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Good practice guide for calibration of industrial power transformer loss measurement systems

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Summary

This good practice guide aims to serve as valuable reference for power transformer manufacturers, utilities, and inspectors on the relevant aspects of calibration of industrial loss measurement systems (LMS) used for the loss measurement of power transformers and reactors. It presents an overview of the required calibration and verification measures to assure that power transformer efficiency tests performed by power transformer manufacturers are accurate and reliable.

After a short general description of the LMS and its components, this guide presents the LMS calibration requirements from among others written standards (IEC and IEEE) and utilities with specific attention to the aspect of traceability. The main part of the guide provides detailed information on LMS calibration approaches (component and system calibrations) with an in-depth description of reference setups, practical aspects, calibration certificates and possibilities for error correction, and information on calibration intervals and cross-checks. The findings and recommendations of the guide can be summarised as follows.

The loss measurement accuracies required according to IEEE and the Ecodesign Directive are 3 % and 5 % respectively at PF = 0.01. However, utilities purchasing power transformers and reactors already require better accuracies 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 covers all possible errors in the LMS and can reach the best accuracy levels, down to 0.2 % at a power factor PF = 0.01. ‘Component calibration’ of the components in an LMS (voltage channel, current channel, power meter) is a good alternative if accuracy is less critical. It should be assured that the component calibration of the LMS power meter includes test points at low power factors down to at least PF = 0.01, but preferably to 0.001 or zero. In either calibration, it should be assured that the reference setup is significantly more accurate, ideally a factor 3 – 5, than the LMS specifications. The combination of system calibration and component calibration brings the advantages of both methods together providing best accuracy and reliability, coverage of all measurement ranges, and reliability in case of failures of LMS components.

All LMS calibrations must be traceable to (inter)national reference standards. This is best achieved by a National Metrology Institute (NMI) or calibration laboratory that is ISO/IEC 17025 accredited for this calibration. Power transformer manufacturers, end-users that purchase their products and independent inspectors should therefore always verify that an LMS calibration certificate is indeed issued “*by a laboratory accredited for the quantities calibrated and reported under the accreditation*” (IEC 60060-2). The latter can be readily checked by verifying whether the ISO/IEC 17025 accreditation logo is shown on the certificate.

Many practical aspects affect the measurement results of an on-site LMS calibration. Effects of electro-magnetic interference and ground loop currents should be minimised by careful shielding and grounding of the measurement equipment. LMS voltage channels and current channels should always be calibrated with the actual burden of cable length and power meters connected to their secondary outputs. The equipment should furthermore be located in the actual test bay, positioned as during normal use. Only

then, meaningful calibration results are achieved that represent the errors of the LMS during its actual use in power transformer loss tests.

In case adjustments to the LMS are required to bring the LMS back to its specifications, it is crucial that the LMS is 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 calibrations. 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 and furthermore is not able to track stability of his LMS over the years.

LMS calibration certificates should contain all relevant information for power transformer manufacturers and their customers to determine the errors of the LMS used for testing power transformer losses, and the uncertainty in these errors. For component calibrations, the results of LMS error and measurement uncertainty should be stated in such a way that this information can be readily used to perform a calculation of the overall LMS accuracy along the guidance given in IEC TC 60076-19 [1].

Calibration certificates report the LMS errors during the time of the calibration, and thus calibrations should be regularly repeated to assure continuous insight in the errors of the LMS and in the stability of these errors. According to IEC 60060-2, the general rule is that LMS equipment should be calibrated annually [2]. Longer calibration intervals, up to 5 years, are allowed but lead to a significant risk of incorrect LMS test results due to possible unnoticed errors or drifts in the LMS. Given the importance and impact of reliable and accurate loss tests, a general re-calibration period of maximum 3 years after initial yearly calibrations seems the most appropriate choice. In general, more frequent calibrations increase the trust of customers in the correctness of the LMS test results on power transformer losses, and thus reduce discussions on the reliability of the test results.

Next to the regular repetition of LMS calibrations, cross-checks should be regularly performed as a ‘sanity check’ of the calibration status of the LMS and to assure insight in the LMS errors in between formal LMS calibrations. This is particularly important if there is a wish to extend calibration intervals after initial yearly calibrations of a new LMS. These cross-checks can include comparisons of test results achieved by different LMS (in different test bays), and verification of the LMS power meter and low-voltage electronics of current and voltage channels by using a calibrator that is able to generate precision low-voltage current and voltage signals. The cross-check results should be also documented well.

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1 Introduction

The efficiency of power transformers and reactors is very important, first and most 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 lifetime 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 50-MVA 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 overall cost of operating the electricity grid infrastructure and lead to significant 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 CO2 emissions per year [3]. 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 [4]. For transformers below 3.15 MVA, requirements are set on the maximum load losses (LL) and no-load losses (NLL), whereas larger power transformers have to achieve a minimum so-called Peak Efficiency Index (PEI). 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 perform reliable loss tests, suitable loss measurement systems (LMSs) are required with sufficient accuracy. At present, several instrumentation manufacturers offer commercial systems for such power transformer and reactor loss measurements. Calibration of these commercial LMS is crucial to prove their accuracy and reliability. Traditionally, the individual components of the LMS (voltage channel, current channel, and power meter) are calibrated and the individual calibration results are combined to achieve an indication of the total LMS accuracy. Alternatively, the LMS can be calibrated as a complete system [5, 6], rather than just calibrating the individual LMS components. Such a “system calibration” has the major advantage that it covers all possible systematic errors of the transformer LMS as installed in the test bay of the power transformer manufacturer.

This guide aims to provide guidance to the power transformer industry and calibration service providers by describing best LMS calibration practices, based on the laboratory and on-site calibration experiences of the partners in the EU “TrafoLoss” joint research project [7]. This guidance hopefully contributes to a more harmonised European approach in LMS calibration.

The outline of this guide is as follows. Chapter 2 introduces the working principle of LMS and its main components. In chapters 3 and 4, the calibration requirements on both accuracy and traceability from standardisation organizations and utilities are presented. The different LMS calibration approaches and measures to assure the validity of the calibration are discussed in detail in chapter 5, including practical calibration aspects and suitable reference setups. Chapter 6 finally illustrates the procedure of determining calibration intervals and executing cross-checks. Chapter 7 closes this guide by summarizing the main findings and recommendations.

2 Loss measurement systems

Figure 1 presents a single-phase schematic of the typical industrial LMS used by power transformer manufacturers to verify the losses of their products. The LMS has three main components: voltage scaling devices and current scaling devices to scale the large test voltage and test current to values that can be handled by the third component, a precision wattmeter (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.

