# Comparison of Reference Setups for Calibrating Power Transformer Loss Measurement Systems

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***Abstract*— A unique comparison has been performed of two reference setups for the calibration of industrial power transformer loss measurement systems (TLMSs). The setups are developed by the Van Swinden Laboratorium (VSL), Delft, The Netherlands and Physikalisch-Technische Bundesanstalt (PTB), Brunswick, Germany, with the aim to calibrate industrial TLMS as a complete system, rather than just via its individual components, with an uncertainty better than 50 $\mu$W/VA, for voltages up to 100 kV, currents up to 2 kA, and power factors down to 0. The results of the comparison show excellent agreement of the PTB and VSL reference setups, both for the individual components as for the complete system. The phase agreement in the VSL and PTB component calibration results is better than $(2 \pm 5)$, $(5 \pm 12)$, and $(10 \pm 15)$ $\mu$rad for all calibration points in current ratio, voltage ratio, and power, respectively. In the full system comparison, the difference in the results of the VSL and PTB systems is less than 12 $\mu$W/VA for currents up to 1000 A and voltages up to 70 kV, with a $-7$ $\mu$W/VA difference averaged over all comparison measurements. This is well within the present 25 $\mu$W/VA measurement uncertainty of each of the VSL and PTB reference setups.**

***Index Terms*— Calibration, comparison, high voltage, load loss (LL), loss measurement, power measurement, power transformer losses, power transformers, shunt reactor, uncertainty.**

## I. Introduction

ACHIEVING higher energy efficiency across the whole energy chain, from energy production via energy transmission to energy use, is an important way to avoid wasting scarce energy resources. The clear rationale for the present emphasis on energy efficiency is that energy lost via poor energy efficiency also needs to be generated, and thus has both an economic as well as environmental impact. To support the development of a more sustainable energy future, the European Union (EU) has made a 20% reduction of energy consumption via improved energy efficiency one of their three "20/20/20" goals for 2020 [1]. This goal is supported by the 2009 Ecodesign Directive that aims to improve the environmental performance of energy-related products through better design [2]. As part of this directive, efficiency requirements have already been set on products such as air conditioners, computers, fans, and lighting—the latter leading to a ban of traditional incandescent light bulbs in Europe.

Impact studies have revealed that power transformers constitute significant energy losses in our society, up to 3% of the total energy demand. The saving potential in the EU through more efficient power transformer designs is estimated as high as 16 TWh/year, corresponding to 50% of the total electricity consumption in Denmark, and 3.7 Mt of $CO_2$ emissions [3]. This has led the EU to place, as part of the Ecodesign Directive, efficiency requirements on transformers with higher than 1-kVA rating that is put on the EU market after July 1, 2015 [4]. For transformers below 3.15 MVA, requirements are set on the maximum load losses (LLs) and no-LLs, whereas larger power transformers have to achieve a minimum so-called peak efficiency index.

As a consequence, power transformer manufacturers now have to unambiguously prove that their products meet the Ecodesign requirements [5]. This makes the reliable and accurate measurement of transformer losses an even more important product test than it already was in the past. Several commercial systems are available for power transformer loss measurements. Calibration of these commercial transformer loss measurement systems (TLMSs) is crucial to prove their accuracy and reliability. NRC, Canada, has pioneered the calibration of TLMS as a complete system [6], rather than just calibrating the individual TLMS components. Such a "system calibration" has the major advantage that it covers all possible systematic errors of the TLMS as installed in the test bay of the power transformer manufacturer. Based on their analog current-comparator technology, NRC achieves ultimate on-site uncertainties of 0.15% in loss power at PF = 0.01 [6], [7]. RISE, Sweden, Europe, has worked on a similar system exploiting digital technologies, but their uncertainty is limited to a few percent at PF = 0.01 due to limitations of their feedback loop [8]. Steiner and Bonin [9] developed a system not requiring feedback loops, but the accredited uncertainty of their system at PF = 0.01 is currently only 3%, comparable to the uncertainties of the TLMS they aim to calibrate.

In the framework of a European Joint Research Project, both Van Swinden Laboratorium (VSL), Delft, The Netherlands, and Physikalisch-Technische Bundesanstalt (PTB), Brunswick,

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Germany, have developed reference setups with complementary approaches for the system calibration of TLMS [10], [11], in order to support the European power transformer manufacturer industry in meeting the Ecodesign requirements via readily available TLMS system calibration services with sufficiently high accuracy. After a description of the respective VSL and PTB reference setups, this paper gives the approach and results of a full comparison of these two setups. The comparison covers both the three main components of the reference setups, as well as the setups as a whole.

## II. TLMS Calibration Setups

Commercial TLMSs consist of three main components: voltage transformers (VTs), current transformers (CTs), and a three-phase power meter. The VTs and CTs are used to scale the high voltages and high currents, respectively, down to the level where they can be measured with the high-accuracy power meter. If a power transformer under test would be ideal and have no losses, the current during the loss test would be exactly 90° in phase with respect to the applied voltage. The main measurement challenge of TLMS during a loss test is to measure the small deviation of the phase angle from 90° caused by the small actual transformer losses. To do this accurately, all main components of the TLMS should be designed for very low phase errors.

