses.

Measuring circuit and performing the measurement:



1- Power supply
2- Supply (intermediate) Transformer
3- Current Transformers

5- Power Analyser
6- Transformer under test
4- Voltage Transformers

4-1: Connection diagram for measuring no-load losses

In general according to the standards, if there is less than 3% difference between the effective (U) value and the average (U') value of the supply voltage, the shape of the wave is considered as appropriate for measurements. If the supply voltage is different than sinusoid, the measured no-load losses have to be corrected by a calculation. In this case, the effective (r.m.s.) value and the average (mean) value of the voltage are different. If the readings of both voltmeter are equal, there is no need for correction.

During measurements, the supply voltage U´ is supplied to the transformer by the average value voltmeter. In this way, the foreseen induction is formed and as a result of this, the hysteresis losses are measured correctly. The eddy-current losses should be corrected according to equation below.

$$P_m = P_0 \cdot (P_1 + k \cdot P_2)$$

P_m : Measured loss

P_0 : no-load losses where the voltage is sinusoidal

Here :

$P_0 = P_h + P_E = k_1 \cdot f + k_2 \cdot f^2$

$$k = \left[\frac{U}{U'}\right]^2$$

P_1 : The hysteresis loss ratio in total losses $(P_h) = k_1 \cdot f$

P_2 : The eddy-curent loss ratio in total losses $(P_E) = k_2 \cdot f^2$

At 50 Hz and 60 Hz, in cold oriented sheet steel, $P_1 = P_2$ =% 50. So, the P_0 no-load loss becomes:

$$P_0 = \frac{P_m}{P_1 + k \cdot P_2}.$$

Here: $P_1 = P_2 = 0{,}5$.

According to IEC 60076-1; $P_m = P_0.(1+d)$. Here

$$d = \left[\frac{U' - U}{U'}\right].$$

During no-load loss measurement, the effective value of the no-load current of the transformer is measured as well. In general, in three phase transformers, evaluation is made according to the average of the thre phase currents.

Before the no-load measurements, the transformer might have been magnetised by direct current and it's components (resistance measurement or impulse tests). For this reason, the core has to be demagnetised. To do this, it has to be supplied by a voltage value (increasing and decreasing between the maximum and minimum voltage values for a few minutes) higher than the rated voltage for a certain time and then the measurements can be made.

The no-load currents are neither symmetrical nor of equal amplitude in three phase transformers. The phase angles between voltages and currents may be different for each of three phases. For this reason, the wattmeter readings on each of the three phases may not be equal. Sometimes one of the wattmeter values can be 0(zero) or negative (-).

5 - Dielectric tests

The following insulation tests are performed in order to meet the transformer insulation strength expectations.

Unless otherwise requested by the customer, the following test are performed in the following order (IEC 60076-3) :

- **Switching impulse test** : to confirm the insulation of the transformer terminals and windings to the earthed parts and other windings, and to confirm the insulation strength in the windings and through the windings.
- **Lightning impulse test** : to confirm the transformer insulation strength in case of a lightning hitting the connection terminals.
- **Separate source AC withstand voltage test** : to confirm the insulation strength of the transformer line and neutral connection terminals and the connected windings to the earthed parts and other windings.
- **Induced AC voltage test (short duration ACSD and long duration ACLD)** : to confirm the insulation strength of the transformer connection terminals and the connected windings to the earthed parts and other windings, both between the phases and through the winding.
- **Partial discharge measurement** : to confirm the "partial dicharge below a determined level" property of the transformer insulation structure under operating conditions.

According to standards, the transformer windings are made to meet the maximum operating voltage **U_m** and the related insulation levels. The transformer insulation levels and the insulation test to be applied according to IEC 60076-3 is shown in the below table.

Winding structure	Maximum operating voltage U_m kV	tests				
		Lightning impulse (LI)	Switching impulse (SI)	Long duration AC (ACLD)	Short duration AC (ACSD)	Applied voltage test
uniform insulated	$U_m \leq 72{,}5$	type (note 1)	na	na (note 1)	routine	routine
uniform and gradually insulated	$72{,}5 < U_m \leq 170$	routine	na	special	routine	routine
	$170 < U_m < 300$	routine	routine (note 2)	routine	special (note 2)	routine
	≥ 300	routine	routine	routine	special	routine

Note 1 : In some countries, in transformers with $U_m \leq 72{,}5$ kV applied as routine test and the ACLD test is applied as routine or type test.

Note 2 : If the ACSD test is defined, the SI test is not applied.

In case of a transformer with one or more than one gradual insulation, if foreseen by the induced voltage test, the switching impulse test is determined according to the maximum U_m voltage winding. The foreseen test voltage can not be reached in lower U_m voltage windings. In this case, the ratio between the tap changer's optimum tap position and the windings shall be such arranged that, the lowest U_m voltage winding reaches the most appropriate value. This is acceptable (IEC 60076-3).

If chopped wave is requested during ligthning impulse (LI) test, the peak value of the chopped wave is 1.1 times the full wave value (10% higher).

For transformers with the high voltage winding U_m > 72.5 kV, the lightning impulse (LI) test is a routine test for all windings of the transformer.

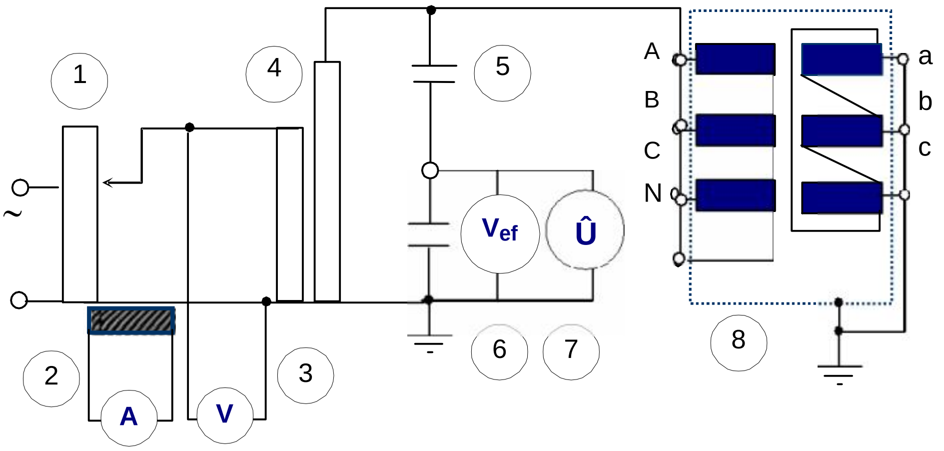
Repeating the dielectric tests :

If no modification is made in the internal insulation of a transformer, only maintenance is made, or if insulation tests are required for a transformer which is in operation, and if no agreement is made with the customer, test is performed with test voltages at 80% of the original test values. However, the long duration induced voltage test (ACLD) is always repeated with 100% of the original value. For new transformers with factory tests completed, tests are repeated always with 100% of the original values (IEC 60076-3 section 9).

6- Separate source AC withstand voltage test

The aim of this test is to check the insulation strength between the windings and earthed core, other windings, construction pieces and the tank, with foreseen test voltage. In this way, the insulation strength of the transformer is tested against excessive voltages due to operational system instabilities, malfunctions, operational mistakes and transient events.

Test circuit and performing the test



1- Adjustable voltage transformer

2- Current transformer and ampermeter

3- Test transformer input voltage voltmeter

4- Test transformer

5- Capacitive voltage divider

6- Effective voltage voltmeter

7- Peak value voltmeter (Peak value/ $\sqrt{2}$)

8- Transformer under test

Figure 6.1: Separate source AC withstand voltage test connection diagram

During the Separate source AC withstand voltage test, the frequency of the test voltage should be equal to the transformer's rated frequency or should be not less than 80% of this frequency. In this way, 60 Hz transformers can also be tested at 50 Hz. The shape of the voltage should be single phase and sinusoidal as far as possible.

This test is applied to the star point (neutral point) of uniform insulated windings and gradual (non-uniform) insulation windings. Every point of the winding which test voltage has been applied is accepted to be tested with this voltage.

The insulation tests of the input terminals (phase inputs) of the gradual insulation windings is completed during induced voltage test. (Section 7).

The test voltage is measured with the help of a voltage divider. The test voltage should be read from voltmeter as peak value divided by $\sqrt{2}$. Test period is 1 minute. All the terminals of the winding under test should be connected together and the voltage should be applied here. Meanwhile, the terminals of the non tested windings should be connected together as groups. Non-tested windings, tank and the core should be earthed. The secondary windings of bushing type current transformers should be connected together and earthed. The current should be stable during test and no surges should occur.

7- Induced AC voltage test

The aim of this test is to check the insulation both between phases and between turns of the windings and also the insulation between the input terminals of the graded insulation windings and earth.

During test, normally the test voltage is applied to the low voltage winding. Meanwhile the other windings should be left open and earthed from a common point.

Since the test voltage will be much higher than the transformer's rated voltage, the test frquency should not be less than twice the rated frequency value, in order to avoid oversaturation of the transformer core. The test voltage value is choosen according to the U_m' value of the winding with highest operating voltage. Other windings should be kept at a test level closest to their own operation voltage.

The test voltage can either be measured on a voltage divider connected to the HV terminal or on a voltage transformer and voltmeter which have been set together with this voltage divider at the LV side. Another method is to measure the test voltage with a peak-value measuring instrument at the measuring-tap end of the capacitor type bushing (if any).

Test period which should not be less than 15 seconds, is calculated according to the equation below;

120 seconds x (Rated frequency / Test frequency)

The test is accepted to be succesful if no surges, voltage collapses or extreme increases in the current has occurred.

As seen in table at section 5, the induced voltage tests are classified as short duration or long duration and according to the operation voltage being less or more than 72.5 kV, in IEC 60076-3 standard. Different routine, type and special tests are performed accordingly. In transformers with the highest operation voltage less than 72.5 kV, partial-discharge measurement is not mandatory. However in transformers bigger than 72.5 kV, partial-discharge measurement during induced voltage tests is mandatory.

Short duration induced voltage test (ACSD) :

a) Uniform insulated windings

The test connection of a transformer is the same as operating connection. Three phase, symmetrical voltage is applied to the transformer under test. Normally the test voltage is twice the rated voltage. This voltage should not be more than the test voltage. To be safe, the tap position of the transformer under test should be appropriate. The value of the test voltage (between phases and between phase and earth) is measured at the LV side on an accurate voltage transformer.

Test connection

1- Synchronous generator
2- Test transformer
3- Current trans. and ampermeter
4- Voltage trans. and voltmeter
5- Transformer under test

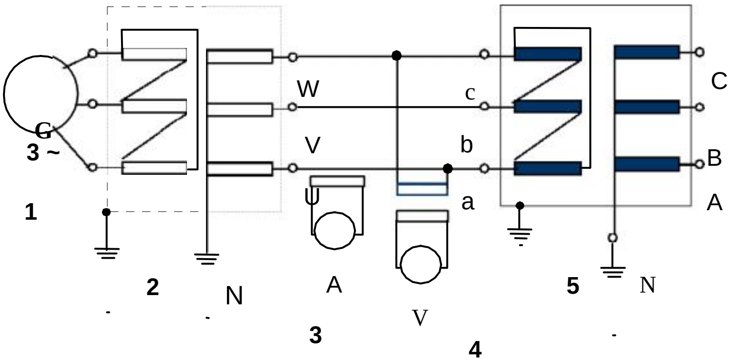


Figure 7.1: Induced AC voltage test connection diagram

In transformers with U_m < 72.5 kV, normally partial discharge measurement is not performed. Test period is as explained above. The voltage level to be applied is given in standards.

