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Frequency Response Test of MV Inductive Voltage Transformers for Power Quality Applications

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Abstract. Power quality maintenance is a concern that has currently reached all levels of electric systems. This concern is mainly due to the increased connection of nonlinear devices and loads with high sensitivity to power quality disturbances on distribution, transmission and generation complexes. However, to enable power quality measurements on medium (MV) and high voltage networks, voltage transducers are necessary. There are different types of voltage transducers commercially available. The inductive voltage transformers (IVTs) are most commonly used for MV systems. However, it is well-known that some types of voltage transducers may not present a linear transformation ratio for harmonic frequencies, including IVTs. Therefore, to overcome this nonlinearity of voltage transducers, the IEC published a technical report addressing guidelines and recommendations regarding the use of instrument transformers for power quality applications (IEC/TR 61869-103). In this context, this paper is aimed at performing a frequency response test on three MV IVTs using the mentioned IEC document in order to guarantee accurate harmonic voltage measurements. Moreover, a laboratory structure at the Federal University of Uberlândia is implemented for evaluating the frequency response on MV transducers.

Key words. Inductive voltage transformers, frequency response, power quality measurements, harmonic distortions, test set-up.

1. Introduction

Over recent years, the concern regarding the maintenance of power quality (PQ), especially due to the increase of harmonic content, has reached all levels of electric systems – distribution, transmission, and generation. The harmonic content increase has happened mainly due to the intensified connection of nonlinear equipment in electrical systems. These nonlinear devices range from electro-electronic loads, such as switched-mode power supplies, rectifiers, and inverters used in houses and industries; to devices used in transmission systems such as High-Voltage Direct Current (HVDC) links and Flexible Alternating Current Transmission System (FACTS); to power converters used in wind and photovoltaic plants, which have gained space in the world as sources of electricity generation [1]. This scenario increases the need for correct and accurate measurements of voltage and current for monitoring PQ indicators, and further evaluating the demand for mitigation strategies to maintain the indicators within the established limits. In Brazil, the PQ indicators limits are set by the Brazilian Electricity Regulatory Agency (ANEEL) by means of the technical report PRODIST - Module 8 [2] for distribution networks, and by the National Electric-System Operator (ONS) by means of the Grid Procedures - Submodule 2.8 [3] for the Power Grid.

However, to enable PQ measurements on medium (MV) and high voltage (HV) networks, the use of instrument transformers is required since Power Quality Analyzers are not designed to withstand these voltage and current levels. When dealing specifically with voltage measurements, a variety of voltage transducers is commercially available, such as voltage inductive transformers (IVTs), capacitive voltage transformers (CVTs), capacitive voltage dividers (CVDs), resistive-capacitive voltage dividers (RCVDs), among others. On networks up to 145 kV, IVTs are usually installed for protection and measurement purposes, whereas, above 145 kV, CVTs are used as these possess greater economic viability [4].

Moreover, for harmonic distortion measurements on the Power Grid, the Brazilian norm requires accurate measurements for frequencies up to the 50th harmonic order [3]. Nevertheless, the literature demonstrates that some types of voltage transducers may not have a linear transformation ratio (magnitude and phase) outside rated frequency [5]-[10].

In light of these facts, the International Electrotechnical Commission (IEC) has published a technical report exposing the issues and addressing the recommendations regarding the use of instrument transformers for PQ measurements, that being the IEC/TR 61869-103 [5]. To overcome the nonlinearity of some types of voltage transducers for harmonic measurements, the document presents a frequency response test procedure (magnitude and phase) that needs to be performed in order to allow for the use of these devices in PQ measurements.

