XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6−11, 2009, Lisbon, Portugal

CHARACTERIZATION ISSUE OF POWER QUALITY INSTRUMENTS

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Abstract − This paper analyzes some aspects related with metrological characterization of instrument for power quality monitoring in order to move a step toward the definition of a full performance verification protocol. This protocol should include not only test situations reported in related standards, but also an array of different voltage and current fluctuations - related to common Power Quality issues - that may be encountered in actual power systems. This performance analysis is particularly interesting because it can be found that different power quality instrument, fully meeting characteristics prescribed in standard, may still disagree significantly in some actual measurements. The aim of discussion carried out in the paper is also the specification of requirements of a test system devoted to calibration and verification of a PQ monitor such as it is done in type testing. After a preliminary discussion about technical and theoretical issues related to performance analysis of these instruments, a proposal of test protocol definition based on design of experiment is presented with reference to some PQ phenomena.

Keywords Power Quality Instrument, Metrological Characterization, Experimental Design.

1. INTRODUCTION

In the last years, an increasing number of electrical customers have experienced remarkable drawbacks caused by electrical Power Quality (PQ) issues in power supply systems. These phenomena have always been present in power system, but only recently they are causing serious problems with significant consequence from economical point of view. In fact, new electronic devices used in electrical installations are more sensitive to PQ issues with respect to those of older technology, because they contain control systems equipped by microprocessors that can suffer of large malfunctions due to even small variations of supplying conditions.

Although PQ measurement systems play a crucial role in spheres of extreme significance from economical and technological point of view, their calibration and performance assessment still present unresolved technical and theoretical issues related to the difficulties of guaranteeing metrological traceability through classical approaches. Because of that, different implementations of PQ monitors that fully meet definitions reported in standard ([1]-[5]) can still disagree significantly in some actual measurements.

Mainly it happens, because the standards include performance specifications, but without a well defined procedure for their verifications. The ambiguity contained in these procedures in terms of limited number of testing conditions and not full definition of test waveforms determines an ambiguity in performance assessment so leaving a certain degree of freedom to instrument manufacturers. In addition, a test system for performance assessment of PQ monitor system, in order to check the accuracy requirements in agreement with standards, needs characteristics not easy to achieve and, consequently, very difficult to proof. In fact, it is important to underline that calibrating power quality measurement equipments should have a legal status similar to other measurement equipment used for commerce, because they could become a key instrument in energy market. A final aspect to account is the effect of transducers being inserted between the power system and the instrument. They are acknowledged but not addressed in detail in standards.

This paper moves a step into direction of defining a comprehensive test protocol able to ensure that the implementation is correct and different meters will agree with all types of actual measurements. Tests should include not only the complete set of IEC test situations, but also an array of different PQ situations that may be encountered in actual use. The aim of discussion carried out in the paper is also the specification of requirements of the test system for calibration and verification of a PQ monitor such as it is done in type testing. The full suite of tests should be recommended when a new product is placed on the market and in case of a dispute between two parties on a measurement result.

Some additional tests are proposed in order to test proper flagging, influence relation among measurement parameters. To face the difficult task of waveform test definition when numerous parameters should be chosen and accounted together, the authors propose the use of an optimal design of experiment. This approach allows, at the same time, to reduce the number of experimental tests, with respect of those needed by analysis of all combinations of parameters, and to obtain repeatable and reliable results.

Finally, proposal of test protocol definition based on design of experiment was presented with reference to some PQ phenomena.

2. POWER QUALITY MEASUREMENT

Power quality is the characteristic of the electricity supplied at a given customer through an electrical system, evaluated against a set of reference technical parameters along time. Therefore, in order to state the power quality level, a measurement instrument has to monitor one or many technical parameters, in continuously way and along a remarkable time interval (weeks or months).

The fundamental reference for power quality monitoring instruments is EN 61000-4-30 [3]. If fact, this standard, in its first section, defines the methods for measurement and interpretation of results for power quality parameters in 50/60 Hz a.c. supply systems.