In transformers with U_m > 72.5 kV , normally this test is performed together with partial discharge test. The voltage levels and application periods are given in figure 7.2 below. The measurement and evaluation levels for partial discharge are:

$U_2 = 1{,}3 \cdot U_m / \sqrt{3}$ *phase – ground* ve $U_2 \quad 1{,}3 \cdot U_m$ *phase – phase*

A : 5 minutes
B : 5 minutes
C : test period
D : ≥ 5 minutes
E : 5 minutes
U_m : maximum operation

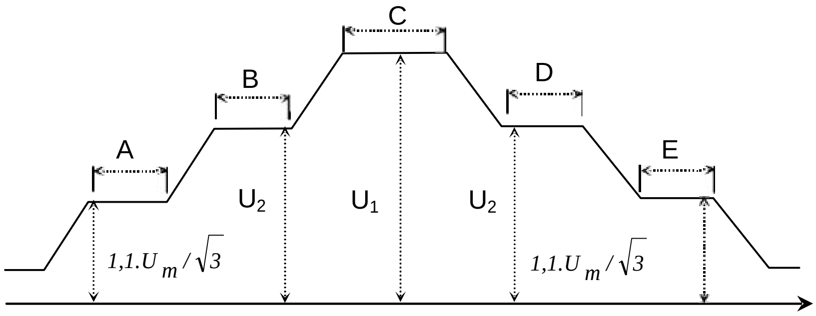


Figure 7.2: Test period voltage-time diagram

b) non-Uniform insulated windings

There are two different methods for three phase transformers:

1. Together with partial-discharge measurement, phase—earth strength test.
2. Together with partial-discharge measurement, inter-phase strength test while the star point is earthed. This test is performed as explained in section **a)** above.

Only phase – earth test is applied to single phase transformers. In three phase transformers, the test voltage is applied to the phase terminals as single phase. The test is repeated for each phase. So, the foreseen test voltage is applied once to each HV input. In such transformers, the induced voltage test and the voltage test applied to the phase terminals are considered to be performed together.

The single phase voltage application should be $U_2 = 1{,}5 \cdot U_m / \sqrt{3}$ in phase – earth test.

In phase – phase test, $U_2 = 1.3 \, . \, U_m$ in partial – discharge measurement. In transformers with U_m = 420 ve 550 kV and test value is 460 kV and 510 kV, the partial–discharge voltage level is taken as $U_2 = 1.3 \, . \, U_m$ in phase-phase test and as $U_2 = 1{,}2 \cdot Um / \sqrt{3}$ in phase-earth test..

1- Synchronous generator
2- Test transformer
3- Current trans. and ampermeter
4- Voltage trans. and voltmeter
5- Transformer under test
6- Capacitive voltage divider

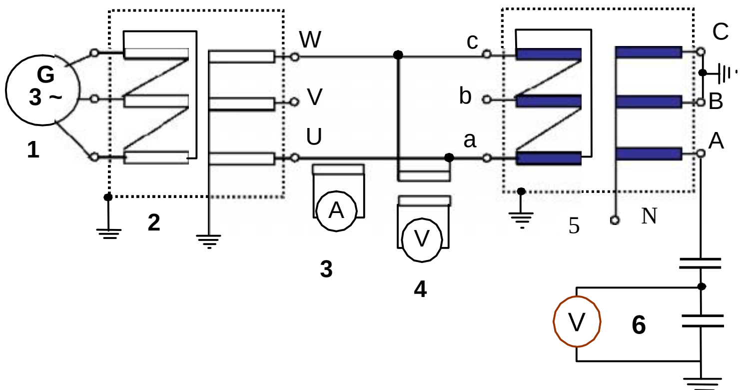


Figure 7.3: Single phase induced voltage test in non-uniform insulated windings connection diagram

The test connection in figure 7.3 is given for a transformer with HV neutral point insulated according to 1/3 test voltage.

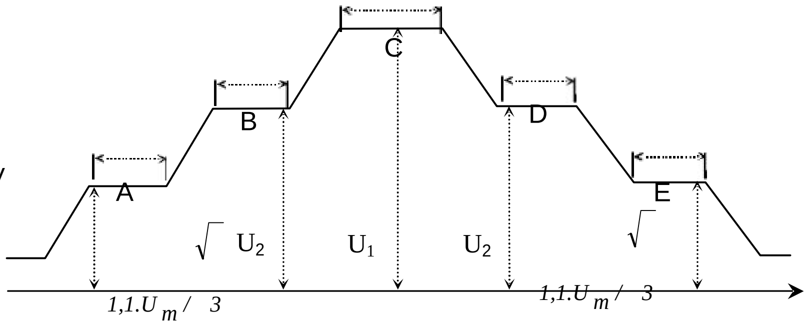
<u>Long duration induced voltage test (ACLD)</u> :

For uniform and gradual insulation windings.

In three phase transformers, it is applied either to terminals respectively as single phase connection, or symmetrically as three phase connection.

The star point (if any) is earthed during test, the other windings are earthed from; star point if they are star connected and from any terminal or from power supply if they are delta connected. The test application period and values are given in figure 7.4 .

A : 5 minutes
B : 5 minutes
C : test period
D : 60 minutes for $U_m \geq 300$ kV
30 minutes for $U_m < 300$ kV
E : 5 minutes
U_m : Maximum operation voltage



A

Figure 7.4: Long duration induced voltage test, voltage-time diagram

In all voltage steps of the test, partial-discharge measurement is made. The details of partial-discharge measurement are explained in section 8. The voltages according to earth should be as; $U_1 = 1{,}7 \cdot U_m / \sqrt{3}$ and $U_2 = 1{,}5 \cdot U_m / \sqrt{3}$ and partial-discharge measurement should be made at all HV line terminals.

The test is accepted as succesful if there are no test voltage collapses, a sudden increase in test current, smoke, abnormal sound, gas bubbles during test. The details about evaluation of test and partial-discharge measurement results are given in standards (e.g. IEC 60076 – 3).

8- Partial Discharge Measurement

It aims to measure the partial discharges which may occur in the transformer insulation structure during test.

Partial-discharges are electrical arks which form the surges between electrodes of any area of the insulating media of a transformer between the conductors. These discharges may occur in air bubbles left in the insulating media, gaps in the solid materials or at the surfaces of two different insulators. Although these discharges have small (weak) energy, the thermal energies due to these discharges can cause aging, deformation and tear of the insulating material.

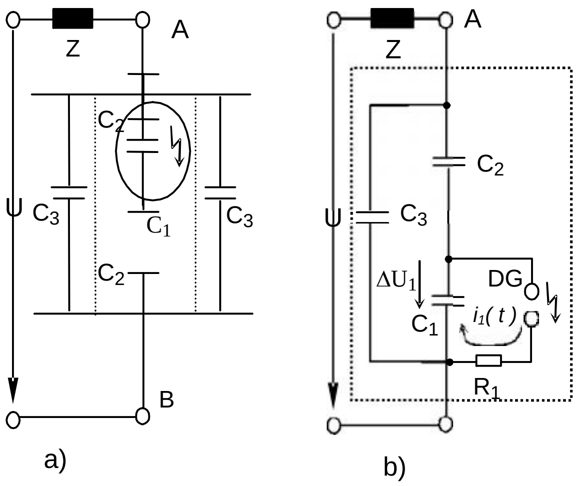
The following conditions can be determined during partial-discharge measurement;

- To determine whether a partial-discharge above a certain value has occurred in the transformer at a pre-defined voltage
- To define the voltage values where the partial-discharge starts by increasing the applied voltage (partial-discharge start voltage) and the value where the partial-discharge ceases by decreasing the applied voltage (partial-discharge cease voltage).
- To define the partial-discharge strength at a pre-defined voltage

How Partial-Discharge occurs and measured magnitudes :

The structure where a partial-discharge occurred in an insulating media is shown in the simplified figure 8.1. As seen on the simpliified diagram, the impulses forming on the discharge point cause a Δ**U** voltage drop at the transformer line terminals. This forms a measurable **"q"** load at the measuring impedance. This load is called apparent load and given in **pC** (Pico-Coulomb) units.

During measurements; ΔU voltage drop, average value of apparent partial-discharge current, partial-discharge power, impulse count within a time unit, partial-discharge start and cease voltages can also be determined.

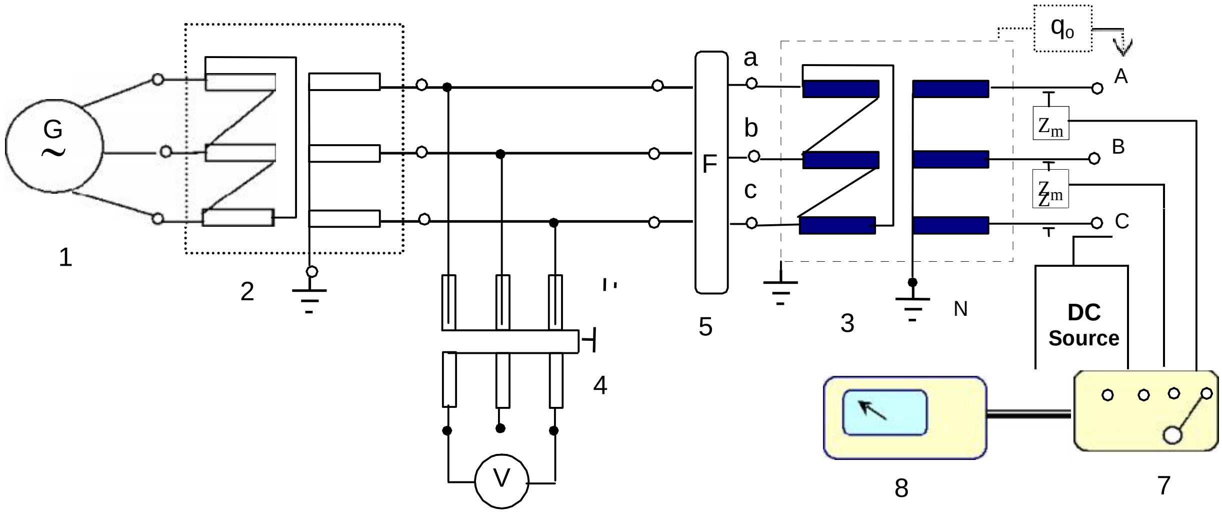


U : Applied Voltage
Z : Impedance of the supply circuit
C_1: Capacitance of the discharge part
C_2: Capacitance of the discharge part and serially connected insulator
C_3: Capacitance of the other parts of the insulator
R_1: Discharge resistance
DG: Discharge gap

Figure 8.1 a) simple schematics of an insulator with gas gap b) equivalent circuit

Measuring circuit and application

Partial-discharge measurement structure of a transformer and related circuit in accordance with IEC 60270 is explained below.



1- supply generator
2- supply transformer
3- test transformer
4- voltage transformer and measuring circuit
5- filter
6- measuring impedance
7- selective switch
8- measuring instrument and ossiloscope
q_o- calibration generator

Figure 8.2: Partial discharge measuring connection circuit

The measurement circuit in figure 8.2 is formed according to Bushing-tap method stated in standards.

Before starting to measure, complete measurement circuit should be calibrated. For this, a calibrator (Calibration generator) is necessary. The calibrator produces a q_0 load with a predefined value. Calibrator is connected to the test material in parallel. The q_0 load produced in the calibrator is read at the measuring instrument. These steps are repeated at all terminals of the transformer to be measured at no-voltage.

$K = q_0 / q_{0m}$

K : correction factor
q_0 : load at the calibrator
q_{0m} : load read at the measuring instrument

Application of the test

After the calibration operations are completed, the calibration generator is taken away from the measuring circuit. When the power system is connected (supply generator switch is closed), the voltage level will be too low (remenance level). This value which is considered as the base noise (interference) level of the measuring system should be less than half of the guaranteed partial-discharge level.

