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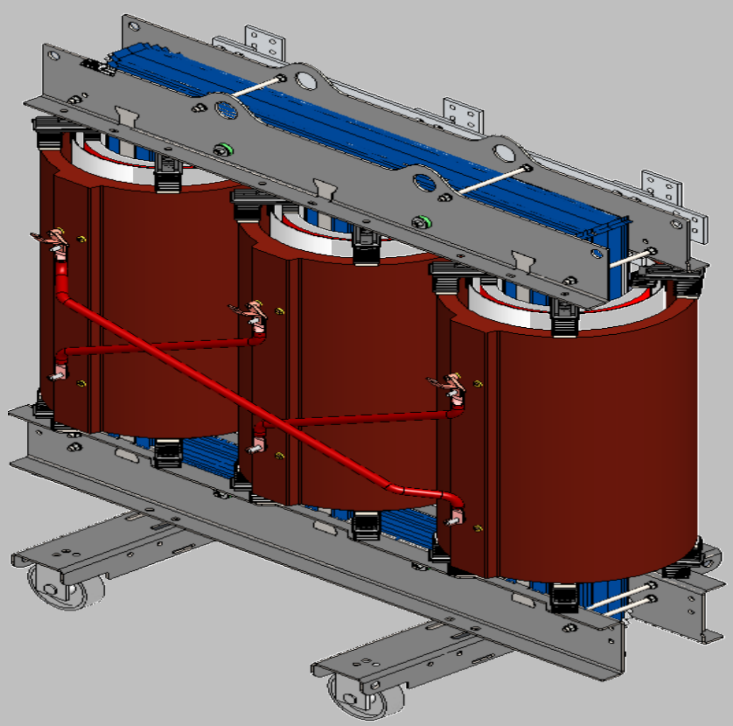
Test description for dry-type transformers chapter for type tests



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Test lab cast resin transformers

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1. Scope

This is a general test description for dry-type transformers at SGB and will apply if no specific customer requirements are given for the individual tests.
Special customer standards or values are not included in this description.
If not indicated, the description is exemplary for a three-phase transformer with two winding systems.
Auxiliary parts of the transformer are also not included, except as indicated e.g., temperature sensors.

The scope of this chapter describes “type” tests, this means the standard require these tests for a new design or significant design changes (see IEC 60076-1:2011 chapter 3.11.2).

Transformer type means e.g.:

- representative electrical values (e.g., voltage, power)
- representative design

Design variations that are clearly irrelevant to a particular type test would not require that type test to be repeated.

Design variations that cause a reduction in values and stresses relevant to a particular type test do not require a new type test if accepted by the purchaser and manufacturer.

2. Standards

Part 11: Dry-type transformers
IEC 60076-11:2018

Replacement for
DIN EN 60726
(VDE 0532-726):2003-10

with reference to:

IEC 60076-1:2011	Power transformers – General
IEC 60076-2:2011	Temperature rise for liquid-immersed transformers
IEC 60076-3:2013	Insulation levels, dielectric test´s and external clearances in air
IEC 60076-4:2002	Guide to the lightning impulse and switching Impulse testing – Power transformers and reactors
IEC 60076-16:2011	Transformers for wind turbine application
IEC 60060	High voltage test techniques
IEC 60310:2004	Railway applications – Traction transformers and inductors on board rolling stock
IEC 50329:2010	Railway applications – Fixed installations – Traction transformers
IEC 60529:1989	Degrees of protection provided by enclosures (IP code)

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3. Lightning impulse test

3.1. Standard

IEC 60076-11:2018 clause 14.3.1 // part 3 clause 13

3.2. Aim

The lightning impulse voltage test is executed as a type test to prove the constructive coordination of the transformer (e.g., insulation in the winding turn-to-turn, layer-to-layer, terminal-to-constructive parts, etc.). The impulse also reproduces the stress peaks and switching surges in the net.

3.3. Test

3.3.1. Test wave

The test can be executed with various parameters, usually it is:

- Full-wave in negative polarity with 100 % BIL level

Wave shape T_1 = 1.2 µs ± 30 % T_2 = 50µs ± 20 %

Other possibilities include (special tests, only on customer request)

- Full-wave in positive polarity with 100 % BIL level

Wave shape T_1 = 1.2 µs ± 30 % T_2 = 50µs ± 20 %

- Full-chopped-wave on the tail in negative polarity with 100% or 110 % BIL level

Wave shape T_1 = 1.2 µs ± 30 % T_2 = 4.5µs ± 34 %

- Full-chopped- wave on the tail in positive polarity with 100% or 110 % BIL level

Wave shape T_1 = 1.2 µs ± 30 % T_2 = 4.5µs ± 34 %

Also, technically possible but not practical with our generator configuration (special tests, only on customer request)

- Switching impulse
- Front of wave chopped

3.3.2. Remarks to wave shapes on special cases

For some transformers, it is necessary to apply a resistor on the windings which are not being tested, separately from the winding upon which testing is taking place
(The maximum resistance therefore is 400 Ω).
Remark: In all circumstances, the voltage appearing during the impulse test at the other line terminals shall not be more than 75 % of their rated lightning impulse withstand voltage for star-connected windings, or 50 % for delta-connected windings. The lowest value of impedance at each terminal needed to achieve the required wave shape shall be used.

During the testing of the neutral (special tests, only upon customer request) the T1 has a maximum time of 13 µs. Also, the transformer is always to be switched to the maximum possible voltage during this test.

For certain test circuits and test objects, e.g., testing transformer windings with a very low impedance (generally the low voltage side), it can be extremely difficult within the stated tolerances may be impossible to achieve the IEC required wave form (front time T1, Time to half-value T2 or overshoot ß). In these cases, larger tolerances will be acceptable, the test will be carried out based on the relevant standard.

A time to chopping of between 2 µs and 3 µs can be accepted per an agreement between the supplier and customer, provided that the peak value of the lightning impulse wave is achieved before the chop.

3.3.3. Voltage level (BIL)

The voltage level is chosen with the corresponding Um, according to

- IEC 60076-11:2018 (clause 11.1, table 3, List 1 or List 2)

Or for special requirements (only upon customer request)

- IEC 60076-16:2011 (clause 4.6, table 1, List 2 or List 3)
- IEC 60076-3:2013 (table 2)

The tolerance for the voltage level is ± 3 % of the BIL.

3.3.4. Winding to be tested

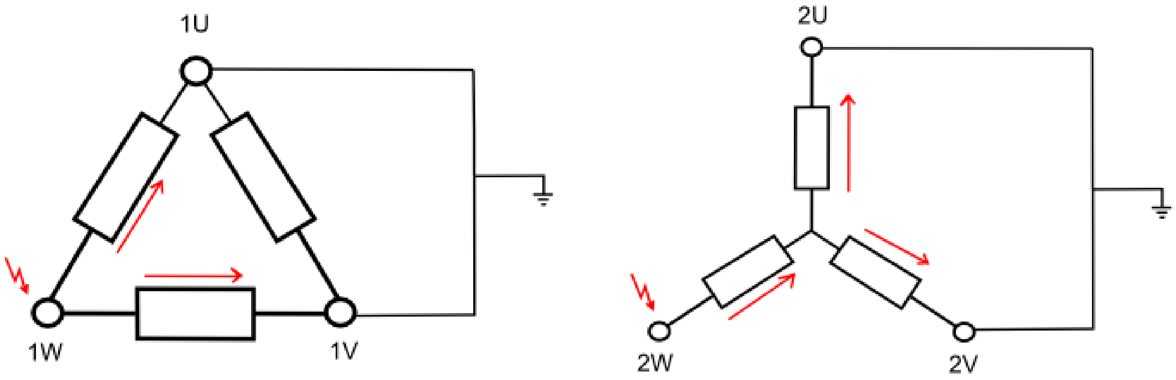
Impulse testing is required on all winding connections/terminals (e.g., U, V, W) which have a rated voltage ≥ 3.6 kV or with higher insulation coordination through a special standard or an agreement between supplier and purchaser.

3.3.5. Transformer connection between the test

The test is executed with the winding interconnection e.g., in delta, star or zig-zack.

Through this, it is ensured that all coils will be tested on both the upper and lower terminals.

Remark: Impulse on a neutral terminal is a special test and must be explicitly ordered.



picture 1: impulse-test voltage distribution between the interconnections

All other terminals and the core and frame of the transformer including the temperature sensors, will be shorted and grounded.

3.3.6. Tapping position for test

If the tapping range is ± 5 % or less, then the lightning impulse tests shall be made with the transformer connected on the principal tapping.

If the tapping range is larger than ± 5 % then, unless otherwise agreed, the two extreme tapping´s and the principal tapping shall be tested, one tapping for each of the three individual phases of a three-phase transformer or the three single-phase transformers designed to form a three-phase bank (e.g., phase U tap 1, phase V tap 3 and phase W tap 5).

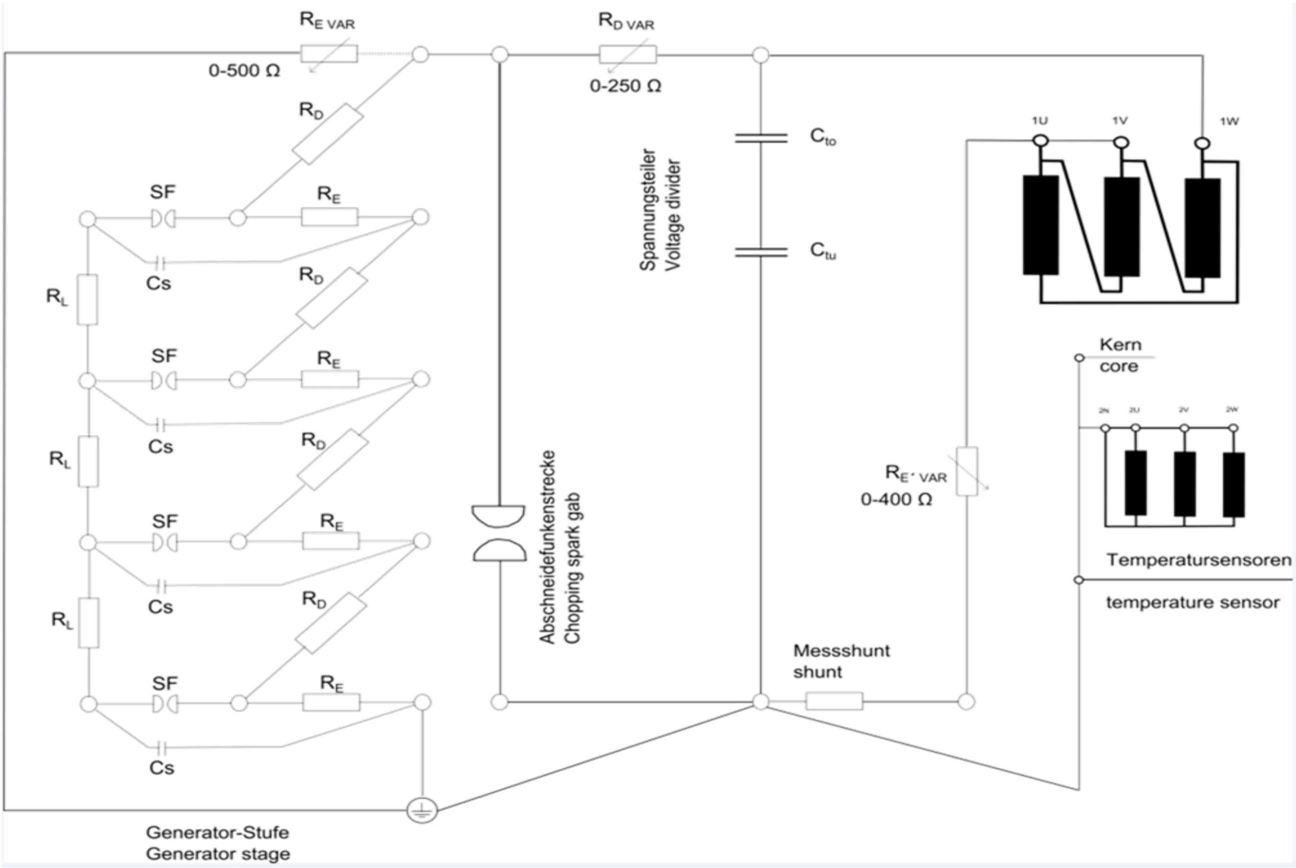
3.3.7. Test setup

For the test, the terminal to be tested will be connected with a MARX generator. The terminals which are not to be tested are connected through the ground of the generator via a shunt (measuring of current).
Using various resistors, the time for the wave shape could be influenced.
Between the generator and the tested winding is a voltage divider to measure the impulse voltage.

