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BSI Standards Publication

Power transformers

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

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National foreword

This British Standard is the UK implementation of EN 60076-19:2015. It is derived from IEC/TS 60076-19:2013. It supersedes PD IEC/TS 60076-19:2013 which is withdrawn.

The CENELEC common modifications have been implemented at the appropriate places in the text. The start and finish of each common modification is indicated in the text by tags ▮C〉 〈C▮.

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Power transformers - Part 19: Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors (IEC/TS 60076-19:2013 , modified)

Transformateurs de puissance - Partie 19: Règles pour la détermination des incertitudes de mesure des pertes des transformateurs de puissance et bobines d'inductance
(IEC/TS 60076-19:2013 , modifiée)

Leistungstransformatoren - Teil 19: Regeln für die Bestimmung von Unsicherheiten in der Messung der Verluste von Leistungstransformatoren und Drosselspulen
(IEC/TS 60076-19:2013 , modifiziert)

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Europäisches Komitee für Elektrotechnische Normung

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Foreword

This document (EN 60076-19:2015) consists of the text of IEC/TS 60079:2013 prepared by IEC/TC 14 "Power transformers", together with the common modifications prepared by CLC/TC 14 "Power transformers".

The following dates are fixed:

• latest date by which this document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2016-06-25
• latest date by which the national standards conflicting with this document have to be withdrawn	(dow)	2018-06-25

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

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

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

C〉 The losses of the transformers (no- load and load losses) are object of guarantee 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. Furthermore, regional regulations, such as the European Union directive for EcoDesign, may also pose requirements on establishment of reliable values for losses. 〈C

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.

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

This European Standard 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 procedures can also be applied to loss measurements on power transformers and reactors as evaluation of the achievable performance of a test facility in the course of prequalification processes, as estimations of achievable uncertainty in the enquiry stage of an order or prior to beginning final testing at manufacturer´s premises and for evaluations of market surveillance measurements.

Evaluation of uncertainty in testing is often characterized as “top-down” or “bottom-up”, where the first one relies on inter-laboratory comparisons on a circulated test object to estimate the dispersion and hence the uncertainty. The latter method instead relies on the formulation of a model function, where the test result y is expressed as a function of input quantities. This function is often the formula used for the calculation of the result. The “bottom-up” method is applied in this Document. 〈C

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.

C〉 It is recommended that guarantee and penalty calculations should refer to the best estimated values of the losses without considering the measurement uncertainties, based on a shared risk concept, where both parties are aware of and accept the consequences of non-negligible measurement uncertainty.

In cases where the losses are required to conform to stated tolerance limits, it is recommended that the estimated uncertainty is less than the tolerance limit. This situation will occur for example in market surveillance activities. In lieu of other specifications it can be noted that 3 % is often used as estimate for the required uncertainty. 〈C

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

C〉 Standards mentioned in the text but not indispensable are listed at the end of the document.

This European document is based on IEC/TS 60076-19. The technical content of the TS was not changed, but small numerical mistakes and consistent use of symbols in Annex A were corrected. The introduction was modified to enhance clarity. 〈C

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POWER TRANSFORMERS –

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

1 Scope

C〉 This European Standard 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. 〈C

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.

C〉 EN 60076-1:2011, *Power transformers – Part 1: General* (IEC 60076-1:2011)

EN 60076-2:2011, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers* (IEC 60076-2:2011) 〈C

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:

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

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:

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

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:

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

which is rearranged to:

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

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:

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

7.3 Reporting to rated current and reference temperature

The measured loss P_2 is assumed to be composed of I^2R loss and additional loss P_{a2}. The relation between these at the reference current I_N is:

$$P_2 = I_N^2 R_2 + P_{a2}$$

The total load loss P_{LL} at reference temperature as defined in IEC 60076-1:2011, Annex E is:

$$P_{LL} = I_N^2 \times R_r + P_{ar} = I_N^2 R_2 \frac{t+\theta_r}{t+\theta_2} + P_{a2} \frac{t+\theta_2}{t+\theta_r}, \quad (7)$$

where the equivalent resistance R_2 of the windings during the load test performed at temperature θ_2 may be estimated from the equivalent resistance R_1 obtained at temperature θ_1 by the relation:

$$R_2 = R_1 \frac{t+\theta_2}{t+\theta_1}$$

where t is a parameter related to the thermal coefficient of winding resistance (235 for copper and 225 for aluminium).

Likewise the resistance R_r at the reference temperature θ_r is given by:

$$R_r = R_2 \frac{t+\theta_r}{t+\theta_2}$$

The additional loss at reference temperature is:

$$P_{ar} = P_{a2} \frac{t+\theta_2}{t+\theta_r}$$

7.4 Uncertainty budget for the measured power P_2 reported to rated current

7.4.1 General

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

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

7.4.2 Uncertainties of measured load loss power P_2 at ambient temperature θ_2

The uncertainty estimate of load loss power P_2 should be obtained according to Table 2.

For large power transformers, the complete reference procedure described in 10.3.2 should be applied.

For distribution transformer the class index procedure given in 10.3.3 may be sufficiently accurate.

In many cases, when the power factor of the circuit is greater than 0,2, the contribution of the phase displacement can be disregarded.

Table 2 – Measured load loss uncertainties at ambient temperature

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	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_{FD}	1	u_{FD}	10.3
Ampere meter	I_{IM}	u_{IM}	2	$2u_{IM}$	10.4
Combined standard uncertainty calculated as: $u_{P2}=\sqrt{u_C^2+u_V^2+u_{PW}^2+u_{FD}^2+4u_{IM}^2}$					
The expanded uncertainty is $U_{P2}=2u_{P2}$ which corresponds to a level of confidence of approximately 95 %.					

7.5 Uncertainty budget for reported load loss at reference temperature

The results of the load loss test shall be reported to the reference temperature in accordance with IEC 60076-1 (see 7.3).

The loss power and the associated uncertainty contributions are to be expressed in watt (i.e. as absolute uncertainties) in order to obtain correct calculation of the total uncertainty at reference temperature.

The estimate of the uncertainties affecting the $I_N^2R_2$ and additional losses at temperature θ_2 are obtained as indicated in Table 3.

