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Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors

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Foreword

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Introduction

Although the efficiency of a power transformer is very high, the losses (no load and load losses) are object of guaranty and penalty in the majority of the contracts. As a matter of fact, considering the long power transformer life (20 years and more) the cost of the losses play an important role in the evaluation of the total (service) costs and therefore in the investments involved.

A further reason that justifies the attention paid to the losses is that from the generation to the final user, the energy is passing through a number of transformers: step up transformers of generation power stations, interconnecting units for transmission systems, distribution transformers for primary systems (from 100 kV to 400 kV), medium voltage to low voltage transformers in small distribution substations (from 10 kV to 20 kV feeders).

The sum of the losses accrued in the transformer chains may be significant and therefore of importance in nationwide efforts to save energy. A large number of European Countries have instituted measures to conserve energy where losses in electric transmission are an important part.

In power transformers the direct measurement of the efficiency is not recommended because of the uncertainty of this method.

The indirect method based on the measurement of the losses is largely preferred even if the conditions in which such losses are measured differ a little from those that occur in operation.

EN ISO/IEC 17025 requires that the result of any measurement shall be qualified with the evaluation of its uncertainty. A further requirement is that known corrections shall have been applied before evaluation of uncertainty.

This document deals with the measurement of the losses that from a measuring point of view consist of the estimate of a measurand and the evaluation of the uncertainty that affects the estimate itself.

It is well known that when a test result is expressed as numerical quantity it is not an exact number but suffers from uncertainty.

The uncertainty range depends on the quality of the test installation and measuring system, on the skill of the staff and on the intrinsic measurement difficulties presented by the test objects.

The submitted test results is to be considered the most correct estimate and therefore this value has to be accepted as it stands.

The uncertainty shall not be involved in the judgment of compliance for guarantees, tolerances and penalties thresholds.

Guaranty and penalty calculations should refer to the estimated values without consideration of the measurement uncertainties.

1 Scope

This Technical Report illustrates the procedures and criteria to be applied to evaluate the uncertainty affecting the measurements of no load and load losses during the routine tests on power transformers.

Even if the attention is especially paid to the transformers, the document can be also used for the measurements of reactor losses, when applicable.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 60076 series, Power transformers (IEC 60076 series)

EN 60076-1:1996, Power transformers – Part 1: General (IEC 60076-1:1993, mod.)

3 Definitions

For the purposes of this document, the terms and definitions given in EN 60076 apply.

4 Symbols

4.1 General symbols

c	sensitivity factor for contribution to uncertainty, see C.3.4;
F_D	parameter related to correction of power for effect of phase displacement in measuring circuit;
I_M	current measured by the ammeter (normally corresponding to rated current);
I_N	reference current (normally rated current);
k_{CN}	rated transformation ratio of the current transformer;
k_{VN}	rated transformation ratio of the voltage transformer;
P	power;
P_2	power measured at load loss test, but referred to the reference current I_N;
P_{LL}	load loss at reference conditions and corrected for known systematic deviations in the measurement;
P_{NLL}	no-load loss at reference conditions and corrected for known errors in the measurement;
P_W	power measured by the power meter;
R_1	winding resistance measured at cold winding resistance test according to EN 60076-1, 10.1;
R_2	winding resistance estimated for the load loss test;
R_r	winding resistance at reference temperature according to EN 60076-1, 10.1;
t	parameter related to the thermal coefficient of winding resistance;

U_{avg}	voltage measured with an instrument having average rectified mean response;
U_M	voltage measured;
U_N	rated voltage;
U_{rms}	voltage measured using an instrument with true r.m.s. response;
θ	temperature;
θ_1	temperature of transformer winding at cold winding resistance test according to EN 60076-1, 10.2;
θ_2	temperature of transformer winding during load loss test;
θ_r	reference temperature for transformer winding according to EN 60076-1, 10.1;
ε_C	actual phase displacement of the current transformer (rad);
ε_P	actual phase displacement of the power meter (rad);
ε_V	actual phase displacement of the voltage transformer (rad);
$\alpha_{\varepsilon V}$	accuracy of the phase displacement declared in the calibration certificate for the voltage transformer;
$\alpha_{\varepsilon C}$	accuracy of the phase displacement declared in the calibration certificate for the current transformer;
η_C	actual current error of the current transformer (%);
η_V	actual voltage error of the voltage transformer (%);
φ	actual phase angle between voltage and current;
φ_M	phase angle between voltage and current measured with power meter.