In this paper, only main PQ phenomena are considered and they are reported in Tab. I together with measurement parameters that characterize them. In Tab. I the subscript *din* indicates the declared magnitude and *m* indicates the measured magnitude. They are:

- fundamental frequency deviation, that is a change in base power frequency to which all electrical quantities are referred;
- fluctuation of the supply voltage, that is produced by changes in power system configurations and/or loads which commonly happen during a day and result in changes of voltage magnitude. This specific measurement method refers to quasi-stationary signals;
- light flicker, that is produced by rapid amplitude fluctuations in voltage that typically cause visible changes in light from electric lighting sources;
- voltage dips and interruptions, that are reductions of the voltage magnitude at a point in the electrical system below a specified threshold;
- voltage swells, that is an increase of the voltage at a point in the electrical system above a specified threshold;
- voltage unbalance, that is a condition in a polyphase system in which the r.m.s. values of the line voltages (fundamental component), or the phase angles between consecutive line voltages, are not all equals;
- voltage and current harmonics and interharmonics, which are sinusoidal components present in voltage or current in addition to fundamental component at frequency that is an integer multiple or not integer multiple, respectively, of fundamental power frequency;

Depending on the purpose of the measurement, all or a subset of the phenomena on this list may be measured.

For each measured parameter, two classes of measurement performance are defined: Class A and Class B. Class A performance is used where precise measurements are necessary, for example, for contractual applications, verifying compliance with standards, resolving disputes, etc. Any measurements of a parameter carried out with two different instruments complying with the requirements of class A, when measuring the same signals, should produce matching results within the specified uncertainty. Class B may be used for statistical surveys, trouble-shooting applications, and other applications where low uncertainty is not required. In this paper, only class A is accounted. The uncertainty levels required for a class A instrument in [3] are reported in Tab. I for accounted measurement parameters.

Table I. Measurement parameters and uncertainty specifications from [3] for main power quality phenomena

Phenomenon	Measurement Parameter	Maximum Permissible Error in Class A
Frequency deviation	Power frequency	±0,01 Hz.
Fluctuation of the supply voltage	r.m.s. value	±0,1 % of U_{din}
Light flicker	Pst (see [9])	None specified.
Voltage dip/ Voltage swell	Residual voltage/ voltage magnitude	±0,2 % of U_{din}
	Duration	±1 cycle
Voltage interruption	Duration	2 cycle
Supply voltage unbalance	Negative sequence zero sequence	±0,15% of positive sequence
Voltage Harmonics	Harmonic subgroups	±5% U_m $U_m \geq 1\% U_{din}$ ±0,5‰ U_{din} otherwise
Current Harmonics	Harmonic subgroups	±5% I_m $I_m \geq 3\% I_{din}$ ±1,5‰ I_{din} otherwise
Voltage - Current Interharmonics	Interharmonic groups	Identical to those given for harmonics subgroups

It is worthwhile noting that [3] assumes as definition of accuracy: maximum expected deviation of a measured value from its actual value. This is not in agreement with [6] and maximum permissible error was preferred, in Tab. I.

3. PERFORMANCE VERIFICATION

Metrological characterization of instrument adopted for PQ measurement still presents unresolved theoretical, technical and practical issues that, at best author knowledge, are yet not fully addressed by standards or scientific literature. Therefore, it is a real challenge to assess accuracy of measurement results and to guarantee their metrological traceability.

First of all, the severity of PQ phenomena is related to the waveform of electrical input signals. Thus, the same level can be reached with a number of shapes that are theoretically infinite but, in practice, very different waveforms can produce the same effect. So even if the performances are verified in a certain situation, it does not assure that they still apply in very different situations. For example, the same level of flicker can be reached with a single sharp voltage variation or with cyclic smaller changes. Accuracy of an instrument checked in the first situation does not assure at all the same performances in the second. Numerous test conditions are required..

