IEC 60076-19-1

Edition 1.0 2023-05

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Power transformers –
Part 19-1: Rules for the determination of uncertainties in the measurement of the losses of power transformers

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Transformateurs de puissance –
Partie 19-1: Règles pour la détermination des incertitudes de mesure des pertes des transformateurs de puissance

76-19-1-2023

IEC 60076-19-1:2023-05(en-fr)

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ELECTROTECHNICAL
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ICS 29.180

ISBN 978-2-8322-7024-0

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POWER TRANSFORMERS –

Part 19-1: Rules for the determination of uncertainties in the measurement of the losses of power transformers

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The text of this International Standard is based on the following documents:

Draft	Report on voting
14/1105/FDIS	14/1107/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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 document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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INTRODUCTION

The losses of power transformers (no-load and load losses) are the object of guarantee and penalty in many 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 Ecodesign Directive of the European Union (Directive 2009/125/EC), can also pose requirements on the establishment of reliable values for losses.

According to ISO/IEC 17025 and ISO/IEC Guide 98-3, the result of any measurement should be qualified with the evaluation of its uncertainty. A further requirement of those documents is that known corrections shall have been applied before evaluation of uncertainty. These provisions have been applied in this document.

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

This document deals with the measurement of the losses, which 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 of power transformers:

- 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 the 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.

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 procedures developed in this document for evaluation of measurement uncertainty are provided as a tool to assess the soundness of results of loss measurements. Uncertainty is understood as a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [SOURCE: IEV 311-01-02].

In cases where the losses are required to conform to stated tolerance limits, it is recommended that measurement systems are of such quality that their estimated uncertainty is less than the tolerance limit. (As an example, a measurement with a 5 % uncertainty on a test where the tolerance limit is 5 % is acceptable if the measured value lies within the tolerance limit.) This situation can occur for example in market surveillance activities. It can be noted that an uncertainty 3 % is regarded as state-of-the-art for uncertainty of loss.

Treatment of measurement results is defined as follows in IEC 60076-8:1997, 10.1: "The submitted test result shall contain the most correct estimate that is possible, based on the measurements that have been carried out. This value shall be accepted as it stands. The uncertainty margin shall not be involved in the judgement of compliance for guarantees with no positive tolerance or tolerance ranges for performance data of the test object."

In Annex A to Annex C of this document, examples of uncertainty calculations are reported for no-load and load loss measurements on large power and distribution transformers. Annex D provides information on determination of the exponent for applied voltage in no-load loss measurement. Annex E provides information on uncertainty in measurement. Annex F provides information on calculation of uncertainty of losses with different reference temperatures and/or winding material.

International Standards, Technical Reports and Guides which are mentioned in the text of this document, but which are not indispensable to its application, are listed in the Bibliography at the end of this document.

Loss of reactors is not within the scope of this document. A separate part of IEC IEC60076-19 to handle loss of reactors is under consideration.

A problem with symbols has been rectified, where the symbol for voltage has been changed from U to V to avoid confusion with expanded uncertainty. The new symbol is accepted in IEC 60050-121:2002, 121-11-27 for the case when the corresponding electric field is irrotational.

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POWER TRANSFORMERS –

Part 19-1: Rules for the determination of uncertainties in the measurement of the losses of power transformers

1 Scope

This part of IEC 60076 defines the procedures that are applied to evaluate the uncertainty affecting the measurements of no-load and load losses during the routine tests on power transformers.

This document centres on measuring systems utilizing digital instruments, although the procedures can be adapted to evaluation of systems with analogue instruments where further uncertainty sources have to be taken into account.

This document specifies how to determine measurement uncertainty and how to apply corrections for known errors in the measurement chain. Information vis-à-vis judgement and traceability are given in IEC 60076-8:1997, 10.1 and 10.2.

2 Normative references

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

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

IEC 60076-11:2018, *Power transformers – Part 11: Dry-type transformers*

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

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, modified – Notes to entry omitted.]

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
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]

3.4
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, modified – Notes to entry omitted.]

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3.5
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, modified – Note to entry omitted.]

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3.6
traceability
property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty

[SOURCE: ISO/IEC Guide 99:2007, 2.41, modified – "metrological" omitted from the term and notes to entry omitted.]

3.7
accuracy class
class of measuring instruments or measuring systems that meet stated metrological requirements that are intended to keep measurement errors or instrumental uncertainties within specified limits under specified operating conditions

[SOURCE: ISO/IEC Guide 99:2007, 4.25, modified – Notes to entry omitted.]