Table 3 – Absolute uncertainty of the additional losses at temperature θ_2

Quantity	**Component**	**Absolute measurement**	**Sensitivity**	**Contribution**
Measured loss	P_2	$\dot{u}_{P2}$	1	$\dot{u}_{P2}$
$I_N^2R_2$ loss	$I_N^2R_2$	$\dot{u}_{R2}$	I^2	$I^2R\times u_{R2}$
The absolute uncertainty of the additional loss as: $\dot{u}_{Pa2}=\sqrt{\dot{u}_{P2}{}^2+(I_N^2R_2\times u_{R2})^2}$				
The expanded absolute uncertainty is $\dot{U}_{Pa2}=2\dot{u}_{Pa2}$ which corresponds to a coverage probability of approximately 95 %.				

The uncertainty of the total losses P_{LL} reported at reference temperature can be determined starting from the model function given in 7.3:

$$P_{LL} = I_N^2 R_r + P_{ar} = I_N^2 R_2 \frac{t+\theta_r}{t+\theta_2} + P_{a2} \frac{t+\theta_2}{t+\theta_r}$$

In Table 4 the procedure is given for estimating the absolute uncertainty of the total losses P_{LL} reported at reference temperature.

Table 4 – Absolute uncertainty of load losses P_{LL} reported at reference temperature

Quantity	Component	Absolute uncertainty	Sensitivity	Absolute uncertainty contribution
$I_N^2 R_r$ loss	R_r	$\dot{u}_{R2}$	$I_N^2 \frac{t+\theta_r}{t+\theta_2}$	$\frac{t+\theta_r}{t+\theta_2} I_N^2 R_2 u_{R2}$
Additional loss	P_{ar}	$\dot{u}_{Pa2}$	$\frac{t+\theta_2}{t+\theta_r}$	$\frac{t+\theta_2}{t+\theta_r} \dot{u}_{Pa2}$
Mean winding temperature	θ_2	$\dot{u}_{\theta 2}$	$\approx I_N^2 R_r \frac{t+\theta_r}{(t+\theta_2)^2}$	$\frac{t+\theta_r}{(t+\theta_2)^2} I_N^2 R_r \dot{u}_{\theta 2}$
The total standard absolute uncertainty is calculated as: $\dot{u}_{LL} = \sqrt{(\frac{t+\theta_r}{t+\theta_2} I_N^2 R_2 u_{R2})^2 + (\frac{t+\theta_2}{t+\theta_r} \dot{u}_{Pa2})^2 + (\frac{t+\theta_r}{(t+\theta_2)^2} I_N^2 R_2 \dot{u}_{\theta 2})^2}$				
The expanded absolute uncertainty is $\dot{U}_{LL} = 2\dot{u}_{LL}$ which corresponds to a coverage probability of approximately 95 %.				
The expanded relative uncertainty is obtained as: $U_{LL} = \frac{\dot{U}_{LL}}{P_{LL}}$				

NOTE 1 In the table line one, the equality $\dot{u}_{R2} = R_2 u_{R2}$ has been utilized.

NOTE 2 For typical liquid-immersed transformers and assuming t = 235, θ_2 = 20 °C and θ_r = 75 °C, the following sensitivities factors can be used:

$$\frac{t+\theta_r}{t+\theta_2} \cong 1{,}2 \qquad \frac{t+\theta_2}{t+\theta_r} = \frac{1}{\frac{t+\theta_r}{t+\theta_2}} \qquad I_N^2 R_2 \frac{t+\theta_r}{(t+\theta_2)^2} \cong 0{,}0048 I_N^2 R_2$$

For other temperature combinations (as for dry-type transformers) different sensitivity factors could be applied.

NOTE 3 In Table 4, the simplification $\left| -I_N^2 R_2 \frac{t+\theta_r}{(t+\theta_2)^2} + P_{a2} \frac{1}{t+\theta_r} \right| \leq I_N^2 R_2 \frac{t+\theta_r}{(t+\theta_2)^2}$ has been utilized.

8 Three-phase calculations

8.1 Power measurement

For three-phase transformers, the power measurement should be performed using three individual single-phase measuring systems, adding the three measurements.

In this case, the criteria for estimating the uncertainties for the power in each phase are the same previously given for single-phase circuits.

Normally the three measurements of the power are not correlated, and the absolute uncertainty $\dot{u}_T$ of the total power is obtained by the formula:

$$\dot{u}_T = \sqrt{\dot{u}_1^2 + \dot{u}_2^2 + \dot{u}_3^2} \tag{8}$$

where the symbols below the square root represent the absolute uncertainties of the power measurements performed on the individual phases and expressed in watt.

The relative uncertainty is:

$$u_T = \frac{\dot{u}_T}{P_W} \tag{9}$$

where P_W is the sum of the power on all three phases.

All uncertainty contributions are assumed to be uncorrelated.

NOTE Three-phase power measuring circuits using reduced number of measuring elements are sometimes used. It is however very difficult to make a valid uncertainty estimate for such circuits since sufficient knowledge of influencing parameters are difficult to establish. Therefore such circuits are not recommended.

8.2 Reference voltage

The reference voltage is measured during no-load loss tests. If the three-phase system can be considered practically symmetrical, it is acceptable to use the mean value of the three indications of the reference voltage. The quantities can be considered not correlated.

8.3 Reference current

The reference current is measured during load loss tests. If the three-phase system can be considered practically symmetrical, it is acceptable to use the mean value of the three indications of the reference current. The quantities can be considered not correlated.

9 Reporting

9.1 Uncertainty declaration

In accordance with this Technical Specification, the total standard uncertainty of the loss measurements and the expanded uncertainty should be declared.

The expanded uncertainties should be determined multiplying the standard uncertainty by the coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95 %.

9.2 Traceability

All measurements used to establish the losses should be based on traceable calibrations. The chain of traceability should be indicated in the report.

10 Estimate of corrections and uncertainty contributions

10.1 Instrument transformers

Instrument transformers are normally calibrated at different currents (voltages) and at least two different burdens and the errors for the measuring conditions can be obtained by interpolation from the available data given in the calibration certificate.

The calibration certificate should include the expanded uncertainty of the declared ratio errors and phase displacements as well as the applied coverage factor.