Moreover, the severity measurement of a specific PQ phenomenon can be affected by the presence, at the same time, of one or many disturbing influence quantities on the electrical input signal due to others PQ phenomena. It is apparent that some influence quantities must not influence the value of the measured parameter (for example, the measurement of supply voltage unbalance must not be affected by harmonic components present at the same time). Though other influence quantities must influence the value of the measured parameter (f.i., harmonic components must influence the value of r.m.s.). Instrument performance should be tested with and without influence quantities. This implies that a full characterization requires considering combinations of different possible phenomena at different levels severity level with a remarkable increase of number of experimental verifications. In addition, design of experiments, their implementation and results interpretation are not trivial tasks. This implies that usually nobody performs an accuracy verification apart of manufacturer.

Often it is difficult even simply to know what is actually measured by these instruments. This is due to incomplete specifications about hardware and software supplied by manufacturers. Statistical elaborations make relation between phenomena and measurement results even more difficult to understand. In order to perform a proper usage of these devices, users should be aware of: sampling rate, bandwidth, accuracy, resolution, common mode rejection, anti-aliasing filter, window width, number of windows analyzed per second, type of weighted window used, accuracy of the synchronized device, global time synchronization method used and its accuracy, immunity of the instrument to disturbances in the supply voltage, operating environment and so on [1].

Instrument performances significantly depend also by implemented algorithm for PQ index measurement. Simplified procedures could give correct results in most situations but not in all situations. Finally, the electrical quantity to be measured may be either directly accessible, as is generally the case in low-voltage systems, or accessible via measurement transducers that should be accounted.

A. Verification According Standard

Accuracy specifications and verification procedure for a PQ instrument are addressed in [3]. It states that the result of a parameter measurement made by Class A instrument shall be within the specified maximum permissible error given in Tab. I when all other parameters are within their range of variation given in Tab. II.

In order to verify these performances accounting influence quantities, this standard defines three test situations in which accuracy of PQ instruments should be checked at 5 level of severity. First test state is characterized by influence quantities below the detection accuracy, thus there are no influence quantities affecting signals. Other two states, reported in Tab. III, include all steady state phenomena in two growing severity levels.

The uncertainty of an instrument shall be tested for each measured quantity as follows:

- select a measured quantity (for example, r.m.s. voltage);
- holding all other quantities in testing state 1, verify the uncertainty of the measured quantity to be tested at five equally spaced points throughout the range of influence quantity (for example, 0% of U_{din}, 50% of U_{din}, 100% of U_{din}, 150% of U_{din}, 200% of U_{din} for class A);
- holding all other quantities in state 2, repeat the test;
- holding all other quantities in state 3, repeat the test.

For flickermeter, a different verification protocol ([7], [8]) with numerous test situations (voltage variations at different frequencies) should be applied. Anyway, in these tests the effect of other PQ phenomena is not accounted.

Voltage dips, swells and interruptions are not reported in influence parameters. This is done because applying the flagging concept ([3]) when one of these phenomena is acting the others should not be accounted because the measurement parameters are meaningless.

Table II. Range of influence quantities (of the input signals) for class A performance verification

Influence quantities	Range of variation
Frequency	42.5 Hz-57.5 Hz for 50 Hz systems 51 Hz-69 Hz for 60 Hz systems
Voltage magnitude (steady-state)	0% – 200% of Udin
Flicker (Pst)	0 – 20
Unbalance	0% – 5%
Harmonics (THD)	Twice IEC 61000-2-4, class 3
Interharmonics (at any frequency)	Twice EC 61000-2-4, class 3
Mains signalling voltage	0 % – 9 % of Udin
Transient voltages according to IEC 61180	6 kV peak
Fast transients	4 kV peak

B. Limits of Verification According Standard

It is apparent that verification procedure in [3] is only intended to check in a broadly way the correctness of an instrument implementation. It leaves so many degrees of freedom in verifications, that results are not univocal and not reliable. For this reason, there is a surprising number of instruments on the market that claims to be "Class A" and that it isn't true in all the situation.

The performance of whole measurement system of course highly depends from the measurement transducers and their associated uncertainty, so an effective performance tests should include them too. Nevertheless, [3] suggest acknowledging the effects of transducers being inserted between the power system and the instrument but they are but not addressed in detail. Anyway, performance verification tests should be done including the measurement transducers and their associated uncertainty

The described protocol is intended to verify only measurements in steady-state conditions. This is done because most of measurement parameters in transient situations are meaningless (i.e. system frequency or harmonic groups during an interruption) so the results obtained in this situations have to be flagged as not useful. Anyway, checking behavior in dynamic situations, the proper detection of transient situation and flagging of unreliable data is of preeminent importance.

