energies

MDPI

Article

Evaluation of the Accuracy and Frequency Response of Medium-Voltage Instrument Transformers under the Combined Influence Factors of Temperature and Vibration

Mohamed Agazar *, Daniela Istrate and Patrice Pradayrol

LNE (Laboratoire National de Métrologie et d'Essais), 1 Rue Gaston Boissier, 75015 Paris, France; daniela.istrate@lne.fr (D.I.); patrice.pradayrol@lne.fr (P.P.)

* Correspondence: mohamed.agazar@lne.fr

Abstract: Instrument transformers are largely used to measure voltages and currents in public electricity networks. Their performance is essential for Power Quality measurements. Tests and procedures to estimate the effect of single influence factors are performed according to current standards. However, the instrument transformers are exposed simultaneously to more than one factor. The standardized procedures for their characterization with combined influence factors are under construction in Europe. The work in this paper is focused on the development of a new set-up for the determination of the accuracy and frequency response of medium-voltage transformers within the combined influence factors of temperatures and vibrations. The test set-up includes a platform for the combination of temperature and vibrations, a generating system for harmonics up to 9 kHz superposed with 35 kV, 50 Hz voltage and a reference measuring system. The results of several tests carried out on a 35 kV/100 V/50 Hz voltage transformer in the presence of these influence factors are discussed in this paper. They show that the accuracy and frequency response of the voltage transformers are more influenced by temperature than by vibrations.

Keywords: accuracy; frequency response; instrument transformer; combined; temperature; vibration; medium voltage

check for updates

Citation: Agazar, M.; Istrate, D.; Pradayrol, P. Evaluation of the Accuracy and Frequency Response of Medium-Voltage Instrument Transformers under the Combined Influence Factors of Temperature and Vibration. *Energies* **2023**, *16*, 5012. https://doi.org/10.3390/en16135012

Academic Editors: Cheng-I Chen and Yeong-Chin Chen

Received: 22 May 2023
Revised: 22 June 2023
Accepted: 26 June 2023
Published: 28 June 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

AC electrical power transmission and distribution networks have been massively developed for industrial and societal needs since the end of the XIXth century. However, over the last two decades, changes have appeared. The emergence of quantum and digital technologies has led to the development of new renewable energy sources [1,2] and energy storage systems (photovoltaic panels, wind turbines, fuel cells, batteries, etc.). Additionally, the massive arrival of power electronics in much traditional equipment (lighting, power supply of various appliances, etc.) or new uses (electric vehicles, decentralized production, etc.) generates a considerable increase in the level of disturbance in the AC networks.

Instrument transformers (ITs) are used to transform the voltage or the current between its primary and secondary terminals, ensuring safe electrical isolation between both terminals. These high-accuracy electrical devices are installed on the high- and medium-voltage (HV and MV) electrical networks and are often used to measure voltage or current with impact on energy management. Thus, ITs are exposed to the current environment of smart grids and the existing power quality phenomena [3]. Their characterization in conditions as close to reality as possible is necessary and requested [4].

Inductive voltage transformers are designed to respect their accuracy class in conditions defined by the family of standards IEC 61869 [5–7]. The effect of several quantities, such as burden, temperature, magnetic and electric fields produced by adjacent phases and the proximity effect, is considered. However, only one quantity is evaluated at a time. The simultaneous presence of different influence factors often occurs on-site and can lead to an

increase or decrease in IT errors. Additionally, the installed ITs are exposed to the distorted signals flowing through the electric networks. How much confidence can we have in the indications of these transformers? Neither the current standards nor the publications in this field provide indications on the performance of ITs or on the specific tests to be performed in the presence of combined influence factors.

In order to increase knowledge and bring clarification on these subjects, a European project started in 2020, the EMPIR 19NRM05 IT4PQ project, focused on the characterization of ITs used for PQ measurements [8,9]. The work presented in this paper was performed within the project framework. It focuses on the influence of three combined factors: temperature, vibrations and harmonics, on the performance of a medium-voltage inductive IT. Harmonics are analyzed from two points of view: as an influencing factor and as a parameter to measure.

The novelty of the presented work lies in the realization of a complete system allowing the study of combined factors of influence on the performance of an inductive medium-voltage instrument transformer. Temperature constraints, vibrations and harmonics are applied during the operation of the transformer when it is energized. Indeed, the current versions of international standards in the IEC 61869-X series about IT testing take into account the effect of several influence quantities but do not take into account the influence of vibration as an influence factor. In fact, ITs are usually operating in locations subject to vibration produced by different sources (wind turbines, traffic roads, railroads, power transformers, etc.). Generally, the vibration tests are usually performed without powering them, only to validate the mechanical structure. Vibration as an influence factor has never been studied in the past. At the European level, there is a lack of a platform able to combine high voltage and vibrations. The developed platform will be available for industries to test their ITs at the fundamental frequency of 50 Hz and at PQ measurements up to 9 kHz in the presence of vibrations but also combined with temperature, which is one of the most important parameters to handle. In this paper, a medium-voltage IT is tested, and it is demonstrated that at 50 Hz, the influence of temperature is more visible than the vibration. At PQ measurements, it is demonstrated that the vibrations influence the frequency response of the voltage IT at very low temperatures. This last piece of information has to be taken into account by bodies dealing with grid PQ measurements.

The paper is structured as follows: Section 2 describes the whole test platform with a focus on the system used to generate harmonics up to 9 kHz and superpose them with the 50 Hz high voltage. It also describes the test conditions (applied temperature profile, vibration parameters and generated harmonics); Section 3 presents the voltage IT characterization results; and Section 4 concludes this paper.

2. Theoretical Model of ITs in the Presence of Vibration and Temperature

Mechanical vibrations, depending on how the internal structure of the IT is designed, could lead to the displacement of the windings and the core or to the separation and compression of the turns. Any change in the internal mechanical structure (windings and core) ultimately affects the stray capacitances of the IT, leading to a change in its frequency response. In the worst cases, the vibration could produce friction on the magnetic core, affecting its integrity and hence its magnetizing inductance and reducing its life. Excessive vibrations could be seen as a major cause of winding displacement and deformation.

The frequency response of ITs is affected by the stray capacitances as presented in Figure 1, which represents the equivalent circuit of the transformer. There are three types of stray capacitance: The capacitances between turns (Cnp for the primary winding and Cns for the secondary winding, respectively). The internal capacitance of the primary and secondary windings, which are Cp and Cn, respectively. The capacitances between the windings are, respectively, Cb and Ch. In Figure 1, lp and ls are the loss-free coils of the windings, rp and rs are the resistance of the windings, Rp represents the iron and core losses, and "lm" is the magnetizing inductance. At industrial frequencies, the ratio between the primary and secondary voltages is the ratio between the number of turns

between the primary and secondary windings. At frequencies up to a few kilohertz, the stray capacitances could affect the frequency response of the IT.

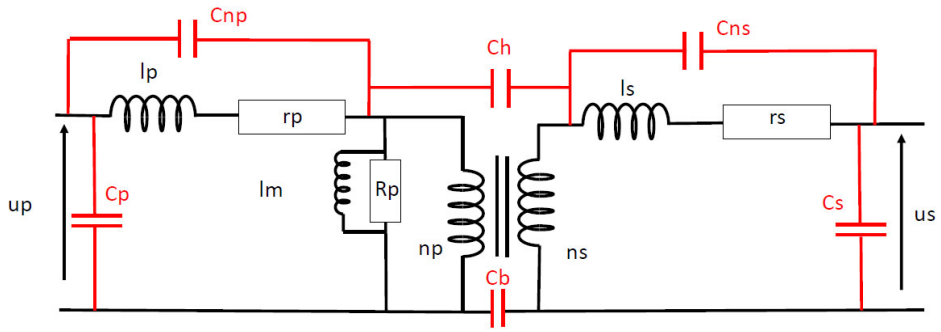


Figure 1. Equivalent circuit of a voltage transformer for frequencies up to a few kilohertz.

The model in Figure 1 could only be valid up to a few kilohertz; for higher frequencies, it is not sufficiently explicit, particularly at the structural scale of the windings. Therefore, a model based on a "discretization" of the windings is preferable. Figure 2 shows that it takes into account all the influences: The specific inductance of each turn, the mutual induction between each turn, the winding resistance, the capacitance between each turn, and the capacitance between each turn and the ground. Since the coil is a continuous wire, the model is composed of a chain of elementary cells, with each cell representing a turn.

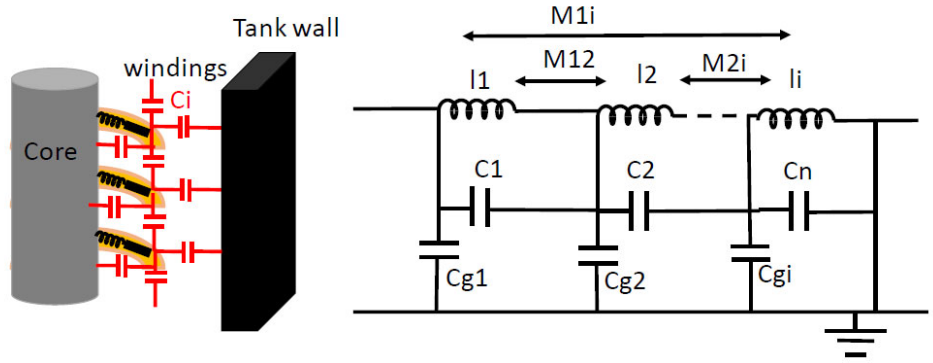


Figure 2. Equivalent circuit of a voltage transformer at very high frequency.

