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Instrument Transformers for Power Quality Measurements: a Review of Literature and Standards

Gabriella Crotti, Palma S. Letizia, Giovanni D'Avanzo, Mario Luiso, Carmine Landi, Fabio Muñoz, Helko van den Brom

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Instrument Transformers for Power Quality Measurements: a Review of Literature and Standards

Gabriella Crotti
Italian National Metrology Institute, INRIM
Torino, Italy
g.crotti@inrim.it

Giovanni D'Avanzo
Dept. of Engineering
University of Campania "Luigi Vanvitelli"
Aversa (CE), Italy
giovanni.davanzo@unicampania.it

Carmine Landi
Dept. of Engineering
University of Campania "Luigi Vanvitelli"
Aversa (CE), Italy
carmine.landi@unicampania.it

Palma S. Letizia
Politecnico di Torino
Italian National Metrology Institute, INRIM
Torino, Italy
p.letizia@inrim.it

Mario Luiso
Dept. of Engineering
University of Campania "Luigi Vanvitelli"
Aversa (CE), Italy
mario.luiso@unicampania.it

Fabio Muñoz
VSL, Dutch National Metrology Institute
Delft, the Netherlands
fmunoz@vsl.nl

Helko van den Brom
VSL, Dutch National Metrology Institute
Delft, the Netherlands
hvdbrom@vsl.nl

***Abstract*—Measurements of Power Quality (PQ) are gaining more importance due to increasing presence of switching power converters that deform the waveform of the distributed voltage further and further away from a sine wave. Especially at medium and high voltage levels, PQ measurements are carried out by means of Instrument Transformers (ITs). A recently started European metrology project, EMPIR 19NRM05 IT4PQ, aims at establishing the methods and procedures for assessing the accuracy of ITs used for PQ measurements. This paper, that is written in the framework of the IT4PQ project, presents a thorough review of the current state-of-the-art of literature and international standards about ITs and PQ. The main results from several papers and the main information from IT and PQ related international standards are summarized.**

Keywords— Instrument Transformer, Power Quality, Power System Measurements, Calibration, Uncertainty, Standard

I. Introduction

In modern power systems, the assessment of Power Quality (PQ) is gaining importance, due to the increasing diffusion of switching power converters, that serve both for loads as well as for generators, mainly from renewable sources [1]. They contribute to inject several types of disturbances into the power systems, that modify the waveform of the distributed voltage further and further away from a sine wave. Whereas PQ measurement methods at Low Voltage (LV) [2] and their functionality testing [3] are very well standardized, especially at Medium Voltage (MV) and High Voltage (HV) levels, PQ is always measured through Voltage and Current Transformers (VTs and CTs), which very often are inductive. Recent papers [4]-[7] show that VTs and CTs can introduce errors up to some percent in harmonic measurements: this fact clearly shows that specific tests, to verify the errors introduced by Instrument Transformers (ITs) when they are used to measure PQ phenomena, are necessary. Despite this, to the best of the authors' knowledge, no papers in literature offer a comprehensive analysis of this topic, nor a specific standard exists. In order to fill this gap, recently, a European metrology research project, EMPIR 19NRM05 IT4PQ [8]-[9], has been funded. It aims at establishing the methods and procedures for assessing the errors introduced by ITs when they are used to measure PQ phenomena: its final scope is to provide the IEC TC 38 (International Electrotechnical Commission Technical Committee) "Instrument Transformers" with the most comprehensive knowledge possible to redact an international standard on this topic. The first task of this project, described in this paper, is to perform a thorough review of literature and standards about ITs and PQ measurements. The structure of the paper is as follows. Section II gives a review of scientific literature about measurements of PQ phenomena and verification of IT performance when measuring PQ phenomena. Section III presents a wide overview of the in-force standards about ITs when used for voltage characteristics in power systems and PQ measurements. Finally, in Section IV the conclusions are drawn.

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II. Literature Review

The study of PQ issues is a matter of great interest in several fields, and, for this reason, the related scientific literature is very extensive. To set limits for future testing of ITs for PQ measurements, one needs to know the PQ levels typically occurring in practice. This section aims to give a brief overview on papers with two specific topics: 1) PQ phenomena found on the MV grid during recent measurement campaigns and 2) ITs performance in PQ measurements.

