FINAL PUBLISHABLE REPORT

Grant Agreement number	17NRM01
Project short name	TrafoLoss
Project full title	Loss Measurements on Power Transformers and Reactors

Project start date and duration:	1 May 2018, 41 months	
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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
RMG1: JV, Norway (Employing organisation); VSL, The Netherlands (Guestworking organisation)		

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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1 Overview

Driven by the Ecodesign Directive 2009/125/EC, CENELEC TC14 “Power Transformers” has expressed the need for more accurate and reliable loss measurements of high-voltage power transformers and reactors, that allow to unambiguously prove that these products comply with specific efficiency requirements of this Directive. This project has addressed this need by developing new measurement systems for transformer and reactor loss measurements up to 230 kV and 2000 A with an uncertainty of better than 50 μW/VA, together with reference setups required for the calibration of these systems with uncertainties down to the 20 μW/VA level.

2 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 TC14 “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.

Industrial loss measurement systems (LMS) available at the start of the project were limited in accuracy to 100 – 300 µW/VA. That was insufficient to meet the need for measurement uncertainties of 50 µW/VA or better, and in turn required 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, CENELEC TC14 also expressed the need for guidance in measurement uncertainty evaluation.

3 Objectives

The overall goal of the project was 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 were:

1. Development of 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 was 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. Development of reference calibration facilities capable of validating the outputs from objective 1. The goal was 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 was 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. Study of 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. Facilitation of the take up of methods, technology and measurement infrastructure developed in the project by the standards developing organisations such as IEC TC14 and CENELEC TC14. To ensure that the outputs of the project were 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, dissemination of the outputs of the project to MSA, and ensure their take up by instrument and power transformer manufacturers.

4 Results

4.1 Objective 1: Advanced industrial LMS with accuracy better than 50 µW/VA

This objective aimed to develop voltage channels to meet the requirements of at least 40 µV/V ratio measurement uncertainty and 30 µrad uncertainty in phase displacement at voltages up to 230 kV. The developed voltage channels should be suitable for use in advanced industrial loss measurement systems (LMS) enabling measurement accuracy of 50 µW/VA when measuring losses of power transformers and shunt reactors. Two different voltage channel designs were developed: a VTT design based on a capacitive voltage divider, and an EPRO design based on an inductive voltage divider. Each design was developed and extensively tested, and finally sent to PTB for validation tests where the performance was compared against a high-accuracy reference transformer.

4.1.1 Capacitive voltage divider

Aim of the VTT voltage divider design was to develop an active capacitive low-voltage arm that could be used with any typical gas-compressed high-voltage (HV) reference capacitor as high-voltage arm while providing small phase displacement. Gas-compressed HV capacitors have relatively good voltage linearity and are immune to the proximity effects whereas the temperature coefficient is relatively high (typically around 30 ppm/K) and related time constants are long. Temperature effects can be minimized by letting the capacitor to stabilize long enough before the measurements and by measuring the voltage channel scale factor before the measurements against another reference. Since different gas-compressed capacitors can be used with the low-voltage arm, the technology can easily be scaled up to 230 kV using suitable capacitor. VTT has already used this low-voltage arm technology with their 200 kV capacitive voltage divider.

The first version of the low-voltage arm is battery-powered, and consists of ceramic capacitors on the feedback loop of a buffer amplifier, providing load-independent output and very small phase error at powerline frequencies. This implementation is similar to the design originally published by PTB [1]. Several low-voltage arm prototypes were built to be used with different gas-compressed capacitors of VTT. Low-voltage arms and the complete voltage dividers were tested at VTT laboratory, and they were found to meet the project requirements for ratio error and phase displacement uncertainty.

After the successful laboratory tests, the voltage divider design was tested in an industrial environment together with reactor manufacturer GE Grid Solutions Ltd. Two voltage dividers with nominal voltages of 20 kV and 100 kV were used as a part of VTT LMS to measure losses of several air-core shunt reactors during two separate measurement sessions. Tests indicated that this kind of voltage channel is applicable even for air-core shunt reactor loss measurements where high magnetic fields are present. Following these tests, the design was slightly improved by changing the battery-operation to a 24 V power supply, improving protection against transients, and by including phase compensation in the output based on active lead-lag phase compensation. The phase-compensated output can be used to trim the naturally low phase error even closer to zero when used with a specific gas-compressed capacitor. Additionally, second measurement channel was included in the low-voltage arm design so that it could be used with gas-compressed capacitors with different capacitance values.

For final accuracy validation of this voltage divider it was sent to the PTB together with a 20 kV gas-compressed capacitor. This voltage divider is presented in Figure 1. Since the low-voltage arm was designed so that it would provide very small phase displacement with typical gas-compressed capacitors, the second channel of the low-voltage arm was planned to be used with one of PTB's gas-compressed capacitor which characteristics were unknown for VTT beforehand.

Internal VTT tests of the final design showed the voltage linearity to be within 16 µV/V over the whole voltage range and a temperature coefficient of -36 ppm/K. The phase displacement was stable within ± 3 µrad over the whole voltage range. The measurement uncertainty at VTT was 30 µV/V and 10 µrad. The VTT characterization indicated that the project's uncertainty requirements of 40 µV/V in ratio measurement and 30 µrad in phase displacement can be met when the ambient temperature is stable and known so that the effect of temperature to the ratio can be corrected for.

Figure 1. VTT voltage channel design: 20 kV gas-compressed capacitor and the active low-voltage arm.

Figure 2. EPRO voltage channel based on 100 kV inductive voltage transformer.

4.1.2 Conventional voltage transformer

The design of the new EPRO voltage divider is based on a standard voltage transformer (100 kV) which has very low natural error and a high stability over time. The divider is presented in Figure 2. The high-voltage side of the transformer is designed so that it uses a very large core, high effective layer length, and minimum space between the high-voltage and low-voltage coils to ensure good performance. The transformer has ranges for 15 kV and 85 kV nominal voltages, but the design can be easily scaled up to 230 kV without trade off in its errors.

The low-voltage side of the transformer was designed to have two different error compensations. The first one is a standard compensation which is constant over the complete voltage range so that it can only be used to adjust the errors systematically without improving the linearity of the system. The second compensation method is a variable error compensation, designed specifically for the project. The variable error compensation can change its value over the input voltage range such that the lower part of the measurement range can be compensated more. This is a very important feature since inductive voltage transformers typically have higher errors in the lower part of their measurement range. Both compensations are based on passive elements which is expected to positively contribute to the long-term stability of the system.

This voltage divider has also an option for digital output from a unit called V-Box which is built into the base structure of the voltage divider. This unit gives possibility to apply separate software corrections for both ratio error and phase displacement for specific voltage levels. This feature was not used in the final evaluation of the voltage transformer in the project (see section 4.1.4).

Internal tests at EPRO showed that the variable error compensation had a good impact on the ratio error and only small impact on the phase error. It was found challenging to design the variable compensation in such a way that can significantly improve both phase and ratio errors. During the internal EPRO tests, ratio errors were less than 20 µV/V and phase displacements typically less than 30 µrad, except at the lowest input voltages of the 85 kV range where the error was almost 60 µrad. Measurement uncertainties at EPRO were 20 µV/V and 20 µrad.

4.1.3 Improved reference setup for voltage transformer calibration

The PTB measuring system that was used to verify the developed VTT and EPRO voltage channels consists of a ratio bridge (ESM IV) and long-term stable voltage transformers. In this project, two different voltage transformers were used to cover the 20 kV and 80 kV test ranges.

The principle of the ratio-based comparison method is shown in Figure 3. The secondary output voltages of the voltage divider under calibration ($\underline{U}_X$ of VT X) and of the reference transformer ($\underline{U}_N$ of VT N) are scaled such that their ratios are close to one using separate very accurate voltage transformers (VT A and VT B) inside the measurement system. The resulting voltages are subsequently compared using a high-resolution sampling system (HRPM) [2].

