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TECHNICAL SPECIFICATION

SPÉCIFICATION TECHNIQUE

Power transformers –
Part 19: Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors

Transformateurs de puissance –
Partie 19: Règles pour la détermination des incertitudes de mesure des pertes des transformateurs de puissance et bobines d'inductance

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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FOREWORD

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Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC 60076-19, which is a technical specification, has been prepared by IEC technical committee 14: Power transformers.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
14/726/DTS	14/736A/RVC

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60076 series, published under the general title *Power transformers*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International Standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

The losses of the transformers (no- load and load losses) are object of guaranty and penalty in the majority of the contracts and play an important role in the evaluation of the total (service) costs and therefore in the investments involved.

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

Corrections and uncertainties are also considered in IEC 60076-8 were some general indications are given for their determination.

This Technical Specification 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 measurand itself.

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 tested objects.

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

In the annexes to this document, two examples of uncertainty calculations are reported for load loss measurements on large power and distribution transformers.

Standards, technical reports and guides mentioned in the text are listed at the end of the document.

It is stated that guaranty and penalty calculations should refer to the best estimated values of the losses without considering the measurement uncertainties.

POWER TRANSFORMERS –

Part 19: Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors

1 Scope

This part of IEC 60076, which is a Technical Specification, illustrates the procedures that should 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, when applicable the specification can be also used for the measurements of reactor losses, except large reactors with very low power factor.

2 Normative references

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

IEC 60076-1:2011, *Power transformers – Part 1: General*

IEC 60076-2:2011, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60076-1 and 60076-2, as well as the following apply.

NOTE The following terms and definitions were taken from ISO/IEC Guide 98-3:2008.

3.1
uncertainty (of measurement)
parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

[SOURCE: ISO/IEC Guide 98-3:2008, 2.2.3]

3.2
standard uncertainty
uncertainty of the result of a measurement expressed as a standard deviation

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.1]

3.3
type A evaluation (of uncertainty)
method of evaluation of uncertainty by the statistical analysis of series of observations

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.2]

3.4
type B evaluation (of uncertainty)
method of evaluation of uncertainty by means other than the statistical analysis of series of observations

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.3]

3.5
combined standard uncertainty
standard uncertainty of the result of measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.4]

3.6
expanded uncertainty
quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.5]

3.7
coverage factor
numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.6]

4 Symbols

4.1 General symbols

F_D	Parameter related to correction of power for phase displacement in measuring circuit
I_M	Current measured by the ammeter (preferably rated current)
I_N	Reference current (normally corresponding to 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 the load loss measurement corrected for known systematic deviations and referred to the current I_N
P_{LL}	Load loss at reference conditions
P_{NLL}	No-load loss at reference conditions and corrected for known errors in the measurement
n	Exponent related to the non-linear behaviour of no-load loss
P_W	Power measured by the power meter
P_{ar}	Additional losses at reference temperature
P_{a2}	Additional losses at temperature θ_2

R_1	Equivalent resistance of the windings at temperature θ_1 according to IEC 60076-1
R_2	Equivalent resistance of the windings at temperature θ_2
R_r	Equivalent resistance of the windings at reference temperature
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 (expressed in degrees Celsius)
θ_1	Temperature of transformer winding at cold winding resistance test according to IEC 60076-1
θ_2	Temperature of transformer windings during load loss test (expressed in Celsius degrees)
θ_r	Reference temperature for transformer windings according to IEC 60076-1
$\Delta_{\varphi C}$	Actual phase displacement of the current transformer (rad)
$\Delta_{\varphi P}$	Actual phase displacement of the power meter (rad)
$\Delta_{\varphi V}$	Actual phase displacement of the voltage transformer (rad)
ε_C	Actual ratio error of the current transformer (%)
ε_V	Actual ratio error of the voltage transformer (%)
φ	Actual phase angle between voltage and current (rad)
φ_M	Phase angle between voltage and current measured with power meter (rad)

