Publishable Summary for 17NRM01 TrafoLoss
Loss Measurements on Power Transformers and Reactors

Overview

The Ecodesign Directive 2009/125/EC requires all power transformer manufacturers to unambiguously prove that their products comply with specific efficiency requirements to reduce grid losses and thereby save on costs and CO2 emissions. Driven by this EU regulation, CENELEC TC 14 "Power Transformers" has expressed the need for metrology research on more accurate and reliable loss measurements of high-voltage power transformers and reactors. This project addresses this need by developing new measurement systems for transformer and reactor loss measurements up to 230 kV and 2000 A with an uncertainty of 50 μW/VA or better, together with reference setups required for the calibration of these systems.

Need

Improved energy efficiency is one of the three targets of the EU 2020 Energy Strategy and a crucial theme in the whole energy chain from electricity generation, transmission, and distribution to the end user. Even small improvements in efficiency can have a large impact, for example when they are made in devices that convert large amounts of energy such as grid power transformers. Therefore, the Ecodesign Directive 2009/125/EC per 1 July 2015 requires all power transformer manufacturers to unambiguously prove that their products comply with specific efficiency requirements.

Power transformer manufacturers need reliable measurement tools to unambiguously demonstrate that their products meet energy efficiency claims and comply with the Ecodesign regulations. Energy efficiency is a key performance criterion for European manufacturers to distinguish themselves from lower-priced lower-quality competition from other parts of the world. To consolidate and further expand their competitive position, the European power transformer and reactor manufacturers expressed the need via CENELEC TC 14 "Power Transformers" for systems that allow more accurate and reliable loss measurements than are currently available with industrial measurement systems.

Utility companies want to make informed buying decisions based on verified efficiency specifications. Since power transformer losses constitute a very significant part of the total cost of ownership of these devices, utility companies are calling for high-accuracy verification of the losses. Increased measurement capabilities are also essential to market surveillance authorities (MSAs) in terms of carrying out their role ensuring fair competition and adherence to the Ecodesign regulations.

Presently available industrial loss measurement systems (LMS) are limited in accuracy to 100 – 300 µW/VA. This is insufficient to meet the present need for measurement uncertainties of 50 µW/VA or better. This in turn requires primary reference setups with 2–3 times lower uncertainties than those developed within the 14IND08 ELPOW project. Given the complexity of high-end loss measurements in industrial environments, CENELEC TC 14 also expressed the need for guidance in measurement uncertainty evaluation.

Objectives

The overall goal of the project is to directly address the need expressed by CENELEC TC 14 "Power Transformers" for metrology research in the area of power transformers and power reactors. The specific objectives of the project addressing this need are:

1. To develop improved measurement techniques and prototypes for highly accurate measuring systems used for loss measurements of power transformers and reactors at very low power factor. The target accuracy is better than 50 µW/VA, at voltage levels of up to at least 230 kV, and current levels of up to at least 2 kA.

2. To develop reference calibration facilities capable of validating the outputs from objective 1. The goal is to generate and measure active loss power at very low power factors under laboratory and industrial conditions, to enable validation of the system performance. The target accuracy is better than 20 µW/VA, at voltage levels of up to at least 230 kV, and current levels of up to at least 2 kA.
3. To study the effects of using non-sinusoidal test signals on the final accuracy of loss measurements and to produce guidelines for evaluating the complex measurement uncertainties associated with loss measurements of high-power, high-efficiency power transformers and large reactors, in order to ensure an EU-wide common and correct approach.
4. To facilitate the take up of methods, technology and measurement infrastructure developed in the project by the standards developing organisations such as IEC TC 14 and CENELEC TC 14. To ensure that the outputs of the project are aligned with their need, communicated quickly to those developing the standards and to those who will use them, and in a form that can be incorporated into the standards at the earliest opportunity. In addition, to disseminate the outputs of the project to MSA, and ensure their take up by instrument and power transformer manufacturers.

