MEETING ECODESIGN EFFICIENCY REQUIREMENTS: ENSURING ACCURACY IN POWER TRANSFORMER LOSS TESTS VIA TLM SYSTEM CALIBRATIONS

Gert RIETVELD
VSL, the Netherlands
gert.rietveld@vsl.nl

Ernest HOUTZAGER
VSL, the Netherlands
ehoutzager@vsl.nl

Milos ACANSKI
VSL, the Netherlands
macanski@vsl.nl

Dennis HOOGENBOOM
VSL, the Netherlands
dhoogenboom@vsl.nl

ABSTRACT

As part of the sustainable energy policies of the EU, the Ecodesign Directive puts efficiency requirements per 1 July 2015 on medium and large power transformers. This increases the importance of unambiguous measurement of power transformer losses, and thus of the accuracy of the transformer loss measurement (TLM) systems used by power transformer manufacturers for verification of these losses. Higher accuracy measurements not only lead to increased confidence in the product at the customers, but also allows for saving costs by designing transformers close to the loss limits. To support high-quality power transformer loss measurements, VSL has developed a reference system for calibration of TLM systems at the best accuracy levels. A significant advantage is that the TLM systems are calibrated as a whole, thereby covering all possible error sources. Using advanced digital signal processing techniques, high currents are generated with adjustable, stable phase with respect to the applied test voltage. Test results show that calibration accuracies of 25 μrad in phase (corresponding to 0.25 % in active power at power factor of 0.01) are achieved for test voltages and currents up to 100 kV and 2 kA respectively – a factor 10 better than typical TLM system specifications.

INTRODUCTION

Power transformer losses are a significant part of the total losses in our electricity grids. These losses not only constitute costs, but they also have a significant impact on the environment via the CO_2 emissions of the power plants providing this loss power. The saving potential via more efficient designs has been estimated as 16 TWh/year and 3.7 Mt of CO2 emissions per year [8]. This has led the European Union to place efficiency requirements on power transformers as part of its Ecodesign Directive [1]. As a consequence, per 1 July 2015, it is not allowed anymore to put power transformers not meeting these (Tier-1) requirements on the European market. Presently, the plans to have even more stringent (Tier-2) requirements per 1 July 2021 are under evaluation whether they are still cost-effective from a lifecycle analysis perspective [9].

The challenge for power transformer manufacturers is to unambiguously prove that their products comply with the new efficiency requirements of the Ecodesign Directive. To this end, the losses of their products are tested using power transformer loss measurement (TLM) systems. In order to provide reliable test results, these TLM systems must have an accuracy of 5 % or better in the loss measurements [1]. Given this tight accuracy requirement, it is of extreme importance that power transformer manufacturers prove that their TLM systems indeed actually achieve these accuracies.

After a short description of transformer loss measurement systems, this paper describes the relevancy of high accuracy in power transformer loss measurements as well as the calibration strategies for ensuring this accuracy. A new reference system is described in detail that is able to calibrate TLM systems as a whole, at accuracy levels that meet the most stringent requirements of power transformer manufacturers and their customers. This is followed by a short discussion on (re-)calibration intervals and some conclusions.

TRANSFORMER LOSS MEASUREMENTS

Fig. 1 shows a typical schematic of a TLM system used for loss measurements of power transformers. In order to determine all relevant loss contributions of a power transformer both load loss and no-load loss measurements are performed, with the secondary windings of the transformer open and shorted respectively. The actual quantity measured by TLM systems is active (loss) power:

$$P_{loss} = V\,I\cos(\varphi) \qquad (1)$$

Since the tests are performed at high voltages and currents, voltage and current transformers (VTs and CTs) are used for scaling these test voltages and currents down to levels that can be handled by a wattmeter (Fig. 1).

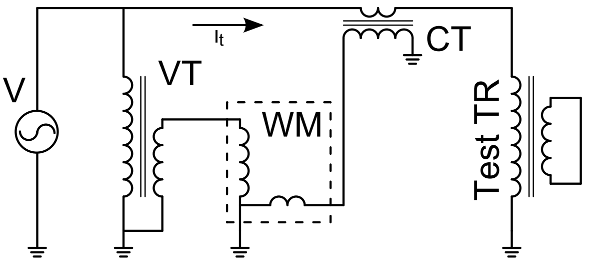

Figure 1. Single-phase schematic of a TLM system consisting of current and voltage transducers (CTs, VTs) and a wattmeter (WM) during a load loss test of a power transformer (Test TR).