3.3.8. MARX generator data

Stages	4
Maximum voltage	400 kV
Maximum Impulse capacitance	4000 nF
Total charging energy	20 kJ
Voltage divider	2 nF
Chopping spark gap maximum voltage	300 kV

3.3.9. Impulse test circuit



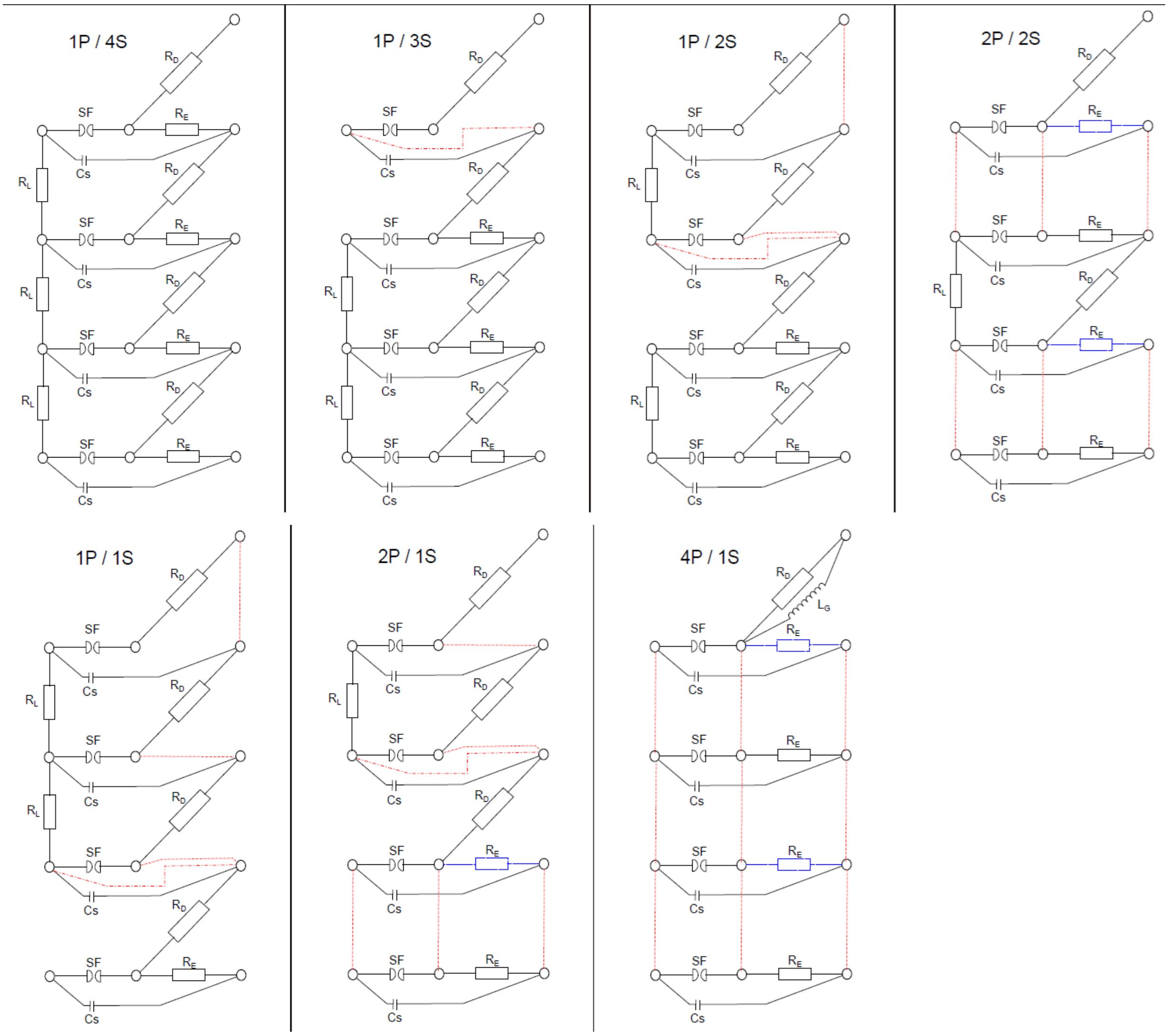
picture 2: impulse test circuit

3.3.10. Example of resistors for the MARX generator

use	pulse form [µs]	pieces	resistance [Ω]	rated energy W_R [kJ]	length *) [mm]	cross section [mm]	identifying color	remarks
R_D	1.2/50	1	122	5	470	14 x 60	light blue	
R_D	1.2/50	4	43	5	470	14 x 60	yellow	
R_D	1.2/50	4	30	5	470	14 x 60	orange	
R_D	1.2/50	4	22	5	470	14 x 60	light brown	
R_E	1.2/50	4	66	5	350	14 x 80	red	stage energy WS = 5 kJ
R_E	1.2/50	4	120	10	350	Ø 80	light brown	stage energy WS = 10 kJ
R_L	1.2/50	3	40000	-	270	Ø 75	dark brown	
R_{LV}	-	1	40000	-	445	Ø 100	dark brown	
R_{ERD}	-	1	4900	-	290	Ø 75	dark brown	charg. energy (generator) W < 25 kJ
L_G	Glanninger coil	1	130µH	-	470	Ø 70	black	

table 1: resistors for the MARX generator

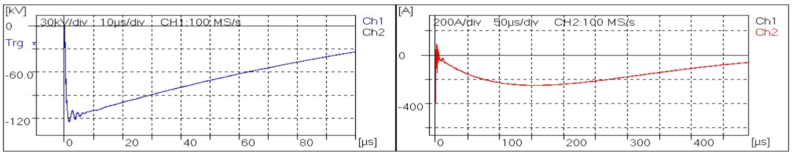
3.3.11. Example of MARX generator connections



picture 3: MARX generator connections

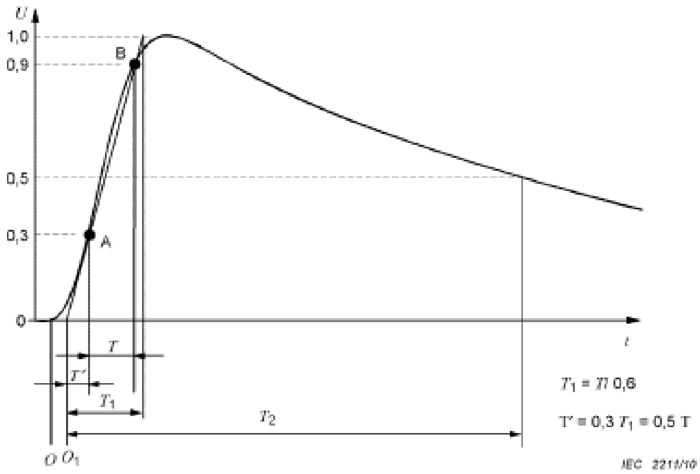
3.3.12. Test procedure for full-wave impulse

Usually the full-wave impulse will be executed with a negative polarity.
As a reference, the first impulse is **between 50 % and 75 %** of the BIL. **1xRW**
Then it is followed by **three 100 %** impulses. **3xFW**



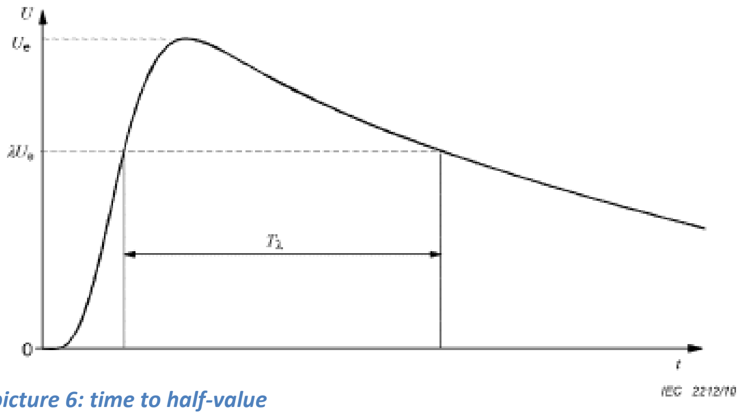
picture 4: impulse voltage voltage/current

The time of the wave shape should be:
front time:
T_1 = 1.2 µs ± 30 % (0.84 µs – 1.56 µs)
(Ascending time between 30 % to 90 % of the voltage has been reached)



picture 5: front time

time to half-value
T_2 = 50 µs ± 20 % (40 µs – 60 µs)
(Descending time from T1 until the wave has reduced to 50 % of the peak value)



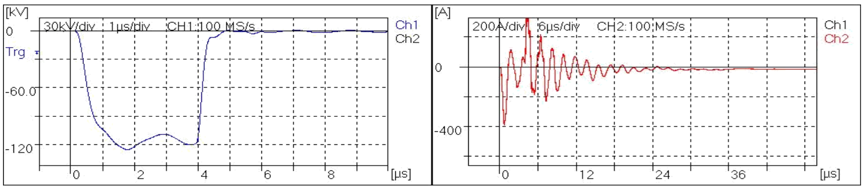
picture 6: time to half-value

Remarks: see 3.3.2 Remarks to wave shapes on special cases

3.3.13. Test procedure for copped-full-wave on the tail impulse

This test is to be conducted only at the explicit wish of the client. In the IEC 60076-3 it is noted as a special test.