Voltage level

The voltage is substantially increased up to the level stated by the specifications and in the meantime the partial-discharge values at the predefined voltage levels are measured at each measuring terminal and recorded. The voltage application period, level and measuring intervals are given in the induced voltage test section.

After the transformer is energised for measuring operations, the partial-discharge value read at the measuring instrument is multiplied with the predefined K correction factor, and real apparent partial-discharge value for each terminal is found.

$q = K \cdot q_m$

q_m : load read at the measuring instrument
K : correction factor
q : Real apparent load

Evaluation

The test is considered to be succesful if the partial-discharge value measured at the transformer's measuring terminals is lower than predefined values or values stated in the standards and no increasing tendency is observed during test.

In addition to the measured partial-discharge level, the below conditions should also be considered in transformers:

- Partial-discharge start and cease voltages are above the operating voltage.
- Depending on the test period, partial-discharge level stays approximately stable.
- Increasing the test voltage causes almost no partial-discharge level change.

9 - On-Load Tap Changer Tests

After the on-load tap changer is mounted on the transformer, the below listed tests are applied at 100% rated auxiliary voltage (excluding item b);

a) When there is no voltage at the transformer, operate the tap changer **8 times** through the whole adjustement range

b) When there is no voltage at the transformer, operate the tap changer **once** through the whole adjustment range at the **85%** of the auxilary rated voltage

c) When the transformer is at no-load condition, operate the tap changer **once** through the whole adjustment range at rated voltage and frequency

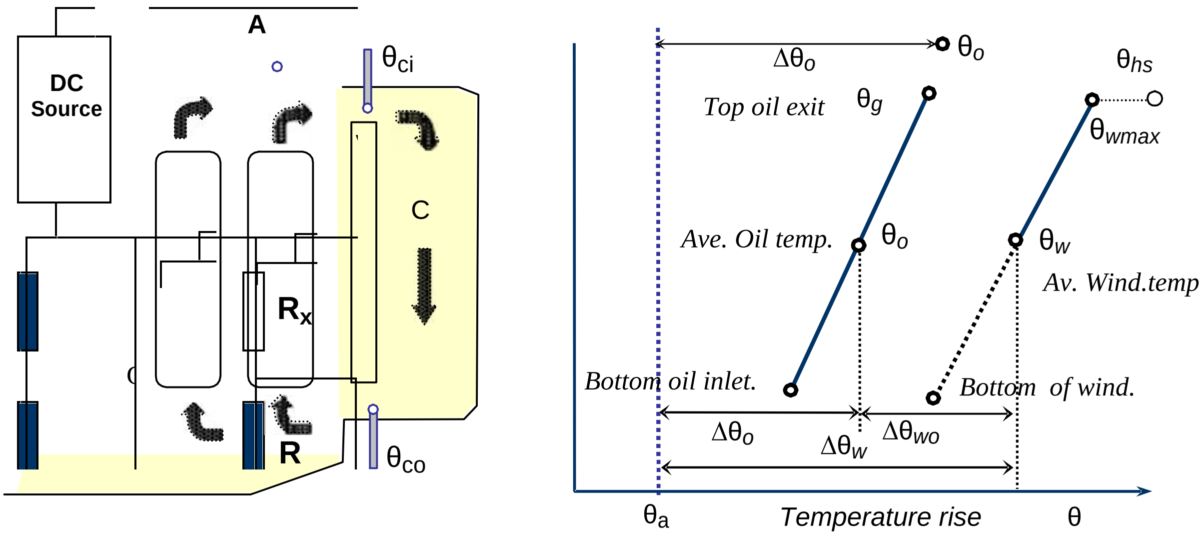
d) When one of the windings is short-circuited and the other winding is loaded with rated current as far as possible, operate **10 times** ±**2** taps at both sides of the rated tap position

10- Temperature-Rise Test

Temperature-rise test is a type test. The oil and winding temperatures are tested whether they are in accordance with both standards and technical specifications or not.

The connections during test, technical specifications of test and measuring instruments are explained in section 3 load losses and section 2 measuring winding resistances.

A simplified temperature distribution is shown in figure 10-1.



θ_o = Maximum oil temperature (under cover)

$\Delta\theta_o$ = Maximum oil temperature rise $\Delta\theta_o = \theta_o - \theta_a$

θ_a = Ambient temperature

θ_w = Average winding temperature

$\Delta\theta_w$ = Average winding temperature rise $\Delta\theta_w = \theta_w - \theta_a$

θ_{ci} = Input temperature to cooler

θ_{co} = Exit temperature from cooler

θ_{wmax} = Maximum winding temperature

C = Cooler

θ_{oavg} = Average oil temperature

$\Delta\theta_{wo}$ = Temperature difference between winding and oil

$\Delta\theta_{oavg}$ = Average oil temperature rise

θ_{hs} = Hot - spot temperature

Figure 10.1: Simplified temperature distribution of a transformer

a) Performing the test

During this test make sure that the transfomer is away from especially outside effects (hot or cold air flows).

The power, voltage and current (which should be recorded during test) measuring principles are the same as section 3 measuring load losses. Unless otherwise requested by the customer, the temperature increase test is made at the highest loss and current ranges.

Since the transformer temperature risings and ambient temperatures should be recorded during test, thermometers are placed in the thermometer pocket on the transformer cover, at the cooler inlet and exit and 1 or 2 meter away from the transformer. Before starting the test, while the transformer is cold (windings are cold and in balance), the temperatures at these thermometers are measured and recorded. The winding temperature is also measured and recorded before starting the test (cold resistance). To reach the operating condiitions, the transformer is placed at the tap position where maximum losses occur. At this condiditon it is supplied with enough current and voltage to cover the short-circuit losses and no-load losses at this tap position.

Whenever appropriate, the cooling system is shut down temporarily for a while to shorten the 1st step of the test for a few hours.

The transformer is loaded with a total calculated from no-load and load losses. In multiple winding transformers, if the power of one of the windings is equal to the total power of other windings, the loading should be made with the total windings' loss.

The maximum current and voltage values during supply are as follows;

Supply Current: $I_b = I_N \cdot \sqrt{\dfrac{P_o + P_k}{P_k}}$ Supply Voltage: $U_b = U_k \cdot \sqrt{\dfrac{P_o + P_k}{P_k}}$

Here :

I_N = Test current (the current at the tap which the test is performed),
P_0 = No-load loss , P_K = Load loss

Temperature rising test is performed in two steps:

1) Supplying with total losses (1st step of test) :
The step where total losses are supplied is continued until the difference between the top oil temperature rising and the ambient temperature becomes saturated (is continued until the difference between top oil temperature and ambient temperature stays below 1°C for 3 hours). This step is called 1st step of the test. During this, the supply values of the transformer, all oil temperatures and ambient temperature should be measured at appropriate time intervals.

2) Supplying with rated current (2nd step of test) :
After the top oil temperature rising is saturated, the transformer is loaded with I_N (the current at test tap position) current for 1 hour. Meanwhile, all oil temperatures and ambient temperatures are measured. After this 1 hour period, the supply is stopped and the circuit is opened (this step is called the 2nd step of the test) and after the circuit is opened, resistance is measured quickly and the cooling curve of the winding is formed, and then by extrapolation of the resistance-time curve, the resistance value at exactly the opening moment of the circuit is found.

After the supply current is stopped, during resistance measurement, the fans and pumps are kept running (if any) (according to IEC 60076-2).

b) Measuring the ambient temperature (cooling air or water temperature)

In air cooled transformers, the air temperature around the transformer should be taken as ambient temperature. According to standards, air temperature is measured by 3 thermometers or thermo elements distributed around the transformer. Measuring is performed in oil inside a container which has a 2 hour time-constant. The containers should be protected against extreme air flow and heat waves. The containers should be placed at three sides of the transformer, 1 – 2 meter away from the transformer and at half height of the coolers. If the transformer is being force cooled (by fans), the forced air inlet should be measured as ambient temperature. The cooling media is measured in the thermometer pocket at the cooling water inlet.

The cooler ambient temperature (cooling air or water temperature) is measured every ½ or 1 hour and recorded and is used in average temperature rise calculations at the last quarter of the test.

c) Calculating the temperature rise of the oil

The top oil temperature can be measured in the thermometer pocket which is on the transformer cover. The difference between maximum measured temperature and ambient temperature is $\Delta\theta_t$.

$\theta_{oavg} = \theta_o - \frac{1}{2} \cdot (\theta_{ci} - \theta_{co})$ average oil temperature

$\Delta\theta_o = \theta_o - \theta_a$ average oil temperature rise

The cooler inlet and exit temperatures are measured by thermometers insulated against ambient air and placed at the cooler pipes. In a transformer with seperate cooler, the oil inlet-exit temperature difference is measured at inlet-exit pipes near transformer tank.

If during the test, the transformer under test can not be supplied with enough current to cover the total losses due to insufficiency of the laboratory power supply, the difference (test losses being not less than 80% of the total losses) shall be calculated as below;

$$\Delta\theta_{on} = \Delta\theta_{om} \cdot \left(\frac{P_n}{P_m}\right)^X$$

$\Delta\theta_{on}$ = temperature rise at total losses P_n
$\Delta\theta_{om}$ = temperature rise at test losses P_m (at measuring losses)
*X = for distribution transformers **0,8** (natural cooling, power <2500 kVA)*
For ON..- cooling **0,9** OF. And for OD..cooling **1,0**

d) Measuring the temperature rise of the winding

After the oil temperature has reached saturation, the transformer is loaded with I_N rated current for 1 hour. This time is considered to be necessary for adapting the balance condition between winding and oil, to operating state. After this time, the loading is finished and the circuit is opened and the resistance of the winding is measured for some time to form the cooling curve.

The heating of the winding is calculated with the below equation;

$$\theta_2 = \frac{R_2}{R_1}(235 + \theta_1) - 235$$

θ_2 : *Temperature of the winding when the circuit is opened*
θ_1 : *Average oil temperature at he beginning of test (cold case)*
R_2 : *Resistance at temperature θ_2 (hot case)*
R_1 : *Resistance at temperature θ (cold case)*

Note: For aluminium winding, 225 should be used instead of 235.

Supplying with I_N rated current for one hour is defined as 2nd step of the test. The oil temperature will decrease a little during this time. The relation between the winding and average oil temperature should be calculated according to below equation..

So: $\Delta\theta_{wo} = \theta_2 - \theta_o(I_N)$.

$\Delta\theta_{wo}$: temperature difference between the winding and the oil

θ_2 : winding temperature (temp.at the circuit opening moment from cooling curve)

$\theta_o(I_N)$: average oil temperature after supplying with (2nd step of the test) I_N for 1 hour

$\theta_y(I_N)$ temperature ; the calculation of oil heating is made according to the method in item c).

The difference between the winding and oil temperatures at the 2nd step of the test:

When the difference betwen the oil and winding temperatures $\Delta\theta_{sy}$, is added to the θ_y, which is in pargraph c) (supplying with total losses), $\Delta\theta_s$ average winding temperature is found:

$$\Delta\theta_w = \Delta\theta_{wo} + \Delta\theta_o$$

In cases where I_N rated current can not be reached due to insufficiency of the laboratory supply, the difference between winding and oil temperatures $\Delta\theta_{wo}$ can be corrected as below:

$$\Delta\theta_{woN} = \Delta\theta_{wom} \cdot \left(\frac{I_N}{I_m}\right)^y$$

$\Delta\theta_{woN}$: *winding-oil temperature difference at rated current*

$\Delta\theta_{wom}$: *winding-oil temperature difference at test current*

y...exponent : ON and OF cooling = 1.6

OD cooling = 2.0

A maximum temperature formed at any part of the winding insulation system is defined as " **hot–spot temperature** " and this value is a parameter showing the heat load limit of the transformer.

