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doi:10.15199/48.2016.05.05

Alternative Methodology to Evaluate the Performance of PQ monitors

Abstract. *This paper presents an alternative methodology for evaluating the functional perfomance of electric power quality measurement instruments, which is elaborated based on the results of the application in laboratory of three procedures found in documents that deal with this subject. It is a proposal which includes the metrological and technical aspects of each electric power quality parameters required by IEC 61000-4-30 through the use of ISO-GUM. From the implementation of this methodology, it is possible to identify the attributes and deficiencies of the instrument under evaluation and show them in a report that expresses its performance.*

Streszczenie. *W artykule zaprezentowano metodologię oceny metod pomiaru jakości energii. Uwzględniono parametry rekomendowane przez normę IEC 61000-4-30 oraz zalecenia ISO-GUM. Metodologia pozwala na ocenę wad i zalet poszczególnych metod.* ***(Metodologia oceny właściwości mierników jakości energii)***

Keywords: Power quality monitors, calibration, IEC 61000-4-30, error measurements
Słowa kluczowe: Metodologia oceny właściwości mierników jakości energii

Introduction

The electricity sector has recently adopted a deverticalized model that imposes new rules in order to satisfy the final consumer. In this context, power quality (PQ) has become one of the most important questions to be addressed [1]. In general, PQ analysis is a way of assessing the continuity of supply and compliance with certain parameters related to the limits established in standards.

For the assessment of PQ parameters, measuring campaigns have been developed and implemented worldwide by regulators, electric utilities and consumers [2, 3]. For this to be possible, it is necessary to provide the electrical network with specialized instruments. This demand has fostered the development and manufacture of many different electric meters that are available today in the market. However, it is noteworthy that the absence or neglect of standardized methods which establish the procedures for measuring PQ parameters can lead to the incompatibility of instruments from different manufacturers due to fact that meters which are not alike can present differing results even when subjected to a single signal [4].

Aiming at reliable measurements, the IEC 61000 standard was published in 2008 – *Electromagnetic compatibility (EMC)- Part 4-30: Testing and measurement techniques - Power quality measurement methods* [5]. Although it is a global document, there is no guarantee that manufacturers of this class of instruments have adopted it. Therefore, analysis methods of meter performance for measuring PQ parameters are made necessary, based on aspects that ensure an international pre-established standard [6].

When looking into specialized literature, there is a set of articles that focus their goals on performance verification of instruments dedicated to PQ measurement parameters. In 2004, a study was published that shows the performance results of different models of PQ meters was published [7], subjected to several modules of tests simultaneously. In this work, there is no mention of standards/documents that have actually been used as standards for calculating measurement errors, or ones that establish the maximum uncertainty limits allowed for each quantity under evaluation. In 2009, a study that proposes verification *in loco* of the functional performance of instruments in the quantification process of the PQ parameters in steady -state was published [8]. Such verification is performed by employing only the tests suggested in IEC 61000-4-30 (2008). However, in this standard it is mentioned that the proposed tests, although necessary, are insufficient to verify if a meter meets the requirements of the standard. In 2010, a study devoted to check the performance of instruments designed to measure voltage dips was published [6]. The other PQ parameters were not included in this article.

There are meters in the market that present certifications developed and issued by the institutes *Power Standard Lab.* [9] and *Israel Electric Co.* [10], even though they are not available in literature.

Besides the aforementioned studies, it is possible to find some documents that propose different assessment tests for PQ parameters that use IEC 61000-4-30 as a base. Part of this group is a study, published in 2010, that presents a methodology for the metrological evaluation of PQ meters [11]. With the same purpose, but with a distinct set of tests, procedures that separately evaluate the metrological and technical requirements demanded by IEC 61000-4-30 for each PQ parameter were published in 2014 [12]. Still in 2014, in Brazil, a public consultation prepared by the National Electric Energy Agency (ANEEL) proposed a methodology that should be provided in the near future as a reference to the type of evaluation in question [13].

Considering the aspects mentioned above, the idea emerged for developing this study which aims at describing and analyzing the three evaluation methods displayed in documents [11, 12, 13]. For this, tests which constitute these methodologies are implemented in the laboratory in order to enable the evaluation of a measuring instrument for each one of them. The results obtained in this process are then analyzed comparatively seeking to identify the advantages and disadvantages related to the adoption of each one. Based on this information, an alternative methodology that optimizes the evaluation process of the functional performance of PQ monitors will be proposed.

Methodologies for Evaluating PQ Measuring Instruments

According to the results from searches in literature pertaining to studies that deal with the mentioned theme, it is possible to identify, among other things, three methodologies that have verifying the performance of PQ monitors as a common objective. Here, they will be referred to as Met-A [13], Met-B [12], and Met-C [11]. Then they will be briefly presented and analyzed.

Met-A

The objective of Met-A is to analyze the functional performance of measuring instruments on the following indicators: Harmonic distortion, voltage unbalance, flicker, short duration voltage variations (SV), and voltage variations in steady state. For this, there is an established sequence of tests which the authors termed "Test Pad". They are classified into 6 large sets of result (Modules), and are accompanied by a numeric identifier. Within this logic of organization, the groups of tests culminated in 42 different tests , divided as follows:

1. Harmonic voltages - Tests 1 to 14;
2. Voltage unbalance - Tests 15 to 18;
3. Flicker - Tests 19 to 24;
4. SVs - 1^{a} part - Tests 25 to 35;
5. SVs - 2^{a} part - Tests 36 to 39; and
6. Steady state voltage - Tests 40 to 42.