4.2 Symbols for uncertainty

u, U	uncertainty – lower case denotes standard uncertainty and upper case denotes expanded uncertainty, the tilde ~ is used to denote absolute uncertainty;
u_C	uncertainty of current transformer ratio;
u_{cal}	uncertainty of calibration;
u_{class}	uncertainty defined by instrument transformer class limit for ratio error or phase displacement;
$u_{F(IM)}$	uncertainty contribution to u_{pd} related to uncertainty in current measurement;
$u_{F(PW)}$	uncertainty contribution to u_{pd} related to uncertainty in power measurement;
$u_{F(UM)}$	uncertainty contribution to u_{pd} related to uncertainty in voltage measurement;
$u_{F(\varepsilon)}$	uncertainty contribution to u_{pd} related to uncertainty in phase displacement of instrument transformers;
u_{IM}	uncertainty of current measurement;
$u_{interpol}$	uncertainty of an interpolation procedure;
u_{LL}	uncertainty of the load loss power;

u_{NLL}	uncertainty of the no-load loss power;
u_{P2}	uncertainty of P_2;
u_{pd}	uncertainty of term F_D;
u_{PW}	uncertainty of P_W;
u_{R1}	uncertainty of resistance R_1;
u_{th}	uncertainty of thermal sensors;
u_U	uncertainty of setting of rated voltage at no-load loss test;
u_{UM}	uncertainty of voltage measurement;
u_V	uncertainty of voltage transformer ratio;
u_{wf}	uncertainty of correction to sinusoidal waveform for no-load-loss;
u_{ε}	uncertainty of phase displacement for complete measuring system;
$u_{\varepsilon C}$	uncertainty of current transformer phase displacement;
$u_{\varepsilon V}$	uncertainty of voltage transformer phase displacement.

5 Power measurement, systematic deviation and uncertainty

In the following, it is assumed that the transformer losses be measured in the conditions prescribed by EN 60076-1 and further that only digital instruments are connected in the measuring circuit.

For three-phase transformers, losses are intended to be measured using three independent single-phase measuring systems.

In general losses are measured using current transformers and voltage transformers in conjunction with a power meter (power analyser). Each is associated with a small systematic deviation and a corresponding uncertainty that has to be evaluated. Systems using electronically aided or electronic based current and voltage transducers can in this analysis be treated the same way as systems with conventional instrument transformers.

The measuring system usually has a known systematic deviation (error). This systematic deviation could be corrected for, or not, and the two cases ask for different approach in the uncertainty analysis.

The measuring system used has an unknown difference between the true value of the input quantity and the value shown on the instrument. This is the uncertainty of the measurement.

6 Procedures for no-load loss

6.1 General

The result of the no-load loss measurement shall be valid at rated voltage. The uncertainty of the loss with respect to the possible difference between measuring voltage and rated voltage is required.

Systematic deviations related to measuring equipment can be characterised by calibration. The current drawn by the test object is distorted, and this may cause a distortion in the voltage that leads to erroneous values for the losses. A correction for the transformer losses is prescribed in EN 60076-1, as well as a limit for the permissible distortion.

6.2 Model function for no-load losses at reference conditions

The no-load loss will exhibit a non-linear relation to applied voltage. The non-linear relation can be established for each object by measurements repeated at different voltages, but usually a power law approximation is sufficient. The model function used for no-load loss uncertainty estimation is given by the following approximation:

$$P_{NLL}=k_{CN}\cdot\frac{1}{1+\frac{\eta_C}{100}}\cdot k_{VN}\cdot\frac{1}{1+\frac{\eta_V}{100}}\cdot\frac{P_W}{1-(\varepsilon_V-\varepsilon_C)\cdot \tan\varphi}\left[\frac{U_N}{k_{VN}\cdot\frac{1}{1+\frac{\eta_V}{100}}\cdot U_M}\right]^n\left(1+\frac{U_{avg}-U_{rms}}{U_{avg}}\right) \qquad \text{Eq. 1}$$