In measuring systems conventional or advanced current transformers may be used:

- conventional transformers with simple magnetic circuit;
- zero flux current transformers;
- two-stage current transformers;
- amplifier-aided current transformers.

For conventional instrument transformers, higher accuracy can be obtained if the calibration is performed at the actual burden during the loss measurement and this solution is recommended for large power transformers.

The advanced devices that employ technologies that enhance accuracy and stability are treated separately due to the difference in characteristics. They operate on the principle of reducing flux in the active core to near zero, thereby reducing both ratio errors and phase displacement to very small values.

In alternative to the conventional inductive voltage transformers, advanced voltage transducers utilise standard compressed gas capacitors in conjunction with various active feedback circuits that minimise ratio errors and phase displacement.

When the phase displacement uncertainty has to be evaluated also for the power meter the formula becomes the following $u_{\Delta\varphi} = \sqrt{u^2_{\Delta\varphi V} + u^2_{\Delta\varphi C} + u^2_{\Delta\varphi P}}$ where $u_{\Delta\varphi P}$ is the uncertainty related to the phase displacement in the power meter.

10.2 Uncertainty contributions of ratio error of instrument transformers

This procedure, valid for both conventional and advanced instrument transformers, is based on the permitted error (e_{class}) according to the requirements for the class of the instrument transformer, the ratio error is estimated $\varepsilon_C = 0$ for current transformers and $\varepsilon_V = 0$ for voltage transformers.

Assuming a rectangular distribution, (see ISO/IEC Guide 98-3) the uncertainty is therefore:

$$u_C = \sqrt{\frac{e^2_{class}}{3}} \qquad u_V = \sqrt{\frac{e^2_{class}}{3}} \tag{10}$$

A necessary prerequisite for this method is that the instrument transformer is used within the admissible ranges of burden and current (or voltage).

10.3 Uncertainty contribution of phase displacement of instrument transformers

10.3.1 General

The combined phase displacement of current and voltage transformers affects the measurand estimate and its effect evaluation should be made for the system rather than for each component.

Depending on the measurement situation, two different options can be envisaged for estimating the phase displacement correction factor F_D and the relevant uncertainty u_{FD}.

The procedures to be applied are given in Table 5.

Table 5 – Procedures for the determination of phase displacement uncertainties

Procedure	Application	Subclause
Complete reference procedure	This procedure is the most correct and should be applied when the power factor is < 0,2	10.3.2
Class index procedure	This procedure gives acceptable results when the power factor is ≥ 0,2	10.3.3

10.3.2 Complete reference procedure

10.3.2.1 General formula

The correction of the measurand for the effect of phase displacement is given by:

$$F_D = \frac{1}{1-\left(\Delta_{\varphi V} - \Delta_{\varphi C}\right)\tan\varphi} \tag{11}$$

where

$\Delta_{\varphi C}$ is the phase displacement for the current transformer (rad);

$\Delta_{\varphi V}$ is the phase displacement for the voltage transformer (rad);

φ is the actual phase angle between voltage and current (corrections for phase displacement of instrument transformers applied).

For advanced instrument transformers the phase displacements can be assumed $\Delta_{\varphi C} = 0$ and $\Delta_{\varphi V} = 0$.

The uncertainty u_{FD} that affect the phase displacement correction F_D depends on various variables but for practical applications it can be estimated by the following simplified relation:

$$u_{FD} \approx u_{\Delta\varphi} \tan\varphi \tag{12}$$

where the uncertainty $u_{\Delta\varphi}$ represents the combined uncertainty of the instrument transformer phase displacements that may be determined as discussed below.

NOTE 1 The phase displacement uncertainty is normally given in absolute values. However the result of Equation (12) will still be the relative uncertainty (using radians and multiply the result with 100, the result will be in percent).

NOTE 2 Corrections using calibration results are in general not possible for advanced instrument transformers.

10.3.2.2 Uncertainty of conventional instrument transformers

The uncertainty is given by the following relation:

$$u_{\Delta\varphi} = \sqrt{u_{\Delta\varphi V}^2 + u_{\Delta\varphi C}^2} \tag{13}$$

where $u_{\Delta\varphi C}$ and $u_{\Delta\varphi V}$ are the standard uncertainties reported in the calibration report.

If the interpolation procedure is applied for determining the contribution of voltage and current transformers to the phase displacement and the corresponding uncertainties cannot be disregarded, it should be composed with the uncertainties determined as above:

$$u_{\Delta\varphi} = \sqrt{u_{int\Delta\varphi V}^2 + u_{\Delta\varphi V}^2 + u_{int\Delta\varphi C}^2 + u_{\Delta\varphi C}^2} \tag{14}$$

where the uncertainties u_{int} are the standard uncertainties attributable to the interpolations. Determination of these phase displacements is discussed below.

This uncertainty are to be estimated, and can, in lieu of other evaluations, be assumed to be 1/3 of that applied interpolation correction.

In the case that the calibration certificate states the accuracy without information on the coverage factor, the corresponding standard uncertainty can be assumed equal to that accuracy divided by $\sqrt{3}$ (rectangular distribution of probability).

10.3.2.3 Uncertainty of advanced instrument transformers

For evaluating the phase displacement uncertainty it is sufficient to consider the accuracy specification and the accuracy of the calibration:

$$u_{\Delta\varphi C} = \sqrt{u_{cal}^2 + \frac{u_{spec}^2}{3}} \quad \text{and} \quad u_{\Delta\varphi V} = \sqrt{u_{cal}^2 + \frac{u_{spec}^2}{3}} \tag{15}$$

where

u_{cal} is the standard uncertainty obtained dividing by the coverage factor the expanded uncertainty for phase displacement given in a calibration certificate. If the coverage factor is not given explicitly, it is common procedure to assume a rectangular distribution and to divide by $\sqrt{3}$;

u_{spec} is the maximum phase displacement defined for the accuracy specification of the instrument transformer.

10.3.3 Class index procedure

No correction is applied to the measured power for phase displacement and therefore $F_D \approx 1$.

