



The Future of Inductive Voltage Transformers in Power Quality Measurement

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Objective – The primary objective of this work is to assess and outline improvement paths for Instrument Transformers (ITs) to accurately measure harmonics as a key Power Quality (PQ) parameter within electrical grids. Additionally, it highlights the importance of considering Inductive Voltage Transformers (IVTs) as a cost-effective and efficient solution for PQ measurement.

Findings – Harmonics, due to their random nature and frequency variability, significantly impact measurement accuracy and grid stability. IVTs, which achieve high accuracy with a 0.1% error in transformation ratio at standard power frequencies (50/60 Hz), face challenges in high-frequency scenarios. At these frequencies, parasitic capacitances and core losses can reduce accuracy and lead to resonance phenomena.

Originality – The work aims to address the problem from three distinct angles: evaluating the performance of IVTs, developing and integrating new compensation systems on operational IVTs and modifying the internal design of IVTs if high-frequency requirements are not met. This approach is innovative from an industrial perspective, providing a unique opportunity to test a wide range of IVTs and directly influence manufacturing processes, thereby facilitating improvements in both design and performance.

Keywords – Power Quality, Instrument Transformers, Voltage Transformers, Harmonics Measurement.

1. Introduction

1.1 Overview on power quality disturbances costs

Measuring PQ has become increasingly important in recent years due to several factors. The large integration of renewable energy in low- and medium-voltage grids, and unconventional consumers like electric vehicle chargers and data centers in the grid has created new voltage and PQ issues. According to the European Power Quality Survey conducted by LEONARDO ENERGY, poor power quality in European networks costs more than €150 billion per year to European stakeholders [1]. Additionally, the ERPI (Electric Power Research Institute) has reported that US industries are experiencing an average total monetary loss of \$127 billion per year [2]. In general, it is difficult to attribute the costs of poor power quality to a specific sector due to its dependence on the type of event and its size. To provide a clearer idea, table 1 presents the costs of some events of power quality disturbances:

Table 1. Cost of some power quality events [1]

Event	Average cost /event
Surge to transient	€120,000 – 180, 0000
Long interruption	€ 90,000
Short interruption in service sectors	€18,000 – 36,000
Short interruption in industry	€7,000 – €14,000
Voltage dip	€2,000 – 4,000

In terms of absolute impact share, figure 1 shows the average impact of each disturbance.

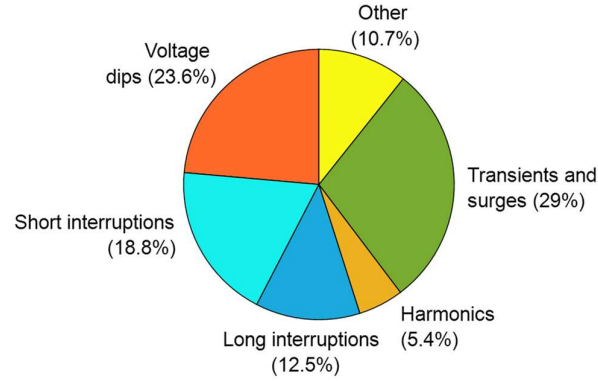


Figure 1 : Average share of power quality disturbances per year, in Europe, corresponding to €150 billion in annual costs [1]

1.2 Impact of harmonic distortion

Harmonics disturbances, which are the focus of our study, account for 5.4% of the total impact share, making them a relatively smaller contributor compared to other disturbances. However, their impact should not be underestimated. Despite their lower percentage in the total impact share, their long-term effects on electrical systems are significant [3]. Unlike short-term disturbances such as voltage dips or interruptions, harmonics lead to cumulative damage over time, affecting system reliability and increasing maintenance costs. Harmonic distortion can also be harmful to transformers, affecting their efficiency and accuracy by generating high losses including:

- **Hysteresis Loss:** This occurs due to the nonlinear magnetic properties of the transformer core and is frequency-dependent. It results from the repeated magnetization and demagnetization of the core material.
- **Eddy Current Loss in the Core:** These losses are caused by circulating currents induced in the transformer core. They depend on the square of the frequency and the thickness of the core material. Thicker materials and higher frequencies lead to greater eddy current losses.
- **Eddy Current Losses in Windings and Conductors:** Similar to core losses, eddy currents can also be induced in the windings and conductors, leading to additional energy dissipation.
- **Resistive Losses :** These occur within the winding conductors due to electrical resistance. At higher frequencies, skin effect and proximity effect can increase resistive losses, further reducing transformer efficiency.