Therefore, this paper aims at performing the frequency response test in three MV inductive voltage transformers according to the methodology established in [5]. These IVTs will be used in the measurement of harmonic voltages for testing a methodology for harmonic responsibility sharing on the network of a wind park in Brazil. Therefore, the accomplishment of the frequency response test is extremely important for evaluating the need for corrections on measurements in order to guarantee accurate harmonic voltage results. In order to reach the main goal of this paper, it was necessary to implement a laboratory arrangement at the Federal University of Uberlândia (UFU) to allow for the performance of the frequency response test on transducers up to 20 kV. This paper is organized as follows: in the next section, the principle of operation and constructive characteristics of the IVTs and CVDs are described. Section 3 describes the IEC/TR 61869-103 frequency response test procedure for voltage transformers (VT) performed in this study. Subsequently, a description is provided of the laboratory setup implemented, equipment used and methodology applied for accomplishing the test at UFU. Finally, the results are presented and discussed in section 5, followed by section 6 containing the conclusions.

2. Employed Voltage Transducers

This section presents an overview regarding the principle of operation and the constructive characteristics of the inductive voltage transformer, which is the VT under test in this study. Moreover, the constructive characteristics of the capacitive voltage divider are also described, since one is used as reference transducer on the tests performed.

A. Inductive Voltage Transformer (IVT)

The principle of operation of IVTs is based on the magnetic coupling between coils, the same principle employed by power transformers. Hence, the high voltage at the primary winding is transformed, proportionally to the transformation ratio, into low voltage at the secondary winding, thus producing the appropriate voltage level for protection and measurement devices. The advantage of this transducer over the capacitive dividers, explained in the following section, is the galvanic isolation, which provides higher safety for operators.

The transformation ratio of the IVT, however, is guaranteed only for rated frequency. When signals with different frequencies are applied to the HV terminal of such equipment, the rated transformation ratio may not be obeyed. In this context, several authors investigated the frequency response of voltage transducers and concluded that some factors, such as constructive characteristics, operating temperature, burden and rated voltage may influence the frequency behavior of IVTs [5]-[7], [9]-[10]. Usually, the frequency bandwidth of IVTs tends to decrease as the rated voltage increases.

The nonlinearity of the IVT may be explained by the equivalent circuit shown in Fig. 1. One notes, therefore, that as the frequency of U_1 increases, the impact of capacitances between windings (C_{12}) and between windings and ground (C_{10} and C_{20}) increases as well. Furthermore, the magnetizing inductance (L_{10}) also varies nonlinearly (hysteretic behavior) with the amplitude and frequency of the primary voltage signal [5]. Thus, the transformation ratio of IVTs for high frequencies may differ considerably from the rated transformation ratio.

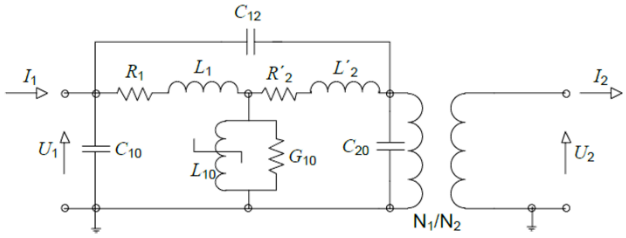

Fig.1. Example of equivalent circuit of inductive voltage transformers [5].

B. Capacitive Voltage Divider (CVD)

Capacitive voltage dividers are composed, basically, of two capacitive units connect in series. Fig. 2 shows the electric diagram, where V_1 represents the voltage at the high voltage terminal, V_2 the voltage at the low voltage terminal, and C_1 and C_2 are the capacitances connected in series.

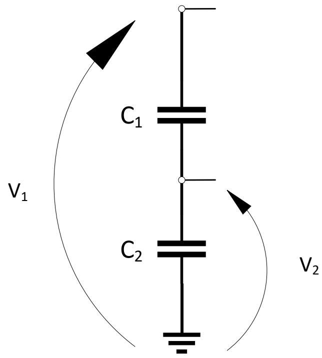

Fig.2. Equivalent circuit of capacitor voltage transformers.