For conventional instrument transformers, the phase displacement uncertainty may be estimated from the maximum value the term F_D could assume for the range of values of $\tan\varphi$ expected to occur and supposing a rectangular distribution of the probability:

$$u_{FD} = \frac{1}{\sqrt{3}} \left| (1 - F_D) \right| = \frac{1}{\sqrt{3}} \left| 1 - \frac{1}{1 - (\Delta_{\varphi V} - \Delta_{\varphi C}) \tan \varphi} \right| \tag{16}$$

where

$\Delta_{\varphi C}$ is the negative class limit (expressed in radiant) for the current transformer phase displacement;

$\Delta_{\varphi V}$ is the positive class limit (expressed in radiant) for the voltage transformer phase displacement.

For advanced instrument transformers, the rules given for the complete reference procedure apply (see 10.3.2).

10.4 Voltage and current measurements

The measurements should be performed by means of digital instruments. The accuracy of the results of each reading, expressed in percentage, is generally given by a formula of the following type:

$$a = b \text{ x } reading + c \text{ x } range \tag{17}$$

where b and c are coefficients related to the accuracy specification of the instrument.

NOTE 1 In some manuals a third term referred to the offset is also indicated.

NOTE 2 The formula for the accuracy evaluation can differ from the one given above, the instrument manuals give the necessary information.

As the uncertainty is normally thought to have a rectangular distribution, the relative standard uncertainty is given by the following relations:

$$u_{UM} = \frac{a}{\sqrt{3}} \quad \text{and} \quad u_{IM} = \frac{a}{\sqrt{3}} \tag{18}$$

respectively for voltage and current measurements.

When in the manual of the instrument the uncertainty is directly given. Attention should be paid to the used coverage factor.

10.5 Power meter

The accuracy of a power measurement performed by means of a power analyzer depends on the errors related to the voltage and current channels, the power factor of the measurand and the instrument reading offset.

As various criteria can be followed for determining the power measurement uncertainty, it is recommended to make always reference to the power analyzer specification and relevant calibration reports.

For power analyzer of good quality, the errors due to the instrument itself can be normally disregarded so that the estimate of the uncertainty can be made through the so called error limits (range characterized by positive and negative values) that the instrument should never exceed in normal range of use and considering rectangular the distribution of the error probability.

In some cases, the power uncertainty can be determined estimating separately the different contributions (voltage and current channels, power factor and offset) and then by combining them.

The standard uncertainty of each term can be obtained dividing for $\sqrt{3}$ the error limits mentioned above. If the single contributions can be considered not correlated, the total standard uncertainty may be obtained by a relation of this type:

$$u_{PW} = \sqrt{u_V^2 + u_I^2 + u_\varphi^2 + u_{off}^2} \tag{19}$$

where

u_V is the contribution related to the voltage channel;

u_I is the contribution related to the current channel (including the contribution of the eventual shunt);

u_φ is the contribution related to the circuit power factor and to the instrument phase displacement;

u_{off} is the contribution related to the offset.

Some instrument specifications report curves (or tables) that give the error limits as a function of the circuit power factor.

Such curves (or tables) can in general be regarded as representative of the maximum error. Assuming a rectangular distribution, the standard uncertainty can be estimated as this maximum error divided by $\sqrt{3}$.

As such curves (or tables) are normally referred to the rated ranges of voltage and current channels, for measurements performed far from these reference conditions, it could be necessary to multiply the obtained value by the ratio:

$$\frac{U_N I_N}{UI} \tag{20}$$

where U_N and I_N are the ranges of the voltage and current channels and U and I the actual readings.

Some instrument specifications allow to determine the uncertainty directly, but in these cases attention should be paid to the coverage factor used to indicate it.

10.6 Correction to sinusoidal waveform

An approximate correction for the value of the no-load loss due to distortion given in IEC 60076-1 is based on the true r.m.s. voltage U_{rms} and to the mean value of the rectified voltage U_{avg}.

Firm background for asserting the uncertainty of the influence of voltage distortion on the value of the no load losses is not available, so that in the absence of other evidence, it is recommended to assign to the no-load loss an uncertainty:

$$u_{wf} = \frac{U_{avg} - U_{rms}}{4U_{avg}} \tag{21}$$

When the indications uncertainty of the voltmeters responsive of the r.m.s. and mean voltages are equal within 3 %, the uncertainty on the correction to sinusoidal waveform may be disregarded.

10.7 Winding temperature at load loss measurement

The temperature of the windings during the load loss measurement is important for subsequent corrections of the results to reference temperature.

The winding temperature can either be directly measured by resistance variations or be estimated from the measurements of other quantities, before the loss measurement.

In both cases a suitable estimate of the uncertainty of the winding temperature is needed. Methods to derive this uncertainty are given below. In general, uncertainties are expected to be in the range of 1 K to 2 K.

The method based on the measurement of the winding resistances is justified for very large transformers and when the windings are presumed not to be in steady state conditions.

For small transformers, determination of winding temperature by measurement of winding resistance is often not justified. In cases where many identical transformers are tested, it can be satisfactory to perform an investigation on one unit as a special test, and use the result for all transformers of a batch.

When for large power liquid-immersed transformers the winding temperature is estimated through the liquid temperature, the same rules prescribed by IEC 60076-2 for the determination of the liquid average temperature during the temperature rise test can be applied.

When optical fibre thermal sensors are provided at the top of the windings for the measurement of the hot-spot temperatures, the average of their indications could be used instead of the liquid pocket temperature.

For liquid-immersed distribution transformers, where the height of the winding rarely exceed 1,5 m, it will be sufficient to consider only the temperature of the liquid in the pocket.

For dry type transformers, the average winding temperature can be determined by the average of the indications of thermal sensors located inside the axial cooling channels. Reference temperature determined through the measurement of the liquid temperature is applicable only if the winding can be considered to be in steady state condition during the test. The winding can be assumed to be in steady state condition if its temperature does not change by more than 1 K. This can be often achieved by keeping the time current application short in comparison with the winding thermal time constant.

10.8 Winding resistance measurement

The winding resistance is usually measured using the volt-ampere method and the uncertainty attributable to the instrument can be expressed with the following relation:

$$u_{R1} = \sqrt{u_{UM}^2 + u_{UIM}^2 + u_{SH}^2} \tag{22}$$

where

u_{uM} is the uncertainty in voltage measurement;

u_{UIM} is the uncertainty in measurement of shunt voltage; and

u_{SH} is the uncertainty of the shunt resistance.

