ACCURACY OF VOLTAGE TRANSFORMERS – DESIGN CRITERIA AND A SURVEY ON THE PRECISION AND REPRODUCIBILITY OF A NEW MODEL-BASED CALIBRATION APPROACH

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ABSTRACT

The accuracy of instrument voltage transformers is very important for a proper mains operation. According to the application of inductive voltage transformers, different accuracy classes are defined in the relevant standards of IEC, IEEE [1, 2]. In the design and manufacturing process of the transformer, manufacturers can consider the accuracy as an important design criteria as the error is dependent on internal losses caused by the stray inductance, the winding resistance, the magnetic core and the external burden.

The accuracy resp. the error of the voltage transformer can be obtained by several different methods. These can be applied in the laboratory, on-site or even online during normal operation. To enhance the mobility for on-site test equipment and to provide an efficient and simple alternative to conventional laboratory equipment, a new model-based calibration approach has been published recently [3]. For verification of this newly developed method comparisons an accredited laboratory (Pfiffner, Switzerland) have been performed and documented in this paper next to the theoretical background of the transformer error and the new model-based approach.

INTRODUCTION

Instrument Voltage Transformers (VT), either inductive (IVT) or capacitive (CVT, CCVT), are used in electrical grids to transform the high system voltage (power frequency) to a lower voltage level (e.g. 100V/√3) for further data processing. Depending on the purpose of installation, the VTs are connected to metering, measuring or protection devices. According to their application – metering, measuring or protection – VTs have to fulfil certain requirements regarding precision, dynamic range or transient performance.

The high accuracy and the intended dynamic range of the transformers can be reached by certain design criteria. The accuracy can be measured by several methods. In the past, different principles were introduced, either for laboratory (overview in [4]) or on-site applications [5]. Additionally, online methods are discussed in literature [6].

If an additional calibration within the lifetime is demanded, the transformers are demounted and calibrated with a comparison to standard transformers or dividers. This can be linked to a relatively large effort as the reference system has to be carried to the field or the VT has to be shipped to the laboratory. These calibration procedures with comparison to standard transformers are well known, used by accredited laboratories and provide a very high precision. Another approach [7] does not require heavy reference equipment but is dependent on a previously performed laboratory measurement and the obtained fingerprint of the VT.

A recently published methodology to calibrate voltage transformers with a model-based approach [3] (low voltages, no HV reference) can be applied in the laboratory or on-site and provides accurate and reproducible results.

In the first part of this paper, the design aspects to achieve the demanded performance, accuracy and a certain dynamic range are discussed.

The second and main part of this paper concentrates on the measurement techniques to calibrate the voltage transformers. Against this background, the authors perform a comparison of the conventional and the model-based measuring procedures in this paper. The intercomparison exercise is done at an accredited laboratory in Switzerland (traced back to European standards, PTB) and with the new model-based approach.

DESIGN CRITERIA

Based on international standards, for a correct design of an IVT three main criteria have to be taken into account:

- transformation ratio
- magnetization curve
- accuracy requirements

In the following subsections all three requirements are discussed in detail [8].

Transformation ratio – first design criteria

Transformation ratio follows a very simple equation (see formula 1).

$$Ratio_{VT} = \frac{V_1}{V_2} = \frac{n_1}{n_2} \qquad \text{Formula 1}$$

The relation between the primary voltage V_1 divided by the secondary voltage V_2 corresponds to the primary numbers of turn n_1 divided by the secondary numbers of turn n_2. This criteria does not consider any system conditions with its impact to the accuracy. It is more usable in the beginning of the design phase.

Magnetization curve – second design criteria

The relation between peak flux density $\hat{B}$ [T] and magnetizing force H [A/m] in the iron core is given by the magnetization curve and depends on the iron core material. When considering the well-known transformer formula (see formula 2), the exact peak flux density at nominal operation point can be adjusted for an IVT.

$$\hat{B} = \frac{\sqrt{2} \cdot V}{2\pi \cdot f \cdot n \cdot A_{Fe}} \quad \text{Formula 2}$$

The peak flux density within the iron core is depending on electrical requirements like voltage V and frequency f and mechanical dimensions like number of turns n and cross-section of the iron core A_{Fe}.

