Power Quality Event Detection - Standards & Beyond

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Abstract

Some of the most common power quality events seen in the power grid are associated with anomalies in the system voltages. Dips, swells, interruptions, etc. are characterized by variations in the voltages which result in adverse effects on the system. While the analysis of such power quality events comes with its own set of challenges, reliable, accurate & timely measurement of voltage under such dynamic conditions forms the foundation for any type of analysis.

Standards such as the IEC 61000-4-30 & the IEEE 1159 present a great amount of detail describing the methodology for evaluation of the voltages required for such purposes along with performance requirements under a variety of conditions. These aid in verifying that measurement devices can produce repeatable & comparable results in an inter-operable fashion under a defined set of conditions with compliance to a certain measurement class. However, real-world scenarios can be vastly different & often the behaviour outside the scope of these conditions can have an impact on the quality & performance of the device.

This paper presents an examination of several scenarios beyond the scope of standard based test conditions & the type of impact design choices can have on the measurements estimated for power quality event analysis. It also discusses error sources, trade-offs & general design considerations associated with measurement techniques for such applications.

1 Introduction – Nature of power quality events

By nature, triggered power quality events have a lot in common with transient anomalies in the power grid in comparison to their other power quality counterpart issues such as flicker, harmonics, etc. As a result, the measurement techniques & analysis methods closely follow those used for transient events. Dips, swells, interruptions, etc. are all characterised by variations in the system voltage which are typically abrupt/sudden in nature & may last for a short duration or persist to evolve into permanent faults.

For analytical purposes, these variations can be categorised as belonging to one or more of the following types of anomalies –

1. Fluctuations in the system frequency
2. Variations in the amplitudes of the voltages
3. Variations in the phase
4. Spectral anomalies

A typical power quality event might consist of one or more of these anomalies occurring simultaneously, resulting in non-typical voltage waveforms that present challenges for effective analysis. Due to the relatively short duration in which such events can occur, measurement techniques would be required to obtain results both quickly & accurately.

2 RMS - Measurement Technique

The fundamental measurement required for the analysis of PQ events such as sags, swells, interruptions & RVC is the root mean square (RMS) of the voltage signals. While the core technique behind the estimation of the RMS value of a signal is conceptually simple, several aspects around it determine the accuracy, response, speed, etc. The importance & relevance of these aspects vary from one application to the other & there’s typically a trade-off determined based on what makes the most sense for a particular application.

Power quality in the broad sense covers a variety of such applications & several characteristics come into play, some of which include –

Characteristics		Application & impact
Computation window	Short (1-2 cycles)	Short duration events
	Long (10/12 cycles)	Long term analysis
Filtering		The amount of filtering has an impact on the accuracy of the RMS as well as response time. Extensive filtering may improve accuracy but at the cost of increased delays & sluggish response to variations in the signal.
Response time		Timely detection of variations in the voltage requires short response time. This is determined by both the RMS computation window as well as the amount of filtering.
Frequency & phase tracking		Accurate frequency measurement & the ability to track the phase of the signals plays a significant role in the determination of the computation window & other related parameters required for RMS estimation.

Table 1: Characteristics of RMS estimation methods

Table 2 of the IEEE 1159 standard [2] categorizes various power quality events based on duration & voltage magnitude -

Categories	Typical duration	Typical voltage magnitude
2.0 Short-duration root-mean-square (rms) variations		
2.1 Instantaneous		
2.1.1 Sag	0.5–30 cycles	0.1–0.9 pu
2.1.2 Swell	0.5–30 cycles	1.1–1.8 pu
2.2 Momentary		
2.2.1 Interruption	0.5 cycles – 3s	< 0.1 pu
2.2.2 Sag	30 cycles – 3 s	0.1–0.9 pu
2.2.3 Swell	30 cycles – 3 s	1.1–1.4 pu
2.2.4 Voltage Imbalance	30 cycles – 3 s	2%−15%
2.3 Temporary		
2.3.1 Interruption	>3 s – 1 min	< 0.1 pu
2.3.2 Sag	>3 s – 1 min	0.1–0.9 pu
2.3.3 Swell	>3 s – 1 min	1.1–1.2 pu
2.3.4 Voltage Imbalance	>3 s – 1 min	2%–15%
3.0 Long duration rms variations		