Winding *hot-spot* temperature rising is calculated a below:

$\boldsymbol{\theta_{hs} = \theta_o + K_{hf} \cdot \Delta\theta_{wo}}$ $\quad$ K_{hf} : hot – spot factor

Hot – spot factor; it can be taken as **1.1** for distribution transformers and **1.3** for power transformers (according to IEC 60076-2).

When the transformer is loaded with total losses at the 1st step of the test, if the test frequency is different than rated frequency, there is no need to make a correction (the required load to heat the oil is defined with total losses). However, for loading with rated current for 1 hour at the 2nd step of the test, correction has to made according to below equation :

$$I_m = I_N \sqrt{\frac{P_{dc} + \left(f_N / f_m\right)^2 P_{ac}}{P_{dc} + P_{ac}}}$$

I_m : test current

I_N : rated current

P_{dc} : direct current loss

f_N : rated frequency

f_m : test frequency

P_{ac} : additional loss

11- Lightning Impulse Test

Impulse test are applied to transformers to confirm their withstand against atmospheric lightnings and transient extra voltages during switchings. As explained in section 5, these tests are defined as type or routine test depending on the operating voltage levels.

Power transformers used in high voltage networks have to face atmospheric discharges (lightnings). The amplitudes of lightning excessive voltages always depend on impulse current and the impulse impedance at the place of the lightning. This value can reach a few times of the transformer winding's operating voltage.

Impulse voltages are formed by an "impulse voltage generator" at laboratories. For oil type transformers; in general, the impulse wave is defined as negative (-) polarity in many standards and it's shape at the line terminal should be as " $T_{front} / T_{tail} = 1.2 \pm 30\% / 50 \pm 20\%$ ***µS*** ". Other than this shape which is defined as full wave (Figure 11.1), the chopping time should be (Figure 11.2) between ***2....6*** µ***S*** for chopped wave at the tail.

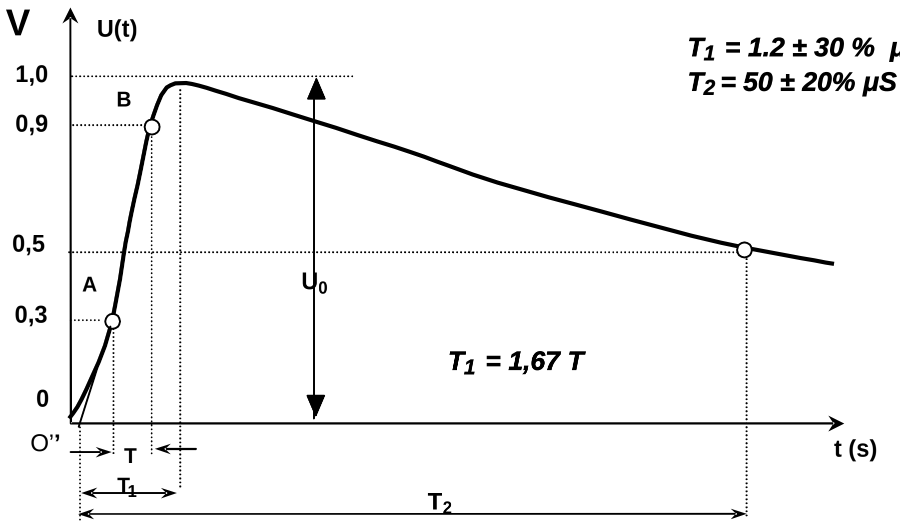


Figure 11.1 : Full wave lightning impulse

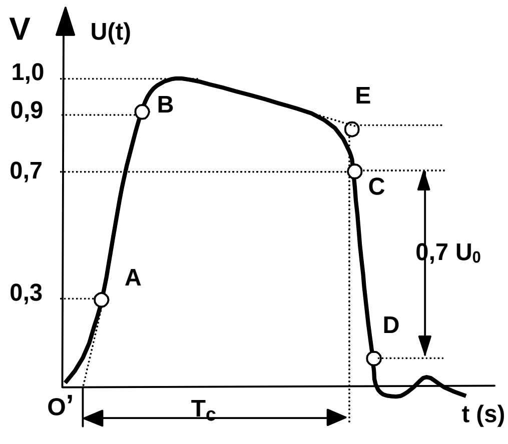


Figure 11.2: Tail chopped lightning impulse

Lightning impulse voltages are applied to each one of the line terminals sequentially, at the amplitude level, with number and method defined in the standards/specifications. During test, the windings which voltage is not applied should be earthed directly or through a small resistance (Figure 11.3 and 11.4).

In three phase transformers, if not requested by the customer to have the test at a special tap position, the test is performed at main tap, maximum and minimum tap positions, each phase being tested at a different tap position.

In the small inductance, low voltage windings of high power transformers, sometimes the half time-value can not reach the time stated in the standards. In such cases, the half time-value can be increased by connecting an appropriate resistance between untested windings and earth. According to *IEC 60076-3* standard, this resistance should be choosen such that, the voltage of these terminals in reference to earth should not be more than 75 % of the test voltage of these terminals and maximum resistance value should be *500* Ω.

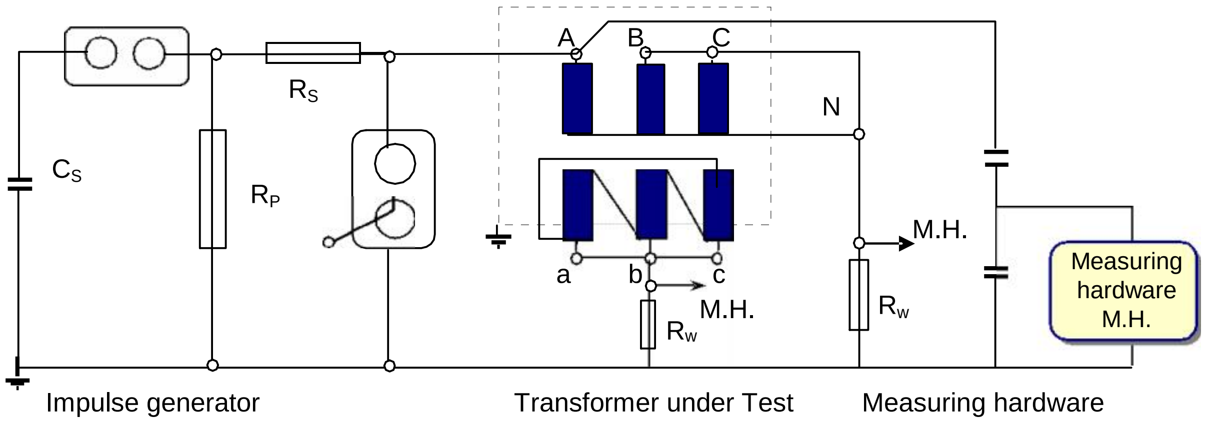


Figure 11.3: Lightning impulse test connection diagram

Although changing according to place of use and aims, the most popularly used voltage divider is “resistance damped capacitive voltage divider”.

Non-inductive, pure ohmic resistance is used for measuring impulse currents. Their values usually range from *0,1* Ω *to 20* Ω.

Coaxial cables are used to transfer the measurement signals to measurement equipment (digital measuring system).

If chopped-wave is to be used, a chopping device is added to the impulse circuit. In impulse voltage circuits generally a multiple chopping device is used.

At first, an oscillogram defining a voltage form at *50%* of the test voltage is used. After the form stated in the standards is obtained, a low amplitude “reference impulse” with *50%* of the test voltage is applied and then “full impulse” at *100%* value with number and order stated in the standards is applied.

The amplitude values of the applied voltages are determined at a digital measurement system through a “voltage divider”. Also, the oscillograms of the applied voltage change through time and changes of capacitive current flowing from tested winding to earth or from un-tested winding to earth are recorded.

The most popular and useful methods defined in the standards for evaluating the impulse voltage tests is matching of the oscillograms. This means, the low amplitude (*%50......%75*) reference wave and full amplitude *(%100*) wave oscillograms should match without any difference.

The arrangement of the test circuit, the effects caused by external interferences and/or earthing arrangement can sometimes cause mismatching of the oscillograms. These should not be considered as fault.

Some of the connection circuits used in lightning impulse test are given in figure 11.4.

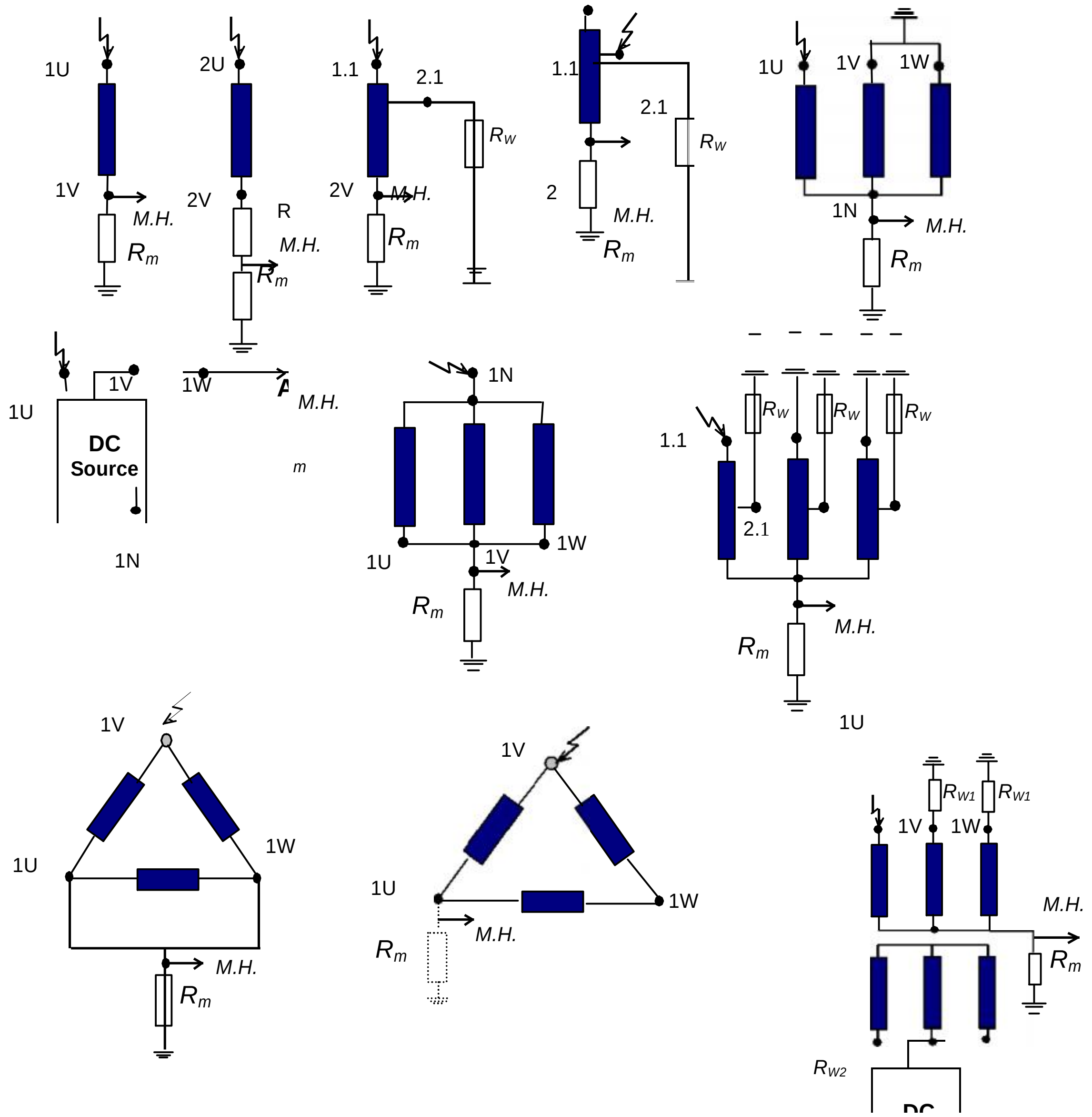


Figure 11.4: Impulse test connection examples for single and three phase transformers

The time differences of the impulse generator stages can cause high frequency oscillations in the first parts of the impulse wave front.

