IMPACT OF THE ECODESIGN DIRECTIVE ON TRACEABILITY IN POWER TRANSFORMER LOSS MEASUREMENTS

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ABSTRACT

Losses constitute a significant part of the total cost of ownership of power transformers. Since these losses have an impact on the environment as well, the European Union has issued a regulation with regard to losses in power transformers, as part of the sustainable energy policies of the Ecodesign Directive. Already for many years, commercial power transformer loss measurement (TLM) systems are used by power transformer manufacturers for verification of the loss specifications of their products. With the new commission regulation, it is more than ever important to calibrate these TLM systems to assure and demonstrate an independently verified accuracy in the tests. Two approaches can be used in calibrations of TLM systems: a component and a system calibration approach. The latter has the advantage that all influence factors of the complete TLM system are taken into account in the calibration. Using state of the art reference equipment, in both approaches calibration accuracies can be achieved down to 20 parts in 10^6 in magnitude and 1 m° in phase, at least a factor 5 better than typical TLM system specifications.

INTRODUCTION

Given the enormous amounts of energy transported in electricity grids, the losses in these grids significantly contribute to the overall energy losses in our society. These losses need to be supplied by power plants, and therefore have an environmental impact via the CO_2 emissions of these plants. In addition, there is a large economic impact since power transformer losses are a significant part, up to more than 75 %, of the total cost of ownership (TCO) for a utility [1]. Studies conclude that it can be prudent to purchase a more expensive, high-efficiency transformer, because it often yields a lower TCO [1], [2]. These considerations, together with the overall EU 2020 aim for higher energy efficiencies [3], recently has led the European Union to put requirements on the losses in small, medium, and large power transformers as part of their efforts to reduce the environmental impact of energy-related products via the European Ecodesign Directive [4].

For power transformer manufacturers, measurement of the losses in their power transformers already is part of the quality verification of their products. With the new requirements of a recent EU regulation, it more than ever is important to assure that these measurements are performed using calibrated test measurement systems with independently verified accuracy.

In this paper we first describe the Ecodesign Directive and the recent requirements on losses in power transformers, followed by a short description of the approach in test systems for measurement of power transformer losses. The main part of the paper is dedicated to the calibration of these test systems to secure reliable outcomes of the power transformer loss measurements.

ECODESIGN DIRECTIVE

Ecodesign is a product design approach with special consideration for the environmental impacts of the product during its whole lifecycle. As a cornerstone of the EU's sustainable industrial policy, the Directive 2009/125/EC (Ecodesign Directive) establishes a framework for the setting of Ecodesign requirements for energy-related products with the aim of fostering an improved environmental performance of products in the internal market [5]. The Directive itself does not set binding requirements on products. On a case by case basis, the list of product groups to be addressed through implementing measures is established in the periodic working plan. Taken into account of the significant sales estimation, the composition of materials, significant impact on the environments, and high potential for improvements, transformers are ranked as the second priority out of 34 product groups to implement corresponding regulations [6]. The commission regulation (EU) No 548/2014 [4], with regard to small, medium, and large power transformers has been adopted by the regulatory committee in May 2014, and will take direct legal effect in all member states on 1 July 2015.

The regulation went through an unceasing evolution and change in a relatively long preparation period. For example, the list of exceptions is containing more and more details. Certain categories of transformers which are designed for special purposes are not covered by the regulation due to their limited energy consumption and saving potential. For medium and large power transformers, the following transformers are not applicable for the regulation:

- Medium Voltage (MV) to Medium Voltage interface transformers up to 5 MVA,
- large power transformers where it is demonstrated that for a particular application, technically feasible alternatives are not available to meet the minimum efficiency requirements set out by the Regulation,
- large power transformers which are like for like replacements in the same physical location / installation for existing large power transformers, where this replacement cannot be achieved without entailing disproportionate costs associated to their transportation and/or installation.