NOTE It is assumed that sufficient time has elapsed to ensure that any transient phenomena incepted at measuring circuit closing have disappeared and stable readings are obtained.

To estimate the uncertainties, for voltage and current measurements, the same procedures indicated in sub-clause 10.4 should be applied.

For the current shunt it is normally sufficient to estimate the uncertainty from the class index disregarding the systematic deviation, that is:

$$u_{sh} = \sqrt{\frac{u_{class}^2}{3}} \tag{23}$$

If the resistance measurement is performed by an integrated instrument, the uncertainty should be that given in the manufacturer specification and confirmed by calibration.

The uncertainty of the equivalent resistance obtained reporting the values at the supplied winding for the load loss measurement, may be obtained combining the absolute uncertainty of the single winding resistances.

The value of the resistance is also affected by the uncertainty contribution of the temperature at which the measurement is carried out, as explained under 10.7.

Annex A
(informative)

Example of load loss uncertainty evaluation for a large power transformer

A.1 General

The following example refers to the evaluation of the uncertainty that can affect the measurement of load loss of a large power transformer performed at ambient temperature and using the three wattmeter method (three separated single-phase measurements).

The example was derived from the real measurement performed on a large oil-immersed three-phase power transformer.

In the example, the determination of the uncertainties was limited to only one of the phases.

The following simplifications have been introduced:

- measurand not modified by the test conditions (invariant) so that only the uncertainties introduced by the method and instrumentation used and by the winding temperature estimate are considered;
- sinusoidal and symmetrical current system;
- constant rated frequency.

It can be noted that the effects of the two last variables are normally on secondary order on the uncertainty estimate when the test complies with IEC 60076-1.

In the text reference is made to the clauses of the main document.

A.2 Transformer ratings

The main transformer characteristics are reported in Table A.1.

Table A.1 – Transformer ratings

Number of phase	3
Rated frequency	50 Hz
Rated power	90 MVA
Rated voltages	240/15 kV
Rated currents	216,5 / 3 464 A
Short-circuit impedance	12,5 %
Load loss at 75 °C (guarantee value)	270 kW
Winding connections	star/delta

A.3 Measuring method and instrumentation used

The transformer was supplied from the high voltage winding with the low voltage winding short-circuited.

Three independent electric measuring systems were provided for the measurement of the loss.

The following instrumentation was used:

- current transformers: rated ratio 300/5 A, accuracy class 0,1;
- voltage transformer: rated ratio 20 000/100 V, accuracy class 0,1;
- power analyzer by which active power, current and voltage were measured;
- six (6) temperature sensors applied to the transformer tank to estimate the average winding temperature.

(Other devices can be used to scale down voltage and current, such as capacitive voltage dividers and advanced current transformers).

The resistance measurements were carried out on both the windings at ambient temperature with the volt-ampere method according to 10.8 and then referred to the winding supplied for the load loss measurement.

A.4 Model function of the measurand and deviation correction (see 7.2)

A.4.1 Model function

The model function for load loss referred to rated current is given by:

$$P_2 = k_{CN}\left(1+\frac{\varepsilon_C}{100}\right)\times k_{VN}\frac{1}{1+\frac{\varepsilon_V}{100}}\times\frac{P_W}{1-(\Delta\varphi_V-\Delta\varphi_C)\tan\varphi}\times\left[\frac{I_N}{k_{CN}I_M}\right]^2$$

A.4.2 Correction of known systematic deviations

The known systematic deviations of the power meter have been assumed to be negligible, as well as for ratio of current and voltage transformers. As rated current was used at the test correction for current is not needed. The phase angle φ of the loss power is obtained from:

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

C〉 The remaining corrective term is given by the following equation: (erroneous K_C replaced by F_D)

$$F_D = \frac{1}{1-\left(\Delta_{\varphi V}-\Delta_{\varphi C}\right)\cdot\tan\varphi}$$ 〈C

The corrected power is therefore:

C〉 $$P_2 = k_{CN}\cdot k_{VN}\cdot P_W\cdot F_D$$ 〈C

A.5 Results of the measurements

A.5.1 Load loss measurements

On one of the phases, the readings of the power analyzer are reported in Table A.2.

Table A.2 – Loss measurement results (one phase)

Test current (corresponding to rated current)	3,608 A
Active power	6,625 W
Test voltage	86,60 V
Power factor $(\cos\varphi_M)$	0,021 2

C〉 The estimate of the phase angle between voltage and current results (see 7.2 and A.6.1):

$$\varphi = \arccos\left(\frac{P_W}{I_M U_M}\right) - \Delta_{\varphi V} + \Delta_{\varphi C} = \arccos\left(\frac{6,625}{3,608\times 86,60}\right) - \left(\frac{0,09}{100} + \frac{0,11}{100}\right)\cdot\frac{180}{\pi} = 88,782 - 0,115 = 88,670°$$

The corresponding tanφ is therefore equal to 43,087. 〈C

The corrective term results the following:

C〉 $$F_D = \frac{1}{1-\left(\Delta_{\varphi V} + \Delta_{\varphi C}\right)\cdot\tan\varphi} = \frac{1}{1-(0,09/100+0,11/100)\cdot 43,087} = 1,0943$$ 〈C

The corrected power is therefore:

C〉 $$P_2 = k_{\mathrm{CN}}\cdot k_{\mathrm{VN}}\cdot P_{\mathrm{W}}\cdot F_{\mathrm{D}} = 60\cdot 200\cdot 6,625\cdot 1,0943 = 86\,997\ \mathrm{W}$$

NOTE This result differs slightly from the result obtained with the full formula given in clause A.4.1 because of the simplifications introduced in A.4.2. 〈C

A.5.2 I^2R loss determination

As in this example the estimate of the load loss uncertainty was referred to one phase, one third of the corresponding total $I_N^2 R_2$ loss was used. The $I_N^2 R_2$ value was assumed equal to 69 500 W at 24,2 °C

A.6 Estimates of the single contributions to the uncertainty budget

A.6.1 Current and voltage transformers

The calibration certificates of the instrument transformers allowed to estimate, for the measuring conditions, the values given in Table A.3 (accuracy class 0,1 according to the IEC standard in force).