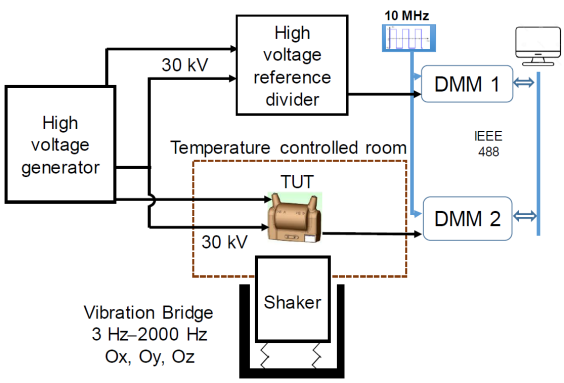
Any interaction, displacement, separation and compression of these successive elements will lead to a modification of the stray capacitance and then the frequency response of the ITs. Axial vibrations will separate or compress the turns; radial vibrations will separate the turns from the core; and vectorial vibrations will produce a complete deformation of the winding.

Regarding the temperature, all the elements constituting the transformer are subject to a change in their electrical properties with the change in temperature. For example, passive components such as resistances, capacitances and inductances are temperature-dependent. The permeability of the magnetic core and the permittivity of the insulating materials (oil, epoxy, etc.) have electrical properties that change with temperature. When designing the mechanical structure with different materials, thermoelectric effects such as the Peltier effect and the Seebeck effect could appear inside or outside the IT, especially where different materials are connected together. As with all electrical devices, a fraction of energy is transformed into heat, producing a rise in IT temperature. For all these aspects, the temperature is one of the influence parameters that is not easy to handle. IT manufacturers have put in a lot of effort to increase the performance of IT at extreme temperatures by using adequate materials with low-temperature dependency, adequate mechanical structures and temperature compensation techniques.

3. Measurement Set-Up and Testing Platform

3.1. Principle

The combined temperature, vibration and harmonic measurement setup is presented in Figure 3. The traceable calibration of IT is carried out by comparison with a standard high-voltage divider. The secondary voltages are measured using two accurate, synchronized digitizers. The measured quantities for the fundamentals and harmonics are the ratio error (Equation (1)) and the phase displacement (Equation (2)). A first calibration of the Transformer Under Calibration (TUT) is performed with sinusoidal waveforms in a controlled environment at (23.0 ± 0.5) °C. Then, its performance is evaluated in the presence of temperature, vibration and harmonic influence factors. A climatic chamber with a 1.0 m^3 volume and controlled temperature and humidity variation is used for the tests. Only the TUT is placed inside the climate chamber, which is installed on a mobile rank.



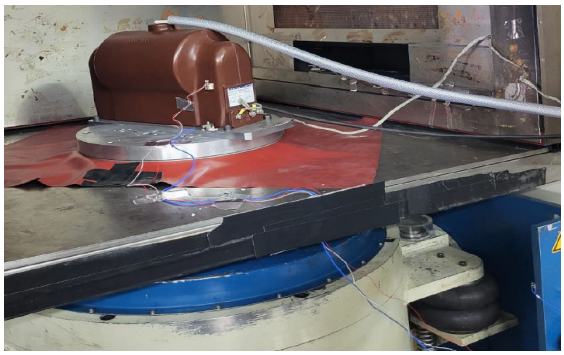
(**a**)



(**b**)



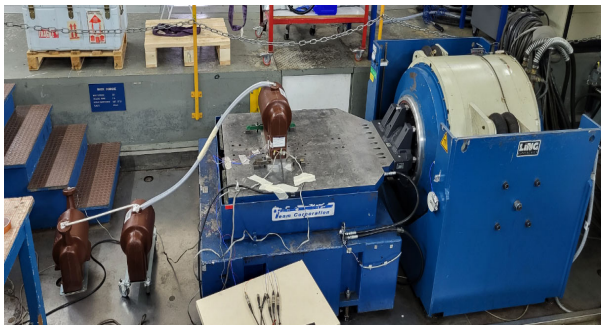
(**c**)



(**d**)



(**e**)



(**f**)

Figure 3. Combined temperature, vibration and harmonic measurement set-up; (**a**) Description of the measuring system; (**b**) An overview of the whole platform, including the vibrating bridge, the temperature

chamber, the high voltage assembly, and the low voltage measuring system; (**c**) Shows the set-up used for the test at 50 Hz; it includes the transformer under test inside the temperature chamber placed on the top of the vibrating bridge, configured with vertical vibrations. The outside transformers are the step-up transformers for the generation of 50 Hz, and the second one is the reference transformer. Both are below the ambient temperature of about 23 °C; (**d**) Two accelerometers are fixed on the transformer for the measurements of vibrations, and a thermocouple is used to measure the temperature of the transformer; (**e**) Shows the measuring system composed of two sampling voltmeters from keysight Type 3458A associated with Labview v.2020 software, one to process the signal from the transformer under test and one to measure the signal from the reference transformer. Both 3458A are synchronized with an external generator, a TTL generator; (**f**) Shows the test of the transformer under horizontal vibrations without the temperature chamber.

For the vibration tests, an electrodynamic LDS shaker was used. The shaker can vibrate with frequencies ranging from 3 Hz to 2 kHz, generate peak-to-peak displacements from 25 mm to 75 mm, and exert a force from 27 kN to 80 kN. Sinusoidal vibrations were applied along three axes (x, y and z). The climatic chamber, with the TUT inside, was placed over the electromagnetic shaker during the vertical vibrations. The shaker position changes for horizontal vibrations such as those that move the platform hosting the TUT.

3.2. Measuring System

The measuring system is composed of a high-voltage divider associated with two accurate, synchronized sampling voltmeters (DMM 1 and DMM 2). When the measurement is performed at only 50 Hz, a standard transformer is used, and for frequencies up to 9 kHz, a capacitive divider is used. The LNE voltage dividers are characterized in terms of temperature coefficient, voltage coefficient and frequency response.

The uncertainty of the calibration of the standard divider is a function of frequency f. It is equal to (0.13 × f + 20) ppm for the ratio error (ppm is a relative value, which means parts per million; 1 ppm = 1 μV/V) and (0.13 × f + 20) μrad for the phase displacement. For the fundamental frequency, the uncertainties are 26.5 ppm for the ratio error and 26.5 μrad for the phase displacement, respectively. At 9 kHz, the uncertainties are 0.11% for the ratio error and 1.1 mrad for the phase displacement.

The sampling voltmeters are the 3458A type from Keysight. They were configured in DC sampling mode, which allows the digitization of signals with a sampling rate of up to 100 kHz. In order to avoid errors resulting from the approximation of an infinite signal by a finite signal when the Discrete Fourier Transform is processed, the signal was sampled over a whole number of periods to satisfy the equation fs = (N/M) × fv. Where fs is the sampling frequency, fv is the frequency of the signal, M is the number of periods, and N is the number of samples. The sampling frequencies were varied depending on the harmonic content to be measured in order to have the best accuracy. Frequencies of 6.4 kHz, 12.8 kHz and 25.6 kHz are used to cover the range of harmonics up to 9 kHz. The resolution of the sampling voltmeters was kept at 18 bits in order to allow a very low voltage quantification error. Each measurement was repeated 10 times to reduce the random errors. The accuracy of the ADCs was checked in terms of voltage ratio and phase error before the measurements.

The temperature inside the controlled room is measured using a calibrated thermocouple fixed on one of the sides of the TUT. Two accelerometers are also fixed on the TUT to check its vibration frequency. Figure 3d indicates their locations.

The measured quantities are the ratio error ε_n and the phase displacement φ_n. They are defined, respectively, by:

$$\varepsilon_n = (kr \cdot V(Sn) - V(Pn))/V(Pn) \quad (1)$$

$$\varphi_n = \varphi(Sn) - \varphi(Pn) \quad (2)$$

where:

ε_n is the ratio error at the frequency n,
kr = Vp/Vs is the rated scale factor of the TUT,
V(Pn) is the value of the primary voltage at the frequency n,
V(Sn) is the value of the secondary voltage at the frequency n,
φ_n is the phase displacement defined as the phase difference between the secondary V(Sn) and primary V(Pn) voltages. The phase displacement is considered positive when the secondary voltage phasor leads the primary voltage phasor.

The frequency varies from 50 Hz (n = 0) to the highest studied harmonic frequency 9 kHz (n = 180).

