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Application of Digital Sampling Method for Voltage Transformer Test Set Calibrations

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***Abstract*-**An application of digital sampling method for calibration of voltage transformer test sets is described. A digital sampling wattmeter with well-known operating principle was configured and used as a reference comparison bridge. Because of its high accurate ratio and phase error measurement capability, any type of test set regardless of their operating voltage ranges could be calibrated. In this paper, the accuracy of ratio error and phase displacement measurements of the sampling bridge is analyzed for nominal voltages with amplitude and phase differences up to 2% and 2crad, respectively. Additionally, a simple automation method in generation and adjustment of ratio and phase error values is also described.

I. Introduction

Calibration of an instrument voltage transformer (VT) is commonly performed by a comparison with a reference voltage transformer by using a voltage transformer test set (VTTS). Basically, ratio error (ε) and phase displacement (δ) of a VT against a reference VT with the same ratio can be expressed as

$$\varepsilon = U_{SX} / U_{SN} - 1 , \qquad \delta = \delta_X - \delta_N \qquad (1)$$

where U_{SX} and U_{SN} are secondary voltages, and δ_X and δ_N are phase errors of VT under test and reference VT, respectively. Since, the reference VT is assumed to be ideal and error-free, a VTTS directly gives the ratio and phase differences of the two secondary voltages as in-phase and quadrature errors of the tested VT (Figure 1).

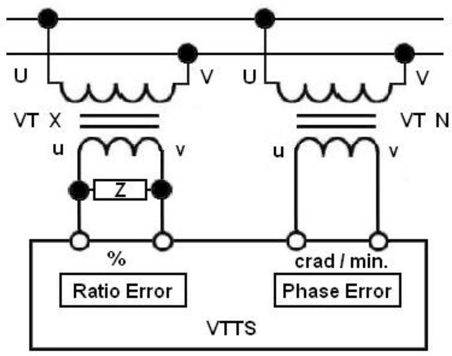

Figure 1. Basic VT calibration circuit with a VTTS

Several types of VTTSs are available commercially; Schering-Alberti type bridges which are manually balanced with R-C configurations, current comparator based self-balancing bridges, and recently designed test sets which use digital sampling algorithms. Although, their operating principles differ from each other; they could perform the measurements in a good agreement within certain measurement ranges. Particularly, all of the methods could give excellent results when performing self-check of the test sets, or when measuring relatively small errors. On the other hand, because of their inherent errors such as interactions between real and imaginary measuring parts of the test sets, which are known as orthogonality problems, the measurement results might be different while measuring relatively high ratio errors and phase displacements. Calibration of any type of test set is required not only for investigation of such fabrication faults but also to be aware of the non-linearity of the measurement results caused by the deviations in the component impedances.

II. Background

A VTTS calibration is performed simply by applying two voltage values, one of which differs from the other by a known amplitude and phase value, and by comparing them with the ratio and phase errors read by the VTTS.

A practical method would be applying a nominal voltage value to both terminals of the VTTS and introducing an R-C circuit to one of the input terminals serially so that the voltage drop on that terminal could be changed in magnitude and in phase (Figure 2). If the input impedance values of each terminal of a VTTS are exactly known, then proper R and C values could easily be calculated and adjusted to obtain any desired ratio and phase differences.

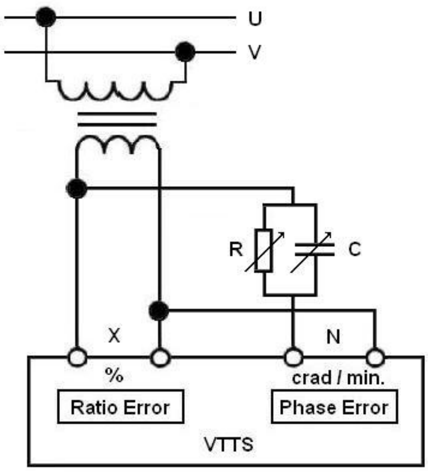

Figure 2. Calibration method for a VTTS with R-C circuit application

In such calibration procedures, the accuracy is directly depending on the precise adjustment of the error values. Since, traceability of such a system is achieved only through the R-C circuit; all of the components used in this circuit must be calibrated before use. Inductive components of resistors and resistive components of capacitors which are responsible for ratio and phase errors in measurement results should be taken into account in evaluation of the calibration results. Moreover, input terminals of VTTSs are generally not purely resistive; therefore inductive components of both terminals should also be taken into account. An impedance analyzer may be integrated into the system to determine and eliminate any source of error coming from R-C circuit and input terminals of a VTTS.