In Met-A, to evaluate the instrument, a method whose procedures are aimed at obtaining numerical indicators that represent the performance of the test equipment are employed. They are:

- **Calculation of errors for classification purposes:** Strategically, different procedures for classifying the results obtained from the measurements are used. The adopted option consists of establishing as a reference, values set for the quality indicators according to the Test Pad, which were implemented in a programmable source and applied during the tests. From these, the errors which are determined by the difference between the reference quantity values and those found and documented by the manufacturers/representatives are calculated in equation (1).

(1) $$Error = \frac{Measured - Ref.Value}{Ref.Value} 100\ [\%]$$

It is also worth noting that, in addition to the described criteria, modules related to voltage harmonics, flicker and voltage variations in steady state, a complementary error evaluation is carried out for the tests. This involves determining the biggest difference between the results provided by each phase, equation (2).

(2)
$$Error/phase = \frac{MaxValue - MinValue}{MaxValue} 100\ [\%]$$

Finally, for the case of SV tests, the calculation of errors related to the duration of events is done. This is done by taking into consideration the time obtained by the equipment and its proximity to the standard value in terms of the number of cycles.

- **Attribution of the performance concepts per test:** Once the equipment performance is expressed when measuring a particular variable in the form of a numerically quantified error, this is subsequently compared to a threshold. The difference between these values determines the concept to be assigned to the meter. The correlation is shown in Table 1.

Table 1. Assigning concepts - Met-A

Parameters	Error ranges [%]	Concept
Steady state voltage	≤ 1	Approved
Harmonic voltages	≤ 2	Approved
Voltage unbalance	≤ 2	Approved
SV Amplitude	≤ 2	Approved
Flicker	≤ 2	Approved

In the case of SVs, besides the amplitude percentage error and number of events, the deviations in the duration of the disturbances in relation to the reference value are also accounted for. Thus, the concept attribution in respect to the duration will be treated as established in Table 2.

Table 2. Assigning concepts SVs duration - Met-A

Error Ranges [Circles]	Concept
≤ 2	Approved
> 2	Disapproved

- **Criteria for approving the Equipment by Module:** After assignment of the concepts, the equipment will be considered approved in a certain module when the errors found in all tests comprising this module are equal to or lower than the limits established in Tables 1 and 2.

Met-B

This is a methodology for assessing the performance of the PQ analyzers based on metrological and technical aspects required by IEC 61000-4-30 [5]. The methodology is composed of questionnaires and laboratory tests. When these are applied to the equipment under test (EUT), they express its performance in the PQ parameters calculation.

Met-B evaluates the aspects required by IEC 61000-4-30 through three types of tests, namely type Q tests (Questionnaires), type V tests (Verification), and type C tests (Calibration). Explained next are the performance tests and procedures for the execution of the aforementioned method.

- **Type Q Tests:** These tests evaluate the technical aspects that are not directly related to electric energy quantities. These aspects are verified using objective questions elaborated in accordance with the requirements of the standard. If the EUT includes the demanded capabilities, the report will be " Comforming". Otherwise, it will be "Non-conforming".
- **Type V Tests** Type V tests are intended to verify the technical aspects directly related to the electric energy quantities. This has to do with comparisons between the results of the EUT measurements and the standard measurement system (SMS) when the EUT is subjected to various signals previously selected. Based on the characteristics of signals employed, it is verified whether or not the EUT makes use of the methods and techniques required by the standard. The signs change according to the ongoing evaluation. The following tests make up the V type tests:
  - Attenuation of harmonics;
  - Real RMS value;
  - Symmetrical components;
  - Filter *anti-aliasing*;
  - Mains signalling voltage on the supply voltage;
  - Measuring underdeviation and overdeviation parameters.

  After executing a type V test, the EUT displays a measurement used for calculating the type V error (E_v) given by the equation (3). If the E_v is less than or equal to the maximum uncertainty permitted by IEC 61000-4-30, the report is "Conforming ". Otherwise it is "Non-conforming ".

(3) $$E_v = |V_{EUT} - V_{SMS}|$$

Where:
V_{EUT} is the measurement result of the EUT; and
V_{SMS} is the measurement result of the SMS.

- **Type C Tests** Type C tests have the objective of verifying the metrological requirements. This is the estimation of measurement errors in accordance with the calibration procedures when quantifying a given PQ parameter. The errors are determined in the measuring range required by the standard. The characteristics of the signals applied to the EUT allow the identification of its metrological performance in three different conditions of the voltage waveform. These conditions refer to the frequency deviation, degree of flicker, degree of unbalance and degree of distortion harmonic signal. Type C tests are divided into:

- *Constant values:* These are tests that verify the metrological performance of the EUT when the characteristics of the measurement parameter are maintained constant in time. They are present in the evaluation of the electrical frequency, the magnitude of the voltage, flicker, voltage unbalance, harmonic and inter-harmonic voltages. Each parameter under evaluation is applied to the EUT separately considering the three wave conditions.
- *Variables values:* These are tests that verify the metrological performance of the EUT when the characteristics of the parameter change over time. They are present in the evaluation of electrical frequency, the magnitude of voltage, voltage unbalance and harmonic voltages. Each parameter in evaluation is applied to the EUT such that the characteristics under analysis vary cyclically for a period equal to an aggregation time interval.
- *Events:* These tests are intended to verify the metrological performance of the EUT in the characterization of voltage dips, swells and interruptions:
  - *Event amplitude:*This quantity is analyzed based on the application of dips and swells with different amplitudes and the same duration on the EUT.
  - *Event duration:* This quantity is analyzed based on the application of dips, swells and interruptions with a constant amplitude and different duration on the EUT.