Core losses can be categorized and understood using the Bertotti formula (1), which separates core losses into three components:

$$P_{totale} = P_h + P_e + P_{exc} = k_h \cdot f \cdot B_{max}^n + k_e \cdot f^2 \cdot B_{max}^2 \cdot d^2 + k_{exc} \cdot f^{1.5} \cdot B_{max}^{1.5} \quad (1)$$

Where P_h , P_e and P_{exc} are hysteresis, eddy current and excess losses respectively. The Bertotti formula highlights the high dependency of transformer losses on both frequency and magnetic induction (B_{max}). As frequency increases, particularly in the presence of harmonics, all three loss components (hysteresis, eddy current, and excess losses) rise significantly and leading to resonance effects, which can amplify distortion levels and create dangerous operating conditions.

1.3 Need of enhancing power quality monitoring

Additionally, several sectors such as medical, telecommunications, and manufacturing, demands a higher quality of power supply due to the use of sensitive electronic components and the financial impact of energy loss and metering errors. Figure 2 presents data on harmonic distortion cost components categorized by different types of disturbances across various sectors. The disturbances listed are detailed in [1]. The percentages indicate the relative impact or cost associated with each disturbance type. As customers and stockholders now demand higher energy standards for maintaining operational efficiency and reducing costs in various industries., standardization bodies have raised the limit of the operating frequency range [4]. This approach has contributed to increasing the focus on PQ monitoring by implementing researchers for a better identification, understanding and classification of network disturbances. It also supports the characterization of the behavior of power grids measuring equipment in the presence of these disturbances [5]. Furthermore, new technologies and solutions have emerged in the field of measurement equipment, incorporating advanced hardware development and refined calibration methods to enhance measurement accuracy. The paper is

structured as follows: Section 2 discusses harmonics measurement challenges, Section 3 examines the relevance of inductive voltage transformers, Section 4 presents improvement strategies, and Section 5 concludes the paper.

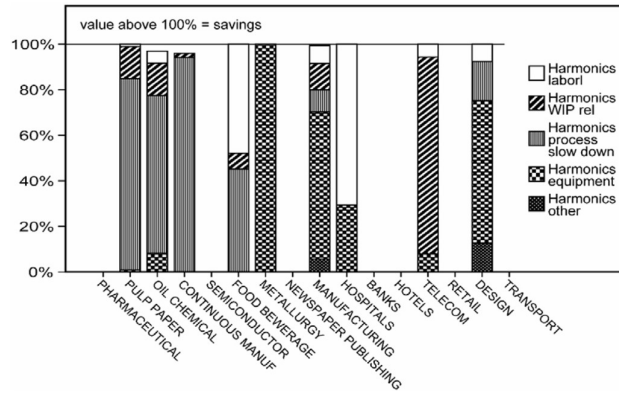


Figure 2: Harmonic distortion cost components categorized by different types of disturbances across various sectors [1]

2. Harmonic Measurement Challenges

2.1 Harmonic Measurement Guidelines. Former standards

The harmonic measurement method and standards were first introduced in [6] as part of power quality (PQ) parameters. This standard outlines the methods for measuring and interpreting results for PQ parameters in 50/60 Hz AC power supply systems. Key indicators include grid frequency, flicker, voltage and current magnitude, unbalance, harmonics, inter-harmonics, rapid voltage variations, and carrier currents.

Since these power quality events are also present in power grids, the approaches and methods described in [6] were adopted for measuring PQ in power grids, particularly for harmonics. However, there was a key difference in implementation: while measurements in AC power supplies were made directly, measurements in power grids required the use of transducers. These transducers, typically ITs, act as intermediaries between the high-voltage transport lines and low-voltage measurement instruments. This is because high-voltage measurement instruments are expensive and difficult to install on operational grids. ITs, mounted directly on power grids, were used to facilitate these measurements.

Despite their widespread use, it was quickly observed that the results provided by ITs for harmonic measurements were not accurate. Additionally, until 2022, there were no standardized methods or guidelines for measuring harmonics using ITs, further complicating the reliability and consistency of these measurements.