Small differences of the cutting time can cause deviations (changes) on the wave after cutting. These should not be taken as fault conditions.

If impulse voltage is required at the technical specifications, impulse applying to this point is given in standards in two ways:

a) Applying a voltage to the parallel connected line terminals which will cause the defined impulse voltage amplitude at the neutr point.

b) Applying the defined impulse voltage directly at the neutr point.

As defined in paragraph “b”, when an impulse is applied at the neutr point, a voltage form with longer front time (up to *13 μS)* is allowed in IEC 60076-3 standard.

12- Switching Impulse Voltage Test

The switching impulse test is applied to confirm the withstand of the transformer's insulation against excessive voltages occuring during switching. During switching impulse voltage test, the insulation between windings and between winding and earth and withstand between different terminals is checked..

The switching impulse voltage is generated in conventional impulse voltage generators at the laboratories. The polarity of the voltage is negative and the voltage waveform should normally be T_1 / T_d / T_2 *20/200/500 µS /figure 12.2) according to IEC 60076-3*.

Due to over-saturation of the core during switching impulse test, a few low amplitude, reverse polarity (e.g. positive) impulses are applied after each test impulse in order to reset the transformer core to it's starting condition (demagnetised). By this way, the next impulse voltage waveform is applied

The tap position of the transformer during test is determined according to test conditions (see section 5)

The on-off impulse voltages are applied to each high voltage terminal sequentially. Meanwhile, the neutral terminal is earthed. The windings which are not under test are left open (earthed at one point). This connection is simlar to the induced voltage test connection. The voltgae distribution on the winding is linear like the induced voltage test and the voltage amplitudes at the un-impulsed windings are induced according to the turn ratio. Meanwhile, necessary arrangements should be made since the voltage between phases will be *1,5* times the phase-neutral voltage.

The test circuit connections of three phase transformers depend on; structure of the core (three or five legged), the voltage level between phases and the open or closed state of the delta winding (if any).

At first, a voltage with *50 %* decresed value is used at the tests, then impulse voltages at full values and at numbers given in standards are used. The peak value of the voltage is measured. The change of the voltage waveform and winding current are measured with a special measuring instrument and recorded. The negativities in the transformer during the test are determined by comptring the voltage and current oscillograms. The sudden collapses of the voltage (surges) and abnormal sounds show deformation of the insulation in the transfomer. The deformation of the voltage waveform and increase in noise due to magnetic saturation of the core should not be considered as fault.

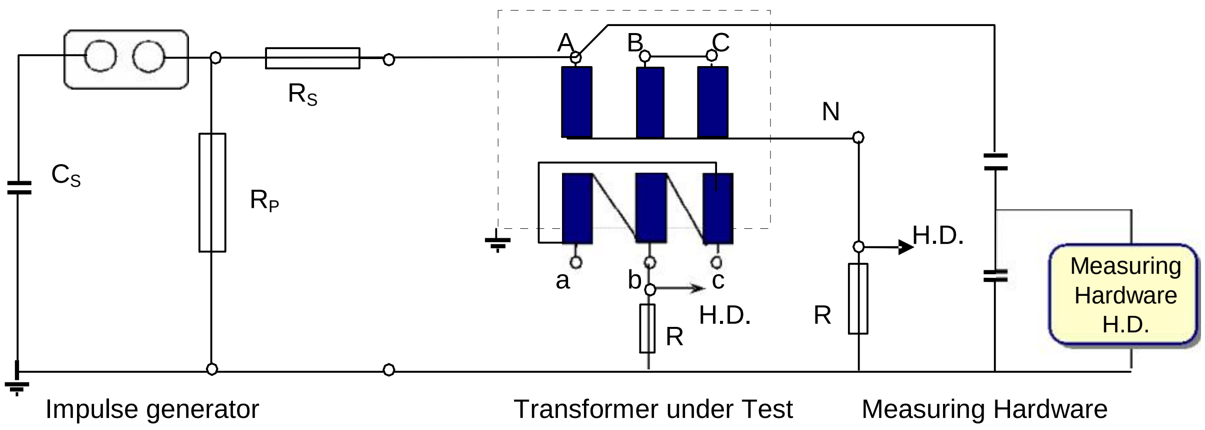


Figure 12.1: Switching on-off impulse test connection diagram

Switching Impulse Voltage Waveform :

Front : $T_1 \geq 100\ \mu S = 1{,}67\ T$

90% value : $T_d \geq 200\ \mu S$

Time for cutting the axis : $T_2 \geq 500\ \mu S$

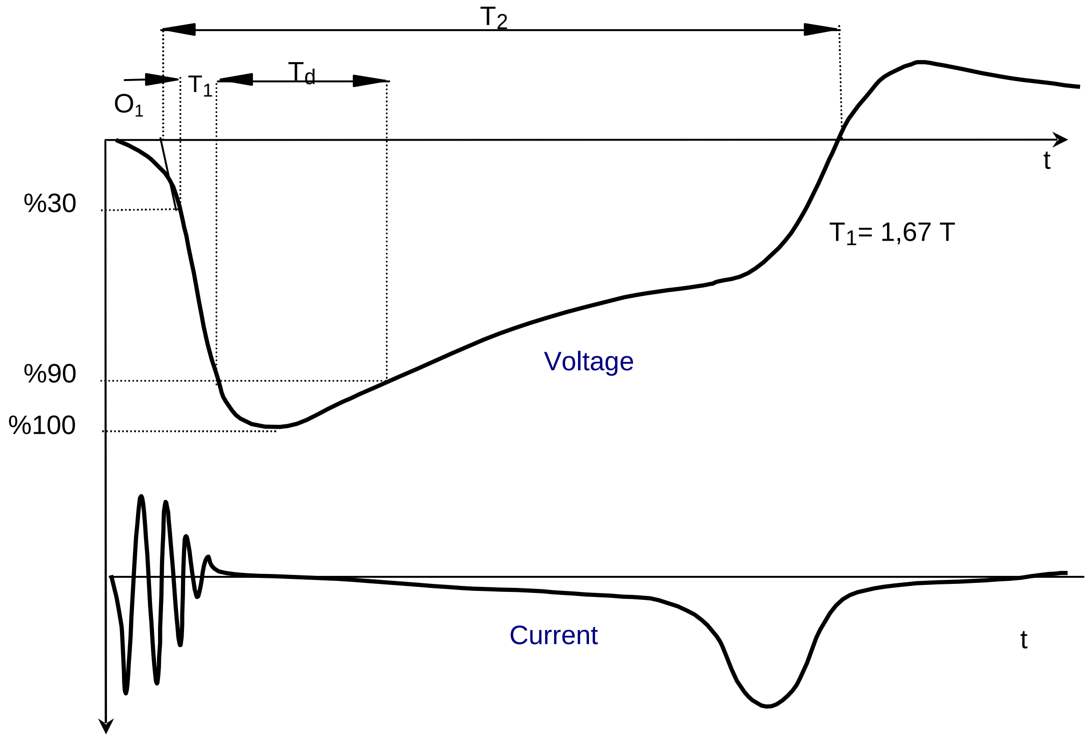


Figure 12.2: Switching impulse voltage waveform

13- Measurement of dissipation factor (tan δ) and capacitance

The capacitance and dissipation/loss factor (Tan δ / cosφ) measurement are made to determine the insulating condition of the transformer's both winding to earth and between the windings, and to form a reference for future measurements during operating the transformer.

There is a small amount of insulating loss in all insulators used in transformer applications at normal operating voltage and frequency. In appropriate insulators, this loss is very small. This loss changes in direct proportion with the " square " of the applied voltage. The insulator and equivalent diagrams are given in figure 13.1.

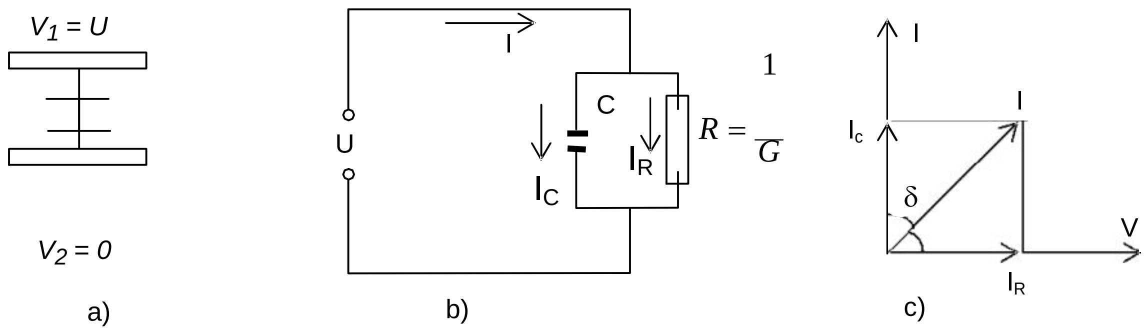


Figure 13.1 a) Insulator b) equivalent circuit c) vector diagram

As seen in figure 13.1, the angle δ 'between the total current " *I* " and capacitive current "I_C" allows to make evaluation about the loss properties of the insulator

The loss angle δ , depends heavily on the thickness of the insulating material and surface condition, structural property of the insulator, type of the material, (humidity, foreign materials/particles, air gaps, etc. which cause ionisation the insulating material).

The conditions which increase the power losses of the insulator also decrease the insulation strength. For this reason, loss angle measurement is a very valuable criteria for evaluating the insulation material at a defined operating frequency. Periodical measurements made during operating are also important to show the general condition of the insulating material. In this way, it is possible to gather information about aging of the solid insulating materials and degradation of the oil.

The active loss of the measurement circuit can be calculated according to below equation:

$$P = U \cdot I \cdot \text{Cos}\ \varphi = U^2 . C. \omega . \tan \delta$$

(it is accepted that in very small angles, Cos φ will be equal to *tan* δ)

Capacitance, tan δ, active loss and Cos φ can be measured by bridge methods at defined voltages or by a "*power factor"* *(Cos* φ*)* measuring instrument.

The measurement is made between windings and between the windings and the tank. During the test, the temperature of the transformer should also be recorded and corrected in accordance with the reference temperature.

The loss factor depends heavily on temperature. For this reason, in order to make comparisons later, it has to be converted to reference temperature (for example *20°C* reference temperature) by a coefficient.

Correction equation :

$F_{20} = F_t / K$

F_{20} : loss factor at 20 °C temperature

F_t : loss factor value at t measuring temperature

K : correction factor is given in the table.

Since extreme humid, rainy and cold conditions shall effect the results of the transformer negatively, measurement should be avoided

Table

Measurement temperature [°C]	Correction factor [K]	Measurement temperature [°C]	Correction factor [K]
10	0,80	45	1,75
15	0,90	50	1,95
20	1.00	55	2,18
25	1,12	60	2,42
30	1,25	65	2,70
35	1,40	70	3,00
40	1,55	Note : Only for trans. With mineral oil	

14- Measurement of zero sequence impedance(s)

The aim of the test is to measure the properties of the mains system transformer in case of unsymmetrical loads and to make required calculations.