A. *Measurement of PQ phenomena*

In this subsection, the occurrence and typical values of common PQ disturbances found in MV grids are analyzed. Information is presented per specific PQ phenomenon.

Supply Voltage Deviation. In [10], 15 different MV (20 kV) supply points are analyzed over 3 years (2014-2016) and the recorded voltage variations range from 96.6 % to 107.3 %. In [11] the maximum voltage reaches the value of 108 % of the nominal voltage U_n (20 kV). In [12], the voltage quality of 9 MW (22 kV) distribution grids with connected wind power plants is analyzed and the maximum voltage reaches the value of 107 % of U_n whereas the minimum value is about 98 % of U_n.

Voltage Unbalance. To quantify the voltage unbalance, the factor k_u, defined as in [13], is evaluated. The limit set by the standard [14] for the k_u factor is 2 %. In [10], all the measured k_u values are in the range between 0.1 % and 0.7 %. In [15], PQ is monitored in substations and distribution feeders at various voltage levels (from 13.8 kV to 138 kV). About 90 % of the monitored installations experience a k_u factor below 1 %. In [11], the measured unbalance factors are below the 0.5 % level. A similar value (0.54 %) is also recorded in [16]. In [12], the maximum k_u factor is observed to be equal to 1.33 %.

Flicker. This PQ phenomenon is evaluated in terms of long term (P_{lt}) and short term (P_{st}) flicker severity [17]. In [18], results of 15 years of PQ monitoring are reported. It has been found that the P_{lt} index quite often exceeds the limit set by standard [17] and the maximum observed value is 1.7. In [10], the maximum observed P_{lt} is 2.5 and the corresponding P_{st} is equal to 3. In [11], P_{lt} ranges from 1.35 to 3.53. Moreover, in [19], that is a paper collecting PQ measurements over 64 weeks in different distribution networks sites, P_{st} reaches a peak value of 5 in a residential site. On the contrary, in [12] and [16], all the measured P_{lt} values are well below the limit and the maximum P_{lt} values recorded are 0.63 and 0.3, respectively.

Harmonic voltage. The harmonic disturbance can be analyzed in two different ways, i.e., the amplitude level of single harmonic tones and the total harmonic distortion (THD). In [10], the THD measured values are far below the limit set by the standard [14] and they range from 1.5 % to 6 % with a mean value of 2 %. The same paper focuses on the 3rd, 5th, 7th and 15th harmonic; all the harmonic amplitudes are well below the standard limit [14], except for the 5th harmonic that reaches the 6 % limit but does not exceed it. In [15], only information about the measured THD is given and about 70 % of the recorded THD values are in the range between 1 % and 3 %. Similar information is found in [11], where the mean value of the recorded THD is about 2 %. Likewise, in [12], the measured THD values are in the range from 1 % to 2.2 %. In [12], a focus on the 15th harmonic is also given and its maximum amplitude is found equal to 0.26 %, which is half the 0.5 % limit [14]. In [19], results related to THD and the 3rd harmonic are given. For the THD, all the values are far below 8 %. The recorded 3rd harmonic amplitudes are below 1 % in almost all the monitored sites except for one commercial site where the mean value is about 2.5 %. In [16], the measured harmonics up to the 50th are reported and it was observed that the odd ones are predominant, whereas all the even harmonics are far below 0.5 %. Also in this case, the highest amplitude level is reached by the 5th harmonic, and it is equal to 2 %. In [17] and [18], the first 11 odd harmonics are evaluated. All the amplitudes are below the limits indicated by the standard [14] and, again, the highest amplitude is reached by the 5th harmonic (0.33 %). In [20] and [20], harmonics measurements at 3 different sites (from 10 kV to 30 kV) are presented. The measured THD values range from 0.96 % to 1.39 %. For single harmonics up to the 25th it was also reported that the odd ones had the higher amplitudes, but that they were always far below 1 %.

Interharmonics. Identifying typical amplitude and frequency of interharmonics is not an easy task since they vary due to the mechanical and electrical parameters of their sources [21]. Therefore, no further useful information was found in this survey.