4 Symbols

4.1 General symbols

F_D	Parameter related to correction of power for phase displacement in measuring circuit
I_{RMS}	Current measured by the ammeter
I_S	Current measured by an advanced measuring system
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 reference current I_N
P_{LL}	Load loss at reference conditions and corrected for known errors 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
P_S	Power measured by an advanced measuring system
P_{ar}	Additional loss at reference temperature
P_{a2}	Additional loss at temperature θ_2
R_1	Resistance of the windings at temperature θ_1
R_2	Resistance of the windings at temperature θ_2
R_r	Resistance of the windings at reference temperature
t	Parameter related to the thermal coefficient of winding resistance
V_{avg}	Voltage measured with an instrument having rectified mean response
V_N	Rated voltage
V_{RMS}	Voltage measured using an instrument with true RMS response
θ	Temperature (°C)
θ_1	Temperature of transformer winding at cold winding resistance test according to IEC 60076-1 (°C)
θ_2	Temperature of transformer windings during load loss test (°C)
Θ_r	Reference temperature for transformer windings according to IEC 60076-1 (°C)
$\Delta_{\varphi C}$	Actual phase displacement of the current transformer (rad)
$\Delta_{\varphi V}$	Actual phase displacement of the voltage transformer (rad)
ε_{CT}	Actual ratio error of the current transformer (% of nominal ratio)
ε_{VT}	Actual ratio error of the voltage transformer (% of nominal ratio)
φ	Actual phase angle between voltage and current (rad)
φ_M	Phase angle between voltage and current measured with power meter (rad)

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4.2 Symbols for uncertainty

4.2.1 General designations

u	Relative standard uncertainty
$\dot{u}$	Absolute standard uncertainty
U	Relative expanded uncertainty
$\dot{U}$	Absolute expanded uncertainty

4.2.2 Specific designations

u_{CT}	Uncertainty of current transformer ratio (expressed in percent of the ratio)
$u_{I\mathrm{RMS}}$	Uncertainty of current measurement
u_{IS}	Uncertainty of current measured by an advanced measuring system
u_{LL}	Uncertainty of the load loss
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 power meter
u_{PS}	Uncertainty of the power indicated by an advanced measuring system
u_{R1}	Uncertainty of the resistance R_1
u_{R2}	Uncertainty of the resistance R_2
u_{SH}	Uncertainty of resistance of current shunt
$u_{V\mathrm{avg}}$	Uncertainty of rectified mean voltage measurement
$u_{V\mathrm{RMS}}$	Uncertainty of RMS voltage measurement
u_{VT}	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
$u_{\Delta\varphi\mathrm{C}}$	Uncertainty of current transformer phase displacement
$u_{\Delta\varphi\mathrm{V}}$	Uncertainty of voltage transformer phase displacement

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NOTE Specific designations can be identified as relative or absolute as defined in the list of general designations.

5 Power measurement, systematic deviation and uncertainty

5.1 General

In this document, 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 measured using three independent (uncorrelated) single-phase measuring systems. These systems may comprise separate instruments or be combined in a three-phase instrument.

In general, losses are measured using current and voltage transformers in conjunction with a power meter. Voltage and current values can be measured with separate instruments or using built-in functions of the power meter. Currents are assumed to be measured as line currents and voltages as line-to-earth voltages.

Any measurement system can be characterised with a systematic deviation (error) and an uncertainty. When known, the systematic deviation should be corrected. If it cannot be corrected, it should be considered as an added uncertainty.

Inductive instrument transformers and resistive shunts used to measure current are considered to have negligible drift and therefore the evaluation of their performance can be appreciably enhanced by using calibration results to correct for known errors and as the basis for estimation of uncertainty.

All other measurement devices should be evaluated from their technical specifications (or accuracy class). Corrections are not applied and uncertainty estimates are based on the specifications. The residual deviations should be considered in the uncertainty estimations. For these cases calibration primarily verifies the specification.

Certain advanced measuring systems employ measuring principles that lead to negligible systematic deviations – but not negligible uncertainties. This should however always be carefully evaluated.

5.2 Traceability

Measurement devices used to establish losses shall have traceable calibrations.

5.3 Model function

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

The model functions presented in 6.2, 7.2 and 7.3 include both the measuring system and the test object in one equation.

5.4 Measuring systems

Measuring systems can be characterized either by a stated overall uncertainty verified by system-wide calibration, or by specifications of their components verified by component calibrations.

This document focuses mainly on uncertainty analysis based on component calibrations.

For systems characterized by an overall uncertainty, simplifications in the uncertainty analysis are possible, see 10.4.

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 performed at rated voltage and frequency and no corrections are to be applied for deviations from rated voltage in the test as there is no formula defined by IEC for such correction. A further consequence is that the uncertainty estimated in this document does not include contributions due to the non-linear behaviour of no-load loss as a function of test voltage.

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