After the execution of a type C test, the EUT displays a set of measurements that are used to assess their metrological performance as a function of measurement errors. These errors are determined according to the ISO-GUM (2008) [**?**]. Thus, based on the measurements coming from the EUT and SMS, the ISO-GUM algorithm is applied to determine the bias (t) and the expanded uncertainty (U). The t and U are used in equation (4) to calculate the error for a type C evaluation (Ec). If Ec is less than or equal to the maximum uncertainty permitted by the standard, the report is “Conforming”. Otherwise it is “Non-conforming”.

(4) $$E_c = max\left(|t| + U\right)$$

Type C tests individually evaluate the performance of the PQ parameters of an EUT. The EUT report of a specific parameter is “Conforming” if all of the test reports related to that parameter are “Conforming”. If not, the report is “Non-conforming”.

The final EUT report will be “Conforming” if all of the reports of the parameters are “Conforming”. If not, the final report is “Non-conforming”.

Met-C

Met-C employs the IEC 610004-30 standard to establish the requirements to be evaluated, and also to identify its variation ranges. In this methodology, two tests are proposed.

- **Influence test:**This test aims to evaluate the performance of the EUT in the presence of a voltage supply of one or more electrical phenomena applied simultaneously (in steady state). For this, during the application of one or more phenomena on the EUT, its measuring performance for all the PQ parameters in question must be analyzed. In fact, in the laboratory, different levels of each PQ phenomena must be selected and applied to the EUT. The parameters to be evaluated are frequency, voltage magnitude, flicker, voltage unbalance and harmonics.
- **Event tests:**These tests address voltage variations in time in order to verify the performance of the EUT with respect to voltage dips and swells. The transitory conditions present in this stage should be provided from the database of real waveforms.

Application results of Methodologies A, B and C

In this section, the results of executing each methodology are shown. They are obtained from their application in a unique PQ analyzer (EUT). For the application of such methodologies, laboratory apparatus are assembled as presented in Figure1. Among the set of the demanded equipment is a programmable source that allows the definition and generation of three phase voltage signals.

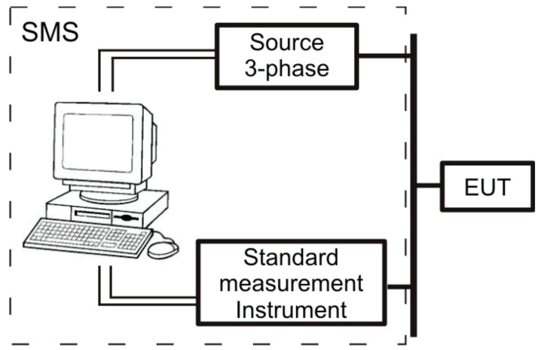

Fig. 1. Schematic laboratory equipment for tests execution.

MET-A Application

For the implementation of Met-A in the laboratory, the values of every quantity in each of the 42 tests prescribed must be selected. After the collection of the measurements from the EUT, the calculation of numerical indicators for the concept assignment is carried out.

Some aspects observed when analyzing the results of the application of Met-A are exhibited next:

1. In test 1 - harmonic distortion module - the errors calculated for phases A, B and C are equal to 0, 2,3 and 2,3 %, respectively. Therefore, since the maximum permitted error is equal to 2 %, the instrument is “Disapproved”. In this case, the value used as a reference for the three phases is equal to 2,10 % (THD programmed value in the voltage source). However, the standard measurement instrument (SMI) indicates that the THD values in phases A, B and C are equal to 2,10, 2,05, and 2,04 %, respectively. If these values are employed in equation (1) the errors of each phase will be equal to 0, 0,05, and 0,9 %, respectively, and consequently, the concept of this parameter is “Approved”.

2. In test 12 - harmonic distortion modules - the THD measurements collected for each EUT phase is 5,01, 4,90 and 4,95 %. When calculating the error/phase using equation (2), the result obtained is 2,19 %. So, the instrument in this test is “Disapproved”. When calculating this coefficient (error/phase), it is assumed that the supply source generates voltage signals with equal THD in all three phases. However, the measurement performed by the reference instrument (SMI) proves otherwise. Therefore, this type of method for the quantification of measurement errors can unfairly disapprove the instrument.
3. In test 15 - voltage unbalance module - the applied signal on the EUT is balanced (Reference value = 0 %). Considering that the template value is used in the denominator of the equation (1), such operation will incur indetermination. Hence, it is concluded that for this test, it is not possible to attribute the concept using the method suggested in this methodology for quantifying the measurement errors.
4. In test 16 - voltage unbalance module - the values derived from EUT measurement and SMS value are respectively equal to 1,86 and 1,73 %. Given that the maximum permitted error in this methodology is equal to 2 %, the instrument was considered concept disapproved. However, the absolute error (the difference between the measured value and the reference) is equal to 0,13 %. This value is smaller than the maximum measurement uncertainty permitted by the IEC 610000-4-30 standard, which is equal to 0,30 % for instruments of class S, and 0,15 % for class A. Thus, if the methodology adopted is in accordance with the limits of uncertainty from the aforementioned standard, the concept of the instrument would be approved.
5. Table 3 presents part of the results obtained from carrying out tests 20 and 24 (phase A) for the flicker module. As can be observed in Table 3, the EUT is approved in test 20 and disapproved in 24, although the absolute errors - column 6 of the aforementioned table - resulting from the difference between the measured values and reference, are equal. The concepts mentioned herein are from the calculation of the percentage error, equation (1), as established by Met-A. This situation is justified by the fact that the denominator of this equation is the reference value, which varies from test to test.