Here after the wave has reached its maximum voltage, using a sphere spark gap on the generator, a „clipping" is conducted. It is basically a controlled flash-over.
This simulates a case of load with a voltage spike in the net when a lightning arrestor responds.



picture 7: chopped impulse voltage voltage/current

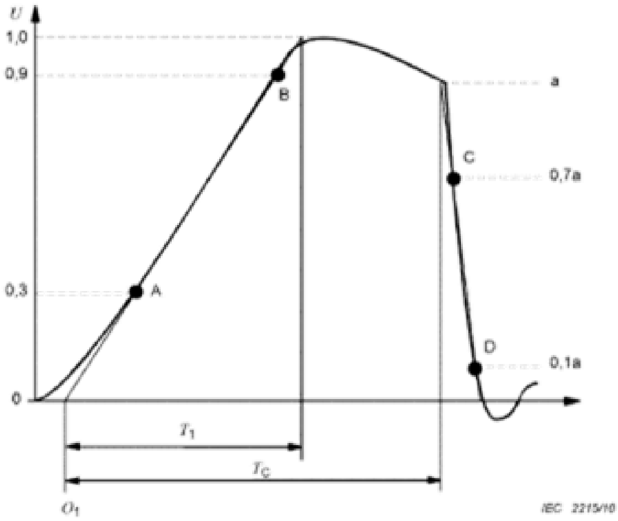
Usually the full-wave impulse will be executed with a negative polarity.

As a reference the first impulse is **between 50 % and 75 %** of the BIL.	**1xRW**
Followed with a **single 100 %** full-wave impulse.	**1xFW**
Then a reference chopped wave which is between 50 % and 75 % of the BIL.	1xCRW
Followed with **two 100 %** chopped impulses.	**2xCFW**
Lastly, **two 100 %** full-wave impulses will take place.	**2xFW**

The time of the wave shape shall be:

front time	T_1 (see 3.3.12 Test procedure for full-wave impulse)
time to half-value	T_2 (see 3.3.12 Test procedure for full-wave impulse)

chopped time on tail
T_C = 4.5 µs ± 34 % (3 µs – 6 µs)
(Descending time from 70 % until the wave has only 10 % of the peak value)



picture 8: chopped time on tail

Remarks: see 3.3.2 Remarks to wave shapes on special cases

3.3.14. Remarks for changing polarity between impulses

Due to the static charge on the surface on the winding, several reduced impulses shall be made with the different polarity before a 100 % impulse.

3.3.15. Commonly used measuring devices for testing

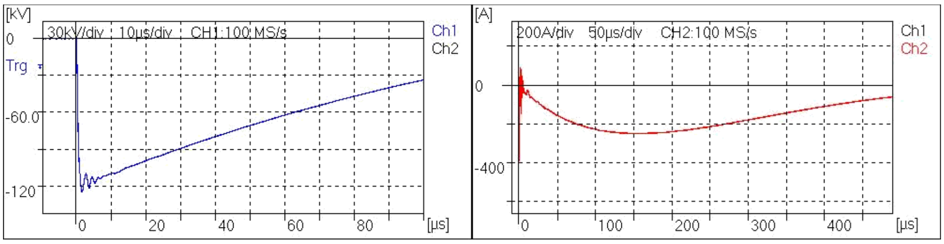
measuring devices	manufacturer	type	range / accuracy	frequency	class
Impulse voltage test-system	High Volt	SMC 2000-400 MIAS 100-14-2B	10 - 400 kV 20 kJ	n.a.	n.a.
Hygro-/Thermo-/Barometer	Greisinger electronic	GFTB 200	- 50 – 100 °C 0 % - 100 % rel. humidity 10.0 – 1100.0 hPa	n.a.	n.a.

Table 2: Commonly used measuring devices

3.3.16. Recorded values for the test

Both the voltage and the current peaks are documented, additionally the wave form through the T1 and T2 will be recorded.

For each impulse, voltage and current diagrams are to be chronicled as seen below.



picture 9: impulse voltage/current

The climate conditions have an influence on the testing therefore they will be recorded:
ambient temperature in [°C], the relative humidity in [%] and the air pressure in [hPa].

3.4. Test criteria

If during testing, one of the impulses has an outer flash-over on the transformer or the oscilloscopic record for the voltage or current is seen as having an unacceptable deviation, this impulse will be discarded and another impulse has to be conducted.

The test is successful if the following is achieved:

- A complete testing sequences
- Wave form that falls within acceptable IEC pre-prescribed values
- The absence of notable differences between the voltage and current graphs recorded during the reference impulse and the full impulses.

4. Temperature rise test

4.1. Standard

IEC 60076-11:2018 clause 14.3.2 // part 2 clause 7

4.2. Aim

The aim of this measurement is to prove that the transformer does not exceed with the required load conditions the temperature requirements given by the standard for the necessary insulation class or the customer specification. Exceeding these temperatures for an undefined/long period could age the transformer faster.

4.3. Measurement - general

In general, there are methods of temperature rise measurement (according to IEC 60076-11:2018, clause 14.3.2.2.1):

- Simulated load method
- Back-to-Back method
- Direct loading method

Back-to-Back method and direct loading method are not always possible.
The standard procedure at SGB is, to execute the measurement in the “Simulated load method”.
For this one measurement is taken in no-load (excitation load), and another one in load condition.

If the transformer has multiple cooling types for continuous load e.g., AN and AF, SGB is testing at the highest of these values, due to the fact that this is the rated power.

4.3.1. Tapping position for measurement

The temperature rise limits shall apply to the principal tapping corresponding to the rated voltage for a tapping range does not exceed ±5 %.

If the tapping range exceeds ±5 %, the temperature rise limits shall apply to the minimum voltage tap at the appropriate tapping power. The standard at SGB in this case is considering the rated power as tapping power.

4.3.2. Temperature sensors for the measurement

- For the cooling medium:
  - Around the transformer or enclosure, four PT100 sensors will be placed in oil filled bottles, at half height of the winding or enclosure, at a distance of around 2 meters to measure the ambient temperature.
  - In case of cooling systems using water-air heat exchanger, the cooling medium temperature will be measured at the intake of the cooling equipment/heat exchanger.
- For the core:
  - On the transformer core a PT100 sensor shall be placed on the center of the upper core yoke.
- For the windings:
  - In the windings, a PT100 sensor is placed in the center phase of each tested winding-system (e.g., 1V, 2V). They are located on the upper part of the winding (around 10 cm below the edge) in the cooling duct (if available, otherwise on the inner surface of the winding).
- Additional Sensors:
  - In case of cooling systems using water-air heat exchanger: cooling fluid outlet and cooling fluid rate [in m^3/h]
  - In case of cooling systems with water-air or air-air heat exchangers: housing air in, housing air out

NOTE 1: If the winding phase-to-phase voltage exceeds 6.3 kV no direct temperature measurement possible (except for e.g., fibre-optical-sensors). This is for example the case on the HV winding at the no- load (excitation load) condition.

NOTE 2: The term water is used generally throughout this document considering and including all cooling fluids.

4.4. Cold resistance

Before measurement, the external cooling medium temperature shall not have changed more than 3 °C in 3 hours before testing. Furthermore, it needs to be ensured that the transformer which needs to be tested, was stored in an ambient temperature close to this at least for 12 h before starting the measurement. This is necessary to ensure stable conditions between the cold resistance and its reference temperature.

The resistance measurement at cold (ambient) state R_{W1} is done between a central and an outer phase line terminal. The actual cooling medium temperature θa_1 will be recorded.

Note: In case of cooling systems using water-air heat exchanger, the ambient temperature and the water temperature will be measured. The cold resistance value will be measured at ambient temperature and corrected to the noted water temperature. The standard specifications are thus fully met. Detailed information and test reports on the procedure are available on request.

To keep the influence of the reactance as low as possible, the measurement is conducted with direct current.

The measurement is conducted with a resistance measurement bridge either manually or an automatic program.
Both systems are based on current-voltage measurements.
For this measurement, a steady current is fed through one connection, on the other connection amperage and voltage are measured. Finally, the resistance is calculated using Ohm's law as shown in the formula below.

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

R= ohmic resistance U=voltage I=current

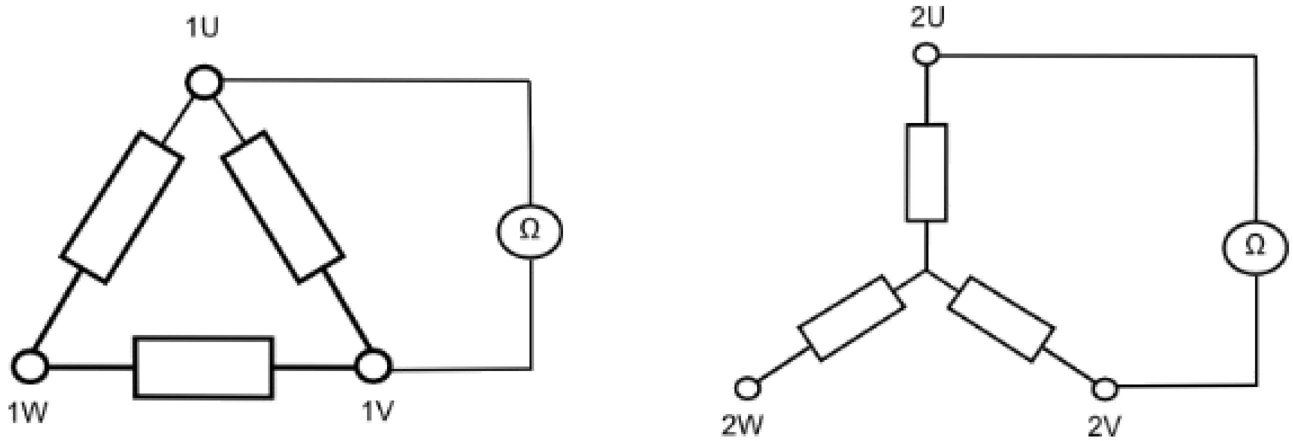
formula 1: ohmic law

The fed current is about $^1/_{15}$ of the rated current.
Because HV and LV is measured simultaneously, the current direction with reference to the winding interconnection e.g., in delta, star or zig-zack has to be chosen.

Approximately, the first 30 seconds of the resistance measurement are not valid, because the current flowing through the turns must stabilize.

The connection for the measurement is basically as close as possible to the winding.

