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Reliable Power Transformer Efficiency Tests

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***Abstract*—Power transformer efficiency measurements are a crucial part of the acceptance tests of a power transformer. These tests have increased importance since the EU Ecodesign Directive per 1 July 2015 has put efficiency limits to power transformers that are sold on the European market. In this paper we present a series of measures to assure that power transformer efficiency tests performed by power transformer manufacturers are accurate and reliable. This includes the development of more accurate industrial loss measurement systems (LMS), optimized LMS calibration approaches, and a reference system for on-site LMS calibration.**

***Index Terms*—power transformers, efficiency, loss, loss measurement, reliability, calibration, accuracy, uncertainty**

I. INTRODUCTION

Power transformer efficiency is a very important parameter, first of all for the utilities that purchase the power transformers, since they have to carry the costs associated to the power transformer losses over the life time of the transformer. These costs are a substantial part of the total cost of ownership to the utility, and can sometimes even exceed the purchase costs. Because of this economic impact of power transformer losses, fines are put on losses exceeding the specified limits, that can be as large as 10000 €/kW. For a 100-kVA transformer with 1 % specified losses, a 3 % excess of the losses (i.e. losses of 1.03 %) would then result in a fine of 150 k€.

Power transformer losses also have a societal impact, since they increase the cost of the electricity grid infrastructure and lead to significant additional CO_2 emissions. An EU impact study has estimated that the saving potential of more efficient power transformer designs is 16 TWh/year and 3.7 Mt of CO_2 emissions per year [1]. This has brought the EU to put requirements on the efficiency of power transformers that are sold on the European market after 1 July 2015 as part of the Ecodesign Directive [2].

These social, economic and environmental effects of power transformer losses have increased the need and relevance for power transformer manufacturers to make reliable loss tests of their products, as part of the factory acceptance tests. To achieve reliable loss tests suitable loss measurement system should be available, with sufficient accuracy.

In this paper we describe new developments and discuss several aspects that are relevant for accurate, reliable power transformer loss measurements. This includes the development of advanced industrial loss measurement systems (LMS), the different LMS calibration approaches and assurance of the validity of the calibration, and the development of reference setups for on-site LMS calibration at the premises of power transformer manufacturers [3].

II. POWER TRANSFORMER LOSS MEASUREMENT SYSTEMS

Fig. 1 gives a schematic of the typical LMS used by power transformers to measure the losses of their products. The LMS has voltage and current scaling devices to scale the large test voltage and test current to values that can be handled by the watt meter (WM). For the current scaling typically conventional current transformers (CTs) are used, whereas the voltage channels either consist of conventional voltage transformers (VTs) or of voltage dividers (VDs) consisting of high-voltage (HV) capacitors (C_{HV}) in combination with low-voltage electronics.

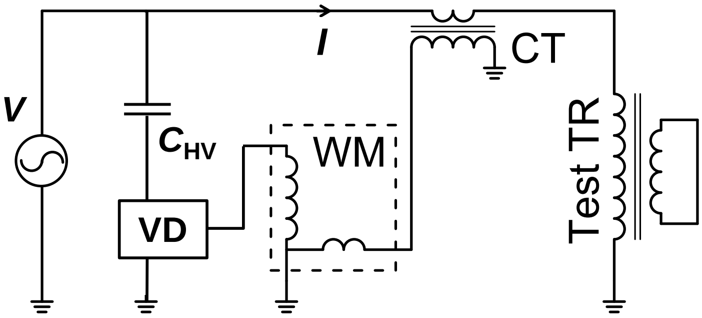

Figure 1: Single-phase schematic overview of an industrial loss measurement setup
for determining the load and no-load losses of power transformers

The key challenge for the LMS in loss power measurements is to measure power with good phase accuracy. This can be readily seen given the loss power P_{loss} for sinusoidal test waveforms is equal to:

$$P_{\text{loss}} = V \cdot I \cdot \cos(\varphi), \tag{1}$$

with the phase angle φ between the voltage V and current I close to 90°. Measuring losses with an accuracy of 3 % at a power factor (PF) of 0.01 thus requires measurement of the deviation of the phase φ from 90° (corresponding to an ideal transformer with no losses) with an accuracy of 300 μrad or 1 minute.