The range of operation at the magnetizing curve may never be in the saturation area, always at the linear zone. Saturation will have a very significant influence to the accuracy behaviour of the IVT [9, 11].

Accuracy requirements – third design criteria

The simplified equivalent circuit diagram, see figure 1, has to be taken into consideration when performing an exact calculation of accuracy depending on load and other conditions (no-load, over-voltages, thermal burden). This theory is consolidated from own experience and literature [10, 11, 12].

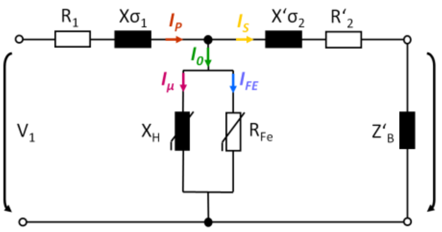

Figure 2: Equivalent circuit diagram of an instrument voltage transformer

$X\sigma_1$,$X'\sigma_2$:Leakage inductance | *R_{Fe}: Iron loss resistance*
R_1,R'_2: Winding resistance | *X_H: Main inductance*
V, I: Voltages/Currents | *Z'_B: Load*

The corresponding vector diagram is shown in figure 2. Depending on the operating conditions, the length of the relevant vectors as well as the angle to each other will be influenced. The difference between magnitudes of V_1 and V_2 is shown as ΔV. The angle resp. phase displacement between the vectors V_1 and V_2 is defined as δV. The vector diagram can be used as a very important tool for analysing various operating conditions.

With respect to the third design criteria, it is easy to calculate the different operating currents with the resulting voltage drops over all circuit elements. Due to this effect, the number of primary turns n_1 has to be modified to compensate the additional voltage drops within the system. Typically with this kind of adjustment, the accuracy vector will be moved to the specified accuracy class to meet all possible operating conditions like no-load, nominal load or simultaneous load according to international standards [11].

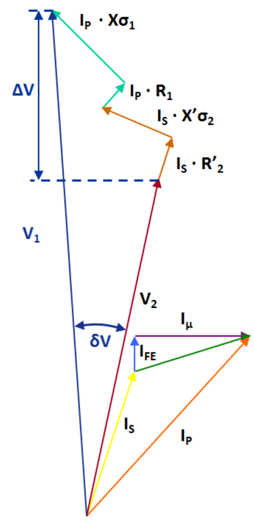

Figure 1: Vector diagram

The no-load current is only depending on the second design criteria. This component is independent to the secondary load. With increasing secondary load, the voltage drops over the primary elements R_1 and $X_{\sigma 1}$ will increase to a more significant parameter. For a correct calculation of the accuracy, the value of the leak inductance $X_{\sigma 1}$ and $X_{\sigma 2}$ is very important. Typically the leak inductance will be calculated by a formula which considers the mechanical relations between the primary winding to the relevant secondary winding. The result of this calculation is a sum of the leak inductance X_σ and has to be divided to $X_{\sigma 1}$ and $X_{\sigma 2}$. Depending on the design of the active part and the number of layers of the secondary winding, the factor can vary between 50% up to 100% of X_σ for $X_{\sigma 1}$. With all this information in mind, the adjustment of the magnitude – respectively the voltage (ratio) error ε_U – can be modified.

The parameter δV – respectively the phase displacement $\Delta\varphi$ – is depending on several factors and is not easy to modify afterwards. With respect to the vector diagram, figure 2, a positive in sign of the $\Delta\varphi$ value is possible by increasing the resistive power loss, a negative in sign by decreasing the resistive power loss. Based on the design of the IVT, the choose of the iron core material – power loss – or the mechanic relation of the width between the primary winding and the secondary winding – leak inductance – has a big influence to the described phenomenon. In case of an air gap within the iron core – typically used for ferro-resonance damping – a positive in sign of the $\Delta\varphi$ value is resulting [13].