III. Digital Sampling Wattmeter Based Reference Bridge

Simply, a reference bridge might be integrated into the setup to get rid of such complex procedure. And, any type of VTTS calibration could be performed by direct comparison with it. The reference bridge, here, is a digital sampling wattmeter (DSWM) based ratio standard with 1ppm resolution in both ratio error and phase displacement measurements.

A. Operating Principle of DSWM

The operating principle of this well-known DSWM (Figure 3a) is based on the use of two sampling voltmeters and on computerized evaluation by means of discrete integration (DI) or discrete Fourier transform (DFT) [1].

Similar to others, it consists of two digital sampling voltmeters (DVMs), a precision voltage transformer, an electronically compensated current transformer with a temperature controlled AC shunt resistor, a computer controlled phase-locking device and software. However, the use of the phase-locking unit differs from that of the others to enable the system to operate not only with digitally synthesized power sources but also with analog sources by phase-locking to their voltage or current output signal [2,3].

The voltage and current signals of a phantom power source are applied to the input terminals of voltage and current transformers. A regulated voltage from secondary terminals of the voltage transformer and a voltage obtained from the shunt resistor, which is connected to the secondary terminals of the current transformer, are then applied to the DVMs. With the help of the software, DVMs are programmed with the calculated appropriate aperture times for the selected samples per period. Each programmed DVM samples the applied voltage signals with the help of trigger signals generated by the phase-locking unit. The data from both DVMs are then transferred to the computer via IEEE488. The ratio and phase angle errors of the voltage and current transformers were corrected by the software.

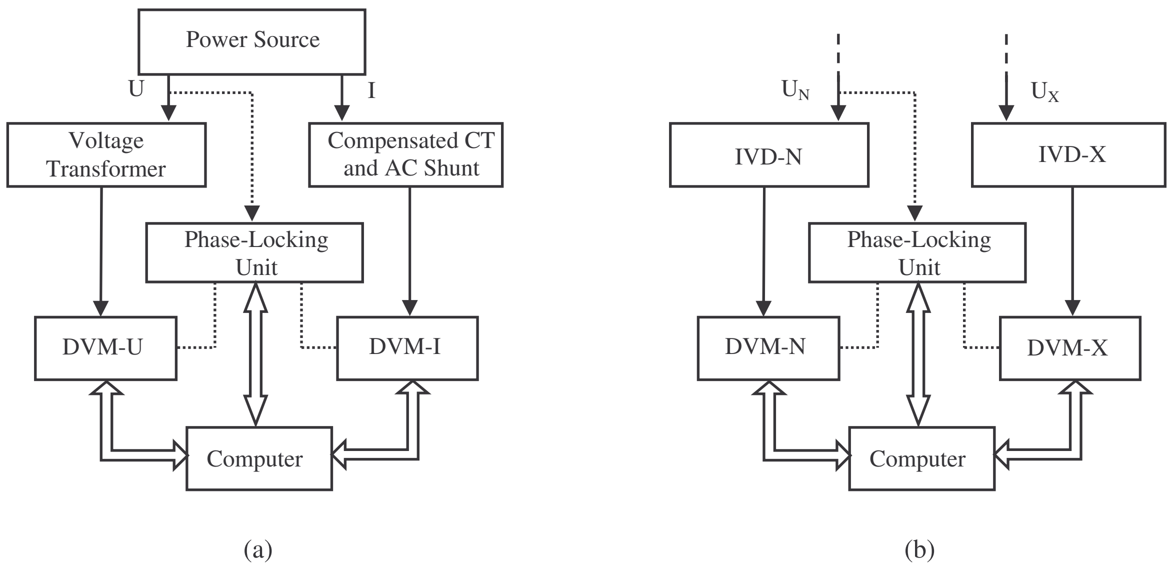

Figure 3. (a) Block diagram of DSWM and (b) DSWM based Reference Bridge

The amplitudes of both signals, the phase angles between them and the total power are calculated mainly by using discrete integration. To check for distorted waveforms and to display the harmonic components, DFT is also used on the software. All available calculated results are displayed during the measurements.