According to the regulation, medium power transformers with rated power smaller than 3150 kVA and medium power pole-mounted transformers must comply with the maximum allowed load losses (LL) and no-load losses (NLL). For MV power transformers with rated power larger 3150 kVA and large power transformers, maximum Peak Efficiency Index (PEI) values are defined. Depending on the type of transformer (liquid-immersed or dry-type), the limit values vary slightly. The LL and NLL value requirements are relaxed by 10 – 20% for transformers with high winding voltages. The medium power transformers with rated power smaller than 3150 kVA equipped with tapping connections allow a 10 – 20 % increment for LL and an extra 5 % for NLL.

The requirements come into action in two tiers. Tier 1 requirements take effect from 1 July 2015 and the tier 2 requirements become valid from 1 July 2021.

In the regulation, it is said, “For the purpose of compliance with requirements of this Regulation, measurements shall be made using a reliable, accurate, and reproducible measurement procedure” (Annex II of [4]). When the market surveillance performs checks, in verification procedure (Annex III of [1]), “the verification tolerances of LL and NLL shall not be greater than the declared value by more than 5%.” According to IEC60076-19 [7], the rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors, it is quite challenging to achieve this 5 % tolerance, especially for NLL measurements. The accuracy of the NLL value actually has significant impact on the accuracy of the PEI value.

TRANSFORMER LOSS MEASUREMENT

The total losses in a power transformer can be divided into several components such as winding losses, leakage flux, and core losses. Figure 1 gives an equivalent circuit for a power transformer where the different loss mechanisms are indicated.

LL and NLL measurements, combined with measurement of the winding resistance and the transformer ratio, can be used to in practice determine the different loss components. The LL measurement consists of shorting the output of the transformer ($Z_b = 0\ \Omega$) and operating the transformer at a reduced voltage. From this measurement the values of L_p, R_p, L_s, and R_s can be deducted, assuming that the impedance ($R_e//L_m$) is much larger than (L_s+R_s). The LL measurement is performed with an open output of the transformer ($Z_b = \infty\ \Omega$). This allows for determination of the core losses, modelled by the impedance ($R_e//L_m$).

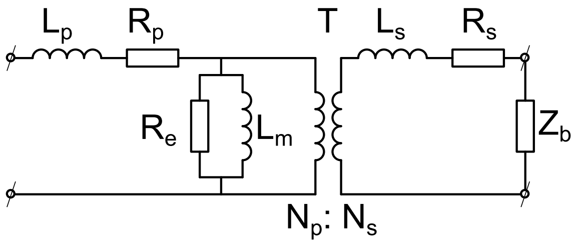


Figure 1. Equivalent circuit of a power transformer, including the different loss mechanisms.

The actual quantity measured by commercial power transformer loss measurement (TLM) systems in the LL and NLL tests is active (loss) power. A schematic of a typical TLM system is given in Figure 2. It consists of voltage and current transformers (VTs and CTs) for scaling the high test voltage and current down to levels that can be handled by a watt meter. The main challenge of the transformer loss measurements lies in the measurement of active power under no-load conditions. In this case the current will be approximately 90º out of phase in respect to the applied voltage (power factor close to zero). The approximate 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 [4]. This puts very stringent requirements on the phase accuracies of the VTs, CTs, and watt meter of the TLM system. For example, if the NLL 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 [7], the individual components of the TLM system need to have phase accuracies of around 100 µrad/5 m° in all their measurement ranges.

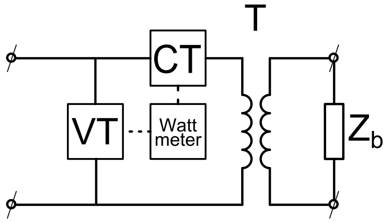


Figure 2. Single-phase schematic of a TLM system consisting of current and voltage transducers and a watt meter.

CALIBRATION OF TLM SYSTEMS

Given the socio-economic importance of transformer loss measurements, VSL, the national metrology institute (NMI) of the Netherlands, recently has developed reference facilities for on-site calibration of commercial TLM systems. In order to cover the complete capabilities of commercial TLM systems, the voltage and current ranges of the VSL reference systems range from 100 V up to 100 kV and from 1 A up to 2000 A, both at 50 Hz and 60 Hz, with uncertainties down to 10 parts in 10^6 in magnitude and 0.5 m° in phase.