IVT's with protection function have to meet the specified protection class over a very wide range of voltage variations. According to IEC standard, the accuracy class has to be fulfilled at 5%, 100% as well as at the over-voltage factor (150% or 190%) of the primary voltage.

IVT's with measuring function (billing too), the accuracy class shall be fulfilled at 80%, 100% and 120% of the rated voltage for IEC standards and 90%, 100% and 110% of the rated voltage for IEEE standards [1, 2].

IVT's with measuring and billing function have to provide a very high accuracy within the standard measuring range. For protection functions, the IVTs have to transmit the primary signal saturation-free for primary short-circuit currents or primary overvoltages. Table 1 provides an overview of all accuracy classes depending on application and international standards.

	Inductive voltage transformers	
	IEEE C57.13; IEEE C57.13.6	IEC 61869-1 IEC 61869-3
M	0.15; 0.3; 0.6; 1.2	0.1; 0.2; 0.5; 1.0; 3.0
P	–	3P; 6P

Table 1: Measurement (M) and protection (P) classes of voltage-measuring devices

CALIBRATION METHODS

Conventional calibration

The conventional calibration method is following the philosophy to measure a test object and compare the result with a reference system – mainly a special inductive transformer – which is calibrated by a meteorological institute like PTB in Europe. The accuracy is determined at real voltage level with real rated burden load at all operating points according the relevant standard. The test facility is optimized so that no unexpected influences occur and the test results affects, see figure 5.

The conventional calibration methods are designed for laboratory applications [4] and have been also adapted to comply with on-site requirements, e.g. [5]. All methods have two things in common. On the one hand these methods guarantee a very high accuracy but on the other hand they are linked to a considerable effort in terms of on-site applications. Next to the reference object a high voltage source, burden boxes and the cabling need to be shipped to the site. Additionally, different shielding and/or filtering concepts need to be considered due to possible interferences in the substation.

Model-Based Calibration

To overcome the drawbacks of the conventional calibration method in terms of on-site calibration and to offer an efficient, accurate and time saving alternative for laboratory applications, recently a new method has been published [3]. This method used low testing voltages (0…4kV) and low testing frequencies (0,1-10Hz) and applies ferromagnetic loss models. It fulfils the requirements of accuracy, mobility and efficiency.

The proposed method to obtain the accuracy of IVT is based on a model-based approach. Every IVT is modelled with its equivalent circuit (see figure 1). Precise measurements allow the determination of the equivalent circuit parameters and the transformation ratio after a possibly conducted winding correction. As metrological restrictions do not allow measuring every parameter, models are applied. The general methodology is shown in Fig. 3. In a first stage, the measurements are performed with low voltages and low frequencies because parasitic effects and high voltage levels at the primary terminal during secondary injection complicate the measurement – especially the open circuit excitation measurement.

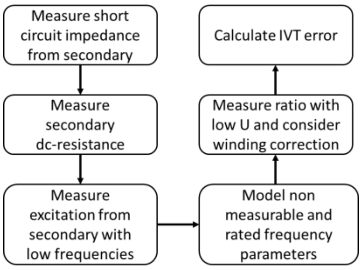

Figure 3: Methodology of the model-based method

First, the short circuit impedance (primary side short-circuited) and the DC resistances of the windings are measured. Due to the DC measurement to obtain the winding resistance, the core is demagnetized afterwards.
The excitation characteristics are measured from the secondary side of the transformer with low voltages and low frequencies. Therefore, the capacitive influence of the primary winding can be reduced (or eliminated) and the test voltage can be limited to a low level. Out of these open-circuit measurement, the dynamic “loss-free-current” of the nonlinear inductance is calculated. In addition, the ferromagnetic losses are modelled to be able to calculate the power losses at rated frequency by applying ferromagnetic loss models. The modelled inductive and resistive currents are added and the voltage-current characteristics at rated frequency are calculated.
After the measurements of the circuit parameters and the application of model calculations the error of the IVT is calculated according to the standards but without considering the real transformation ratio of the transformer.

The complex error is iteratively calculated for any voltage within the voltage range from 0% to 190% of the rated voltage. A separate measurement of the transformer ratio from the primary side with the secondary side open-circuited at a comparatively low voltage follows the error calculations. With this additional ratio measurement, the winding correction is considered in the calculations.