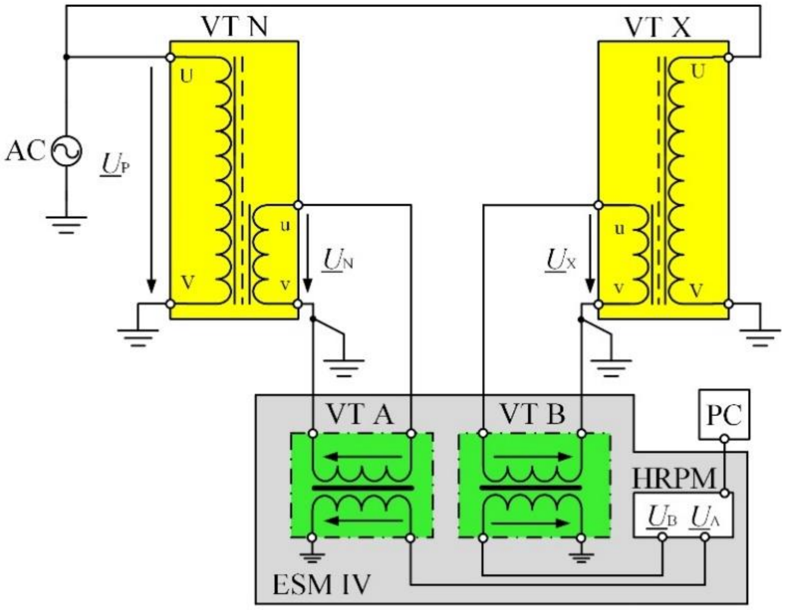

Figure 3. Ratio-based calibration method for voltage transformers at PTB. See text for further explanation.

The PTB measuring system can be used for calibration of voltage channels from 1 kV up to 300 kV in the frequency range from 16.7 Hz to 60 Hz. The system was carefully characterized so that the best possible uncertainty of the voltage transformer calibration system of 4 µV/V and 4 µrad can be achieved without the characteristics of a device under test and without Type A uncertainty contributions. In practise, the estimated uncertainties related to the calibration of the voltage channels developed in this project are 10 µV/V and 10 µrad. The long-term stability of the PTB system has been extremely good so that it can be assumed that there is no drift within the 2 months that was reserved for the validation measurements.

4.1.4 Verification of voltage channels of advanced industrial LMS

The two voltage channels developed in the project by VTT and EPRO were sent for an independent verification of their accuracy to the PTB laboratory where they were compared to the improved reference setup described in section 4.1.3. Each voltage channel was sent with suitable operation instructions for PTB staff to ensure adequate set up and operation of the voltage channels. Unfortunately, travel restrictions due to the COVID-19 pandemic prevented VTT and EPRO staff to attend the verification measurement campaign at the PTB premises. The PTB measurements were performed within 2 months during summer 2021 for EPRO and VTT voltage dividers.

Careful planning of the measurement campaign, including operating instructions and reporting template, allowed PTB to perform the measurements essentially without further practical guidance from EPRO and VTT. In order to reduce interferences, the measurements were performed at 50.2 Hz frequency and optionally at 60 Hz. Two different voltage ranges, 20 kV (low) and 70 kV (high), were used in the characterization.

The analysis of the results was performed by VTT. The results with the uncertainty requirements are presented in Figure 4. The inductive voltage divider developed by EPRO qualified the uncertainty requirements for ratio error except for the lowest test point of the 70 kV range where the result is essentially at the uncertainty limit within the measurement uncertainty. For the phase displacement the uncertainty requirements are met only partly by the EPRO voltage divider. The capacitive voltage divider developed by VTT qualified the uncertainty requirements for ratio error and phase displacement when the temperature dependency and the voltage dependency of the high-voltage capacitor were corrected. The phase displacement of the 20 kV system would also fulfil the uncertainty requirements needed for reference systems. The ratio error of the 70 kV system is not defined since the high-voltage capacitor was provided by PTB and the capacitance value was unknown to VTT, but the phase displacement of this system was well within the uncertainty limits.

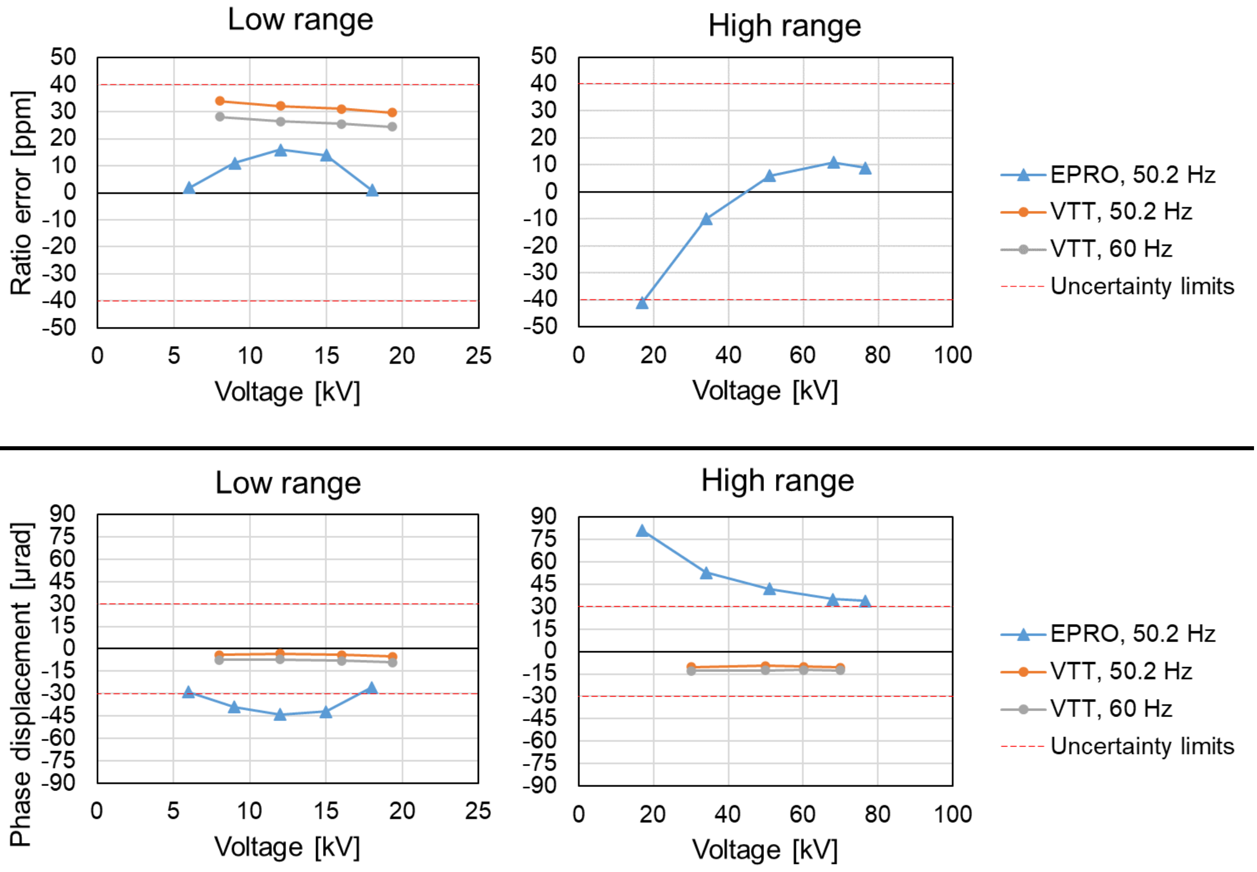

Figure 4. Verification overview of ratio error (top) and phase displacement (bottom) of the two HV voltage channels developed in the project (EPRO, VTT). All results are shown as difference to the PTB reference system. Red lines indicate the project uncertainty limits of 40 ppm and 30 µrad respectively.

4.1.5 Summary

Two new voltage channels suitable for use in industrial advanced loss measurement systems were designed and built. The measurement ranges were 20 kV and 80 kV, but both developed technologies can be scaled up to 230 kV. After internal tests of the voltage dividers by the respective manufacturers EPRO and VTT, their final accuracy was evaluated by comparison to a PTB reference setup for voltage transformer calibrations.