Progress beyond the state of the art

Advanced industrial Loss Measurement Systems (LMS)

Commercial LMS are widely used by High Voltage (HV) transformer and reactor manufacturers. Typical state-of-the-art accuracies in industrial loss measurements are in the range of 1-3 % for power factors down to 0.01, corresponding to a LMS uncertainty of 100–300 µW/VA. Driven by the Ecodesign Directive, utility companies are now calling for 3-5 % accuracies down to a power factor of 0.001, particularly for shunt reactors, requiring LMS uncertainties of 30-50 µW/VA. New high-voltage measurement techniques including prototypes are being realised by this project that will allow this factor of 2–5 improvement in uncertainty with respect to the current state of the art. A further, major advantage of the new techniques is that they will allow three-phase loss measurement of reactors, resulting in significant time saving during tests.

Primary reference setup for calibration of advanced industrial LMS

In the 14IND08 ELPOW project, a reference setup for *reactor* loss measurement was produced with a voltage range of 500 V, as well as reference setups for calibration of transformer LMS up to 100 kV but with an uncertainty of only 50 µW/VA. As required by the power transformer community, this project is realising the extension of this reactor measurement setup to the multi-kV range whilst still maintaining high accuracy. Furthermore present primary reference setups at National Metrology Institutes (NMIs) are being improved by a factor of 2– 5 in uncertainty to better than 20 µW/VA.

Uncertainty evaluation of loss measurements

An important extension of the state of the art is a study of detrimental factors that occur on-site in the industrial environment where these systems are used, such as interference and non-sinusoidal input signals. This will ensure that the required challenging uncertainties can be achieved by industrial end-users. Given the complexity of loss measurements, the uncertainty evaluation of these measurements is also complex. Therefore the project is developing good practice guides to provide end-users with the necessary guidance in this uncertainty evaluation, extending the present guidance of the IEC 60076-19 standard.

<table>
<tr><th></th><th>Industrial
state of the art</th><th>14IND08 ELPOW</th><th>This project</th></tr>
<tr><td>Industrial reactor loss</td><td>100 µW/V
single phase</td><td></td><td rowspan="2">50 µW/VA up to 230 kV
three-phase</td></tr>
<tr><td>Industrial transformer loss</td><td>100–300 µW/VA up to
100 kV three phase</td><td></td></tr>
<tr><td>Primary reference reactor loss</td><td></td><td>10 µW/VA up to 0.5 kV</td><td rowspan="2">10 µW/VA up to 0.5 kV
20 µW/VA up to 230 kV</td></tr>
<tr><td>Primary reference transformer loss</td><td></td><td>50 µW/VA up to 100 kV</td></tr>
</table>

Results

Advanced industrial LMS

A key part of the project is the development of an advanced industrial LMS to move the present 50 μW/VA uncertainty of the 14IND08 ELPOW transformer loss measurement calibration setup from the NMI laboratory to the power transformer industry test floor. This will be a factor 2–5 improvement in total system uncertainty with respect to the current state of the art. Overall LMS system requirements have been defined based on existing literature and the results of a questionnaire, filled out by 13 stakeholders with their requirements concerning advanced LMS measurement range and accuracy.

Since the weakest point of the present industrial LMSs is in the voltage channels, two complementary HV measurement techniques have been designed and constructed: a new high-accuracy inductive voltage divider, and a capacitive divider with buffered output voltage. The capacitive divider has been realised and tested under reference laboratory conditions. Following the successful completion of these tests, the new voltage divider has been implemented in a test system of a reactor manufacturer, GE Grid Solutions Ltd, and has been used to measure the losses of several reactors. Several reactor loss measurements were performed during two separate measurement sessions. The measurements confirmed the correct operation of the capacitive voltage divider under industrial conditions, but some details still need to be improved. This is subject of present work.