In the calibration of a TLMS as a complete system, the accuracy of the TLMS must be verified at different loss levels. Therefore, an essential element of all reference setups for TLMS system calibration is the generation of the calibration signals: high voltage and high current, with adjustable phase angle between current and voltage in order to mimic different power transformer loss levels. These calibration signals are applied to both the TLMS under test and to the measurement part of the reference setup. Presently, two slightly different approaches are used for generation of the calibration signals [6]–[11]: either the voltage and current are generated in parallel or the current is generated via a feedback system that locks the current in amplitude and phase to the applied voltage. In both cases, the voltage and current channels are separated (phantom power technique), so that no true power is dissipated. The following two sections describe the VSL and PTB reference setups, respectively, that each uses one of these two-generation approaches.

### A. VSL Reference Setup for TLMS System Calibration

Fig. 1 schematically depicts the VSL reference setup for TLMS system calibration [10] for voltages up to 100 kV and currents up to 2 kA. The three TLMS channels are placed in parallel (voltage) and series (current), respectively, with the current channels at ground potential, disconnected from the voltage channels. For the generation of the calibration signals, the VSL setup follows the approach taken by NRC in that the test voltage is applied by the power transformer manufacturer, with the reference setup generating the test current at the required magnitude and phase via a feedback loop. In the NRC setup, the feedback loop is implemented using analog current-comparator technology [6]. In the case of the VSL setup, the feedback loop is realized via digital signal processing (DSP).

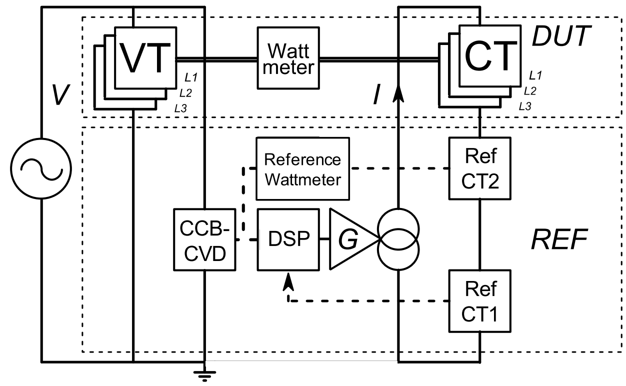


Fig. 1. VSL approach for TLMS system calibration with the three-phase TLMS as DUT (top) and the single-phase reference setup (bottom).

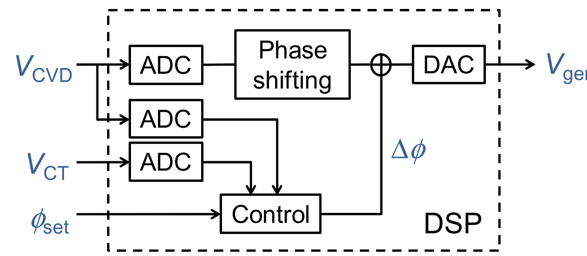


Fig. 2. DSP schematic for measurement and control of the test current in the VSL TLMS reference setup.

The feedback loop in the VSL setup works as follows. The current-comparator-based capacitive voltage divider (CCB-CVD) [12] scales the applied high test voltage down to a level that can be handled by the analog-digital converters (ADC's) in the DSP unit. The DSP shifts the input signal by the required phase angle, and its output subsequently controls a power amplifier (G) that drives a transformer for generating the high calibration current.

The main aim of the DSP algorithms is to assure that the calibration current has a stable and accurate phase with respect to the applied voltage. This is realized in a two-stage process (see Fig. 2). First, a roughly accurate signal $V_{\text{gen}}$ is generated for driving the power amplifier G that generates the test current [Fig. 2 (top)]. To ensure good first-order tracking of voltage variations in magnitude and phase, the output voltage of the CVD $V_{\text{CVD}}$ is measured by a fast 16-bit digitizer. A digital integrator is subsequently used as a fast phase-shifting algorithm to get an approximate 90° copy of this signal. An adjustable mix of the phase shifted and the original voltage signal is finally used by the digital-to-analog converter to drive the power amplifier [13]. The second stage of the control loop aims to realize feedback loop accuracy. Two 24-bit ADCs measure the actually applied voltage and current [Fig. 2 (bottom)], where for the current measurement, the output current of the reference CT (Referred to CT1, Fig. 1, [14]) has first been converted to a voltage $V_{\text{CT}}$ using a wideband 5-A shunt with negligible phase error at power frequencies [15]. The DSP control block calculates the active power, apparent power, and phase angle between current and voltage. Any deviation in the measured phase angle from the set point $\phi_{\text{set}}$ is subsequently used to adjust the mix of the phase shifted and the original voltage signal in the phase-shifting block of the first stage by $\Delta\phi$ until the measured phase equals $\phi_{\text{set}}$. Extensive fine-tuning of the DSP algorithms was needed to assure a low-noise phase relation of better than 5 $\mu$rad between current and voltage under most typical test conditions, i.e., with varying frequency and phase of the applied test voltage [10].