A basic uncertainty of 22ppm has been achieved for active, reactive and apparent power measurements. However, the systematic error of the DSWM is not more than 10ppm for any voltage ratio measurements while DVMs operate in the same ranges. This accuracy consideration makes the DSWM a preferable reference standard for VTTS calibrations.

B. Application of DSWM for VTTS calibrations

DSWM can easily be adopted for voltage ratio measurements with simple modifications in both hardware and software. Since, DVMs have voltage ranges up to 1000V; it is practically possible to operate them in the two highest voltage ranges (100V and 1000V) for direct measurement of VTTS input voltages. However, the accuracy of the voltage measurements in DC sampling mode is limited in these ranges. The best accuracy for sampling process with DVMs can be achieved only in 1V and 10V ranges. To operate the system within best accurate measurement mode, simply, both the voltage and current transducers used in DSWM are replaced with two unique inductive voltage dividers (IVDs) (Figure 3b). These two home-made IVDs are connected to the each input terminals of the VTTS and the outputs are selected between 10:1 and 100:1 to obtain proper voltages for the DVMs 1V or 10V ranges. The accuracies of IVDs are successfully evaluated by build-up technique and the ratio and phase errors of each IVD are saved into the calibration software for the further calculations.

This reference bridge with its successful configuration and algorithm then gives excellent ratio and phase error measurement results while calibrating not only the same order voltages but also the divider function of the VTTS, as well. Internal dividers of VTTS having ratios between 0.5 and 1.5 could easily be calibrated by ratio adjustments of IVDs.

C. Generation of calibration values

As shown in fig. 2, inserting an R-C circuit between two input terminals of a VTTS is a common method to obtain the desired ratio and phase error values. However, it is not applicable for some VTTSs which have variable input impedances. Moreover, it is not easy to make it automatic therefore; the operators have to adjust the required R and C values, manually.

An alternative method for generation of error values is described here. The purpose of this study is the automatic generation of the desired ratio and phase errors. Similar to the generation method used in current transformer test set calibrations [4], the ratio and phase error values are roughly generated by a computer-controlled three-phase power source with a reference wattmeter. Then, fine adjustments are made with the help of an inductive summing unit which consists of isolation transformers and voltage dividers (Figure 4).

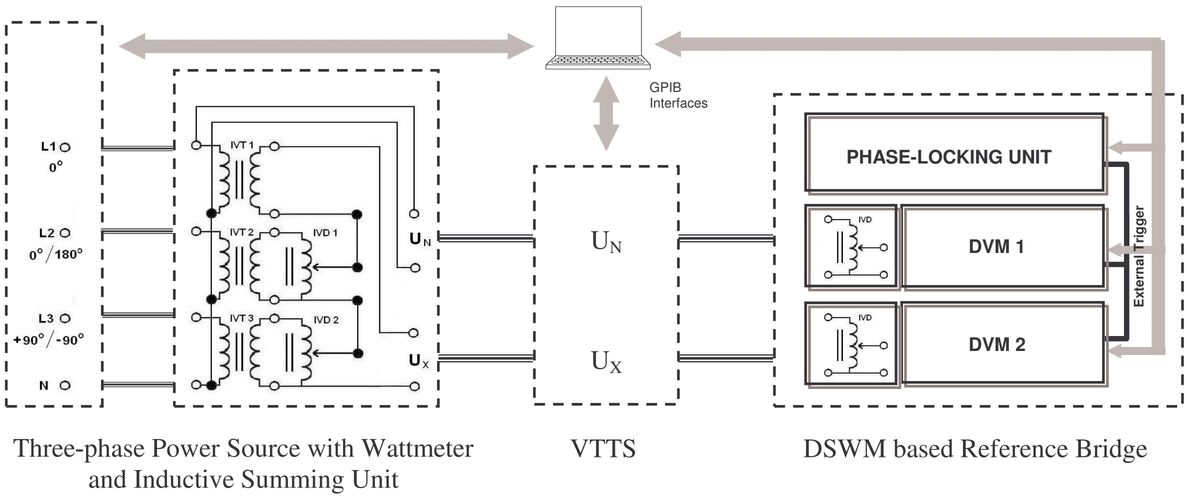

Figure 4. Diagram of VTTS calibration circuit.