3.3. Generation Systems

An important aspect studied and presented in this paper concerns the performance of an inductive voltage IT in the presence of harmonics as well as its frequency response. Research work was performed by the consortium of the IT4PQ project in order to define the maximum amplitudes of harmonics and interharmonics up to 9 kHz present in MV grids. This research is based on the literature [10–12], the expressed need by the standardization committees, and the transient phenomena currently present in medium-voltage grids. Table 1 presents these amplitudes for voltage transformers.

Table 1. Suggested maximum amplitude of harmonic components up to 9 kHz.

Harmonic Order	Relative Amplitude to the Fundamental of 30 kV
2 to 15	10%
16 to 50	5%
51 to 180	2%

The IT4PQ project aims to study IT performance up to the same frequency range. Generating harmonics and superposing them with a 30 kV, 50 Hz supply voltage is not a trivial task [13]. On MV grids, the generation of harmonics at frequencies up to 9 kHz occurs in an uncontrolled manner. In order to evaluate the ITs under controlled conditions, there is a need to develop generators that are not yet available on the market. National metrology institutes around the world have put in big efforts to improve generation systems up to at least 9 kHz. Typically, the best NMI facilities for voltage generation do not go beyond 10 kHz and have very small amplitudes (a few tens of volts) superposed to 35 kV and 50 Hz fundamental. Indeed, the most popular devices are high-voltage amplifiers able to generate up to 35 kV/50 Hz, but due to their limited bandwidth, they cannot supply high amplitudes at high frequencies. Validated and stable generators remain an important tool and are considered an essential part of the test circuit. The generation set-up has to be designed so as to ensure the safety of the devices by avoiding the propagation of harmonics in the 50 Hz generation part. Two methods are developed: one for generating voltage harmonics up to 4 kHz and another for up to 9 kHz.

Two-generation systems were developed to study the performance of the TUT when a distorted signal is applied: a 50 Hz fundamental frequency superimposed with one harmonic that might go up to 9 kHz. A first set-up is used to generate harmonics up to 4 kHz and relies on two step-up transformers of 100 V/35 kV series connected, as illustrated in Figure 4. An audio amplifier with 20 kHz bandwidth and 15 A/120 V output power pilots one voltage transformer to generate the target harmonics. It supplies pure sinusoidal signals with very low total harmonic distortion (typically lower than 0.1%). The audio amplifier is practically suitable for the generation of controlled high-voltage harmonics, or interharmonics when it is associated with a step-up transformer. For the generation of the voltage up to 35 kV and 50 Hz, a power amplifier of type APX160 is used to supply and pilot the second step-up transformer. Figure 4 illustrates the principle of this first method. An RC divider was used to acquire the signals; it has a ratio of 1000 and a flat frequency response up to several hundreds of kHz. Its input impedance is equivalent to a resistor of

100 MΩ in parallel with a capacitance of 10 pF. This low impedance is needed in order to keep the capacitive load as small as possible.

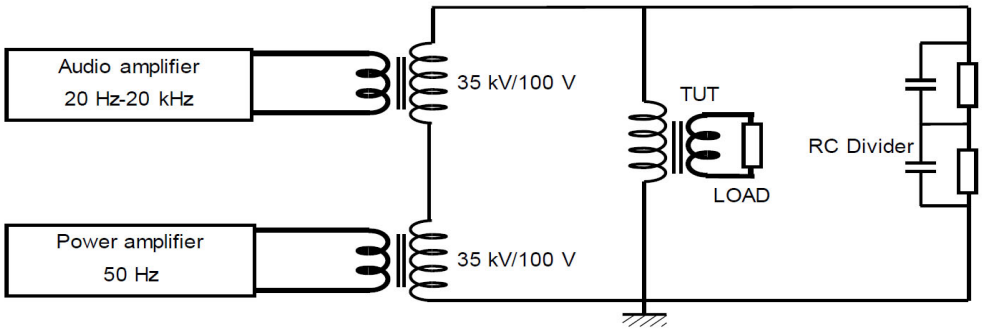


Figure 4. Generation set-up using two step-up voltage transformers arranged in series.

The harmonic generation capabilities of the first generator are presented in Table 2. According to the requirements mentioned in Table 1, the objective was achieved up to the 50th order and partially covered for orders up to the 100th. It was observed that a relative level of 10% is successfully tested up to the 60th order and 3.3% up to the 84th. Above the 84th order, the capability of generation decreases dramatically, e.g., 0.33% for the 96th order. These limitations at high frequencies are essentially due to the maximum permissible admitted secondary current of the step-up transformer, which was 10 A RMS. An example of a generated waveform is presented in Figure 5. It represents the output of the signals measured at the output of the voltage divider via a Labview v.2020 software algorithm and FFT signal processing for the calculation of the quantities to be measured.

Table 2. Generation capabilities of the first generator.

Harmonics Order	Relative Amplitude to the Fundamental of 30 kV
2 to 60	10%
60 to 84	3.3%
84 to 90	1%
90 to 96	0.33%

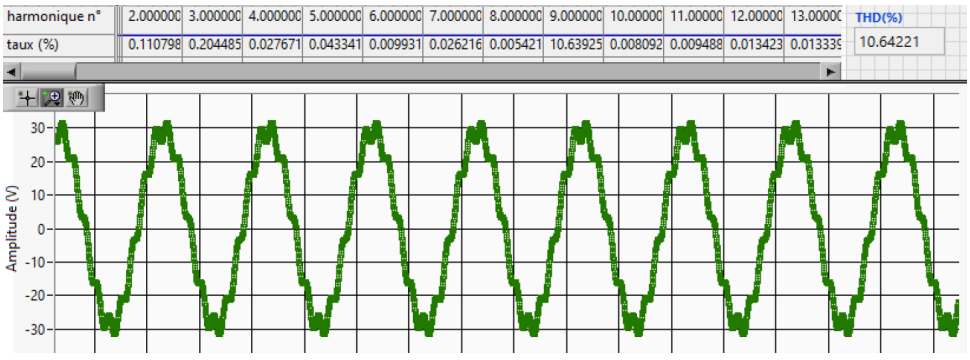


Figure 5. Example of the signal generated by the first generator: 20 kV RMS superimposed with the 9th order having a relative amplitude of 10.6%.

A second generator was set in order to increase the amplitude of the harmonics above the 84th order. This one, used to generate harmonics with frequencies between 4 kHz and 9 kHz, relies on a paralleled arrangement of two generators, according to Figure 6. The 50 Hz high voltage (30 kV) is produced with the same devices as in the first set-up: the APX160-6 kVA amplifier and the step-up transformer. The harmonics from 4 kHz to 9 kHz are generated using a high-voltage amplifier, the TREK PZD2000A, able to deliver peak

voltages up to ±2 kV for frequencies up to 100 kHz and peak currents up to ±200 mA. Two active filters are added in order to protect each generator from the other. A high-voltage capacitor C1, 3 nF/50 kV, is used on the amplifier side. It forms, with the output impedance R1 of the amplifier, an R1C1 high-pass filter with a cutoff frequency in the range of several tens of kHz. A resistor R2 with a value between 100 kΩ and 500 kΩ and a capacitor C2 of 10 nF/50 kV are used to protect the transformer from the high-frequency components. They form a low pass filter with a cut-off frequency in the range of tens of hertz.

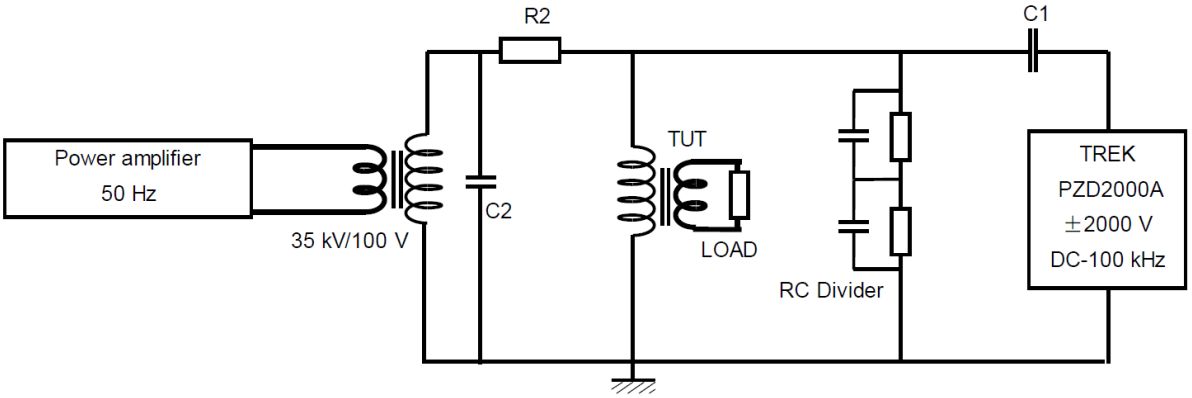


Figure 6. Generation of harmonics up to 9 kHz using two generators arranged in parallel.