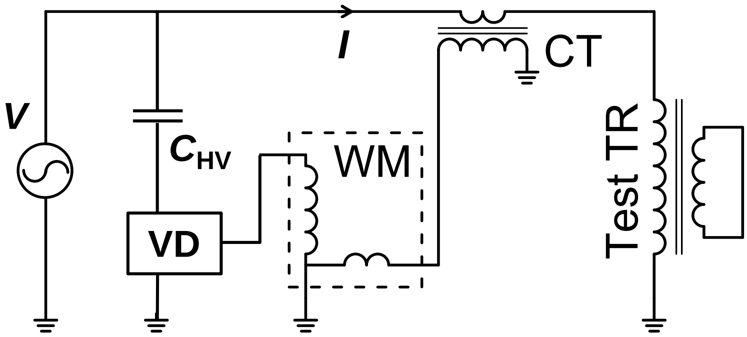


Figure 1: Single-phase schematic overview of an industrial loss measurement setup for determining the load and no-load losses of power transformers.

The key challenge in power transformer and reactor loss measurements is to measure power with good phase accuracy. This can be readily seen from the equation of the loss power P_{loss} for sinusoidal test waveforms:

$$P_{loss} = V \cdot I \cdot \cos(\varphi) \quad (1)$$

with φ the phase angle between the voltage V and current I, and $\cos(\varphi)$ the power factor (PF). For power transformers and reactors having low losses this phase angle is very close to 90°, with a phase angle of 90° corresponding to an ideal transformer or reactor with no losses. In load loss tests of power transformers, the power factor is typically between 0.01 and 0.05, but for reactors the power factor can be as low as 0.002. At a power factor of 0.01, the phase φ is 0.01 rad different from 90°. Measuring losses at PF = 0.01 with an uncertainty of 3 % thus requires measurement of the deviation of the phase φ from 90° with an uncertainty of 3 % of 0.01 rad, which is 300 µrad or 1 minute. In order to achieve this phase accuracy in the LMS, its voltage and current channels and wattmeter should each have a phase measurement accuracy of well below 0.5 minute.

With the increased importance of reliable power transformer and reactor loss measurements, the need arises 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 [7], two new voltage channels have recently been developed with high accuracy and good stability over time. Figure 2 gives photographs of the two dividers. The first divider is a capacitive divider using a high-voltage (HV) capacitor and low voltage electronics with a buffered output to make the divider output voltage independent of measurement burden [8]. The low-voltage (LV) arm consists of ceramic capacitors (290 nF or 3600 nF) on the feedback loop of the buffer amplifier (see schematic in Figure 2) [9], resulting in two measurement ranges. To achieve more measurement ranges, either a HV capacitor with different capacitance value should be used or more capacitors should be added to the LV arm. 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 [8].

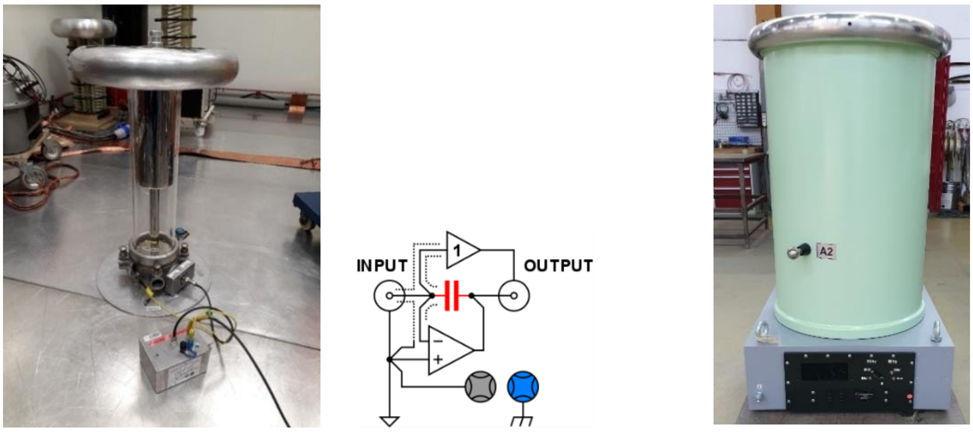


Figure 2: Two high-accuracy HV dividers for inclusion in future advanced LMSs. The left hand shows a capacitive divider with buffered output (see schematic). The right hand shows a conventional voltage transformer with passive error compensation and digital readout.

The second divider is an improved version of an existing conventional design, where the accuracy improvement has been achieved through passive error compensation [10]. 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 [11] or derived technologies, together with metrology digitisers that are synchronised to each other using this timing technology [12]. 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 can be 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.

3 LMS accuracy requirements

Testing losses of power transformers with industrial loss measurement systems is only useful, and the test 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 over the period of several years such that, following initial accurate operation, 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 (still) meets its specification and/or the end user requirements. The calibration in turn is only useful when it is performed with sufficient accuracy and reliability.

The most explicit requirement on the required LMS accuracy in power transformer loss measurements is given by the IEEE standard C57.12.00-2015 [13]. Table 10 in this standard requires an accuracy of 3.0 % in the loss measurements, down to a power factor of 0.01 (see Table I). This corresponds to a phase accuracy of the LMS of 300 μrad, or 1 minute.

Table I: Test system accuracy requirements according to IEEE standard C57.12.00-2015 [13]

Quantity measured	Test system accuracy
Losses	± 3.0 %
Voltage	± 0.5 %
Current	± 0.5 %
Resistance	± 0.5 %
Temperature	± 1.5 °C

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 [14] 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 minute to 0.6 minute). 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.

In turn, the Ecodesign Directive for power transformers indicates in Annex III that for market surveillance of power transformers sold in the European Union:

> “the measured value shall not be greater than the declared value by more than 5 %” for load losses and no-load losses [4].

This is generally interpreted that the measurement uncertainty of any market surveillance test should be better than 5 %, and that power transformer manufacturers should reach at least this accuracy in their loss measurement tests as well.

Finally, the most stringent accuracy requirement is for loss measurements shunt reactors, where the IEC 60076-6 standard [15] states that:

> “The total loss measured … shall not exceed the guaranteed loss by more than 10 %”.

For a useful verification of this requirement, the total loss should be measured with an accuracy of at least 5 %, and ideally better than 3 %. With a typical power factor of 0.002 for reactors, this 3 % accuracy corresponds to 60 μrad (0.2 minute) phase accuracy of the LMS used in the test.

In addition to the requirements from written standards, the customers of the power transformer manufacturers, the utilities that buy the power transformers and shunt reactors, may set their own loss accuracy requirements. As already indicated before, power transformer losses are a significant part of the total cost of ownership to the utility, sometimes even equalling or surpassing the purchase 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. Figure 3 illustrates the rationale behind such an accuracy requirement: 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.