Voltage Dips. Among the PQ voltage variation phenomena, the voltage dips are the most common [15], [22], [23]. Voltage dips are characterized by the duration and the residual voltage [14]. In [16], more than half of the recorded voltage dips has a time duration less than or equal to 5 cycles and 80 % has a residual voltage in the range between 70 % and 90 %. In [22], most of the events (about 94 %) present a residual voltage equal to 70 % to 90 % and their durations range between 0 ms and 100 ms (5 cycles of 50 Hz). Also, in [24] about 60 % of the voltage dips measured in a 22 kV substation has a residual voltage between 70 % and 90 % and time durations lower than 100 ms.

Voltage Swells. Similar to voltage dips, voltage swells are characterized by the time duration and overvoltage. In [16], 70 % of the detected voltage swells has a time duration less than or equal to 1 cycle and maximum magnitude less than 114 % of the rated voltage.

Voltage Interruption. In [16], about 70 % of the events last from 30 cycles to 70 cycles. It is worth noting that in almost all the papers investigated no information about the MV VTs used for the measurement of the PQ disturbances is provided. In [16], a brief section on the frequency behavior of 100 Inductive VTs (IVTs) with different primary voltages is given. In [10], only the rated features of the VTs used is reported.

Summarizing, except for flicker, all the PQ phenomena recorded in the analyzed papers have levels well below the relative limits set by the standard [14].

B. *Verification of IT performance in PQ measurements*

Most of the papers on IT performance when used for PQ measurements deal with the measurement of the frequency behavior of ITs for the measurement of harmonics and interharmonics. In general, great differences in terms of frequency performance can be found between conventional inductive ITs and non-inductive Low Power Instrument Transformers (LPITs). The latter are usually characterized by a flat frequency response [25], [26] whereas inductive ITs (especially IVTs) have worse frequency behavior and show distinctive resonance points (because of the stray capacitances), which decrease in frequency with increasing rated primary voltage [16]. However, inductive ITs already installed in MV for metering and protection purposes are often used also for harmonic and, more generally, PQ measurements. Thus, IT characterization for PQ applications is necessary but not an easy task; in fact, because of the non-linear behavior, they have to be characterized under test conditions close to practical use. In fact, in [27] it was shown that different VT frequency behavior can be found using different approaches for their characterization (sinusoidal sweep at LV or dual-tone signals at MV). A similar result is also presented in [28], where differences up to 1.2 % have been found between the frequency response of a 20 kV VT measured by performing a sinusoidal sweep at LV and by suppling the VT with a signal composed of two tones (fundamental at rated voltage plus harmonic tone at 5 %).

In [29] it is shown that the frequency response of MV VTs depends not only on the primary voltage used for the characterization, but on a complex system of influence factors and is more or less unique for each VT in its specific operating environment. Nevertheless, the authors provide a conservative estimation of harmonics measurement accuracy for 20 kV VTs:

- $f < 1$ kHz, accuracy $< \pm 2$ %;
- $f < 2$ kHz, accuracy $< \pm 4$ %;
- $f < 2.5$ kHz, accuracy $< \pm 6$ %.

Similarly, in [30], a method is proposed for the accuracy specification of MV and HV VTs for harmonics measurement (up to the 100th order).

A different approach to the determination of IT frequency behavior is proposed in other papers. In fact, [4]-[7] propose techniques to measure and compensate the IT non-linearity, leading to a strong reduction of the IT errors contribution in harmonic measurement. In particular, in [4] and [5], the non-linearities are measured and compensated by measuring the spurious phasors at the IT secondary side when it is supplied with a sinusoidal signal at rated voltage and frequency. In [6] and [7], the compensating phasors are measured suppling a VT with dual-tone and multitone signals, respectively. All the techniques [4]-[7] are validated suppling the ITs under test with actual MV waveforms. It is worth noting that in all papers analyzed the IT frequency response is measured starting from the power frequency, not taking into account the performance of ITs in the measurement of subharmonics (i.e., interharmonics with frequencies lower than the mains frequency). At the same time, it is well-known that low-frequency components can dramatically worsen the IT performance [31]. A few other papers have assessed IT performance when used for the measurement of PQ phenomena other than harmonics and interharmonics. In [32], the authors have quantified the impact of CTs on measurement of synchrophasors in presence of amplitude and phase modulations or a frequency ramp. It was shown that, under particular operating conditions, the CTs exceed their accuracy classes affecting the synchrophasors measurement. In [33] a similar analysis is performed on an MV VT which does not exceed its accuracy class for all test conditions. In the same paper [33] the impact of an MV VT on the detection of a voltage dip duration and residual voltage is quantified.