The possibilities of this second generator are presented in Table 3. The maximum amplitudes of the harmonics between 4 kHz and 9 kHz depending on the fundamental amplitude. At 20 kV RMS and 11 kV RMS, harmonic amplitudes of 2% (400 V) and 9% (1000 V) were achieved, respectively. At 30 kV RMS, the harmonic amplitude is 1.5% and responds to the objective mentioned in Table 1. This outstanding performance could be enhanced significantly. Indeed, the voltage quantities that might be generated with the second generator depend on the impedance of the transformer under test and the maximum current generated by both generators. Despite using a high-pass filter on the transformer side, there remains a residual high-frequency voltage on the primary side of the transformer, creating resonance phenomena and current consumption. One possible solution is to increase the value of the resistor R2 and use a step-up transformer with higher voltage levels to compensate for the voltage drop at 50 Hz in R2.

Table 3. Typical amplitude of harmonics between the 80th order and 9 kHz relative to the fundamental amplitude.

30 kV RMS	20 kV RMS	11 kV RMS
1.5%	2%	9%

An example of a generated waveform is presented in Figure 7. It represents the signals measured at the output of the voltage divider via a Labview v.2020 software algorithm and FFT signal processing for the calculation of the quantities to be measured.

3.4. Definition of the Test Conditions

The requirements for ITs are specified in the IEC 61869 series for temperature intervals varying from −5 °C to +40 °C. This interval is wider, from −25 °C to +55 °C, in IEC 60721-3-3 [14] for places without temperature control. Since the possibilities of the LNE test platform allow reaching these extreme temperatures, the chosen test interval was the largest. The voltage transformer under test was placed inside the climatic chamber, where the target temperature was maintained within ±0.5 °C. The applied temperature profile is illustrated in Figure 8 and follows the temperature cycle accuracy test according to [15].

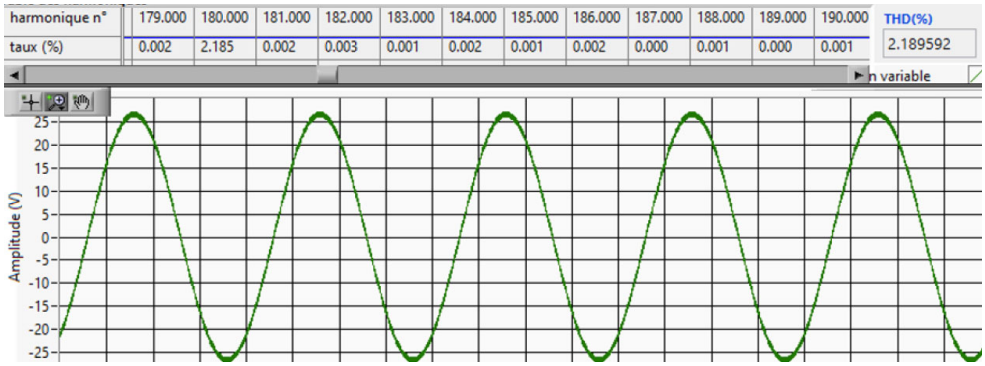


Figure 7. Example of a signal generated by the first generator (18 kV RMS superimposed with the 180th order having a relative amplitude of 2.2%).

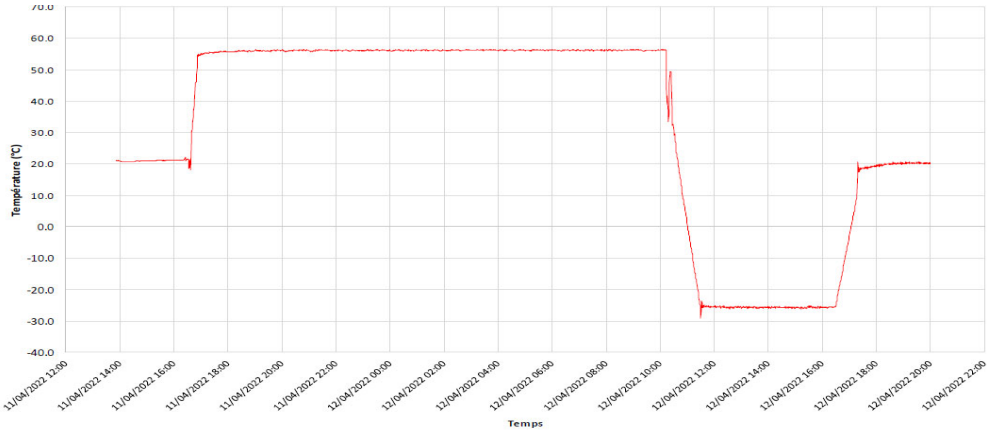


Figure 8. Temperature profile used for the characterization of the voltage transformer under this study.

More challenges appear when designing the tests on ITs in the presence of external vibrations since no procedure or particular specifications exist. Several sources [16–22] were analyzed in order to identify the most appropriate environmental factors. The main parameters that were varied and studied in this work are the frequency, acceleration and orientation of an external vibration to which a transformer is exposed.

The IEC 61869 series indicates seismic vibrations [5], which are usually neglected due to the low vibration frequency of 0.1 Hz. The frequencies of road traffic vibrations are situated between 2 Hz and 6 Hz [16], with a maximum of 30 Hz. The wind turbines generate similar few Hz vibrations [17], depending on the speed of the wind. Higher-frequency vibrations exist in railway applications [18], with vibration frequencies up to 150 Hz. During switching high-voltage circuit breakers, vibration frequencies up to 150 Hz could be generated. Other information on vibration parameters as test factors exists in different standards, defining the environmental test conditions [19–22] for civilian applications and dealing with vibration frequencies up to 150 Hz.

In this work, the frequency of vibration was then varied from 3 Hz to 150 Hz to cover a large range, applied following the three orientations with respect to the Its, and with a maximum acceleration of 4.90 m/s^2. Mechanical vibrations of the transformers are among the factors likely to occur on-site. The main parameters that characterize vibrations are:

- The frequency (in Hz) corresponds to the number of oscillations per second;
- The orientation is vertical (Z) or horizontal (longitudinal X or transversal Y);
- The amplitude of the movement felt by the exposed object is evaluated by the acceleration (in m/s^2).

The study of existing standards and published work [16–22] correlated with the purpose of this study and led to the generation of sinusoidal vibrations with frequencies of 3 Hz, 20 Hz, 100 Hz and 150 Hz. Thus, wide sources are covered, from road traffic vibrations up to railway or circuit breakers, among the typically generated ones. The vibrations were applied in the following three orientations: vertical, longitudinal and transversal. The tests described in this paper are performed with accelerations of vibrations varying between 0.98 m/s^2 and 4.90 m/s^2. The acceleration values are provided as a factor of the gravitational acceleration, g = 9.81 m/s^2. The values were 0.1 g, 0.3 g and 0.5 g, respectively. A Flowchart describing the methodology used to test the accuracy of the TUT at 50 Hz under temperature and vibration is presented in Figure 9.

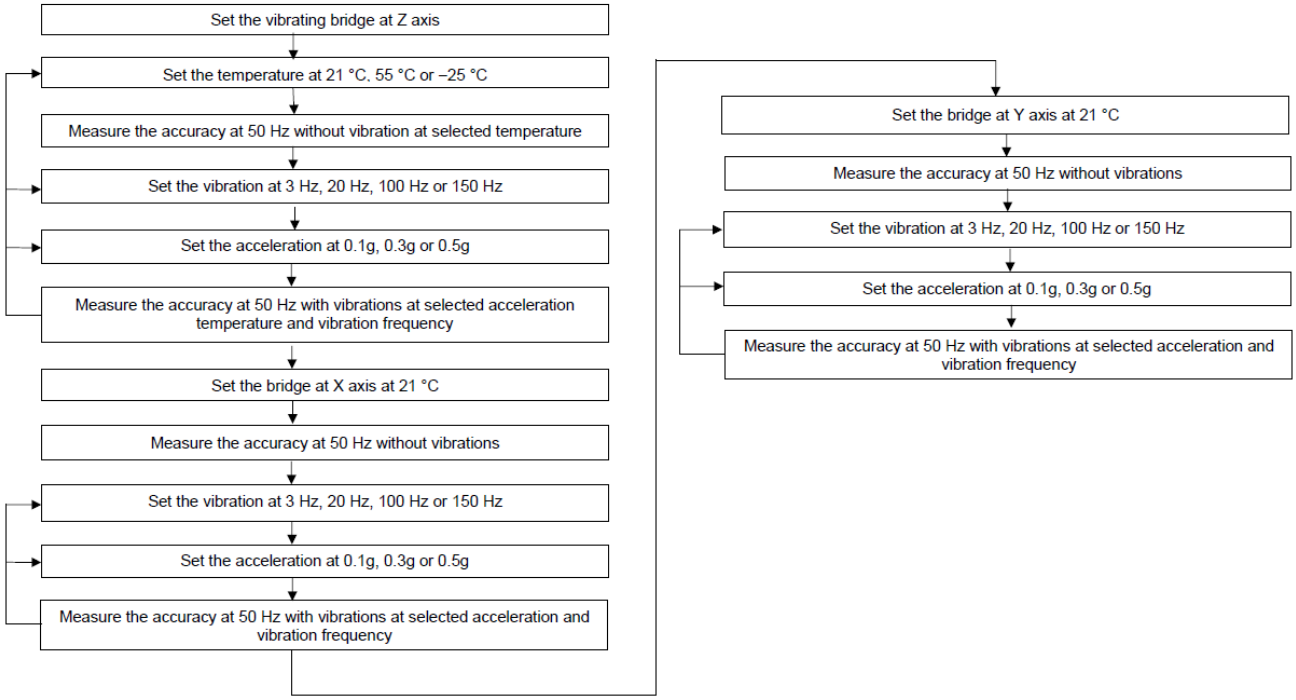


Figure 9. Flowchart describing the methodology used to test the accuracy at 50 Hz of the TUT under temperature and vibration.