An important feature of the VSL reference setup is an additional verification measurement of the actual active power generated by the control loop using a second reference CT and a reference wattmeter (Fig. 1).

The accuracy of the VSL reference setup is determined by its main components. The CCB-CVD [12] that scales voltages ranging from 1 kV up to 100-kV down to the 6-V level required by the ADCs can be calibrated with uncertainties down to 12 $\mu$V/V in magnitude and 12 $\mu$rad in phase. The current is measured with electronically compensated CTs (CT1 and CT2, [14]) that have negligible ratio errors and phase displacements up to 2000 A, well within the 5-ppm and 5-$\mu$rad VSL calibration uncertainty. The relative phase accuracy of the 24-bit ADCs is better than 1 $\mu$rad; the ADC gains are calibrated using the reference wattmeter to better than 20 $\mu$V/V. The wattmeter itself is calibrated with 15-$\mu$W/VA uncertainty over the complete power factor range using the VSL primary power setup [16]. Combining all uncertainty contributions, the total uncertainty of the VSL reference setup is estimated to be 25 $\mu$W/VA, equivalent to 0.25% in loss power at PF = 0.01 [10], with the phase uncertainties of the CCB-CVD and the wattmeter as the two main uncertainty contributions.

The VSL reference setup is transportable and completely automated. This allows efficient calibration of TLMSs on-site at the premises of power transformer manufacturers, and also greatly facilitated the comparison with the PTB setup.

### B. PTB Reference Setup for TLMS System Calibration

A core element of the PTB reference system is a single-phase phantom power source that separately provides both the required high voltage and high current at a programmable phase angle (see Fig. 3). A programmable two-channel voltage generator with 16-bit resolution generates two sinusoidal voltages $U_{\text{U}}$ and $U_{\text{I}}$ with low distortion (<0.01%), high stability ($10^{-6}$/h) and any phase angle $\varphi$ within ±180°, and a resolution of 0.001°. The frequency $f$ of the source can be adjusted arbitrarily.

To achieve high signal fidelity, the voltage amplifier (UA) and the transconductance amplifier (TA) are analog high-power amplifiers with a bandwidth of 15 kHz. The generated voltage $U_{\text{A}}$ and the current $I_{\text{A}}$ of UA and TA are fed to the primary windings of the high-voltage and high-current generation transformers, respectively, and their secondary windings provide the required test voltage $U_{\text{P}}$ and test current $I_{\text{P}}$. The generation transformers offer several rated outputs from 1 to 150 kV and 5 A to 2 kA, respectively. The

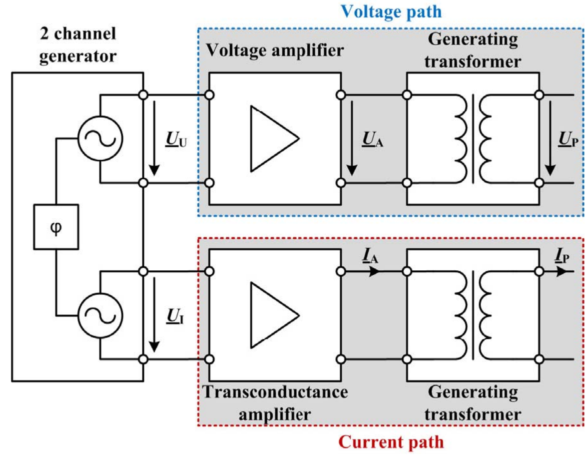


Fig. 3. Schematic of the phantom power source of PTBs high-power standard. The reactive power compensation, connected to the input of the $U_{\text{P}}$ generation transformer, is not shown.

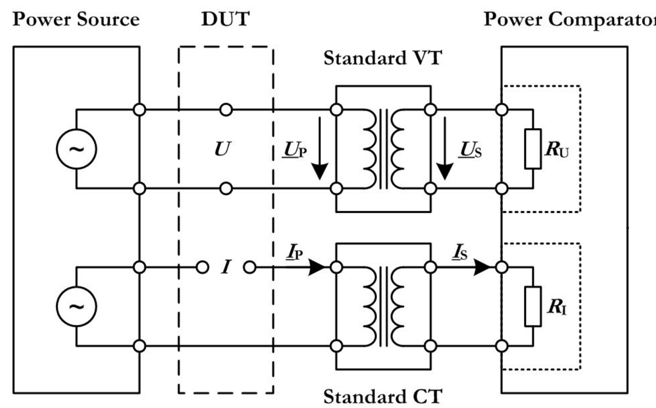


Fig. 4. Scheme of PTBs high-voltage power standard. The DUT is connected to $U_{\text{P}}$ and $I_{\text{P}}$.

stability of the power source, measured at 60 kV and 2 kA in a time span of 30 min, is within 70 ppm for voltage and current and within 50 $\mu$rad for phase angle. This behavior is reflected in the stability of the generated apparent and active power. Nevertheless, this source provides sufficiently stable calibration conditions for TLMS calibrations, as the typical time window for one test point is roughly 30 s. Several measurements based on 20 single readings within a time window of 25 s confirmed that the typical standard deviation is below 2 ppm for voltage and current, and below 3 ppm for active, reactive, and apparent power [11].