At 50/60 Hz, the accuracy of ITs is addressed in [7]. The standard introduces five accuracy classes, which are designed to be robust and achieve near-perfect performance. The accuracy of these transformers is defined by two key parameters: **Ratio Error**, given by formula (2) and **Phase Displacement**, given by formula (3). These parameters are constrained within specific limits, as detailed in table 2, ensuring consistent and reliable performance across different operating conditions.

$$\epsilon = \frac{k_r \times U_s - U_p}{U_p} \times 100 \text{ [%]} \quad (2)$$

$$\Delta\phi = \arg(U_s) - \arg(U_p) \text{ [min]} \quad (3)$$

Table 2. Limits of voltage error and phase displacement for measuring voltage transformers [7]

Class	Voltage (ratio) error ϵ_u $\pm\%$	Phase displacement $\Delta\phi$ \pm Minutes
0.1	0.1	5
0.2	0.2	10
0.5	0.5	20
1.0	1.0	40
3.0	3.0	Not specified

2.2 Standardization improvements

2.2.1 European initiative

Since 2019, the IT4PQ project has focused on developing specific performance indices, reference measurement systems, and test procedures to evaluate the accuracy and uncertainty contributions of ITs in PQ measurements. The project has also provided guidelines and recommendations for the calibration of ITs used in PQM. These contributions were submitted to the Technical Committee 38 of the International Electrotechnical Commission (IEC TC 38 Instrument Transformers) to update the ITs standard [8]. The proposed updates of 2023 version include new high-frequency bandwidth limits, as shown in table 3, which aim to simplify the use and qualification of ITs for high-frequency measurement performance.

Table 3. Accuracy class extensions for wide bandwidth applications [7]

Accuracy class	Ratio error at frequencies shown below			Phase error at frequencies shown below		
	%			Degrees		
WB1	$f_r < f \leq 1$ kHz	$1 < f \leq 1,5$ kHz	$1,5 < f \leq 3$ kHz	$f_r < f \leq 1$ kHz	$1 < f \leq 1,5$ kHz	$1,5 < f \leq 3$ kHz
WB2	$f_r < f \leq 5$ kHz	$5 < f \leq 10$ kHz	$10 < f \leq 20$ kHz	$f_r < f \leq 5$ kHz	$5 < f \leq 10$ kHz	$10 < f \leq 20$ kHz
WB3	$f_r < f \leq 20$ kHz	$20 < f \leq 50$ kHz	$50 < f \leq 150$ kHz	$f_r < f \leq 20$ kHz	$20 < f \leq 50$ kHz	$50 < f \leq 150$ kHz
WB4	$f_r < f \leq 50$ kHz	$50 < f \leq 150$ kHz	$150 < f \leq 500$ kHz	$f_r < f \leq 50$ kHz	$50 < f \leq 150$ kHz	$150 < f \leq 500$ kHz
0,1	± 1	± 2	± 5	± 1	± 2	± 5
0,2 – 0,2 S	± 2	± 4	± 5	± 2	± 4	± 5
0,5 – 0,5 S	± 5	± 10	± 10	± 5	± 10	± 20
1	± 10	± 20	± 20	± 10	± 20	± 20
Protection	± 10	± 20	± 30	-	-	-
The accuracy classes 0,2 S and 0,5 S apply only for current transformers.						

2.2.2 U.S. initiative

Since 2022, the IEEE standard [9] has raised the Total Harmonic Distortion (THD) limits from 5% to 8% to account for the growing integration of renewable energy sources and their unique harmonic contributions. This adjustment was made in response to the widespread infrastructure challenges caused by harmonic distortion levels exceeding the previous 5% threshold. Despite this change, recent studies reveal ongoing issues with high THD levels in power grids. A 2024 study conducted by Whisker Labs using the Ting Sensor Network analyzed the small-scale distribution of THD across the U.S. [10] power grid. With data collected from over 1,000,000 sensors across the U.S. the study found that many U.S. electricity providers continue to experience high THD levels in residential areas, with a significant number of homes exceeding the updated 8% THD limit. The results, summarized in Table 4, highlight the persistent challenges:

Table 4. Utilities with Highest Percentage of THD Exceeding Acceptable Limits (Avg from Feb. to Oct. 2024) [10]

Utility	Homes with THD >5% [%]	Homes with THD >8% [%]
COMMONWEALTH EDISON CO	55.9	36.5
PUBLIC SERVICE CO OF COLORADO	69.0	22.8
PUGET SOUND ENERGY INC	57.0	9.9
BALTIMORE GAS & ELECTRIC CO	67.0	9.2
PUBLIC SERVICE ELEC & GAS CO	50.0	9.1
FLORIDA POWER & LIGHT CO	70.5	8.6
DAYTON POWER & LIGHT CO	33.2	6.9
ATLANTIC CITY ELECTRIC CO	37.4	6.2
CONSOLIDATED EDISON CO-NY INC	21.6	5.6
JEA	26.4	5.5

These findings underscore the significant impact of evolving power grid dynamics and the integration of new technologies on power quality, particularly harmonic distortion, which continues to rise. The data demonstrates that even with updated standards, harmonic distortion remains a critical issue for utilities and consumers.