where

- $k_{CN}\cdot\frac{1}{1+\frac{\eta_C}{100}}$ is a parameter related to the ratio error of the current transformer;
- $k_{VN}\cdot\frac{1}{1+\frac{\eta_V}{100}}$ is a parameter related to the ratio error of the voltage transformer;
- $\frac{1}{1-(\varepsilon_V-\varepsilon_C)\cdot \tan\varphi}$ is a parameter related to the correction for phase displacement;
- $\left[\frac{U_N}{k_{VN}\cdot\frac{1}{1+\frac{\eta_V}{100}}\cdot U_M}\right]^n$ is a parameter related to the actual measuring voltage where the exponent is related to the non-linear behaviour of no-load loss;
- $\left(1+\frac{U_{avg}-U_{rms}}{U_{avg}}\right)$ is defined in EN 60076-1 and is used to compensate for the influence of the distortion on the voltage waveform on the no load loss. Here U_{avg} is the indication of a mean value responding instrument and U_{rms} the indication of an r.m.s. responding instrument.

Eq. 1 can also be expressed as:

$$P_{NLL}=k_{CN}\cdot\frac{1}{1+\frac{\eta_C}{100}}\cdot k_{VN}\cdot\left(1+\frac{\eta_V}{100}\right)^{n-1}\cdot P_W\cdot\frac{1}{1-(\varepsilon_V-\varepsilon_C)\cdot \tan\varphi}\cdot\left[\frac{U_N}{k_{VN}\cdot U_M}\right]^n\cdot\left(1+\frac{U_{avg}-U_{rms}}{U_{avg}}\right) \qquad \text{Eq. 2}$$

The known systematic deviations of the power meter have been assumed to be negligible. The phase angle φ of the loss power is obtained from

$$\varphi=\varphi_M-\varepsilon_V+\varepsilon_C=\arccos\left(\frac{P_W}{I_M\cdot U_M}\right)-\varepsilon_V+\varepsilon_C \qquad \text{Eq. 3}$$

It has been assumed that the power meter establishes the power factor from measurement of power and apparent power at the fundamental frequency of the test voltage.

When the power factor at no-load loss is larger than 0,3, the term relating to phase displacement can be neglected and we have

$$P_{NLL} = k_{CN} \cdot \frac{1}{1+\frac{\eta_C}{100}} \cdot k_{VN} \cdot \left(1+\frac{\eta_V}{100}\right)^{n-1} \cdot P_W \cdot \left[\frac{U_N}{k_{VN} \cdot U_M}\right]^n \cdot \left(1+\frac{U_{avg}-U_{rms}}{U_{avg}}\right) \qquad \text{Eq. 4}$$

NOTE 1 The formula uses the simplified assumption that no-load loss is proportional to the voltage raised to the power *n,* where *n* usually increases with the flux density. This factor is often approximated by *n* = 2.

NOTE 2 In the written formula, some secondary influencing quantities have been disregarded such as frequency, wave shapes, effect of the voltage transformer leads, etc.

NOTE 3 IEEE C57.123-2002 identifies a small temperature effect on no-load losses and gives - 1 % per 15 °C. This effect is not well known and is not identified within IEC. The effect has been disregarded.

6.3 Uncertainty budget

6.3.1 General

An uncertainty budget should list all possible contributions to uncertainty, and an estimate of their magnitudes should be made.

The sensitivity to different uncertainty contributions can in general be deduced form the model function. Contributions to uncertainty in loss measurements from statistical random processes are in general small compared to other contributions and are not further treated here.

Rated values, such as U_N are considered constants and are not included in uncertainty evaluations.