As shown in Fig. 4, the generated voltage $U_{\text{P}}$ and current $I_{\text{P}}$ are fed to the VT and CT of the PTB power standard and to the device under test (DUT). Similar to the VSL system, for a three-phase DUT, the voltage and current channels of the DUT are placed in parallel and series, respectively. The VT and CT transform the primary voltage $U_{\text{P}}$ and current $I_{\text{P}}$ into the precise secondary voltage $U_{\text{S}}$ and current $I_{\text{S}}$, respectively. A precise commercial digital power comparator (DPC) of error class 0.005 measures the relevant quantities at the secondary of the instrument transformers. Dedicated software controls the DPC and reads the measured voltage, the current, their corresponding phase angle, and the active power of the DPC. Subsequently, from these results, the respective power quantities at the primary of the instrument transformers are calculated using their transformer ratios and all relevant corrections, such as the VT and CT ratio errors and phase displacements, and the errors of the DPC in different voltage and current ranges.

Modeling and correcting the ratio and phase errors of the VT and CT are straightforward. The complex current ratio $\underline{F}_{\mathrm{i}}$ of the CT is defined as $\underline{F}_{\mathrm{i}} = \underline{I}_{\mathrm{S}}/\underline{I}_{\mathrm{P}} = (1 + \varepsilon_{\mathrm{i}})/K_{\mathrm{ni}} \times \mathrm{e}^{j\times\delta i}$ and $\underline{F}_{\mathrm{u}} = \underline{U}_{\mathrm{S}}/\underline{U}_{\mathrm{P}} = (1 + \varepsilon_{\mathrm{u}})/K_{\mathrm{nu}} \times \mathrm{e}^{j\times\delta u}$ for the VT. For the setup of the power standard, the 5-A rated current output of the CT is used. An active burden compensation between the CT and the DPC minimizes the effect of the burdens of different DPC current ranges and reduces the CT burden to that of the test lead impedance, which is less than 10 m$\Omega$. The battery-powered CT is an electronically aided current comparator with ratio errors and phase errors, calibrated directly against the primary standards of the PTB [17], well within the limits of 3 $\mu$A/A and 5 $\mu$rad. Therefore, no corrections for the CT in the software of the power standard have been used.

In contrast to the CTs, the VT errors are not negligible and usually depend largely in a nonlinear manner on the applied test voltage. The errors are, therefore, tabulated and stored into a calibration file. To correct for the VT errors automatically in the software, the errors $\varepsilon_{\mathrm{u}}$ and $\delta_{\mathrm{u}}$ are determined, based on a least-square interpolation routine using a Laurent series. The uncertainties for VTs up to 120 kV/$\sqrt{3}$, including the additional contributions due to the interpolation algorithm, are 3 ppm and 4 $\mu$rad ($k = 2$).

The error of the DPC active power measurement depends on the voltage and current range and on phase angle. A model has been developed, which allows the determination of the error in active power, based on the previous calibration of the device-internal voltage error, current error, and phase error of each voltage- and current-range combinations [18]. This model has been integrated in the software, to correct for the results of the DPC. The typical residual error within a recalibration interval of 1 year is below 5 $\mu$V/V and 5 $\mu$A/A for the voltage and current error and below 3 $\mu$rad for phase angle. Together with the calibration uncertainties, a minimum expanded uncertainty of 7–10 $\mu$W/VA for the corrected DPC readings is attained.

Using conservative uncertainty estimates for the components of the PTB high-power standard, its combined uncertainty is 40 $\mu$W/VA [5]. The uncertainty contributions for the VT, CT, and DPC mentioned above would lead to a minimum type-B uncertainty of 12 $\mu$W/VA ($k = 2$) for all power factors. Adding the type-A uncertainty, as well as some smaller additional effects (burden, cabling, and grounding), the overall uncertainty of the PTB setup might be reduced after some years of experience to about 20 $\mu$W/VA.

## III. Comparison Plan

To verify the claimed uncertainty levels of the VSL and PTB reference setups, a comparison between the two setups was performed consisting of two parts [19]. First, the three main components of the setups were compared: voltage channels, CTs, and power meters. The second comparison concerned the reference setups as a whole, with either the PTB setup or the VSL setup generating the calibration signals. In case of significant differences between the VSL and PTB reference setups in the second part of the comparison, the results of the first part could be used to trace the cause of this difference.