All voltage channels developed in the project, including those of the LMS reference setups, will be evaluated in November 2020 at the premises of one of the project partners against its high-accuracy high-voltage reference standard. To this end, this reference standard has been carefully evaluated and improved in accuracy to better than 10 μV/V for voltage up to 100 kV. Present work concentrates on extending the measurement range to 230 kV, with the same uncertainty.

Primary reference setup for calibration of advanced industrial LMS

For the calibration of future commercial advanced LMS products, two NMI primary reference setups with complementary measurement approaches have been constructed that are a factor of 2–5 better in uncertainty than the 50 μW/VA setups of the previous 14IND08 ELPOW project. One of the reference setups has an extended measurement range of 230 kV (line-to-ground) in order to cover HV reactor loss measurements.

Several lines of research are underway to enhance the uncertainty of the present NMI primary power transformer reference setups by a factor of 2–5 to better than 20 μW/VA. These include:

- Development of new three-stage electronically-compensated current transformers (CTs) for the accurate measurement of test currents ranging from 1 A to 2000 A with an uncertainty of better than 10 μA/A in magnitude and 10 μrad in phase displacement. The CTs have been designed and are presently under construction following the delivery of the required components.
- A new sampling power measurement technique has been developed and characterised, especially for the low power factors relevant for transformer loss measurements. After an extensive evaluation, the measurement uncertainty in the (low-voltage) power measurement has been reduced from 15 μW/VA to less than 10 μW/VA.
- The voltage scaling technique of one of the reference setups, based on a high-voltage capacitor and current-comparator-based low-voltage electronics, has been thoroughly evaluated. Comparison of the calibration results of the components of the voltage divider and the divider as a whole showed agreement to better than 8 μV/V for voltages up to 100 kV. Together with the improved power measurement uncertainty, this is a major step forward in achieving the required 20 μW/VA uncertainty in the overall LMS calibration.
- A HV parallel plate capacitor has been rebuilt and is presently being evaluated. This will be a key instrument for determining the absolute value and voltage dependence of the dissipation factor (tan δ) of HV capacitors used in the voltage channels of the reference setups. Work has also started on the accurate characterisation of a high-voltage capacitance bridge (HVCB) that is needed to perform the DF measurements.

- The accuracy of an existing reference high-voltage transformer has been evaluated, and improvements have been realised that allowed to reach an uncertainty of better than 10 μV/V in magnitude and 10 μrad in phase displacement. This reference transformer will be used to evaluate the accuracy of the new HV voltage channels developed in the project.

A first draft of a good practice guide on LMS calibration has been prepared, summarising the pro's and con's of LMS component and system calibration, including a discussion of the achievable uncertainties. The draft also includes a first discussion on calibration intervals and cross-checks versus risk. The contents of the draft good practice guide have been used to train DNVGL–KEMA inspectors of power transformers. Based on the guide, also a paper has been prepared that has been presented to the wider power transformer industry at the ICTRAM'2019 conference. The feedback received at these occasions is presently used to prepare a final version of the LMS calibration guide.

An important aspect of future research in the project is a study of the additional detrimental factors that occur on-site in the industrial environment where these systems are used, such as signal pollution, interference, amplitude and frequency instability of the applied test voltage, etc. This will ensure that the required uncertainties can be achieved in end-user environments.

Uncertainty evaluation of loss measurements

Given the technical complexity of accurate loss measurements, the uncertainty evaluation of transformer and reactor loss measurements is also complex. The project is developing the necessary guidance for power transformer and reactor manufacturers for the measurement uncertainty evaluation of their products. To this end, extensive input was provided to the present revision of the IEC 60076-19 standard on uncertainty evaluation of power transformer loss tests. In addition, the IEC and CENCELEC 60076-19 standards are presently being extended by the project to uncertainty evaluation of reactor measurements. Together with the Chief Stakeholder ABB AB Power Transformers, a mathematical model function for uncertainty analysis of reactor loss measurements has been drafted. The model is presently being refined and discussed with other reactor manufacturers. Work has started to prepare example calculations based on the mathematical model.