The main challenge in transformer loss measurements lies in the measurement of active power under conditions where the current is approximately 90º out of phase in respect to the applied voltage, corresponding to a power factor close to zero. The close-to-90º phase shift means that the active power is approaching very small values, which still needs to be measured at an accuracy of 5 % according to the new regulation [1]. This puts very stringent requirements on the phase accuracies of the VTs, CTs, and wattmeter of the TLM system. For example, if the loss measurement of a power transformer results in a power measurement at a power factor of 0.01, a 5 % measurement accuracy of the TLM system corresponds to a total phase accuracy of 500 µrad or 25 m°. In order to achieve such overall accuracy [3], the individual components of the TLM system need to have phase accuracies of at least five times better, 100 µrad or 5 m°, in all their measurement ranges. Indeed, several instrument manufacturers in the market presently are offering commercial instrumentation that claims to meet these challenging requirements.

RELEVANCE OF ACCURACY

The accuracy in loss test measurements plays a crucial role in the final determination whether a power transformer meets its efficiency requirements. In order to save material costs, manufacturers may want to design and build transformers with an actual loss very close to the required limit. Fig. 2 shows that in this case, for an inaccurate test measurement there is a significant chance that the test result shows a loss value above the limit and thus fails to detect the actual compliance of the transformer. Only when the loss test measurement has a high accuracy, better than the difference between the actual loss and the required limit, correct statements can be made on whether requirements are met, with a minimum chance of 'false negative' test results. Vice versa, better accuracy in the loss measurements allows transformer manufacturers to design and realise transformers close to the required limits and still unambiguously prove their products meet the requirements. In this way, high accuracy paves the way to cost savings.

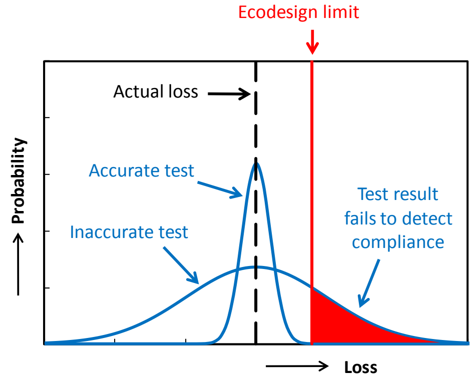

Figure 2. Impact of measurement accuracy in power transformer loss measurements

ENSURING ACCURACY VIA CALIBRATION

Proving the accuracy of TLM systems can only be achieved via calibration of these systems using an even more accurate reference setup. In order to make a TLM calibration a significant exercise, the reference setup should at least be 3 to 5 times more accurate than the TLM system itself, that is better than 30 µrad (0.1 min) for the individual TLM components and better than 100 µrad (0.3 min) for the complete TLM system. For less accurate reference systems, a situation similar to that depicted in Fig. 2 arises: based on the calibration results, no reliable statement can be made whether the TLM system meets its specifications.

Given the large size and weight of the TLM components they have to be calibrated on-site in the test facility. This has the additional advantage for the transformer manufacturer that calibration is performed with the actual (secondary) wiring and burdens, and that the TLM system is shorter out of operation. The two calibration methods used are shortly described in the following sections, including their advantages and disadvantages.

Component calibration

In the component TLM calibration each individual component in the setup is calibrated, that is the voltage transducers, the current transducers, and the wattmeter (see Fig. 1). The main advantage of this approach is that all measurement ranges of all three components can be covered in the calibration [2]. Since the required calibration reference systems can relatively easily developed, component calibration is the by far the most common TLM calibration technique. However, combining the results of the individual calibrations into a total TLM accuracy following [3] is not always easy. More importantly, this method is limited in the achievable accuracy for the total TLM system, and does not reveal any system-related errors.