Table 3. Results of tests 20 and 24 - Phase A - Met-A

Test	EUT [Pst]	Reference [Pst]	Error [%]	Concept Concept	Absolute Error [Pst]
20	2,830	2,800	1,071	Approved	0,030
24	0,250	0,280	10,714	Disapproved	0,030

Having shown that, it is possible to conclude that the selection of different maximum errors from the maximum uncertainty suggested by the IEC 61000-4-30, justifies the points commented in item 3. Furthermore, it is observed that the error quantification method employed in Met-A can result in gaps which distort the actual performance of the instrument in evaluation.

Met-B Application

For the application of Met-B, according to the authors, a SMS that is able to secure a TUR (Test Uncertainty Ratio) greater or equal to 2 is demanded. It is noteworthy that in some situations, the required TUR is not met by the source that generates the signals used in the tests. In this case, it is necessary to use an SMI containing the set TUR.

Having carried out the assembly of laboratorial apparatus for performance of the tests, the values that each quantity must assume in type V and C tests are selected. After collecting the measurements from the EUT and SMS, the procedures established in ISO-GUM for the uncertainty calculation are employed.

The following are comments on some aspects related to the tests of the aforementioned methodology.

Type Q Tests

The EUT is in accordance with all technical specifications that are not directly related to the electric energy required by IEC 61000-4-30.

Type V Tests

Observing the results of the type V tests, note that the EUT presents, for all tests, smaller errors than the uncertainty allowed for class S analyzers (U_S). Thus, it can be affirmed that the measurement methods implemented in EUT are in accordance with those required by IEC 61000-4-30.

Type C Tests

Analyzing the results of type C tests, the following aspects are observed:

- In the frequency test - constant values, the maximum E_c determined is equal to 10 mHz. This value is 5 times smaller than the allowed uncertainty for class S measurement meters (50 mHz). However, in the variable values tests, the maximum E_c obtained is equal to 200 mHz. It is concluded that the instrument is reliable if the frequency has no variation in time;
- In the flicker test - constant values, the E_c calculated for flicker in the three phases are above the uncertainty permitted by the standard.

It should be emphasized that this methodology provides the error curves (graph that shows the errors presented by the measurement system according to its reading), for each quantity in evaluation. This allows a more detailed diagnosis of the measuring system by means of identifying the region where the meter is more reliable.

Met-C Application

The document available in the literature on Met-C does not mention laboratorial specifications, and does not show the methods for quantifying the performance of the instrument in evaluation. Therefore, instrument evaluation is performed according to the requirements and the maximum uncertainty permitted by IEC 61000-4-30.

Here are some comments resulting from the analysis of obtained outcomes:

- In the influence test, the measurements of the frequency parameters, the voltage magnitude, the voltage unbalance and voltage harmonics proceeding from the EUT are within acceptable values by IEC 610000-4-30;
- Also in the test, when evaluating flicker, the EUT presented measurement errors within the limits established by IEC 61000-4-30 for 15 of the 25 tests performed. However, in some conditions, the EUT did not provide the measured values of flicker.
- In the event tests, the EUT obtained admissible results when assessing the amplitude of the dips and swells, as well as the duration of the dips. However, the errors in the evaluation of the duration of the swells reached a level 3 times greater than the permitted uncertainty.

Considering that in practice the phenomena manifest simultaneously at times, the tests proposed by Met-C are characterized as recommended for evaluating the functional performance of PQ measurement instruments. However, it must be emphasized that the mentioned methodology does not permit identification if the meter presents technical or metrological restrictions. This is because it does not present tests as shown in Met-B, which is dedicated to this purpose.

Comparative Evaluation of the Methodologies

From the previous sections, it is possible to observe that the methods used in this study are based on three aspects to evaluate the performance of a measuring instrument. They are: i) the performance tests, ii) the quantification method of measurement error, and iii) the strategy of report attribution. These three aspects and also the results from applying each of the methods in laboratory tests are used in the comparative evaluation.

Performance Tests

The performance tests enable evaluating the EUT in the laboratory through its submission to voltage waveforms which generally are similar to what can be found in the electric grid. Note that the equipment used to generate the signals is not analyzed in this study. It should also be emphasized that metrology specialists strongly recommend that the equipment have a level of uncertainty for each PQ parameter at least twice smaller than the uncertainty evaluation. If this condition is not met, the results are not valid. Therefore, especially for the evaluation of Class A instruments, the laboratory structure may require high investments.

The selection of the signals used in the tests can be performed considering a range of measuring parameters internationally recognized. The three methodologies in evaluation in this study apparently structured their performance tests according to the international directives of the IEC 61000-4-30 standard. In other words, they meet the measuring range set for each parameter, and seek to verify that the measurement protocol used by the meter is according to that required. Nevertheless, the testing methodologies notepad analyzed in this study are significantly different.

From the analysis of the testing notepad, it is also possible to verify that Met-C is composed of a set of steady state tests, for which there is a simultaneous presence of more than one type of phenomenon per signal. For this reason, the signals used in the Met-C are more similar to those in the electric grid than the ones in the other methodologies. In addition, with more than one phenomenon in the same signal, it is possible to reduce the duration of the tests, without altering the number of variables and the measurement range of each parameter. Met-A does not use signals with the simultaneous presence of more than one PQ parameter.

Further analyzing the performance tests used by the methodologies under study, it is possible to observe that Met-B is the only one that divides its tests into three different types in order to separately identify the technical and metrological constraints of the EUT.

Quantification Methods of Measurement Errors

In evaluations of functional performance instruments, the use of documents which permit the international standardization of requirements and protocol measurement is natural. This is an efficient way to eliminate the possibility of an instrument being approved by one methodology and disapproved by another, simply due to different PQ parameter variation ranges used during the tests. For the same reason, it is also natural to internationally standardize the methods of calculating the measurement errors.