By definition, the zero impedance "Z_0" ; is three times the impedance measured by forcing a current at the rated frequency between parallel connected phase terminals and star point, in star or zigzag connected windings as seen in figures 14.1 and 14.2.

$$Z_o = 3 \cdot \frac{U_o}{I} \quad \Omega/\text{phase}$$

Zero impedance is used in short-circuit protection and earth short-circuit current calculations.

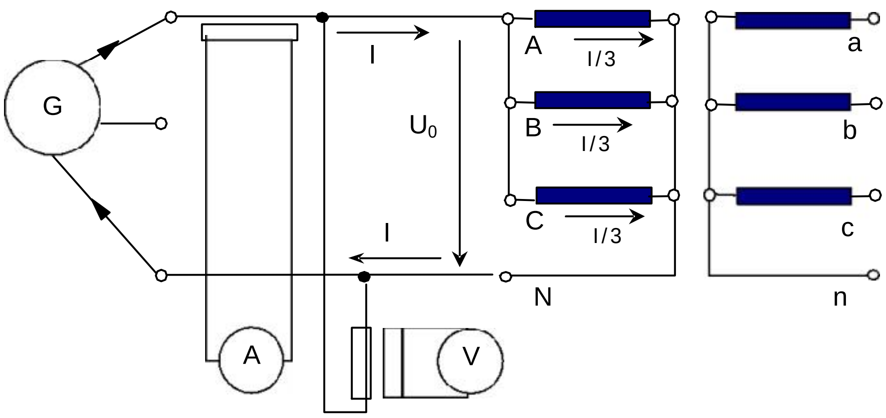


Figure 14.1:No-load zero impedance measurement connection diagram

The zero impedance depends on the connection of the transforrmer and structural property of the transformer. The zero impedance consists of R_0 real and X_0 imaginary parts. Here, since $R_0 << X_0$, R_0 is negligible. In this case, the zero impedance equals zero reactance.

Zero imopedance can only be measured in windings with star point taken out. Measurement is made at the rated tap position and with the active part assembled in the tank. The zero impedance of delta connected windings and windings with the star point not possible to take out, is infinite in magnitude.

If the other winding of the transformer is delta connected or if there is a delta connected balance winding, the star point of the star (or zig-zag) connected winding can be loaded with maximum rated current during Z_0 impedance measurement. Meanwhile, it is seen that the U_0 test voltage is 15% to 27% of the rated phase-neutr voltage of the transformer. In cases where there is no counter magnetic current, for example in start-star connected, three legged transformers with no balancing winding, this test current should be maximum $0{,}3xI_N$ in order to avoid excessive heating of the constructive parts.

In transformers with both windings star connected and the star points taken out, there are two different zero impedances.

1) No-load zero impedance Z_{00}

While one of the star connected windings is measured, the ends of the other winding is kept open. Figure 14.1

2) Short-circuit zero impedance **Z_{0K}**

While one of the star connected windings is measured, the ends of the other winding and the star point is short-circuited. Figure 14.2

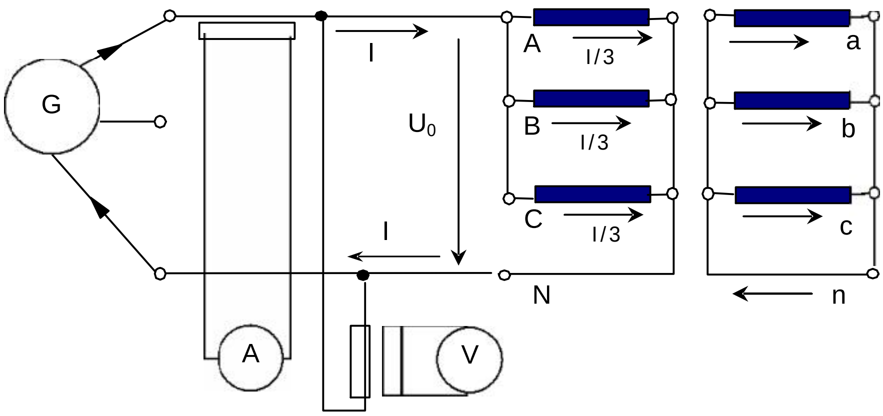


Figure 14.2: Short-circuit zero impedance measurement Y-Y winding

The zero impedance can also be expressed as percentage. In this case;

$$z_o = Z_o \cdot \frac{I_N}{U_N}$$

z_0 = relative zero impedance (%)
I_N = Rated phase current (A)
U_N = Phase-neutral rated voltage (V)
Z_0= Zero impedance (Ω / phase)

15- Determination of sound level

Aim of measurement; To confirm that the sound (noise) level of the transformer and related equipments meet the customer's demands and/or standards

Explanations about transformer noise is given in IEC 60076-10.

Main causes of a transformer noise is explained below :

1) Core noise ; caused by the magnetic forces between magnetositriction and core sheet steel

2) Noise of the transformer's load (current) ; caused by current passing in the windings, and by electromagnetic forces formed at the magnetic screenings at the tank walls..

3) Noise of the cooling equipments ; caused by fans and pumps of the cooling system.

An effective and important noise source is the core of the transformer. The noise of the core depends on the magnetic property of the core material (sheet steel) and flux density. The sound frequency is low (twice the rated frequency). The magnetic forces formed in the core cause vibration and noise.

The load noise occurs only on the loaded transforrmers and is added to the no-load (core noise). This noise is caused by the electromagnetic forces due to leakage fields. The source of the noise are tank walls, magnetic screenings and vibrations of the windings.

The noises caused by the core and windings are mainly in the 100-600 Hz frequency band.

The frequency range of the noise (aerodynamic/air and motor/bearing noise) caused by cooling fans is generally wide. The factors effecting the total fan noise are; speed, blade structure, number of fans and arrangements of the radiators. The pump noise is not effective when the fans are working and it's frequency is low.

During noise measurements below precautions are very important to ensure the accuracy of the results :

- The transformer should be placed in a room with minimum echo properties. It should be placed on a base with no direct vibrations or should be placed on wheels. All mechanical components/equipments on the transformer should be fixed to avoid vibration with the transformer.

- During measurement, the transformer should be supplied at rated voltage and rated frequency.

Microphone positions :

If the height of the transformer under test is less than 2,5 m, the microphone position should be at half height.. If the height of the transformer is more than 2.5 m, measurements should be made at 1/3 and 2/3 heights.

If only the cooling equipments are operating, the microphone position is; at half height for cooling equipments which are taller than 4 m, at 1/3 and 2/3 height for cooling equipments which are shorter than 4 m height.

Measurements should be made all around the transformer. There should be maximum 1 m distance between two measurements.

<u>The distance of the microphone from the main radiating surface</u> :

a) If the coolers of the transformer are not operating or if the coolers are more than 3 m away from the transformer, the microphone should be 0,3 m away from the main radiation surface.

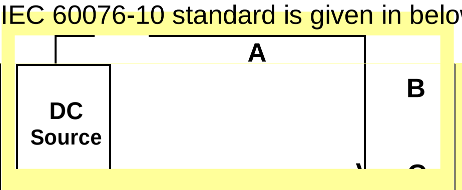
b) If the transformer cooling system is operating (while the pumps and fans are working), the microphone should be 2 m away from the main radiation surface. The transformer is energised as below ;

1. only the transformer is energised. The cooling equipments and oil circulation pumps are out of service.
2. transformer is energised. The cooling equipments and the oil pumps are in service.
3. transformer is energised. The cooling equipments are out of service, oil pumps are in service.
4. transformer unenergized, cooling equipment and any oil pumps in service.

Before starting the measurement procedure, the back ground noise level of the measurement room should be determined. If there is more than 8 dB (A) difference between back ground noise level and transformer noise level, no correction of the transformer's noise level is required.

If the difference is between 3 dB (A) and 8 dB (A), a correction is required according to standards. If the difference between the back ground noise level and transformer noise level is less than 3 dB, a measurement is not necessary.

The correction factor for the back ground noise level's effect on transformer's noise level according to IEC 60076-10 standard is given in below table and equations:



	Difference between back ground noise before measurement and back ground noise after measurement first L_{bgA} – last L_{bgA}	comment
≥ 8 dB	-	Measurement OK
< 8 dB	< 3 dB	Measurement OK
< 8 dB	> 3 dB	Measur.must be repeated
< 3 dB	-	Measur. must be repeated

A- The average sound pressure level corrected by weight is calculated according to below equation :

$$\overline{L}_{pA} = 10 \log \left[10^{0,1 \overline{L}_{pA0}} - 10^{0,1 \overline{L}_{bgA}} \right] - K$$

$\overline{L}_{bgA}$: the smaller of the *average* back ground *noise levels*

$\overline{L}_{pA0}$: *average measured noise level*

K : *ambient noise corection factor*

The ambient correction value "K " depends on the properties of the materials around the noise source and the sound absorption properties of the measurement room and calculated as below :

$$K = 10 \log \left[1 + \frac{4}{A/S} \right] \qquad A = \alpha S_v$$

S : Main propagation area at measurement distance
α: average sound absorbtion coefficient (see IEC 60076-10 table 1)
S_V : all surface of the test room including ceiling, floor and walls

Factors effecting the measurement results :

1. Internal effects about the structure of the transformer (measuring frequency, flux/induction at the core, mass, sheet steel quality of the core and operating type)

2. External effects :

 - (measuring distance) is one of the main factors effecting the noise level. According to acoustic laws; the sound pressure level decreases in linear proportion with the square of the distance **" d "** from the defined source (equivalent centered sphere). For example, if the sound level is measured in 2m, sound level in a "d" distance is ;

   $L_{p(d)} = L_{p(2m)} - 20. \log (d / 2)$ here ; d should be taken in meters.

 - The sound level changes by the square of the frequency :

   $L_{p(f)} = L_{p(50)} + 20. \text{Log} (f / 50)$

   For example, if a 60 Hz transformer is measured at 50 Hz, below value should be added to the noise value at 50 Hz ;

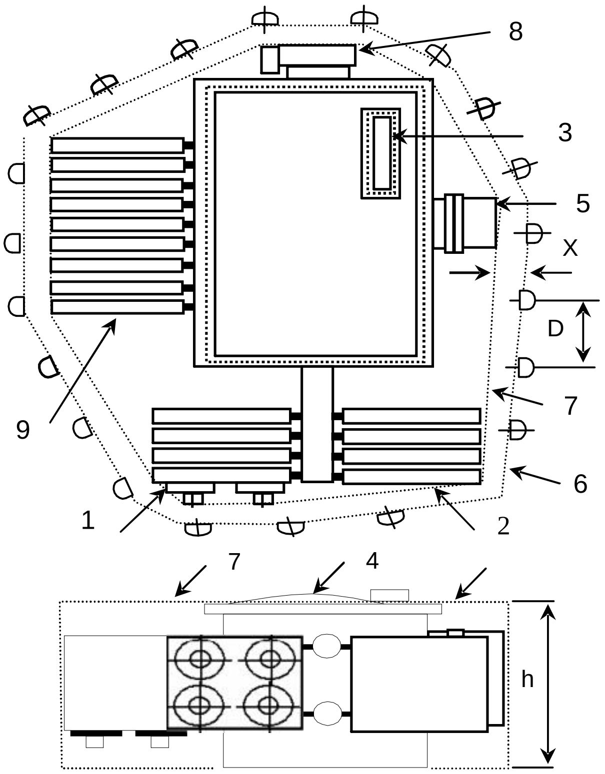
   $\Delta L_p = 20.\log (60 / 50) = 1,6$ dB should be added.

