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An overview of measurement standards for power quality

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Abstract. Power Quality (PQ) is a vital aspect of electrical power systems, which cannot be neglected anymore, as an ample PQ guarantees the essential compatibility between consumer equipment and the electricity network. The analysis of electrical parameters related to distributing electricity is recognized as a complex engineering problem. It remains a critical task to maintain and improve PQ in modern evolving networks as the overall system performance highly depends on it. Future smart grids will also require a further increase in PQ levels in terms of observability, affordability, data exchange, flexibility, and net metering, thus making the network much more complex as it will be featuring a large amount of variable renewable-based distributed generation. This will further require the need for the introduction of novel, efficient and intelligent monitoring, control, and communication systems with various demand manageable resources. In this paper, a review and comparisons have been made for different IEEE and IEC measurement standards that are used for PQ with a specific focus on harmonic distortion as it is one of the most important parameters in PQ and some guidelines have been suggested for future electricity networks.

Key words: power quality, measurement standards, voltage harmonics, current harmonics, distortions.

INTRODUCTION

The growing demand for service quality, safety, reliability, and efficiency, as well as the inclusion of increasingly environmental and sustainable energy sources, is making the management of electricity networks more complex (Lizana et al., 2018; Khalid et al., 2019; Nolasco et al., 2019a; Stanisvavljevis & Kati, 2019). Now a more flexible and efficient electricity system is needed, which is mostly referred to as Smart Grid (SG). To achieve this milestone, a combination of new technologies including Distributed Generation (DG), Renewable Energy Sources (RES) with storage capacity, and the latest Information and Communication Technologies (ICT) is needed (CIGRE 719, 2018; Gandoman et al., 2018; Rodrigues Junior et al., 2019). However, the installation of these new devices will also increase Power Quality (PQ) issues (Marais et al., 2018). Two major causes of issues related to PQ and Electromagnetic Compatibility (EMC) have been identified, first at the consumer equipment end (load) and second at the distribution and transmission systems end (Rönnberg & Bollen, 2016). The emissions by these new types of devices will require new measurement techniques (Morsi & El-Hawary, 2011; Khorasani et al., 2017).

In case an electricity network is not working properly, then it requires investigation, elimination, and the initiation of corrective actions (Yang et al., 2018). To collect real-time data, PQ analysers are commonly used tools. The most commonly used are handheld analysers, but some are installed in the distribution and transmission system (Gallo et al., 2010; Randy Barnett, n.d.). These analysers can measure PQ aspects like power factor (PF), voltage, current, voltage and current harmonics, voltage dips and swells, frequency, power/voltage/current unbalance, flickers, etc. (Saqib & Saleem, 2015; Bhonsle & Kelkar, 2016; Patiño & Lópe, 2018). Most of the PQ problems can be identified if the analyser is able to measure and record these parameters. IEEE PQ standard, IEC and National Fire Protection Association (NFPA) 70B provide some insight information for understanding PQ issues and corresponding corrective measures (Patel et al., 2017). Every manufacturer provides its software with its test equipment for data analysis. Fig. 1 is showing the supply and demand side points where the PQ measurements can be made (Schneider Electric, n.d.-a).