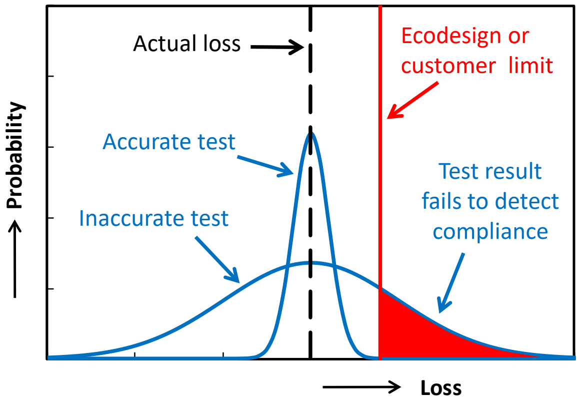


Figure 3: Visualisation of the risk on obtaining incorrect test results when an inaccurate loss measurement system is used in the test. For the accurate test, all test results would prove the compliance of the transformer with the Ecodesign or customer loss requirements. For the inaccurate test, there is a significant risk (with associated financial consequence) that the test result fails to detect this 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, a request was once made by a manufacturer 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 gives 30 μrad), and was one of the drivers for development of the high-accuracy reference setups in the TrafoLoss project [7].

4 Traceability

Calibration of industrial loss measurement systems is crucial to prove that these systems indeed meet the accuracy requirements set by written standards and by customers of power transformer manufacturers. Given the importance of these LMS calibrations, they have to meet specific requirements – in analogy to the performance requirements on the LMSs themselves.

An important calibration requirement according to IEC 60060-2 is that:

> “any calibration shall be traceable to national and/or international standards” [2].

This means that there should be an unbroken chain of measurements linking the LMS calibration results to (inter)national measurement standards, where each measurement in the chain has a measurement value and uncertainty. Following statements on 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].

These two statements underline the stringent requirement for an independent, documented proof of the accuracy of the LMS. Purchasing an LMS from a reputed instrument manufacturer is insufficient to guarantee this LMS meets the accuracy requirements from standards and end users summarized in the previous chapter. Documented evidence via a calibration certificate of the LMS is needed to proof the traceability to national and/or international measurement standards and to unambiguously prove that the LMS indeed has sufficient accuracy.

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” [2].

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” [2],

and thus meet the main traceability requirement of IEC 60060-2.

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 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 given in ISO 9001.

It is noted that any ISO/IEC 17025 accreditation of a calibration service provider always concerns a certain technical scope of activities, published by the accreditation organisation (on its website) that has granted the accreditation. Power transformer manufacturers, end-users that purchase their products and independent inspectors should therefore always verify that an LMS calibration certificate is indeed issued "*by a laboratory accredited for the quantities calibrated and reported under the accreditation*". The latter can be readily checked by verifying whether the ISO/IEC 17025 accreditation logo is shown on the certificate.

Calibrations performed by National Metrology Institutes (NMIs) generally are considered traceable to national and/or international standards, as these institutes develop and maintain the national measurement standards in their respective countries. However, to improve the international acceptance of calibration certificates issued by NMIs, a Mutual Recognition Arrangement (MRA) has been started by the CIPM as part of the international metrology infrastructure where NMIs recognise each other's calibration capabilities. An overview of the NMI calibration measurement capabilities (CMCs) that are part of this MRA are publicly accessible via the Key Comparison DataBase (KCDB, [19]). Several NMIs have CMCs accepted in the KCDB that cover the calibration of the LMS components as well as calibration of the LMS as a whole (see section 5.1).

In case the LMS calibration if performed by the user himself, he has to ensure that his "*calibration shall be traceable to national and/or international standards*". This requires to have quality procedures in place, with adequately trained personnel and reference equipment that itself is calibrated by an NMI or an ISO/IEC 17025 accredited calibration laboratory.

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.

5 LMS calibration

To unambiguously prove that an LMS is meeting the imposed accuracy requirements, it must be calibrated so that the test results become traceable to national or international measurement standards with a known accuracy. 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.

In this chapter two different LMS calibration approaches are presented, together with the reference setups used to perform these calibrations. Subsequently, several practical aspects of the calibration are addressed, as well as the certificates resulting from the calibrations and the possibility to make error corrections to the LMS.

5.1 Calibration approaches: component and system calibration

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 Figure 1). Each of these three calibrations require a dedicated reference setup. Since the required reference systems can be relatively easily developed, this ‘component calibration’ is by far the most common LMS calibration technique. A major advantage of the ‘component calibration’ approach is that it is relatively easy to perform and that each individual LMS component can be calibrated on all its ranges. However, once the calibration results of the individual components are available, they must be combined to achieve the total LMS accuracy. Even though IEC TS 60076-19 provides guidance on how to do this [1], it is a rather complex and cumbersome process, even for an experienced test engineer. A further significant disadvantage of the method, next to the complex overall uncertainty evaluation, is that the component calibration does not cover all possible error sources of the system as a whole. These error sources include interference between the three phases of the LMS, interference between the current and voltage channels, effect of cabling, mistakes in measurement software (calculations), and other system effects [20, 21] .

To cover these limitations, and to enhance the overall confidence in the LMS tests, recently a second LMS calibration method is developed. Here the LMS is calibrated as a whole, using a reference system that simulates power transformers with different losses to the LMS [5, 6, 20, 22]. Such an overall ‘system calibration’ has the major advantage that it covers all systematic effects of the LMS, including possible errors in the LMS test software. The system calibration is more difficult to perform, but can lead to significantly lower final LMS uncertainties than the component calibration. As mentioned in Chapter 3 (see Figure 3), this is a very significant advantage when it comes to verifying whether a power transformer meets certain loss limits. A further advantage of system calibration is that it applies actual (phantom) loss powers to the LMS under test and thus can be performed for a series of phase angles between voltage and current that correspond to those in actual transformer loss measurements [6, 21] . For the power transformer manufacturer and its customers, the certificates of LMS system calibrations are very easy to interpret as they directly contain the overall accuracy of the LMS system at the typical test points used in power transformer loss measurements, not requiring any further uncertainty calculations.

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 [5, 6, 20, 22]. Since each calibration measurement in the system calibration is performed at a certain voltage-current combination, it practically impossible to cover all voltage and current ranges (note that an LMS with 10 voltage ranges and 13 current ranges has in total 130 possible voltage-current combinations). Therefore, typically the voltage-current combinations mostly used by the manufacturer in his power transformer tests are covered in the system calibration.

In conclusion, best accuracy and highest reliability is achieved in LMS system calibrations. Component calibration is a good alternative if accuracy is less critical. The combination of system calibration and component calibration brings the advantages of both methods together providing best accuracy and reliability, coverage of all measurement ranges, and reliability in case of failures of LMS components.

5.2 Reference setups for 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. This preferably should be done with the LMS in its actual test bay, positioned as during normal use

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 specifications.