This transducer has as its main characteristic the linearity over the frequency domain [5], [8]. This relationship is observed in (1), which indicates voltage V_2 as a function of the high voltage V_1. Thus, voltage V_2 depends only on the values of C_1 and C_2, which do not vary with the frequency.

$$V_2 = \left(\frac{C_1}{C_1 + C_2} \right) \cdot V_1 \quad (1)$$

3. IEC/TR 61869-103 Test Procedure for VT Frequency Response

The technical report IEC/TR 61869-103 aims at providing guidelines for the use of instrument transformers concerning the measurement of PQ parameters. This section presents the test procedure described in this document.

The test procedure depends on the linearity characteristic of the voltage transducer; as such there exist two possibilities. The first procedure is applied when evidence is shown that the frequency response of the transducer is not affected by the presence of the fundamental voltage and variable burden. The second procedure is applied when the frequency response of the transducer is affected by the fundamental voltage. Both procedures are described in the following.

A. VTs with Frequency Response not Affected by Fundamental Voltage and Varying Burden

In these cases, the test is performed at a lower voltage level than the nominal, where a sinusoidal voltage is applied at a single frequency, starting at 15 Hz, and the frequency is varied until the 50^{th} harmonic order. The standard [5] does not provide details for the frequency step. The voltage level applied to the high voltage terminal should be chosen so that the secondary voltage (output signal) has an appropriate level, in order that it is measured with sufficient accuracy.

The test circuit consists of a power amplifier and a signal generator. The transducer under test must be connected to the amplifier output. A reference transducer is connected in parallel to the equipment under test. The different outputs of the transducer under test and of the reference transducer are compared using a suitable high resolution sampling magnitude and phase comparator. If the applied voltage is below the maximum input voltage of the instrument used for comparison, the voltage can be measured directly, without the need for the reference transducer. The scheme for carrying out the test is described in Fig. 3, however, without the step-up transformer. The reference transducer should have a known frequency response, suitable reference transducers are CVD and RCVD.

B. VTs with Frequency Response Affected by Fundamental Voltage

In the second case, the test should be performed by applying a fundamental voltage close to or equal to the nominal voltage with harmonics or subharmonics superimposed over the fundamental voltage signal. The harmonic level should range from 0.2% to 3% of the fundamental voltage amplitude for HV transducers, whereas for MV transducers, the harmonics must range from 2% to 10% of the fundamental voltage. If relevant, the burden dependence of the frequency response is analyzed during the test.

The test circuit, in this case, is the same as that shown in Fig. 3, which now includes the step-up transformer, since a fundamental voltage close to the nominal of the transducer under test is required. The signal generator must now supply harmonics superimposed on the fundamental sinusoidal signal from 15 Hz to the 50^{th} harmonic order. It is also important to measure the harmonic distortion at the output of the step-up transformer, as this can act as a low pass filter for harmonics.

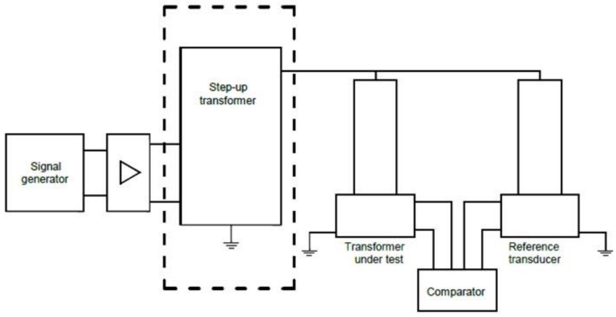

Fig.3. Scheme for the VT frequency response test [5].

4. Test Set-up and Methodology

According to the explanation mentioned in section 2.A, one infers that the frequency response of IVTs may be influenced by the presence of fundamental voltage on their HV terminal [5]. Therefore, the procedure described in section 3.B was chosen to be performed. However, to reach this goal, the implementation of a laboratory setup capable of supplying the IVTs with fundamental voltage close to the nominal was required, as well as capable of controlling additional harmonic signals. Thus, this section describes the laboratory setup implemented, the equipment used and methodology applied for performing the test.