3.1 Interruption, sustained	> 1 min	0.0 pu
3.2 Undervoltages	> 1 min	0.8–0.9 pu
3.3 Overvoltages	> 1 min	1.1–1.2 pu
3.4 Current overload	> 1 min	

Table 2: IEEE 1159: Categories of PQ events based on duration & voltage magnitude

The IEC 61000-4-30 specifies the fundamental criteria for the measurement technique required to obtain class A compliant RMS estimates of the voltage [1] –

3.22
r.m.s. voltage refreshed each half-cycle
***U*rms(½)**
value of the r.m.s. voltage measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle

The key aspects in this definition of the RMS are –

1. Measurement window – 1 cycle (based on the fundamental frequency)
2. Refresh rate – 1 half cycle
3. Phase tracking – Fundamental zero crossings

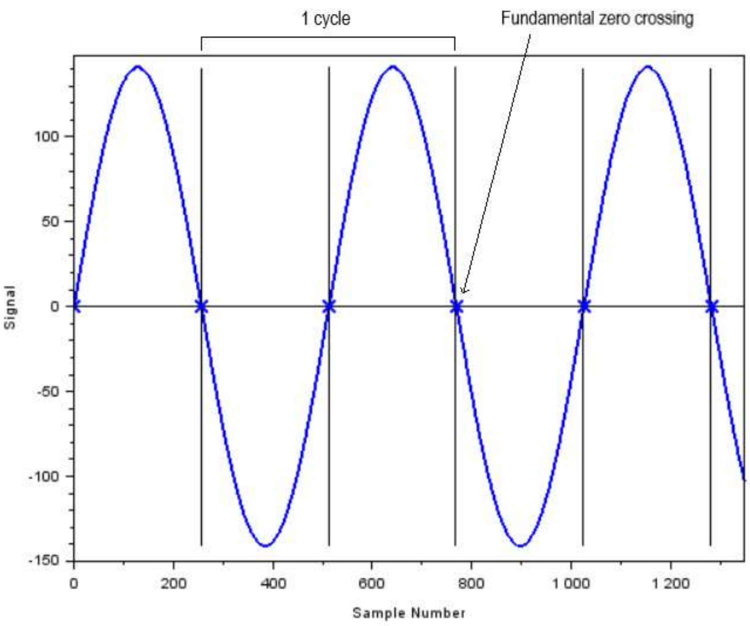


Fig.1: Urms(½) measurement technique

Section 3 describes the accuracy, timing, synchronization, etc. requirements applicable to these measurements as well as the associated tests to verify class A compliance.

3 Standards & requirements

Several standards cover power quality events such as sags, swell, interruptions, etc. in detail but the ones that specifically focus on the measurement technique & the applicable compliance requirements are –

1. IEC 61000-4-30: Testing and measurement techniques – Power quality measurement methods

   Specifies the magnitude & duration measurement uncertainties that instruments must meet for class A/S compliance. Also provides details about the logic to be followed for the detection & evaluation of power quality events. Two requirements are of particular importance with respect to class A compliant estimation of the RMS of the voltage for power quality event evaluation –

   a. Magnitude accuracy - Within +/- 0.2% of the declared input voltage magnitude [1].
   b. Duration accuracy – 1 cycle according to the fundamental frequency.

   Both these requirements must be adhered to across a variety of system conditions involving variations in the amplitude, frequency, etc. as detailed in the IEC 62586-2.

2. IEC 62586-2: Power quality measurement in power supply systems – Part 2: Functional tests and uncertainty requirements

   Specifies the tests that need to be performed to verify compliance with the measurement methods & uncertainty requirements mentioned in the IEC 61000-4-30.

The latter goes into great detail while describing the test methodology for compliance verification. The following are some of the important takeaways from these tests pertaining to RMS estimation which serve as a reference for analysis against phenomena that can be seen in more realistic scenarios –

3.1 Independently synchronized measurements

The voltage RMS values (Urms(½)) estimated in a three-phase system must be synchronized to the individual zero crossings of the respective phase for generating accurate & independent measurements. The test corresponding to this is described in A4.1.1 of the IEC 62586-2 [3] which also specifies that the steps in the voltages must be made on zero crossings.

