A New Approach For In-situ Calibration of Voltage Transformers

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***Abstract*—In this paper the theoretical background and the application of a novel model-based approach is proposed being able to obtain the accuracy class of instrument voltage transformer (IVT) on-site (in-situ). It has several advantages to other known methods (model based or with usage of a reference object) as it does not need a fingerprint of the IVT based on laboratory tests and it is possible to perform the measurements without the need of having high voltage and heavy equipment on-site available. The new method can achieve high accuracies compared to test results from calibration laboratories. This paper concentrates on medium voltage transformers up to 35 kV.**

Keywords*—*Instrument Voltage Transformer; Accuracy; On-Site-Test

I. Introduction

Instrument voltage transformers (IVT) are used in electrical grids for metering or protection purposes. The high requirements regarding their precision demand a calibration of the objects before installation. The accuracy classes of IVT are different for protection and metering transformers [1] and are classified depending on the maximum ratio error and phase displacement between the vectors of the primary voltage and the secondary voltage related to the primary side. This calibration is performed in the laboratories of the manufacturers, operators or testing institutes. Once calibrated, the IVT typically operates without re-calibration for its lifetime. In some cases, e.g. reconstruction of the switchyard, the accuracy of the IVT is reconfirmed with a laboratory test or extensive on-site measurements [2]. Discussed on-site or online approaches, e.g. [3, 4, 5], are different to the proposed method as they need a reference object or the fingerprint of the transformer. The accuracy of the IVT is dependent on the installed burden, the leakage inductance, the winding resistance and the excitation current at power frequency. Core or winding deformation as a result of external influences, for example, can thus result in a change of the error of the IVT. In addition it may be interesting to obtain the excitation characteristics of IVT out of field measurements for ferroresonance analysis or simulation programs to simulate the dynamic behavior of the transformer.

Against this background it is very helpful to have the opportunity to get information about the accuracy class and the excitation curve out of field measurements. Thus, this test might be added to standard measurements in respect of on-site testing resp. condition based maintenance or delivery approval.

II. On-Site Measurements

Currently, different on-site tests are performed to get information about the condition of IVT [6, 7]. In this context, partial discharge measurements or dielectric response analyses are executed, oil samples are taken to do oil analysis (breakdown voltage, dissolved gas analysis, etc.) or visual inspections are conducted to find leakages, for example.

The accuracy of IVT is generally not verified as part of the test and maintenance strategies of the operators. Nevertheless, a simple ratio check is often performed and also recommended [8]. The ratio is measured with comparatively low voltages. As the error of IVT is a nonlinear function of the applied voltage (nonlinear inductance), the ratio obtained from low voltage measurements cannot be understood as the error at rated voltage. Further, the phase displacement is generally not measured.

Compared to maintenance procedures for power transformers or other cost intensive equipment, the tests at instrument transformers should be less complex and expensive as IVT have a much lower initial value than the mentioned equipment. This fact motivates an on-site calibration method obtaining the accuracy of IVT with less effort and less costs, from a technical and economical point of view.

III. Theoretical Background

A. Standard Requirements

The accuracy classes and test procedures are defined in the listed standards next to other important definitions, notes and test techniques for instrument transformers.

- IEC 60044
- IEC 61869 (successor of IEC 60044)
- IEEE C57.13
- ANSI C93.1 (CCVT)

The defined accuracy classes in turn define maximum values for the ratio error and phase displacement. According to IEC, the error is defined by (1).

$$\varepsilon = (V_b{*}Kr - V_1)/V_1 {*}100\% \qquad (1)$$

V_b is the secondary voltage of the transformer, V_1 is the primary voltage of the transformer and K_r is equal to the nominal ratio. The phase displacement is defined as the angle between primary and secondary voltage vectors.

Metering transformers have to fulfil the specified accuracy class between 80 % and 120 % of the rated voltage (IEC) respectively between 90 % and 110 % (IEEE). Detailed information about the accuracy classes and the requirements regarding voltage level and burden range can be found in the accordant standard.

B. Equivalent circuit and vector diagram

An equivalent circuit of an IVT is presented in Fig. 1. The ideal transformer without any losses (ratio after winding correction of the manufacturer) is connected to the T equivalent circuit (TEC) of a transformer. The dashed notation indicates the reference to the secondary side. The standard TEC is completed with a concentrated primary winding capacitance C_p'' as this is influential at secondary side measurements. At frequencies around power frequency, the elements C_{ps} and C_s can be neglected. The nonlinear inductance L_H represents the voltage-current behavior of the magnetic unit. L_H is assumed to be frequency independent. The dependence on frequency is modeled with R_{Fe}.