To study the influence of harmonics combined with temperature and vibration factors, a low-level, high-frequency sinusoidal voltage was superimposed on the 50 Hz high voltage. The amplitude of voltages with frequencies from 150 Hz to 2000 Hz was 5% of the nominal voltage of the tested transformer, while higher frequencies up to 3000 Hz were generated with 3% of the nominal voltage. A flowchart of the methodology used to determine the frequency response of the TUT under temperature and vibration is presented in Figure 10.

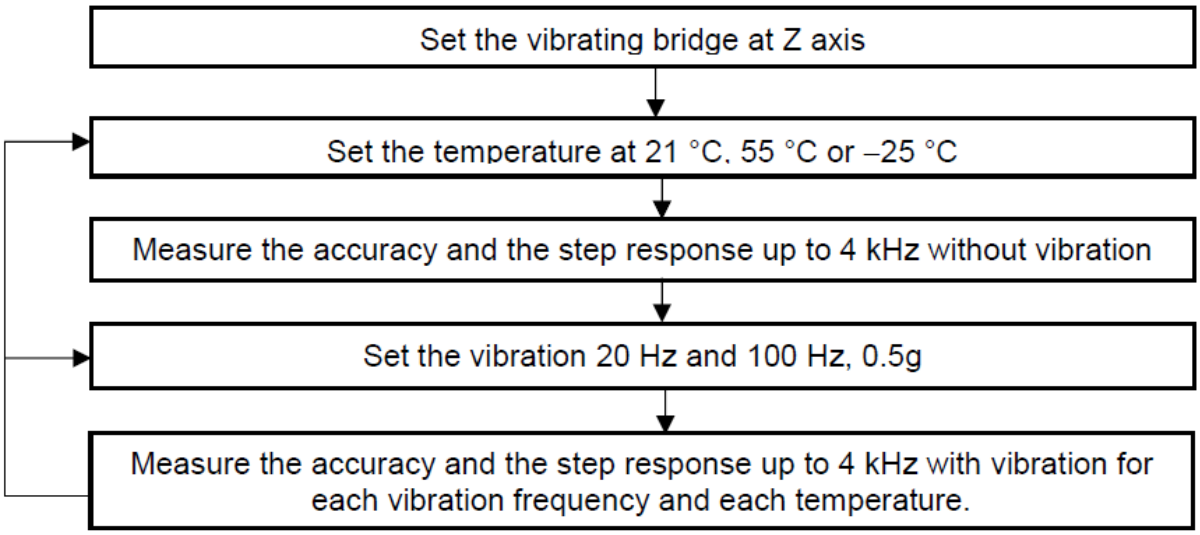


Figure 10. Flowchart of the methodology used to determine the frequency response of the TUT under temperature and vibration.

4. Instrument Transformer Tests

The transformer under test (TUT) is a 1% class and is designed to work in a temperature range of −25 °C to +55 °C. The tests were performed with a resistive burden of 1 VA. The measurement setup was calibrated before every series of tests, and the corresponding corrections were applied. The influence of each factor is analyzed first, followed by the results obtained when combined temperature, vibration and harmonics were generated.

4.1. Influence of Temperature on Accuracy at 50 Hz

The TUT was calibrated at 18 kV, 24 kV and 30 kV for each temperature level. The values of ratio error and phase displacement obtained at 21 °C are considered references, and the variations of the measured quantities from the reference values are listed in Table 4 for the tested temperature. The obtained results, Figures 11 and 12, outline that the highest influence of the temperature on the TUT performance appears at 18 kV and −25 °C. Variations of 650 ppm in ratio error and 254 µrad in phase displacement, with respect to the reference values, are obtained.

Table 4. Ratio error, Δε, and phase displacement, Δφ, deviations from the measurements at 21 °C.

Voltage (kV)	−25 °C		+55 °C	
	Δε	Δφ (µrad)	Δε	Δφ (µrad)
18	$-6.5 \cdot 10^{-4}$	254	$1.4 \cdot 10^{-4}$	1.7
24	$-4.9 \cdot 10^{-4}$	211	$1.3 \cdot 10^{-4}$	0.1
30	$-4.1 \cdot 10^{-4}$	188	$1.2 \cdot 10^{-4}$	0.4

It was also observed that the voltage deviation from 18 kV to 30 kV is more visible at low temperatures. For the ratio error, we observed a voltage deviation of about 275 ppm at −25 °C and less than 30 ppm at 21 °C and 55 °C. For the phase displacement, the voltage deviation is about 90 µrad at −25 °C and less than 40 µrad at 21 °C and 55 °C. These results are in agreement with similar work performed in the JRP IT4PQ [23].

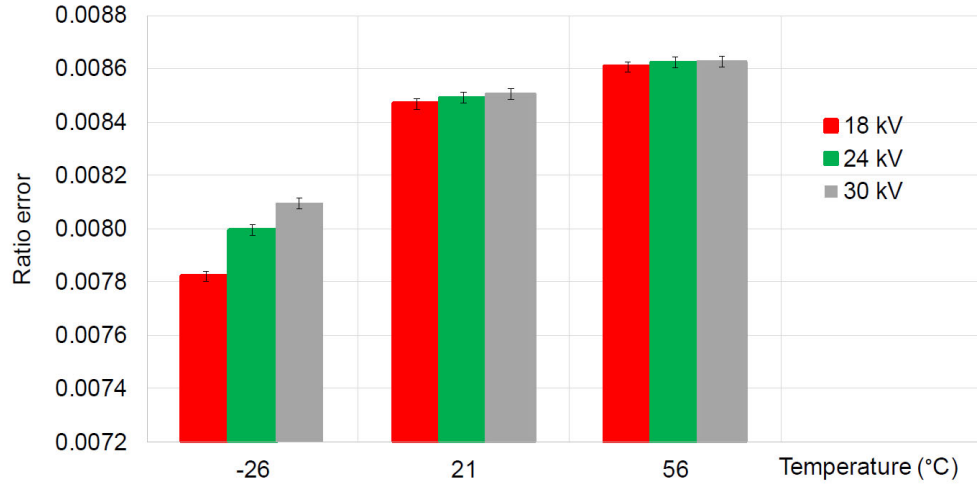


Figure 11. Influence of temperature on the accuracy of the TUT at 50 Hz; Measurement of ratio error.

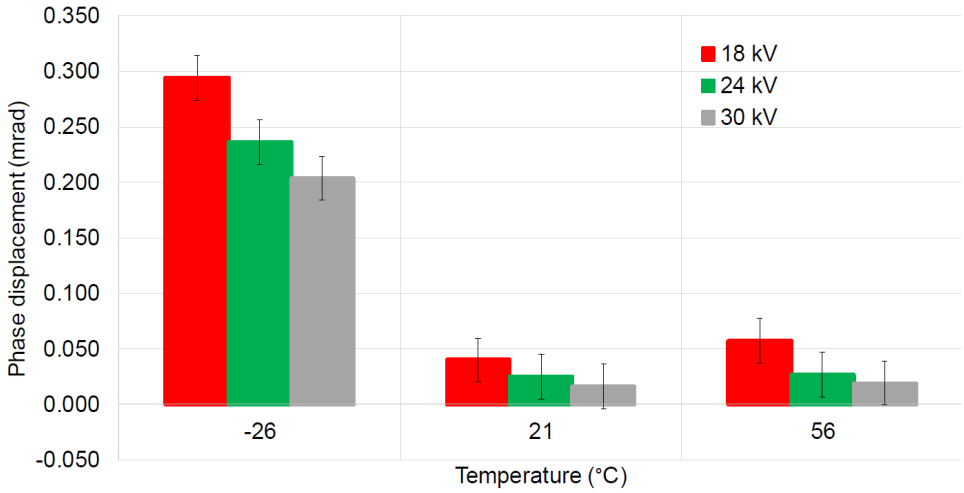


Figure 12. Influence of temperature on the accuracy of the TUT at 50 Hz; Measurement of phase displacement.