Table III. Uncertainty testing states for class A performance

Influence quantities	Testing state 2	Testing state 3
Frequency	f_{nom} – 1 Hz ±0.5 Hz	f_{nom} + 1 Hz ±0.5 Hz
Voltage magnitude	Consequent to below quantities	Consequent to below quantities
Flicker	Pst = 1 ± 0.1 – rectangular modulation at 39 changes per minute	Pst = 4 ± 0.1 rectangular modulation at 110 changes per minute
Unbalance	0.73% ± 0.5 % Phase A 0.80% ± 0.5 % Phase B 0.87% ± 0.5 % Phase C all phase angles 120°	1.52% ± 0.5 % Phase A 1.40% ± 0.5 % Phase B 1.28% ± 0.5 % Phase C all phase angles 120°
Harmonics	10 % ± 3 % 3rd at 0° 5 % ± 3 % 5th at 0° 5 % ± 3 % 29th at 0°	10 % ± 3 % 7th at 180° 5 % ± 3 % 13th at 0° 5 % ± 3 % 25th at 0°
Inter-harmonics	1 % ± 0.5 % at 7.5 f_{nom}	1 % ± 0.5 % at 3.5 f_{nom}

The test procedure is not univocally applicable to all PQ measurement parameters. In fact, voltage dips, swells and interruptions are not included in influence quantities so it unclear if procedure is applicable or not. It is a strong limitation for some of the most important PQ parameters (f.i. In Italy, only number of interruption is refunded as lack of PQ from utility). Actually, one of greatest challenge is to perform a reliable test for verification of measuring methods of such events so another specific paper is presented [9].

Nevertheless, the procedure application is also ambiguous for some phenomena included among influence quantities. For instance, unbalance is reported among influence quantities with a range 0-5% so that testing procedure application should require that measurement parameters of unbalance have been performed at five equally spaced points throughout this range. The problem comes from how to obtain these unbalance severity indexes. Very different magnitudes of the line voltages (fundamental components), or the phase angles can lead to the same level of unbalance. The choice is arbitrary and it is left up to the of verifier so that even instruments that calculate unbalance measuring only fundamental components amplitude, can be certified as correctly implemented even completely neglecting relative phase angles, if these parameters is not accounted in test situations. Same considerations can be done also for harmonic and interharmonic components for which degrees of freedom dramatically increase: a different number of components, harmonic orders, interharmonic frequencies, harmonic amplitudes, phase angles have to be included in effective performance verification.

In test states, the levels of influence quantities are only broadly defined, for instance system frequency is defined with a tolerance of 0.5 Hz (see Tab III). The reason of this choice is the practical difficult to implement and to verify these parameters during such a complex test situations in which all PQ phenomena act together. Anyway, it clear that this degree of indeterminations is against repeatability of test.

Standard states that some influence quantities must not influence the value of the measured parameters while other influence quantities must. Anyway, it is not clearly said which are right influence relations. Tab IV reports, at best author knowledge, influence of steady state PQ phenomena on measurement parameters indicating with a Y the correct influence and N an incorrect influence. Please note that frequency deviation should not influence none of other measurement parameter (PQ meters should lock on system frequency). At the same time, with an unstable system frequency all other measurement parameters should be flagged. Rms variations affecting fundamental component reflect correctly also on unbalance. During a dip/swell/interruption all parameters are affected but they are all meaningless except for those characterizing the specific phenomenon. Harmonics and interharmonics could affect threshold overcome that is related with dip/swell/interruption measurement. Interharmonics components affect directly the Pst measurement [13].

A final, but not negligible aspect is that all the influence quantities are accounted all together so no information about positive or negative interactions among them can be deducted. Therefore, it is possible that a meter behavior could be worst when a single influence parameter is present.