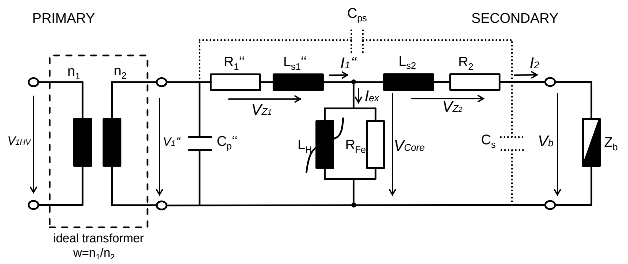

Fig. 1. Equivalent circuit of instrument voltage transformers

The voltage drops V_{Z1} and V_{Z2} across the primary and secondary impedances result in a voltage V_b that is different from V_1'' in magnitude and angle. According to Möllinger and Gewecke [9], this error of the IVT can be determined with the diagram in Fig. 2. The vector of the secondary voltage V_b is drawn on the vertical axis. The end of this vector is considered as the zero-point of the scale. The abscissa is divided in minutes (1% - 34.4 min) whereas the ordinate is divided in percent of the primary voltage (the drawn voltage vectors are divided by the primary voltage to get percent).

The error becomes negative when the secondary voltage vector is smaller than the primary. When the transformer is operated in no-load condition, the excitation current I_{ex} causes a voltage drop across R_1'' and L_{s1}''. This is indicated by point A in Fig. 2. The distance 0-A is called "no-load error". When the transformer is loaded with a burden, the additional current I_2 causes a voltage drop across both primary and secondary impedances (R_1'', L_{s1}'', L_{s2}, R_2). The "load error" (distance A-B) is independent of the primary voltage and proportional to the burden. Once drawn, the error for any load can be easily obtained from the diagram by shifting point B in direction of Δ Sn (change of power level) or by circular shifting point B in direction of Δ cosβ (change in power factor). Point A is not influenced by the load. When the applied voltage is changed, point A shifts due to the change of excitation current I_{ex} and loss angle ρ.

The previous explanations where made with the assumption of a transformer ratio equal to the nominal value. Manufacturers usually perform a winding correction to enable a point of operation in between the positive and negative error limits for the intended operation range of the transformer. In the vector diagram (Fig. 2), the winding correction is considered with a shift of the zero-point with the percentage correction to $-\varepsilon_u$.

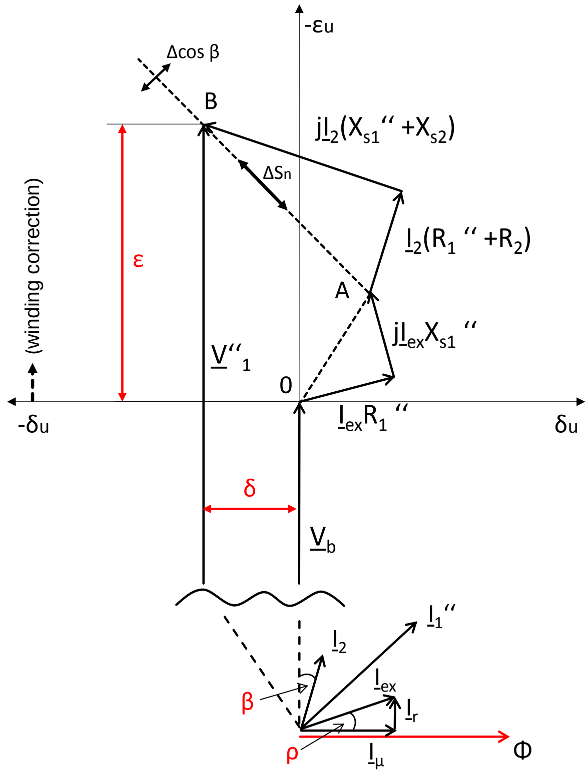

Fig. 2. Vector diagram of the voltage transformer of Fig. 1 according to Möllinger and Gewecke with the ratio error (ε) and the phase-angle error (δ)

C. Ferromagnetic Losses

The magnetic cores of IVT are typically built of stacked or wound silicon-iron steel sheets of non-oriented (NO) or grain-oriented (GO) material. An external magnetization causes macroscopic (dB/dt) and microscopic (moving domain walls) eddy currents which in turn cause power losses in the form of joule heating [10]. These power losses are divided into static and dynamic power losses and are dependent on conductivity and intrinsic material structure. The static losses are assumed to be frequency independent but dependent on flux density (intrinsic material structure) whereas the dynamic losses are dependent on frequency and flux density. The classical eddy current losses as one part of the dynamic losses are dependent on the conductivity of the material whereas the additional eddy current losses are dependent on the response of the material structure on an alternating external field.