4.4.1. Test setup

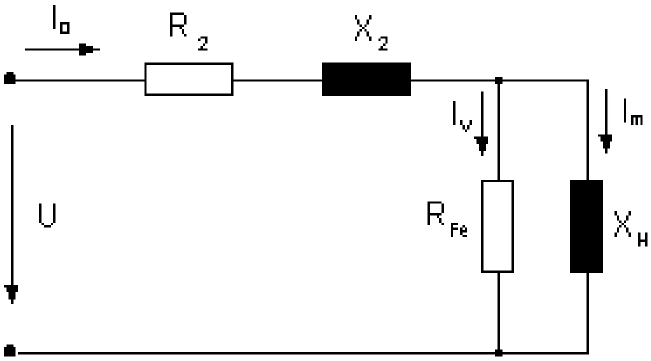


picture 10: phase to phase resistance

4.5. No - load (excitation load) measurement

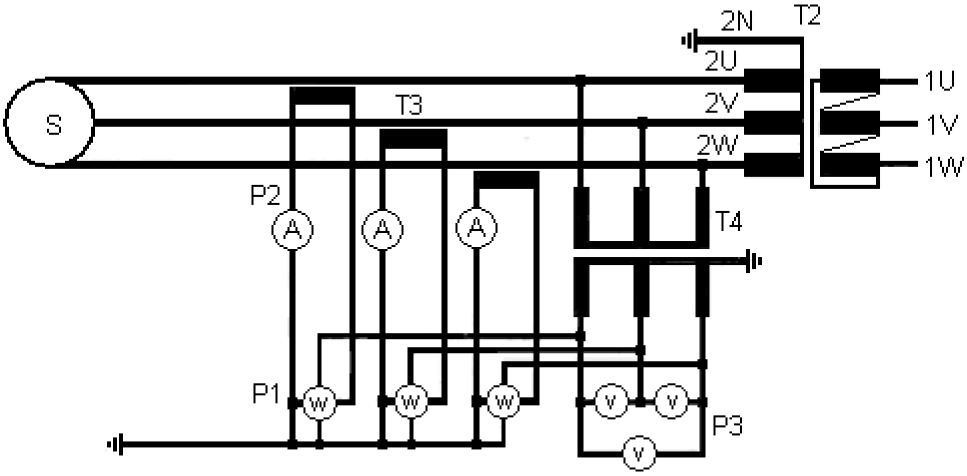
This test is conducted much like a no-load losses measurement (chapter for routine tests, clause 6). It is carried out the rated frequency f_R and the measurement voltage is applied as close as possible to the rated voltage U_R.

4.5.1. Equivalent circuit diagram for a transformer in no-load



picture 11: transformer in no-load

4.5.2. Test setup no - load (excitation load)



picture 12: Test setup for no-load

S: electricity supply

T2: transformer to be tested

T3: current transformer

T4: voltage transformer

P1: wattmeter

P2: amperemeter (I_{RMS})

P3: voltmeter (U_{RMS})

4.5.3. Switching off

The measurement can be switched off when the transformer has reached a „steady state condition“. According to IEC 60076-11:2018 (clause 14.3.2.4) this is when the temperature rise (from core and windings) does not exceed more than 1 K per hour.

4.5.4. Hot resistance

Due to the fact that the resistance at hot (at shutdown) state R_{W2}, changes directly with the cooling of the transformer after the switching off, it cannot directly be measured (Some time is needed to disconnect the transformer feeding and connect the resistance measurement). Therefore, the resistance over a time period of 12.5 minutes in 30 second intervals is measured and the R_{W2} is calculated with a linear extrapolation.

The cooling medium temperature at hot (at shutdown) state θa_2 will also be recorded.

It is necessary that the resistance measurement is taken in the same manner as described in chapter 4.4 Cold resistance. This means using the same connection point on the terminals, measuring range of the Resistance-Bridge, etc.

4.6. Load measurement

This test is conducted much like the load losses measurement (chapter for routine tests, clause 7) (but always with 100 % current).

If the transformer is to encounter especially strong harmonics during operation than this can be considered (IEC 60076-11:2018, chapter 4.2 d)). If the total harmonic content of the load current exceeds 5 %, then the extra losses due to these harmonic currents shall be considered by increasing the test current for the temperature rise test.

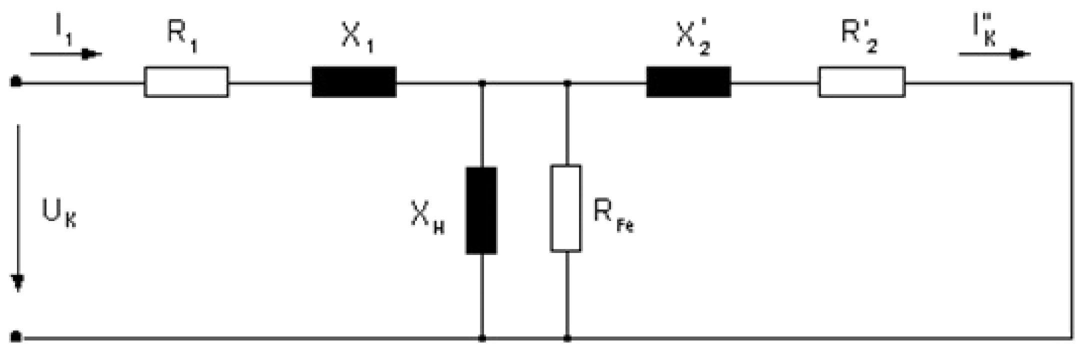
Note: The mean value is used for the individual allowances for each winding system during the test. The winding systems are afterwards calculated based on the individual test performance.

In the case of overload classes for EN 50329, IEC 62695 or IEC 60146, short-term overloads will not be tested. Depending on the standard, an equivalent overload or only the long-term overload will be tested.
For this purpose, the transformer is tested with the respective load for continuous operation (including any harmonic surcharges) until steady state (see 4.6.3 Switching off). Then the load is increased according to the overload.

Note: A long-term overload correspond a time from 480 sec. till 7200 sec.

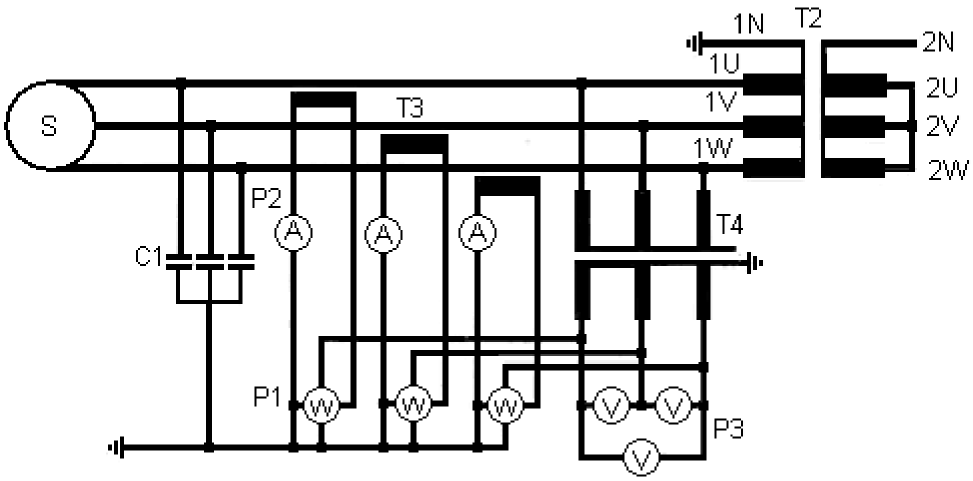
The system with the lower current (e.g., HV) is fed and another system/s are short-circuited. This is also dependent on the loading cases of the transformer.

4.6.1. Equivalent circuit diagram for transformer in load (short-circuit)



picture 13: transformer in short-circuit

4.6.2. Test setup load



picture 14: test setup for load measurement

S: electricity supply
T2: transformer to be tested
T3: current transformer
T4: voltage transformer
C1: capacitor bank
P1: wattmeter
P2: amperemeter (I_{RMS})
P3: voltmeter (U_{RMS})

4.6.3. Switching off

The measurement can be switched off when the transformer has reached a „steady state condition“. According to IEC 60076-11:2018 (clause 14.3.2.4) this is when the temperature rise (from core and windings) does not exceed more than 1 K per hour.

4.6.4. Hot resistance

Due to the fact that the resistance at hot (at shutdown) state RW2, changes directly with the cooling of the transformer after the switching off, it cannot directly be measured (because some time is needed to disconnect the transformer feeding and connect the resistance measurement). Therefore, the resistance over a time period of 12.5 minutes in 30 second intervals is measured and the RW2 is calculated with a linear extrapolation.

The cooling medium temperature at hot (at shutdown) state θa_2 will also be recorded.

It is necessary that the resistance measurement is taken in the same manner as described in chapter 4.4 Cold resistance. This means using the same connection point on the terminals, measuring range of the Resistance-Bridge, etc.

4.7. Commonly used measuring devices for measurement

measuring devices	manufacturer	type	range / accuracy	frequency	class
Micro Ohmmeter	IBEKO Power AB - DV Power	RMO40T	0.1 µΩ - 2kΩ -> ±(0.1 % rgd + 0.1 % FS) 2 kΩ – 10 kΩ -> ±(0.2 % rgd + 0.1% FS) 5 mA - 40A DC	DC	n.a.
Micro Ohmmeter	IBEKO Power AB - DV Power	RMO60T	0,1 µΩ – 2 kΩ 5 mA – 60 A DC ±(0.2 % rgd + 0.2 % FS)	DC	n.a.
Precision Power Analyzer	ZIMMER	LMG 500	U rms 1000 V / I rms 32 A U pk 3200 V / I pk 120 A	DC - 10 MHz	0.01-0.03
Precision Power Analyzer	ZIMMER	LMG 310	U rms 1000 V / I rms 30 A U pk 2000 V / I pk 60 A	DC - 1 MHz	0.05
LV-current-transf.	H&B	Ti 48	2.5-500 A/5 A	50/60 Hz	0.1
LV-current-transf.	epro	NCD 3000d	10 - 3000 A	50/60 Hz	0.1
HV-voltage-transf.	epro	NVRD 40	2-40 kV/100 V	50/60 Hz	0.02
HV-current-transf.	epro	NCO 60	1-600 A/5 A	50/60 Hz	0.01
Data Acquisition Unit	YOKOGAWA	DA100-13-1F 2x DU100-12 DT300-11	0-250°C / 0.1 K	50/60 Hz	n.a.
Temperature recorder	Logoscreen nt		0-250°C / 0.1 K	50/60 Hz	n.a.

Table 3: Commonly used measuring devices

4.8. Recorded values for the measurement

Between a central and an outer phase line terminal

- Resistance at cold (ambient) state R_{W1} at ambient temperature θa_1
- Resistance at hot (at shutdown) state R_{W2} at ambient temperature θa_2

- All voltages [V], amperages [A] and losses [W] (in R.M.S.) during the measurement are recorded.

- Temperatures of core and windings $\theta_{core}, \theta_{winding\ 1V}, \theta_{winding\ 2V}$

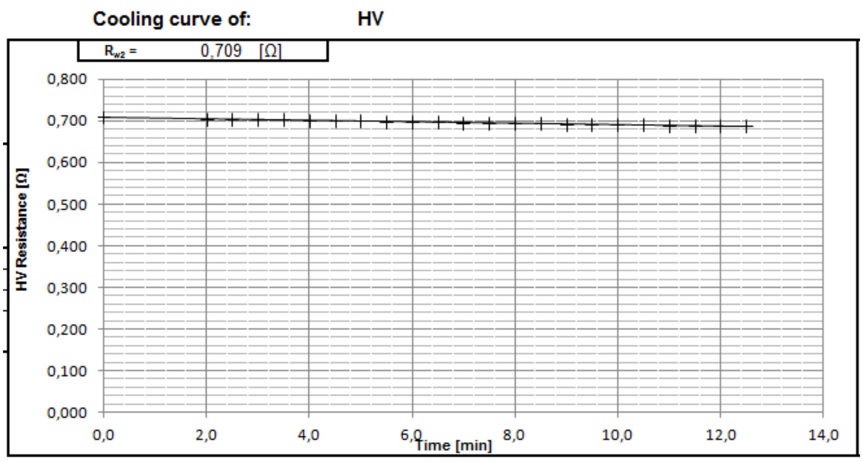
REMARKS: All Values are recorded separately for no-load and load condition.
Except cold resistance (only before the first measurement) and $\theta winding\ 1V$ (only between load condition, if applicable [see 4.3.2])

4.9. Calculations for the measurement

For the first step, the average winding temperature rise for all windings-systems, will be calculated separately for no-load and load measurement (according to IEC 60076-2:2011 clause 7.6).