The magnetic properties of the materials used to realize the voltage transformers change with thermal and mechanical treatment and with frequency, too. The temperature affects the magnetic properties of materials by varying their electromagnetic parameters like saturation magnetization and magnetocrystalline anisotropy [24]. Thermal compensation techniques that rely on the use of adapted alloys are applied by transformer manufacturers. However, −25 °C remains an extremely low temperature. The deviations obtained reflect both types of changes: internal to the TUT and external, related to the connections and the cable. It is to be noted that the 10^{-4} order deviations increase the errors but are not outside the precision class of the studied transformer.

4.2. Influence of Vibration on Accuracy at 50 Hz

As for the temperature, the measurements without any vibrations are considered the reference for each axis and are compared with the measurements when vibrations are applied. The analysis of the results obtained after varying the three vibration parameters: orientation, frequency and acceleration, did not reveal deviations higher than those produced by the temperature.

The most important deviations are observed when transversal vibrations (along the width of the TUT, *X*-axis) are applied. These variations are shown in Figures 13 and 14 for

two vibration frequencies: 3 Hz and 100 Hz, respectively, but at the same acceleration of 0.5g (m/s^2). These values correspond to the 24 kV, 50 Hz supply voltage of the TUT.

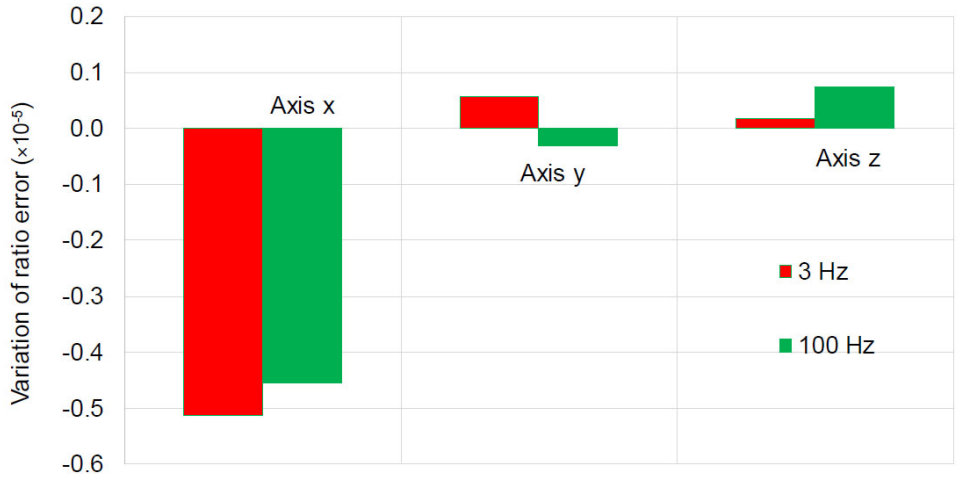


Figure 13. Influence of the axis and frequency of vibration on the accuracy of the TUT at 50 Hz; Results of ratio errors.



Figure 14. Influence of the axis and frequency of vibration on the accuracy of the TUT at 50 Hz; Results of phase displacement.

Their effects are on the order of 50 ppm deviation for the ratio error and 6 µrad for the phase displacement.

4.3. Influence of Combined Temperature and Vibration on Accuracy at 50 Hz

According to the flowchart in Figure 9, the combined temperature and vibrations affect the accuracy at 50 Hz at vertical vibration (*Z*-axis). The influence of both parameters, temperature and vertical vibration, applied simultaneously, can be analysed from Figure 15 for ratio error and from Figure 16 for phase displacement. It can be noticed that the highest deviation from the reference situation (no vibration at 30 kV) is obtained at −25 °C. The ratio error varies by -1.2×10^{-5} from the reference situation when the transformer vibrates vertically at 3 Hz. The impact on the phase displacement is more visible for 100 Hz vertical vibration at −25 °C. The highest difference with respect to the reference situation is −27 µrad. The influence of the two parameters, temperature and vibration, applied simultaneously did not reveal greater effects than when they were applied separately.

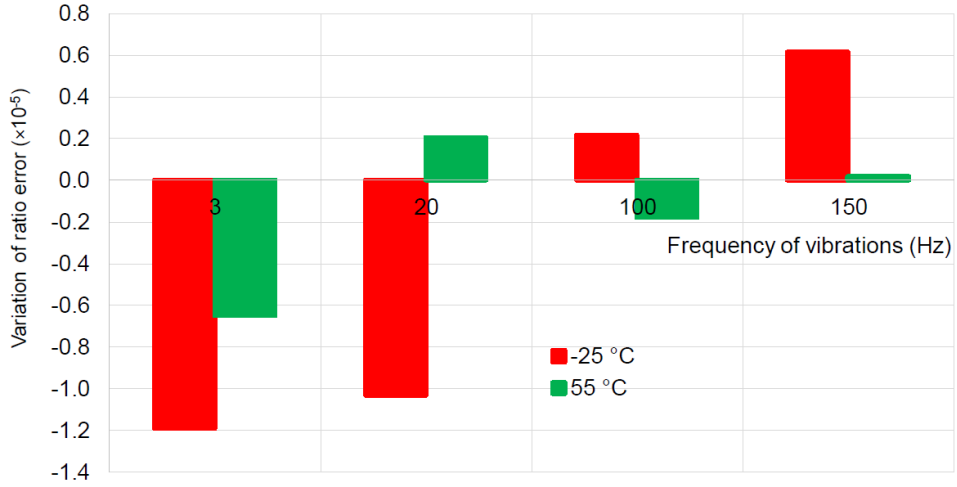


Figure 15. Influence of combined temperature and vibration on the accuracy of the TUT at 50 Hz against vibration frequency and temperature (−25 °C and 55 °C) at 30 kV and 0.5g acceleration; Change of ratio error.

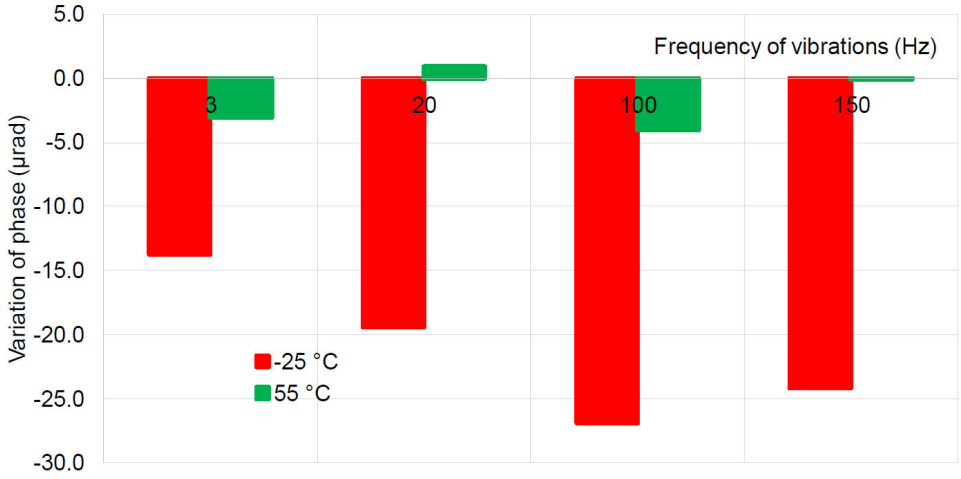


Figure 16. Influence of combined temperature and vibration on the accuracy of the TUT at 50 Hz against vibration frequency and temperature (−25 °C and 55 °C) at 30 kV and 0.5 g acceleration; Change of phase displacement (in µrad).

4.4. Influence of Hamonics on Accuracy at 50 Hz

According to the flowchart in Figure 10, the combined temperature, vibration and harmonics on the accuracy at 50 Hz are performed at vertical vibration (*Z*-axis). The influence of harmonics on the indications of the TUT was determined by calculating the ratio error and phase displacement with the 50 Hz primary and secondary voltages, even if one harmonic existed in the circuit. Several series of measurements were performed with the temperature adjusted at +21 °C, +55 °C and −25 °C. For one temperature, the first measurement was performed without vibrations or harmonics. This measurement is the reference for further comparisons. Then, the shaker was set to generate vertical vibrations at 0.5g (m/s^2) with a 20 Hz frequency. With these settings, several measurements were performed by generating 30 kV, 50 Hz, and one harmonic from 150 Hz up to 4000 Hz with an amplitude of 5% of the fundamental. A new set of measurements was performed similarly while the shaker vibrated at 100 Hz. For each measurement point, the ratio error and the phase displacement were determined. The results are presented in Tables 5 and 6 in terms of variations with respect to the reference measurements. These tables indicate a non-significant influence of harmonics with and without vibrations for the three temperatures. The maximum variation is less than 30 ppm for the ratio error and less than 30 µrad for the

phase shift. These variations do not go beyond the accuracy class of the transformer, and they are probably due to the uncertainty of measurement, which is in the same range. The TUT operation is not affected by the presence of harmonics and vibrations. The performance is slightly different with and without vibration or with and without harmonics. The 3D charts in Figures 17 and 18 summarize the difference between the resulting amplitude and phase with and without vibrations.

Table 5. Difference between the resulting amplitude and phase errors with and without 20 Hz vertical vibrations.