The PTB verification tests showed that the developed inductive voltage divider achieved the 40 µV/V uncertainty requirement for ratio error. However, for meeting the 30 µrad phase displacement requirement, corrections needed to be applied. These for example can be implemented as software corrections in the digital readout box that was developed together with the voltage divider.

For the developed capacitive voltage divider, the PTB verification tests showed that it achieved the uncertainty requirements for both ratio error and phase displacement. With a 20 kV high-voltage capacitor and after tuning the low-voltage electronics, the phase displacement was around 10 µrad, close to the level required for reference level instrumentation. Results achieved for the 70 kV range demonstrated that the low-voltage arm design can be used with any gas-compressed HV capacitor and still achieve good ratio linearity and small phase displacement.

In conclusion, the first JRP objective of developing improved measurement techniques and prototype voltage channels for highly accurate measuring systems used for loss measurements of power transformers and reactors at very low power factor with at least 50 µW/VA uncertainty up to 230 kV and 2 kA has been achieved.

4.2 Objective 2: Primary reference setups for calibration of advanced industrial LMS with accuracy better than 20 µW/VA

This objective aimed to develop primary reference facilities capable of calibrating the advanced industrial LMS developed in 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 of advanced industrial LMS. 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. To achieve the required uncertainty of the present primary power transformer reference setups, each component (voltage channel, current channel and power meter) of the developed system needs to have 2-5 times better uncertainty than 20 µW/VA.

4.2.1 Good practice guide on LMS calibration

Reliable loss measurements support the drive for higher efficiency in power transformers and shunt reactors. A crucial element to ensure reliable loss measurements is traceable calibration of the system used for these tests. In order to provide useful guidelines for end-users for the calibration of advanced industrial LMS, a good practice guide is formulated including the development of more accurate industrial LMS, improved LMS calibration approaches, and a reference system for on-site LMS calibration together with practical and other related measurement issues, e.g. determination of calibration interval, performance of cross-checks and error compensation.

The loss measurement accuracies required by utilities can go down to an accuracy of better than 0.5 % at PF = 0.01, corresponding to a power measurement uncertainty of 50 µW/VA. At these accuracy levels, great care is required in the LMS calibration to correctly verify that this accuracy indeed is achieved. ‘System calibration’ of the LMS as a whole is more complex to perform but covers all possible errors in the LMS and reaches the best accuracies. The best confidence in the LMS tests is achieved when this ‘system calibration’ is combined with a calibration of the LMS components over all ranges. All LMS calibrations must be traceable to (inter)national reference standards. This is best achieved by a laboratory that is ISO\IEC 17025 accredited for this calibration.

When the LMS is adjusted, the LMS should be calibrated both before and after the adjustment to know the actual LMS behaviour and drift in the past. A general re-calibration period of 3 year is recommended to power manufacturers but the actual interval has to be decided by themselves by balancing the calibration costs and costs of possible corrective actions. Cross-checks are an effective and convenient tool to monitor the accuracy between calibrations as they serve as a ‘sanity check’ of the calibration status of the LMS.

The good practice guide presents a series of measures to assure that power transformer efficiency tests performed by power transformer manufacturers are accurate and reliable. It stimulates further development of more accurate industrial LMS, the use of optimized LMS calibration approaches, and use of ISO/IEC 17025 accredited reference systems for on-site LMS calibration. The guide is focused on a practical and consistent interpretation of the necessary elements of an LMS calibration application.

4.2.2 Primary reference setups 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. The aimed uncertainty of these reference setups is a factor of 2–5 better than the 50 µW/VA of future advanced LMS systems. The VSL reference system has extended the measurement range of 230 kV (line-to-ground) to not only cover power transformers loss tests, but also HV reactor loss measurements with an uncertainty of 20 µW/VA in loss power. The TUBITAK reference system aims to reach an uncertainty of 20 µW/VA and at least better than 50 W/VA depending on the voltage level and power factors.

VSL reference system

A primary reference setup has been developed in VSL for on-site system calibration of LMSs. The basic approach of the calibrations is that the reference system simulates a power transformer with different losses to the LMS. A digital feedback loop assures generation of a current with stable and known phase with respect to the applied high voltage. Via optimized feedback loop parameters and careful calibration of the components in the reference setup, an overall accuracy of better than 0.2 % in loss power at PF = 0.01 is achieved (corresponding to 20 µW/VA in loss power). This low uncertainty meets the calibration requirements of even the most advanced industrial LMS.

Figure 5 gives more details on the VSL reference setup for system calibration of industrial LMS. A current-comparator-based capacitive voltage divider provides a low-voltage copy of the applied high voltage. A digital signal processing (DSP) unit subsequently generates a driving signal for the transconductance amplifier G that generates the high test current. The actual applied current is measured with an active electronically-compensated current transformer (CT). The DSP unit subsequently compares the actual phase of the current with the desired setpoint and adjusts the driving signal until the actual current phase matches the setpoint. A second current transformer and a reference watt meter is used to verify the readings from the digital feedback loop. Such an independent verification is important in case a deviation of the LMS is detected during the calibration, and the power transformer manufacturer subsequently starts to question the accuracy of the reference system with which the LMS is calibrated.

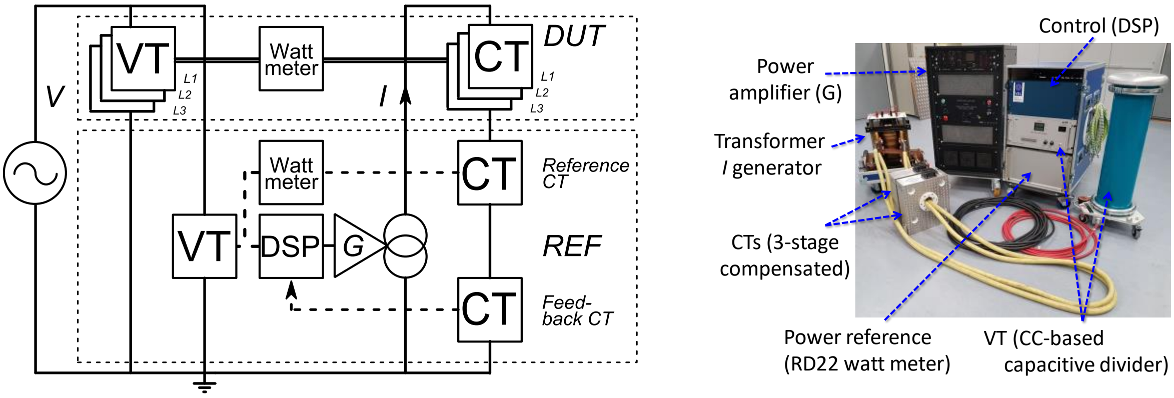

Figure 5. Detailed schematic of the VSL reference setup for LMS system calibration (left, lower half, REF), and a picture of its actual components (right). The top part of the schematic shows the customer system (DUT), with three voltage channels (VTs) and current channels (CTs) put in parallel/series respectively.

Table I shows the overall accuracy of the reference setup based on careful calibration of all its components. This uncertainty budget proves that the setup achieves an accuracy of better than 0.2 % at power factors down to 0.01, for voltages up to 230 kV and currents up to 2 kA. In a comparison of the VSL and PTB LMS reference setups this accuracy was independently verified. The measured difference in the VSL and PTB results was less than 12 µW/VA (0.12 % loss power at PF = 0.01) for currents up to 1000 A and voltages up to 70 kV [3]. This is well within the measurement accuracies of the VSL and PTB reference setups.

Table I. Uncertainty budget of the VSL reference setup for on-site LMS calibration at PF = 0.01, for voltages up to 230 kV and currents up to 2000 A. The final 0.15 % uncertainty corresponds to 15 µW/VA uncertainty in the loss power.