A voltage signal which is used for simulating the secondary voltage of a reference VT, is generated by the first phase of the PC-controlled power source and applied both to N input of the VTTS and to the first input of the inductive summing unit. An in-phase voltage signal which differs from the reference signal with 0º or 180º is generated by the second phase of the source and applied to the second input of the inductive summing unit. Finally, a quadrature-phase voltage signal which differs from the reference signal with ±90º is generated by the third phase of the source and applied to the third input of the inductive summing unit. All signals first applied to isolation transformers since it is necessary to ground the N and X voltage signals on the VTTS, safely. The second and the third signals from the isolation transformers are then applied to separate IVDs, and the secondary terminals of first isolation transformer and of the IVDs are connected serially. The output of this summing unit now, is an approximate total of three isolated signals. And, this signal can be applied to the X terminal of a VTTS. Any error desired for a VTTS calibration can be obtained with the combination of PC-controlled three-phase power source and inductive summing unit.

However, the auxiliary IVDs will be no longer accurate when they are connected to the terminals of VTTSs particularly of VTTSs which have variable inductive components. The variation of the impedances in any input terminals of a VTTS results in impedance matching problems, and the voltage drops on the terminals might be different from the calibrated output voltages of the IVDs. The same approach would be possible for the isolation voltage transformers since the accuracy of 1:1 transformation ratio of such transformers are also dependent on their secondary loads. However, the experimental studies have shown that the total errors in application of desired ratio and phase error values would never vary more than 1% from the calculated values. Unfortunately, this relatively small variations result in high errors, e.g. 200ppm uncertainty while applying 2% ratio error or 2crad phase displacement. Therefore, the configuration described here is used only for generation of error values.

In the future, it is planned to buffer the outputs of the devices used in the inductive summing unit so that the errors form their sensitivity to the loads will be eliminated. Then, there will be no need to use a reference bridge in the calibration system.

IV. Verification

The auxiliary instruments such as three-phase power source, wattmeter, isolation transformers and voltage dividers are only required for generation, and there is no need to calibrate them. Moreover, the instability of the power source does not affect the accuracy of measurements therefore; it is not taken into account. Only, the accuracy of DSWM based Reference Bridge has been evaluated, since the VTTS calibration system is traceable to National Standards through it. Accuracy of the calibration system has been evaluated concerning all probable error sources, including IVDs, DVMs and the phase-locking unit.

The ratio and phase angle error values of IVDs have been found for all ratio taps while they are directly connected to the DVMs which are operated in DC sampling mode [5]. Since the input impedances of DVMs are over 10GΩ (almost open circuit) while operated in this mode, the calibration results of IVDs are highly reliable. Calibration uncertainties for ratio and phase errors of IVDs are less than 2ppm and 2µrad, respectively. The calibration results of these two unique IVDs have been corrected within the software. Additionally, to be aware of unwanted variations in the ratio or phase calibration values of IVDs, the connections are interchanged at each measurement point and checked the reversal results.

DVMs are calibrated just before use, since the ratio measurement errors of the DVMs are directly dependent on their DC calibrations. The phase angle errors, which arise from the time base behavior of DVMs, were checked by applying the same voltages (as parallel and inverted) to both DVMs and calculating the phase angle differences. The probable timing errors of the phase-locking device, which lead to phase errors, were also taken into account. After the offset values defined above were found and corrected within the software, the bridge (without IVDs) was calibrated with a reference inductive voltage divider and a phase standard. The measurements performed in 10V ranges of the DVMs showed that high accurate ratio and phase error measurements could be performed by DSWM based bridge in certain voltage ranges. After all error corrections, total measurement uncertainty of the reference bridge has been found not more than 5ppm and 5µrad for ratio and phase error measurements, respectively.

V. Conclusions

An automatic calibration system for voltage transformer test sets has been developed. The ratio and phase error values are generated by a computer-controlled three-phase power source and adjusted with the help of an inductive summing unit which consists of isolation transformers and voltage dividers. The traceability of the system is from a digital sampling wattmeter based reference bridge. The overall accuracy of the system is independent of the measured ratio and phase error values including dividers.

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