A final important step forward with respect to the state-of-the-art is a study on the effects of non-sinusoidal waveforms on loss measurement uncertainty. So far, all LMS calibrations are performed with sinusoidal waveforms only. This is close to the actual conditions during reactor loss measurements, but far away from the conditions during no load loss measurement of transformers, where the current Total Harmonic Distortion can easily be 60 %. The final aim of this activity is to provide more clarity on the loss measurement uncertainty under these non-ideal conditions. A literature review has been performed on the non-sinusoidal waveforms during power transformer and reactor loss measurements. Based on this review, test conditions are identified under which waveforms will be collected by the project partners during actual transformer or reactor tests at the locations of 2 project stakeholders. A first set of waveforms occurring during no-load-loss (NLL) transformer tests have been received from stakeholder Royal Smit Transformers. From the analysis of these waveforms it appeared that higher resolution is needed in the raw data. New waveforms with higher sampling rate will be recorded in the coming months.

Impact

The main overall impact of the project lies in the metrology support it provides for successful implementation of the Ecodesign Directive 2009/125/EC on power transformer efficiency, which positively impacts European industry, NMIs, market surveillance authorities and standardisation development organisations. So far, the project has disseminated its aims and results to a variety of stakeholders via a mid-term stakeholder workshop, conference presentations, peer-reviewed papers, its website, a training course on "Power Transformer Loss Measurements: Accuracy, Calibration, Traceability & Uncertainty evaluation", and input to standards development organisations.

A major achievement in the past year is the extensive early uptake of the project results by the stakeholder community: one of the new LMS voltage channels has been used in actual on-site loss measurements of reactors at the premises of GE Grid Solutions Ltd, whereas the two primary reference setups for on-site system calibration of power transformer loss measurement systems has been used for LMS calibrations at in total 13 stakeholder premises.

Impact on industrial and other user communities

The project is stimulating innovation and impacting the competitiveness of the European HV manufacturing and test industries by providing them with advanced measurement systems for unambiguous determination of the quality of their products. The reduced uncertainty that this new instrumentation allows for in loss measurements can be used to reduce safety margins proportionately, thus decreasing production costs. This will support the European electrical power industry in keeping its competitive advantage with respect to lower-priced but also lower-quality competitors. The development of the ultra-accurate measurement technologies, including two industrial prototype implementations, is keeping the European transformer and instrumentation industry at the forefront of industrial loss measurements of power transformers and reactors. Early impact of the project is achieved via testing of the new industrial prototype voltage divider at the premises of a reactor manufacturer, GE Grid Solutions Ltd. The subsequent use of the voltage divider in testing of several HV reactors proved that lower test uncertainties indeed can be achieved with the new instrumentation.

Next to the new industrial LMS facilities, improved calibration services are being established that will provide power transformer and reactor manufacturers and MSA with access to on-site calibration of such LMS facilities at voltages up to 230 kV and currents up to 2 kA. Another early uptake of the project results is the on-site calibration of industrial transformer LMSs using the improved reference setups developed in the project at Royal Smit Transformers, ABB, GE, Best, Eltaş, Astor, STD, BETA, Sönmez, Schneider, Maksan, and Ulusoy. Both these activities and the voltage divider testing are important verifications of the accuracy of new instrumentation developed in the project under actual on-site conditions at stakeholder premises, ensuring that the developed instrumentation will indeed achieve the envisaged impact.

The good practice guide for LMS calibrations under development by the project will be beneficial for ensuring a uniform approach in Europe for LMS calibration and support consistency in loss measurement results in tests performed by power transformer and reactor manufacturers. An early uptake of this knowledge has been achieved via the training of DNVGL-KEMA inspection experts in the HV industry on several aspects of Power Transformer Loss Measurements such as accuracy, calibration, traceability and uncertainty evaluation. Based on the guide, also a paper has been presented to the wider power transformer industry at the ICTRAM'2019 conference. The feedback received at these occasions is presently used to prepare a final version of the LMS calibration guide.