The actual comparison was performed at the PTB premises, between November 27, 2017 and December 1, 2017. The complete VSL reference setup was contained in six flight cases and transported to PTB using a small van. Before the comparison start, an extensive plan was made containing the envisaged test points for each part of the comparison. The expectation was that each of the component comparisons would show an agreement of the results within the combined VSL and PTB uncertainties, which is 6 $\mu$rad, 12 $\mu$rad, and 15 $\mu$W/VA for, respectively, current phase displacement, voltage phase displacement, and power. For the system comparison, the agreement in loss power at low-power factors was expected to be better than 35 $\mu$W/VA (with the total PTB setup uncertainty taken equal to that of the VSL setup).

## IV. Component Comparison Results

This chapter describes the results achieved in the comparison of the three main components of the VSL and PTB reference setups for TLMS calibrations: CTs, voltage channels, and power meters.

For comparison of the VSL and PTB current scaling calibration capabilities, one of the reference CTs of the VSL setup was calibrated both by VSL and PTB at 50 and 60 Hz. This CT has three current ratios, 400:1, 200:1, and 100:1, corresponding to nominal input currents of 2000, 1000, and 500 A, respectively. (Each range has a 5-A nominal secondary output current.) For the CT calibration, VSL used its sampling current ratio bridge [20] with 5 ppm and 5 $\mu$rad ($k = 2$) expanded measurement uncertainty in current ratio and phase displacement, respectively, over the complete measurement range, including the 3 ppm/3 $\mu$rad of the traceability provided by NRC. The PTB calibration was performed using the primary PTB standards for current ratio [17], with best-expanded uncertainties of 2 ppm and 3 $\mu$rad ($k = 2$) for currents between 10% and 120% of nominal current.

Fig. 5 shows the CT comparison results for both ratio error and phase displacement, for currents ranging from 1% (0.2%) to 120% for each of the three CT ranges, at a measurement frequency of 60 Hz. The results show an excellent agreement between the VSL and PTB calibrations, with differences in ratio and phase displacement never exceeding 2 ppm and 2 $\mu$rad, respectively, even for the smallest currents where the VSL and PTB uncertainties are between 4 and 6 ppm/$\mu$rad.

The comparison of the VSL and PTB voltage scaling calibration capabilities was performed in a similar way. Six ranges of the CCB-CVD in the VSL reference setup, covering voltages from 2 kV up to 100 kV, were calibrated both by VSL and PTB at 50 and 60 Hz. The CCB-CVD consists of an high-voltage (HV) capacitor $C_{\mathrm{HV}}$, an low-voltage (LV) capacitor $C_{\mathrm{LV}}$, and low-voltage electronics exploiting a current

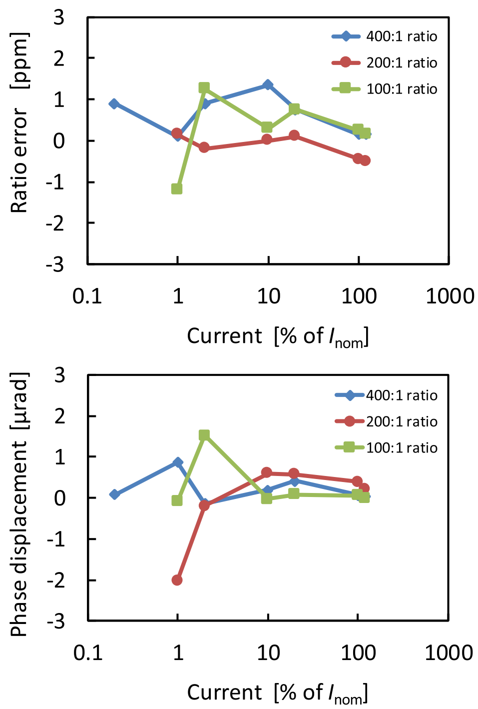


Fig. 5. Difference in ratio error (top) and phase displacement (bottom) of the VSL and PTB calibration results of an electronically compensated CT for each of its three current ratios as a function of applied current at a frequency of 60 Hz. Uncertainties in the differences are 6 ppm/6 $\mu$rad for currents at 2% $I_{\text{nom}}$ and below, and 5 ppm/5 $\mu$rad for higher currents (all $k = 2$ expanded uncertainties).

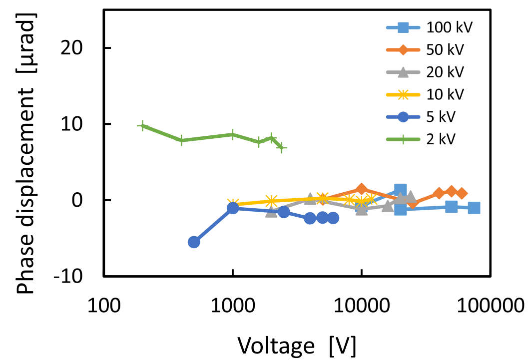


Fig. 6. PTB calibration results of the phase displacement of six voltage ranges of the VSL CVD as a function of voltage, at 50 Hz, with 5-mrad ($k = 2$) calibration uncertainty.