Regarding the measurement errors quantification methods, from the analysis of the methodologies under study, it is possible to verify that Met-A does not employ an internationally recognized uncertainty calculation method. On the other hand, Met-B follows the ISO-GUM recommendations to calculate the measurement error, a method accepted by *Bureau International des Poids et Mesures*. As for Met-C, it was verified that the document available in this work for its laboratory reproduction, does not make mention of the method used when calculating the error. For this reason, the recommendations of ISO-GUM were adopted for Met-C.

Attribution of the Performance Report

The attribution of the performance report is a direct consequence of the measurement error quantification method employed, and also the procedures established for each methodology. In fact, the report is a consequence of the comparison between the results from the instrument performance quantification (measurement errors) and the maximum uncertainty determined by each method.

Although IEC 61000-4-30 presents its maximum uncertainty recommendations for each PQ parameter, recognized and used worldwide, each methodology can establish the values that suit it. In this study, it was verified that Met-B and Met-C adopt the maximum uncertainty suggested by IEC 61000-4-30. On the other hand, Met-C presents its own maximum levels of allowed errors.

Table 4 shows the reports of the application of the three methodologies used in this work. It is possible to observe when evaluating parameter voltage unbalance, that Met-A is the only methodology that presented report "Non-conforming". This is because Met-A has i) an error quantification method different from those of the other methodologies, and also because it adopts for this parameter ii) a limit of measurement error different from that suggested by IEC 61000-4-30.

Table 4. EUT Results from the Application of the Three Methodology in Study

Quantities	Met-A	Met-B	Met-C
General Aspects	Not Evaluated	Conf.	Not Evaluated
Frequency	Not Evaluated	Non-Conf.	Conf.
Voltage Magnitude	Conf.	Conf.	Conf.
Fluctuation	Non-Conf.	Non-Conf.	Non-Conf.
Did and elevation	Non-Conf.	Conf.	Non-Conf.
Unbalance	Non-Conf.	Conf.	Conf.
Harmonics	Non-Conf.	Conf.	Conf.

conf.=conforming

Also from Table 4, it is possible to verify when evaluating the flicker parameter that the three methodologies lead to "Non-conforming"reports. Nevertheless, by analyzing the results in detail, it can be noticed that the calculated measurement errors are significantly different. Besides the differences between the voltage signals used in each method, a justification for this result is the fact that the measurement error calculation methods are distinct.

Thus, it is possible to conclude that the approval of an instrument "1" by Met-A, of an instrument "2"by Met-B, and of an instrument "3"by Met-C does not guarantee equivalent measurements even when these three devices are simultaneously subjected to the same signal. This is due to the differences between the performance tests, the error calculation methods, and the maximum acceptable limits present in each of these methodologies.

It is worth noting that these differences make it impossible to establish a traceability metrological of the instrument.

Based on the aspects mentioned herein, there is a need for the development of an alternative methodology for assessing the functional performance of the PQ measuring instruments. Besides associating the procedures identified as most desirable in a single document, the alternative methodology serves as a pattern that will enable the establishment of the traceability chain.

Proposal for an Alternative Methodology for Evaluating PQ Measuring Instruments

The methodology proposed in this section considers the main advantages observed when the analysis of Met-A, Met-B and Met-C was made. For this reason, besides the simultaneous presence of PQ parameters in signals used in laboratory tests, three types of tests are elaborated to evaluate the metrological and technical requirements of the instruments, based on the directives of the IEC 61000-4-30 standard

Type Q Tests

These tests evaluate technical aspects that are not directly related to the PQ parameters (measurement ranges and *flagged*). Such aspects are verified through objective questions elaborated in accordance with the requirements of the IEC 61000-4-30. In order to answer the questions that comprise the type Q tests, the test executor must inspect the device manuals and compare the results with what is required by the standard. If the EUT includes the demanded capacities, the report will be “Conforming”. Otherwise, it will be “Non-conforming”.

Type V Tests

The type V tests evaluate the technical requirements directly related to electric energy. These are tests that generate voltage signals with certain characteristics to verify that the EUT makes use of the methods and measurement techniques required by the standard. They are:

Harmonic Attenuation The objective of this test is to evaluate the attenuation of harmonic components in the electric frequency measurement. The execution of harmonic attenuation action aims to filter out components that can interfere with the frequency measurement method. The frequency value is calculated by determining the number of signal crossings over a period of 10 s. For this, the EUT is subjected to signals with voltage harmonics. These signals have three or more zero crossings during the cycle of the nominal frequency (f_{nom}). Employing the signal generated by equation (5), one or more known harmonic orders are inserted in the voltage signal, and thus the number of crossings in a period of 10 s increases. If the EUT does not attenuate the harmonics added to the signal, it will present a different value to that expected, and for this reason, it is not in accordance with what the standard demands.

(5) $$v\left(t\right) = U_{din}\cos\left(2\pi f_{nom}t\right) + \sum_{m} U_m \cos\left(2\pi m f_n t + \theta_m\right) \quad V$$

Where:

U_{din} is the nominal voltage employed in the test; U_m is the harmonic voltage amplitude selected by the test executor; and θ_m is the angle of the harmonic voltage amplitude selected by the test executor.

Real RMS value This test aims to evaluate if the algorithm implemented to calculate the voltage magnitude is the real RMS value. For this, the EUT is subjected to non-sinusoidal waveforms (square waves, triangular waves, rectified waves, etc.).

Symmetrical components This test aims to evaluate if the algorithm implemented to calculate the voltage unbalance is the method of symmetrical components or of CIGRE. For this, the EUT is subjected to three-phase systems that demonstrate, by means of the results found, if the method used to quantify the unbalance is one of those required by the standard.