Table A.3 – Calibration of voltage and current transformers

Instrument transformer	Rated ratio	Accuracy class	Ratio error (%)		Phase displacement (centiradians)	
			Value	Accuracy	Value	Accuracy
Current	300/5	0,1	+0,09	±0,01	–0,11	±0,02
Voltage	20 000/100	0,1	+0,08	±0,01	+0,09	±0,01

The values given above should include also the effects of burdens and connections. For the accuracy (or uncertainty) also the effects of the interpolations between calibration curves should be considered.

A.6.2 Instrument transformer ratio error uncertainties (see 10.2)

Because of the good accuracy classes of the used instrument transformers, the contribution of the ratio errors to the total uncertainty was of secondary order and therefore it was disregarded.

A.6.3 Instrument transformer phase displacement uncertainties (see 10.3)

The uncertainty introduced by the instrument transformers are to be estimated starting from the accuracy (a_{FV} and a_{FC}) of the phase displacements declared in the calibration certificates.

For the example, using the values indicated in Table A.3, the absolute standard uncertainties on the phase displacements is to be evaluated as follow:

C〉 $$u_{\Delta\varphi C} = \frac{0{,}02}{\sqrt{3}} = 0{,}011\,5 \text{ crad}$$

$$u_{\Delta\varphi V} = \frac{0{,}010}{\sqrt{3}} = 0{,}005\,8 \text{ crad}$$

and

$$u_{\Delta\varphi} = \sqrt{u_{\Delta\varphi V}^2 + u_{\Delta\varphi C}^2} = \sqrt{0{,}011\,5^2 + 0{,}005\,8^2} = 0{,}012\,9$$

NOTE In some cases, in the calibration certificates the uncertainty is directly indicated with a given confidence level and therefore the standard uncertainties can be directly obtained from these data. 〈C

A.6.4 Power analyzer uncertainties (see 10.5)

C〉 According to the manual for the instrument used, the accuracy on power measurement is obtained by the combination of a number of terms: 〈C

$$F = \pm\left[a\frac{U_X}{U_N} + b\frac{I_X}{I_N} + c\frac{U_X \mathrm{\ x\ } I_X}{U_N \mathrm{\ x\ } I_N} + d\,\frac{U_N \mathrm{\ x\ } I_N}{P_X} + e \right]$$

(other combinations can be proposed according to the manual of the instrument used and to its accuracy class)

For the measurement at which the example refers to (very low power factor) the dominant term was the fourth that depends on the power factor.

C〉 The accuracy determined in accordance with the above relation resulted in ±0,91 %. 〈C

The corresponding standard uncertainty estimated in accordance with the rules given in 10.4 was:

$$u_{PW} = \frac{0{,}91}{\sqrt{3}} = 0{,}53\ \%$$

For the current measurement, the same instrument assured an accuracy of ±0,21 % at which the following standard uncertainty corresponds:

$$u_{IM} = \frac{0{,}21}{\sqrt{3}} = 0{,}12\ \%$$

C〉 According to the manual for the instrument used, the accuracy for voltage measurement is ±0,18 %, which corresponds to the following standard uncertainty: 〈C

$$u_{UM} = \frac{0{,}18}{\sqrt{3}} = 0{,}10\ \%$$

A.6.5 Corrective term uncertainty (see 10.3.2)

C〉 The uncertainty u_{FD} related to the phase displacement correction can be evaluated with the following simplified relations:

$$u_{FD} \approx u_{\Delta\varphi} \cdot \tan\varphi$$ 〈C

The uncertainty in φ is not significant.

Therefore the uncertainty of the corrected power is:

C〉 $$u_{FD} = 0{,}012\,9 \cdot \tan\varphi = 0{,}012\,9 \cdot 43{,}087 = 0{,}56\ \%$$ 〈C

A.6.6 Uncertainty of the resistance at temperature θ_2 (see 10.8)

C〉 The standard uncertainty due to the measuring instruments is assumed equal to 0,35 % and that attributable to the winding temperature estimate equal to 2 K, with the latter deemed to be negligible. 〈C

A.7 Uncertainty of the load loss measured at ambient temperature (see 7.4)

C〉 The uncertainties that affect the load loss at ambient temperature can be estimated using the results of the previous elaborations and are summarized in Table A.4. 〈C

Table A.4 – Uncertainty contributions

Quantity	Estimate	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution (%)
CT ratio error	η_C	u_C	1	-
VT ratio error	η_V	u_V	1	-
Power meter	P_W	u_P	1	0,53
Phase displacement	$\frac{1}{1-(\Delta\varphi v-\Delta\varphi c)\tan\varphi}$	u_{FD}	1	C〉 0,56 〈C
Ampere meter	I_M	u_{IM}	2	0,24

The combined standard uncertainty of load loss measured at ambient temperature is given by:

C〉 $$u_{P2} = \sqrt{u_P^2 + u_{FD}^2 + u_{IM}^2} = \sqrt{0{,}53^2 + 0{,}56^2 + 0{,}24^2} = 0{,}81\ \%$$ 〈C

It is noted that in the uncertainty estimate, the contributions of practically interest are those related to the power meter and phase displacement.

A.8 Expanded uncertainty of the measured load loss (see 7.4)

The expanded relative uncertainty is:

C〉 $$U_{P2} = 2\ u_{P2} = 2 \cdot 0{,}81 = 1{,}61\ \%$$ 〈C

Passing to the absolute expanded uncertainty:

C〉 $$\dot{U}_{P2} = \frac{U_{P2}}{100} P_2 = \frac{1{,}61}{100} 86{,}997 = 1{,}4\ \text{kW}$$ 〈C

On the test report, the estimated result of the measurement should be given with the indication of the expanded uncertainty.