3. Relevance of inductive voltage transformer

ITs are a critical component of power grids, ensuring accurate reflection of the grid's real-time state under both normal operating conditions and failure scenarios. IVTs are generally favored over Resistive-Capacitive Voltage Dividers (VDs) and sensors in medium-voltage applications, such as railway and power grids, due to their superior accuracy and long-term stability at standard frequencies (50/60 Hz). Nowadays, offer robust performance with a lifespan exceeding 30 years, achieving a measurement uncertainty as low as 0.1%, alongside low manufacturing costs.

However, IVTs have a limited frequency range and perform reliably for harmonic measurements up to 2 kHz. Beyond this range, IVTs begin to self-generate low-order harmonics and can experience resonance due to parasitic capacitance in the windings. Additionally, at high frequencies, core losses can negatively impact measurement accuracy. Figure 3 illustrates the frequency response of a 10 kV/100 V with an accuracy class of 0.2, represented by its ratio error. The IVT was supplied with a nominal voltage of 10 kV at a frequency of 50 Hz. A frequency sweep was conducted by superposing a 10% harmonic of the fundamental signal at a 0° phase shift, covering a range from 100 Hz to 10 kHz. The frequency response shows a drop of -3 dB starting at 2700 Hz, which aligns with the general expectations for the harmonic measurement performance of IVTs.

In contrast, resistive-capacitive VDs provide advantages for measuring high-frequency voltages, offering a wider frequency range and improved accuracy for harmonic measurements exceeding 100 kHz [11]. As shown in Figure 4, a 45 kV RC divider was tested using a frequency sweep of 100 V, covering a range from 100 Hz to 10 MHz. The results demonstrate that the voltage drop of -3 dB begins at approximately 7.9 MHz, underscoring the accuracy of voltage dividers as a function of frequency. However, their accuracy is typically limited to 0.5%, and they are commonly entirely SF₆-insulated. In addition, they are approximately four times more expensive than traditional voltage transformers, making IVTs a more economical/environmentally-friendly choice for PQ measurement

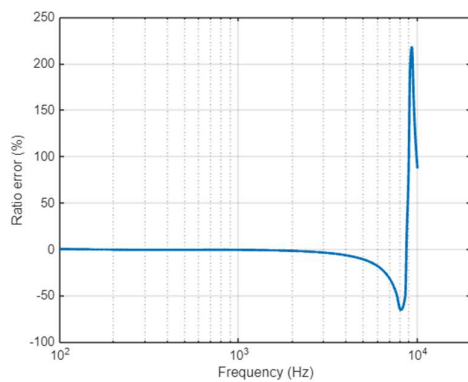


Figure 3: Ratio error of a classic 10kV/100V IVT as a function of harmonic frequency sweep.

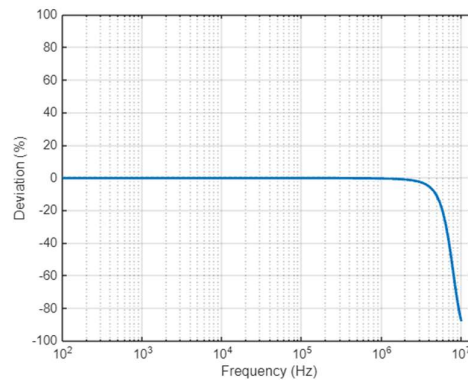


Figure 4: Voltage deviation between output and input of a 45 kV RC voltage divider.

Finally, over 30,000 IVTs have been deployed by a manufacturer since 2020 [12]. These devices, widely installed along power grids and overhead on trains, demonstrate a continuous market demand for this equipment. Assessing their capability to measure harmonics and developing compensation methods to reduce measurement uncertainty have become major requirements. These approaches can potentially save significant costs and provide rapid solutions by eliminating the need to replace existing transformers with new sensors.