System calibration

To circumvent the limitations of component calibrations, calibration of TLM systems as a whole is preferable [4]. Such a calibration has the capability to reach better overall accuracy and moreover will include all possible systematic error terms. A further significant advantage is that the calibration applies actual (phantom) loss power to the TLM system and thus can be performed for a series of phase angles between voltage and current, which correspond to those in actual transformer loss measurements. A disadvantage of TLM system calibrations is that the required reference system is relatively complex to realise. Up to recently, only one (analogue) system existed worldwide that was able to reach accuracies significantly better than the required minimal value of 100 µrad (0.3 min) [4]. The remainder of this paper describes a new digital / sampling reference system developed by VSL for performing TLM system calibrations.

TLM SYSTEM CALIBRATION

Fig. 3 schematically presents the approach for the TLM system calibration, together with the main components of the VSL reference system. In the calibration, test voltages up to 100 kV are applied to both the single-phase reference system and the three-phase TLM system under test, set in series–parallel for current and voltage channels respectively. The reference system subsequently generates a current up to 2000 A with an adjustable, stable phase with respect to the applied voltage, using a digital signal processing (DSP) unit, which is the heart of the reference system. During the calibration, for each test point at a certain voltage, current and power factor setting, the active power reading of the TLM system is compared to that of the reference system.

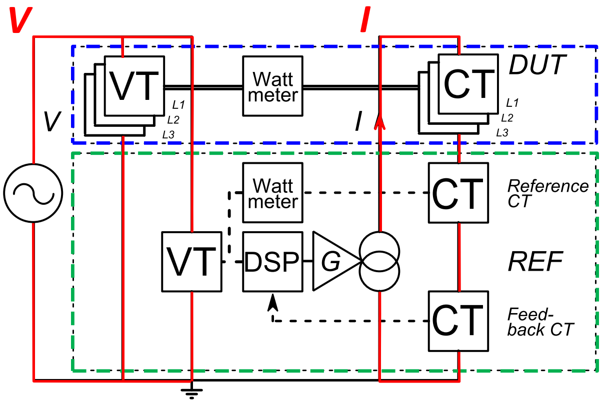

Figure 3. Schematic approach of a TLM system calibration, where the TLM system under test (DUT, top) is placed in parallel with a reference system (REF, bottom). Crucial element in this approach is the simultaneous generation of voltage and current test signals with stable and accurate phase relation.

Reference system components

The reference system consists of a calibrated voltage divider to measure the applied high test voltage, a transconductance amplifier to generate the high current, measured by two CTs, and a DSP for amplitude- and phase control of the current with respect to voltage. A reference wattmeter is used for verification of the DSP measurements.

The voltage divider of the reference system consists of a high-voltage capacitor and a low voltage unit with a precision capacitor and a current-comparator-based correction circuit to achieve high accuracy [5]. The output of the divider is a scaled copy of the applied high-voltage with better than 10 µrad uncertainty. The generated current is measured by two current transformers with electronic compensation [6], one for the feedback and one for the verification measurement with the reference wattmeter. The CTs are calibrated with an uncertainty of 5 µrad [7], and the reference wattmeter is calibrated with a 15-µrad uncertainty.

In the actual implementation of the reference system great attention is paid to correct grounding and shielding of the instrumentation and connecting cables, in order to allow for on-site operation under harsh EM interference conditions.

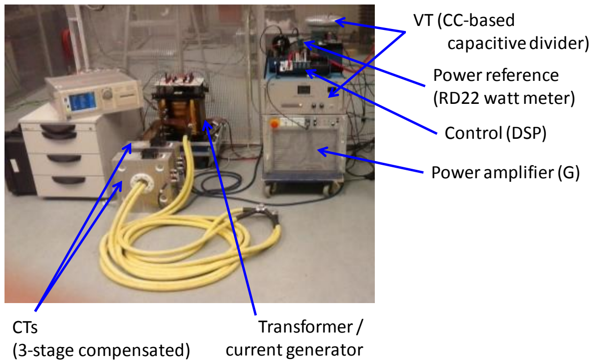

Figure 4. Picture of the main components in the actual VSL reference TLM system calibration system.

Digital feedback loop

The great benefit of using DSP above an analogue approach [4] is that it allows for flexibility and easy automation while at the same still reaching excellent accuracies. The DSP of the VSL reference system is completely based on digital filters which define the relation between voltage and current (input and output of the DSP, as shown in Fig. 5). As in the analogue approach of So et al. [4], first a 90° copy of the voltage input signal is made. The phase of the subsequently generated output signal that drives the current source is the adjustable mix of the original voltage signal and its 90° digital copy (I and Q in Fig. 5, bottom). A second DSP measures the actual phase shift between the input voltage and the applied current. The output of this second process is used to adjust I and Q in the first DSP until the measured phase matches the set-point.