C〉 If the uncertainty is given in relative value, the load loss at ambient temperature 24,2 °C is to be expressed as follows:

$$87{,}0\ \text{kW} \pm 1{,}6\ \%$$ 〈C

Alternatively, if the uncertainty is given in absolute value:

C〉 $$87{,}0\ \text{kW} \pm 1{,}4\ \text{kW}$$

The result shall be also completed with the indication of the coverage factor, which for the example made was k = 2 (confidence level of about 95 %). 〈C

A.9 Uncertainty for reported load loss at reference temperature (see 7.5)

C〉 The additional loss at ambient temperature is given by:

$$P_{a2} = P_2 - I_N^2 \cdot R_2 = 86\ 997 - 69\ 500 = 17\ 497\ \text{W}$$

The absolute uncertainty of the measured loss and $I_N^2 R$ loss are obtained as follows:

$$\dot{u}_{P2} = \frac{u_{P2}}{100} P_2 = \frac{0{,}80}{100} 86\ 997 = 696\ \text{W} \quad \text{and} \quad \dot{u}_{R2} = \frac{u_{R2}}{100} I_N^2 R_2 = \frac{0{,}35}{100} 69\ 500 = 243\ \text{W}$$

The absolute uncertainty of the additional loss at temperature θ_2 is given by (see Table 3):

$$\dot{u}_{Pa2} = \sqrt{\dot{u}_{P2}^{\ 2} + (I_N^2 R_2 \cdot u_{R2})^2} = \sqrt{696^2 + 243^2} = 737\ \text{W}$$ 〈C

C〉 The reported load loss at reference temperature is calculated for copper conductors with *t*=235, reference temperature $\theta_r = 75$ °C and ambient temperature $\theta_2 = 24{,}2$ °C is given by:

$$\frac{t+\theta_r}{t+\theta_2}=1{,}196 \qquad \frac{t+\theta_2}{t+\theta_r}=0{,}836 \qquad I_N^2 R_2 \frac{t+\theta_r}{(t+\theta_2)^2} \cong 0{,}004\,6\, I_N^2 R_2$$

The reported loss at the reference temperature is thus given by:

$$P_{LL} = 1{,}196\, I_N^2 R_2 + 0{,}836\, P_{a2} = 83\,122 + 14\,627 = 97\,749 \text{ W}$$

The various contributions to the absolute uncertainty are calculated according to Table 4:

$$\text{For } I_N^2 R_2 \text{ loss: } \frac{t+\theta_r}{t+\theta_2} I_N^2 R_2 u_{R2} = 1{,}196 \cdot 69\,500 \cdot 0{,}35/100 = 291 \text{ W}$$

$$\text{For additional loss: } \frac{t+\theta_2}{t+\theta_r} \dot{u}_{Pa2} = 0{,}836 \cdot 737 = 616 \text{ W}$$

$$\text{For mean winding temperature: } \frac{t+\theta_r}{(t+\theta_2)^2} I_N^2 R_r\, u_{\theta 2} = 0{,}004\,6 \text{ x} \cdot 69\,500 = 320 \text{ W}$$

The combined absolute standard uncertainty is given by:

$$\dot{u}_{LL} = \sqrt{(1{,}196\, I_N^2\ R_2\ u_{R2})^2 + (0{,}836\, \dot{u}_{Pa2})^2 + (0{,}004\,6\, I_N^2\ R_2\ u_{\theta 2})^2} = \sqrt{291^2 + 616^2 + 320^2} = 753 \text{ W}$$

The expanded absolute uncertainty is obtained as:

$$\dot{U}_{LL} = 2\ \dot{u}_{LL} = 2 \cdot 0{,}753 = 1{,}51 \text{ kW}$$

which corresponds to a coverage probability of approximately 95 %.

The relative standard uncertainty is then:

$$u_{LL} = \frac{\dot{u}_{LL}}{P_{LL}} 100 = \frac{753}{97\,749} 100 = 0{,}77 \text{ \%}$$

and the expanded relative uncertainty:

$$U_{LL} = 2\ u_{LL} = 2 \times 0{,}77 \approx 1{,}5 \text{ \%}$$

which corresponds to a level of confidence of approximately 95 %. 〈C

A.10 Presentation of the results

On the test report, the estimated result of the load loss measurement should be given with the indication of the expanded uncertainty.

[C⟩ If the uncertainty is given in relative value, the load loss at reference temperature 75 °C is expressed as follows:

$$97,7\ \mathrm{kW} \pm 1,5\ \%$$ ⟨C]

Alternatively, if the uncertainty is given in absolute value:

[C⟩ $$97,7\ \mathrm{kW} \pm 1,5\ \mathrm{kW}$$

The text shall be also completed with the indication of the coverage factor that for the example made was k = 2 (coverage factor of about 95 %).

NOTE The probability that the loss is higher than (97,7+1,5) kW is therefore 2,5 %. ⟨C]

Annex B
(Informative)

Example of load loss uncertainty evaluation for a distribution transformer

B.1 General

The following example refers to the evaluation of the uncertainty that affect the measurement of load loss performed on a distribution transformer, at ambient temperature and using a three phase power analyzer.

In the text, reference is made to the clauses of the main document, while the numerical example was derived from a real measurement experience performed on a three-phase distribution transformer.

B.2 Transformer ratings

The main transformer ratings are reported in Table B.1.

Table B.1 – Transformer ratings

Number of phase	3
Rated frequency	50 Hz
Rated power	2 000 kVA
Rated voltages	6 000/420 V
Rated currents	192,5 / 2 749 A
Short-circuit impedance	6 %
Load loss (guarantee value)	13 600 W
Winding connections	Delta/star

B.3 Measuring method and instrumentation used

The transformer was supplied from the high voltage winding with the low voltage winding short-circuited.

The following instrumentation was used:

- three system power analyser by which the active power, currents and voltages were measured;
- current transformers: rated ratio 200/5 A, accuracy class 0,1;
- temperature sensors applied to the transformer tank or windings to estimate the average winding temperature.

B.4 Model of the measurand (see 7.2)

C⟩ The model function for load loss referred to rated current and ambient temperature is the following (considering that no voltage transformer is used): ⟨C

$$\text{[C⟩}\ P_2 = k_{CN}\left(1+\frac{\varepsilon_C}{100}\right)\cdot\frac{P_W}{1+\Delta_{\varphi C}\tan\varphi}\cdot\left[\frac{I_N}{k_{CN}\times I_M}\right]^2\ \text{⟨C]}$$

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:

$$\text{[C⟩}\ \varphi = \varphi_M + \Delta_{\varphi C} = \arccos\left(\frac{P_W}{I_M U_M}\right) + \Delta_{\varphi C}\ \text{⟨C]}$$

The corrective term for phase displacement is given by:

$$\text{[C⟩}\ \frac{1}{1+\Delta_{\varphi C}\tan\varphi}\ \text{⟨C]}$$

When the ratio error of the current transformers and its uncertainties are very low, the model may be reduced as follows:

$$\text{[C⟩}\ P_2 = k_{CN}\ \cdot\ \frac{P_W}{1+\Delta_{\varphi C}\tan\varphi}\cdot\left[\frac{I_N}{k_{CN}\times I_M}\right]^2\ \text{⟨C]}$$

B.5 Results of the measurements

On the examined transformers, the following measuring results at ambient temperature were obtained from the power analyzer are reported in Table B.2.