4.9.1. Calculation for hot resistance R_{W2}

Therefore, the hot resistance R_{W2} is needed. The calculation is done by a linear extrapolation (see picture below).



picture 15: cooling curve example

4.9.2. Calculation $\Delta\theta e$ (for no-load)

$$\Delta\theta_e = \frac{R_{W2}}{R_{W1}} * (\theta_k + \theta_{a1}) - (\theta_k + \theta_{a2})$$

formula 2: calculation Δθe

R_{W1}	cold resistance, in [Ohm]		
R_{W2}	hot resistance from no-load measurement, in [Ohm]		
θa_1	ambient temperature at the measurement of the cold resistance, in [°C]		
θa_2	ambient temperature at the measurement of the hot resistance, in [°C]		
θ_k	material constant	copper ≙235	aluminum ≙225
$\Delta\theta_e$	average winding temperature in no-load condition, in [K]		

4.9.3. Calculation $\Delta\theta c$ (for load)

$$\Delta\theta_c = \frac{R_{W2}}{R_{W1}} * (\theta_k + \theta_{a1}) - (\theta_k + \theta_{a2})$$

formula 3: calculation Δθc

R_{W1}	cold resistance, in [Ohm]
R_{W2}	hot resistance from load measurement, in [Ohm]
θa_1	ambient temperature at the measurement of the cold resistance, in [°C]
θa_2	ambient temperature at the measurement of the hot resistance, in [°C]
θ_k	material constant copper ≙235 aluminum ≙225
$\Delta\theta_c$	average winding temperature in load condition, in [K]

4.9.4. Calculation $\Delta\theta c$ corrected for test current (for load)

If the testing current used does not meet the correct testing current or a harmonic content should be considered (see 4.6 Load measurement) then a correction is allowed according to this formula.

Note: Only in a range for current between ± 10 % (according to IEC to 60076-11:2018, clause 14.3.2.3).

$$\Delta\theta_{c,cor} = \Delta\theta_c * \left(\frac{I_r}{I_t}\right)^q$$

formula 4: calculation Δθc (corrected)

$\Delta\theta_{c,cor}$	temperature rise of the winding at the rated load condition
$\Delta\theta_c$	temperature rise of the winding at the test current
I_r	rated value of current
I_t	input test current
q	factor for cooling = 1.6 for AN 1.8 for AF, AFAF or AFWF

4.9.5. Calculation $\Delta\theta c'$ (total)

Finally, the total winding temperature rise shall be calculated (according to IEC to 60076-11:2018, clause 14.3.2.2.2)

$$\Delta\theta_{c'} = \Delta\theta_{c,cor} \left[1 + \left(\frac{\Delta\theta_e}{\Delta\theta_c}\right)^{1/K1}\right]^{K1}$$

formula 5: calculation Δθc´ (total)

$\Delta\theta_e$	average winding temperature in no-load condition, in [K]		
$\Delta\theta_{c,cor}$	average winding temperature in load condition, in [K]		
or if applicable	$\Delta\theta wc$ corrected for test current (for load)		
or	$\Delta\theta wc$ corrected for harmonics (for load)		
$\Delta\theta_{c'}$	total average winding temperature, in [K]		
K1	factor for cooling =	0.8 for AN	0.9 for AF, AFAF or AFWF

4.9.6. Calculation of the max. temperature on the winding surface

The maximum temperature to be expected on the winding surface is given as additional information. However, the Temperature rise test only serves to determine the winding temperature rise and therefore there is no guarantee for the maximum temperature on the winding surface!

$$\theta w_{MAX} = \Delta\theta_{c'} + \left(\theta_{W,load} - \theta_{a,load} - \Delta\theta_c\right) + \theta a_{MAX}$$

Θw, max	maximum temperature to be expected on the winding surface, in [°C]
$\Delta\theta_{c'}$	total average winding temperature, in [K]
Θw, load	winding temperature measured via temperature sensor (see 4.3.2 Temperature sensors for the measurement), in [°C]
Θa, load	temp. of cooling medium in load condition, in [°C]
$\Delta\theta_c$	average winding temperature in load condition uncorrected, in [K]
Θa, max	Max. temp. of cooling medium, in [°C]

4.10. Temperature rise test on transformers with winding in multi-tier design

The individual LV systems will be measured for hot resistance separately. For calculation of 4.9.5 Calculation $\Delta\theta c'$ (total) the average temperature rise value will be used.

4.11. Procedure at temperature rise test with water cooling (AFWF)

A linear operating curve is assumed for all conversions of the water temperature.

The procedure below is applied to fulfil IEC 60076-11:2018 chapter 10.1 and 14.3.2.1 in a practical method.

For direct water-cooled systems only:

- The maximum available water fluid rate is 4.5-5 m³/h.
- The water inlet temperature depends on the season and varies between 5-25 °C.

For the cold resistance, the actual *cooling fluid inlet* temperature (water temperature) will be used as reference temperature instead of the ambient air temperature (see 4.3.2 Temperature sensors for the measurement).

The procedure at SGB for this is to measure, the cold resistance at ambient air temperature, with the transformer being placed in this ambient for at least 12h and converted to the temperature of the water inlet temperature by recalculation with the method described in 4.9.2 or 4.9.3, which can be applied equally for recalculation of two cold resistance with different ambient reference temperatures.

Note: It was ensured by measurements (see 5.2 Comparison of different methods for cold resistance measurement at temperature rise test with water cooling (AFWF)) that, there is no difference to the measurement of the cold resistance with running cooling system up to stability with cooling fluid inlet as reference, in comparison to:

- Measuring the cold resistance at winding in steady state without cooling system and converted the resistance to the water inlet temperature.
- Using the ambient air temperature as reference for the cold resistance measurement at winding in steady state without cooling system.

For the hot resistance calculation, the actual *cooling fluid inlet* temperature will be used instead the ambient air temperature in the described formulars in chapter 4.5.4 & 4.6.4 & 4.8 & 4.9.2 & 4.9.3.

<u>Any changes to the above procedure must be specified during the tender stage and require a separate confirmation!</u>

4.12. Test criteria

The test is successful if the following is achieved:

- The measured / calculated average winding temperature rise $\Delta\theta c'$

does not exceed the specified value for the insulation system according to IEC 60076-11:2018 (clause 10.1, table 2). e.g., class F = 100 K

or lower value by agreement between supplier and purchaser.

If transformer installation altitude is higher than 1000 m the average winding temperature rise $\Delta\theta c'$ shall be corrected according to IEC 60076-11:2018 (clause 10.3).
Per 100m above 1000m <u>0.5 %</u> for AN <u>1 %</u> for AF, AFAF or AFWF
Any altitude correction shall be rounded to the nearest whole number of K.

5. Appendix

5.1. Example test certificate

Lightning impulse test

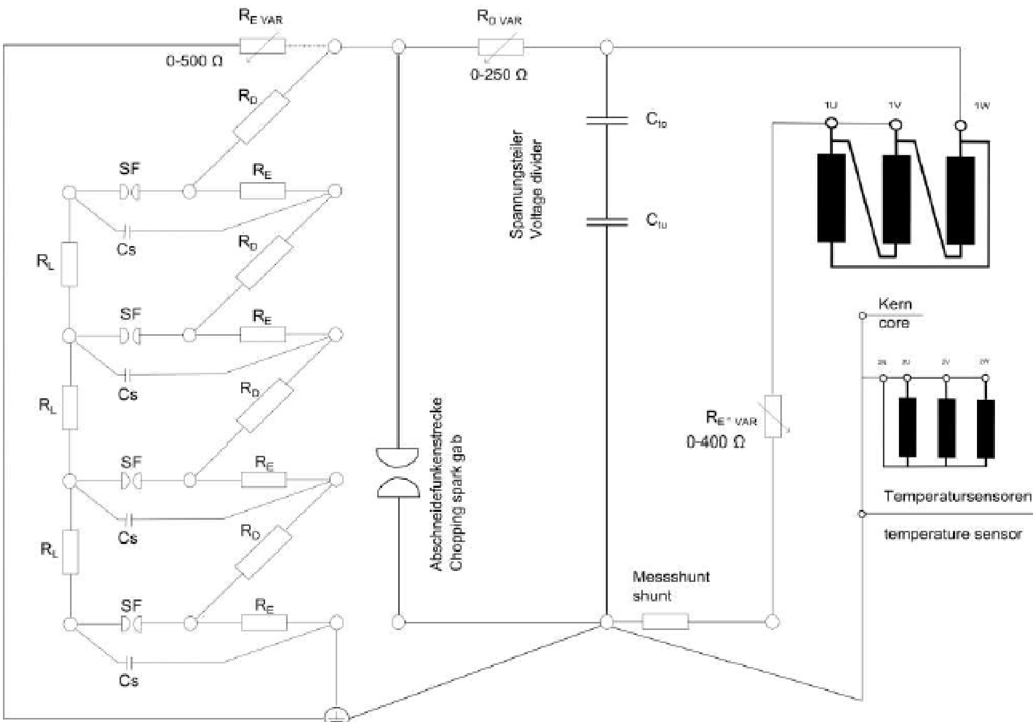
(according to Standard: IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

	HV	LV		
			Temperature [°C]:	22,8
LI [kV]:	170,0	0,0	Humidity [%]:	33,9
			Air-pressure [hPa]:	970,2

Measurement carried out in Protection IP00

Schaltung des Stoßkreises
Impulse test circuit



Example pictures and schematics refer to a standard transformer. Deviations from the actual product may be possible.