 - For measurements made at voltages other than rated voltage, the noise pressure level is corrected according to the equation below:

   $\Delta L_p = 40.\log (U_{anma} / U_{test})$

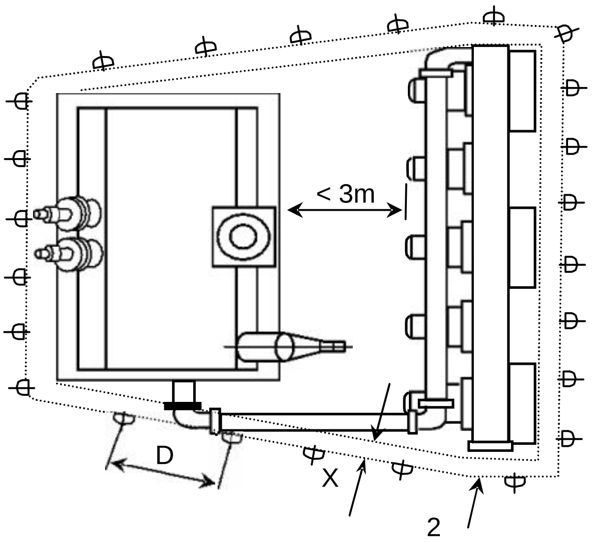
   For example, If a 420 kV rated voltage transformer is supplied with 410 kV voltage, the below value is added to the measurement results.

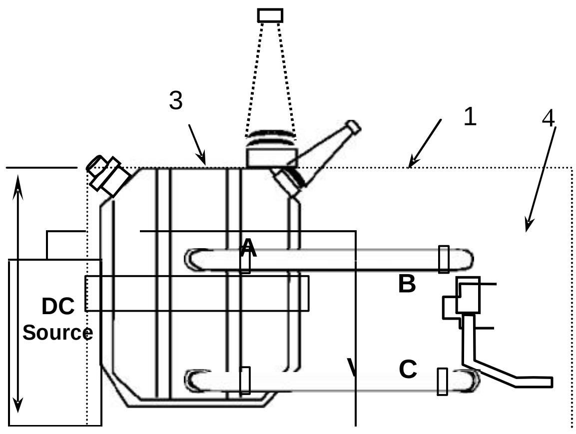
   $\Delta L_p = 40.\log (420 / 410) = 0,42$ dB ≈ 0,5 dB



1- Horizontal air cooling
2- Natural cooling
3- Dome
4- Tansformer tank
5- Cable box
6- Measurement profiler
7- Sound propagation surface
8- Tap changer
9- Vertical forced air cooling
h- Tank height
x- Measurement distance
D- Microphone distance

Figure 15.1: Microphone locations for measuring noise level in transformers with cooling equipment mounted on the tank





1- Sound propagation surface
2- Measurement profile
x- Measurement distance
3- Transformer tank
h- Tank height
4- Forced air cooling

D- Microphone distance

Figure 15.2: microphone locations for measuring noise level in transformers with a seperate forced air cooling equipment closer than 3 meters.

16- Measurement of harmonics of the no-load current

They are measured to use whenever necessary during the operating of the transformer.

In general, the ratio of harmonic currents in the rated current is less than 1%. The amplitude of the harmonics component depends on the property of transformer's core material, induction degree, core design, connection of windings and impedance of the transformer's supply circuit.

The measurement of current and voltage harmonics are done during the no-load losses and currents measurement (section 4) by the same test connection. The measurement circuit connection diagram is given in figure 16.1.

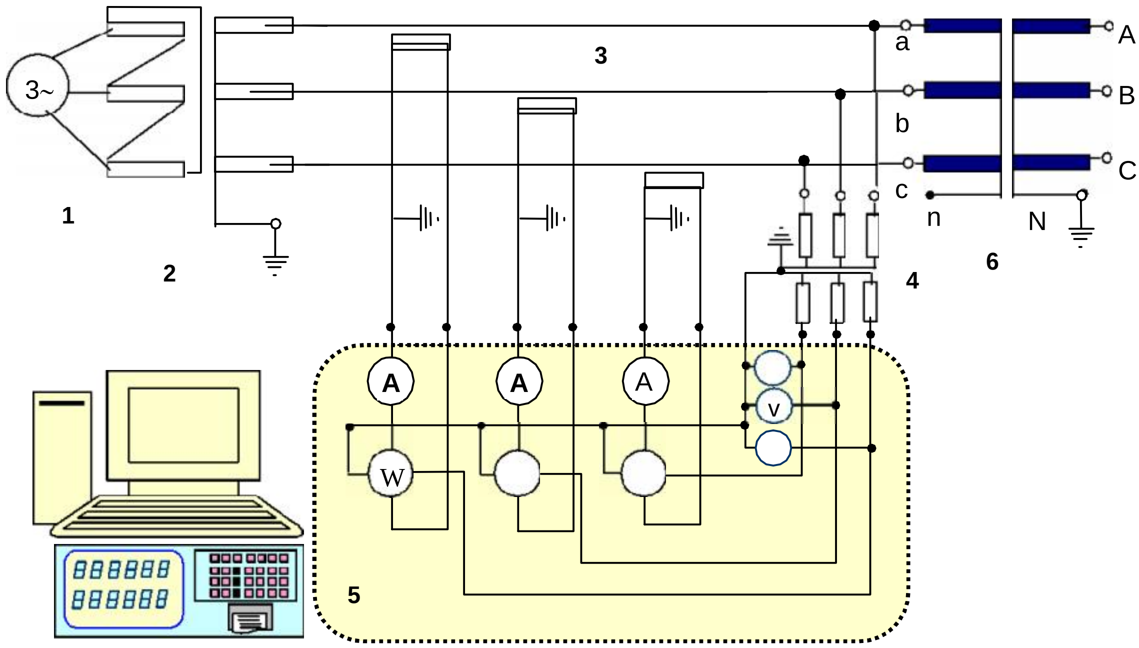
The supply voltage of the transformer at the test laboratory should be sinusoidal. Beause of the possible defects in the no-load cuurent, the supply voltage may devaite from sinus wave. To avoid this, the test generator and the connections of the test transformer should be appropriate and should make sure that they are at the lineer operation area of their magnetic characteristics. The measurement currents and voltages are connected to the analyser through measurement current and voltage transformers. Because of this, the operation areas of the measurement transformers should also be linear. By this way, the measurement transformers will not produce harmonics.

The measurements are repeated for each of the three phases. The measurements are usually made at the strongest harmonics (3., 5., 7., and 9.).

The effective value of the no-load current:

$$I_{eff} = \sqrt{\sum_{i=1}^{n} I_i^2}$$

. Here I_i: Values of harmonics currents



1- Power supply
2- Supply (intermediate) Transformer
3- Measurement Current Transformers
5- Harmonics Analyser / Power Analyser
6- transformer under Test
4- Measurement Voltage Transformers

Figure 16.1: Harmonics measurement connection diagram

17- Measurement of insulation resistance

The insulation resistance measurements are made to determine the insulation conditions of the transformer's windings to earth, between windings and to form a reference for future measurements during operating.

During measurement the currents (charge, absorbtion and leakage currents) flowing in the resistance formed by the insulator are measured. This current changes heavily according to humidity of the insulator, foreign materials in the insulator and temperature.

By comparing the results obtained in insulation resistance mesurements with periodical measurements, the insulation condiitons can be evaluated. For comparison they have to be at the same temperature (e.g. *20°C* reference temperature).

In insulation resistance measurements about the insulation state of the transformer, "the method of variation of resistance by test period" is one of the best methods to apply since it is simple and accurate.
The insulation resistance is measured with a measuring instrument. The test voltage is "direct voltage" and can be between *1000 V d.c. and 5000 V.d.c*.

The measuring points are "between the windings and between winding and tank", the hard to measure places can be connected to the "*Guard*" circuit of the instrument to have more accurate results.The temperature and humidity during test should also be recorded.

The values at *15th sec, 30th sec, 45th sec* and *60th sec* and 10th min. after the voltage is applied, should be recorded. Also, the ratio of insulation resistance in 60th sec (R_{60}), to insulation resistance in 15th second (R_{15}) can be given as absorbtion ratio in the test report. Also, the ratio of the value in 10th minute to value in 1st minute can be given as " polarisation index (PI) ".

The correction factor of values (by multiplying) measured in transformer oil temperature according to *20* °C reference temperature is given in below table:

M : D.C. Power Supply (Megger)
G : Guard / Shield end
T : Transformer tank

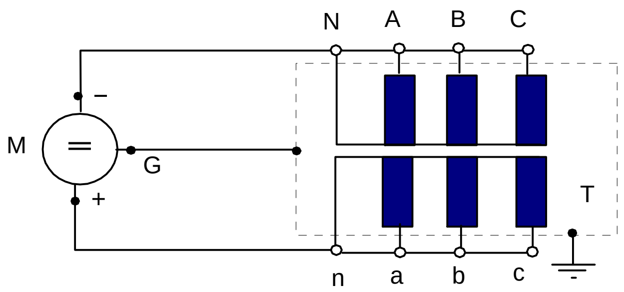


Figure 17.1 : Measuring insulation resistance in a YNyn0 transformer

Measuring Temperature ° C	**Correction factor**	**Measuring Temeperature ° C**	**Correction factor**
-10	0,13	35	2,80
-5	0,18	40	3,95
0	0,25	45	5,60
5	0,36	50	7,85
10	0,50	55	11,20
15	0,75	60	15,85
20	1,0	65	22,40
25	1,40	70	31,75
30	1,98	75	44,70

Power Transformers Test Laboratory I (*OSB Lab. I*)

ROTATING MACHINES

Generator I	:	S = 10.000 kVA U = 6.000 V I = 962 A f = 50-60 Hz	synchronous
Motor I	:	P = 2500 kW	Asynchronous
Generator II	:	S = 3.000 kVA U = 6.000 V I = 289 f = 100-180 Hz	synchronous
Motor II	:	P = 1000 kW	Asynchronous

TEST TRANSFORMERS and REACTOR

Transformer :
S = 15.000 kVA
U = 6.000(6.600) / 2.028 -111.500(122.300) V
I = 1443 A / 975........78 A
f = 50-180 Hz

Reactor :
S = 3.000(4.500) kVAr
U = 6.000(6.600) V
I = 285 (428) A
f = 100-180 Hz

COMPENSATION CAPACITOR BANKS

A total of 151,2 MVAr with 252 groups of each 600 kVAr with rated voltage 12 kV capacitors.