Two approaches are possible for the calibration of TLM systems. The first approach is to calibrate the individual components of the TLM system and use the IEC60076-19 standard [7] to subsequently calculate the total TLM system uncertainty. The second approach is to make a calibration of the TLM system as a whole [8]-[10]. This calibration is more complex to perform, but has the significant advantage that all effects affecting the overall system accuracy are included. In the following sections, both approaches are described.

Component calibration

In the component level TLM calibration each individual component in the setup is characterised and calibrated, that is the voltage transducers, the current transducers, and the wattmeter (see Figure 2). Combining the results of these individual calibrations, the final TLM accuracy is determined afterwards [7].

The VSL calibration of the wattmeter in the TLM system is performed using a high-accuracy sampling wattmeter [11]. In the past two decades many NMIs have developed similar sampling systems for power measurements at the best uncertainty level, and uncertainties better than 20 parts in 10^6 in magnitude and 1 m° in phase angle are commonly achieved. Since the TLM wattmeter can easily be taken out of the TLM system, there is no stringent need to calibrate this component on-site.

Figure 3 shows the VSL approach for on-site calibration of current transformers. The ratio error of an unknown CT is compared to that of a reference CT, using a sampling ratio bridge [12]. Under laboratory conditions total uncertainties of 5 part in 10^6 and 0.3 m° are reached. In an on-site measurement, this is slightly larger due to among others additional effects of stray fields, ground loops, and the use of long measurement cables.

The calibration of the TLM voltage channels can be performed either in a similar sampling approach as Figure 3, but now using a reference VT, or with a high-voltage capacitance bridge (HVCB) and a high-voltage reference capacitor [13]. Figure 4 shows pictures of an actual on-site calibration of a TLM system, where a HVCB is used for the voltage channel calibration.

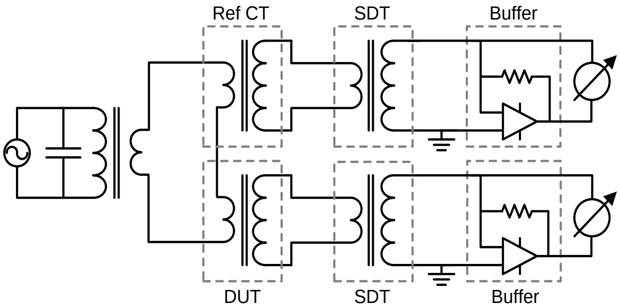


Figure 3. Schematic overview of the VSL CT sampling current ratio bridge. From left to right the generation of the high primary current including a capacitance bank, the CT-under-test (DUT) and the reference CT, step-down transformers (SDT), operational amplifiers with 100 Ω precision AC resistors (current buffers), and digital sampling voltmeters.

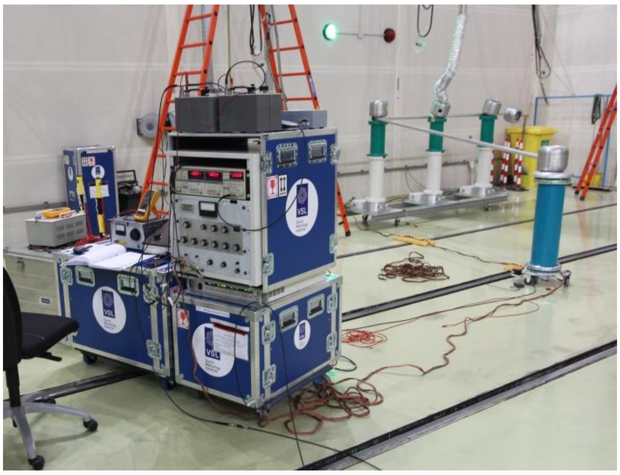
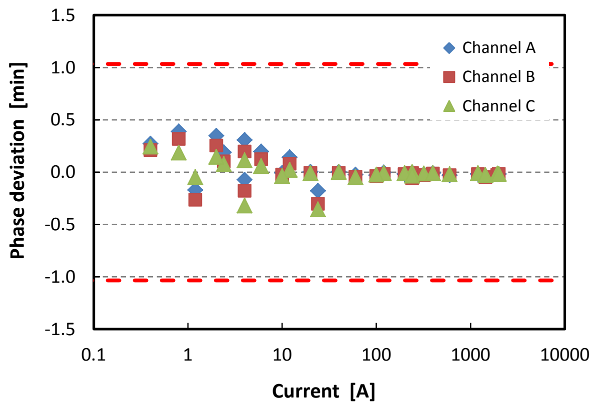