5.2.1 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 [23, 24, 25]. Figure 4 shows an example of calibration reference equipment during an actual on-site component calibration of the current and voltage channels of an industrial LMS. If very high-end references and test bridges are used, uncertainties can be achieved on-site of better than 0.002 % in ratio or magnitude and better than 20 μrad (0.06 minute) in phase respectively. However, the harsh calibration environment of a transformer test hall may hamper achieving such accuracies due to disturbing effects of stray fields, ground loops, and the use of long measurement cables further discussed in section 5.3. Figure 5 shows the phase displacement results of the LMS calibration depicted in Figure 4. In this particular case, in four days all 23 ranges of the voltage and current channels of the commercial three-phase LMS system were calibrated by an NMI with uncertainties down to 0.003 % in magnitude and 0.1 minute in phase displacement respectively.

The calibration of the LMS power meter does not necessarily have to be performed on-site. In the power meter calibration, *it is crucial to include low power factors*, down to at least 0.01, but preferably to 0.001 or zero. 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 only magnitude errors are significant, such a calibration is not relevant and meaningful for an application in loss measurements were phase errors dominate (see chapter 2). Therefore, the calibration of power meters used in LMSs must be performed at low power factor values where the phase errors of the power meter dominate.

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 respectively.

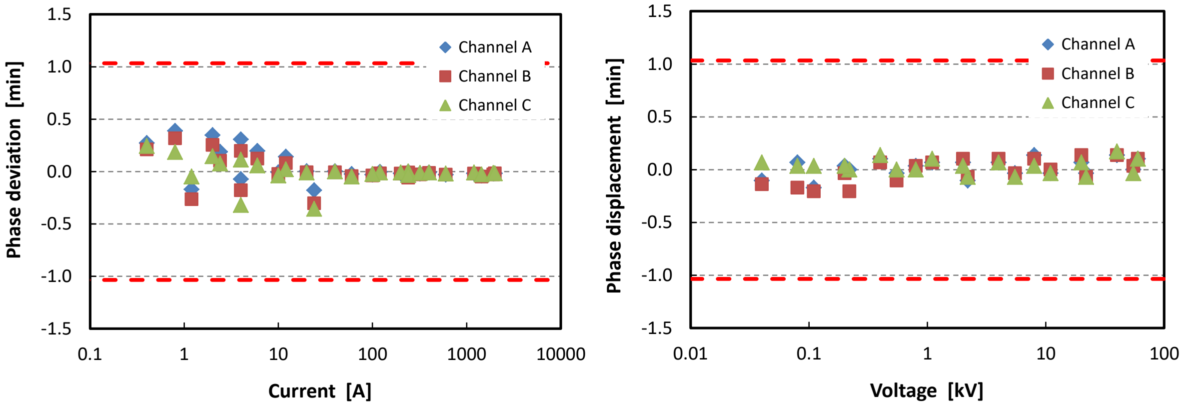


Figure 5: Phase displacement of the current channels (left) and voltage channels (right) of a commercial LMS as determined during an actual on-site calibration.

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 [1], this uncertainty calculation is found to be quite complex to perform, even for experienced test engineers. Moreover, as already mentioned in the previous section, 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 rad).

It is noted that for LMSs that use direct digital readout of the voltage and current channels component calibration essentially cannot be performed anymore, 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.

5.2.2 LMS System Calibration

In view of these developments of advanced LMSs, and to assure the highest level of reliability in LMS tests, several NMIs have developed reference setups for ‘system calibration’ of LMS as a whole [5, 22, 26, 27]. The approach taken in the LMS system calibration is that the reference setup simulates a power transformer with different losses to the LMS system, see Figure 7. To this end, the reference setup generates a test current with a stable and accurately known phase angle with respect to the applied high test voltage. Subsequently the loss measurement readings of the LMS are compared those of the reference setup. 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.

The generation of the voltage and current signals can either be realized via parallel simultaneous generation of the voltage and current test signals, see Figure 6 [26, 27], or via a control loop that generates the current based on the measured phase of the applied high voltage, see Figure 7 [5, 22]. The first approach requires very stable high-power amplifiers to assure that the test signals do not drift, in particular not in phase, during the time of the calibration. The second approach relies on an advanced feedback loop to accurately track and control the current in phase with respect to the applied voltage, even when this voltage has certain frequency, phase and amplitude variations. The main elements of both approaches are a generation part (up to 230 kV voltage and 2 kA or 4 kA current) together with reference measurement facilities. Both reference setups are 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.

As example of the first approach, without a few details such as feedbacks, is given in Figure 6. Measurement uncertainties are scaling from 20 μW/VA up to 50 μW/VA depending on the applied and measured levels in voltages and power factors. This includes instabilities of the generated high voltage and high current signals. Figure 7 gives an example of the second approach, where variations of the high voltage signal are tracked by a carefully-designed feedback loop to ensure that the phase between voltage and current is stable within a few μrad (0.1 m° or 0.01 min).

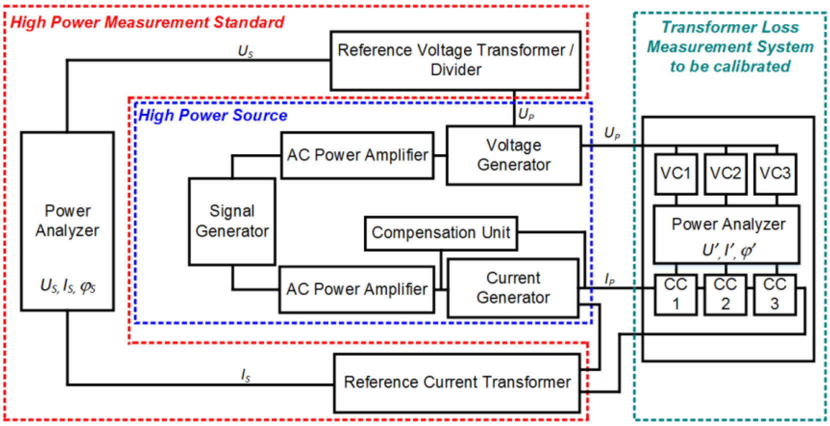


Figure 6: Schematic overview of the first approach for system calibration of an industrial LMS, using simultaneous generation of voltage and current ('high power source').