Remarks:

more information?
see general test description

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Lightning impulse test

(according to Standard: IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

	Up [kV]	T1 [µs]	T2/Tc [µs]	Ip [A]
2V tap3 54% LI RW	-94,057	1,055	55,176	-284,44
2V tap3 100% LI FW	-170,007	1,068	55,368	-509,61
2V tap3 100% LI FW	-169,788	1,070	55,390	-507,68
2V tap3 100% LI FW	-170,121	1,070	55,410	-509,48
2U tap3 54% LI RW	-91,757	1,019	55,452	-273,03
2U tap3 100% LI FW	-170,323	1,034	55,616	-502,52
2U tap3 100% LI FW	-169,727	1,036	55,611	-501,62
2U tap3 100% LI FW	-170,023	1,036	55,605	-502,52
2W tap3 54% LI RW	-91,292	1,186	54,871	-293,58
2W tap3 100% LI FW	-170,303	1,210	55,064	-543,38
2W tap3 100% LI FW	-169,702	1,209	55,090	-541,06
2W tap3 100% LI FW	-169,958	1,205	55,129	-541,84

RW= reduced full wave
CRW= chopped reduced wave
FW= full wave
CFW= chopped wave

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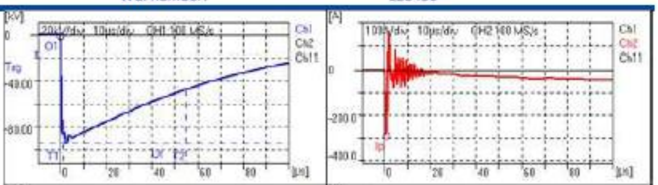
Lightning impulse test

(according to Standard: IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

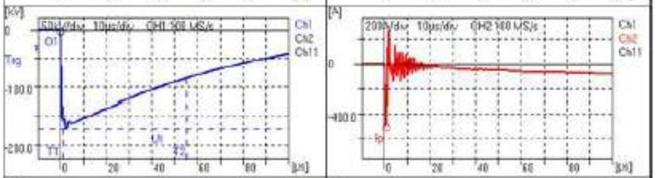
2V tap3 54% LI RW

Up [kV]: -94,057
T1 [µs]: 1,055
T2/Tc [µs]: 55,176
Ip [A]: -284,44



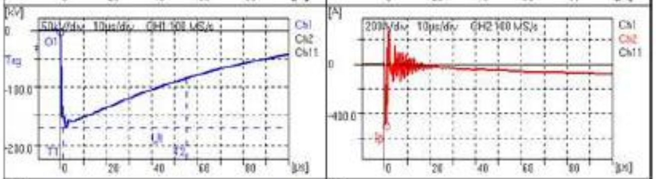
2V tap3 100% LI FW

Up [kV]: -170,007
T1 [µs]: 1,068
T2/Tc [µs]: 55,368
Ip [A]: -509,61



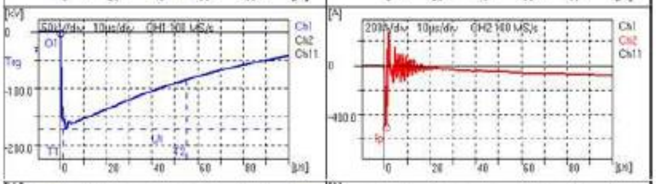
2V tap3 100% LI FW

Up [kV]: -169,788
T1 [µs]: 1,07
T2/Tc [µs]: 55,39
Ip [A]: -507,68



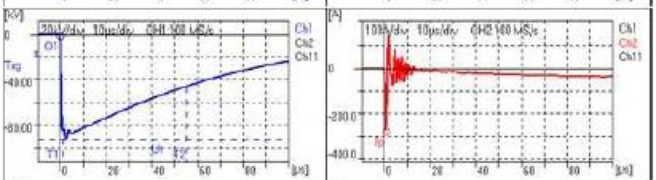
2V tap3 100% LI FW

Up [kV]: -170,121
T1 [µs]: 1,07
T2/Tc [µs]: 55,41
Ip [A]: -509,48



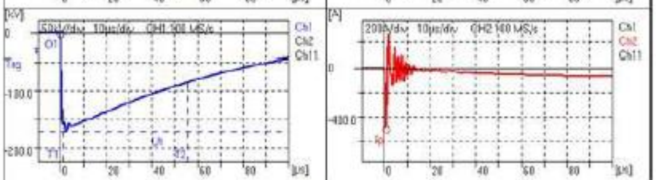
2U tap3 54% LI RW

Up [kV]: -91,757
T1 [µs]: 1,019
T2/Tc [µs]: 55,452
Ip [A]: -273,03



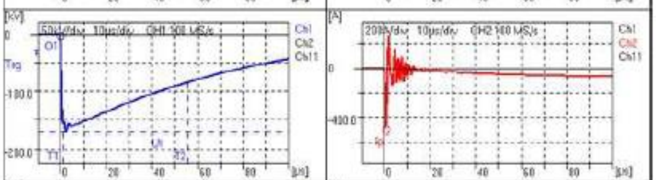
2U tap3 100% LI FW

Up [kV]: -170,323
T1 [µs]: 1,034
T2/Tc [µs]: 55,616
Ip [A]: -502,52



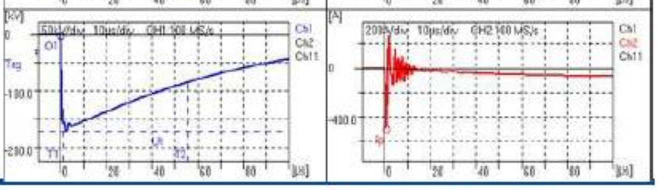
2U tap3 100% LI FW

Up [kV]: -169,727
T1 [µs]: 1,036
T2/Tc [µs]: 55,611
Ip [A]: -501,62



2U tap3 100% LI FW

Up [kV]: -170,023
T1 [µs]: 1,036
T2/Tc [µs]: 55,605
Ip [A]: -502,52



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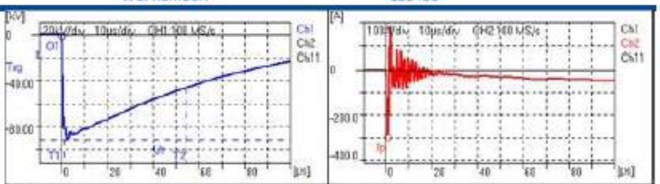
Lightning impulse test

(according to Standard: IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

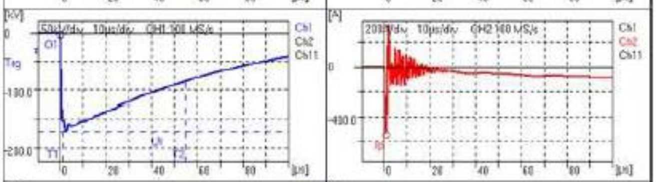
2W tap3 54% LI RW

Up [kV]:	-91,292
T1 [µs]:	1,186
T2/Tc [µs]:	54,871
Ip [A]:	-293,58



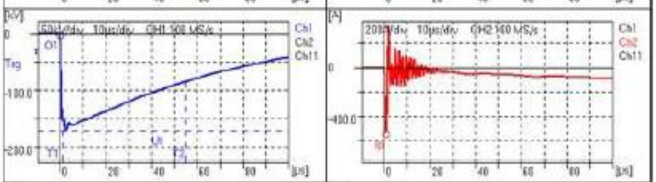
2W tap3 100% LI FW

Up [kV]:	-170,303
T1 [µs]:	1,21
T2/Tc [µs]:	55,064
Ip [A]:	-543,38



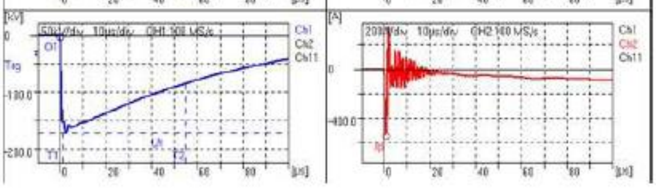
2W tap3 100% LI FW

Up [kV]:	-169,702
T1 [µs]:	1,209
T2/Tc [µs]:	55,09
Ip [A]:	-541,06



2W tap3 100% LI FW

Up [kV]:	-169,958
T1 [µs]:	1,205
T2/Tc [µs]:	55,129
Ip [A]:	-541,84



Temperature rise test

(according to IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

Testing power [kVA]: 3900 // 3900 — at 100% Rated power
Testing voltage [V]: 30000 // 690 — Measurement in tap 3
Testing current [A]: 75 // 3263 — at Protection IP00 & Cooling AF

Results of heat run test at Loading method excitation loss:

winding temperature rise ΔΘe HV [K]:	1,2
winding temperature rise ΔΘe LV [K]:	4,0

Results of heat run test at Loading method load loss:

winding temperature rise ΔΘc HV [K]:	70,8	*100,2%*
winding temperature rise ΔΘc LV [K]:	54,8	*100,2%*

Test results were subjected to a calculation that reflects the harmonic losses

Results of heat run test at Loading method load loss and excitation loss:

winding temperature rise ΔΘc´ HV [K]:

70,8*[1+(1,2/70,8)^1,11]^0,9 = 71,5 K

winding temperature rise ΔΘc´ LV [K]:

54,8*[1+(4/54,8)^1,11]^0,9 = 57,4 K

Temperature at Max. temp. of cooling medium 55°C:

Θw HV [°C]: 126,5   Θw LV [°C]: 112,4

Remarks:

more information?
see general test description

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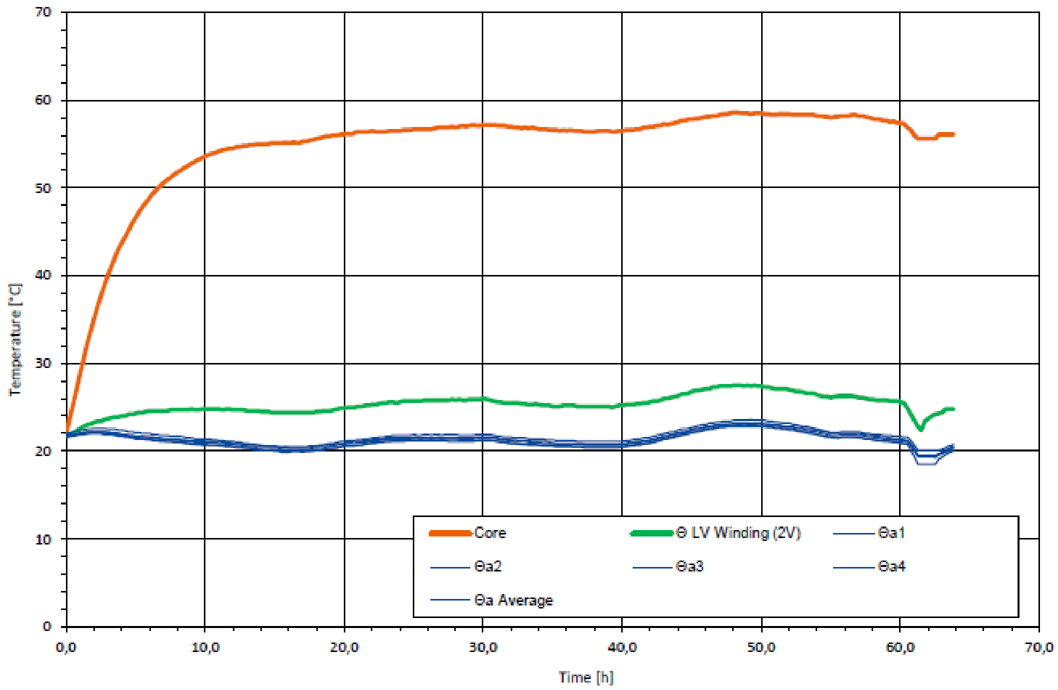
Temperature rise test