With the increased importance of reliable power transformer and reactor loss measurements, the need arose for the advanced LMSs with accuracies of 0.5 – 1 % at PF = 0.01. This approximately is a factor 3 improvement with respect to the typical specifications of present LMSs. An evaluation of the commercial power transformer LMSs available on the market, and power transformer manufacturer experiences with these LMSs, showed that in particular the accuracy of the LMS voltage channels should be improved. Therefore, as part of the TrafoLoss project [3], two new voltage channels have recently been developed with high accuracy and good stability over time. Fig. 2 gives photographs of the two dividers. The first divider is a capacitive divider with a buffered output to make the divider output voltage independent of measurement burden [4]. The low-voltage arm consists of ceramic capacitors (290 nF or 3600 nF) on the feedback loop of the buffer amplifier (see schematic in Fig. 2) [5]. This divider has already successfully been used as part of a LMS to measure the losses of an air-core shunt reactor with 0.5 % accuracy at PF = 0.01 [4].

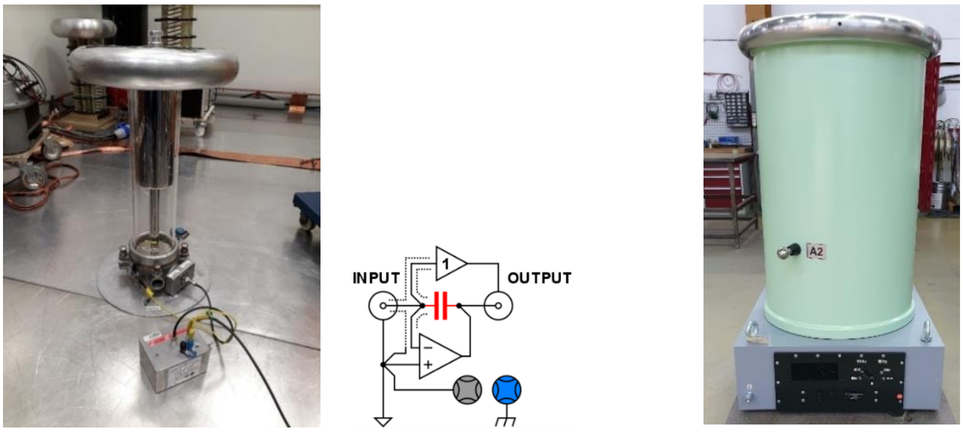

Figure 2: Two high-accuracy HV dividers for inclusion in future advanced LMSs.
The left hand shows a capacitive divider with buffered output (see schematic).
The right hand shows a conventional voltage transformer with passive error compensation and digital readout.

The second divider is an improved version of an existing conventional design, where the accuracy improvement has been achieved through passive error compensation [6]. A further improvement is the addition of direct readout of the secondary voltage signal using a time-synchronised digitiser. This direct readout has several advantages. First, it allows for further digital compensation of the remaining ratio errors and phase displacements. Second, it removes the long conventional secondary wiring, reducing both the burden on the voltage transformer output and the possible effects of interference.

Such direct readout devices have become available via the development of time dissemination equipment based on the white rabbit protocol [7] or derived technologies, together with metrology digitisers that are synchronised to each other using this timing technology [8]. A trend in LMS development is to apply this technology to directly digitise both the voltage and current signals at the output of the voltage and current scaling devices. The time-stamped digital measurement values are subsequently transferred via a fiber connection to a central unit in the test control room, where the loss power is calculated. Apart from the above-mentioned improvement in accuracy and reduction in interference effects, this in practice also allows for more convenient LMS operation.