Anti-aliasing filter The purpose of this test is to verify if the application of anti-aliasing filter is in accordance with the demand of the IEC 61000-4-30 standard. According to this document, the EUT should at least measure up to the 40th harmonic. In fact, the filtering of frequencies higher than those it is theoretically able to provide is required of the EUT. In this test, using equation (5), one or more known harmonic orders with frequencies above that indicated as a limit is inserted in the signal. By applying to the EUT only harmonic orders superior to what the meter is said be able to identify, the THD must be zero. If the value of the THD is different from zero, the EUT does not comply with what the standard requires.

Measurement of communication voltage signals This method measures the level of the voltage signal at the carrier frequencies specified by the user. For this, the EUT is subjected to communication signals at different frequencies.

Measuring parameters of overdeviation and underdeviation This test is designed to evaluate the measurement methods of parameters of overdeviation and underdeviation. For this, the EUT is subjected to various voltage levels above and below the U_{din}.

After the execution of a type V test, the EUT displays a measurement that is used for calculating the type V error (E_v), given by the equation (6). If $E_v$is less than or equal to the maximum uncertainty permitted by the standard, the report is “Conforming”. Otherwise it is “Non-conforming”.

(6) $$E_{\mathrm{V}} = \left|V_{EUT} - V_{SMS}\right|$$

Where:

V_{EUT} is the measurement derived from EUT;

V_{SMS} is the measurement derived from SMS.

Type C Tests

The type C tests of this methodology aim to verify the metrological requirements of the EUT through the application of a set of signals which have one or more PQ phenomena on the EUT, and employing an uncertainty calculation method present in ISO-GUM. Following is the description of the type C tests:

Influence test With the tests laid down in this stage, the frequency, the voltage magnitude, flicker, the voltage unbalance and voltage harmonics are analyzed. Table 5 shows the sequence that should be employed when performing the 25 proposed tests. The five different levels that each parameter can assume, cover the measuring range required by the IEC 61000-4-30 standard. They are shown in Table 6.

Table 5. Tests ands Levels influence test

Test	Frequency	Voltage/Unbalance	Flicker	Harmonics
1	Level 1	Level 1	Level 1	Level 1
2	Level 1	Level 1	Level 1	Level 2
3	Level 1	Level 1	Level 2	Level 3
4	Level 1	Level 2	Level 2	Level 4
5	Level 1	Level 2	Level 3	Level 5
6	Level 2	Level 2	Level 3	Level 1
7	Level 2	Level 3	Level 4	Level 2
8	Level 2	Level 3	Level 4	Level 3
9	Level 2	Level 3	Level 5	Level 4
10	Level 2	Level 4	Level 5	Level 5
11	Level 3	Level 4	Level 1	Level 1
12	Level 3	Level 4	Level 1	Level 2
13	Level 3	Level 5	Level 1	Level 3
14	Level 3	Level 5	Level 2	Level 4
15	Level 3	Level 5	Level 2	Level 5
16	Level 4	Level 1	Level 2	Level 1
17	Level 4	Level 1	Level 3	Level 2
18	Level 4	Level 2	Level 3	Level 3
19	Level 4	Level 2	Level 3	Level 4
20	Level 4	Level 3	Level 4	Level 5
21	Level 5	Level 3	Level 4	Level 1
22	Level 5	Level 4	Level 4	Level 2
23	Level 5	Level 4	Level 5	Level 3
24	Level 5	Level 5	Level 5	Level 4
25	Level 5	Level 5	Level 5	Level 5

Variables Value Tests In this test, the parameters to be analyzed are frequency, voltage magnitude, voltage unbalance and voltage harmonics.

For its implementation in the laboratory, it is necessary i) to select the values of the parameters in evaluation which cover the variation range required by the standard, and ii) to switch these values periodically during the aggregation period under study. It is noteworthy that at least three samples must be taken at the end of the test. For example, for the evaluation of frequency (51-69 Hz), the values used in the tests are equal to 52, 54, 56, 58, 60, 62, 64, 66 and 68 Hz. The first test starts with a frequency equal to 52 Hz, and it is increased every 2 seconds until the end of the measurement interval of 10 s. Note that the reference value is equal to 56 Hz. The second test starts with the frequency equal to 54 Hz. In the third, it is 56 Hz, and so on, until they cover the range required by the standard.

Event Tests These tests have the purpose of verifying the metrological performance of the EUT when considering the characterization of the amplitude and duration of the dips, swells and interruptions voltage. Note that for these parameters, the IEC 61000-4-30 standard does not define a variation range because these are non-stationary phenomena in time. In this stage, three kinds of tests are proposed:

The amplitude of the event This quantity is analyzed based on the application of dips and swells with different amplitudes and the same duration on the EUT. The amplitude of the pre-event tension must be equal to U_din. A set of values that can be used in this type of test are presented next. Initially, the EUT is subjected to five equal voltage sags 0,15, 0,35, 0,55, 0,75 and 0,85 % of the voltage with a constant duration of 1 s. With this, the EUT must present a set of five measurements for the evaluation of the voltage amplitude.

Duration of the event This quantity is analyzed based on the application of dips, swells and interruptions, with different durations and the same voltage amplitude on the EUT. The amplitude of the pre-event tension must be equal to U_din. Initially the EUT is subjected to five elevations with durations equal to 0,2, 0,7, 1,2, 1,7 2,2 and 3,0 s and voltage amplitude equal to 135 %. With this, the EUT must present a set of five measurements for its evaluation of the duration of the event.