A. Test Set-up

The scheme shown in Fig. 3 was implemented in the High Voltage Laboratory of the Federal University of Uberlândia (UFU) – Santa Mônica Campus. The equipment used, according to Fig. 3, is the following:

1) Signal Generator and Power Amplifier

The signal generator-power amplifier used was a controlled power source from California Instruments model CSW5550 [11]. This power source is able to generate sinusoidal signals up to 300 V (phase-neutral) and frequency up to 5 kHz. Moreover, the source allows for the generation of distorted signals by the addition of harmonic components with amplitude set at a percentage of the fundamental voltage.

2) Step-up Transformer

The Step-up transformer used was a 5 kVA single-phase oil-filled transformer. The transformer specifications are shown on Table I.

Table I. – Step-up transformer specifications.

Rated Power	5 kVA
High Voltage	34.5 kV / √3
Low Voltage	254V
Frequency	60 Hz
Impedance	3 %
Type	Single-phase

3) Transducers Under Test

The tested transducers were three inductive voltage transformers. The technical specifications of the IVTs are shown on Table II.

Table II. – Inductive voltage transformer specifications.

Output max.	500 VA
Primary Voltage	34.5 kV / √3
Secondary Voltage	115 / √3
Transformation ratio	300
Frequency	60 Hz
Accuracy Terminals 2X1-2X2	0.3P75

4) Reference Transducer

The reference transducer used was a capacitive voltage divider that has a primary voltage of 50 kV. As addressed in section 2, the CVD presents a linear response over a wide range of frequencies. This type of equipment is also recommended in [5] as a reference transducer. The technical specifications of the CVD are shown on Table III.

Table III. – Capacitive voltage divider specifications.

Primary Voltage	50 kV
Secondary Voltage	115
Transformation ratio	434.78
C_1	497 pF
C_2	216,191 pF

5) Comparator

Finally, a Fluke 190-104/S ScopeMeter [12] was used to acquire the secondary voltage signals of the three IVT under test and the CVD. This ScopeMeter has four isolated channels, a bandwidth of 100 MHz and 1.25 GSamples/s of total sampling speed available for the channels.

The complete setup for performing the test is shown in Fig. 4. The power source was placed in another room. Therefore, there were cables connecting its output to the step-up transformers, and the source was controlled remotely by the internet.

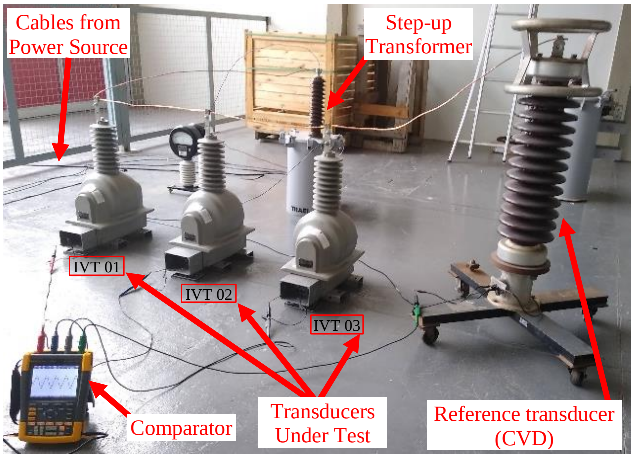

Fig.4. Test set-up at UFU for the frequency response test.

B. Test Methodology

The methodology used to perform the frequency response test followed the procedure described in [5]. However, even though the test procedure oriented the use of voltage signals starting from 15 Hz to the 50th harmonic order, it did not provide details for the frequency step. Therefore, the test was performed with the superposition of sinusoidal signals of all harmonic orders from the 2nd to 50th, which means that the frequency step used was 60 Hz.