III. LMS CALIBRATION ASPECTS

Industrial loss measurement systems are used by power transformer manufacturers to test the quality of their products. However, such a test is only useful, and its results are only indisputable, if the loss measurement system is of proven, adequate quality. Specifications are an indication of the expected LMS behaviour, but cannot be taken for granted. The LMS manufacturer might have failed to realise the specifications, or the LMS may have drifted so that following initial accurate operation, over the period of several years the LMS has moved outside its specifications. Calibration of the LMS thus is required to determine the LMS accuracy and to determine whether the LMS meets its specification and/or the user requirements. In turn, the calibration is only useful when it is performed with sufficient accuracy and reliability.

This chapter first gives an overview of the LMS accuracy requirements in different standards and legislation. Then several LMS calibration aspects are discussed: the two available calibration approaches, how to assure LMS quality when adjustments have to be made to the LMS, and how often calibration should be performed. Finally, the quality assurance of the LMS calibration is covered. Reference systems suitable for LMS calibration are presented in the next chapter.

III.a LMS Accuracy Requirements

The most explicit requirement on the required LMS accuracy in power transformer loss measurements is given by the IEEE standard C57.12.00-2010 [9]. Table 20 in this standard requires an accuracy of 3.0 % in the loss measurements, down to a power factor of 0.01.

The IEC 60076 series of standards on power transformers only gives an indication of the required LMS accuracy. Chapter 10 of the IEC 60076-8 [10] mentions that for advanced measuring systems, “the resulting phase angle error for the complete system may be of the order of 100 μrad to 200 μrad (0,3 min to 0,6 min). With such systems, an overall maximum error of ±3 % may be achieved for the loss determination down to a power factor of 0,02 or even lower.” This may be taken as a hint that such uncertainties are preferred for loss measurements, but there is no hard requirement.

Finally, the Ecodesign Directive for power transformers indicates in Annex III that for market surveillance “the measured value shall not be greater than the declared value by more than 5 %” for load losses and no-load losses [2]. This is generally interpreted that the measurement uncertainty of the market surveillance test should be better than 5 %, and that power transformer manufacturers should reach such accuracy in their loss measurement tests as well.

However, the customers of the power transformer manufacturers, the utilities that buy the power transformers and shunt reactors, may set their own accuracy requirements. As already indicated earlier, power transformer losses are a significant part of the total cost of ownership to the utility, sometimes even equaling the acquisition costs. Therefore, the utility may not only set a maximum declared loss value for the power transformer, but also set requirements on the accuracy with which this loss value is measured. Fig. 3 illustrates the rationale behind such requirements: loss measurements with good accuracy reduce the risk of incorrect decisions, such as a measurement value that fails to detect compliance of a transformer with the customer or Ecodesign requirements. Or vice versa, a measurement value that fails to detect non-compliance. In general, high-accuracy loss measurements reduce the margin of discussions between manufacturer and customer. Furthermore, they provide the power transformer manufacturer with a tool to design his products closer to the customer limit. This is a competitive advantage, since less expensive materials can be used for a transformer with higher losses. As an extreme example, the authors were once asked on their measurement capability to verify that a transformer, designed to have 0.997 % losses, would surely meet the customer requirement of at most 1 % losses. This request would require a loss measurement with better than 0.003 % accuracy (0.3 % at PF = 0.01), and was one of the drivers for development of the high-accuracy reference setup described in the next chapter.