Uncertainty source	[%]
Voltage scaling - HV cap	0.05
Voltage scaling - LV unit	0.07
Current scaling	0.05
Power measurement	0.08
Noise	0.05
System effects	0.07
Total uncertainty (k = 2)	0.15

As with the advanced industrial LMS, a critical part of the VSL reference setup is the voltage channel. In the VSL setup, this is a capacitive voltage divider (CVD) consisting of a low-voltage current-comparator unit (MIL2500A), combined with high-voltage (HV) and low-voltage (LV) capacitors, see Figure 6. The advantage of this approach over a conventional voltage transformer is that it is much less bulky and thus more suitable for on-site measurements. It moreover excels in achieving good phase displacement uncertainties, which is a key requirement for a reference voltage channel used in loss measurement calibrations. An initial VSL evaluation of the reference divider showed uncertainties of better than 6 ppm in ratio and 6 µrad in phase displacement [4].

Parallel to the evaluation of the industrial voltage channels developed in the project (see objective 1), also a verification of the VSL reference voltage channel was done against the PTB reference system for calibration of HV voltage transformers (Figure 3). This PTB validation showed excellent agreement with the initial VSL results. For the 20 kV range, the PTB and VSL results do not differ more than 7 µV/V in ratio error and 4 µrad in phase displacement. For the 100 kV range, the results are even better with agreement of 3 µV/V in ratio error and again 4 µrad in phase displacement (see Figure 6a). All these differences are well within the combined measurement uncertainties. Part of the difference in ratio error is likely caused by extra uncertainties due to temperature variations during the validation measurements. The results also confirm the excellent linearity of the VSL CVD divider that was already found in the earlier VSL verification of the CVD [4]. The PTB measurements typically show only 1 µrad variation in phase displacement as a function of voltage for the two voltage ranges that were calibrated, and the variation in the difference of PTB and VSL result for phase displacement is never more than 2 µrad over the complete voltage range (see Figure 6b).

These results prove that the VSL capacitive voltage divider meets the project’s uncertainty requirements of 20 ppm in ratio and 10 µrad in phase for use as a reference voltage divider in calibration of transformer loss measurement systems.

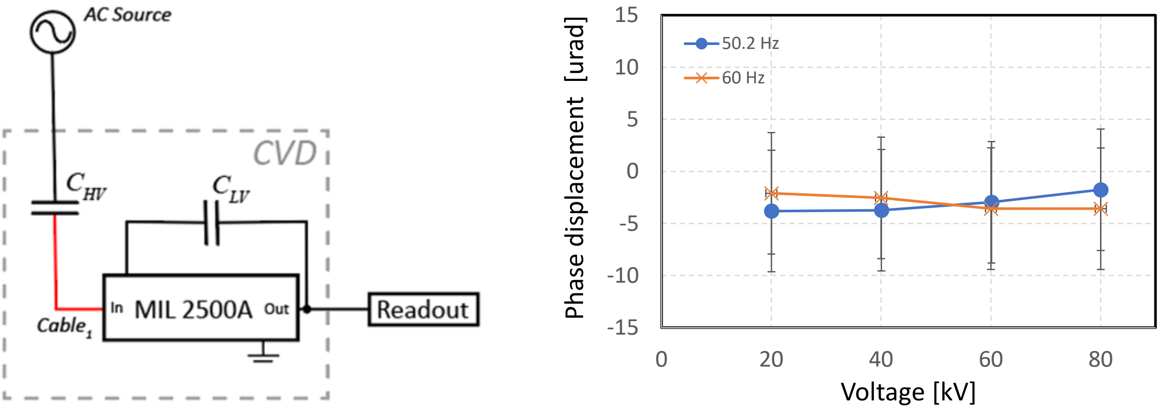

Figure 6. (a) Schematic of the VSL reference capacitive voltage divider (CVD, left): a low-voltage MIL2500A unit, combined with high-voltage (HV) and low-voltage (LV) capacitors. (b) Difference in phase displacement between the PTB and VSL calibration results at 50.2 Hz and 60 Hz on the VSL reference CVD.

Significant effort has been spent on improving the uncertainties at high currents. The current loop is highly inductive so that the amplifier has to deliver a remarkable amount of reactive power, which limits the output current of the amplifier itself. Therefore, the loop inductance needs to be compensated with capacitors. One of the major challenges is the significantly high noise level when compensation capacitors are connected, which is due to the high DC noise level in the RLC circuit. An originally used DC blocker algorithm suffers from vexing quantization problem that creates more DC bias than it blocks. To solve these problems, an additional step-up capacitor has been used so that the inductance is compensated in the primary high current loop instead of in the secondary drive loop of the amplifier. Furthermore, a “leaky integrator” and a noise-shaping trick called “fraction-saving” to eliminate the quantization problem are applied in the DC block [5]. After applying these solutions, the noise level with compensation at power factor 0 is less than 10-20 ppm depending on the stability of the HV voltage.

JV primary power reference system

An important requirement for achieving better than 20 μW/VA uncertainty in power transformer loss measurements is the ability for measuring power at primary 120 V, 5 A levels with better than 10 μW/VA uncertainty (see Table I). To this end, JV has evaluated the sampling primary power set-ups at VSL, PTB and JV. These set-ups consist of three key components: digitizer, voltage scaling and current scaling. Based on this evaluation, a sampling primary power set-up has been proposed to measure electrical power at close-to-zero power factors at power line frequencies (45 Hz – 65 Hz) with a maximum uncertainty of less than 10 μW/VA. The proposed set-up uses two HP3458A digital voltmeters in DC sampling mode, a 1:150 or 1:300 voltage transformer or an inductive voltage divider for voltage scaling, and a 5-A JV shunt to convert the current to a voltage.

TUBITAK reference system

A second reference system for the system calibration of power transformer and reactor LMSs up to 230 kV and 2 kA has been developed by TUBITAK via several improvements on previous versions in both generation capacity and measurement uncertainty. The setup can be configured either for transformer LMS calibrations up to MV level or for reactor LMS calibrations above MV level. The achieved measurement uncertainties scale from 20 μW/VA up to 50 μW/VA depending on the voltage level and power factor. A typical setup configuration is given in Figure 7. Instead of a feedback loop that controls the phase of the current with respect to the applied voltage as in the VSL approach, here the test voltage and current are synchronously generated, using a dual-channel signal generator and suitable high-power amplifiers.

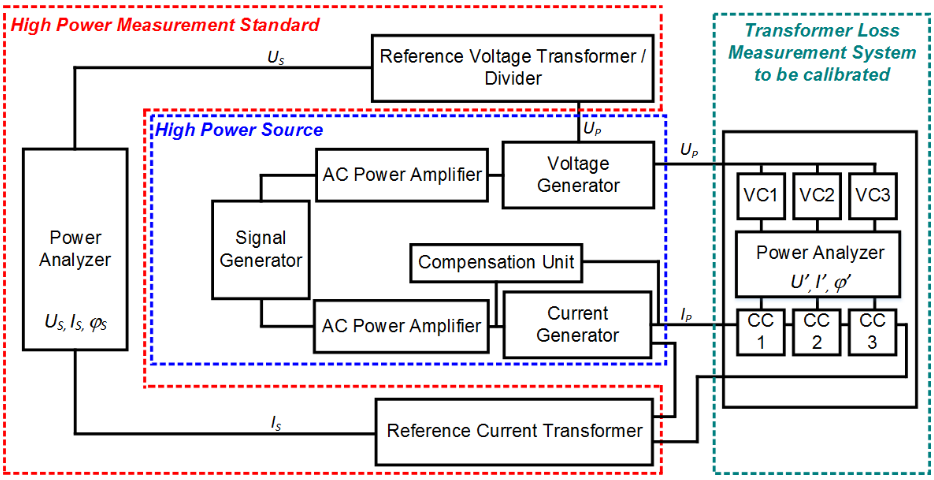

Figure 7. Simplified block diagram of TUBITAK reference calibration setup for LMSs.

The main advantage of the TUBITAK reference system is the capability of parallel and synchronous generation of voltage and current signals either in LV level via a precise dual-channel generator together with linear AC power amplifiers or in HV and HC output levels via configurable step-up generators with a feed-back control. Several improvements were made to the different components in the setup to fulfill the requirements of industry (such as reactor measurements up to 230 kV) and also several system-based improvements to manage project targets (such as better measurement uncertainties) have been successfully completed during the project schedule.