Figure 4. Pictures of actual on-site calibration of the CTs (top) and VTs (bottom) of a TLM system using a sampling current ratio bridge and a high-voltage capacitance bridge as reference respectively.

Figure 5 shows the result of the TLM calibration depicted in Figure 4. In this particular case, VSL was able to calibrate all 23 ranges of the voltage and current channels of the commercial three-phase TLM system with excellent uncertainties down to 0.003 % in magnitude and 1.5 m° in phase respectively.



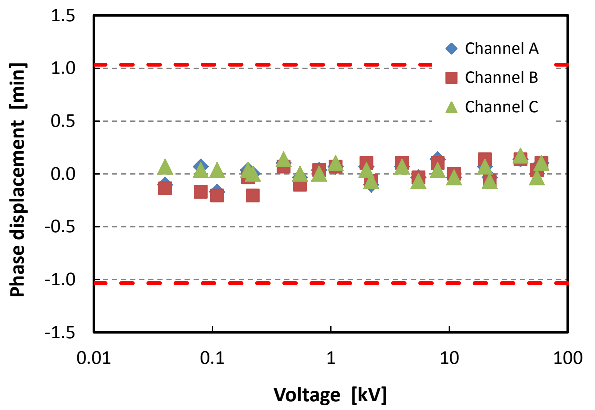


Figure 5. Phase displacement of the CTs (top) and VTs (bottom) of a commercial TLM system as determined by VSL during an on-site calibration.

System calibration

Whereas an on-site component calibration does give the errors of the voltage and current channels of a TLM system under actual installation conditions, such as the burden of the installed wiring in the facility, it does not include possible interference between the three phases of the TLM system and other system effects. Therefore, calibration of a TLM system as a whole is preferable; this will include all possible error terms.

In a TLM system calibration, the TLM system is put in parallel with a reference system (see Figure 6). Both the voltage and current test signals need to be generated simultaneously, with a stable and well-known phase relation (power factor). To simplify the calibration, the reference system is single phase so that the TLM voltage and current channels have to be placed in parallel and series respectively during the calibration.

Separating the voltage and current channels as depicted in Figure 6 has the advantage that no true power is dissipated and that there is full control of the current set point. A very significant challenge is the phase locking of the high current to the high voltage test signal. This requires a control loop with sufficiently low noise to allow for accurate calibrations, as well as excellent tracking of changes in test voltage frequency or phase [8].

VSL presently is developing a reference system for TLM system calibrations which the capability of current locking to the high voltage test signal. The system consists of a voltage divider, reference CT, high current source, and a control loop based on digital signal processing (DSP) (see Figure 6). The voltage divider scales the high test voltage down to a level that the DSP can handle and use as a phase reference. The output of the DSP will be fed to a power amplifier which in turn drives a transformer for generating the high current. In this way, the test current can be varied from 0 – 2 kA with adjustable phase respect to the high voltage. This gives the ability to characterize the TLM system at a wide range of set points which best cover the actual working points used in practice during load-loss measurements of power transformers. The advantage of using DSP instead of current comparator technology [8] as the heart of the control loop is that DSP has the ability of adding various filtering and other signal processing algorithms. This is useful since high-voltage generators rarely have good stability and low harmonic distortion.

An important part of the setup is an additional reference CT and reference wattmeter for verification of the actual active power generated and set by the control loop.