Harmonic (Hz)	−25 °C		21 °C		+55 °C	
	Δε (−)	Δφ (μrad)	Δε (−)	Δφ (μrad)	Δε (−)	Δφ (μrad)
150	2.1×10^{-5}	2.5	2.2×10^{-5}	−10.2	-7.0×10^{-6}	−0.9
250	1.8×10^{-5}	−3.9	2.7×10^{-5}	5.3	6.0×10^{-6}	−1.6
350	1.7×10^{-5}	−22.0	$6. \times 10^{-6}$	11.5	1.0×10^{-5}	3.4
450	7.0×10^{-6}	−17.2	1.3×10^{-5}	17.5	1.3×10^{-5}	11.8
550	-1.7×10^{-6}	13.8	-3.9×10^{-6}	−4.2	1.4×10^{-5}	2.2
650	-9.0×10^{-6}	−8.1	-1.4×10^{-5}	−14.0	2.9×10^{-6}	−18.1
1000	-2.0×10^{-5}	3.6	3.0×10^{-6}	−4.9	2.1×10^{-5}	6.4
2000	-2.3×10^{-6}	18.0	6.9×10^{-7}	−10.1	-9.4×10^{-7}	−8.2
3000	2.4×10^{-5}	−8.9	1.8×10^{-5}	−11.1	-8.9×10^{-6}	−24.4
4000	9.2×10^{-6}	15.5	8.6×10^{-8}	−6.0	2.8×10^{-5}	−5.9

Table 6. Difference between the resulting amplitude and phase errors with and without 100 Hz vertical vibrations.

Harmonic (Hz)	−25 °C		21 °C		+55 °C	
	Δε (−)	Δφ (μrad)	Δε (−)	Δφ (μrad)	Δε (−)	Δφ (μrad)
150	2.4×10^{-5}	−8.9	2.0×10^{-5}	−10.2	2.6×10^{-5}	0.6
250	-6.6×10^{-6}	7.3	1.0×10^{-5}	8.2	1.6×10^{-5}	9.7
350	-9.7×10^{-6}	−20.4	1.2×10^{-5}	0.4	1.6×10^{-5}	2.3
450	1.5×10^{-6}	21.1	7.3×10^{-6}	4.6	1.5×10^{-5}	−26.8
550	2.8×10^{-5}	−2.4	1.6×10^{-5}	−15.4	-3.5×10^{-6}	−8.8
650	-1.1×10^{-5}	9.3	7.4×10^{-7}	8.5	-5.8×10^{-6}	−8.0
1000	-1.9×10^{-5}	3.7	1.5×10^{-5}	−7.5	-1.0×10^{-5}	15.5
2000	2.1×10^{-5}	16.0	1.7×10^{-7}	−4.5	1.1×10^{-5}	−10.2
3000	2.3×10^{-5}	1.8	5.8×10^{-6}	−16.4	-4.8×10^{-6}	5.5
4000	1.3×10^{-6}	−3.3	4.3×10^{-6}	3.3	1.1×10^{-5}	1.1

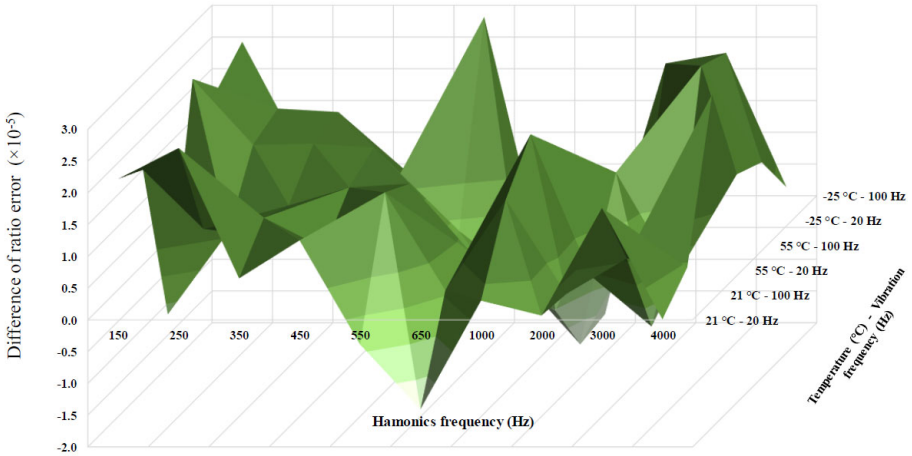


Figure 17. Difference between the resulting amplitude with and without vibrations regarding temperature and harmonic frequency.

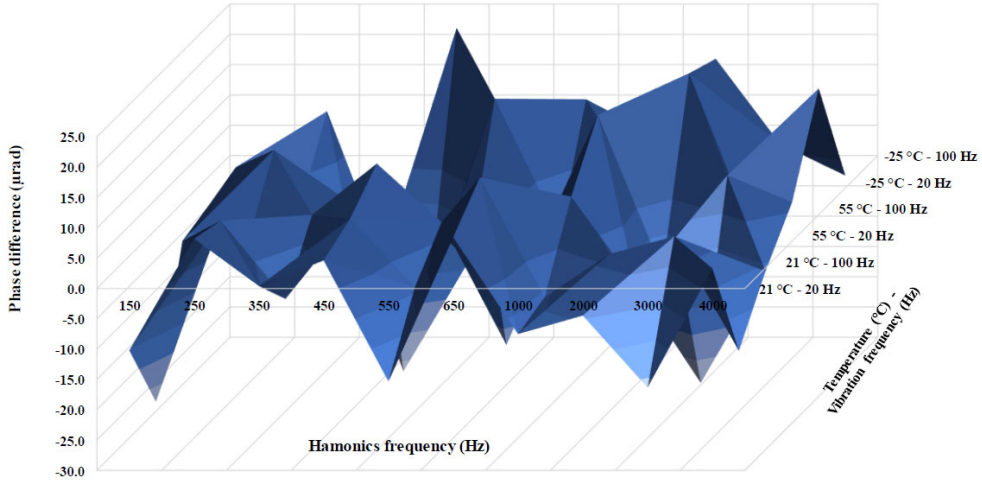


Figure 18. Difference between the resulting phase with and without vibrations regarding temperature and harmonic frequency.

4.5. Frequency Response of the TUT under Temperature and Vibration

The measurements with harmonics were exploited from another point of view: to evaluate the performance of inductive voltage transformers in PQ measurements in the presence of multiple influence factors (temperature and vibrations). In this sense, the sampled secondary voltages of the reference system of the TUT were analyzed by applying the Fourier transform. Both the RMS values of the 50 Hz component of the injected harmonic were determined. For each acquisition, the ratio error is computed two times according to Equation (1): the fundamental-based ratio is calculated with the 50 Hz component, and the harmonic-based ratio is calculated with the amplitude of the generated/measured harmonic.

The results present the deviation of the harmonic-based ratio with respect to the fundamental-based ratio. The measurements were performed at the same temperatures as previous tests. The shaker vibrations had 20 Hz and 100 Hz applied vertically or longitudinally with respect to the TUT. The amplitude of the fundamental was 30 kV, and the amplitudes of the generated harmonics were 1.5 kV up to 4 kHz. As already observed for inductive voltage transformers [12,25], the deviation of the ratio becomes larger with the increase in the frequency of the injected harmonic, no matter the environmental temperature or the frequency of vibrations (Figure 19). It can be noticed that deviations less than 1% appear for harmonics with frequencies less than 650 Hz. For frequencies up to 4 kHz, an important ratio error deviation of −18% was observed.

The influence of vibrations on the frequency response of the TUT was not clearly visible at ambient and high temperatures, as shown by the results in Figure 19. The differences between the results obtained at 21 °C and those obtained at 55 °C in terms of ratio errors are within 0.05%, no matter the vibration frequencies. On the contrary, higher variations, a maximum of 0.35%, are obtained between the results at −25 °C and those at 21 °C. Indeed, the green and red curves in Figure 19 show non-linear behaviour when the TUT operates at −25 °C and for low-order harmonics, H3–H13. These observations confirm the first result: the highest influence on the performance of inductive voltage transformers comes from the negative temperature.

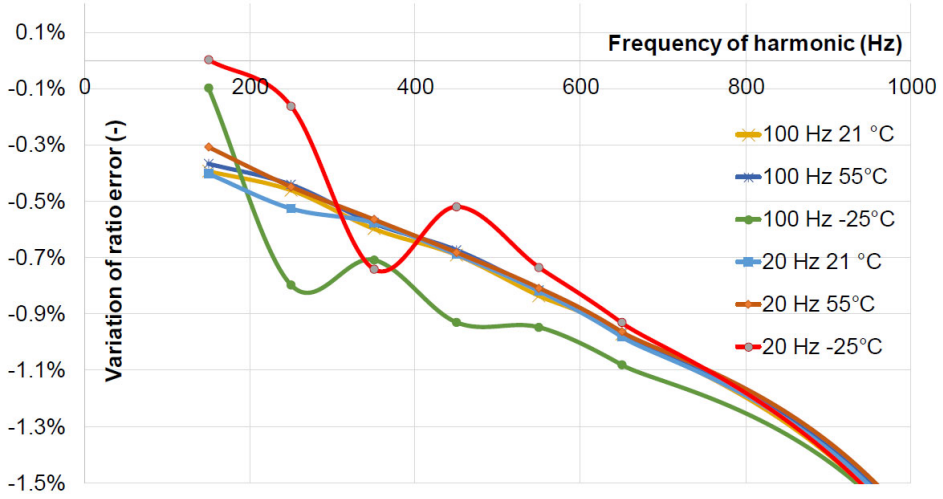


Figure 19. Ratio error variation with respect to the 50 Hz reference error as a function of harmonic frequency in the presence of vibration and temperature constraints.