(according to IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

Loading method= excitation loss at connection: LV 690 V

Voltage [V]:	Currents [A]:	Losses [W]:	Temperature [°C]:			
U_{12} 690,6	I_1 5,600	P_1 1489	Core	22,1	Θa1	22,0
U_{23} 692,0	I_2 4,000	P_2 1159			Θa2	21,8
U_{31} 689,9	I_3 5,600	P_3 1895	Θ LV Winding (2V)	21,8	Θa3	21,6
$\bar{U}$ 690,8	$\bar{I}$ 5,100	∑ 4543			Θa4	21,6
Measured values after	*0,00 h*				Θa Average	21,8
U_{12} 685,8	I_1 5,400	P_1 1416	Core	56,1	Θa1	20,8
U_{23} 687,3	I_2 3,800	P_2 1122			Θa2	20,5
U_{31} 685,0	I_3 5,400	P_3 1822	Θ LV Winding (2V)	24,8	Θa3	20,1
$\bar{U}$ 686,0	$\bar{I}$ 4,900	∑ 4359			Θa4	20,2
Measured values after	*63,84 h*				Θa Average	20,4



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Temperature rise test

(according to IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

Loading method= excitation loss at connection: LV 690 V

Calculation of winding temperature:

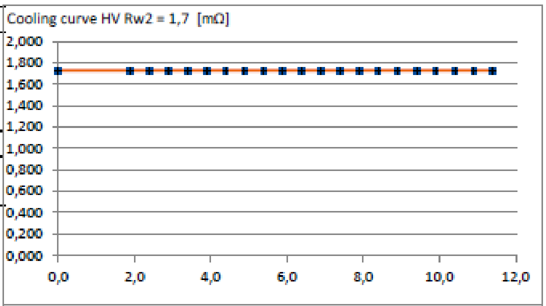
$$\Delta\Theta e = \frac{Rw2}{Rw1} * (\Theta k+\Theta a1) - (\Theta k+\Theta a2)$$

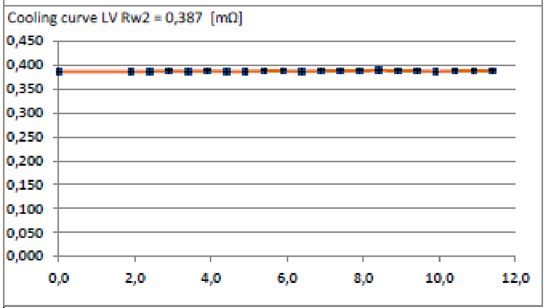
1 = Switch on
2 = Shutdown

ΔΘe = winding temperature rise Θa = temperature of cooling medium

Θk = Material constant: Cu = 235, Al = 225

Time [min]	HV R [mΩ]	LV R [mΩ]		Θa [°C]
R_{w1}	1,727	0,383		21,5
0,0	**1,728**	**0,387**		**20,4**
1,9	1,728	0,387		
2,4	1,728	0,387		
2,9	1,728	0,388		
3,4	1,728	0,387		
3,9	1,728	0,388		
4,4	1,728	0,387		
4,9	1,728	0,387		
5,4	1,728	0,388		
5,9	1,728	0,388		
6,4	1,728	0,387		
6,9	1,728	0,388		
7,4	1,728	0,388		
7,9	1,728	0,388		
8,4	1,728	0,389		
8,9	1,728	0,388		
9,4	1,728	0,388		
9,9	1,728	0,387		
10,4	1,728	0,388		
10,9	1,728	0,388		
11,4	1,728	0,388		





winding temperature rise HV [K]:

ΔΘe HV = 1,2

winding temperature rise LV [K]:

ΔΘe LV = 4,0

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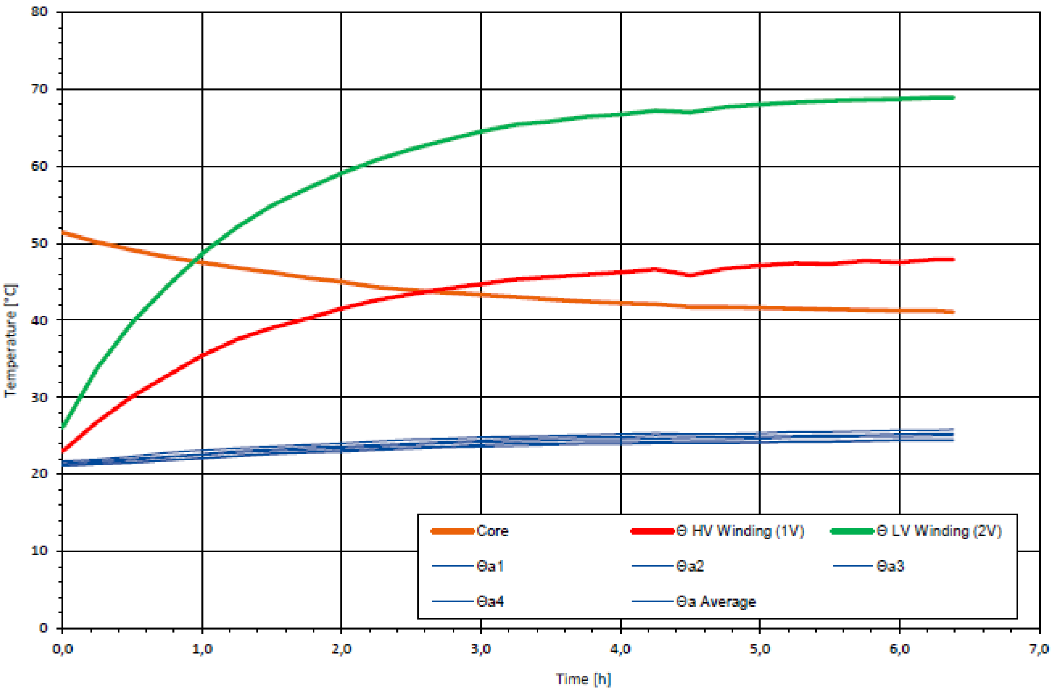
Temperature rise test

(according to IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

Loading method= load loss and short-circuit: LV 3900 kVA

Voltage [V]:	Currents [A]:	Losses [W]:	Temperature [°C]:			
U_{12} 3421,6	I_1 75,900	P_1 9831	Core	51,4	Θa1	21,7
U_{23} 3422,9	I_2 76,100	P_2 8562	Θ HV Winding (1V)	23,0	Θa2	21,4
U_{31} 3430,4	I_3 75,600	P_3 8544	Θ LV Winding (2V)	26,1	Θa3	21,1
$\bar{U}$ 3425,0	$\bar{I}$ 75,900	∑ 26937			Θa4	21,1
Measured values after	*0,00 h*				Θa Average	21,3
U_{12} 3431,1	I_1 75,900	P_1 11732	Core	41,1	Θa1	25,8
U_{23} 3436,2	I_2 76,100	P_2 10438	Θ HV Winding (1V)	47,9	Θa2	25,3
U_{31} 3445,0	I_3 75,700	P_3 10497	Θ LV Winding (2V)	68,9	Θa3	24,5
$\bar{U}$ 3437,4	$\bar{I}$ 75,900	∑ 32666			Θa4	24,4
Measured values after	*6,39 h*				Θa Average	25,0



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Temperature rise test

(according to IEC 60076-11:2018)

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

Loading method= load loss and short-circuit: LV 3900 kVA

Calculation of winding temperature:

$$\Delta\Theta c = \frac{Rw2}{Rw1} * (\Theta k+\Theta a1) - (\Theta k+\Theta a2)$$

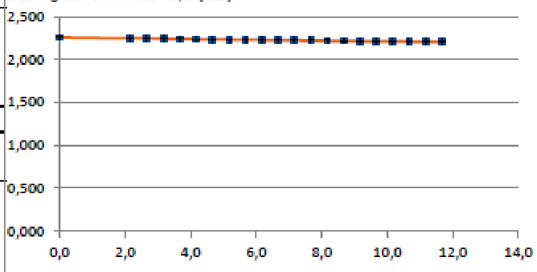
1 = Switch on
2 = Shutdown

ΔΘc = winding temperature rise Θa = temperature of cooling medium

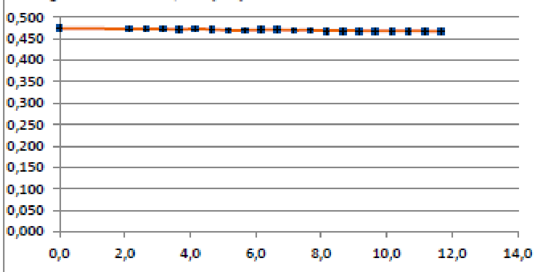
Θk = Material constant: Cu = 235, Al = 225

Time [min]	HV R [mΩ]	LV R [mΩ]		Θa [°C]
R_{w1}	1,727	0,383		21,5
0,0	**2,257**	**0,475**		**25,0**
2,2	2,248	0,473		
2,7	2,246	0,473		
3,2	2,243	0,473		
3,7	2,241	0,472		
4,2	2,238	0,473		
4,7	2,236	0,472		
5,2	2,233	0,470		
5,7	2,231	0,470		
6,2	2,229	0,471		
6,7	2,226	0,471		
7,2	2,224	0,470		
7,7	2,222	0,470		
8,2	2,220	0,469		
8,7	2,218	0,469		
9,2	2,215	0,469		
9,7	2,213	0,468		
10,2	2,211	0,468		
10,7	2,209	0,468		
11,2	2,207	0,468		
11,7	2,205	0,467		

Cooling curve HV Rw2 = 2,3 [mΩ]



Cooling curve LV Rw2 = 0,475 [mΩ]



winding temperature rise HV [K]:

ΔΘc HV = 72,1

winding temperature rise LV [K]:

ΔΘc LV = 55,8

Appendix

SGB order number:	123456789/10	Serial-number:	123456
Type:	DTTH1NG 3150/30	Wd. number:	123456

Test results / 3.1 Acceptance test certificate according to DIN EN 10204:2004

Routine testing	Guarantee values:	tolerance:	Measured values:	deviation:	Test passed
Dielectric tests					
Induced AC withstand voltage test LV:	1,38 [kV]; 200 [Hz]; 30 [sec.]				✔
Measurement of voltage ratio and check of phase displacement					
Ratio at connection HV / LV [%]:	30000/690	± 0,50	-0,03		✔
Measurement of winding resistance at 22,0 °C					
Measurement of winding resistance HV LV	--	--	--	--	✔
Measurement of no-load loss and current at 50 Hz					
Po [W]:	4750	+0,0%	4507	-5,12%	✔
Io [%]:			0,155		✔
Measurement of short-circuit impedance and load loss at 120 °C					
Pl at 3900 kVA; HV/LV [W]:	34031	+0,0%	32543	-4,37%	✔
ez at 3900 kVA; HV/LV [%]:	10,55	±18,0%	11,30	7,10%	✔
Po + Pl [W]:	38781	+0,0%	37050	-4,46%	✔
PEI (at k[PEI] 0,37 = 1451 kVA) [%]:	99,348	--	99,379	0,03%	✔
Measurement of partial discharge					
PD max. HV at 1,3 x Rated voltage [pC]: (Background level 1 [pC])	≤10	--	1		✔
Measurement of A-weighted sound level by sound pressure method at no load					
Lp / 1m [dB(A)] AN:			55,1		✔
Lp / 1m [dB(A)] AF:			64,1		✔
Lw [dB(A)] AN:	94	0	71,0	-24,51%	✔
Lw [dB(A)] AF:			79,9		✔
Lightning impulse test					
Up [kV]	170	±3%	170,323	0,19%	✔
T1 [µs]	1,2	±30%	1,019	-15,08%	✔
T2 [µs]	50	±20%	55,616	11,2%	✔
Temperature rise test					
winding temperature rise Δθc' HV [K]:	85	--	71,5		✔
winding temperature rise Δθc' LV [K]:	85	--	57,4		✔

Approved by / Regensburg,

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5.2. Comparison of different methods for cold resistance measurement at temperature rise test with water cooling (AFWF)

Note: Cold resistance measurement was done without running cooling system with windings at ambient air temperature of the test lab. According to the calculation method, described in "02.04.80-11.005 - Test description for dry-type-transformers for type tests" the measured cold resistance is calculated to the cold resistance at water inlet temperature, which is used for the calculation of the winding temperature rise. The measured cold resistance value below is given for information only and not directly used in the evaluation.