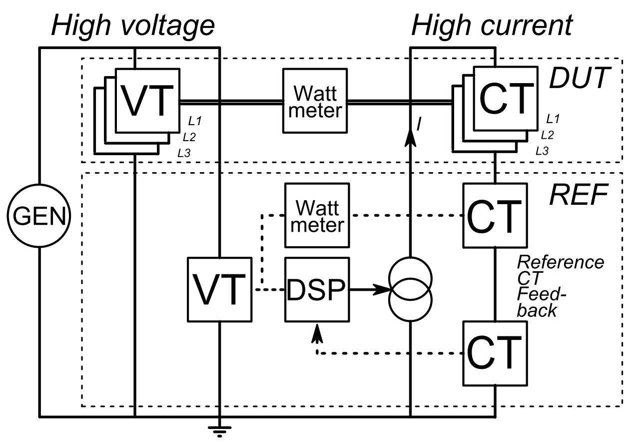


Figure 6. Schematic approach of a TLM system calibration, where the TLM system under test (DUT) is placed in parallel with a reference system (REF). Crucial element in this approach is the simultaneous generation of voltage and current test signals with stable and accurate phase relation.

CONCLUSION

New EU regulation related to the aims of the Ecodesign Directive per 1 July 2015 puts efficiency requirements on placing on the market or putting into service power transformers in electricity grids. Manufacturers and network operators now are required to unambiguously prove that new power transformers meet these requirements. It therefore is important to calibrate the commercial TLM systems used for testing and measurement of the load-loss and no-load-loss of power transformers. Only with a calibrated TLM system power transformer losses can be determined in a demonstrated reliable way.

VSL has developed unique facilities with excellent accuracies for the component calibration of power transformer loss measurement systems. In an actual on-site calibration, uncertainties down to 0.003 % in magnitude and 1.5 m° in phase have been achieved. Present work is focusing on realization of a reference setup for complete system calibration of TLM systems. It is expected that a first prototype will be operational in 2015, and ready for on-site calibrations in 2016.

REFERENCES

[1] Leonardo Energy. Online: http://www.leonardo-energy.org/

[2] Copper Development Association. Online: http://www.copper.org/environment/sustainable-energy/transformers/

[3] "The 2020 climate and energy package," EC. Online: http://ec.europa.eu/clima/policies/package/

[4] Commission Regulation No 548/2014, 21 May 2014, on "Implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to small, medium and large power transformers"

[5] Ecodesign. Online, http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/

[6] EPTA Ltd, Greece; PE International, Germany; NTUA, Greece: "Study for preparing the first Working Plan of the Ecodesign Directive", Report for tender No: ENTR/06/026
Revised Final Report: 06 December 2007. Online, http://ec.europa.eu/enterprise/policies/sustainable-business/files/workingplan_finalreport_en.pdf

[7] IEC60076-19, "Power transformers – Part 19: Rules for the determination of uncertainties in the measurement of the losses on power transformers and reactors", 2013

[8] E. So, P.N. Miljanic, and D.J. Angelo, 1995, "A computer-controlled load loss standard for calibrating high-voltage power measurement systems", *IEEE Trans. Instr. Meas.*, vol. 44, no. 2, 425-428

[9] E. So and E. Hanique, 2001, "In-situ calibration of high-voltage three-phase transformer loss measuring systems", *IEEE Trans. Instr. Meas.*, vol. 50, no. 2, 422-425

[10] T. Steiner and C. Bonin, 2013, „Calibration of loss measurement systems for large power transformers," *Proc. ISH 2013 conference*, 854-858

[11] L. Jol and G. Rietveld, 2004, "Improved sampling wattmeter for low frequencies (45 Hz – 55 Hz)", *Proc. CPEM 2004 conference*, 297-298

[12] H.E. van den Brom, G. Rietveld, and E. So, 2015, "Sampling Current Ratio Bridge for Calibration of Current Transducers up to 10 kA with $5{\cdot}10^{-6}$ Uncertainty," accepted for publication in *IEEE Trans. Instr. Meas.*, vol. 64, 1-7

[13] O. Petersons, W.E. Anderson, 1975, "A wide-range high-voltage capacitance bridge with one ppm accuracy", *IEEE Trans. Instr. Meas.*, vol. 24, no. 4, 336-344