Summarizing, currently a number of works suggest procedures and measurement system architectures to use to verify ITs performance in harmonic measurements and related compensation techniques. However, many other PQ phenomena are not yet considered in the studies about ITs, so there is not a complete knowledge about the behaviour of ITs when they are used for PQ measurements.

III. Standards Review

ITs have been designed, standardized, designed, and tested mainly for protection and metering purposes. However, nowadays, there is a growing demand for investigating and measuring PQ at a given point of the system using ITs. In LV applications, instruments can perform measurements with a high degree of accuracy and complying with measurement classes prescribed by [2] without ITs. For HV and MV applications, VTs and CTs are needed. Given the wide diffusion of inductive VTs and CTs in particular, these are usually inserted in the measurement chain before PQ instruments. Nevertheless, information available about their impact on the PQ measurement is not yet consolidated. For this reason, procedures, limits, and methods to calibrate ITs in PQ measurement are needed. In this section, a standard review of ITs for PQ measurement, voltage characteristics in power systems and PQ measurement methods is presented.

A. Standards on ITs

The most relevant documents that cover the standardization of ITs are those drafted by the technical committees (TC) of Institute of Electrical and Electronics Engineers (IEEE), European Committee for Electrotechnical Standardization (CLC), and IEC. The first noteworthy document is the technical report (TR) IEC 61869-103 [34] drafted by IEC TC38, which describes ITs for PQ measurements. At present, the behavior of ITs for PQ measurement is not well investigated. In fact, more information is available for Electronic Instrument Transformers (E-ITs) and LPITs, to which several standards are dedicated, i.e., [35] and [36], which will be complemented and replaced by the IEC 61869 standards family. This standards family applies to ITs with analogue or digital output having rated frequencies from 15 Hz up to 100 Hz and defines the standard accuracy class for VTs as well as CTs. However, the standard accuracy class is assigned by accuracy tests performed at the rated frequency with different amplitude and burden.

Although some part of the IEC 61869 standard family provides additional general requirements for LPITs and E-ITs, currently, only few PQ phenomena are included. In fact, in standards [35] and [36], additional accuracy requirements specifically defined for ITs in case of harmonic and interharmonic measurements up to the 50th harmonic order, are included. In particular, these requirements range from 1 % up to 20 % for the ratio error and from 1 mrad up to 35 mrad for phase displacement. Furthermore, the same standards define several tests to verify the immunity of the ITs under unidirectional transients. In [37] and [38] there are additional requirements applicable to inductive ITs for use with devices having rated frequencies from 15 Hz up to 100 Hz with different amplitudes and burdens. However, these standards do not include measurement setups or methods to evaluate the performance of ITs in the presence of PQ phenomena. Although [34] is not a standard, it represents a first approach to standardize the use of ITs in PQ measurements in 50 Hz or 60 Hz AC power systems as in the aim of the IEC 61869 standards family. From [34] three pieces of useful information are worth reporting. The first is that measurement of PQ disturbances according to [2] requires improved frequency response (magnitude and phase) as well as transient response from the ITs. Different PQ phenomena can affect the frequency response parameters in a different way.

A second observation of [34] is that the test procedure for ITs depends on the frequency linearity characteristics. If the frequency response of the IT can be proven to be not affected by the presence of the fundamental amplitude and varying burden, the frequency response test can be performed at an amplitude level lower than the rated amplitude by applying a single tone sine wave and varying the frequency. When the frequency response of the IT is affected by the presence of the fundamental, the test should be performed by applying a signal at a fundamental frequency close to or equal to the nominal amplitude with harmonics and interharmonics added with different amplitudes.

Thirdly in [34] it is concluded that there should be several IT classes for the measurement of PQ, each for different performance. For each class, all parameters should be defined and tested against influence quantities. The uncertainty and error limits should be the same as the limits of [2] for PQ meters. Moreover, [34] suggests possible new test points for some PQ phenomena, in particular for dips, swells, interruptions and their post effects which can be observed in ITs when nominal parameters of the power supply system are restored. For example, if there is a sudden interruption of primary voltage at 180 degrees, the magnetic core of the IT is fully magnetized in the positive direction. After the primary voltage restoration, the output on the secondary will depend on the angle relationship between the memorized phase angle at which the primary voltage was turned off, and the phase angle at which the primary is turned on again.