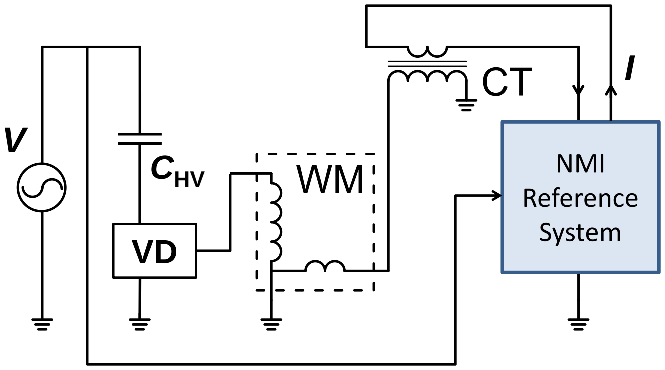


Figure 7: Single-phase schematic overview of the second approach for system calibration of the industrial LMS of Figure 1, using a feedback loop to generate a current with known, stable phase with respect to the applied voltage.

As an example of an actual implementation for the second approach, Figure 8 gives more details on an NMI reference setup for system calibration of industrial LMSs that follows the approach given in Figure 7 [22]. A current-comparator-based capacitive voltage divider (CCB-CVD) 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 (Ref. CT1). The DSP unit compares the actual phase of the applied 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 wattmeter is used to verify the readings from the digital feedback loop. This verification is considered important in case a deviation of the LMS is detected during the calibration, and the accuracy of the reference system with which the LMS is being calibrated is subsequently questioned.

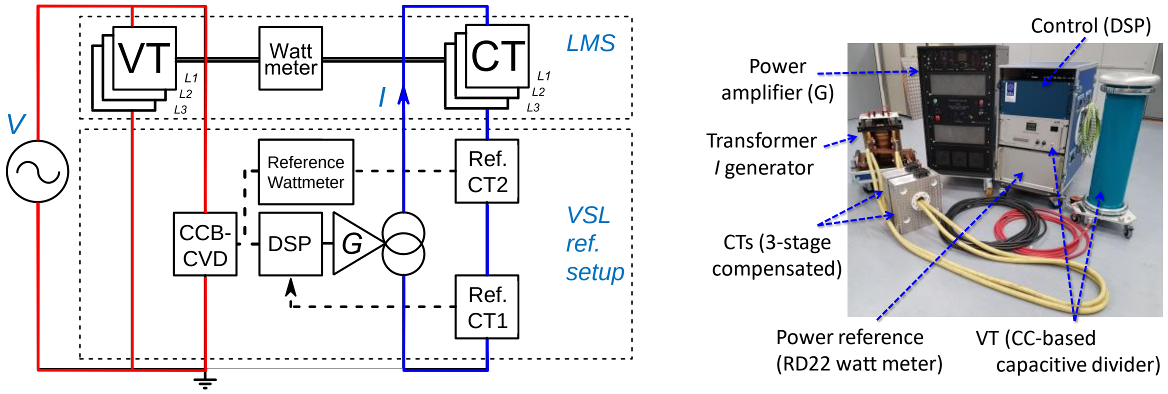
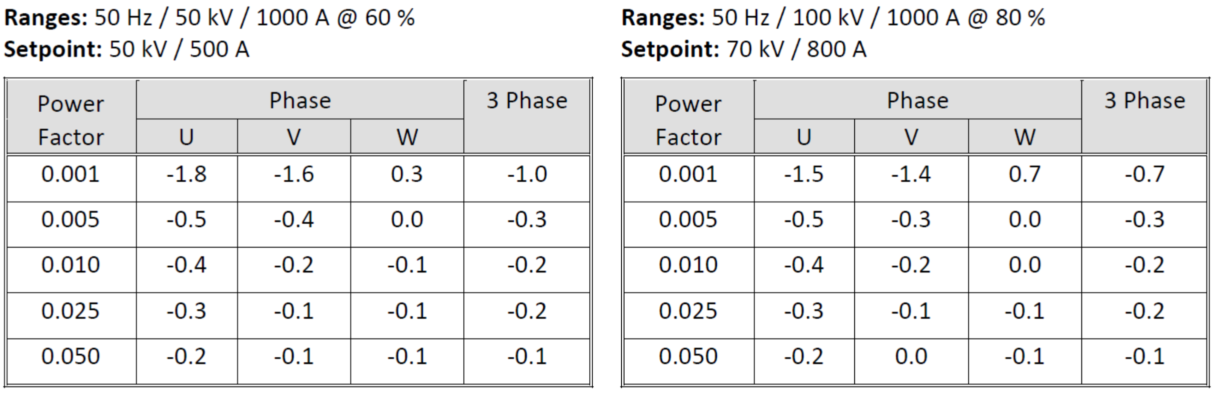


Figure 8: Detailed schematic of an NMI reference setup for LMS system calibration (left), and its actual components (right). Note that the reference system is single channel, so that the LMS under test (top box left) has its three voltage and current channels put in parallel and series, respectively, during the calibration.

After careful calibration of each of the three main elements of the reference setup, voltage divider, current transformers and reference wattmeter, to the level of better than 0.001 % in ratio or magnitude and 10 μrad (0.03 minute) in phase, an overall system uncertainty of better than 0.2 % at a power factor of 0.01 can be achieved for voltages up to 230 kV and currents up to 2 kA [5, 22]. This is sufficient to meet the most demanding LMS calibration requirements. It even allows for calibration of reactor loss measurement systems with 1 % uncertainty at a typical reactor loss power factor of 0.002.

In a recent comparison of two NMI LMS reference setups, this accuracy was independently verified. The measured difference in the two NMI results was less than 0.12 % in loss power at PF = 0.01 for currents up to 1000 A and voltages up to 70 kV [28]. This was well within the respective measurement accuracies of the two NMI reference setups.

If the reference system is fully automated, the system calibration of an LMS takes around two days for calibration of fifteen to twenty voltage-current combinations at a single power line frequency, with one additional day for a second frequency. Figure 9 shows an example calibration result of a system calibration of an advanced industrial power transformer LMS. The certificate shows the error (in %) of the LMS loss measurement readings for certain voltage-current combinations at different power factors. In this way the power transformer manufacturer and his customers get direct information, without any further required analysis, on the accuracy of the LMS used in testing the losses of its power transformers.



Ranges: 50 Hz / 50 kV / 1000 A @ 60 %
Setpoint: 50 kV / 500 A

Power Factor	Phase			3 Phase
	U	V	W	
0.001	-1.8	-1.6	0.3	-1.0
0.005	-0.5	-0.4	0.0	-0.3
0.010	-0.4	-0.2	-0.1	-0.2
0.025	-0.3	-0.1	-0.1	-0.2
0.050	-0.2	-0.1	-0.1	-0.1

Ranges: 50 Hz / 100 kV / 1000 A @ 80 %
Setpoint: 70 kV / 800 A

Power Factor	Phase			3 Phase
	U	V	W	
0.001	-1.5	-1.4	0.7	-0.7
0.005	-0.5	-0.3	0.0	-0.3
0.010	-0.4	-0.2	0.0	-0.2
0.025	-0.3	-0.1	-0.1	-0.2
0.050	-0.2	0.0	-0.1	-0.1

Figure 9: Detail of a calibration certificate from a system calibration of an advanced industrial power transformer LMS, showing the relative error (in %) of the LMS loss measurement reading for each of the three phases of the LMS as well as for the combined 3-phase loss reading. The uncertainty in the indicated LMS loss error values is 0.5 %, except for PF = 0.001 where the uncertainty is 2.0 %.