Table 6. Influence test values

Frequency and Flicker Values

	Level 1	Level 2	Level 3	Level 4	Level 5
Frequency [Hz]	52	56	60	64	68
Flicker [Pst]	0,5	1	1,5	2,5	3,5
$\Delta V/V[\%]$	0,2735	0,5470	0,8205	1,3675	1,9145
Rectangular variations per minute equal to 1620					

Magnitude and Voltage unbalance values

	Level 1	Level 2	Level 3	Level 4	Level 5
Phase 1	20	50	80	100	120
Phase 2	21 $\angle 242$	48 $\angle 242$	83 $\angle 242$	99 $\angle 242$	120 $\angle 242$
Phase 3	18 $\angle 118$	53 $\angle 122$	77 $\angle 118$	102 $\angle 122$	122 $\angle 118$
u_2	4,45	4,04	2,91	2,03	2,33
All values are expressed in percentage of % U_{din}					

Voltage harmonics values

h	Level 1	Level 2	Level 3	Level 4	Level 5
1/2	1,0	2,5	5	7,5	10
3/2	10	1,0	2,5	5	7,5
2	7,5	10	1,0	2,5	5
3	5	7,5	10	1,0	2,5
5	2,5	5	7,5	10	1,0
7	1,0	2,5	5	7,5	10
8	10	1,0	2,5	5	7,5
9	7,5	10	1,0	2,5	5
All values are expressed in percentage of % U_{din}					

Real Signals These tests address voltage variations in time in order to verify the performance of the EUT in respect to dip and swell voltages. The transitory conditions present in this stage must originate from the database of real waveforms.

After the execution of a type C test, the EUT displays a set of results that are used to evaluate its metrological performance. This performance is estimated in accordance with the ISO-GUM. Having the measurements of the EUT and the standard values coming from the SMS, the ISO-GUM algorithm is applied to calculate the estimated values of the bias (t) and the expanded uncertainty(U). Equation (7) determines the type C evaluation error. If (E_c) is less than or equal to the permitted maximum uncertainty, the report is "Conforming". Otherwise it is "Non-conforming".

(7) $$E_{\text{C}} = max\left(|t| + U\right)$$

EUT Final Report

The tests shown in this work individually evaluated the performance of the EUT on the measurement of PQ parameters. The EUT report of a given parameter is "Conforming", if all test reports related to that parameter are "Conforming". Otherwise, the report is "Non-conforming". The final report of the EUT is "Conforming", if the reports of all parameters are "Conforming". Otherwise, the final report is "Non-conforming".

Application Example of the Proposed Methodology

Conforming to metrology experts, the relationship between the SMW uncertainties and those required by IEC 61000-4-30 - TUR - must be greater or equal to 2.

In this study, the application of the methodology in question was carried out using the system shown in Figure 1. The three-phase source has a U_{din} equal to 127 V phase-neutral and a nominal frequency equal to 60 Hz. The EUT, according to the manufacturer, was developed based on class S requirements of the IEC 61000-4-30.

Following are the main results obtained from the execution of the new methodology.

Execution of Type Q Tests

Considering the performance of type Q tests, it was possible to conclude that:

- The EUT executes measurements of the electric frequency every 10 s;
- It provides measurements in all four time intervals required by the standard (12 cycles, 180 cycles, 10 minutes and 2 hours) for the parameters of the magnitude, the voltage unbalance and harmonic voltages;
- The EUT carries out the measurements of the flicker (Pst and Plt);
- Measurements up to the 40th harmonic order are made available;
- The flagging concept is adequately employed;
- The voltage and duration measurements are available for the dip, swell and interruption parameters.

Execution of Type V Tests

In the execution of type V tests, the EUT was subjected to seven different voltage signals. Measurements of the electric frequency were collected every 10 s. For the other parameters, measurements were taken every 12 cycles. The characteristics of the voltage signals generated to perform the type V tests are:

Harmonic attenuation: To execute this test, a signal was generated according to the following function:

$$v(t) = U_{din}\left(\cos(2\pi f t) + 0,3\cos(2\pi f 25 t + 30)\right) \quad V$$

Real voltage value: At this stage of the tests, two signals were applied to the EUT:

1. A square wave with rms voltage equal to U_{din}; and
2. A triangular waveform with rms voltage equal to U_{din}.

Symmetrical components: To implement this test, a three-phase system with the following functions was applied to the EUT:

$$v_{\mathsf{A}}(t) = U_{din}\cos(2\pi \cdot 60t) \quad V$$
$$v_{\mathsf{B}}(t) = U_{din}\cos(2\pi \cdot 60t + 249) \quad V$$
$$v_{\mathsf{C}}(t) = U_{din}\cos(2\pi \cdot 60t + 125) \quad V$$

Filter *anti-aliasing*: To realize this test, a signal according to the following function was used:

$$v(t) = U_{din}\left(\cos(2\pi f t) + 0,1\cos(2\pi f 60 t)\right) \quad V$$

Measurement of parameters of overdevation and under deviation : For the mentioned test, two signals were used:

1. A sinusoidal waveform with rms voltage value equal to 0,95×U_{din};
2. A sinusoidal waveform with rms voltage value equal to 1,05×U_{din}.

After the execution of type V tests, the measurement results were applied to equation (6) to determine the E_v. Table 7 shows these errors together with the permitted uncertainties (U_s).