Table IV. Influence of PQ phenomena on measurement parameter

	Power frequency	**r.m.s. value**	**Pst**	**Residual voltage**	**Dip/Swell Duration**	**Negative/zero sequence**	**Harmonic subgroups**	**Interharmonic groups**
Frequency Deviation.	Y	N	N	N	N	N	N	N
Amplitude Fluctuation	N	Y	N	N	N	Y	N	N
Light flicker	N	Y	Y	N	N	N	N	Y
Dip/Swell/ Interruption	Y	Y	Y	Y	Y	Y	Y	Y
Unbalance	N	Y	N	N	N	Y	N	N
Harmonics	N	Y	N	Y	Y	N	Y	N
Inter-harmonics	N	Y	Y	Y	Y	N	N	Y

It is apparent that, for sake of simplicity, many practical situations are mistreated by procedure for implementation verification described in [3] but they have to be checked for full performance verification. This paper is aimed to move an initial step into direction of overcoming the aforementioned limits and ambiguity so obtaining a clean and reliable performance analysis protocol.

4. ADDITIONAL TEST PROPOSAL

As it is previously briefly motivated, in authors' opinion, some modifications should be included in future standard development. Number of test conditions should be greatly increased in order to include some remarkable performance issues. Tests should verify proper influence/uninfluenced of PQ phenomena on all measured quantities. They should check not only steady state conditions but also the behavior in dynamic situations and proper flagging application. Test description should be more detailed and tolerance in test parameters definitions should be decreased at best hardware capability. The accuracy assessment should be done by an external certified laboratory not simply declared by manufacturers [10]-[13]. In the following same additional test situations are presented.

A. Influence test

In order to check proper influence relation, attention should be paid to all measurement parameters while a single PQ phenomenon is generated in a steady state. Test protocol could be defined in accordance with standard procedure of [8]. An instrument should satisfy proper influence or non-influence relation according with tab. IV and within accuracy limits. As an example, referring to flicker, while the signals of test protocol are generated ([9]), the measured values of all other parameters should be checked. Flickermeter test signals are sinusoidal voltages with a superimposed sinusoidal or rectangular amplitude modulation. Therefore, some parameters should be unaffected, (i.e. power frequency, negative/zero sequence and harmonic subgroups) other should be affected in a proper way: rms value should fluctuate with the amplitude of the modulation and interharmonic groups around the fundamental tone should have half of the amplitude of modulation. Obviously, also proper Pst values should be obtained. This approach could be applied also to all other PQ phenomena: during performance verification of a specific PQ measurement parameter all other measuring parameter should be checked in order to asses the proper influence/non influence relation. At this moment, the lack of standard verification protocols makes obviously arbitrary the application of this procedure at the other PQ phenomena.

B. Flagging test

This test set should reproduce dynamic change in input signal and proper flagging have to be verified. The transitory situations could be deducted by standard library of measured real waveforms (see fig. 1a taken from [1]) or generated in simplified scenario as those reported in fig. 3 and fig. 4. Each of the waveforms should stress certain types of real measurement situation.

In Fig. 3 a real three phase dip event is reported in terms of instantaneous line to neutral voltage normalized on nominal peak value (fig. 3a) and rms value normalized on nominal rms value (fig. 3b). The rms value is measured each sample with a sliding window synchronized with the duration of 1 cycle of fundamental period. The rms values corresponding to instantaneous voltage zero crossing corresponding to [3] definition are empathised with a symbol corresponding to the line. This is a common transitory situation coming from phase to ground short circuit. It is apparent that a single phase monitoring detects a normal behavior on the first line, a dip event on the second line, and a swell event on the third line.

As for waveforms generated in simplified scenario, transitory test 1 (see fig.2) reproduces a situation in which the amplitude of a certain system parameter rapidly decreases and after a certain time come back to an amplitude that is close to its nominal value. Transitory test 2 (see fig.3) reproduces a situation in which the amplitude of a certain system parameter oscillates around its nominal values. As an example, these tests could be applied for emulating the system frequency changes that apply in power systems due to dynamic changes in operating conditions. In fact, a sudden loss of generation or load in one area would be seen as a frequency disturbance, similar to that reproduced in fig. 2 in other areas of the power system. To perform this test, same parameters have to be chosen: the relative frequency amplitude before (A_b) and during (A_d) and after (A_r) the event, the fall time (T_F), the event duration (T_D) and the raise time (T_R). Different choices of parameters lead to different test situations.