Finally, it is noted that LMS system calibration can be used to verify LMS component calibration. If component calibration is performed close in time to a system calibration of the same LMS, the component calibration results (with its calculated system uncertainty following [1]) can be compared with the system calibration result. If the difference between the two results is larger than the combined uncertainties, either something is not correct with the component calibration, or there are some unknown influences in the measuring equipment set up.

5.3 Practical aspects

The on-site calibration of LMS systems has many practical aspects which affect the measurement results as well as their uncertainty, such as:

- Impact of wiring and burdens on voltage and current channels
- Interference
- Grounding
- Quality of the calibration signal (harmonics, frequency stability)
- Temperature variations
- Power meter resolution
- Possible adjustment of the LMS

These aspects are discussed in the follow paragraphs of this section.

Burden

The accuracy of LMS voltage channels and current channels can significantly depend on the burden connected to their outputs. This is particularly true for passive, conventional (non-electronic) voltage and current transformers. The burden first of all consists of the impedance of the secondary wiring used to connect the secondary output of the voltage and current channels to the LMS power meter, and secondly of the input impedance of the power meter itself. Depending on the size of the test hall and the configuration of the LMS, the length of the secondary wiring typically is several tens of meters, up to even 100 meters. The input impedance of the voltage channels of modern digital power meters is in the MΩ-range and thus can be neglected. For the current channels, the input impedance of the power meter can be significant and moreover will vary with the output current level of the current channel. Some industrial LMSs always scale the primary current to an output current at the 1 A level, whereas other LMSs use a fixed-ratio current transformer, causing the output current to vary from mA to A level for typical primary currents used in power transformer tests. In the first case, the input impedance of the power meter will be always the same, whereas in the latter case it will vary with primary current level and can become very significant at low primary currents. For this reason, it is very important to always calibrate voltage and current channels with the actual burden imposed by the secondary wiring and the power meter – both in component calibrations and in system calibrations. Only then, meaningful calibration results are achieved that represent the errors of the LMS during its actual use in power transformer loss tests.

In LMS component calibrations, the impact of the input impedance of voltage/current test set (used as reference) on the actual burden of the LMS components should be considered. For example, commercial voltage transformer bridges have input impedances between 12 kΩ up to 380 kΩ, which is significantly lower than the MΩ-range input impedance of modern power meters connected to the LMS voltage channels, and thus can affect the measurement results. Additionally, the errors of standard current transformers (in particular passive ones) used in the reference system should be re-checked on their burden dependence when different lengths of secondary wirings are used between test hall and the control room.

Interference

The high-voltage test halls can be harsh environments for performing high-end LMS tests and calibrations. In addition, long cables, sensitive to pick up of unwanted interference, are required to cover the distances in the test halls, for example between the primary parts of the LMS in the test hall and its secondary parts in the control room. Therefore, attention should be paid to minimise such interference, in particular when the calibration or test is performed at the frequency of the local mains. This requires good shielding of all measurement cables and careful grounding of both the LMS and the reference setup used in the LMS calibration [22].

Grounding

Safety requirements sometimes make it difficult to prevent ground loops. This can be remedied by using measurement cables with double shields, such as triaxial cables for the secondary wiring of the voltage channels and double-shielded twisted-pair cables for the secondary wiring of the current channels. In this case, the outer shield can be used as safety ground and connected to ground at both ends, whereas the inner shield of the cable can be used as a measurement ground and connected to ground at only one end of the cable. A star ground should be strictly used in the measurement circuit, with high-quality low-ohmic ground connections.

Furthermore, it is recommended to use power meters and digitisers with good common mode signal suppressions. Finally, interference from computer control and readout can be reduced using a fibre connection to the measurement equipment that ensures galvanic separation between the computer and the measurement setup.

HV test signal

The high-voltage signal used in the calibration will inevitably contain distortions, depending on the quality of the HV generator. In the case of component calibration, this will generally not be a problem as the same distortion is present in the signal of both the reference and the LMS voltage channel, and measurement bridges are designed to handle this well. In LMS system calibrations, the impact of the distortions on the measurement result depends on how much harmonic power is generated, and the difference in bandwidth of the LMS and the reference system. Harmonic power is only generated when the distortion is present at the same frequency in both voltage and current. In addition, harmonic power levels are typically low since power is the product of voltage and current: 1 % harmonic distortion in both voltage and current at the same frequencies only gives rise to 0.01 % harmonic power. Finally, the presence of harmonic power is not a problem in the LMS system calibration if the bandwidth of the power meter in the LMS and in the reference setup is similar. A reference system based on sampling digitisers and a sampling reference power meter will have the same bandwidth as digital power meters used in modern LMS, and not be sensitive to harmonic distortions in the applied voltage [22]. An explicit test of this has been performed for such a system where no difference in the LMS calibration result was found with either using a test voltage with 0.5 % Total Harmonic Distortion (THD) or with 10 % THD. However, a reference system based on analog current comparators that measures the losses at power line frequency [5] requires the use of voltage sources that are below 1 % THD in order to assure that the difference in measurement bandwidth is not causing erroneous calibration results.

Temperature

The LMS voltage and current transducers are mostly located in a non-conditioned area (mostly without climate control) in or near the test hall. During on-site calibrations, temperature variations will affect the stability of the LMS components and of the reference system. This particularly affects high-voltage capacitors since their capacitance value has a typical temperature coefficient of about 25 ppm/°C. Fortunately, the temperature effect on the dissipation factor (DF) of HV capacitors is very small, and this DF is the relevant parameter in loss measurements at low power factors. In all on-site calibrations, the effect of temperature variations should be carefully taken into account in the estimation of the final calibration uncertainty.

Power meter resolution

Digital power meters used in a LMS might use a fixed number of digits in their readings, which would limit the resolution when displaying measured values in watts, kW or MW. Loss power readings from some power meters used in LMS systems are limited in resolution to 3 significant numbers while performing measurements at power factors below 0.01. Any instability in the last digit then contributes 100 ppm to the overall uncertainty which is far from the targeted total uncertainty. This can for example be solved by extending the sampling time (integration time) in the power measurement from typically 1 second to 10 seconds or more, and by repeating the measurements until better than 10 ppm noise is achieved.