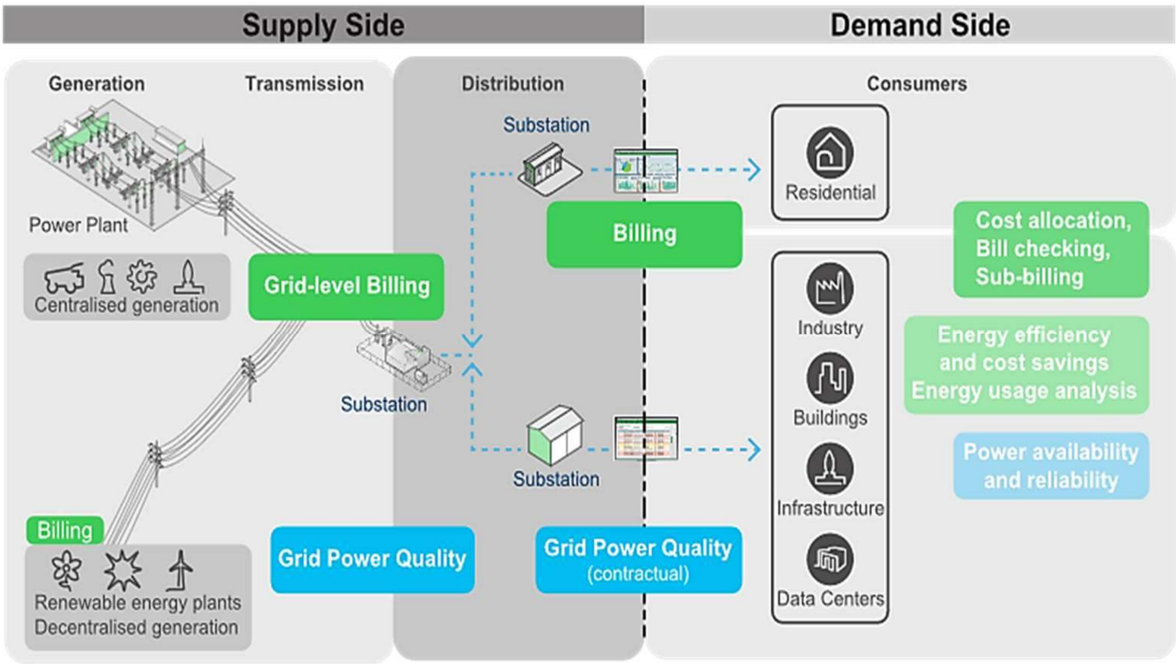

Figure 1. Measurement applications both in supply and demand side.

Noncompliance with certain PQ standards can have very serious effects on the electrical instrument, e.g., transients are extremely short-duration voltage surges that can even destroy a device (Sensors, 2019). Usually, they are caused by lightning strikes, but a high-frequency switching load can be the cause as well (Shankar et al., 2018; Vinnakoti & Kota, 2018; Jamil et al., 2019; Kitzig et al., 2019;). In addition, the most common culprits of PQ are voltage sag (the decrease in voltage) and swelling (higher voltage) (Najafi et al., 2019; Safavizadeh et al., 2019). Due to a sudden drop of large loads across the line, voltage swell can occur while sags are more troublesome and can cause contactors and relays to drop out completely (Mahela et al., 2015; Schneider Electric, n.d.-b). Electronic equipment like Programmable Logic Controllers (PLCs), computers, and Variable Speed Drives (VFD) can malfunction (Heidari et al., 2019; Todeschini et al., 2019; Wu et al., 2019b). Voltage unbalance can cause motor failure as the current values reach six to ten times the nominal current (Albadi et al., 2015). Usually, advanced signal processing techniques are used in the identification of these PQ issues (Nolasco et al., 2019b; Wang & Chen, 2019).

Electrical power has mainly two categories; active and reactive power. Active power is the actual dissipated power while reactive power is the portion of power due to stored energy, which returns to the source in each cycle (Montoya et al., 2020). The combination of 'true' power and reactive power is called apparent power. Current and voltage are used for the measurement of AC power and they should be in pure sinusoidal waveforms at the fundamental frequency of 50/60 Hz. The instantaneous power at any instant is defined as:

$$p = V_m \, sin(wt + \theta_v). I_m \sin(wt + \theta_i) \quad (1)$$

Further simplification can give:

$$p = \frac{V_m I_m}{2} = \frac{V_m}{\sqrt{2}} . \frac{I_m}{\sqrt{2}} = V_{rms} . I_{rms} \quad (2)$$

Therefore, accurate values of RMS voltage and current are required for the measurement of power. However, both the available current and voltage are distorted and sometimes completely in non-sinusoidal waveforms (Grasso et al., 2018; Qiu et al., 2019). These distortions can introduce errors in the measurements if they have significant values. Specific filters are used for the correction of this distorted wave (Benzahia et al., 2019).

As both the voltage and current are distorted, an analysis only at the fundamental frequency of 50/60 Hz is not a suitable option (Donolo et al., 2016). The main cause of distorted waves is the presence of harmonics (Albadi et al., 2015). The severity of the harmonic distortion depends upon the magnitudes of different harmonic frequencies and the Total Harmonic Distortion (THD) (Straczynski, 2018). Harmonics are better measured at their source as they lessen further upstream from the equipment (Kamel et al., 2018). The IEC standards 61000-2-2, 61000-2-4, 61000-2-8, 61000-2-12, 61000-2-16, CENELEC EN 50160, and IEEE 519 standard define these voltage limits for low, medium and high voltage supply public networks in details. Detailed characteristics of these supply networks are given in Table 1 (CIGRE 719, 2018). For the measurements and evaluation, IEC 6100-4-7 and 61000-4-30 standards are used. Table 2 (Schneider Electric, n.d.-a) describes the main PQ problems that occur in a network due to these distortions.