The first series of improvement concerned signal generation and in LV power measurement. A few ppm stability in amplitude of both voltage and current signal generation and a few µrad level resolution in phase between them have been successfully obtained by integrating a two-channel PXI-chassis programmable signal source operated with a feed-back control after characterizing it with a calibrator, that in turn is traceable to the national sampling-based AC power measurement standard. This reference sampling-based AC power measurement standard with a typical measurement accuracy of better than 20 μW/VA has been re-characterized together with its internally installed voltage dividers and current shunts up to certain frequency level which covers harmonic measurements as well.

The second series of improvements concerned high-current stability and frequency bandwidth of the current channel. A significant improvement in the high current generation unit has been achieved by integrating a booster stage and a feed-back circuit to balance the input and output currents by supplying additional power via external windings placed in the feed-through window of the inductive step-up current transformer. The capability of this compensation and the booster circuit is 5 % of the total power, which is quite enough to supply the typically maximum 2 % loss during half-an-hour operation. At the same time, a linear amplifier together with transconductance power amplifier has been re-configured for the generation of high currents with any harmonics up to 50th and with 20 % amplitude of the fundamental signal. Zero-flux current transformers have been designed for such applications and calibrated with the reference compensated current comparator after re-characterisation over wider frequency bandwidth.

The third improvement concerned the voltage channel in both capability and traceability. A primary calibration setup has been developed to increase generation and measurement capabilities up to 230 kV at power line frequencies, and to improve uncertainties well below 20 ppm and 20 μrad in measurement of ratio error and phase displacements, respectively. Calibration method typically comprises three stages: characterization of a reference HV capacitance bridge with an uncertainty of below 10 ppm, finding ratio and dissipation factors of a set of LV and HV low-loss standard capacitors with an additional uncertainty of well-below 10 ppm, and transferring measured errors to the VT under calibration by repeating similar measurements with the bridge after connecting same capacitors to primary and secondary sides of the VT. To verify and validate the performance of the developed primary calibration setup, a bilateral comparison (EURAMET.EM-S43) between UME and PTB has been started by using transfer standards consisting of two reference voltage transformers. First results indicate that the new primary calibration setup of UME is in good agreement with the PTB results taking into measurement uncertainties account.

For on-site calibrations, particularly for the calibration of reactor LMSs in which higher voltage levels are needed as much as possible, a capacitive voltage divider together with the reference capacitance bridge is used. The capacitive divider is needed to be calibrated instantly where placed and by taking environmental conditions into account to achieve best uncertainties given for laboratory conditions.

On-site calibrations and experiences

Both reference LMS calibration setups have been used extensively on-site at the test laboratories of 16 transformer and reactor manufacturers for annual calibration of their LMSs (around 38 systems in total).

Even though almost all of these industrial LMSs were analyzed periodically before through component-based calibrations within the last decade, a number of deviations in the results have been found while performing system calibrations. These included deviations due to large drifts in LMS equipment, inadequate LMS electronics, faulty wiring or incorrect calculations.

The system calibrations thus appeared to be of high significance, not just for the LMS calibration but also to ensure correct LMS tests during its normal use after the calibration. Once deviations were found in LMS system calibrations, together with the end-users, the power transformer manufacturers, the source of these deviations was found and subsequently solved. This included evaluation of the effect of long cables, of EM interference, of grounding configurations and of any ground-loop currents. Further analyses concerned environmental conditions, in particular ambient temperature when HV capacitors were used, electromagnetic interferences between HV and high current carrying cables, and any cross-interference between CTs and VTs placed in short distances or in horizontal/vertical position with respect to each other. These on-site experiences had led to improvements of the reference setups and to new requirements for on-site LMS system calibrations.

4.2.3 Dissipation factor of high-voltage capacitors

The basic reference for measurement of losses of high volage equipment is in general a high volage capacitor, and to wit, its loss factor. The traditional HV reference capacitor has a coaxial electrode system in a pressurised gas vessel. The voltage induced change of the capacitance depends mostly on accurate alignment of the coaxial system, and after careful aligning, the voltage sensitivity can be negligibly low compared to the temperature dependence of typically $2 \cdot 10^{-5}\ (\mathrm{F/F})\ \mathrm{K}^{-1}$. Traceability of loss factor, relevant for loss measurements, is realised at only low voltage, typically below 1 kV. No more than three National Metrology Institutes are known to perform such realisations. The calibration of capacitors for their loss factor at higher voltage is based on assuming that the loss factor does not change with the applied voltage. Even though existing experimental evidence supports this assumption, there is no traceable verification available yet.

Therefore, a loss factor realisation up to 40 kV was built and tested. A crucial element of this realisation is a HV capacitor with parallel – and movable – plates as shown in **Error! Reference source not found.**. According to theory, one can compare the loss of the variable reference with the (unknown) loss of a fixed capacitor for different values of the variable reference. In a graph of loss factor versus capacitance of the variable capacitor, the intercept at zero capacitance represents the true loss of the fixed capacitor. For performing these measurements, a well-characterised HV capacitance bridge is needed.

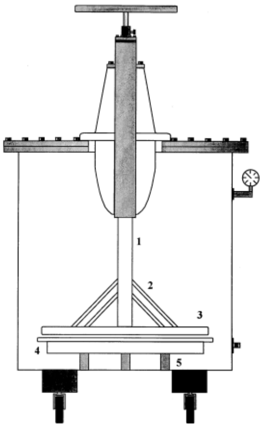

Figure 8. The capacitor with parallel and movable plates

An existing variable guard-ring capacitor has been rebuilt by RISE for enhanced mechanical stability and pressure tightness. In process of rebuilding, a mechanical adjustment was introduced to enable setting the lower plate to be closely parallel with the upper one. Success of the adjustment was proven by utilising a Lasertracker, providing a dimensional uncertainty of 0.05 mm. The deviation from plane of the electrode to the upper flange of the vessel was less than 0.15 mm. The top cover was replaced by a new one, replacing a 12 mm thick steel cover with a 50 mm aluminium one, drastically enhancing stability when pressurising the vessel. The internal pressure was selected to be SF6 at an absolute pressure of 1.5 bar.

RISE furthermore acquired a used HV capacitance bridge Guildline 9910A, which is specified at an uncertainty of 10 ppm and 10 µrad. Careful investigation revealed that internal capacitive coupling distorted the bridge balance by up to a few ppm/µrad. Rebuilding the internal circuitry with added shielding reduced this effect to a manageable level. A second problem is the non-negligible resistance of the ratio windings in the bridge. This can cause measurement errors by two mechanisms; one is the interaction between the capacitance of the two capacitors connected to the windings. This can be handled by performing four-terminal measurement in accordance with the bridge's manual. Another, more insidious, effect is the interaction between ratio winding resistance and cable centre-conductor to shield capacitance. For this bridge at 50 Hz the effect is 1.7 µrad/nF on the C_s-side and 3 µrad/nF on the C_x-side. A possible way to handle this is to ensure that the shields of the cable connecting the high voltage capacitors to the bridge are at the same potential as their centre conductors. This can be achieved using a voltage follower driving the shield. For this it is however necessary that the shields are not earthed at the high voltage capacitor and care has to be exercised not to compromise safety of personnel nor overloading the amplifier.