If the LMS power meter is read out via a computer of the reference system, it should be assured that the LMS power meter is in the same setting as during normal loss tests of power transformers. In addition, it should be verified that the LMS customer software to read out the power meter during power transformer loss tests does not use any corrections on the loss power as measured by the power meter.

LMS adjustments

In general, a calibration determines and reports the error of the LMS without any adjustments to the instrumentation. However, in case the calibration shows that the LMS has drifted outside its specifications, for example in its voltage channels, adjustments to the LMS may be required. It is crucial that in this case, 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 and furthermore is not able to track stability of his LMS over the years.

5.4 Calibration certificates

LMS calibration certificates should contain all relevant information for power transformer manufacturers and their customers to determine the errors of the LMS used for testing power transformer losses, and the uncertainty in these errors. The ISO/IEC 17025 standard provides good guidance on what information thus is required on LMS calibration certificates.

Some attention points for LMS calibration certificates based on this standard and on review of LMS certificates issued by LMS calibration providers in the past decade:

- Good indication must be provided of all the components that constitute the LMS. For a system calibration of an LMS with capacitive voltage dividers this can be up to 16 elements.
- For each calibration point, an indication of the ranges used and the applied test voltage / current in these ranges must be given. The correct indication of the ranges is important as LMSs typically have many voltage and current ranges, and tests at a certain voltage or current can thus be done in different LMS ranges.
- Settings of the digital power meter during the calibration, e.g. ranges and the use of filters or averaging.
- Component calibration of the power meter should cover the ranges used in the LMS *and include test points at low power factors* (PF = 0.01 or lower). As mentioned in section 5.2.1, only such a calibration gives the necessary information on the phase error of the power meter.
- In case of system calibrations, the software version of the customer LMS has to be noted, and/or which scaling factors are being used in the LMS software or firmware. For LMS current channels, typically nominal scaling factors are used, but for LMS voltage channels based on HV capacitors,

often non-nominal scaling factors are used to correct for the typically far-from-nominal capacitance value of these capacitors.

- Clear indication of the measurement uncertainty.
- For component calibrations, the results of LMS error and measurement uncertainty should be stated in such a way that this information can be readily used to perform a calculation of the overall LMS accuracy along the guidance given in IEC TC 60076-19 [1].
- Traceability to national and/or international measurement standards should be explicitly mentioned, and proof of accreditation should be explicitly visible (e.g. via the logo of an accreditation organisation).

5.5 Error correction by software

The LMS calibration certificates report the LMS errors for different ranges and operating conditions. Once these are known, it in principle opens up the possibility for increasing the LMS accuracy by correcting for these errors. Typically, this is not done by the power transformer manufacturers and the reported errors are taken into account in the final accuracy evaluation of the system. This approach is motivated by the complexity of the error correction given the multiple LMS ranges, which makes any error correction prone to errors.

Should the LMS owner want to correct LMS errors based on the LMS calibration certificate, careful administration of the full process is critical. First of all, it should be ensured that the right sign of the correction is applied: if the certificate for example shows a positive error for a certain LMS range, the correction to be made on the raw data is negative. One needs to be fully sure about the assigned sign of the correction since it is very easy to make mistakes, in which case the error of the LMS is increased rather than reduced. Secondly, great care should be taken to make the correct error corrections for each of the (many) LMS voltage and current ranges, and for any combination of these ranges. Once the corrections are implemented, it is highly recommended to store the results both with and without error correction (corrected data and raw data). This makes it possible to always check the error correction, and in case mistakes are found, to re-apply improved corrections to the raw measurement data. The PTB AC power standard for transformer loss measurements has implemented this method of error correction, and based on extensive correction tables for the voltage transformer, current transformer and for the many ranges of the digital power meter used in the setup, the final uncertainty of the setup was improved to better than 40 μW/VA [26].

In summary, given the complexity of the LMS error correction process and its proneness to errors, power transformer manufacturers are strongly advised to keep the present practice to not make any corrections and to include the reported LMS errors in their final uncertainty evaluation.

6 Calibration intervals and cross-checks

6.1 Calibration intervals

Calibration certificates report the LMS errors during the time of the calibration, and thus only give a ‘snapshot’ in time of the LMS errors. Therefore, calibrations should be regularly repeated to assure continuous insight in the errors of the LMS and in the stability of these errors.

The IEC 60060-2 standard requires that calibrations

> “should be repeated annually, but the maximum interval shall not be longer than five years” [2].

The optimal interval between successive LMS 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 [21]. 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 at the same time significantly increases the risk of major costs brought by possible incorrect loss measurements performed in the later part of the 5-year period [6]. If indeed the LMS appears to be out of specifications during an LMS calibration, corrective actions must be taken. Next to the large costs associated with these corrective actions, they may also significantly damage the reputation of the power transformer manufacturer.

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 specification. 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. 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 Figure 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.

It is therefore strongly recommended to follow the best practices of the precision measurement industry in determining calibration intervals.

- The typical re-calibration interval used in the precision measurement industry for calibration of active electronic equipment, such as power meters, is 1 year. This aligns with the requirement of the IEC 60060-2 standard that generally calls for annual calibrations. In case of a combination with LMS system calibrations, it is advised to have the power meter calibrated before the system calibration is performed.
- For the LMS current and voltage channels, re-calibration periods may be used between 1 and 3 years, depending on the stability of the technology used in the current and voltage scaling. Many LMSs use active electronics in the low-voltage part of the voltage scaling and/or current scaling. In line with the re-calibration interval for power meters this calls for more frequent calibrations, for example every 1 – 2 years. For electronics where the accuracy is maintained by current

comparator technology, intervals of 2 – 3 years may become feasible. Conventional passive voltage transformers (VTs) and current transformers (CTs) are well known for their long-term stability so that also here re-calibration every 2 – 3 years seems a feasible option.

- System calibration of LMSs should be repeated with similar intervals as the component calibrations indicated above, so every 1 – 3 years, depending on the technology used in the current and voltage scaling. Given the active electronics used in the power meter, this meter should always be calibrated every year.

After relatively frequent calibrations in the first years after acquisition of the LMS, an impression is achieved of the actual drift and stability of the LMS components. Based on this information, calibration intervals may be extended, if desired, to e.g. 3 years for active voltage and current channels, 3-5 years for conventional passive transformers, and 3 years for system calibrations. When opting for these longer calibration intervals, the frequent performance of cross-checks as discussed in the next section becomes important.

In any case, the final responsibility for determining the re-calibration interval is for the owner of the LMS, the power transformer manufacturer. As already indicated above, in these considerations calibration costs and costs of possible corrective actions have to be balanced and the outcome 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 maximum 3 years after initial more frequent calibrations seems more appropriate than the present frequently chosen 5-year interval. The 5-year interval is also very disputable given the experience of NMI LMS calibration providers that LMS systems they calibrate after such a long interval too frequently show errors due to e.g. loose wiring or errors that have drifted outside the specifications.