In (Balasubramaniam & Prabha, 2015), a critical review of power quality problems and their solutions in relation to international standards is being made. Most of the focus is on total harmonic distortion and their related IEEE standards. In (Panda, 2002), the modified wavelet transform is used for the analysis of PQ parameters. The survey in (Sivakumar et al., 2016) discussed PQ events, parameters and their controlling techniques focusing on voltage, sags, harmonic distortions and flickering. In (Patel et al., 2017), the focus is on harmonic distortion, voltage disturbances, energy wastage, and poor PF in line with IEEE standards. A review of power quality and monitoring is made and a PQ solution with internet monitoring is described (Dhingra & Sharma, 2014).

Table 1. Characteristics of different voltage supply systems

Parameter	Low Voltage Supply (up to 1 kV)	Medium Voltage Supply (1 kV to 36 kV)	High Voltage Supply (36 kV to 150 kV)
Voltage variations	10 and - 15% range and the same apply for all 10 min RMS values	should not exceed ± 10%.	-
Voltage unbalance	95% of the 10 min mean RMS value of the negative phase sequence component should be in range of 0 to 2% of positive phase.	95% of the 10 min mean RMS value of the negative phase sequence component should be in range of 0 to 2% of positive phase.	95% of the 10 min mean RMS value of the negative phase sequence component should be in the range of 0 to 2% of positive phase.
Harmonics and THD	THD ≤ 8% while individual harmonics should be 95% of the 10 min mean RMS value for one week.	THD ≤ 8% while individual harmonics should be 95% of the 10 min mean RMS value for one week.	Individual harmonics should be 95% of the 10 min mean RMS value for one week while THD is still under consideration.

Table 2. Problems in the electrical network and their consequences

Parameter	Measurement	Influence on installation	Influence on performance
Power Factor	PF	Low PF generates additional losses in the installation. Energy provider is charging penalties to the customer	Cable heating (cables need to be oversized)
Voltage and current harmonics	THDv THDi	Negative sequence harmonics (V_2) are slowing the motors down. Harmonics generates extra losses in the installation	Early failure of some devices, mainly motors.
Permanent or frequent deviations of voltage	V	Devices may work outside their specified range, and they may consume mainly motors	Early failure of some devices, mainly motors
Voltage sunbalance	Vimb	Voltage unbalance generates extra losses in motors.	Early failure of some devices, mainly motors

The paper (Barros & Diego, 2016) gives an extensive overview of power quality issues in ships. Power quality issues, instrumentation, and standards are also discussed. In (Albadi et al., 2015), a case study and literature review about unbalancing in power systems in Oman is discussed. The study showed that unbalance levels are below 1% of the specified limit. A survey of harmonic distortion and power quality measurements has been made in (Gopalakrishnan et al., 2002), in accordance with IEEE 519 standards. Simulation has also been carried out that shows the improvement in PF from 0.74 to 0.9 and a reduction in current THD as well. In (Smith, 2008), a detailed review of CELEC EN 50160 standards is made with a focus on voltage and frequency characteristics and their limits. Some measurement requirements and applications of these standards are also discussed.

Many studies have focused on the review of power quality issues and standards applied to electric motors (Gnacinski & Tarasiuk, 2016), photovoltaic power generation (Seme et al., 2017; Hacke et al., 2018; Elkholy, 2019; Smadi et al., 2019), microgrids (Senthil Kumar et al., 2015; Van den Broeck et al., 2018; Wu et al., 2019a), electric vehicles (Khalid et al., 2019; Khan et al., 2019), energy storage (Das et al., 2018) and shipboard power systems (Barros & Diego, 2016; Rodrigues et al., 2018). In Table 3, a detailed comparison of our paper with other papers on power quality standards is shown. In most of the studies, the focus is only on one standard and a review is made highlighting the pros and cons. Our study comprises of five different standards and covers a broader prospect. Most of the eariler studies focused on one parameter and there has not been a single review study in terms of PQ measurments and their impact. Accurate PQ measurements are extremely important for the monotoring and smooth oprtaion of any grid and for that these standrads needs to be followed.