3.2 1 cycle period estimation

A key parameter required for obtaining Urms(½) values that're measured over 1 cycle & refreshed every half cycle is the frequency. The IEC 61000-4-30 specifies the following for measurement of this frequency value [1] –

"The cycle duration for Urms(½) depends on the frequency. The frequency might be determined by the last non-flagged power frequency measurement (see 4.7 and 5.1), or by any other method that yields the uncertainty requirements of Clause 6."

This frequency value plays a crucial role in determining the accuracy of the RMS measurements.

3.3 Fundamental frequency

The magnitude & duration accuracy requirements mentioned above are required to be maintained across a wide range of frequencies above & below the nominal value of 50Hz or 60 Hz. Table 3 of the IEC 62586-2 outlines this –

Nominal Frequency	Range
50 Hz	42.5 Hz – 57.5 Hz
60 Hz	51 Hz – 69 Hz

Table 3: IEC 62586-2: Frequency range for accurate RMS estimation

4 Practical scenarios

The three aspects mentioned above form the foundation for a variety of tests, but practical scenarios don't adhere to many of these constraints & it's not unlikely for several anomalies to occur at the same time during a power quality event. While these tests focus on verifying consistent measurement across instruments complying with the class A requirements, there're reasons for instrument manufacturers to go above & beyond them. The following section describes several scenarios which highlight the need for this.

4.1 Impact of fundamental frequency

Consider the following power quality event where a slight variation in the frequency is seen prior to a dip in the voltage –

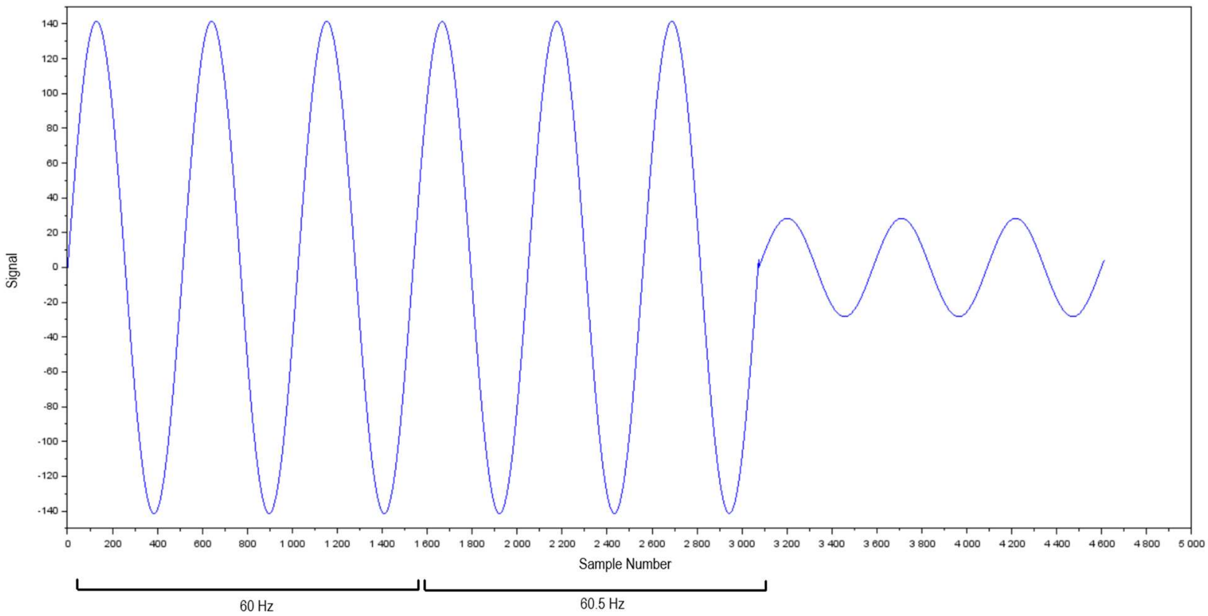


Fig.2: Voltage dip after a fluctuation in the system frequency

The measured frequency plays a key role in determining the accuracy of the RMS value of the voltage as it's used to determine the period that corresponds to 1 cycle of the signal. As mentioned in section 3.2, the IEC 61000-4-30 states that this frequency may be determined by the last non-flagged power frequency measurement. Section 5.1.1 of the standard also defines that the power frequency reading shall be obtained every 10 s [1]. This presents a few challenges –

1. A new frequency value is obtained once every 10s which is a significantly slow update rate, especially when dealing with triggered events.
2. The frequency is estimated over a large window of 10s & this averages out any minor variations as well as introduce a large delay in the transition from one frequency value to the next.