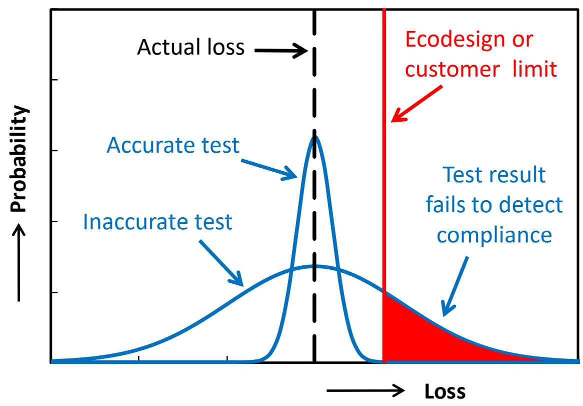

Figure 3: Visualisation of the risk on obtaining incorrect test results for inaccurate loss measurements. For the accurate test, all test results would prove the compliance of the transformer with the Ecodesign or customer requirements. For the inaccurate test, there is a significant risk (with associated financial consequence) that the test result fails to detect this compliance.

III.b LMS Calibration, Adjustment, and Verification

To unambiguously prove that an LMS is meeting the imposed accuracy requirements, it must be calibrated. In the calibration, reference instrumentation is used to determine the deviation of the LMS from the ideal nominal measurement value. Based on the calibration results a statement can then be made on whether the LMS indeed meets its specification and/or the user requirements.

There are two basic approaches in LMS calibration. The first, traditional, method is to calibrate the individual components of the LMS: the voltage scaling, current scaling, and the power meter (see Fig. 1). Subsequently, the individual calibration results must be combined to achieve the total LMS accuracy. A major advantage of the 'component calibration' is that it is relatively easy to perform and that each individual LMS component can be calibrated on all its ranges. However, the component calibration does not cover all possible error sources of the system as a whole, such as interference between the three phases of the LMS and other system effects [11].

In the second, more recent, method the LMS is calibrated as a whole [11-14]. Such a 'system calibration' has the major advantage that it covers all systematic effects of the LMS, including possible errors in the LMS test software. This calibration is more difficult to perform, but leads to lower final LMS uncertainties than the component calibration. To simplify the calibration, reference setups for LMS system calibration are single phase, so that the LMS voltage and current channels have to be placed in parallel and series respectively during the calibration [11-14].

If the calibration results lead to the conclusion that the LMS is not meeting its specifications or user requirements, either corrections have to made to future test results or the LMS has to be adjusted to bring the LMS back into its required accuracy. However, when the LMS is adjusted, the LMS should be calibrated *both before and after the adjustment* to maintain an overview of the actual LMS behaviour and drift over the years. Unfortunately, this is not common practice in LMS calibration. If adjustments are made and only the final calibration results are provided that prove the LMS is (again) meeting its specifications, the power transformer manufacturer has no clue on the actual LMS accuracy just before the LMS adjustment. Indeed, if the LMS was outside its accuracy specifications before the adjustment, the loss measurements performed before the adjustments were not meeting the expected accuracy requirements. As Fig. 3 visualises, this has the serious risk that incorrect test results were obtained and subsequently incorrect conclusions were drawn on the question whether a power transformer is compliant with its loss requirements or not.

The IEC 60060-2 standard mentions that calibrations "should be repeated annually, but the maximum interval shall not be longer than five years" [15]. The optimal interval between successive calibrations depends on many factors, such as the calibration accuracy, LMS stability, required overall LMS accuracy and the risk that the power transformer manufacturer is willing to take [13]. In practice, many power transformer manufacturers opt for the maximum 5-year interval. This may at first sight seem to save on calibration costs, but increases the risk of significant costs brought by possible incorrect loss measurements performed near the end of the 5-year period [13]. If that indeed appears to be the case during the LMS calibration, corrective actions should be taken. Next to the costs associated with the corrective actions, they may also significantly damage the reputation of the power transformer manufacturer.