TEST SETUP AND TEST OBJECTS

Model-Based Calibration

The model-based calibration is performed with a recently released product, the so called *VOTANO 100* from *OMICRON electronics*. It clearly reduces the size and effort compared to conventional methods. The test device unit automatically performs the test according to the description before.
The main unit is placed in the safe area in a distance to the test object where high voltages might be occurring during the test (see figure 2). The interface between main unit and device under test is the switch- and booster box. The main unit operates with safe voltages up to 40V and the booster can produce voltages up to 4kV. The switch- and booster box also ensures a safe working environment as it includes safety features as surge arrestors and suppressor diodes.

Figure 4: Test setup "model-based-calibration" with OMICRONs *VOTANO 100*

Accredited Calibration Laboratory

The objects were tested at the accredited calibration test laboratory at PFIFFNER Company in Switzerland. All four test objects were placed together at a transport support and are measured according to IEC and the circuit diagram, illustrated in figures 5 and 6.

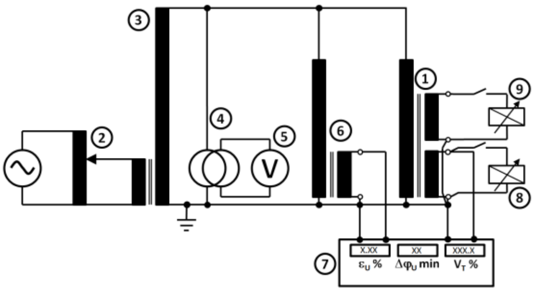

Figure 5: Test setup for accuracy measurement on IVT's

A voltage source generates the test voltage at rated frequency (2, 3) and is measured by an inductive voltage divider system (4, 5). The accuracy of the test object (1) is measured in relation to the calibrated reference transformer (6) and displayed by a measuring bridge (7). The burden variations are realized by (8) and (9).

Figure 6: Accredited test facility at PFIFFNER Company

Test Objects

Four different epoxy insulated voltage transformers have been tested (DUT1-DUT4).
The test object 1 has two secondary windings for metering application. Additionally, three IVT (2-4) with single secondary metering windings have been tested. Test objects 2 and 3 do have a protection winding next to a metering winding. These da-dn windings have additional requirements regarding the dynamic performance (5% - max. 190% rated voltage) but less requirements regarding the accuracy.

The test objects have the following specification:

Test object	DUT 1	DUT 2	DUT 3	DUT 4
Description	Epoxy 1 pol.	Epoxy 1 pol.	Epoxy 1 pol.	Epoxy 1 pol.
U_{PR} [kV]	60/√3	30/√3	20/√3	25
Sec. wind. 1	1a-1n	1a-1n	1a-1n	a-n
$U_{SR\,1}$ [V]	100/√3	100/√3	100/√3	25
Burden [VA]	20	30	30	12.5
Class	0.2	0.2	0.5	0.5
Sec. wind. 2	2a-2n	da-dn	da-dn	–
$U_{SR\,2}$ [V]	100/√3	100/3	100/3	–
Burden [VA]	20	50	30	–
Class	1.0	3P	6P	–

MEASUREMENTS AND RESULTS

The four instrument voltage transformers have been measured/calibrated with the discussed methods under the same environmental conditions. The results from the accredited calibration laboratory at Pfiffner Instrument Transformers Company are traced back to the national standard of PTB Germany.
The 60kV IVT (DUT 1) has two metering secondary windings with an accuracy class of 0,2 resp. 1,0. Next to the comparison of the accuracy of the described calibration techniques, it can be proved, if the influence of additionally loaded secondary winding can be obtained correctly with the model-based calibration.
The measured transformer errors are displayed in the so-called error-diagram. The complex error of the VT (ratio error and phase displacement) is displayed in one diagram. The ratio error is drawn on the vertical axis and the phase displacement is drawn on the horizontal axis [12].
The errors of DUT 1 are determined with a difference of ±0,006% and ±0,4min for rated voltage (figure 7). When the second secondary winding W2 is loaded in parallel to W1 (W1+W2), the error gets more negative and so the phase displacement. The difference between the model-based and the conventional methods stays the same. The accuracy class is 0,2 with limits of ±0,2% and ±10min. The differences between the model-based approach and the conventional method are less than 5% of the class limits in ratio and phase.