6.3.2 Standard and expanded uncertainty for no load loss

Table 1 – No-load loss uncertainty, general case

Quantity	Estimate	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Variance	See sub-clause
CT ratio error	η_C	u_C	1	u_C	u_C^2	10.1.2
VT ratio error	η_V	u_V	n-1	(n-1) · u_V	$(n-1)^2 \cdot u_V^2$	10.1.2
Power meter	P_W	u_{PW}	1	u_{PW}	u_{PW}^2	10.3
Phase displacement	$\frac{1}{1-(\varepsilon_V-\varepsilon_C)\cdot \tan\varphi}$	u_{pd} = 0	1	0	0	10.2.3 or 10.2.4
Voltage	U_N	u_U	n	N · u_U	$n^2 \cdot u_U^2$	10.4
Correction to sinusoidal waveform	$1+\frac{U_{avg}-U_{rms}}{U_{avg}}$	u_{wf}	1	u_{wf}	u_{wf}^2	10.6
	Standard uncertainty u_{NLL}			=√(right)	=sum(above)	
	Expanded uncertainty U_{NLL}			=2 · above		

Table 2 – No-load loss uncertainty without correction for phase displacement

Quantity	Estimate	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Variance	See sub-clause
CT ratio error	η_C	u_C	1	u_C	u_C^2	10.1.2
VT ratio error	η_V	u_V	$n-1$	$(n-1) * u_V$	$(n-1)^2 * u_V^2$	10.1.2
Power meter	P_W	u_{PW}	1	u_{PW}	u_{PW}^2	10.3
Phase displacement	1	u_{pd}	1	u_{pd}	u_{pd}^2	10.2.2
Voltmeter	U_N	u_U	n	$n \cdot u_U$	$n^2 * u_U^2$	10.4
Correction to sinusoidal waveform	$1+\frac{U_{avg}-U_{rms}}{U_{avg}}$	u_{wf}	1	u_{wf}	u_{wf}^2	10.6
	Standard uncertainty u_{NLL}			=√(right)	=sum(above)	
	Expanded uncertainty U_{NLL}			=2 · above		

Where the standard uncertainty in both cases is calculated as

$$u_{NLL} = \sqrt{u_C^2 + (n-1)^2 \cdot u_V^2 + u_{PW}^2 + u_{pd}^2 + n^2 \cdot u_u^2 + u_{wf}^2} \qquad \text{Eq. 5}$$

and the expanded relative uncertainty is $U_{NLL} = 2^* u_{NLL}$, which corresponds to a coverage probability of approximately 95 %.

7 Procedures for load loss

7.1 General

In load loss measurements the reported loss shall be valid at the rated current and at the reference temperature. In general the measurement is not performed at the precise current and temperature level intended and the value valid at reference conditions must be deduced.

7.2 Model function for load loss at reference conditions

EN 60076-1 requires that the measured value of load loss be corrected with the square of the ratio of rated current to test current. The power thus obtained is then recalculated from actual to reference temperature.

The model function for the measured power P_2 referred to the rated current I_N

$$P_2 = k_{CN} \cdot \frac{1}{1+\frac{\eta_C}{100}} \cdot k_{VN} \cdot \frac{1}{1+\frac{\eta_V}{100}} \cdot P_W \cdot \frac{1}{1-(\varepsilon_V-\varepsilon_C)\cdot \tan\varphi} \cdot \left[\frac{I_N}{k_{CN} \cdot \frac{1}{1+\frac{\eta_C}{100}} \cdot I_M} \right]^2 \qquad \text{Eq. 6}$$

which is rearranged to

$$P_2 = k_{CN} \cdot \left(1+\frac{\eta_C}{100}\right) \cdot k_{VN} \cdot \frac{1}{1+\frac{\eta_V}{100}} \cdot P_W \cdot \frac{1}{1-(\varepsilon_V-\varepsilon_C)\cdot \tan\varphi} \cdot \left[\frac{I_N}{k_{CN}\cdot I_M}\right]^2 \qquad \text{Eq. 7}$$

where

- $\left[\frac{I_N}{k_{CN}\cdot I_M}\right]^2$ is a parameter related to the actual current measured during the test related to the reference current for which the transformer shall be tested;
- other terms are as defined in 6.2.

The known systematic deviations of the power meter have been assumed to be negligible. The phase angle φ of the loss power is obtained from

$$\varphi = \varphi_M - \varepsilon_V + \varepsilon_C = \arccos\left(\frac{P_W}{I_M \cdot U_M}\right) - \varepsilon_V + \varepsilon_C \qquad \text{Eq. 8}$$

It has been assumed that the power meter establishes the power factor from measurement of power and apparent power at the fundamental frequency of the test voltage.