3. Only the last non-flagged power frequency value may be used & with an estimation window of 10s, any frequency value that may be estimated during a power quality event such as the dip shown above would be flagged as unfit for use.
4. If the power quality event is significant enough to result in the operation of protection equipment, there's a very small window (typically cycles) for reliable estimation of frequency, RMS, etc. & a 10s window would be far too large.

While the method suggested by the standard would be good enough to meet all tests required for class A compliance, there's incentive for manufacturers to go beyond & rely on methods which operate more efficiently during such system anomalies.

In the case of the example shown above, the last non-flagged power frequency of 60 Hz would be used for the entire duration of the event even though there may have been a variation prior or after the event for a short duration of time.

4.2 Fault incidence angle

Several tests in the IEC 62586-2 mention that voltage steps required for sags, swells & interruptions must be made on zero crossings of the respective phases [3]. This ensures reliable, consistent & repeatable results across instruments which could belong to different vendors. However, events like these are unlikely to adhere to such rules in practical scenarios. The point on the waveform where a fault begins (commonly referred to as the fault incidence angle) can be completely arbitrary & measuring instruments would have to cope with such scenarios.

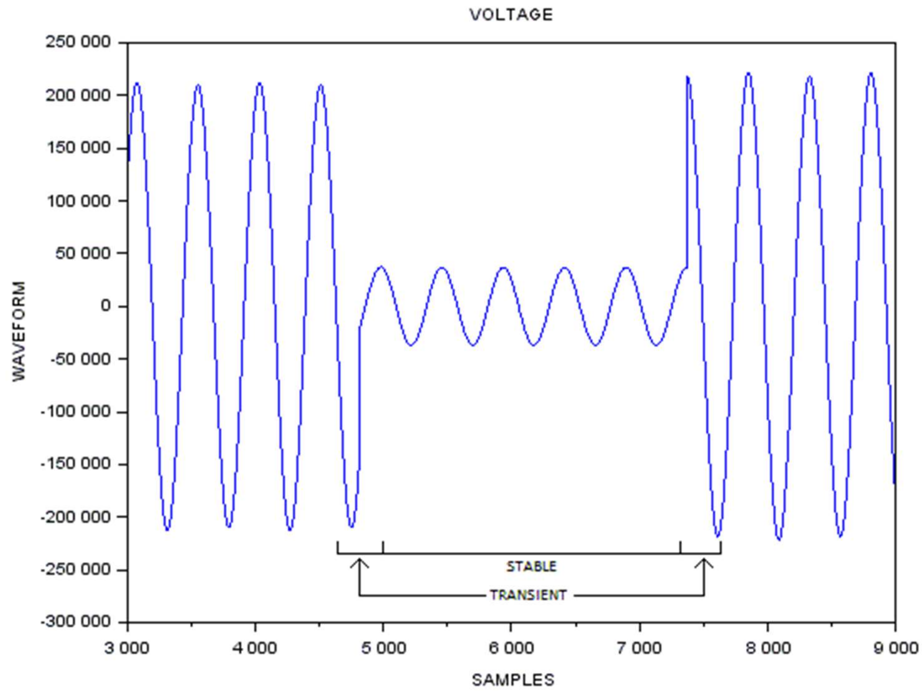


Fig.3: Voltage dip with a non-zero incidence angle

Estimating accurate RMS values at or in the immediate vicinity of a transient is a challenge & the measured values would typically be unreliable. The key goal in such situations is to ensure that the measurement technique can switch from producing unreliable measurements to reliable ones in a short period of time. This would typically be in the order of cycles since protection equipment can operate very fast & clear the fault.

The standards focus primarily on events which begin & terminate on cycle boundaries, but it'd be useful for manufacturers to both design & test measurement equipment for such scenarios to ensure optimal operation.

4.3 Phase tracking

While estimating class A compliant Urms(½) values in a three-phase system, it's important to ensure that the measurements are made over a 1 cycle window that's refreshed every half cycle on each phase in an independent manner.