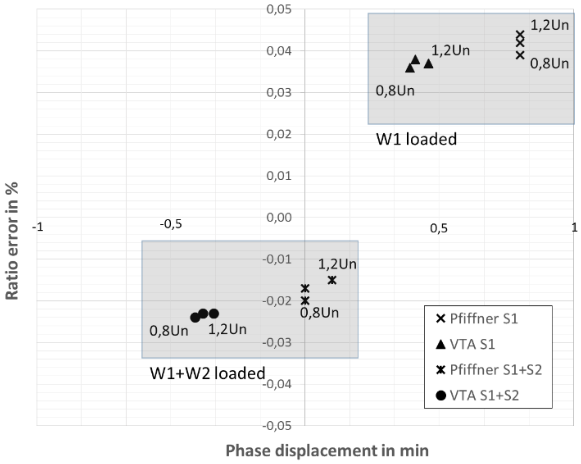

Figure 7: Measurement results of DUT 1 for different load condition of the two secondary windings

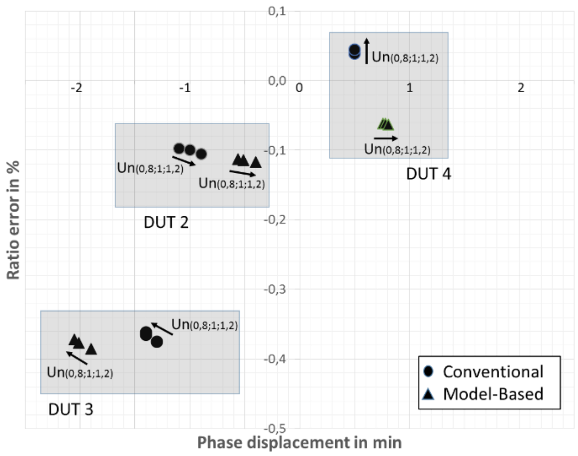

Figure 8: Measurement results of DUT 2 - DUT 4

In figure 8, the measured transformer errors of test objects 2, 3 and 4 are displayed. The maximum difference between the conventional and the model-based calibration method is ±0,015% and ±0,5min for rated voltage at DUT 2. As this test object also is a class 0,2 VT, the differences between conventional and model-based calibration are 7,5% in ratio and 5% in phase compared to the class limits. The errors of test object 3 vary slightly over the applied voltage. This trend can be seen in the results of both calibration methods. The difference between the conventional and the model-based calibration method is ±0,012% and ±0,6min for rated voltage (results in less than 3% of the class limits of this class 0,5 VT). The DUT 4 shows similar behaviour and can again be obtained with both applied calibration methods. The maximum differences are ±0,107% and ±0,3min for DUT 4. This results in differences below 20% related to the class 0,5 limits in ratio and below 2% in phase.

DISCUSSION

As the differences between the model-based approach and the conventional method are less than 25% of the class limits of the individual VT, the model-based approach can be used as an alternative calibration method. It can be stated, that IVT up to class 0,2 have been tested with comparable results between the two calibration methods. In the tests, the model-based calibration shows very good applicability and reproducibility. The mobility and the reduced testing effort bring good advantages compared to conventional tests in terms of on-site application as well as for in-house calibration.

The errors of DUT 2 and DUT 3 show a dependence on the applied voltage. This phenomenon is caused by the nonlinear inductance of the magnetic core. As the model-based approach uses the excitation characteristics of the magnetic core to calculate the no-load error, this nonlinear trend is very similar to the conventional measurement.

As only voltages far below rated voltage are used, this approach does not fully substitute conventional calibration but is a good, reliable, reproducible and accurate alternative.

To further verify the new model-based calibration approach several test objects have been tested and also a certification process has been completed.

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