Table 3. Comparison of our survey with other surveys

Surveys	IEC 61000-4-7	IEC 61000-4-13	IEC 61000-4-30	CIGRE JWG C4.24	IEEE 519-2014
(Balasubramaniam & Prabha, 2015)	×	×	×	×	√
(Sivakumar et al., 2016)	×	×	×	×	√
(Patel et al., 2017)	×	×	×	×	√
(Dhingra & Sharma, 2014)	×	×	×	×	×
(Barros & Diego, 2016)	√	×	√	×	√
(Albadi et al., 2015)	×	×	√	×	×
(Gopalakrishnan et al., 2002)	×	×	×	×	√
(Smith, 2008)	×	×	×	×	×
Our Article	√	√	√	√	√

The rest of the article is as follows: harmonic distortions are discussed in detail in the next section. In Section 3, an overview of different PQ standards is given. Finally, the conclusion and recommendations are given in Section 4.

HARMONIC DISTORTIONS

One of the most important factors in PQ are harmonic distortions, if experiencing distorted sinewave, blown fuses, overheating (transformers, motors, neutral), unusual audible noise and tripping of circuit breakers in larger distribution equipment, then these are the indication of harmonics (Lu, 2018; Rabehi et al., 2018; Montoya et al., 2019). The indication of harmonics in electrical systems is a distorted sine wave for voltage and current (Mustafa et al., 2019). In distribution systems, nonlinear loads are the major cause of harmonic currents (D. Wang et al., 2019). A nonlinear load will draw a current that has a different waveform compared to the supply voltage waveform. The supply voltage is then distorted by the flow of these harmonic currents through impedances that in the results generates voltage harmonics (Tokic et al., 2018). Mainly inverter drives and power electronics circuits with higher switching frequencies as they create variations in amplitude and/or phase angle and the harmonic components of the fundamental frequency cause inter-harmonics (Pérez Vallés & Salmerón Revuelta, 2019), (Xu et al., 2019). Harmonics values can be analysed using Fourier series, which will give:

- Fundamental sinusoidal frequency (50 or 60 Hz),
- integer multiples of the fundamental frequency (harmonics),
- DC component at zero frequency (if applicable).

The h[th] order harmonic is the component having 'h' times the fundamental frequency. Recently, a new term has been introduced which is called super harmonics that refers to the distortion of voltage or current in the frequency range from 2 to 150 kHz (Moussa et al., 2019). Active power electronics converters connected to the grid are responsible for much higher frequencies (Chattopadhyay et al., 2014; Prieto T.J. et al., 2016). A description of harmonic distortions effecting the fundamental signal is given in Fig. 2. The equation for the harmonic expansion $y(t)$ is presented below:

$$y(t) = Y_0 + \sum_{k=1}^{\infty} Y_k \sqrt{2}\, sin(k\omega t - \emptyset_k) \qquad (3)$$

where Y_0 – DC components, mostly considered zero; Yk – RMS value of k[th] harmonic; ω – angular frequency; $\emptyset k$ – Harmonic component displacement at zero time.

THD is an indicator of the distortion in a signal. For a signal y, it is defined as:

$$THD = \frac{\sqrt{Y_2^2 + Y_3^2 + \cdots Y_k^2}}{Y_1} \qquad (4)$$

THD is the ratio of the RMS value of all the harmonic components of the signal y, to the fundamental $Y1$. It is generally expressed in percentage. For current harmonics, it is:

$$THD_i = \sqrt{\sum_{k=1}^{K} (\frac{i_k}{i_1})^2} \qquad (5)$$

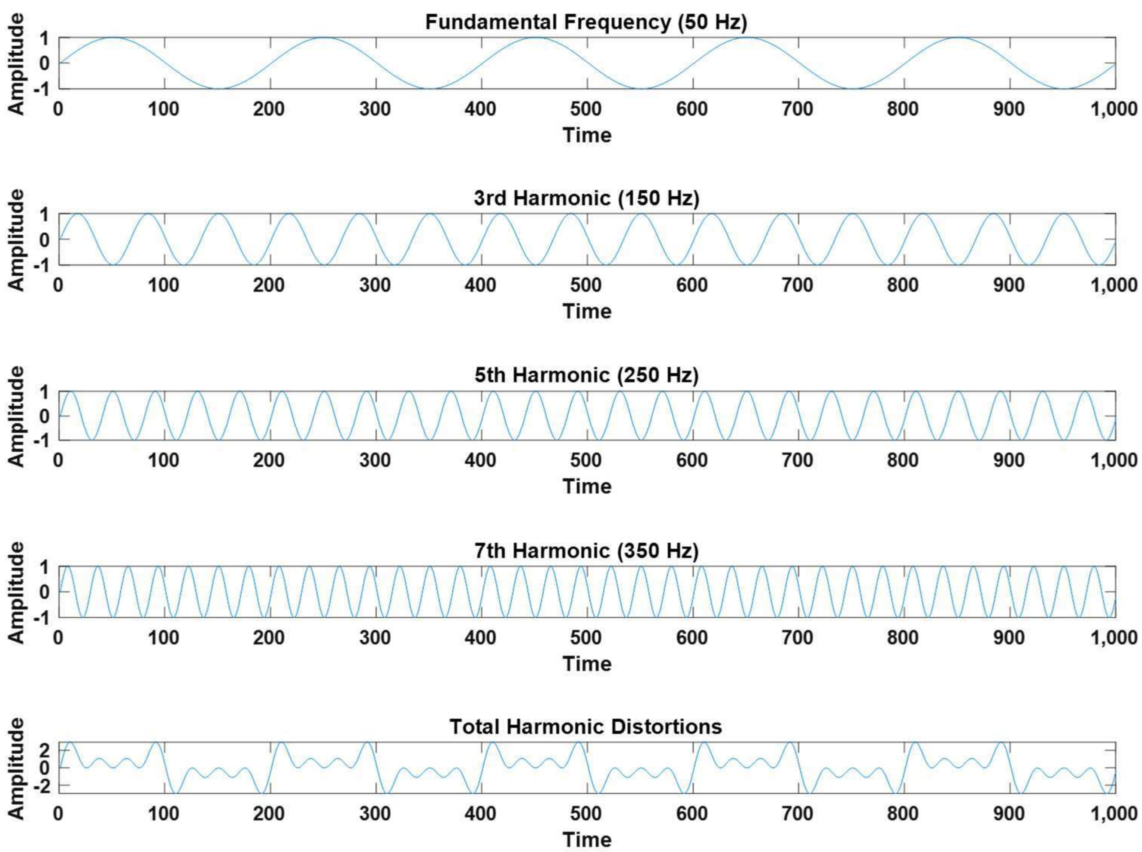

Figure 2. Harmonics distortions.

For voltage harmonics, the equation is:

$$THD_V = \sqrt{\sum_{k=1}^{K} (\frac{V_k}{V_1})^2} \quad (6)$$

Now the distorted voltage and current can also be expressed in Fourier series as follows:

$$v(t) = V_0 + \sum_{n=1}^{\infty} V_n \cos(n\omega t - \emptyset_n) \quad (7)$$

$$i(t) = i_0 + \sum_{n=1}^{\infty} i_n \cos(n\omega t - \theta_n) \quad (8)$$

Now, the formula for average power will become:

$$P_{av} = V_0 i_0 + \sum_{n=1}^{\infty} \frac{V_n i_n}{2} \cos(\emptyset_n - \theta_n) \quad (9)$$

Now the RMS voltage and current can be calculated using the below equations:

$$V_{rms} = \sqrt{V_0^2 + \sum_{n=1}^{\infty} \frac{V_n^2}{2}} \quad (10)$$

$$i_{rms} = \sqrt{i_0^2 + \sum_{n=1}^{\infty} \frac{i_n^2}{2}} \quad (11)$$

The PF is calculated by the following expression:

$$PF = \frac{P_{av}}{V_{rms} . i_{rms}} \quad (12)$$

The RMS current is increased by the current harmonics and they can decrease the valve PF:

$$PF = (Distortion\ factor).(Displacment\ factor) \quad (13)$$

Here, the distortion factor can be defined as:

$$Distortion\ factor = \frac{RMS\ Fundamental\ Current/Voltage}{RMS\ current/Voltage} \quad (14)$$

Moreover, it will be:

$$Distortion\ Factor = \frac{1}{\sqrt{(1 + (THD)^2}} \quad (15)$$

EVALUATION OF HARMONICS AND THEIR EFFECTS

The worldwide organization of the IEC is responsible for the standardization of the electrical and electronic fields in collaboration with the International Organization for Standardization (ISO). They provide a wide range of standards for devices, networks, PQ, measurement techniques, safety purposes, etc., both for the consumer and industrial sector. Similarly, IEEE has some of its own standards.