In other words, this implies that a phase tracking scheme is required which operates independently on each phase. The challenge with such a scheme is the efficient tracking of the phase during & after a sudden disruption in the waveform. The IEC 62586-2 details a few tests which help verify the ability of an instrument to generate accurate results when subjected to changes in the amplitude. One such test is described in section 6.4.2 of the standard -

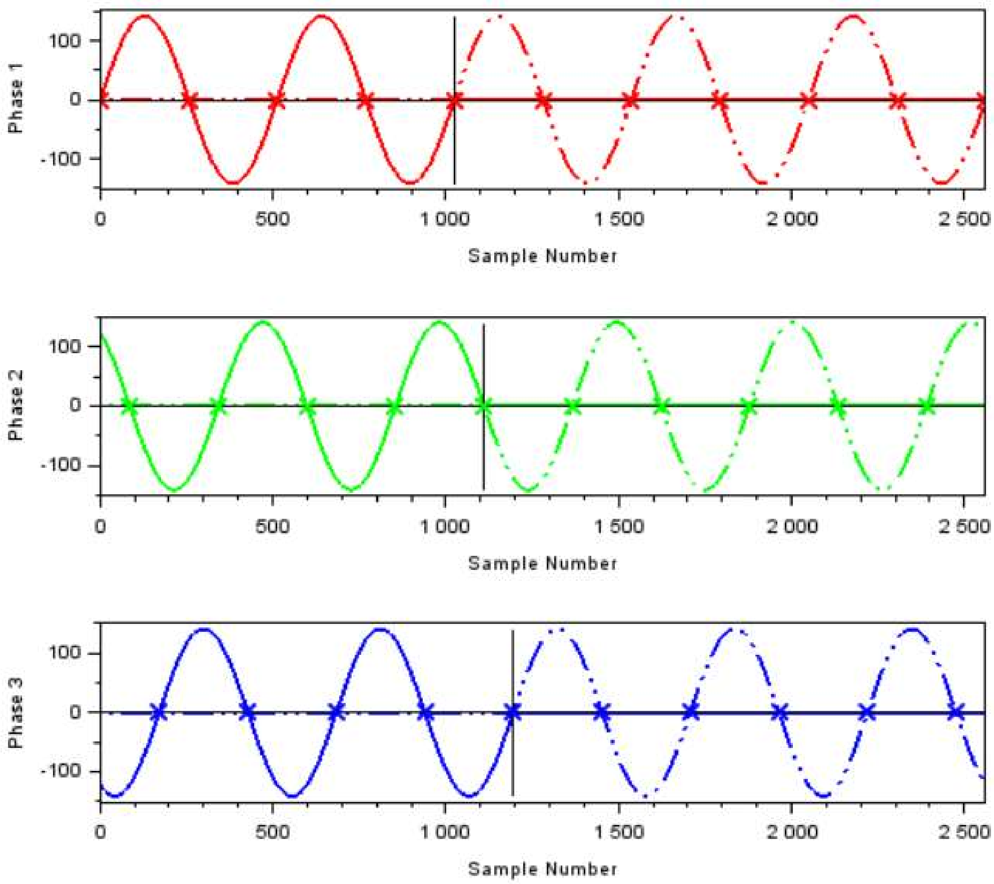
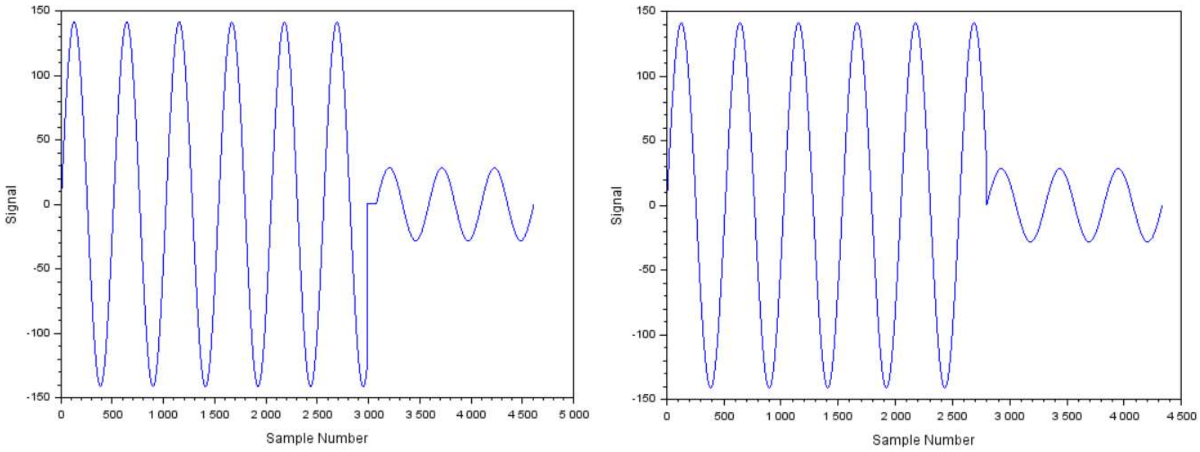