Time [min]	HV	LV		Θa [°C]
	R [mΩ]	R [mΩ]		
R_{w1}	435,1	0,916		20,1

Time [min]	HV	LV		Θa [°C]
	R [mΩ]	R [mΩ]		
R_{w1}	422,2	0,889		12,8
0,0	**601,0**	**1,218**		**12,2**

picture 16 example for recalculation in test report

Results of heat run test at Loading method load loss and excitation loss:

winding temperature rise Δθc' HV [K]:

101,3*[1+(4,3/101,3)^1,11]^0,9 = 104,1 K

winding temperature rise Δθc' LV [K]:

88,6*[1+(9,7/88,6)^1,11]^0,9 = 95,4 K

Temperature at Max. temp. of cooling medium 38°C:

θw HV [°C]: 154,6 θw LV [°C]: 141,7

picture 17 calculation for AFWF temperature rise test method 1

Transformer condition: in steady state with cooling in operation

Reference for cold resistance: Water inlet

Reference for hot resistance: Water inlet

Results of heat run test at Loading method load loss and excitation loss:

winding temperature rise Δθc' HV [K]:

101,9*[1+(4,7/101,9)^1,11]^0,9 = 104,9 K

winding temperature rise Δθc' LV [K]:

89,3*[1+(10,3/89,3)^1,11]^0,9 = 96,5 K

Temperature at Max. temp. of cooling medium 38°C:

θw HV [°C]: 154,9 θw LV [°C]: 142,1

picture 18 calculation for AFWF temperature rise test method 2

Transformer condition: in steady state without cooling in operation (windings at ambient temperature)

Reference for cold resistance: Ambient air temperature

Reference for hot resistance: Water inlet

Results of heat run test at Loading method load loss and excitation loss:

winding temperature rise Δθc' HV [K]:

101,9*[1+(4,7/101,9)^1,11]^0,9 = 104,9 K

winding temperature rise Δθc' LV [K]:

89,3*[1+(10,3/89,3)^1,11]^0,9 = 96,5 K

Temperature at Max. temp. of cooling medium 38°C:

θw HV [°C]: 154,9 θw LV [°C]: 142,1

picture 19 calculation for AFWF temperature rise test method 3

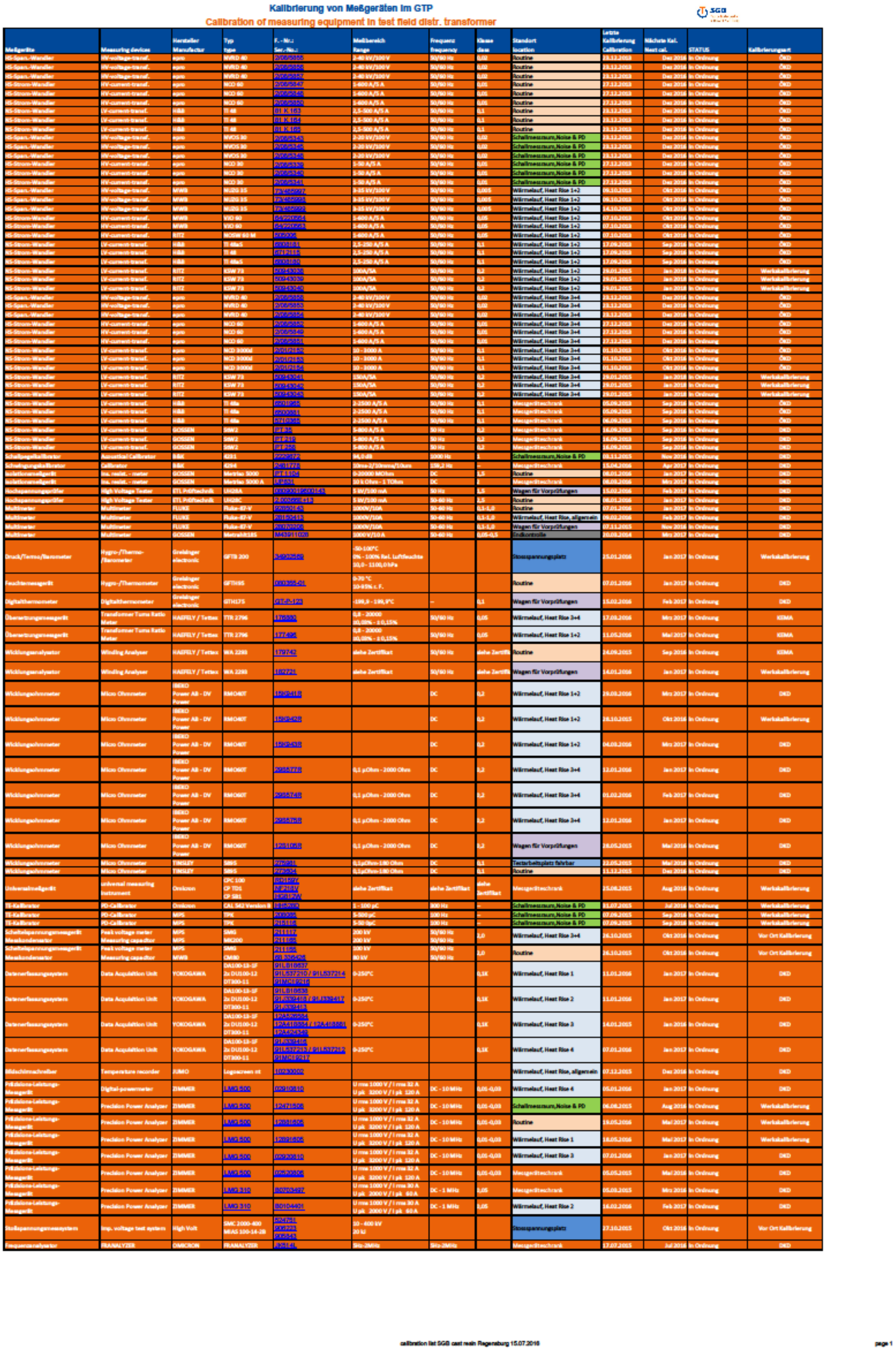
Transformer condition: in steady state without cooling in operation (windings at ambient temperature)

Cold resistance measured at ambient air temperature and calculated to water inlet temperature.

Reference for cold resistance: Water inlet

Reference for hot resistance: Water inlet

5.3. Example calibration list



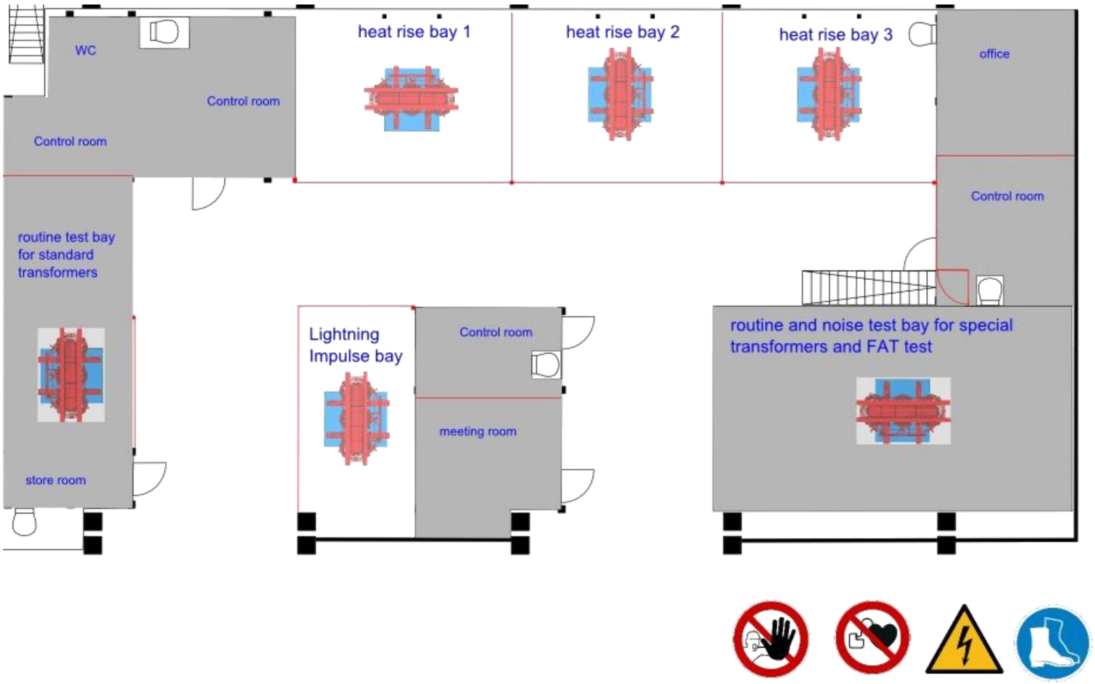
Kalibrierung von Meßgeräten im GTP

Calibration of measuring equipment in test field distr. transformer

Meßgeräte	Measuring devices	Hersteller Manufactur	Typ type	F.-Nr.: Ser.-No.:	Meßbereich Range	Frequenz frequency	Klasse class	Standort location	Letzte Kalibrierung Calibration	Nächste Kal. Next cal.	STATUS	Kalibrierungsart

calibration list SGB cast resin Regensburg 15.07.2016 page 1

5.4. Test lab layout



picture 20: test lab layout

picture 21: routine and heat rise bays

picture 22: PD and sound chamber

5.5. List of pictures, formulas, tables and sources

LIST OF PICTURES:

LIST OF FORMULAS:

LIST OF Tables:

list of sources:

- D.J. Kraaij - Die Prüfung von Leistungstransformatoren
- Wikipedia
- IEC