Calibration of the bridge has been achieved by using a set of more than 20 reference capacitors of type Genrad 1404 or equivalent. Both 100 pF and 1000 pF units are used. A null detector (Lock-in amplifier Stanford Research 850) was verified to be linear for both in-phase and quadrature. A measurement with the null detector of bridge unbalance was made for setting 1:1.000000. Deliberately offsetting the bridge (e.g. by 100 ppm) provided a calibration for the unbalance measured. This measurement is an absolute calibration of bridge error at unity setting and does also provide very accurate measurement of the capacitance ratio of all capacitors. Paralleling ten 100 pF units and comparing with one of the 1000 pF units provided the link between them. Using these capacitance values, it is the possible to calibrate all major settings of the bridge (1, 2, 5, … 100) as well as the minor settings (1.1, 1.0, 0.9 … 0.1). Calibration for loss is achieved with resistors mounted in series with the low voltage connection of a designated 1000 pF capacitor. Effect of the parasitic capacitances to earth have been taken into account. The result of the calibration was that the errors of the bridge could be determined at a resolution of about 10^{-7} in both amplitude and phase. The evaluated uncertainty of the bridge is $\leqslant 10^{-6}$ in both magnitude and phase for ratios from 1.1 to 1:100. Uncertainty for ratios 200, 500 and 1000 are higher, but comfortably lower than 10 ppm/µrad.

Final measurements on the variable capacitor using the characterised HV capacitance bridge were however unsatisfactory. At increased operating voltages an unforeseen problem with mechanical vibration was discovered. The electrostatic force between the plates has proven to be sufficient to excite a mechanical vibration, which was discovered by the fact that loss factor increased substantially with the applied voltage making further measurements momentarily meaningless. The resonance frequency was approximately 42 Hz and some further experiments are planned with high voltage applied at a frequency further removed from the mechanical resonance, e.g. 60 Hz. The hope is that the separation of frequency will be sufficient to obtain reliable results.

4.2.4 Summary

Two primary reference facilities have been developed by two NMIs, with complementary approach, which are capable of calibrating the advanced industrial LMS developed in objective 1 as a complete system. The target accuracy of the reference setups 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. To achieve this uncertainty, each component of the reference setup (voltage channel, current channel, and power meter) was evaluated with uncertainty better than 10 µW/VA.

The basic approach of the VSL reference system is to simulate a power transformer with different losses to the LMS. A digital feedback loop assures generation of a current with stable and known phase with respect to the applied high voltage. The VSL reference system achieved an overall system accuracy of better than 0.2 % in loss power at PF = 0.01 for all current up to 2 kA and voltages up to 230 kV. An important factor for this achievement is the careful evaluation of the reference voltage divider in the reference setup. Initial VSL evaluation of the reference voltage divider showed uncertainties of 6 ppm in ratio and 6 µrad in phase displacement. These numbers were confirmed in an independent evaluation against the PTB reference system for HV voltage divider calibrations. For reaching low noise at high currents, the loop inductance of the primary current loop needs to be compensated with capacitors, and a dedicated solution was developed for eliminating the high DC noise level in the resulting RLC circuit. With this solution, noise levels at 2 kA reduced from several hundreds of ppm to less than 10-20 ppm, only depending on the stability of the generated high voltage.

The TUBITAK reference system for the system calibration of power transformer and reactor LMSs uses synchronized generation of the voltage and current signals. Significant improvements have been made in the voltage and current measurement channels, in signal generation and in the power measurements. Following these improvements, the recent measurement uncertainties of TUBITAK are scaling from 20 W/VA up to 50 W/VA depending on voltage level and power factor.

Both reference LMS calibration setups have been used extensively on-site at the test laboratories of 16 transformer and reactor manufacturers for annual calibration of their LMSs (around 38 systems in total).

RISE has built a facility for determining the dissipation factor of high-voltage capacitors up to 40 kV. This facility is based on a HV capacitor with parallel movable plates that is compared at different plate distances to a fixed capacitor using a HV capacitance bridge. Following significant improvements to the bridge, its errors are within 1 ppm in both magnitude and phase for ratios from 1.1 to 1:100. The final measurement results on the variable capacitor were however unsatisfactory due to a mechanical vibration caused by the electrostatic force between the plates at increased operating voltages. Further experiments are planned with high voltage applied at a frequency further removed from the 42-Hz mechanical resonance, e.g. 60 Hz.

In conclusion, the second JRP objective of realising 2 NMI reference setups capable of performing a system calibration of industrial LMS at very low power factors with at least 20 μW/VA uncertainty up to 230 kV and 2 kA voltage and current levels has been realised.

4.3 Objective 3: Effect of non-sinusoidal waveforms and Uncertainty evaluation of loss measurements of reactors

This objective aimed 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.

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 (NLL) measurement of transformers, where the current Total Harmonic Distortion (THD) can be more than 85 %. Therefore, the impact of these distortions on the final accuracy of loss measurements of power transformers needs to be identified.

Given the technical complexity of accurate loss measurements, the uncertainty evaluation of transformer and reactor loss measurements is also complex. The project has started to extend the IEC and CENCELEC 60076-19 standards on the uncertainty evaluation of power transformer losses to shunt reactor loss measurements, by drafting a mathematical model function for uncertainty analysis of reactor loss measurements.

4.3.1 Effect of non-sinusoidal waveforms

The impact of non-sinusoidal test signals on the final accuracy of loss measurements of power transformers can be accessed via errors in the measurement of the difference in average-voltage and rms-voltage ($V_{\text{avg-rms}}$) and/or of harmonic power. Presently, Loss Measurement Systems (LMSs) are calibrated using sinusoidal test signals, whereas during actual loss tests there can be significant harmonics present in the test signal. Information from the literature and actual test information from transformer manufacturers show that these non-sinusoidal test signals essentially only occur during no-load loss (NLL) tests of power transformers.

Both IEEE and IEC standards give formulas for correction of the measured NLL losses to losses at a pure sine wave. These formulas are different, with the IEEE formula having a quadratic correction on the eddy current losses P2 [6] [7], and IEC a linear correction on the complete measured losses Pm [8]:

$$IEEE\colon\ \mathrm{P}_0 = \frac{P_m}{P_1 + kP_2}, k = \left(\frac{V_{rms}}{V_{avg-rms}}\right)^2 \tag{1}$$

$$IEC\colon \mathrm{P}_0 = P_m(1+d), d = \frac{V_{avg-rms} - V_{rms}}{V_{avg-rms}} \tag{2}$$

$$\%\text{correction} = \frac{|P_0 - P_m|}{P_m} \cdot 100\% \tag{3}$$

with

$$V_{avg-rms} = \left(\frac{2}{T}\int_0^{\frac{T}{2}} V_{ex}(t)dt\right) \cdot \frac{\pi}{2\sqrt{2}} \tag{4}$$

Where P_0 is the corrected value and P_m represents the measured losses. The IEEE formula separates the hysteresis and eddy current losses as P_1 and P_2 in per unit values respectively. If actual values are not given, IEEE recommends using 0.5 per unit for each. $\mathrm{V}_{\mathrm{ex}}(t)$ represents the instantaneous voltage value at time t, with time period T. $V_{avg-rms}$ is calculated by (4) and known as rectified average root-mean-square (rms) value, which is adjusted according to a voltmeter responsive to the mean value of voltage but scaled to read the rms voltage of a sinusoidal wave having the same mean value. $\mathrm{V}_{\mathrm{rms}}$ is the true rms value. IEEE and IEC propose correction limits of 5 % and 3 % respectively to correct the measured no-load losses to a sinusoidal excitation voltage basis [7, 9].

Measurement campaign

In order to capture the voltage and current waveforms during an actual NLL test, a measurement campaign was executed at Royal Smit Transformers during the NLL measurements of a 600-MVA, three-phase, 60-Hz power transformer (380 kV / 138 kV) with Y-Y connections (autotransformer). The transformer was equipped with an auxiliary 10.6 kV winding (Y connection) for the purpose of energizing the transformer during NLL tests. The waveforms during the NLL measurement of the power transformer were obtained from the LMS connected to this auxiliary LV winding. Measurements are repeated for at least three times at 70, 80, 90, 95, 100, 105, 110 and 115 % of the rated voltage. Waveforms are recorded for both voltage and current of the three phases.

The three-phase loss measurement system (LMS) used by Royal Smit Transformers for power transformers loss measurements consists of three high-voltage current-comparator-based capacitive voltage dividers [9], three cascaded current transformers with a high-current and low-current part, and a wideband sampling power meter (Yokogawa WT3000). The WT3000 made it feasible to measure and record the test current and voltage wave shapes as represented at the low-voltage and low-current outputs of the voltage dividers and current transformers. Tests are performed with Line-to-Neutral connections of the LV windings.