It therefore is recommended to follow the precision measurement industry practice of calibrating electronic equipment such as power meters every year. For the current and voltage scaling channels, longer re-calibration periods may be used, depending the stability of the technology used in the current and voltage scaling. Ideally, the actual drift and stability of the LMS components is first determined by relatively frequent calibrations in the first years after the acquisition of the LMS, followed by extended calibration intervals based on the actual LMS drift. The final re-calibration interval has to be determined balancing calibration costs and costs of possible corrective actions and thus may be different for different power transformer manufacturers. However, given the importance and impact of reliable and accurate loss tests, a general re-calibration period of 3 years seems more appropriate than the present frequently chosen 5-year interval.

In IEC 60076-8 it is recommended that “the test department shall possess routines for continuously maintaining the quality of measurements. This should be by regular checking and calibration routines for components and for the complete system. It may comprise both in-house functional comparisons between the alternative systems, checking the stability and periodical re-calibration of components” [10]. Cross-check routines indeed are highly valuable for monitoring and verifying the LMS calibration status in between calibrations. They typically are not performed with the same accuracy as a formal calibration, as they serve as a ‘sanity check’ of the calibration status of the LMS.

III.C Traceability

Similar to the performance requirements on LMSs themselves, there are performance requirements posed on the equipment used for calibration of the LMSs. An important requirement according to IEC 60060-2 is that “any calibration shall be traceable to national and/or international standards” [15]. This means that there should be an unbroken chain of measurements linking the LMS calibration to international measurement standards, where each measurement in the chain has a measurement value and uncertainty. Following statements on the LMS specifications, IEEE standard C57.123-2010 explains that “having traceability is a prerequisite to being able to achieve this specification. It provides a means to have documented evidence of the magnitude and phase errors of the various components of the measurement system and their associated uncertainties” [16]. Similarly, IEC 60076-1 requires that “all measuring systems used for the tests shall have certified, traceable accuracy and be subjected to periodic calibration, according to the rules given in ISO 9001. Specific requirements on the accuracy and verification of the measuring systems are described in IEC 60060 series and IEC 60076-8” [17].

The IEC 60060-2 standard gives more background on how the traceability can be achieved. This can be either done by the user himself, or “alternatively, any user may choose to have the performance tests made by a National Metrology Institute or by a Calibration Laboratory accredited for the quantity to be calibrated” [15]. The advantage of the latter approach is explained in a note of paragraph 4.1 of this standard, where it is remarked that “calibrations performed by a National Metrology Institute, or by a laboratory accredited for the quantities calibrated and reported under the accreditation, are considered traceable to national and/or international standards” [15]. Formal accreditation of the company performing the LMS calibration is an important guarantee that the LMS calibration is performed by qualified personnel following adequate, independently reviewed, measurement procedures. The accreditation should preferably be done according to the ISO\IEC 17025 standard for test and calibration laboratories [18], which has specific requirements to ensure correct test and measurement values, next to the more general quality requirements as also given in the ISO 9001 standard.

Indeed, with the increased relevance of reliable transformer loss measurements, the request for LMS calibrations performed under ISO\IEC 17025 accreditation is increasing as well. Following this trend, power transformer manufacturers might even want to become accredited themselves in the future for the loss tests they are performing, as accreditation gives an undisputed, independent proof of the quality of the tests.

IV. REFERENCE SETUPS FOR ON-SITE LMS CALIBRATION

LMS calibrations have to be performed on-site at the premises of the power transformer manufacturers, since the equipment is too large to be transported to the calibration laboratory. In addition, it is important to calibrate the LMS with the same secondary cabling as during normal use so that possible errors due to loading of the current and voltage channel by the secondary cabling are included in the calibration.

In order to realize a meaningful LMS calibration, the reference setup should be more accurate than the LMS specifications or LMS user accuracy requirements. Typically, a test uncertainty ratio (TUR) of 3 – 5 is required, meaning that the reference setup should be 3 – 5 times more accurate than the LMS.