Table 7. Execution results of the type V tests

Test	E_{V}	U_{S}
Harmonic attenuation	0,002 Hz	0,05 Hz
Real RMS value - signal 1	0,020 V	0,635 V
Real RMS value - signal 2	0,030 V	0,635 V
Symmetrical components	0,04 %	0,30 %
Anti-aliasing filter	0,01 %	0,30 %
Inferior deviation parameter	0,03 %	0,50 %
Superior deviation parameter	0,05 %	0,50 %

Table 8. Execution results of type C tests

Parameters	E_{C}	U_{S}	**Report**
Influence test			
Electric Frequency	0,014 Hz	0,050 Hz	Conforming
Voltage Magnitude	0,13 V	0,63 V	Conforming
Voltage fluctuation	Undetermined	5%	Non-Conforming
Voltage unbalance	0,03 %	0,30 %	Conforming
Harmonic Voltages	0,12 %	0,50 %	Conforming
Variables Values tests			
Electric frequency	0,21 Hz	0,050 Hz	Non-Conforming
Voltage magnitude	0,14 V	0,63 V	Conforming
Event Tests			
Sag amplitude	0,31 V	1,27 V	Conforming
Sag duration	0,008 s	0,032 s	Conforming
Amplitude elevation	0,28 V	1,27 V	Conforming
Elevation duration	0,015 s	0,032 s	Conforming
Interruption duration	0,006 s	0,032 s	Conforming
Amplitude of real signals	0,603 V	1,27 V	Conforming
Duration of real signals	0,064 s	0,032 s	Non-Conforming

From Table 7, it is observed that the values of E_v for all tests are smaller than the permitted uncertainties. Thus, it can be said that the measurement methods used in the EUT are in accordance with those required by IEC 61000-4-30.

Execution of Type C Tests

At this stage of laboratory tests, 275 measurements were performed during the "influence test", 39 in the "varying values test", and 142 in the "event tests ", totaling 456 measurements. Having the measurements of the EUT and the SMS, t and U were calculated according to the uncertainty expression of the ISO-GUM algorithm (with a coverage factor of 95 %). Then the t and U are used in equation (7). Table 8shows, for each test, the highest value of E_C found, considering the three phases of the system. Also displayed in this same table, is the value of the uncertainty permitted (U_s) by the standard.

Analyzing the test C results shown in Table 8, the following aspects can be identified:

Influence Tests: The measurements proceeding from the EUT of the frequency parameters, the voltage magnitude, the voltage unbalance and harmonics are acceptable considering the limits established by the IEC 610000-4-30 standard. Although the evaluation of the flicker has presented Pst within

Table 9. EUT Results from the Application of Methodologies A,B,C, and that proposed in this study

Parameters	**Proposal**	**Met-A**	**Met-B**	**Met-C**
Gen. Aspects	conf	N/E	conf	N/E
Frequency	Non-conf	N/E	Non-conf	conf
Magnitude	conf	conf	conf	conf
Fluctuation	Non-conf	Non-conf	Non-conf	Non-conf
Dip and swell	Non-conf	Non-conf	conf	Non-conf
Unbalance	conf	Non-conf	conf	conf
Harmonic	conf	Non-conf	conf	conf

conf.=conforming, N/E=Not Evaluated

the limits established by IEC 61000-4-30 for 15 of the 25 tests performed. In some conditions, the measuring instrument did not provide the measured values of Pst.

Varying value tests: In the frequency test, the E_c is identified above the permitted value. In addition, it is noteworthy that the E_c found in this test is 14 times larger than the E_c identified in the influence test. The other parameters are below the thresholds established by the standard.

Event Tests In the amplitude and duration tests of the event, the E_c calculated met the metrological requirements demanded by the standard. However, the E_C calculated in the duration of the "real signals event test" were twice larger than the permitted uncertainty.

EUT final performance

Column 1 in Table 9 shows the EUT reports for each parameter of each method executed in this study.

Considering the results from the implementation of the proposed methodology, it is possible to observe that the EUT meets most of the requirements demanded by the IEC 61000-4-30 standard. However, according to the criteria established to issue the final report of the instrument, the EUT cannot be classified as a class S analyzer.

Additionally, in Table 9 it is verified that the proposed methodology exhibited different results from those found by methodologies A, B and C, in one or more parameters.

Conclusions

The main objective of this study was to propose an alternative methodology for analyzing the functional performance of PQ monitors, based on three works found in the literature that optimize this process. For this, initially the tests proposed in these methods were implemented in laboratory and applied to a single PQ analyzer. Having acquired the results from the tests of these methodologies, a comparative evaluation between them was carried out. The main results observed are:

- The three methodologies in evaluation i) meet the variation range established in the IEC 61000-4-30 standard for each PQ parameter, and ii) seek to verify if the measurement protocol employed by the instrument is in accordance with that required. However, significant differences were verified between the notepad of the tests of the mentioned methodologies.
- Regarding the quantification methods of the measurement errors, it was noticed that Met-A employs the calculation of percentage error, and Met-B makes use of a guide for the uncertainty expression - ISO-GUM. Since the document that presents Met-C does not mention how to proceed on quantifying the measurement error, the procedures suggested by ISO-GUM were employed in this study. After analyzing the results achieved in the laboratory, it was noted that the method of calculating the percentage error has gaps that can lead to a misinterpretation of the real performance of the instrument in evaluation.
- It was verified in this study that Met-B and Met-C employ the maximum uncertainty suggested by IEC 61000-4-30. On the other hand, Met-A presents its own maximum levels of permitted uncertainty.
- From the comparative evaluation it was possible to infer that an "1"instrument approved by Met-A, may not provide equivalent measurement for the "2"and "3"instruments, approved respectively by Met-B and Met-C, even when these three pieces of equipment are simultaneously subjected to the same signal. This is due to differences between the performance tests, the error calculation methods, and the maximum acceptable limits present in each of these methodologies.

The alternative methodology for evaluating the PQ measuring instruments proposed in this work compiles the procedures identified as the most recommendable by comparative evaluation in a single document and serves as a pattern that will enable the establishment of a traceable chain. In fact, such methodology employs the ISO-GUM for the estimation of measurement error and demands the instrument to meet all the requirements of the IEC 61000-4-30 (the measurement protocols, ranges and uncertainties of PQ parameters).

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