Results analysis

With the increase of the applied voltage, the current distortion increases significantly up to 88 % THD at the highest voltage level of 115 % of rated voltage, while the voltage distortions almost stay at the same level of around 3 % except at the highest voltage level where it increases to approximately 5 %.

The major harmonic current components are 3rd, 5th, 7th and 11th order harmonics. For the highest voltage levels, the 9th and 13th order current harmonics become slightly significant as well. In the voltage signals, the 5th, 7th and 11th harmonics are the main non-fundamental components that become significant for test voltage levels above 100 % of rated voltage.

Table 2 also shows the harmonic power which is lower than 0.1 % of the total active power for most of the test cases, except for the harmonic power at 115 % rated voltage level, where it is about 1.6 % of the total active power and generated by the transformer (negative sign). It is found that the 5th and 7th harmonic power are the most dominant ones, followed by the 3rd harmonic.

Table II. Voltage, current, power and harmonic power during a NLL test of a 600 MVA autotransformer

Voltage Level [%]	Rectified average rms voltage [kV]	Phase rms voltage [kV]	Phase rms current [A]	Active power [kW]	Harmonic power [kW]
70 %	4.316	4.319	5.05	58.89	0.05
80 %	4.894	4.897	5.63	75.64	0.07
90 %	5.515	5.520	6.25	97.62	0.09
95 %	5.823	5.829	6.78	110.6	0.11
100 %	6.131	6.140	8.09	126.2	0.12
105 %	6.431	6.445	12.25	146.7	0.11
110.6 %	6.744	6.784	33.46	186.5	-0.27
114.7 %	6.944	7.037	85.44	232.7	-3.90

Next to the presence of harmonic power, the distortion of the voltage waveforms has an impact on the measurement of $V_{\text{avg-rms}}$ used in equations (1) – (3) to correct the measured loss power. Table 3 shows the correction percentage calculated by IEEE and IEC methods for the waveforms in the present NLL tests. The two formulas give very close results with varying THD level. In the present tests, the maximum correction is about 1.32 % for 115 % rated voltage level and the minimum one is about 0.07 % for 70 % rated voltage level.

Table III. NLL correction values according the IEC and IEEE formula's (1) – (3)

Voltage level [%]	Rectified average rms voltage [kV]	Phase rms voltage [kV]	$V_{\text{rms}}/V_{\text{avg-rms}}$ [%]	Voltage THD [%]	Correction [%]	
					IEEE	IEC
70 %	4.316	4.319	100.07	3.4	0.07	0.07

80 %	4.894	4.897	100.06	3.3	0.08	0.08
90 %	5.515	5.520	100.09	3.3	0.10	0.10
95 %	5.823	5.829	100.10	3.4	0.11	0.11
100 %	6.131	6.140	100.15	3.3	0.14	0.14
105 %	6.431	6.445	100.22	3.3	0.21	0.21
110 %	6.744	6.784	100.59	3.8	0.58	0.58
115 %	6.944	7.037	101.34	5.5	1.32	1.31

Discussion

In the presented NLL tests, the amount of harmonic power is around 0.1 % of the total active power for the voltage level up to 105 % of the rated voltage, increasing to 0.3 % and 1.6 % for 110 % and 115 % of rated voltage respectively. Given the bandwidth of the used LMS, it is expected that the higher harmonic powers are still measured with an accuracy of 0.1 % of total power. So overall, the accurate measurement of this harmonic power is not critical for NLL measurement. However, in the tests at 100 % and 115 % rated voltage, the voltage THD increases from around 3 % to 5 % and the transformer starts to generate respectively 0.3 % and 1.6 % harmonic power instead of consuming. This leads to a lower total loss measurement value. Further experiments and/or theoretical analyses are required to confirm this finding and to further evaluate the impact of this.

A general evaluation of the bandwidth of typical components in LMSs reveals that most modern LMSs will have sufficient bandwidth for reliable loss measurements. The main impact will be on voltage in case conventional voltage transformers are used, but even then, an accuracy of better than 10 % for the harmonic power losses (for the cases explored here) can be expected for bandwidths up to 1 kHz. Capacitive voltage dividers have sufficient bandwidth to ensure a reliable measurement with likely better than 1 % accuracy up to 1 kHz.

When the THD is about 3.3 %, the difference between the true rms and rectified average rms value is lower than 0.1 %. If an error is made in the voltage THD measurement of 5 % or 10 %, the ratios between the $V_{\text{avg-rms}}$ values and the rms values vary accordingly, so the change in the correction factors is at most 0.1 % and 0.2 % respectively for the present NLL waveform at 115 % of rated voltage. In combination with the expected accuracy of the LMS system in the THD measurements discussed above, the correction factors likely will be better than 0.1 %.

4.3.2 Uncertainty evaluation of reactor loss measurements

EU Commission Regulation 548 to implement the Ecodesign Directive on small, medium and large power transformers [10] increased the importance of accurate measurement of the losses of power transformers and related HV grid instrumentation such as shunt reactors. Given the complexity of the instrumentation in these loss measurements, industry guidance is needed to determine the uncertainties in these loss measurements. At present, IEC TS 60076-19:2013 gives such guidance for the uncertainty evaluation of power transformer loss measurements, however, no guidance is given for the uncertainty evaluation of reactor loss measurements [11]. Therefore, VSL, RISE together with Hitachi Energy, the Chief Stakeholder of the project, worked on filling this gap by presenting a detailed method for evaluation of reactor loss uncertainties.

First, a review of three different methods to measure the reactor loss has been performed. In the most convenient method, the three-phase power measurement method, the high voltages and currents are scaled down with precision voltage and current transducers to the input voltage/current levels of the power meter, that subsequently determines the loss power. Based on the model function of non-load loss measurements of power transformers, a model function has been developed for reactor loss measurements using this three-phase power measurement method. For each of the three phases in the reactor loss measurement, the following model function is valid:

$$P_{reactor} = \left\{ k_{CN} \frac{1}{1+\frac{\varepsilon_C}{100}} \right\} \cdot \left\{ k_{VN} \left(1 + \frac{\varepsilon_V}{100}\right) \right\} \cdot P_W \cdot \left\{ \frac{cos(\phi)}{cos\left(\phi + \Delta_{\phi W} + \left(\Delta_{\phi V} - \Delta_{\phi C}\right)\right)} \right\} \cdot \left[\frac{V_N}{k_{VN} \cdot V_{rms}} \right]^2 \tag{5}$$

Here, the first two terms indicate the nominal scale factors of current k_{CN} and voltage k_{VN} respectively, with their respective ratio error correction terms. P_W is the reading of the wattmeter, and the term following it relates to the correction of phase displacement of the current and voltage transducers and of the wattmeter on the phase ϕ between reactor voltage and current. The final term is a factor related to the actual voltage where the exponent (taken as 2 in lieu of other information) is related to the non-linear behaviour of the losses.

The loss of a shunt reactor is small, typically around 0.2 % of the total power, or expressed otherwise, the phase ϕ is close to 90°, making the power factor low, around 0.002. As a consequence, errors in phase are expected to dominate in the uncertainty analysis. For this reason, the term $\Delta_{\phi W}$ has been introduced with respect to the existing no-load loss uncertainty evaluation of power transformers [11] to call to attention that the uncertainty in P_W (the wattmeter reading) includes an important term related to its phase displacement. The difference from wattmeter phase displacement to the other devices (voltage and current transducers) is that this value quite often is not provided, neither by the instrument manufacturer nor by calibration providers. The latter typically provide calibration values at power factor values near 1, whereas the value of $\Delta_{\phi W}$ can only be deduced from calibrations performed at low power factor. Therefore, when having a power meter used in reactor loss measurements calibrated by a calibration provider, it should be explicitly requested to include test points at low power factor.