It is important to highlight that the transformation ratio of the CVD was not the same as the IVTs, thus instead of comparing the output voltage of the IVTs with the CVD directly, it was necessary to calculate the voltage at the HV terminal of the IVTs. This was performed by multiplying the output of the reference transducer by its transformation ratio, then, this value was used to calculate the real transformation ratio of the IVTs according to (2).

$$TR_{IVT(f)} = \frac{U_{SEC-CVD(f)} \times TR_{CVD}}{U_{SEC-IVT(f)}} \quad (2)$$

where:
$TR_{IVT(f)}$ is the real transformation ratio of the IVT for a given frequency;
$U_{SEC-CVD(f)}$ is the output voltage of the CVD for a given frequency;
TR_{CVD} is the transformation ratio of the CVD;
$U_{SEC-IVT(f)}$ is the output voltage of the IVT for a given frequency.

In the following, the phase shift of the IVTs was calculated according to (3):

$$PS_{IVT(f)} = PA_{IVT(f)} - PA_{CVD(f)} \quad (3)$$

where:
$PS_{IVT(f)}$ is the phase shift of the output voltage of the IVT in relation to the phase shift of the voltage at the HV terminal for a given frequency;
$PA_{IVT(f)}$ is the phase angle of the output voltage of the IVT for a given frequency;
$PA_{CVD(f)}$ is the phase angle of the output voltage of the CVD for a given frequency.

It is important to highlight that before applying (2) and (3), the Fourier series were applied to the acquired waveform. In total, seven periods were acquired at a sample rate of 83.33 kSamples/s, the RMS magnitudes and phase angles of the frequency components of the output voltage were calculated for each 60 Hz period; after, the arithmetic mean was used to calculate the $(U_{SEC-CVD(f)}; U_{SEC-IVT(f)})$ and $(PA_{CVD(f)}; PA_{IVT(f)})$ values.

5. Results and Discussion

After applying (2) and (3) on the voltage measurements of the three IVTs in the range from 2nd (120 Hz) to the 50th (3000 Hz) harmonic order, the graphs presented in Fig. 5

and Fig. 6 were obtained. The graphs present the real transformation ratio and phase shift of the IVTs, respectively. It is appropriated to recall that the rated transformation ratio corresponds to 300.

First, one notes that the most significant discrepancies from the rated transformation ratio occurred at frequencies below 1000 Hz (16^{th} order), and the largest error occurred at the frequency of 540 Hz (9^{th} order), in which the transformation ratios were 312.6, 313.3, and 312.6 for IVT 01, IVT 02 and IVT 03, respectively. However, among all the transformation ratios calculated over the frequency range analyzed, none reached an error higher than 5% of the rated transformation ratio.

Moreover, one notes that IVT 03, in general, has a lower transformation ratio than the others. However, the frequency response of the three IVTs behaves similarly as shown in Fig. 5.
In terms of the phase shift, as shown in Fig 6, the IVTs presented small variations, yet no one reached a phase shift error higher than 5º. Furthermore, one notes that the phase shift tends to increase negatively as the frequency increases.

Even though the harmonic distortion indicators do not consider the phase angle in their calculation, when dealing with the sharing of harmonic responsibilities, the need for precise phase angle measurements becomes evident.