And finally, as given in Annex E, the load loss power P_{LL} referred to rated current I_N and to reference temperature θ_r

$$P_{LL} = P_2 \cdot \frac{t+\theta_2}{t+\theta_r} + I_N^2 \cdot R_1 \cdot \left(\frac{t+\theta_r}{t+\theta_1} - \frac{t+\theta_2}{t+\theta_1} \cdot \frac{t+\theta_2}{t+\theta_r}\right) \qquad \text{Eq. 9}$$

Here t is a constant set to 235 for copper and to 225 for aluminium windings. The winding resistance R_1 has been determined at “cold winding resistance” at a temperature θ_1. The temperature of the winding θ_2 at the time of the load loss test will in general be determined at the time of test and can be different from θ_1. In the event that the load loss test is made in immediate conjunction with the winding resistance measurement, $\theta_2 = \theta_1$ can be assumed.

Eq. 9 is identical to the procedure given in EN 60076-1, Annex E for temperature corrections.

In most cases it is however possible to assume that the relative uncertainty of ohmic loss is representative of the uncertainty of the temperature correction. This is given in the uncertainty budget below.

NOTE In the written formula, some secondary influencing quantities have been disregarded, such as frequency, wave shapes, effect of the voltage transformer leads, etc.

7.3 Uncertainty budget for measured power P_2 referred to rated current

7.3.1 General

An uncertainty budget should list all possible contributions to uncertainty, and an estimate of their magnitudes should be made.

The sensitivity to different uncertainty contributions can in general be deduced form the model function. Contributions to uncertainty in loss measurements from statistical random processes are in general small compared to other contributions and are not further treated here.

Rated values, such as I_N and θ_r are considered constants and are not included in uncertainty evaluations.

7.3.2 Standard and expanded uncertainty for measurement of measured load loss power P_2 at ambient temperature

Table 3 – Uncertainty in the general case

Quantity	Estimate	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Variance	See sub-clause
CT ratio error	η_C	u_C	1	u_C	u_C^2	10.1.2
VT ratio error	η_V	u_V	1	u_V	u_V^2	10.1.2
Power meter	P_W	u_{PW}	1	u_{PW}	u_{PW}^2	10.3
Phase displacement	$\frac{1}{1-(\varepsilon_V-\varepsilon_C)\cdot \tan\varphi}$	u_{pd}	1	u_{pd}	u_{pd}^2	10.2.4 or 10.2.3
Ampere meter	I_M	u_{IM}	2	$2 \cdot u_{IM}$	$4 \cdot u_{IM}^2$	10.5
Winding temperature	θ	$\tilde{u}_\theta$	$c_3 = \frac{1}{t+\theta}$	$c_3 \cdot \tilde{u}_\theta$	$c_3^2 \cdot \tilde{u}_\theta^2$	10.7
	Standard uncertainty u_{P2}			=√(right)	=sum(above)	
	Expanded uncertainty U_{P2}			=2 · above		

Table 4 – Uncertainty without correction for phase displacement

Quantity	Estimate	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Variance	See sub-clause
CT ratio error	η_C	u_C	1	u_C	u_C^2	10.1.2
VT ratio error	η_V	u_V	1	u_V	u_V^2	10.1.2
Power meter	P_W	u_{PW}	1	u_{PW}	u_{PW}^2	10.3
Phase displacement	1	u_{pd}	1	u_{pd}	u_{pd}^2	10.2.2 or 10.2.3
Ampere meter	I_M	u_{IM}	2	$2 \cdot u_{IM}$	$4 \cdot u_{IM}^2$	10.5
Winding temperature	θ	$\tilde{u}_\theta$	$c_3 = \frac{1}{t+\theta}$	$c_3 \cdot \tilde{u}_\theta$	$c_3^2 \cdot \tilde{u}_\theta^2$	10.7
	Standard uncertainty u_{P2}			=√(right)	=sum(above)	
	Expanded uncertainty U_{P2}			=2 · above		

NOTE 1 The parameter t relates to thermal coefficient of winding resistance, and is taken as 235 for copper and as 225 for aluminium.

NOTE 2 In the case that temperature change during load loss test is significant, e.g. in tests on large transformers with measurements on several tap changer positions, more appropriate procedures are given in E.3.