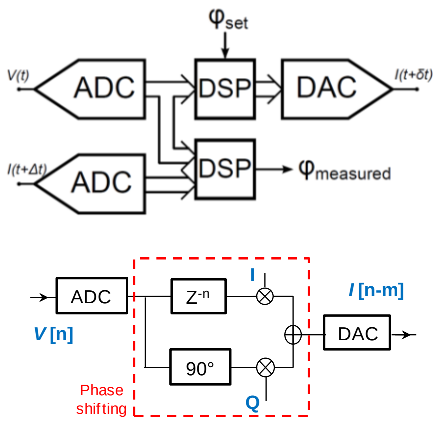

Figure 5. Schematic overview of the 2 DSP units in the digital feedback system (top) and internal details of the top DSP unit (bottom). The phase $\varphi_{\text{measured}}$ is used to adjust φ_{set} (via I and Q) until $\varphi_{\text{measured}}$ equals the required value.

The current has to follow variations in voltage as fast as possible in order to maintain a stable phase angle between voltage and current under all actual test conditions. The biggest challenge in the overall DSP approach lies in reducing the latency between the input and output signal, which is realised by using fast ADCs in the first DSP. Their limited accuracy is compensated by the second DSP that has high-accuracy (but slower) ADCs. The time constant of the control loop is in the order of a few hundred ms, which is sufficient to compensate slow phase drifts in applied voltage and drifts due to e.g. warming of the power amplifier.

Test results

The DSP-based feedback loop of the VSL reference system has been extensively tested using several high voltage sources with different stability. For a high-voltage source driven by a stable function generator, the algorithms in the DSP are not very critical for the feed-back loop behaviour, and noise levels of less than 10 μrad in the phase angle between voltage and current are readily achieved. However, in the actual on-site TLM system calibrations the voltage is generated by the customer, and either driven by the mains voltage or by a separate generator. In both cases, the variations in frequency and phase of the applied high voltage are significantly larger, which makes the selection and parametrization of the DSP filters and algorithms much more critical.

Initial tests with a voltage driven by the mains supply resulted in a phase noise between 30 and 60 μrad. Fig. 6 shows the final results achieved after significant improvement of the feedback algorithm. The test is performed at 50 kV, 1000 A and the phase angle set to PF = 0.01. The graph shows the readings of the DSP that controls the feedback loop as well as of the reference wattmeter. With the optimised algorithm, the phase noise of the feedback loop is again reduced to less than 10 μrad, but now also for high voltage signals with significantly varying phase.

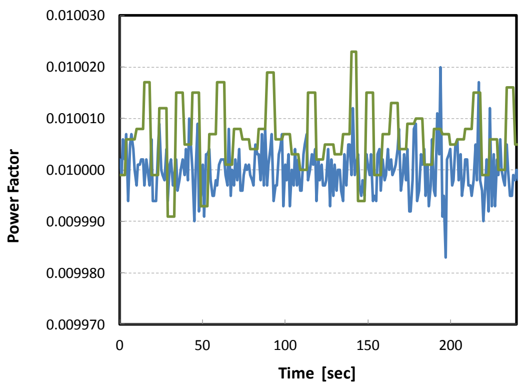

Figure 6. Stability in power factor set at 0.01 during a 50 kV, 1000 A test of the feedback loop in the VSL reference system, as measured by the DSP (bottom, noisy trace) and the reference wattmeter (top trace), with the high test voltage driven by the mains voltage.

Fig. 6 also shows excellent agreement between the DSP and reference wattmeter readings: the difference in readings of around 8 μrad (0.03 min or 0.5 m°) is well within the 15-μrad measurement uncertainty of both reference wattmeter and DSP system.

Following these good results, the VSL reference system has been used in an actual on-site calibration of a TLM system. Also under these industrial conditions, the reference system behaved as expected. The digital implementation of the reference system allowed for automated calibration of all power factors at a certain voltage and current, thereby significantly saving time. The final calibration uncertainties achieved were as low as 25 μrad (0.25 % in active power at PF = 0.01).

