The following article is the final version submitted to IEEE after peer review; hosted by PTB; DOI: 10.7795/EMPIR.17NRM01.CA.20190411. It is provided for personal use only.

A Sampling-Based Ratio Bridge for Calibrating Voltage Transformers

E. Mohns, G. Roeissle, S. Fricke and F. Pauling

Acknowledgement: Parts of the presented work are used in the projects 17NRM01 (TrafoLoss) and 17IND06 (FutureGrid II) which have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

Full Citation of the original article published be IEEE:

E. Mohns, G. Roeissle, S. Fricke and F. Pauling, "A Sampling-Based Ratio Bridge for Calibrating Voltage Transformers," 2018 Conference on Precision Electromagnetic Measurements (CPEM 2018), Paris, 2018
DOI: 10.1109/CPEM.2018.8501245

Available at:
https://doi.org/10.1109/CPEM.2018.8501245

A Sampling-Based Ratio Bridge for Calibrating Voltage Transformers

E. Mohns, G. Roeissle, S. Fricke and F. Pauling

Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany
Enrico.Mohns@ptb.de

***Abstract* — This paper describes the setup of a sampling-based ratio bridge for calibrating voltage transformers. The advantage of this ratio method is that voltage transformers with different transformer ratios can be easily compared. Initial measurements of the components of the bridge indicate low systematic errors, negligible voltage dependency and low phase errors around 50 / 60 Hz. This indicates an attainable uncertainty of below 2 ppm for the ratio error and 0.5 µrad for the phase displacement of voltage transformers.**

***Index Terms* — Voltage transformer, high voltage, sampling, precision measurements, uncertainty.**

I. Introduction

The testing of voltage transformers (VTs) designed for use in medium-voltage or high-voltage grids often takes place in test centers using standard voltage transformers (SVTs) of the error class 0.02 or better, with a bridge as the comparing element. The Physikalisch-Technische Bundesanstalt (PTB) offers calibration services for such SVTs. The present bridge at PTB is based on the difference method by measuring the voltage difference between the standard transformer (N) of the PTB and the transformer under test (X) and offers uncertainties on the order of $2 \cdot 10^{-7}$ [1]. A disadvantage of this difference method is that calibrations of VTs that have different transformer ratios are only possible by means of a high-resolution auxiliary inductive voltage divider (IVD). It scales one of the two secondary voltages of N or X in order to make these voltages equal before they are connected to the bridge.

The new ratio-based bridge presented here circumvents this problem by directly measuring the voltages of the secondary windings of VT N and X by means of two accurately adjustable voltage transformers and a two-channel sampling system that has high ratio accuracy. The modular setup of this bridge is highly flexible and can be easily adapted in the future to the calibration of non-conventional voltage transformers that have analog outputs or even digital outputs. Another intended application of this bridge is the fundamental determination of the ratio and phase errors of the SVTs of PTB by using an active capacitive voltage divider [2] with low voltage dependence.

II. Setup of the Ratio Bridge for Voltage Transformers

The principle of the ratio-based comparison method is shown in Fig. 1. The transformer under test (X) and the SVT (N) are connected to the high AC voltage U_p. Their secondary sides with the voltages U_X and U_N, which are usually on the order of 100 V, are connected to the ratio bridge (gray area, "ESM IV"). At the input of this bridge, two very accurate VTs, (A) and (B), together with an independent setting of their nominal divider ratio D_n, are used to scale U_X and U_N to the voltages U_B and U_A. The separate adjustment of VT (A) and (B) serves two purposes: (i) to prevent the inputs of the "HRPM" two-channel sampling system from overloading; and (ii) to bring the ratio of U_B and U_A close to one.

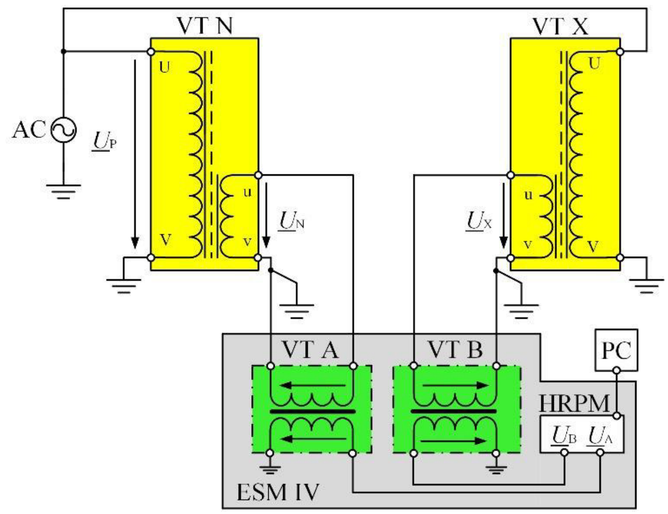

Fig. 1. Ratio-based calibration method for VTs.