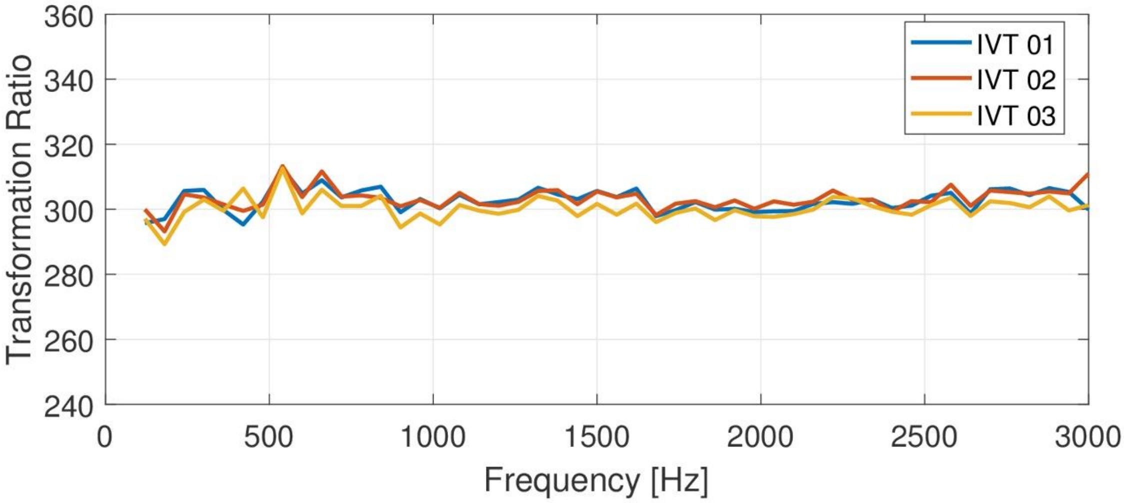

Fig.5. Transformation ratio of the three IVTs under test.

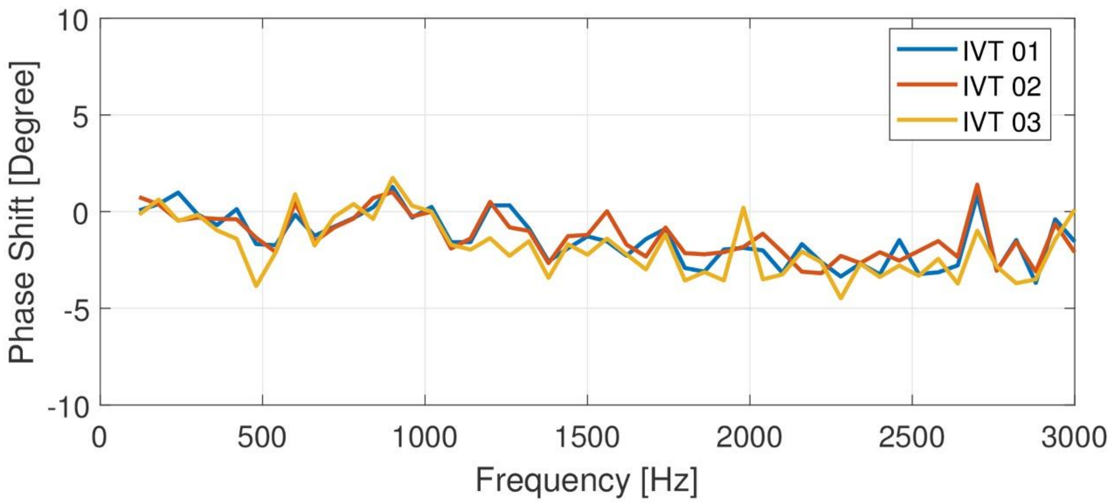

Fig.6. Phase shift of the three IVTs under test.

6. Conclusion

The main goal of this paper was to perform the frequency response test on three MV IVTs. Consequently, to achieve this goal, a laboratory setup was implemented, enabling the IVTs to be supplied with rated fundamental voltage, as well as to control the harmonic content as presented in section 4. The step-up transformer used was able to deliver the nominal voltage to the ITPs and the power source was capable of controlling the harmonic content superimposed on the fundamental voltage. The only difference was found in the starting frequency, which corresponded to 60 Hz instead of 15 Hz. Therefore, the implemented laboratory setup achieved the proposed objective. Moreover, the implementation of this test set-up at UFU allows for the performing of frequency response tests on other transducers up to 20 kV.

Furthermore, based on the results for the frequency response test, the IVT tested went on to present transformation ratios and phase shifts with errors lower than 5% and 5º, respectively. However, since the frequency response of the IVTs is known, the compensation of their measurements is highly recommended when the transducers are used for measuring voltages to determine the responsibility sharing of harmonic voltage distortions, since the methodologies demand high accuracy of the measurements, both magnitude and angle, for obtaining a reasonable result.

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