CALIBRATION INTERVALS

In order to assure a continuous confidence in TLM test results achieved by a power transformer manufacturer, the TLM system has to be calibrated regularly. The actual determination of the optimal interval between successive TLM calibrations depends on the accuracy of the calibrations, the stability of the components in the TLM system, the overall required TLM accuracy, and the risk that the power transformer manufacturer is willing to take. As Fig. 7 schematically depicts, calibration costs decrease for longer calibration intervals, but at the same time the costs increase that are associated with the risk of corrective actions required when the TLM system appears to be out of its requirements at the time of re-calibration. Next to costs, such corrective actions may also cause significant damage to the image of the manufacturer.

The typical re-calibration interval used in the precision measurement industry for electronic equipment is 1 year. It thus is good practice to use this interval for the wattmeter of TLM systems. For the component calibration interval of the current and voltage channels and for the calibration interval for TLM system calibrations longer intervals may be used, but only after the stability has been determined via more frequent (e.g. annual or bi-annual) initial calibrations. If after some years longer calibration intervals are chosen, it is highly recommended to regularly perform cross checks in order to confirm the calibration status of the TLM system and its components in between successive calibrations.

As already indicated above, not only the TLM stability but also the required overall system accuracy plays an important role in determining the calibration interval. As Fig. 2 has shown, significant financial gain can be achieved by the manufacturer if his TLM system has a top-level accuracy (an aspect not considered in Fig. 7). Since the TLM accuracy decreases over time, only more-frequent calibrations (e.g. annual or bi-annual) can safeguard the best accuracy levels.

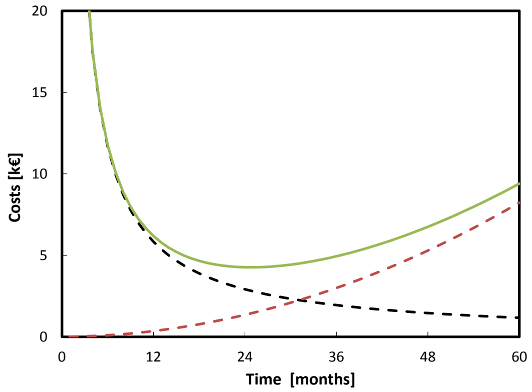

Figure 7. Cost of calibration and of risks as a function of TLM calibration interval (dashed lines). Taking only these costs into account, the optimum calibration interval is around 24 months, where the total costs are minimal (solid line).

Since several factors with varying relevance to the TLM owners play a role in determining calibration intervals, there is no single optimal calibration interval. For each TLM system, the balance has to be made of calibration costs on the one hand, and risks, reputation, and financial advantages of high accuracy on the other hand. Still, given the requirement to unambiguously prove power transformers put on the European market are meeting the Ecodesign requirements, calibration intervals as long as 5 years are disputable. Manufacturers that discern themselves by high-end products may go for 1-year intervals, which are only extended after a sufficient calibration history has been built up.

CONCLUSIONS

With the tier-1 Ecodesign requirements for power transformers active per 1 July 2015, the need has increased for power transformer manufacturers to unambiguously prove that their products meet these efficiency requirements. VSL has developed a new reference system for on-site calibration of transformer loss measurement systems for voltages up to 100 kV and currents up to 2000 A.

A crucial property of the setup is that it performs a high-accuracy calibration of the TLM system as a whole, thereby covering all possible error sources. The reference system generates a current with an adjustable, stable phase with respect to the applied voltage, using a digital signal processing (DSP) unit. After extensive tests and improvements of the DSP algorithms, phase noise levels of better than 10 µrad (0.03 min or 0.6 m°) have been achieved under actual on-site conditions. During an actual on-site TLM system calibration, the reference setup proved its flexibility and ease of operation, reaching an overall accuracy of 25 µrad (0.25 % in active power at PF = 0.01).

The determination of re-calibration intervals is discussed, showing that calibration costs have to be balanced against risks, reputation, and financial advantages of high accuracy. The present frequent practice of 5-year calibration intervals is probably inadequate given the high impact on already delivered products if the TLM system appears not to meet the required accuracy specifications after 5 years.

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