Using the definitions $\underline{F}_\mathrm{N} = \underline{U}_\mathrm{N} / \underline{U}_\mathrm{P}$ and $\underline{F}_\mathrm{X} = \underline{U}_\mathrm{X} / \underline{U}_\mathrm{P}$ for VT (N) and (X), as well as $\underline{D}_\mathrm{A} = \underline{U}_\mathrm{A} / \underline{U}_\mathrm{N}$ and $\underline{D}_\mathrm{B} = \underline{U}_\mathrm{B} / \underline{U}_\mathrm{X}$ for VT (A) and (B), from the measured complex voltage ratio $\underline{\Gamma}_\mathrm{BA} = \underline{U}_\mathrm{B} / \underline{U}_\mathrm{A} = \underline{F}_\mathrm{X} / \underline{F}_\mathrm{N}\ \underline{D}_\mathrm{B} / \underline{D}_\mathrm{A}$, the ratio error ε_X and the phase error δ_X of VT (X) can be determined according to

$$\begin{aligned} \underline{F}_\mathrm{X} &= \underline{\Gamma}_\mathrm{BA} \cdot \underline{F}_\mathrm{N} \cdot \frac{\underline{D}_\mathrm{A}}{\underline{D}_\mathrm{B}} \\ \varepsilon_\mathrm{X} &= \frac{\left|\underline{F}_\mathrm{X}\right|}{F_\mathrm{X,nom}} - 1 = \left|\underline{F}_\mathrm{X}\right| \cdot K_\mathrm{X,nom} - 1\,. \\ \delta_\mathrm{X} &= \arg\left\{\underline{F}_\mathrm{X}\right\} \end{aligned} \tag{1}$$

To obtain low uncertainties for the bridge readings ε_X and δ_X, it is important that the sampling system and the VTs (A) and (B) have low systematic errors and associated uncertainties.

The sampling system [3] for measuring the complex voltage ratio $\underline{\Gamma}_\mathrm{BA}$ is based on a 24-bit sigma-delta ADC with sampling rates of up to 50 kS/s (NI 9239) and enhanced by means of an

This is an author-created, un-copyedited version of an article accepted for publication in 2018 Conference on Precision Electromagnetic Measurements (CPEM 2018), **DOI:** 10.1109/CPEM.2018.8501245. The presented work are used in the projects 17NRM01 (TrafoLoss) and 17IND06 (FutureGrid II) which have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

improved differential pre-stage. This differential pre-stage provides two voltage ranges of ± 10 V and ± 1 V in order to achieve a high signal-to-noise ratio. Further improvements are related to the input buffers, the MOS switch, the instrumentation amplifiers and the low-pass filters in order to achieve high linearity, and thus to attain low uncertainties of the measured ratio. The typical relative uncertainty is ± 0.2 ppm for a ratio of 1:1 (for example, for 5 V / 5V) and below ± 1 ppm for a ratio of 1:2 or 2:1 (for example, 3V / 6 V).

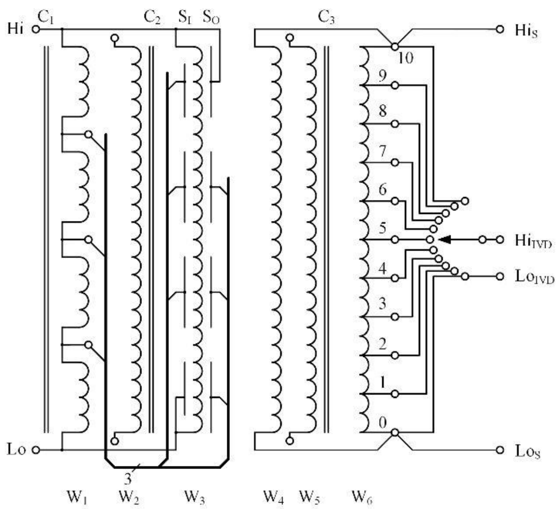

Fig. 2. Structure of the two-stage voltage transformer.