Depending on the material of the magnetic core, the power losses are nonlinear over frequency. Compared to NO silicon iron, GO silicon iron is more nonlinear especially at low frequencies below approximately 10 Hz [11]. Additionally, the power losses over frequency differ depending on the ongoing magnetization process. The nonlinear behavior of the ferromagnetic losses is considered in the methodology of the presented method in the next section.

IV. Methodology

The proposed method to obtain the accuracy of IVT is based on a model-based approach. Every IVT is modeled with its equivalent circuit according to Fig. 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 methodology is shown in Fig. 3.

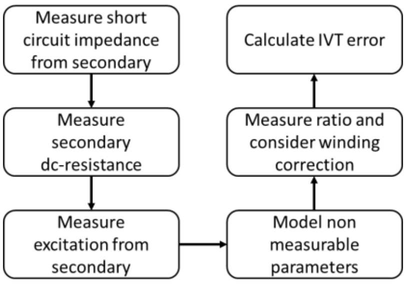

Fig. 3. Methodology of the model-based method

In a first stage, the measurements are performed with low voltages and frequencies because parasitic effects and high voltage levels at the primary terminal during secondary injection complicate the measurement – especially the open circuit excitation measurement. 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 should be demagnetized afterwards.

The excitation characteristics are measured from the secondary side of the transformer with low voltages and low frequencies (see Fig. 4 and [12]). 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 modeled 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 as in (1) according to Figures 1 and 2. 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 is following the error calculations. With this additional ratio measurement, the winding correction is considered in the calculations.

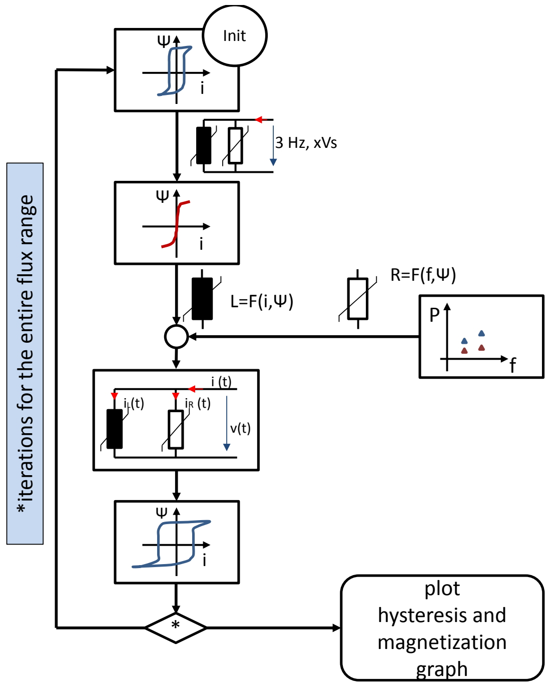

Fig. 4. Algorithm for measurements and calculations needed to determine the magnetization characteristics at rated frequency out of low frequency data [12]

V. Application of the Model Based Approach

The new method is tested with laboratory measurements at different IVT. The results of a 12 kV IVT (Fig. 5) are presented in more detail and the results of additional IVT are listed in TABLE I. For verification, the results are compared to the results obtained from a metrological institute (calibration lab). In this case, the error was measured with a comparative method.

The test object has an accuracy class of 0.2 (IEC) and a rated burden of 15 VA. The measurements were conducted with a test-setup in the laboratory consisting of a signal generator, power amplifier and oscilloscope. The measured data was saved and evaluated in Matlab. To take the winding correction into account, the ratio was measured with a CPC 100 from OMICRON at a voltage of 2 kV.