4.2 Symbols for uncertainty

c	Sensitivity factor for contribution to uncertainty
u	Standard uncertainty
$\dot{u}$	Absolute standard uncertainty
U	Expanded uncertainty
$\dot{U}$	Absolute expanded uncertainty
u_C	Uncertainty of current transformer ratio (expressed in percent of the ratio)
u_{IM}	Uncertainty of current measurement
u_{LL}	Uncertainty of the load loss at reference temperature
u_{NLL}	Uncertainty of the no-load loss
u_{P2}	Uncertainty of P_2
u_{FD}	Uncertainty of term F_D
u_{PW}	Uncertainty of the power indicated by the analyzer
u_{R1}	Uncertainty of the equivalent resistance R_1
u_{R2}	Uncertainty of the equivalent resistance R_2
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
$u_{\Delta\varphi}$	Uncertainty of phase displacement for complete measuring system
$u_{\Delta\varphi C}$	Uncertainty of current transformer phase displacement
$u_{\Delta\varphi V}$	Uncertainty of voltage transformer phase displacement

5 Power measurement, systematic deviation and uncertainty

5.1 General

In the following, it is assumed that the transformer losses are measured in the conditions prescribed by IEC 60076-1 by means of digital instruments.

For three-phase transformers, losses are intended to be measured using three independent single-phase measuring systems. These systems may be made by separate instruments or a combined in a three-phase instrument.

In general, losses are measured using current and voltage transformers in conjunction with a power meter (power analyser).

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

Systematic deviations related to measuring equipment can be characterised by calibration.

If not negligible, systematic deviations introduced by the measuring system should be corrected before the uncertainty estimate.

5.2 Model function

The uncertainty estimation includes uncertainties in the measuring system as well as in the tested object (transformer or reactor).

Thus the model functions presented below includes both the measuring system and the test object in one equation.

5.3 Measuring systems

Measuring systems can be characterized either by a stated overall uncertainty, or by specifications of its components.

For systems characterized by an overall uncertainty, simplifications in the uncertainty analysis are possible, but in this document this has not been utilized since calibration on the system level are not generally available.

As a consequence, all type of measuring systems should be specified also on the component level.

6 Procedures for no-load loss measurement

6.1 General

The test procedure is given in IEC 60076-1.

The no-load loss measurement shall be referred to rated voltage and frequency and to voltage with sinusoidal wave shape.

The current drawn by the test object is non-sinusoidal, 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 IEC 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 exhibits a non-linear relation to applied voltage that can be established by measurements repeated at different voltages.

For the uncertainty determination at rated voltage, a power law approximation is sufficient.

The model function used for no-load loss uncertainty estimation is the following:

$$P_{NLL} = k_{CN}\frac{1}{1+\frac{\varepsilon_C}{100}} \times k_{VN}\frac{1}{1+\frac{\varepsilon_V}{100}} \times \frac{P_W}{1-\left(\Delta_{\varphi V}-\Delta_{\varphi C}\right)\tan\varphi} \times \left[\frac{U_N}{k_{VN}\frac{1}{1+\frac{\varepsilon_V}{100}}U_M}\right]^n \times \left(1+\frac{U_{avg}-U_{rms}}{U_{avg}}\right) \quad (1)$$

where

$k_{CN}\frac{1}{1+\frac{\varepsilon_C}{100}}$ is the parameter related to the ratio error of the current transformer (CT);

$k_{VN}\frac{1}{1+\frac{\varepsilon_V}{100}}$ is the parameter related to the ratio error of the voltage transformer (VT);

$\frac{1}{1-\left(\Delta_{\varphi V}-\Delta_{\varphi C}\right)\tan\varphi}$ is the parameter related to the correction for phase displacement (F_D);

$\left[\frac{U_N}{k_{VN}\frac{1}{1+\frac{\varepsilon_V}{100}}U_M}\right]^n$ is the 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 used to compensate for the influence of the distortion on the voltage waveform on the no load loss. U_{avg} is the indication of a mean value responding instrument and U_{rms} the indication of an r.m.s. responding instrument (see IEC 60076-1).

Equation (1) can also be expressed as:

$$P_{NLL} = k_{CN} \frac{1}{1+\frac{\varepsilon_C}{100}} \times k_{VN}\left(1+\frac{\varepsilon_V}{100}\right)^{n-1} \times \frac{P_W}{1-(\Delta_{\varphi V}-\Delta_{\varphi C})\tan\varphi} \times \left[\frac{U_N}{k_{VN} \times U_M}\right]^n \times \left(1+\frac{U_{avg}-U_{rms}}{U_{avg}}\right) \quad (2)$$

The known systematic deviations of the power meter may be assumed to be negligible.