Fig.4: Representation of test 6.4.2 of the IEC 62582-2 - Check dips / interruptions in polyphase system

This test involves introducing an interruption on the three phases at certain points of time in line with their zero crossings. Similar to the scenarios described in section 4.2, this only evaluates the performance of the instrument when the changes in the amplitude are confined to line up with the zero crossings.

Depending on the method being employed, a sudden change in the phase of a waveform with an arbitrary incidence angle can result in errors in the tracking mechanism which may last for a relatively significant duration of time. As the fault incidence angle can be completely random during an event, it’s important for instruments to be capable of quickly regaining phase lock once the event has passed. There may also be a permanent change in the phase of the signal & the phase tracking mechanism would be required to re-establish phase lock in a short period of time.



(a) (b)

Fig.5: Voltage dip - (a) Temporary loss of phase (b) Permanent phase shift

4.4 Frequency measurement channel

Section 5.1.3 of the IEC 61000-4-30 states the following when describing the choice of the frequency measurement channel & the behaviour in case the chosen reference channel loses voltage –

Class A

- The frequency measurement shall be made on the reference channel.
- The manufacturer shall specify the behaviour of frequency measurement whenever the reference channel loses voltage.

Even if an instrument does not rely on the 10 s power frequency measurement for determining the period to be used for the computation of the 1 cycle RMS, it’s possible that the same frequency measurement channel is used for this purpose. The design choices employed here can impact the accuracy & reliability of the RMS measurement method in a variety of ways –

1. The zero crossings on all three phases of a system must be independently tracked for accurate estimation of the RMS. If the frequency measured on the reference channel plays a role in this, it’s possible that anomalies such as the ones described in previous sections can negatively impact the RMS measurement on all three phases.

2. The manufacturer’s choice regarding the behaviour in case of loss of voltage, which is covered to an extent in some of the tests mentioned in the IEC 62582-2, can impact the performance of the measurement method in terms of duration of uncertainty, reliability during abrupt changes in the phase of the waveforms, recovery of voltage on the reference voltage channel, etc.

While the standard ensures that consistent & deterministic results are produced by instruments when subjected to zero cross aligned dips & interruptions on the reference channel/s, manufacturers would stand to benefit from evaluating the performance of their design under non-ideal scenarios.

5 Conclusion

This paper highlights the key aspects of power quality event analysis & presents a study on standard based requirements & tests for RMS estimation as well as the scope & incentive to exceed these. Following are some notable takeaways –

1. Requirements & tests mentioned in the IEEE & IEC standards pertaining to magnitude & duration accuracy are aimed towards verification of consistent results across instruments from different vendors under deterministic conditions.
2. System parameters often tend to deviate from these constraints under practical scenarios & it's beneficial to design measurement techniques with the goal of exceeding the concerned standards.
3. Fundamental frequency measurement, phase tracking, windowing, filtering, behaviour during transients, etc. are some of the critical areas which contribute to the overall performance of an instrument under non-ideal scenarios.
4. Due to the nature of PQ events, specific focus on the behaviour of measurement techniques around sudden or arbitrary changes in the waveforms can yield better results.
5. Inclusion of non-standard tests like the ones mentioned in this paper during the design & verification of measurement techniques can prove beneficial for the purpose of obtaining an insight into the performance & efficacy of the design during non-ideal conditions.

References

[1] IEC 61000-4-30:2015: Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques – Power quality measurement methods
[2] IEEE 1159-2019 - IEEE Recommended Practice for Monitoring Electric Power Quality
[3] IEC 62586-2:2017: Power quality measurement in power supply systems - Part 2: Functional tests and uncertainty requirements