In general, more frequent calibrations increase the trust of customers in the correctness of the LMS test results on power transformer losses, and thus reduce discussions on the reliability of the test results. Given the requirement to unambiguously prove that power transformers put on the European market are meeting the Ecodesign requirements, power transformer manufacturers that discern themselves by high-quality products may therefore go for 1-year calibration intervals, which are only extended after sufficient calibration history has been built up.

6.2 Cross-checks

As stated in the previous section, calibration certificates only give a ‘snapshot’ in time of the LMS errors. Therefore, next to the regular repetition of these calibrations, also cross-checks should be regularly performed to assure insight in the LMS errors in between formal LMS calibrations. This is particularly important if there is a wish to extend calibration intervals a few years after initial frequent calibrations of a new LMS.

IEC 60076-8 states 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” [14].

‘Regular checking’ of the LMS components and of the complete LMS system indeed is highly valuable for monitoring and verifying the LMS calibration status in between calibrations and thus maintaining the quality of the test measurements. Such checks 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.

The standard mentions the option of performing in-house functional comparisons between alternative systems. It indeed is very useful to have multiple transformers of the same model or produced in the same batch tested at different test bays, and subsequently compare the loss test results. The (minor) differences in these results should align with the difference in LMS errors from the LMS calibration certificates.

Test engineers should always be aware of possible errors in the LMS. If unexpectedly high or low losses are found in certain tests, a basic functionality check of the LMS should be performed. This can among others include verification of the use of the correct LMS ranges as well as verification of the LMS wiring (cables and connectors).

Finally, the calibration status of power meters and of low-voltage electronics of current and voltage channels can be verified in between calibrations by using calibrators that can generate precision low-voltage current and voltage signals.

Similar to the formal calibration results, the findings of any cross-checks should be filed as part of the documentation that proves the calibration status of LMS.

7 Conclusions

Reliable loss measurements support the drive for higher efficiency in power transformers and shunt reactors, and more accurate measurements are needed to meet the demanding requirements. LMS calibration is a crucial means to prove the accuracy and reliability of the loss tests performed with these systems. Therefore, a series of useful guidelines for end-users are formulated as ‘good practice guide’ for the calibration of advanced industrial LMS, aiming to contribute to better and more harmonised best practices in LMS calibration in Europe.

The loss measurement accuracies required according to IEEE and the Ecodesign Directive are 3 % and 5 % respectively at PF = 0.01. However, utilities purchasing power transformers and reactors 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 covers all possible errors in the LMS and can reach the best accuracy levels, down to 0.2 % at a power factor PF = 0.01. In this approach, actual (phantom) loss powers are applied to the LMS under test and with phase angles between voltage and current that correspond to those in actual transformer loss measurements [6, 21]. For the power transformer manufacturer and its customers, the certificates of LMS system calibrations are very easy to interpret as they directly contain the overall accuracy of the LMS system at the typical test points used in power transformer loss measurements, not requiring any further uncertainty calculations. A small disadvantage of this calibration approach is that it is not practical to cover all possible test points (voltage – current combinations).

‘Component calibration’ of the components in an LMS (voltage channel, current channel, power meter) is a good alternative to ‘system calibration’ if accuracy is less critical. A major advantage of the this approach is that it is relatively easy to perform and that each individual LMS component can be calibrated on all its ranges. However, once the calibration results of the individual components are available, they must be combined to achieve the total LMS accuracy. Even though IEC TS 60076-19 provides guidance on how to do this [1], it is a rather complex and cumbersome process, even for an experienced test engineer. It should be assured that component calibration of the LMS power meter includes test points at low power factors down to at least PF = 0.01, but preferably to 0.001 or zero.

In either calibration, it should be assured that the reference setup is significantly more accurate, ideally a factor 3 – 5, than the LMS specifications. The combination of system calibration and component calibration brings the advantages of both methods together providing best accuracy and reliability, coverage of all measurement ranges, and reliability in case of failures of LMS components.

All LMS calibrations must be traceable to (inter)national reference standards. This is best achieved by a National Metrology Institute (NMI) or calibration laboratory that is ISO/IEC 17025 accredited for this calibration. Power transformer manufacturers, end-users that purchase their products and independent inspectors should therefore always verify that an LMS calibration certificate is indeed issued “*by a laboratory accredited for the quantities calibrated and reported under the accreditation*” (IEC 60060-2). The latter can be readily checked by verifying whether the ISO/IEC 17025 accreditation logo is shown on the certificate.

Many practical aspects affect the measurement results of an on-site LMS calibration. Effects of electro-magnetic interference and ground loop currents should be minimised by careful shielding and grounding of the measurement equipment. LMS voltage channels and current channels should always be calibrated with the actual burden of cable length and power meters connected to their secondary outputs. The equipment should furthermore be located in the actual test bay, positioned as during normal use. Only then, meaningful calibration results are achieved that represent the errors of the LMS during its actual use in power transformer loss tests.

In case adjustments to the LMS are required to bring the LMS back to its specifications, it is crucial that the LMS is 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 calibrations. 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 and furthermore is not able to track stability of his LMS over the years.

LMS calibration certificates should contain all relevant information for power transformer manufacturers and their customers to determine the errors of the LMS used for testing power transformer losses, and the uncertainty in these errors. For component calibrations, the results of LMS error and measurement uncertainty should be stated in such a way that this information can be readily used to perform a calculation of the overall LMS accuracy along the guidance given in IEC TC 60076-19 [1].

Calibration certificates report the LMS errors during the time of the calibration, and thus calibrations should be regularly repeated to assure continuous insight in the errors of the LMS and in the stability of these errors. According to IEC 60060-2, the general rule is that LMS equipment should be calibrated annually [2]. Longer calibration intervals, up to 5 years, are allowed but lead to a significant risk of incorrect LMS test results due to possible unnoticed errors or drifts in the LMS. Given the importance and impact of reliable and accurate loss tests, a general re-calibration period of maximum 3 years after initial yearly calibrations seems the most appropriate choice. In general, more frequent calibrations increase the trust of customers in the correctness of the LMS test results on power transformer losses, and thus reduce discussions on the reliability of the test results.

Next to the regular repetition of LMS calibrations, cross-checks should be regularly performed as a ‘sanity check’ of the calibration status of the LMS and to assure insight in the LMS errors in between formal LMS calibrations. This is particularly important if there is a wish to extend calibration intervals after initial yearly calibrations of a new LMS. These cross-checks can include comparisons of test results achieved by different LMS (in different test bays), and verification of the LMS power meter and low-voltage electronics of current and voltage channels by using a calibrator that is able to generate precision low-voltage current and voltage signals. The cross-check results should be also documented well.

8 References

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