Once again referring to system frequency, the transitory situation reproduced in fig. 3 can be found in the utility grid linked to wind turbine due to wind power fluctuations. From mathematical point of view this situation can be described with two parameters: relative amplitude of fluctuations, ΔA, and period of fluctuation, T_f. Again, different choices of parameters lead to different test situations.

In this transitory situation, PQ instruments were expected to work properly. A non trivial problem is what the proper behaviour is. With timing values experienced in practices, the proper behaviour has to be flagging measurements results as unreliable due to system frequency instability.

The transitory tests could be carefully extended to other parameters with minor changes. For instance, applying transitory shape 1 to rms values a single phase dip test is obtained. Also in these situation data have to be flagged. Anyway, the extension is not always straightforward. For instance, applying transitory shape 2 to rms values, a steady state situation can be found. In fact, with practical values for parameters, this situation is a voltage amplitude modulation that is a steady state condition for most measurement parameters as widely accounted in flicker test protocol [9].

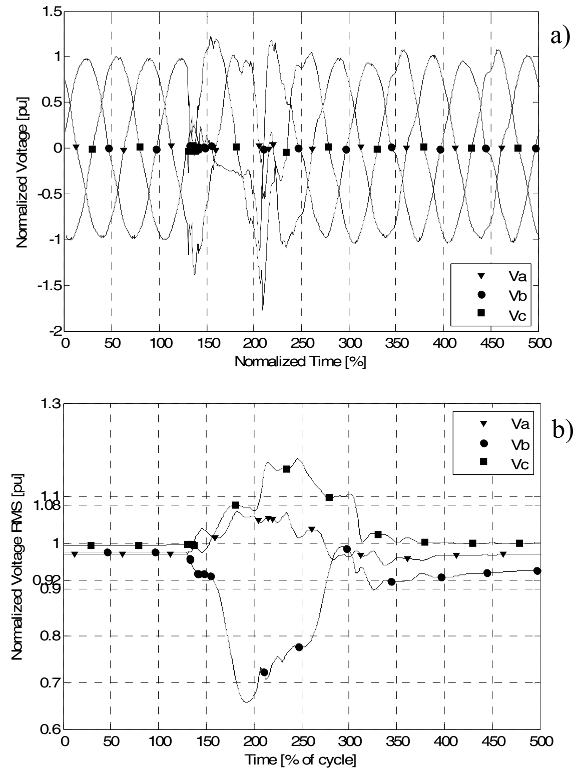

Fig. 1 Thee phase voltage dip: a) instantaneous voltages; b) line-neutral rms values.

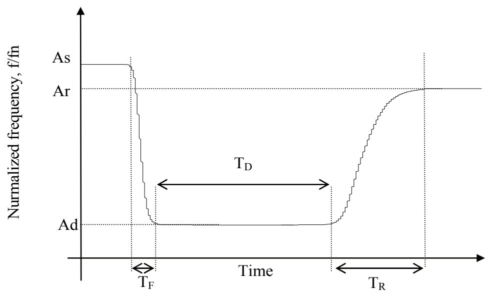

Fig. 2. Normalized amplitude variation for transitory test 1.

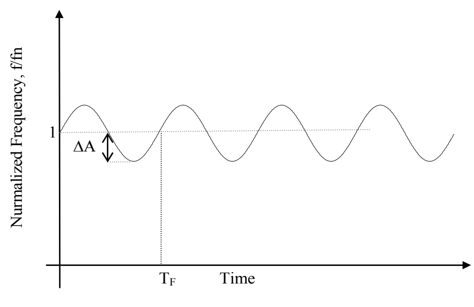

Fig. 3 Normalized amplitude variation for transitory test 2.