Fig. 5. 12 kV IVT for the prototypal application of the new method

The excitation characteristics of the test object are shown in Fig. 6. The measured hysteresis plots (measuring frequency of 6 Hz) are plotted next to the calculated hysteresis plots for rated frequency of 50 Hz. Without obtaining the excitation characteristics as suggested in Fig. 4, the current would be determined incorrectly. In this case, the error of the IVT would be calculated incorrectly as well.

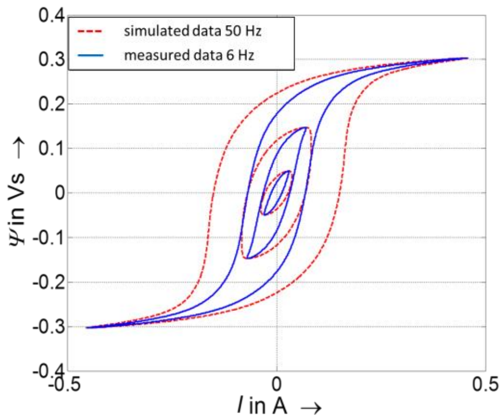

Fig. 6. Measured (f = 6 Hz) and simulated (f = 50 Hz) hysteresis plots of the 12 kV IVT representing the parameters L_H and R_{FE} of Fig. 1

With knowledge of the parameters of the equivalent circuit (short circuit impedance, secondary dc resistance, modelled excitation characteristics) and the transformer ratio the complex error of the IVT can be calculated. In Fig. 7 and Fig. 8 the voltage dependent ratio error and phase displacement are shown next to the data obtained from a calibration laboratory using a reference transformer according to the standard.

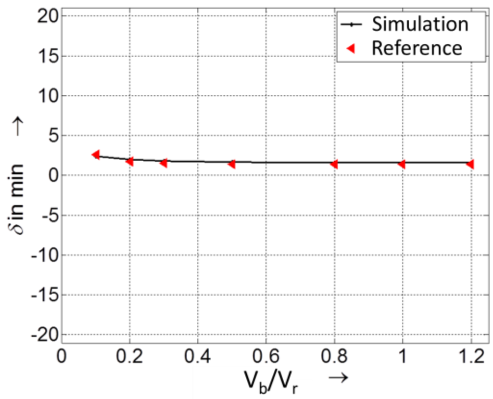

Fig. 7. Comparison of the simulated phase displacement (new method) with reference data from a calibration laboratory

The phase displacement obtained from the new model-based approach to determine the error of IVT is very similar to the reference data. Between 80 % and 120 % of the applied voltage (rated voltage V_r), the maximum difference is 0.25 min. Depending on the core material the errors can be very nonlinear over the applied voltage. In this case, this test object is equipped with a core build of grain-oriented silicon iron. Thus, the error is very linear over a wide range of the voltage.

The ratio error over the applied voltage is shown in Fig. 8. Again, the data obtained from the new model-based method are comparable to the reference data from the calibration laboratory. The maximum difference between the simulated data and the reference data is lower than 0.01 %.

The calculated errors of two additional IVT (Sim.), again compared to reference data obtained from a laboratory calibration (Cal.) at rated voltage are shown in TABLE I.

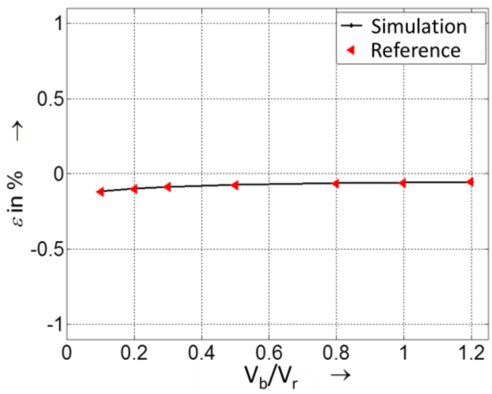

Fig. 8. Comparison of the simulated ratio error (new method) with reference data from a calibration laboratory

The results show a good applicability and accuracy of the introduced method as the simulated/calculated errors can be compared to the reference data with a maximum difference of approximately 0.03 % and 1 min.

TABLE I. COMPARISON OF CALCULATED IVT ERROR (NEW METHOD) AND REFERENCE DATA AT RATED VOLTAGE

IVT	*ε in %*		*δ in min*	
	Sim.	Cal.	Sim.	Cal.
20/√3 kV-100/√3 V	-0.237	-0.268	6.36	6.1
35/√3 kV-100/√3 V	-0.302	-0.267	-9.2	-8.3

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