A highly successful midterm stakeholder workshop was held in September 2019 in Aachen, Germany, together with the 17IND06 FutureGrid II JRP and in conjunction with the 10th IEEE international workshop on Applied Measurements in Power Systems (AMPS). The more than 70 participants in both workshops were given updates of the projects progress via two project overview presentations, followed by lively discussions during 15 poster presentations by the project partners.

Impact on the metrology and scientific communities

The project is developing leading edge HV measurement technologies, not only via the primary reference setups for NMIs (reflected in new Calibration and Measurement Capabilities (CMCs)), but also via advanced industrial LMS with unprecedented accuracy for the power transformer industry. Knowledge dissemination to the academic and metrology community has been done at the mid-term stakeholder workshop and AMPS 2019 conference. Furthermore, the project results have been published in 6 peer-reviewed papers, and via 14 presentations at the CPEM 2018, ISH2019, AMPS2019, and ICTRAM2019 conferences.

The project objectives and progress have been presented to the attendants of the 2018 and 2019 meetings of the EURAMET TC-EM contact persons meeting. The early project results have been presented to metrology specialists in the area of the project at the May 2019 meeting of the EURAMET TC-EM Sub-committee “Power and Energy” experts group. Cooperation on transformer loss measurement reference systems has also been initiated with the national metrology institutes of China (NIM) and Australia (NMIA). With NIM a formal collaboration agreement has been signed, and as part of this collaboration a NIM researcher has worked for 3 months at one of the project partners on the development and characterisation of a reference setup of LMS calibrations.

A good practice guide for LMS calibrations has been drafted that aims to provide useful guidance to NMIs and industrial calibration laboratories performing these calibrations. The draft has been presented to the wider stakeholder community at the ICTRAM 2019 conference, and is presently being finalised based on the comments received. The final version of the guide will be submitted to EURAMET and made available to end-users such as transformer manufacturers and MSA.

Impact on relevant standards

The project contributes to the implementation of the Ecodesign Directive 2009/125/EC which restricts the losses of power transformers placed on the European market after 1 July 2015. The execution of this regulation is supported via the development of industrial LMS and of primary reference setups for LMS system calibration and validation. The H2020 INTAS project supports MSAs via proper procedures and guidelines for market surveillance as required by the Ecodesign Directive and this project has provided input to this via participation in INTAS project surveys, via new expertise that is available for use in on-site test verifications and by attending INTAS project meetings, including the final INTAS project meeting in February 2019.

The project is a direct response to needs expressed by CENELEC TC 14 on loss measurements at very low power factors. The project R&D program and progress was presented at the 2018 and 2019 CENCELEC TC 14 meetings, and useful feedback was received to steer the project activities. Work has started to update the CLC Technical Specification 60076-19 with guidance in uncertainty evaluation of reactor loss measurements. Once the relevant material is available, NEC/TC 14-38 has agreed to submit a New Work Item Proposal, based on the project outcomes.

Longer-term economic, social and environmental impacts

This project will have a wider impact on the power transformer and reactor manufacturing industry. The HV transmission network is the backbone of our electricity supply chain, and thus requires its components to meet the highest quality standards. The project's results will allow the European electrical power industry to produce grid components of the required high quality and unambiguously demonstrate their performance at a level that presently is unavailable. Improved measurement uncertainties will also allow detection of the impact of small design improvements on transformer and reactor efficiency. It furthermore reduces the need to design products with 'better-than-spec' performance to guarantee 'on-spec' performance. The improved accuracy delivered by this project will reduce the required safety margin, and allow manufacturers to claim a guaranteed performance that is very close to the actual performance.