The phase angle φ of the loss power is obtained from:

$$\varphi = \varphi_M - \Delta_{\varphi V} + \Delta_{\varphi C} = \arccos\left(\frac{P_W}{I_M U_M}\right) - \Delta_{\varphi V} + \Delta_{\varphi C} \quad (3)$$

NOTE 1 It is observed that the formula of the loss determination is expressed only through the product of a number of factors to facilitate the estimation of the total relative uncertainty of the measurement.

NOTE 2 It has been assumed that the power meter establishes the power factor from measurement of active power and apparent power at the fundamental frequency component of the test voltage.

NOTE 3 The Equations (1) and (2) use 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. As this factor is often approximated by n = 2, this exponent can be used for the uncertainty estimate.

NOTE 4 In the written formula, some secondary influencing quantities have been disregarded such as frequency.

NOTE 5 IEEE C57.123-2002 identifies a small temperature effect on no-load losses and gives – 1 % per 15 K temperature rise. This effect, not well known and not identified within IEC, has been disregarded.

6.3 Uncertainty budget for no-load loss

The uncertainty estimate of no-load loss power can be obtained as given in Table 1.

In the majority of the cases, the uncertainty estimate with the class index procedure described in 10.3.3 is sufficiently accurate as in the determination of the standard uncertainty the following contributions can be disregarded:

- the uncertainty related to the phase displacement when the power factor is greater than 0,2;
- the uncertainty on the correction to sinusoidal waveform when the indications of the voltmeters responsive of the r.m.s. and mean voltages are equal within 3 %.

Table 1 – Measured no-load loss uncertainties

Quantity	Component	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	See subclause
CT ratio error	ε_C	u_C	1	u_C	10.2
VT ratio error	ε_V	u_V	n-1	$(n-1)u_V$	10.2
Power meter	P_W	u_{PW}	1	u_{PW}	10.5
Phase displacement	$\frac{1}{1-(\Delta\varphi_V-\Delta\varphi_C)\tan\varphi}$	$u_{\Delta\varphi} \approx 0$	1	≈ 0	10.3
Voltage	U_N	u_{UM}	n	nu_{UM}	10.4
Correction to sinusoidal waveform	$1+\frac{U_{avg}-U_{rms}}{U_{avg}}$	u_{WF}	1	u_{WF}	10.6
Combined standard uncertainty calculated as: $u_{NLL} = \sqrt{u_C^2+(n-1)^2u_V^2+u_{PW}^2+n^2u_{UM}^2+u_{WF}^2}$					
The expanded relative uncertainty is $U_{NLL} = 2u_{NLL}$, which corresponds to a level of confidence of approximately 95 %.					

7 Procedures for load loss measurement

7.1 General

The test procedure is given in IEC 60076-1.

In load loss measurements the measured loss shall be referred to rated current or to be reported at this current if performed at a reduced current. Moreover, the results of load loss measurements shall be reported to the reference temperature.

7.2 Model function for load loss measurement at rated current

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

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

$$P_2 = k_{CN} \frac{1}{1+\frac{\varepsilon_C}{100}} \times k_{VN} \frac{1}{1+\frac{\varepsilon_V}{100}} \times \frac{P_W}{1-(\Delta_{\varphi V}-\Delta_{\varphi C})\tan\varphi} \times \left[\frac{I_N}{k_{CN}\frac{1}{1+\frac{\varepsilon_C}{100}} I_M}\right]^2 \quad (4)$$

which is rearranged to:

$$P_2 = k_{CN}\left(1+\frac{\varepsilon_C}{100}\right) \times k_{VN} \frac{1}{1+\frac{\varepsilon_V}{100}} \times \frac{P_W}{1-(\Delta_{\varphi V}-\Delta_{\varphi C})\tan\varphi} \times \left[\frac{I_N}{k_{CN} I_M}\right]^2 \quad (5)$$

where

$\left[\frac{I_N}{k_{CN} I_M}\right]^2$ is the 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.

NOTE 1 It is observed that also in this case the formula of the loss determination is expressed only through the product of a number of factors to facilitate the estimation of the total relative uncertainty of the measurement.

NOTE 2 In the written formula, some secondary influencing quantities have been disregarded, such as frequency and wave shapes.

The phase angle φ of the loss power is obtained from:

$$\varphi = \varphi_M - \Delta_{\varphi V} + \Delta_{\varphi C} = \arccos\left(\frac{P_W}{I_M U_M}\right) - \Delta_{\varphi V} + \Delta_{\varphi C} \quad (6)$$