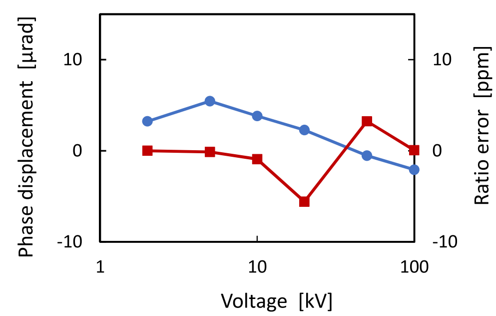


Fig. 7. Difference in ratio error (squares) and phase displacement (circles) of the VSL and PTB calibration results of the VSL CVD for six of its ranges at nominal voltage and 50-Hz frequency. The difference uncertainties are 12 ppm/12 $\mu$rad ($k = 2$), limited by the VSL calibration uncertainty.

comparator [12]. The VSL CCB-CVD calibration consisted of calibration of the ratio error and phase displacement of the $C_{\text{HV}}/C_{\text{LV}}$ capacitance ratio, and of the six ranges of the low-voltage electronics, using a high-voltage capacitance bridge [21]. The VSL calibration uncertainty of the complete CCB-CVD is estimated to be 12 ppm and 12 $\mu$rad ($k = 2$) in ratio error and phase displacement, respectively. This includes the combined uncertainty of both calibrations, as well as an extra uncertainty accounting for the possible detrimental effects of the cables, in particular, the 5-m-long triax cable between the HV capacitor and the low-voltage electronics. The PTB calibration was performed by applying a high voltage to the CCB-CVD as a whole, and subsequently comparing its output voltage to that of PTB standard VTs that maintain the PTB primary voltage ratio scale, using a sampling voltage ratio bridge [22]. The build-up method of the VT ratio scale is based on a CVD, solely used as a transfer device, and on the knowledge of the characteristics of a compressed-gas capacitor [23]. The best PTB voltage ratio calibration uncertainties are estimated as 4 ppm and 5 $\mu$rad ($k = 2$) in ratio error and phase displacement, respectively.

Fig. 6 shows the PTB calibration results at 50 Hz for the phase displacement of the six ranges of the VSL CCB-CVD. For all of the voltage ranges, except for the 2-kV range, the phase displacement of the low-voltage electronics is essentially compensated by the phase displacement of the $C_{\text{HV}}/C_{\text{LV}}$ capacitance ratio. The results of Fig. 6 are of particular importance as it confirms the excellent linearity of the VSL capacitive divider better than 3 $\mu$rad over 10%–120% of all its ranges. If furthermore proves the quality of the PTB traceability chain in voltage ratio, based on conventional VTs that show a very low drift over time, but have significant nonlinear errors over their voltage range. According to the results of Fig. 6, these errors indeed apparently have been determined at the 5-$\mu$rad uncertainty level.

Fig. 7 shows the ratio error and phase displacement results of the VSL–PTB voltage ratio comparison for six ranges of the VSL CVD at a measurement frequency of 50 Hz. The results show an excellent agreement between the VSL and PTB calibrations, with differences in ratio and phase displacement never exceeding 6 ppm and 5 $\mu$rad, respectively, which are well within the combined comparison uncertainty of 12 ppm/12 $\mu$rad ($k = 2$), dominated by the VSL calibration uncertainty. The good agreement in the VSL and PTB results proves that the VSL calibration of the voltage divider components indeed results in a correct estimation of the errors of the overall divider. These apparently are not significantly affected by cable effects and other possible disturbances.

Finally, a power comparison was performed using the high-accuracy wattmeter of the verification measurement in the VSL reference setup as the transfer standard. This wattmeter was calibrated by VSL with 15 $\mu$W/VA uncertainty for power factors between 0 and 1 using the VSL primary power setup [16]. The PTB calibration is performed on a "sister system" of the PTB primary power standard that is operated in PTBs instrument transformer laboratory for redundancy purposes.

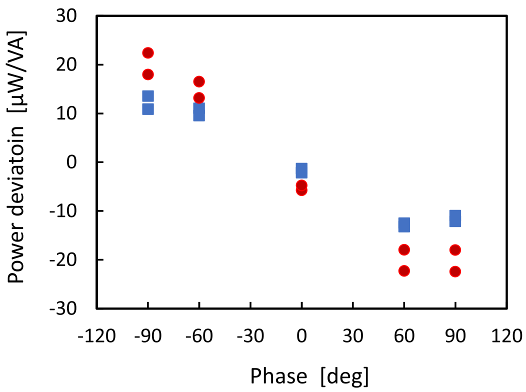


Fig. 8. VSL (dots) and PTB (squares) results of the calibration of a high-accuracy wattmeter as a function of phase between voltage and current, at 100 V, 52.6 Hz, and both 1-and 5-A currents. The difference uncertainties are 15 $\mu$W/VA ($k = 2$), limited by the VSL calibration uncertainty.