IV.a LMS Component Calibration

For the LMS component calibration, conventional calibration equipment can be used. The LMS voltage and current channels for example can be calibrated using a reference voltage divider and current transformer respectively, together with an adequate measurement bridge [19, 20]. Fig. 4 shows the calibration equipment during an actual on-site LMS component calibration of the current and voltage channels. During a similar calibration campaign, it was found that the power meter formed a significant burden to the current channels, next to the secondary wiring, so that the current channels had to be calibrated with the power meter connected in order to achieve meaningful calibration results.

Figure 4: Pictures of an actual on-site LMS component calibration of the current channels (left) and voltage channels (right), using a sampling current ratio bridge and a high-voltage capacitance bridge [19, 20].

The calibration of the power meter itself does not necessarily have to be performed on-site. In the power meter calibration it crucial to include low power factors, down to at least 0.01. Typical power meter applications relate to energy measurements with power factors close to 1, and therefore most power meter calibrations are performed at these power factors. However, since at power factors near 1 the phase errors of the power meter do not play a significant role, such a calibration is not relevant and meaningful for an application in loss measurements.

Following the component calibration, the total LMS uncertainty has to be evaluated. Even though the IEC 60076-19 standard provides extensive guidance in this uncertainty evaluation, including calculation examples [21], this uncertainty calculation is experienced as quite complex. Moreover, as already mentioned in the previous chapter, the component calibration does not cover systematic errors of the system as a whole. Therefore, component calibration is a convenient LMS calibration method, but not suitable if best accuracies are to be achieved, for example in the calibration of advanced LMS with specifications of 0.5 – 1 % accuracy at PF = 0.01 (phase accuracy 50 – 100 μrad).

LMS component calibration may even become obsolete in the case when all LMSs will eventually use direct digital readout. In that case, the voltage and current channels essentially cannot be tested separately, since in such systems only the final loss power value is available to the user and not the individual voltage and current readings. Any attempt to still calibrate the digital outputs of the voltage and current channels will be hampered by the different digital protocols used by the different LMS equipment manufacturers in their communication with the central control unit. Moreover, in the final loss power value the phase (= timing) error of the individual digital readout units is not important, but only the difference in this phase error for the two units used to read out a particular LMS voltage and current channel. This means that for an LMS with digital readout, LMS system calibration likely is the only remaining feasible option.

IV.b LMS System Calibration

In view of these developments of advanced LMSs, and to assure the highest level of reliability in LMS tests, a reference setup has been developed for ‘system calibration’ of LMS as a whole. The approach in the LMS system calibration is that the reference setup simulates different losses to the LMS system and compares the LMS loss measurement results with those measured by the reference setup, see Fig. 5 [14]. To this end, the reference setup generates a test current with a stable and accurately known phase angle with respect to the applied high voltage. This can either be realized via parallel generation of the voltage and current test signals [22], or via a control loop that generates the current based on the measured phase of the applied high voltage, as depicted in Fig. 5 [12, 14].

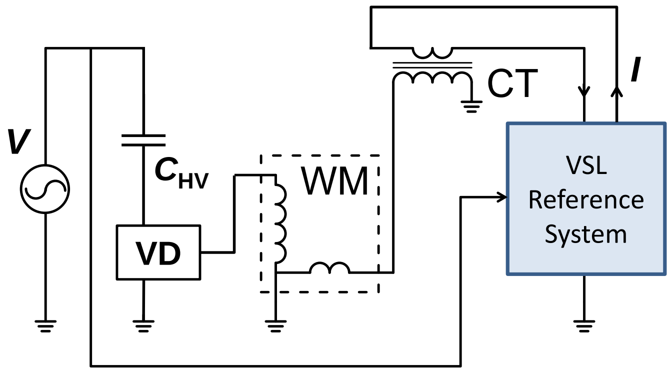

Figure 5: Single-phase schematic overview of system calibration of the industrial LMS of Fig. 1. The reference setup is able to generate currents with different, stable, phase angles with respect to the applied high voltage, thereby simulating a power transformer with different losses to the LMS.

Fig. 6 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 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 a 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.