Table B.2 – Measured quantities

Test current (corresponding to rated current)	4,812 A
Power meter indication at rated current (P_W)	337,5 W
Test voltage	365,0 V
Power factor ($\cos\varphi_M$):	0,111
Measured active power at rated current:	13 500 W
The indications of the three power systems were of the same order.	

The estimate of the phase angle between voltage and current results (see 7.2):

$$\text{[C⟩}\ \varphi = \arccos\left(\frac{P_W}{I_M\cdot U_M}\right) + \Delta_{\varphi C} = \arccos\left(\frac{337{,}5}{4{,}812\cdot\sqrt{3}\cdot 365{,}0}\right) + \frac{0{,}035}{100}\cdot\frac{180}{\pi} = 83{,}63 + 0{,}02 = 83{,}65\,^\circ\ \text{⟨C]}$$

The corresponding tanφ is therefore equal to 8,99.

The corrective term results the following:

$$\text{[C⟩}\ F_D = \frac{1}{1+\Delta_{\varphi C}\tan\varphi} = \frac{1}{1+\dfrac{0{,}035}{100}\cdot 8{,}99} = 0{,}997\ \text{⟨C]}$$

The corrected power is therefore:

C〉 $$P_2 = k_{CN} \cdot P_W \cdot F_D = 40 \cdot 337{,}5 \cdot 0{,}997 = 13\,460 \text{ W}$$ 〈C

B.6 Estimate of the single contributions to the uncertainty formation

B.6.1 General

Following the indication given in the main document, the single contributions to the formation of the uncertainty that affected the measurand are discussed.

B.6.2 C〉 Power meter (see 10.5) 〈C

According to the instrument manual, the accuracy of the measured power is given by the combination of a number of terms. For the cases under consideration the accuracy resulted of ±0,57 %.

The corresponding standard uncertainty estimated is:

C〉 $$u_{PW} = \frac{0{,}57}{\sqrt{3}} = 0{,}33\,\%$$ 〈C

For the current measurement, the same instrument assured an accuracy of ±0,42 % at which the following standard uncertainty corresponds:

C〉 $$u_{IM} = \frac{0{,}42}{\sqrt{3}} = 0{,}24\,\%$$ 〈C

For the voltage measurement, the instrument assured an accuracy of ±0,25 % at which the following standard uncertainty correspond:

C〉 $$u_{UM} = \frac{0{,}25}{\sqrt{3}} = 0{,}14\,\%$$ 〈C

B.6.3 Current transformers (see 10.3)

For the measurement, current transformers of accuracy class 0,1 according to the IEC standard in force) were used.

C〉 For the type of transformer under test the values of the ratio error and displacement error given by the calibration certificate can be considered, as indicated in Table B.3. Uncertainty statements have been given as standard uncertainty in the table. 〈C

Table B.3 – Calibration of the current transformers

Rated ratio	**Accuracy class**	**Ratio error** (%)		**Phase displacement** (centiradians)	
		ε	u_c	**Value**	C〉 $u_{\Delta\varphi_c}$ 〈C
200/5	0,1	0,0	0,01	+ 0,035	0,01
NOTE The errors reported in the table are those measured including burden and connections corresponding to the instrument used.					

B.6.4 Corrective term uncertainty (see 10.3.2)

The corrective term uncertainty is given by.

C〉 $$u_{FD} \approx \frac{u_{\Delta_{\varphi C}}}{100} \cdot \tan\varphi \cdot 100 = 0{,}01 \cdot 8{,}99 = 0{,}09\ \%$$ 〈C

B.7 Uncertainty of the load loss measured at ambient temperature (see 7.4)

The uncertainty affecting the load loss at ambient temperature can be estimate using the results of the previous elaborations as summarized in Table B.4.

Table B.4 – Uncertainty contribution

Quantity	Estimate	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution
Power meter	P_W	u_P	1	0,33 %
C〉 Phase displacement	$\frac{1}{1+\Delta_{\varphi C}\tan\varphi}$	u_{FD}	1	0,09 % 〈C
Ampere meter	I_M	u_{IM}	2	0,48 %

C〉 The combined uncertainty of load loss P_{LL} measured at ambient temperature is given by:

$$u_{LL} = \sqrt{u_P^2 + u_{FD}^2 + u_I^2} = \sqrt{0{,}33^2 + 0{,}09^2 + 0{,}48^2} = 0{,}59\ \%$$ 〈C

B.8 Expanded uncertainty of the load loss (see 7.4)

The relative expanded uncertainty is:

C〉 $$U_{LL} = 2\,u_{LL} = 2 \cdot 0{,}59 = 1{,}18\ \%$$ 〈C

Passing to the absolute expanded uncertainty:

C〉 $$\dot{U}_{LL} = \frac{U_{LL}}{100} P_{LL} = \frac{1{,}18}{100} 13{,}5 = 0{,}16\ \text{kW}$$ 〈C

On the test report, the estimated result of the measurement should be given with the indication of the expanded uncertainty.

If the uncertainty is expressed in relative value, the load loss at ambient temperature is to be declared as follows:

13,5 kW ± 1,32 %

Alternatively, if the uncertainty is given in absolute value:

13,5 kW ± 0,18 kW

C〉 The result shall be also completed with the indication of the coverage factor that for the example made was k = 2 (coverage factor of about 95 %). 〈C

Bibliography

[C⟩ EN 61869-1, *Instrument transformers – Part 1: General requirements* (IEC 61869-1)

EN 61869-2, *Instrument transformers – Part 2: Additional requirements for current transformers* (IEC 61869-2)

EN 61869-3, *Instrument transformers – Part 3: Additional requirements for inductive voltage transformers* (IEC 61869-3)

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CLC/TR 50462:2008, *Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors* ⟨C]

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