Fig. 2 shows the winding configuration of the constructed voltage transformers VT A (or VT B) of the bridge, which is based on the combination of a two-stage voltage transformer and an inductive voltage divider that has one decade. The inner working core, C1, which is made of nanocrystalline material [4], comprises the primary winding, W1 (4 x 400t), and an auxiliary winding, W2 (8 x 16t). The maximum voltage is 300 V at 50 Hz, while the maximum core impedance is 700 kΩ to prevent loading effects to VT (N) or (X).

A set of four cores as a shell around this makes up the magnetic core for the second stage, C2. The primary winding, W3, is wound in four sections (4 x 400t) and four layers to allow the use of enameled copper wires with sufficient thickness. Additionally, the four sections of W3 are shielded inside and outside by means of eight screens $S_{I,k}$ and $S_{O,k}$ ($k = 1\dots 4$), which are driven from W1 with the respective 0 %, 25 %, 50 %, 75 % and 100 % potentials. This reduces capacitive currents within W3 and leads to small phase errors.

The secondary winding W4 (160t), which has a ratio of 0.1, and an auxiliary winding, W5 (16t), which has a ratio of 0.01, are wound around W3. Finally, the core, C3, and its winding, W6 (10 × 16t), represent an inductive voltage divider that is connected to the secondary winding, W4. Thus, ratios from 0.01 to 0.10 can be adjusted. The purpose of the auxiliary winding, W5, is to allow the IVD section to be calibrated using Thompson's method.

III. Measurement results

The first stage of VT (A) and (B) was measured at various voltages between 1 V and 300 V. The results obtained were in the range from -1 ppm to -10 ppm and 8 µrad to 45 µrad. They agree very well with the calculated errors $\underline{E}_1 = - R_{P1} / \underline{Z}_{M1}$ of the first stage based on the primary winding resistance R_{P1} and the measured complex impedance of the magnetic core $\underline{Z}_{M1}$. As the resistance of the primary winding R_{P2} and the impedance $\underline{Z}_{M2}$ of the second stage are around 10 Ω and 100 kΩ, respectively, the error of the second stage $|\underline{E}_2|$ is about 100 ppm. Ideally, this would lead to an error of the whole two-stage structure of $\underline{E} = - \underline{E}_1 \cdot \underline{E}_2$, which, by using the values given, is below 10^{-8} in the voltage range from 10 V to 300 V and at 50 Hz. In practice, effects due to stray magnetic fields around the core and capacitive effects will occur and deteriorate the given estimated errors.

However, the initial results of the evaluation indicate that the output-related errors in all ranges of the VT do not exceed 0.5 ppm and 0.5 µrad. The effective output resistance for each setting of the VT between 0.01 and 0.1 is below 0.5 Ω. Thus, loading effects due to the input impedance of several hundred MΩ and some pF of the two-channel sampling system can be neglected.

Another verification was performed in order to intrinsically check the ratio accuracy of the bridge under an input voltage of 60 V and different settings of the nominal ratio D_n of VT (A) and (B). For equal ratios D_n from 0.10 : 0.10 to 0.05 : 0.05, the error difference measured (i.e., the bridge reading) was below 0.2 ppm and 0.1 µrad. For different ratios of VT (A) and (B) from 0.05 : 0.10 to 0.09 : 0.10, the error differences measured were not higher than 1.5 ppm and 0.3 µrad. This indicates that the attainable uncertainty of the bridge presented is below 2 ppm or 0.5 µrad. More results will be shown during the conference.

References

[1] Ramm, G.; Moser, H.: "Eine neuartige, rechnergesteuerte und selbstkalibrierende Spannungswandler-Meßeinrichtung", PTB-Mitteilungen, Vol. 106, 4/96

[2] E. Mohns, J. Chunyang, H. Badura and P. Raether: "An Active Low-Voltage Capacitor for Capacitive HV Dividers", CPEM 2018 Conf. Digest, July 2018.

[3] E. Mohns, G. Roeissle, S. Fricke and F. Pauling: "An AC Current Transformer Standard Measuring System for Power Frequencies", IEEE Trans. Instrum. Meas., vol. 66, no. 6, pp. 1433-1440, June 2017

[4] OMEM, "TA42", see www.omemspa.com