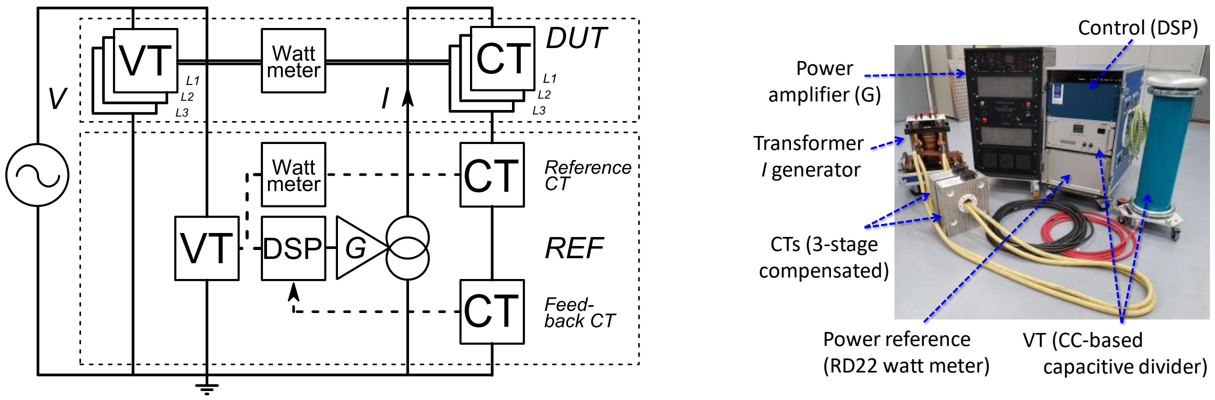

Figure 6: Detailed schematic of the VSL reference setup for LMS system calibration (left), and its actual components (right).

In the final implementation of the reference setup, extensive attention was paid to shielding and grounding to ensure correct operation under the non-ideal and sometimes even harsh conditions of the test site of the power transformer manufacturer. A triax cable is used to connect the HV capacitor with the low-voltage current-comparator electronics of the reference voltage channel. It was verified that even 20 meters of triax cable does not change the voltage reading by more than 0.05 % at PF = 0.01 (5 μrad). Similarly, the CT output cable is a double-shielded twisted pair cable. In both cases, the shielding was on-site verified on its effectiveness. A star ground is strictly used in the measurement circuit, and fiber readout of the DSP ensures that there is no interference with between the analog measurement circuit and the digital readout by the PC in the control room of the test site.

The reference setup in the mean time has been used for several on-site LMS system calibrations. The digital approach of the feedback loop together with extensive automation of the data acquisition process proved to be a real advantage. It allows for LMS system calibration at 21 voltage and current combinations for both 50 Hz and 60 Hz, and each at 5 power factors, within the time frame of a single weekend. In each on-site calibration measurement, the readings of the digital DSP and the reference power meter are compared and found to agree with each other well within the reference system accuracy.

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 100 kV and currents up to 2 kA. In a recent 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 [23]. 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 100 KV AND CURRENTS UP TO 2000 A.

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

V. CONCLUSION

Reliable loss measurements support the drive for higher efficiency in power transformers and shunt reactors. In order to meet the demand for increased accuracy in these measurements, two new voltage channels with improved accuracy and stability have been developed for inclusion in future advanced LMS: a capacitive divider with buffered low-voltage output, and a conventional voltage transformer with passive and digital compensation techniques.

The loss measurement accuracies required according to IEEE and the Ecodesign Directive are 3 % and 5 % respectively at PF = 0.01. However, utilities already require better accuracies, in order to reduce their total cost of ownership. This can go down to an accuracy of better than 0.5 % at PF = 0.01. 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. 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.

A reference setup has been developed for on-site system calibration of LMSs. Here, 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. This low uncertainty meets the calibration requirements of even the most advanced industrial LMS.

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