Total Rated power : 151.200 kVAr

INDUSTRIAL VOLTAGE TEST EQUIPMENTS

HV. Series Resonant System :
U = 600 kV(2x300 kV), 1- Phase
S = 2.400 kVA
I = 4 A (2xparalel 8 A) f= 50 Hz
Manufacturer: *Hipotronics*

Capacitive Voltage-Divider :
800 kV/0,1 kV 50÷180 Hz
Yapımcı firma: *Hipotronics*

Peak-Voltmeter :
$U / \sqrt{2} - U_{eff}$ Voltmeter
Class 0,5 50÷180 Hz
Manufacturer: *Hipotronics*

HV Filters :
70 kV, 50 A, 3 pcs
Manufacturer: *ISOFARAD*

TRANSFORMER LOSS MEASURING SYSTEM

Current Channels :
5 ÷ 4.000 A / 5 A
Class 0,1, 100 kV, 50/60 Hz-150 Hz
Manufacturer: *Haefely, TMS 580*

Voltage Channels :
100 ÷ 100.000 V/100 V
Class 0,1, 50/60 Hz-150 Hz
Manufacturer: *Haefely TMS 580*

IMPULSE VOLTAGE TEST EQUIPMENTS

Impulse voltage generator:
Number of stages : n = 12
Max. Stage Voltage : U_L = 200 kV
Max. Total Voltage : U= 2400 kV
Max. Total Power : W= 240 kJ
Cap. of each stage : C= 1 μF
Manufacturer : *Haefely*

Multiple Chopping Device:
12-stage
Capacitance : 7200 pF/Stage
Lightning Impulse Voltage : ±2400 kV
Manufacturer : *Haefely*

Voltage Divider:
R-Damped- Capacitive Divider
Lightning Impulse Voltage : ±2400 kV
Switching Impulse Voltage: ±1300 kV
Capacitance : 350 pF
Manufacturer : *Haefely*

Digital Impulse Meas. System :
High Resolution Impulse Analysing System 4 Channels
Accuracy : ±1%
Type : HIAS-743
Manufacturer : *Haefely*

MEASURING BRIDGES and MEASURING INSTRUMENTS

Schering Measuring Bridge :
Type : 2801
Accuracy : 0,5%
Capacitance : 0...... 10^5 μF
tan δ : 0...... 350%
Manufacturer : *TETTEX*

Press-Gas Capacitor:
Capacitance : 50 pF
Voltage : 400 kV a.c.
Manufacturer : *TETTEX*

Turn Ratio Measuring Instrument:
Type : TR-MARK II R
Accuracy : 0,05%
Measuring range : 0,8.........13000
Manufacturer : *RAYTECH*

Resistance Measuring Instrument:
Type : WR 100-R 2
Accuracy : 0,1%
Measuring range : 10^{-6} 10^5 Ω
Manufacturer : *RAYTECH*

Digital Thermometer:	20 Channels programmable	
	Type	: 2620
	Manufacturer	: *FLUKE*
Partial-Discharge: Measuring Instrument	Frequency	: 0,1 kHz ÷ 10 MHz
	Measuring range	: 0,1 pC.......100000 pC
	RIV	: 850 kHz and 1 MHz
	Type	: ICMsys8
	Manufacturer	: *Power Diagnostix*
Insulation-Resistance: Measuring Instrument	Voltage	: 5000 V. d.c.
	Measuring range	: 15 TΩ
	Type	: MIT 510
	Manufacturer	: *MEGGER*
Sound Level: Measuring Instrument	Measuring instrument	: type 2250 B
	1/3-1/3 oktav filtre	: type BZ 7223
	Microphone	: type 4189
	Calibrator	: type 4231
	Manufacturer	: *BRUEL & KJAER*
Vibration Measuring Instrument:	Measuring range	: 1 – 1000 ms^{-2}, 10 Hz.......1 kHz
	Type	: 5500
	Manufacturer	: *METRIX INSTRUMENT CO.*
Loss Factor: Measuring Instrument	Measuring range	: 0 ÷ 12 kV
	Type	: M2H-MCM
	Manufacturer	: *DOBLE Engineering Company*
Ossiloscope:	4- Channels	
	Type	: 2014
	Manufacturer	: *TEKTRONİX*
Corona Detector:	Type	: ULD-40
	Manufacturer	: *HOTEK*
Thermal Camera:	Type	: Ti 25
	Manufacturer	: *FLUKE*

Power Transformers Test Laboratory I (*ASB Lab.* I)

ROTATING MACHINES

Generator : S = 330 kVA synchronous
U = 500 V
I = 381 A
f = 50 Hz

Motor : P= 300 kW Asynchronous

Generator : S= 500 kVA synchronous
U= 800 / 1400 V
I = 361 / 206
f = 150 Hz

TEST TRANSFORMERS

Transformer : S = 4700 / 1000 / 4700 kVA
U = 34500 / 800-1400 / 64000 V
I = 79 A / 721........412 A / 42 A

COMPENSATION CAPACITOR BANKS

A total of 22,5 MVAr with 45 groups of each 500 kVAr with rated voltage 6 kV and total of 22,5 MVAr with 90 groups of each 250 kVAr with rated voltage of 3 kV capacitors.

Total Rated power : 45.000 kVAr

REACTORS

Reactor I : S = 3x(24-240) kVA; 50 Hz;
U = (200-800 V-Δ) (200√3-800√3 V-Y)
I = 120-2080 A

Reactor II : S = 1000 kVA; 150 Hz;
U = 800 V
I = 722 A

INDUSTRIAL VOLTAGE TEST EQUIPMENTS

H.V. Test Transformer : U= 350 kV/0,4 kV, 1- Phase
S= 75 kVA
I= 0,2 A/ 188 A f= 50 Hz
Manufacturer: Messwandlerbau-Bamberg

Capacitive Voltage-Divider : 350 kV/0,1 kV 50÷200 Hz
Manufacturer: Messwandlerbau-Bamberg

Peak-Voltmeter : $U / \sqrt{2} - U_{eff}$ Voltmeter
Class 0,5 50÷200 Hz
Manufacturer: Messwandlerbau – Bamberg

TRANSFORMER LOSS MEASURING SYSTEM

Current Channels :	5 to 4.000 A / 5 A Class 0,1, 100 kV, 50/60 Hz-150 Hz *Manufacturer*: Haefely, TMS 580
Voltage Channels :	100 to 100.000 V/100 V Class 0,1, 50/60 Hz-150 Hz *Manufacturer*: Haefely TMS 580

IMPULSE VOLTAGE TEST EQUIPMENTS

Impulse voltage generator:

Number of stages	: n = 10
Max. Step Voltage	: U_L = 200 kV
Max. Total Voltage	: U= 2000 kV
Max. Total Power	: W= 200 kJ
Cap. of each step	: C= 1 μF
Manufacturer	: Passoni+Villa

Multiple chopping device:

8-stage, Dry Air Pressurized

Capacitance	: 6000 pF/stage
Lightning Impulse Voltage	: ±1800 kV
Manufacturer	: Passoni+Villa

Voltage Divider:

R-Damped-Capacitive Divider

Lightning Impulse Voltage	: ±2000 kV
Switching Impulse Voltage	: ±1450 kV
Capacitance	: 400÷1600 pF
Manufacturer	: Passoni+Villa

Digital Impulse Measuring System: Digital Data Acquisition Analysis System

Accuracy	: ±1%
Type	: SDA-C
Manufacturer	: Passoni+Villa

MEASURING BRIDGES and MEASURING INSTRUMENTS

Schering Measuring Bridge :

Type	: 2801
Accuracy	: 0,5%
Capacitance	: 0......10^5 μF
tan δ	: 0...... 350%
Manufacturer	: TETTEX

Press-Gas Capacitor

Capacitance	: 50 pF
Voltage	: 400 kV a.c.
Manufacturer	: TETTEX

Turn Ratio Measuring Instrument:

Type	: TR-MARK II R
Accuracy	: 0,05%
Measuring range	: 0,8.........13000
Manufacturer	: RAYTECH

Resistance Measuring Instrument:

Type	: WR 50-R 2
Accuracy	: 0,1%
Measuring range	: 10^{-6} 10^{5} Ω
Manufacturer	: RAYTECH

Digital Thermometer: 20 Channel programmable
Type : 2620
Manufacturer : FLUKE

Power Measuring Unit: *Wide Band Power Analyser*
(Wattmeter-Voltmeter-Ampermeter)
Type : D 6000 T
Accuracy : 0,1%
Manufacturer : *NORMA*

Partial-Discharge Measuring Instrument::Frequency: 0,1 kHz ÷ 10 MHz
Measuring range: 0,1 pC.......100000 pC
RIV : 850 kHz and 1 MHz
Type : ICM*sys*4
Manufacturer : Power Diagnostix

Insulation-Resistance Measuring Instrument: Voltage : 5000 V. d.c.
Measuring range : 15 TΩ
Type : MIT 510
Manufacturer : MEGGER

Insulation-Resistance Measuring Instrument: Voltage: 5000 V. d.c.
Measuring range : 10
TΩ Type : BM 21
Manufacturer : MEGGER

Noise Measuring Instrument: Measuring instrument : type 2230
1/3-1/3 octave filter: type ZF 0020
Microphone : type 4155
Calibrator : type 4230
Manufacturer : BRUEL & KJAER

Vibration Measuring Instrument: Measuring range : $1.....1000 ms^{-2}$, 10 Hz.......1 kHz
Type : 5500
Manufacturer : METRIX INSTRUMENT CO.

Loss Factor Measuring Instrument: Measuring range : 0 ÷ 12 kV
Type : M2H
Manufacturer : DOBLE Engineering Company

Ossiloscope: 2- Channel
Type : 2012
Manufacturer : TEKTRONİX

Corona Detector: Type : ULD-40
Manufacturer : HOTEK

Thermal Camera: Type : Ti 25
Manufacturer : FLUKE

Distribution Transformers Test Laboratory II (*ASB Lab II*)

TEST TRANSFORMERS

Transformer : S = 315 kVA
U = 400 / 400-3600 V
I = 455 A / 455.......51 A

Rotating Transformer : S = 160 kVA
U = 380 / 760 V
I = 243 A / 455.......122 A

Frequency Converter : Güç = 300 kW
U = 400 V
Frequency = 50-150 Hz

COMPENSATION CAPACITOR BANKS

A total of 720 kVAr with 12 groups of each 60 kVAr with rated voltage 0,5 kV capacitors.

Total Rated power : 720 kVAr

MEASURING TRANSFORMERS

Precision Current Transformers

3 pieces Current transformers: 5-10-25-50-100-250-500 A /5A
10 VA, Class 0,05, 3,6 kV, 50/60 Hz
Manufacturer: EPRO

Precision Voltage Transformers

3 pieces voltage transformers : 400-1000-2000-3000 V/100 V
10 VA, Class 0,05, 50/60 Hz
Manufacturer: EPRO

INDUSTRIAL VOLTAGE TEST EQUIPMENT

H.V. Test Transformer : U= 100 kV/0,4 kV, 1- Phase
S= 100 kVA
I= 1 A/ 250 A f= 50 Hz
Manufacturer: BEST

Capacitive Voltage-Divider : 100 kV/0,1 kV 50÷200 Hz
Manufacturer: Messwandlerbau-Bamberg

Peak-Voltmeter : $U / \sqrt{2} - U_{eff}$ Voltmeter Digital
Class 0,5 50÷200 Hz
Manufacturer: Messwandlerbau – Bamberg

AC Voltage Test Instrument : Type : 3158
Measuring range : 0.........6 kV
Manufacturer : HIOKI

HV Filter : 70 kV, 50 A, 3 pcs
Manufacturer : ISOFARAD

MEASURING BRIDGES and MEASURING INSTRUMENTS

Turn-Ratio Bridge:	Accuracy	: ±0,1%
	Voltage	: 220 V a.c.
	Measuring range	: 1.........1000
	Manufacturer	: Hartmann+Braun
Turn Ratio Measuring Instrument:	Type	: PWR 3
	Accuracy	: 0,1%
	Measuring range	: 0,9.........1000
	Manufacturer	: SCHÜTZ
Resistance Measuring Instrument:	Type	: MRC 6100 N
	Accuracy	: 0,1 %
	Measuring range	: 10^{-6}.......10^{2}
	Ω *Manufacturer*	: SCHÜTZ
Resistance Measuring Instrument:	Type	: WR 50-R 2
	Accuracy	: 0,1%
	Measuring range	: 10^{-6} 10^{5} Ω
	Manufacturer	: *RAYTECH*
Digital Thermometer:	20 Channel programmable	
	Type	: 2620
	Manufacturer	: FLUKE
Power Measuring Unit: **(Wattmeter-Voltmeter-Ampermeter)**	Wide Band Power Analyser	
	Type	: D 6000 T
	Accuracy	: 0,1%
	Manufacturer	: NORMA
Voltmeter, average-value:	Digital,	
	Type	: D 4045
	Accuracy	: 0,1%
	Manufacturer	: NORMA
Insulation-Resistance Measuring Instrument:	Voltage	: 5000 V. d.c.
	Measuring range	: 500
	GΩ Type	: BM 11 D
	Manufacturer	: MEGGER

Literature :

- IEC Standards 60076 Power Transformer– all parts
- The testing of Transformer.