It is worth noting that all standards written so far by IEC TC38 do not consider uncertainty assessment in IT calibration. To fill the void, TC38/JWG 55 is working to write a document dealing with the uncertainty of IT calibration from 15 Hz up to 3 kHz.

B. *Voltage characteristics in power systems*

The description of PQ is of fundamental importance within the power-supply systems' community. Fault or other events such as short circuits and lightning strikes occurring within user installations or public networks can disturb or degrade the supply voltage. International technical standards on PQ specify the expected characteristics of electricity at the point of supply of public networks at LV, MV, and HV, 50 Hz or 60 Hz [14], as well as the methods of assessing PQ [39]. The PQ phenomena reported in [14] and [39], are continuous, and discontinuous phenomena. In particular, the continuous phenomena are frequency deviation, supply voltage deviation, voltage unbalance, harmonic voltage, interharmonic voltage and flicker, whereas discontinuous phenomena are voltage interruptions, dips, swells, and transients. The definitions of these PQ phenomena are reported in the "terms and definitions" section of [14] and [39]. In the next paragraphs, the limits defined in these standards are presented. These limits are relevant for the envisaged testing of ITs for PQ measurements as well.

Frequency deviation: The maximum limit, indicated in [14] and [39], for synchronous and non-synchronous connection to an interconnected system is ± 4 % and ± 15 %, respectively. As clarified in [40], the steady-state power-system frequency is directly related to the rotational speed of the generators in the system. At any instant, the frequency depends on the balance between the load and the capacity of the available generation. When this dynamic balance changes, small changes in frequency occur.

Supply voltage deviation: The maximum limit, indicated in [14] and [39], for synchronous and non-synchronous connection to an interconnected system is ± 10 % and + 10 % / –15 % of nominal voltage, respectively. Ref. [39] describes the recommended values for MV systems based on the declared voltage.

Voltage unbalance: The voltage unbalance is classified by [40] in the category of low-frequency phenomena conducted as a type of disturbance in steady-state and short-term amplitude variations, from 3 s up to 1 minute, with variations from 2 % up to 15 %. This standard also clarifies that voltage unbalance can produce harmonic distortions. The degree of inequality is defined through the voltage unbalance factor k_u [13]. The maximum limit for voltage unbalance k_u is ± 15 %.

Flicker: As described in [14] and [39], voltage fluctuations are described by the short-term and long-term flicker severity indices P_{st} and P_{lt}. Ref. [13] covers voltage-fluctuation compatibility levels in MV networks. This standard is considered because voltage fluctuations in MV networks, by being transferred, with or without alteration, to LV networks, can cause flicker. Ref. [17] covers the compatibility levels of flicker in LV networks. This standard defines compatibility levels of $P_{st} = 1$ and $P_{lt} = 0.8$.

Harmonic and interharmonic voltage: The compatibility levels for harmonic and interharmonic voltage are given in [13] as reference values for long-term effects, such as thermal effects on cables, transformers and motors, and for short-term effects. The short-term effects relate mainly to disturbing effects on electronic devices that may be susceptible to harmonic levels sustained for 3 s or less. Regarding interharmonic voltage, [41] provides general guidance on the effect of interharmonics on some known susceptible items of equipment. The limits for harmonic and interharmonic voltage up to 9 kHz range from 0.3 % to 8 %, which already includes an additional factor to consider the short-term effects. The corresponding compatibility level for the total harmonic distortion (THD) is 11 %. It is worth noting that there are no clear indications for the levels of harmonic and interharmonic currents. The limiting current values should be developed on a case-by-case basis considering the specifications of the power system, connected user loads and arrangements for other users. However, the maximum level of harmonic and interharmonic current to balanced and unbalanced three-phase equipment in MV grids can range from 0.6 % up to 40 % with maximum corresponding compatibility level for the THD of 48 %.