5. DESIGN OF EXPERIMENT

One of the most critical aspects of performance verification of PQ measuring instrument is the enormous number of verification tests that should be performed for each measuring parameter. Generally specking, in fact, it should be necessary to choose influence quantities to be taken into account and, for each of them, explore all the possible interval of variation recommended in [3], so that different tests should be performed accounting all the combinations of influence quantities at different levels that are included in admissible range of variation. It is clear that this kind of testing requires an amount of experiments that increases exponentially and it could be practically unrealizable. In order to reduce amount of experiment, a possible approach could be based on a reduced number of tests with a random choice of the severity levels for each of the influence quantities. Anyway, this approach should be not proper to carry out repeatable results.

In order to reduce the number of tests and obtain repeatable results, the authors propose the use of an optimal design of experiment. The optimal design of experiment [14] is a structured and organized method for determining the relationship between several influence quantities affecting a process and the output of that process. It is based on statistically analysis of forced changes made methodically as directed by mathematically systematic tables. In other words, experimental design is a scientific approach that allows an experimenter making intentional changes to the inputs of a process or system to identify and observe the reasons for the changes that occur to the response. The changes are statistically chosen but not random so this approach carries out repeatable results.

For experimental designs, user has to choose the influence quantities and levels to be account. Tab. VII reports, a reduced set of experiments where the same five parameters (frequency, flicker, unbalance, harmonics, interharmonics) and three levels are accounted as done by in [3] and reported in Tab. III. With this approach, many different combinations are tested so allowing an analysis of positive or negative interactions among PQ phenomena. This could be considered an extension of the test conditions of [3].

The same approach could be adopted in designing the test waveforms when multiple parameters should be chosen. As an example, Tab. VI reports the parameters and levels that could be accounted for testing unbalance. Of course the number of levels and the values could be increased or changed. Tab. VII reports the parameters and levels that could be accounted for testing THD with two harmonic components. Also the number of harmonics could be one of design parameters and varied.

6. CONCLUSIONS

This paper presented an analysis about the way to carry out a comprehensive performance analysis of instruments adopted for power quality monitoring. Some additional tests are proposed in order to test proper flagging, influence relation among measurement parameters. Finally, a proposal of test protocol definition based on design of experiment was presented with reference to some PQ phenomena.

Table V. Set of experiments

Test Number	Frequency	Flicker	Unbalance	Harm.	Interharm.
1	Lev. 0	Lev. 0	Lev. 0	Lev. 0	Lev. 0
2	Lev 1	Lev 2	Lev 2	Lev 1	Lev 1
3	Lev 1	Lev 2	Lev 1	Lev 2	Lev 2
4	Lev 1	Lev 1	Lev 1	Lev 2	Lev 1
5	Lev 2	Lev 1	Lev 2	Lev 2	Lev 2
6	Lev 2	Lev 1	Lev 1	Lev 2	Lev 1
7	Lev 1	Lev 1	Lev 2	Lev 2	Lev 1
8	Lev 1	Lev 1	Lev 2	Lev 1	Lev 1
9	Lev 1	Lev 1	Lev 1	Lev 1	Lev 1
10	Lev 2	Lev 2	Lev 1	Lev 1	Lev 1
11	Lev 1	Lev 2	Lev 1	Lev 1	Lev 2

Table VI. Parameters and levels accounted in design experiment for unbalance measurement verification

Parameter	**Lev 1**	**Lev 2**	**Lev 3**
1st line neutral voltage, [U_{1n}/U_{din}]	102 %	97 %	95 %
2nd line neutral voltage, [U_{2n}/U_{din}]	102 %	97 %	95 %
3rd line neutral voltage, [U_{3n}/U_{din}]	102 %	97 %	95 %
1st line to 2nd line phase angle, [deg]	130	120	110
2st line to 3rd line phase angle, [deg]	130	120	110

Table VII. Parameters and levels accounted in design experiment for THD measurement verification

Parameter	**Lev 1**	**Lev 2**	**Lev 3**	**Lev 4**
1st Harmonic order	3	5	11	21
1st Harmonic Rms [V]	1	3	7	10
2st Harmonic order	3	5	11	21
2st Harmonic Rms [V]	1	3	7	10

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