4. Improvement strategy

Harmonics have traditionally been treated as parasitic elements in various domains, typically eliminated through filtering techniques. However, in our case study, assessing the frequency response of transformers requires harmonics to be considered an integral component of the transformer's input signal. This introduces a particularly challenging concept that demands a well-structured research strategy, bolstered by strong industrial collaboration. To address measurement challenges, research focuses on several key aspects:

First of all, understanding transformer manufacturing processes and their influence on frequency response. Secondly, developing reference measurement systems to accurately characterize transformers under realistic operating conditions. Figure 5 illustrates an installation of an innovative High-Voltage/High-Frequency (HV/HF) Generation and Measurement bench. This system consists of a Matsusada HV/HF amplifier, a reference VD, and a data acquisition (DAQ) system. It is capable of generating voltages up to ± 20 kV (full scale) over a frequency range from DC to 4 kHz at full scale, and up to 20 kHz at 10% of the scale. This setup is particularly suitable for testing 15 kV grid transformers.

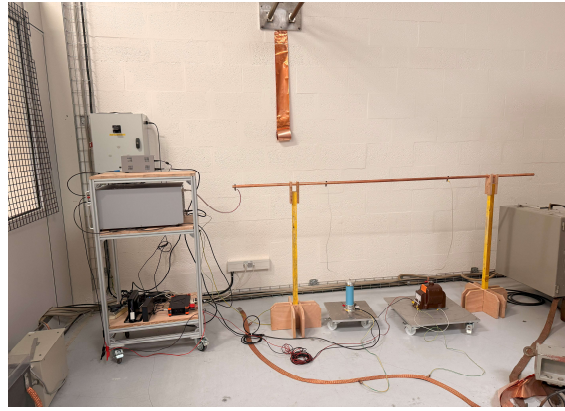
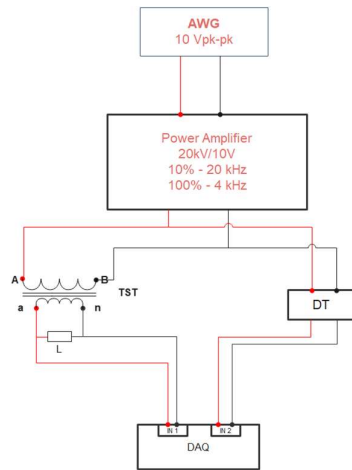


Figure 5: HV/HF generation and measurement bench

Thirdly, designing compensation systems that allow measuring harmonic with operational IVTs with high accuracy [13]. The approach we aim to achieve is as follows: while analyzing the frequency response of the IVT (Inductive Voltage Transformer) across a specified frequency range and ensuring the reliability of the results, we intend to develop either a passive or active compensation system. This system will attenuate the resonance to an acceptable level or shift it, making it suitable for use in electrical networks. Figure 6 illustrates the desired response compared to the original one.

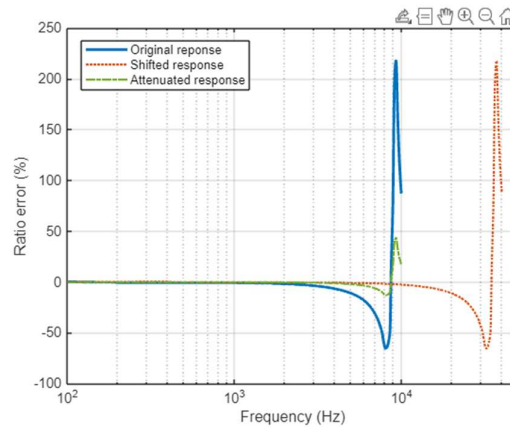


Figure 6: Difference between original, shifted, attenuated ratio error diagramme

5. Conclusion

In this work, the problematic of PQ measurement was introduced, highlighting several phenomena such as harmonic distortion, voltage fluctuations, and transients, along with their significant economic impacts on power systems. The discussion outlined the current state of harmonic measurement, among other critical PQ parameters, emphasizing the growing need for accurate and reliable monitoring tools. The state of harmonic distortion was explored in detail, underscoring the necessity of measuring harmonics to ensure grid stability and compliance with regulatory standards. However, the challenges associated with this task, such as measurement uncertainty, sensor limitations, and the complexity of harmonic analysis, were also addressed. The role of Instrument Voltage Transformers (IVTs) as a low-cost and fast-deployable solution for harmonic measurement in power grids was explained. IVTs offer a promising alternative to traditional sensors, particularly in scenarios where retrofitting or replacing existing infrastructure is impractical. Several paths for improvement were proposed to enhance the performance of IVTs. These approaches not only address the technical challenges but also offer significant cost savings by leveraging existing infrastructure, thereby avoiding the need for expensive sensor replacements.

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