Voltage dips, swells and interruptions: According to [14], [39], and [40], dips, swells, and interruptions consist of three parts: (1) start threshold, (2) duration, and (3) end threshold. Based on [40], voltage dips, swells and interruptions are usually caused by fault events. The interruptions are special cases of dips with a duration up to 3 minutes (short) or greater than 3 minutes (long). Refs. [42] and [43] define methods and test levels for devices connected to MV networks able to tolerate voltage interruption. Ref. [44] covers voltage dips, swells, and interruptions in terms of their sources, effects, and measurement methods. This standard shows the statistical measures of voltage dips, swells and interruptions that occurred in 85 measurement sites. From these results, it can be deduced that the average number of voltage dip occurrences has a maximum for residual voltages between 85 % and 70 % and durations between 0.02 s and 0.1 s in the case for overhead networks and between 90 % and 85 % and between 0.02 s and 0.1 s for underground networks.

Transient overvoltage: Based on [14], [39], and [40], transient overvoltages are conducted phenomena at high frequency that can be divided into oscillatory and unidirectional or impulsive transients. These standards define also bursts of transients and multi-transient events. The difference is based on the typical spectral content and duration for single events and period for multi-transient events and burst. The duration time of impulsive transients varies from 50 ns or less to 1 ms or more, whereas the duration time of oscillatory transients varies from 5 µs up to 0.3 ms with spectral content between 1 kHz and 5 MHz. Regarding amplitudes, [2] and [40] recommend limits up to 800 % and 200 %, respectively. Ref. [45] defines single transients and bursts of transients and their characteristics, such as polarity, rise time, impulse duration, burst duration and burst period.

C. PQ measurement methods

The IEC 61000 family of standards on electromagnetic compatibility standardizes most aspects of PQ and provides indications on measurement methods. Ref. [2] is the main document and is completed by [46] and [47] which address the specific requirements for harmonics and flicker, respectively. However, in many cases, although there are several standards on specified PQ phenomena, there are no standards on ITs that cover measurement limits, methods, and measurement setup for these phenomena. However, it is worth mentioning that there are standards on PQ measuring instruments. Ref. [3] is a part of the IEC 62586 standard family and defines test points to verify the accuracy of PQ measuring instruments. Since ITs are employed to scale down voltage and current at the primary side of the PQ instrument, these kinds of tests should be performed also on ITs. In this section, the most important parts of the collected information are presented.

Frequency deviation: To perform frequency deviation measurements, according to [2] it is necessary to obtain a frequency reading every 10 s. As the power frequency may not be exactly 50 Hz or 60 Hz, within a 10 s time interval the number of cycles may not be an integer number; in these cases, the output is the ratio of the largest integer number of cycles counted during the 10 s time interval, divided by the cumulative duration of these cycles.

Supply voltage deviation: According to [2], the measurement of supply voltage deviation must be performed by evaluating the supply voltage in successive 10-minute windows, i.e., 1008 intervals of 10 minutes in a week. The international standard [39] also recommends assessment methods for continuous PQ phenomena, such as supply voltage deviation.

Voltage unbalance: To perform voltage unbalance measurements, according to [2], it is necessary to consider the method of symmetrical components. The fundamental component of the voltage is measured over a 10-cycle (12-cycle) time interval for 50 Hz (60 Hz) power systems.

Harmonic and interharmonic voltage: The harmonic and interharmonic components of the voltage can be evaluated in two ways: (1) Individually by their relative amplitude which is the harmonic voltage related to the fundamental voltage; (2) Globally, by the THD. According to [2] and [46], the basic measurement time interval is a 10-cycle (12-cycle) time interval for 50 Hz (60 Hz) power systems. Consequently, the frequency resolution of the Fourier components is 5 Hz.

Voltage dips, swells and interruptions: Based on [2], dips and swells should be measured considering a threshold equal to ± 10 % of the declared supply voltage to define the starting time. The hysteresis used to define the end time is typically set to 2 %. Regarding interruptions, the threshold is 10 % of the declared voltage amplitude.

Transient overvoltage: According to [2] and [47] the result of a transient measurement depends on the nature of the transient and on the parameters considered. Ref. [2] defines several methods to detect transient voltages and to evaluate parameters of transients.

IV. Conclusions

This paper has presented a deep review of literature and standards about ITs used for PQ measurements. It highlights that, currently, a specific standard about the testing of ITs to be used for PQ measurements does not exist. Moreover, even though there are some literature papers that show the performance of ITs when they are used to measure some PQ phenomena, a comprehensive knowledge of the ITs behavior in the presence of PQ phenomena has not been developed yet.

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