Given the large amounts of energy transmitted by power transformers, higher efficiencies and lower losses have an estimated saving potential of 3.7 Mt of CO_2 emissions per year. This project underpins the realisation of the European 2020 goals on higher efficiency, recognised by the EURAMET Strategic Research Agenda, via the development of a high-quality metrological infrastructure for loss measurements in power transformers and reactors. Without such an infrastructure, the requirements of the Ecodesign Directive cannot be successfully implemented by manufacturers nor monitored by MSA, and this important area for energy savings will not fully contribute to the goal of CO_2 reduction.

A secure and affordable electricity supply is of utmost importance for our society and specifically for European industry. The lower cost of ownership of transformers for utilities will lead to more affordable customer bills and reduced fuel poverty. The project will also support to the European HV power transformer and instrument manufacturing industry and enhance European competitiveness to secure jobs in Europe.

List of Publications

[1] E. Mohns, G. Roeissle, S. Fricke, and F. Pauling, "*A Sampling-Based Ratio Bridge for Calibrating Voltage Transformers*", CPEM 2018 conference proceedings. DOI: 10.7795/EMPIR.17NRM01.CA.20190411 available online: https://doi.org/10.1109/CPEM.2018.8501245

[2] G. Rietveld, E. Mohns, E. Houtzager, H. Badura, and D. Hoogenboom, *"Comparison of two Reference Setups for Calibrating Power Transformer Loss Measurement Systems"*, IEEE Trans. Instrum. Meas., 2019. DOI: 10.5281/zenodo.3561900 available online: https://zenodo.org/record/3561900#.XicXMse7KUk

[3] E. Mohns, J. Chunyang, H. Badura, P. Raether, *"A Fundamental Step-Up Method for Standard Voltage Transformers Based on an Active Capacitive High-Voltage Divider"*, IEEE Trans. Instrum. Meas., 2019. DOI: 10.7795/EMPIR.17NRM01.CA.20190408 available online: https://oar.ptb.de/resources/show/10.7795/EMPIR.17NRM01.CA.20190408

[4] J. Havunen, E-P Suomalainen, J. Tornberg, J. Hällström, T. Lehtonen, and A. Merviö, *"Measuring Losses of an Air-Core Shunt Reactor with an Advanced Loss Measuring System"*, ISH 2019 conference proceedings, 2019. DOI: 10.5281/zenodo.3521194 available online: https://zenodo.org/record/3521194#.XicW2Me7KUk

[5] A. Bergman, Allan Bergman, Bengt Jönsson, Gert Rietveld, Mathieu Sauzay, Jonathan Walmsley, and John-Bjarne Sund, *“Estimating Uncertainty in Loss Measurement of Power Transformers”*, ISH 2019 conference proceedings, 2019. DOI: 10.5281/zenodo.3559837 available online: https://zenodo.org/record/3559837#.XicWrMe7KUk
[6] G. Rietveld, Ernest Houtzager, Dennis Hoogenboom, and Gu Ye, *“Reliable Power Transformer Efficiency Tests”*, ICTRAM 2019 conference proceedings, 2019. DOI: 10.5281/zenodo.3559845 available online: https://zenodo.org/record/3559845#.XicWhce7KUk
[7] G. Rietveld, E. Mohns, E. Houtzager, H. Badura, and D. Hoogenboom, *“Comparison of two Reference Setups for Calibrating Power Transformer Loss Measurement Systems”*, IEEE Trans. Instrum. Meas., 2019. DOI: ok10.1109/TIM.2018.2879171 available online: http://dx.doi.org/10.1109/TIM.2018.2879171

Project start date and duration:		1 May 2018, 36 months
Coordinator: Dr.ir. Gert Rietveld, VSL Project website address: www.trafoloss.eu	Tel: +31 15 2691645	E-mail: grietveld@vsl.nl
Chief Stakeholder: Daniel Wikberg, ABB AB Power Transformers		
Internal Funded Partners: 1 VSL, The Netherlands 2 RISE, Sweden 3 TUBITAK, Turkey 4 VTT, Finland	External Funded Partners: 5 EPRO, Austria	Unfunded Partners: 6 PTB, Germany