With the integration of new technologies in the conventional grid, many new PQ disturbances are arising. The study of this emission for this new equipment is urgently needed. Now, the focus should not only be on 'normal harmonic emissions' like third, fifth, and seventh order, but instead, the research should be focused on harmonics (up to 2 kHz), super-harmonics (between 2 to 9 kHz) and emission (greater than 9 kHz). Below are some standards that are related to PQ:

A. IEC 61000-4-30

This standard (IEC, 2000) is related to power quality measurements and the interpretation of their results using AC power supply with 50 Hz or 60 Hz. Most of the PQ indicators related to this standard, their details and ranges are elaborated in Table 4 (IEC, 2000). It focuses on emissions ranging from 2 kHz to 150 kHz.

Table 4. Power quality parameters in IEC 61000-4-30

Parameter	Class	Sampling time	Measurement Uncertainty
Power Frequency	A	10s	± 10 mHz (42.5 Hz to 57.5 Hz / 51 Hz to 69 Hz)
	S		± 50 mHz (42.5 Hz to 57.5 Hz / 51 Hz to 69 Hz)
Supply Voltage	A	10-cycle time (50 Hz) 12-cycle time (60 Hz)	Within ± 0.1% of *V*din, over the range of 10% to 150% of *V* din.
	S		Within ± 0.5% of *V*din, over the range of 20% to 120% of *V* din.
Flicker	A	10 min	0.2 P_{st} to10 P_{st}.
	S		0.4 P_{st} to 4 P_{st}.
Supply Voltage Dips and Swells	A	RMS voltage over 1 cycle commencing at a fundamental zero crossing (refreshed each half-cycle)	± 0.2% of V_{din}
	S		± 1.0% of V_{din}
Transient Voltages and Unbalances (3-phase systems)	A & S	10-cycle time (50 Hz) 12-cycle time (60 Hz)	Below ± 0.15% for both V_2 and V_0.
Voltage Harmonics and Inter-harmonics	A & S		10% to 200%
Signalling Voltage on the supply voltage (ripple control signal)	A	Corresponding 10/12-cycle RMS	0% to 15% of V_{din}.
	S	Manufacturer Specifications	Manufacturer Specifications
RVC	A S	The arithmetic mean of the last 100/120 *Vrms* (1/2) values and the new value is calculated (only if new valve)	Thresholds in the range of 1% to 6% of V_{din} might be considered. Otherwise, the user will define its own value.
Current and harmonic currents	A	10-cycle time (50 Hz) 12-cycle time (60 Hz)	Below ± 1% in the range of 10% to 100% of the specified RMS current.
	S	Manufacturer Specifications	Below ± 2% in the range of 10% to 100% of the specified RMS current.

As described in the Tables 5, two classes are defined in this standard, Class A (precision measurements are required) and class S (for statistical surveys or power quality assessment). Both classes have different measurement incertainty for different PQ parameters. The reference measurement unit for this standard is shown in Fig. 3. The measurement unit contains a transducer unit that converts the signal from one from one energy to another. Then the value of the signal is measured, and results are display. For further evaluation of the signal, there can be some additional options like FFT, spectrum analysis etc.

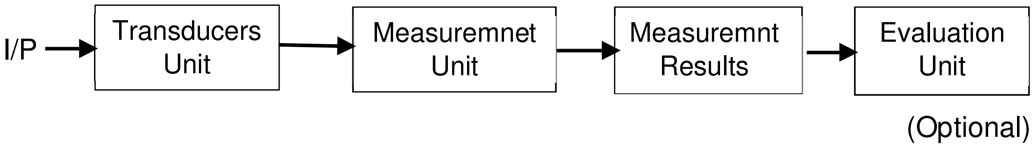

Figure 3. Block Diagram of a measuring unit.

The range of 2 kHz to 9 kHz can also be found in IEC 61000-4-7:2002, while Comité International Spécial des Perturbations Radioélectriques (CISPR 16) covers disturbances from 9 kHz to 150 kHz. The measurement methods in CISPR 16 may be complex or expensive to implement, due to their gapless measurement and accuracy requirements, and it provides a large amount of data (IEC, 2000).