5. Conclusions

A platform was developed to test voltage instrument transformers when multiple influence factors (temperature, vibrations and harmonics) are applied during the operation of the transformer. Two systems based on voltage transformers piloted by electronic amplifiers and able to generate harmonics up to 9 kHz were realized and used in the laboratory as well as on the test platform. The amplitude levels achieved by these systems are outstanding. The architecture of the generators will be essential for testing laboratories to offer new testing conditions to better assess instrument transformers.

The results indicate that temperature is the parameter with the highest influence on the studied inductive voltage transformer's performance. At low temperatures, the ratio error, the phase displacement, the voltage deviation, and the frequency response of the transformer are strongly affected.

The mechanical external vibrations combined with temperature, as an influence factor, have much less influence; the change in ratio error and phase displacement at 50 Hz depends on the axis of vibration but does not have a strong influence. Changes in the order of tens of ppm for ratio error and tens of μrad phase displacement were observed. The frequency response of the transformer has not been affected by the presence of vibrations either. Variations of the same order were observed also with the presence of harmonics up to 4 kHz.

However, using the studied inductive voltage transformer to measure disturbances present on the supply voltages can be performed up to 650 Hz with increased error (deviation up to 1.1% from the 50 Hz precision). Indeed, several causes explain the increased errors associated with the increased frequency of harmonics. Mainly the saturation of the core material, the skill effect caused by high-order harmonic current, the AC resistance loss in the transformers and the stray impedances.

The study allowed for the creation of new facilities for instrument transformer testing with multiple external influence factors (temperature, vibration and harmonics).

Author Contributions: M.A.: Design of the reference measurement set-ups. Development of the generation systems. Carry out performance tests with separate and combined influence factors: vibrations and temperatures. D.I.: Elaboration of test procedures. Carry out performance tests with separate and combined influence factors: vibrations and temperatures. P.P.: Managing the electromagnetic shaker and climatic chamber. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [European Metrology Programme for Innovation and Research], Funder ID [10.13039/100014132] grant number [19NRM05 IT4PQ], co-financed by the Participating States, and from the European Union's Horizon 2020 research and innovation programme.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Rönnberg, S.; Bollen, M. Power quality issues in the electric power system of the future. *Electr. J.* **2016**, *29*, 49–61. [CrossRef]
2. Justo, J.J.; Mwasilu, F.; Lee, J.; Jung, J.-W. AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renew. Sustain. Energy Rev.* **2013**, *24*, 387–405. [CrossRef]
3. Peretto, L. The role of measurements in the smart grid era. *IEEE Instrum. Meas. Mag.* **2010**, *13*, 22–25. [CrossRef]
4. European Association of National Metrology Institutes (EURAMET). Available online: https://msu.euramet.org/current_calls/pre_norm_2019/documents/cen_priority_009.pdf (accessed on 20 May 2023).
5. *IEC 61869-1:2017*; Instrument Transformers—Part 1: General Requirements. IEC: Geneva, Switzerland, 2017.
6. *IEC 61869-3:2011*; Instrument Transformers—Part 3: Additional Requirements for Inductive Voltage Transformers. IEC: Geneva, Switzerland, 2011.
7. Grasset, H. *How to Use the New IEC 61869 Series Standards*. White Paper, Ref. 998-2095-11-20-17AR0_EN. 2017. Available online: https://www.se.com/ww/en/download/document/998-2095-11-20-17AR0_EN (accessed on 20 May 2023).
8. EMPIR 19NRM05 IT4PQ Project Website. 1 April 2023. Available online: https://www.it4pq.eu (accessed on 20 May 2023).
9. Crotti, G.; Van Den Brom, H.E.; Mohns, E.; Tinarelli, R.; Luiso, M.; Styblikova, R.; Agazar, M.; Cayci, H.; Mazza, P.; Meyer, J.; et al. Measurement Methods and Procedures for Assessing Accuracy of Instrument Transformers for Power Quality Measurements. In Proceedings of the Conference on Precision Electromagnetic Measurements (CPEM), Denver, CO, USA, 24–28 August 2020; pp. 1–2.
10. Bollen, M.; Rönnberg, S.; Zavoda, F.; Langella, R.; Djokic, S.; Cuifo, P.; Meyer, J.; Cuk, V. Consequences of Smart Grids for Power Quality: Overview of the Results from CIGRE Joint Working Group C4.24/CIRED. In Proceedings of the IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Turin, Italy, 26–29 September 2017. [CrossRef]
11. Crotti, G.; Giordano, D.; D'Avanzo, G.; Femine, A.D.; Gallo, D.; Landi, C.; Luiso, M.; Letizia, P.S.; Barbieri, L.; Mazza, P.; et al. Measurement of Dynamic Voltage Variation Effect on Instrument Transformers for Power Grid Applications. In Proceedings of the 2020 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Dubrovnik, Croatia, 25–28 May 2020. [CrossRef]
12. Meyer, J.; Stiegler, R.; Konzelmann, S.; Kilter, J. Practical Aspects of Accurate Harmonic Voltage Measurements in Transmission Systems. In Proceedings of the 20th International Conference on Harmonics & Quality of Power (ICHQP), Naples, Italy, 29 May–1 June 2022. [CrossRef]
13. Istrate, D.; Khamlichi, A.; Soccalingame, S.; Rovira, J.; Fortune, D.; Sira, M.; Simon, P.; Garnacho, F. Laboratory calibration of energy measurement systems (EMS) under AC distorted waveforms. *Sensors* **2020**, *20*, 6301. [CrossRef] [PubMed]
14. *IEC C 60721-3-3:2019*; Classification of Environmental Conditions—Part 3-3: Classification of Groups of Environmental Parameters and Their Severities—Stationary Use at Weatherprotected Locations. IEC: Geneva, Switzerland, 2019.
15. *IEC 61869-6:2016*; Instrument Transformers—Part 6: Additional General Requirements for Low-Power Instrument Transformers. IEC: Geneva, Switzerland, 2016.
16. Cremona, C. *Investigations et Evaluations Dynamiques des Ponts*; Guide Technique du Laboratoire Central des Ponts et Chaussées (LCPC). 2009. 123p. Available online: https://www.ifsttar.fr/fileadmin/user_upload/editions/lcpc/GuideTechnique/GuideTechnique-LCPC-GTINPONT.pdf (accessed on 27 June 2023).
17. Nguyen, D.-P.; Hansen, K.; Zajamsek, B. Human perception of wind farm vibration. *J. Low Freq. Noise Vib. Act. Control* **2020**, *39*, 17–27. [CrossRef]
18. *IEC 61373:2010*; Railway Applications—Rolling Stock Equipment—Shock and Vibration. IEC: Geneva, Switzerland, 2010.
19. *IEC 60068-2-6: 2007*; Test Fc: Vibration (Sinusoidal). IEC: Geneva, Switzerland, 2007.
20. *IEC 60721-1:2002*; Classification of Environmental Conditions—Part 1: Environmental Parameters and Their Severities. IEC: Geneva, Switzerland, 2002.
21. *IEC 60721-2-9:2014*; Classification of Environmental Conditions—Part 2–9: Environmental Conditions Appearing in Nature—Measured Shock and Vibration Data—Storage, Transportation and In-Use. IEC: Geneva, Switzerland, 2014.
22. *IEC 60068-2-47:2005*; Environmental Testing—Part 2–47: Tests—Mounting of Specimens for Vibration, Impact and Similar Dynamic Tests. IEC: Geneva, Switzerland, 2005.
23. Crotti, G.; Letizia, P.S.; Meyer, J.; Stiegler, R.; Agazar, M.; Istrate, D.; Chen, Y.; Mohns, E.; Cayci, H.; Ayhan, B.; et al. Performance evaluation of instrument transformers in power quality measurements: Activities and results from 19NRM05 IT4PQ Project. In Proceedings of the 27th International Conference on Electricity Distribution, Rome, Italy, 12–15 June 2023.

24. Couderchon, G. Alliages fer-nickel et fer-cobalt—Propriétés magnétiques. *Tech. L'ingénieur* **1994**, *2*, D2130. [CrossRef]
25. Crotti, G.; Giordano, D.; D'Avanzo, G.; Letizia, P.S.; Luiso, M. A New Industry-Oriented Technique for the Wideband Characterization of Voltage Instrument Transformers. *Measurement* **2021**, *182*, 109674. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.