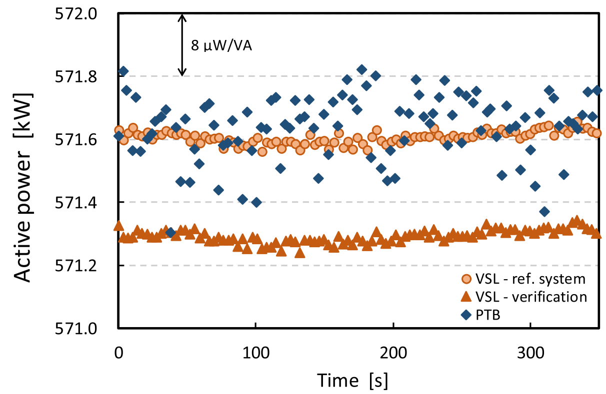


Fig. 9. Typical result of the system comparison of the VSL and PTB reference setups at 51 Hz, 50 kV, 500 A (25-MVA apparent power), and PF = 0.022.

It is traceable to the PTB primary power standard [24] and has a 6 $\mu$W/VA calibration uncertainty for all power factors. The signal levels in the comparison were chosen to match the typical voltage and current channel output of the PTB and VSL reference systems, i.e., 100 V and 1/5 A.

The results of the power comparison are given in Fig. 8. The agreement at PF = 1 is excellent with a difference in VSL and PTB results of only (3 ± 15) $\mu$W/VA. At PF = 0, there is a detectable difference between the VSL and PTB results of (10 ± 15) $\mu$W/VA, possibly caused by a slight phase error in the VSL setup. In the complete system verification described in Section V, the PTB results for the VSL verification wattmeter were used.

## V. System Comparison Results

Following the component comparison, the VSL and PTB reference setups for TLM calibration were compared as a complete system. First, the PTB setup was used to generate the high-voltage and high-current calibration signals, with the VSL system as the DUT. Subsequently, the VSL approach for a current generation was used, with the PTB setup supplying the high voltage and the VSL setup generating the high current using its DSP feedback loop. The comparison consisted of 25 current–voltage combinations, covering all typical conditions in LL measurement tests: the voltage was varied from 10 to 75 kV, the currents ranged from 100 A up to 2000 A, with frequency either 51 or 60 Hz. The 51-Hz frequency was chosen to reduce the effect of inevitable 50-Hz interference, whereas the results are still quite representative for a 50-Hz frequency. For each current–voltage combination, measurements were performed at six power factors: 1, 0.5, 0.1, 0.01, 0.001, and 0, respectively. A single comparison measurement lasted approximately 30 s, and care was taken to assure that the VSL and PTB measurements covered the same time period.

Fig. 9 shows a typical result of a comparison of the complete VSL and PTB systems, using the PTB phantom power generator to generate the 50-kV, 500-A test signals. Clearly, the stability of the calibration signals is excellent during the 6-min period of the measurement. This made the exact respective timing of the PTB and VSL measurements essentially unimportant. The experimental standard deviation in both the VSL reference measurement (ADCs) and verification measurement (wattmeter) is around 2 $\mu$W/VA, and essentially the same for all other voltages and currents using the PTB generation system. Using the VSL current generation via the DSP feedback loop, the standard deviation in the measurements was significantly higher, around 15 $\mu$W/VA. Apparently, the PTB voltage generator has a certain frequency and/or phase variations that are difficult to track by the VSL feedback loop. Still, by averaging over the 30-s period of a single comparison measurement, a type-A uncertainty of better than 3 $\mu$W/VA was readily achieved in the average active power values. The larger than usual noise in the PTB measurements of Fig. 9 is possibly caused by powerline interference with the internal DPC synchronization.

The VSL reference measurements of the ADCs in Fig. 9 are in excellent agreement with the PTB measurements with a difference of only 2 $\mu$W/VA at 25-MVA apparent phantom power, whereas the VSL verification measurements of the wattmeter are 12 $\mu$W/VA lower. The exact cause of this small discrepancy is not clear. It may be related to instabilities of the reference wattmeter or to another source of systematic uncertainty in the verification measurement. Over the past two years of on-site measurements with the VSL reference setup, the agreement between VSL reference and verification measurement varied from site to site and ranged from the excellent agreement within the 2–3-$\mu$W/VA measurement noise, to differences of up to 12 $\mu$W/VA as found in this comparison.