The contribution of the total phase displacement uncertainty $\mathrm{u}_{\Delta\phi}$ to the reactor loss measurement uncertainty can be expressed as:

$$u_{FW} \approx \tan\phi \cdot u_{\Delta\phi} \tag{6}$$

When the power factor is close to zero, as the case for reactor loss measurement, this equation can be simplified as:

$$u_{FW} \approx \frac{u_{\Delta\phi}}{PF} \tag{7}$$

Finally the total phase displacement uncertainty $\mathrm{u}_{\Delta\phi}$ can be calculated as the combination of the phase uncertainties of voltage transducer, current transducer and power meter:

$$u_{\Delta\phi} = \sqrt{u_{\Delta\phi V}^2 + u_{\Delta\phi C}^2 + u_{\Delta\phi W}^2} \tag{8}$$

In the evaluation of the three phase uncertainty contributions, both the instrument specifications and the instrument calibration uncertainty have to be taken into account as they typically are of the same order of magnitude.

As demonstration of the method, an example calculation has been prepared based on a typical industrial loss measurement. The calculation shows that, for a typical reactor power factor of around 0.002, the phase displacement errors indeed are dominant. In fact, the contribution of the magnitude uncertainties can even be ignored as long as they are less than 0.5 %. In this situation, the uncertainty evaluation becomes very simple, requiring only the formulas (7) and (8) given above.

4.3.3 Summary

A study has been performed on the effects of non-sinusoidal test signals on the final accuracy of loss measurements, in particular of power transformer no-load loss measurements where the current Total Harmonic Distortion (THD) can be more than 85 %. Voltage and current waveforms have been captured during an actual NLL test of a 600-MVA, three-phase, 60-Hz power transformer (380 kV / 138 kV) with Y-Y connections (autotransformer). The maximum IEEE and IEC loss correction values for the NLL measurements on the autotransformer appear to be about 1.3 % for the maximum measured voltage THD of 5.5 % at 115 % nominal voltage. The amount of harmonic power is around 0.1 % of the total active power for the voltage level up to 105 % of the rated voltage, increasing up to 1.6 % at 115 % of rate voltage.

Given the bandwidth of the used LMS, it is expected that the higher harmonic powers are still measured with an accuracy of 0.1 % of total power. However, it seems that the quality of the generator in NLL tests has a significant impact on the NLL measurement values, since harmonic power is generated at the highest test voltages, lowering the overall loss measurement value. Clearly, the high voltage THD is an indicator for this effect. Further research is required to confirm this result.

A guideline has been developed for evaluation of the complex measurement uncertainties associated with loss measurements of large reactors. Based on the model function of non-load loss measurements of power transformers, a model function has been developed for reactor loss measurements using the three-phase power measurement method. The low loss of a shunt reactor results in low power factors, typically around PF = 0.002. As a consequence, the phase errors are found to dominate in the uncertainty analysis. An example calculation based on a typical industrial reactor loss measurement even shows that, for such power factors, the contribution of the magnitude uncertainties can be ignored as long as they are less than 0.5 %.

In conclusion, the third JRP objective has been successfully achieved since new insight has been obtained on the effects of using non-sinusoidal test signals on the final accuracy of loss measurements, and a guideline has been produced for evaluating the measurement uncertainties associated with reactor loss measurements.

5 Impact

The main overall impact of the project lies in the metrology support it has provided 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. The project has disseminated its aims and results to a variety of stakeholders via 2 international stakeholder workshops, 16 conference presentations, 9 peer-reviewed papers, its website, a training course on “Power Transformer Loss Measurements: Accuracy, Calibration, Traceability & Uncertainty evaluation”, and via input to standards development organisations, in particular to CENELEC TC14 “Power transformers”.

A major achievement 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 have already been used more than 20 times for on-site LMS calibrations at stakeholder premises.

Impact on industrial and other user communities

The project has stimulated innovation and impacted 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, has kept the European transformer and instrumentation industry at the forefront of industrial loss measurements of power transformers and reactors. An early impact of the project was 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. Following this proof of the new technology, one unit of the final voltage divider has been sold to a test laboratory to be used for reactor loss measurements.

Next to the new industrial LMS facilities, improved calibration services have been established that provide power transformer and reactor manufacturers and MSAs with access to on-site calibration of such LMS facilities at voltages up to 230 kV and currents up to 2 kA. A major uptake of the project results are the on-site calibrations of industrial transformer LMSs using the improved reference setups developed in the project at among others Royal Smit Transformers, ABB, GE, SGB, Best, Eltaş, Astor, STD, BETA, Sönmez, Schneider, Maksan, and Ulusoy.

These on-site calibration 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 has been used to prepare the final version of the LMS calibration guide.

Two highly successful stakeholder workshops have been held. The workshops were held in September 2019 and June 2021 respectively, and advertised and held together with the 17IND06 FutureGrid II JRP. Both workshops were attended by more than 70 participants. Updates were presented of the projects progress and final results via two project overview presentations, followed by lively discussions. The presentations (both sheets and videos) of the final stakeholder workshop can be found here.

Impact on the metrology and scientific communities

The project has developed 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 and final stakeholder workshops and at the AMPS 2019 conference. Furthermore, the project results have been published in 9 peer-reviewed papers, and via 16 presentations at the CPEM 2018, ISH2019, AMPS2019, ICTRAM2019, CPEM2020 and I2MTC 2021 conferences.

The project objectives and progress have been presented to the attendants of the 2018, 2019 and 2020 meetings of the EURAMET TC-EM contact persons. The project results have also been presented to metrology specialists in the area of the project at the May 2019 and May 2021 meetings of the EURAMET TC-EM Sub-committee “Power and Energy” experts group. The project partners have cooperated with the national metrology institutes of China (NIM) and Australia (NMIA) on the subject of transformer loss measurement reference systems. A formal collaboration agreement was signed with NIM, and as part of this collaboration a NIM researcher has worked for 3 months with one of the project partners on the development and characterisation of a reference setup of LMS calibrations. Further collaboration was started with JV (Norway) on improvement of primary power measurement techniques that are the basis for the power measurements in the LMS calibration reference setups.

A good practice guide for LMS calibrations has written that provides useful guidance to NMIs and industrial calibration laboratories performing these calibrations. The guide has been presented to the wider stakeholder community at the ICTRAM 2019 conference, and has been finalised based on the comments received during this conference. The final version has been made available to end-users such as transformer manufacturers and MSAs with the TrafoLoss website and via sharing with the CENELEC TC14 members.

Impact on relevant standards

The project has contributed 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, 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 was 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, 2019, 2020 and 2021 CENCELEC TC14 meetings, and useful feedback was received that steered the project activities. It was suggested and agreed by the TC14 members at the final project stakeholder workshop that the project work on uncertainty evaluation of reactor loss measurements will not be shared as a New Work Item Proposal (NWIP), but in the form of a report. The background for this decision is that the present revision of the IEC 60076-19 standard is taking much longer than expected and in fact still on-going, so that the submission of a NWIP is not opportune. When the project work is shared as a report, it is available for use in future improvements of the 60076-19 standard at the earliest convenience of IEC and CENELEC.

Longer-term economic, social and environmental impacts

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 allow the European electrical power industry to produce grid components of the required high quality and to unambiguously demonstrate their performance at a level that was unavailable at the start of the project. The improved measurement uncertainties 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 reduces the required safety margin and allows 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 has underpinned 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 could not have been successfully implemented by manufacturers nor monitored by MSAs, and this important area for energy savings would not have fully contributed 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 also supported to the competitiveness of European HV power transformer and instrument manufacturing industry and thereby to secure high-quality jobs in Europe.

6 List of publications

[1] E. Mohns, G. Roeissle, S. Fricke, and F. Pauling, “*A Sampling-Based Ratio Bridge for Calibrating Voltage Transformers*”, Proceedings of the 2018 Conference on Precision Electromagnetic Measurements (CPEM 2018). DOI: 10.7795/EMPIR.17NRM01.CA.20190411 available online: https://doi.org/10.1109/CPEM.2018.8501245

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[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., Vol. 68, No. 6, pp. 2121 – 2128 (2019). DOI: 10.7795/EMPIR.17NRM01.CA.20190408
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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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