Fig. 10 shows an overview of the main 22 comparison results between the VSL reference measurement and the PTB measurement at PF = 0, which is the most critical measurement in TLMS system calibrations. The first 10 measurements are with PTB test signal generation and the following 12 measurements with VSL current generation. For each generation option, two sets of measurements are performed, at 51 and 60 Hz, respectively. Within a set of six or six measurements, the current is increased from 100 A in the first measurement up to 1600–2000 A in the last measurement. No clear systematic difference is found in the VSL–PTB

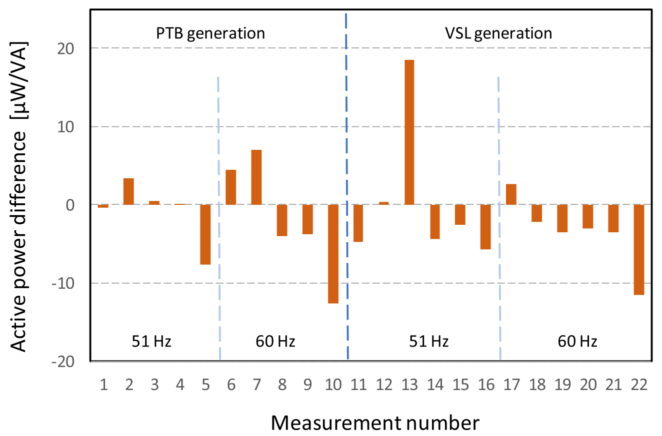


Fig. 10. Difference in active (loss) power measured by the VSL reference measurement and the PTB setup at PF = 0 for the main 22 comparison measurements (see text for further explanation).

differences, except possibly for the four measurements at the highest currents (at the end of each set) that have an average difference of $-9$ $\mu$W/VA. The largest VSL–PTB difference is 18 $\mu$W/VA for measurement 13, at 75 kV and 500 A. Averaged over all 22 comparison measurements, the VSL–PTB loss power difference is $-1$ $\mu$W/VA. All VSL–PTB differences decrease by 6 $\mu$W/VA if the VSL results are taken as the average of VSL reference and verification measurement, which is the normal VSL practice in on-site TLMS calibrations (although slightly greater confidence is given to the ADC reference measurements). In this case, for currents of 1000 A and lower, the difference in VSL and PTB results is always within 12 $\mu$W/VA.

All VSL–PTB measurement differences are well within the 35 $\mu$W/VA joint measurement uncertainty, and even very well within the 25 $\mu$W/VA measurement uncertainty of either the VSL or PTB reference setup.

## VI. Conclusion

A unique comparison has been performed of two reference setups for TLMS calibration, developed by VSL and PTB, respectively. The comparison covered the three main components of the reference setups, CTs, VTs, and power meter, as well as the setups as a whole. In the comparison of the complete setups, voltages ranging from 10 to 75 kV and currents between 100 and 2000 A were used, with power factors varying between 1 and 0.

The comparison of the VT, CT, and power meters making up the VSL and PTB TLMS reference setups appeared to be very informative. In general, they confirmed the traceability chains for voltage ratio, current ratio, and primary power maintained by PTB and VSL. The phase agreement in the VSL and PTB component calibration results is better than $(2 \pm 5)$, $(5 \pm 12)$, and $(10 \pm 15)$ $\mu$rad for all calibration points in current, voltage, and power, respectively. In particular for voltage, this is an unexpectedly good result. The voltage channel comparison furthermore confirmed the excellent linearity of the VSL capacitive divider—better than 3 $\mu$rad over 10%–120% of all its ranges—and confirms the PTB traceability chain based on conventional VTs (with highly nonlinear errors) at that same uncertainty level.

The comparison of the complete VSL and PTB reference setups gave excellent results. For currents of 1000 A and lower, the difference in VSL and PTB results was always within 12 $\mu$W/VA with an average $-5$ $\mu$W/VA difference over all 18 comparison measurements. For currents above 1600 A, the average difference between VSL and PTB results was $-15$ $\mu$W/VA. These differences are well within the 25 $\mu$W/VA present measurement uncertainty of each of the two reference setups.

The good comparison results are an important confirmation of the VSL and PTB measurement capabilities in TLMS system calibration. The full automation of the systems greatly helps to make efficient measurements, and the transportability of the VSL system makes it ideally suited for on-site calibration of TLMS at the premises of power transformer manufacturers as part of their actions to unambiguously prove that their products meet the stringent requirements of the Ecodesign Directive.

Future work will cover an extension of the voltage range and further improving the (already very good) uncertainty level, in order to allow for calibration of shunt reactors, which typically have even lower losses than power transformers. As part of this development, improvements in voltage ratio measurement capability will be made and confirmed via future comparisons. VSL aims to furthermore improve the DSP feedback loop and to find the better agreement of reference and verification measurement under all on-site test conditions. A final subject of further research will be the possible effect of high voltage on the CT errors: in the actual use of the TLMS, the CTs are at high voltage, whereas the TLMS calibration presently is performed with the CTs at ground potential.

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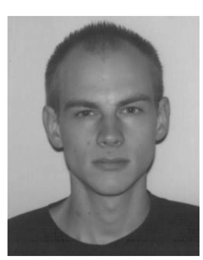

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