B. IEC 61000-4-7

This standard (IEC 61000-4-7 Standard, 2002) deals with the measurement instrument envisioned for quantifying spectral disturbances up to 9 kHz. As shown in Fig. 4 (IEC 61000-4-7 Standard, 2002), the measurement unit consists of an anti-aliasing filter, A/D-converter, a synchronizer, and, if needed, a window-shaping unit with a Discrete Fourier Transform (DFT) based processor output coefficients a_m and b_m. Then there are special parts related to current and voltage assessment. Frequencies above the measuring shall be attenuated. To obtain the appropriate attenuation, the instrument may sample the input signal at a frequency much higher than the measuring frequency.

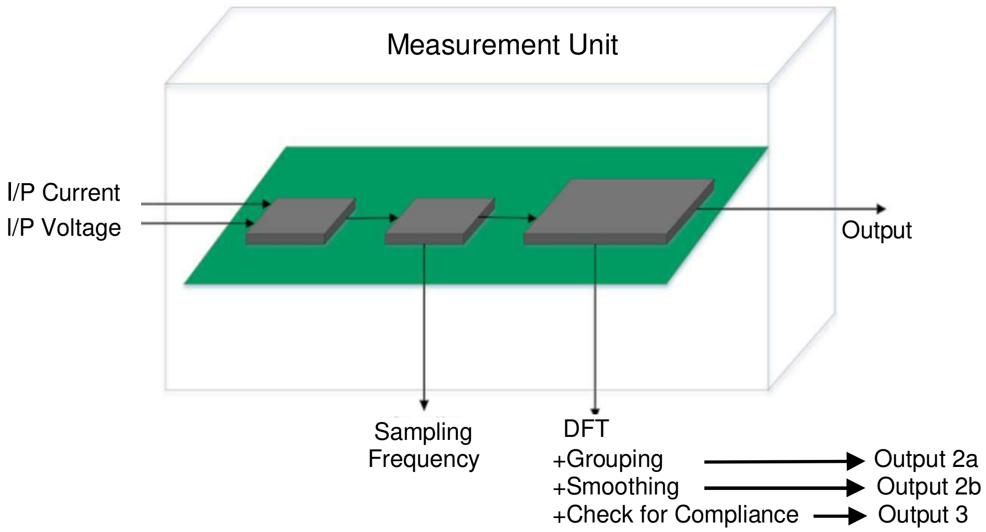

Figure 4. The general structure of the measuring unit.

In the case of the voltage test, the peak value should be between 1.4 to 1.42 times its RMS value, it shall reach between 87°, and 93° after zero crossing and the voltage drop ΔV across the impedance of the current sensing part and the wiring shall not exceed a peak voltage of 0.5V. The procedure of smoothing (OUT 2b of Fig. 4) shall be modified according to the entries in Table 5.

Table 5. Window width and sampling rate

Frequency	Cycle N in window	Sampling rate (ms)
50	10	≈ 1/200
60	12	≈ 1/200
50	16	≈ 1/320
60	16	≈ 1/267

The long-term stability of the test voltage shall be maintained within ± 2% and the frequency shall be maintained within ± 0.5% of the selected value. For a three-phase supply, the three-line voltage shall have a phase relationship of 0°; 120°± 1.5°; 240° ± 1.5°. The voltage harmonic distortion of the Equipment under Test (EUT) voltage V shall not exceed the following values with the EUT connected and operating under the specified test conditions, 0.9% for the 3rd, 0.4% for the 5th, 0.3% for the 7th, 0.2% for the 9th harmonic, respectively. While for even harmonics, it should be 0.2% for orders from 2nd to 10th and 0.1% for 11th to 40th.

C. IEC 61000-4-13

This part of IEC 61000 standard (IEC, 2003) is used for domestic, commercial, and small industrial environments. It outlines the immunity testing range for harmonics and inter-harmonics for low voltage networks that are equipped with a rated current up to 16 A (per phase) including frequencies up to 2 kHz for 50 Hz systems and 2.4 kHz for 60 Hz systems. There are three classes in this standard, which are as follows:

- Class 1: This class is applicable to protect devices that are very sensitive to disturbances in the power supply.
- Class 2: This is applied to the Points of Common Coupling (PCC) and is mostly used in industrial environments.
- Class 3: It is only applicable to in-plant points of common coupling which are used in industrial environments, e.g., new plants or an extension of the old plants.
- Class X: It is still open, and it will be defined in future standards.

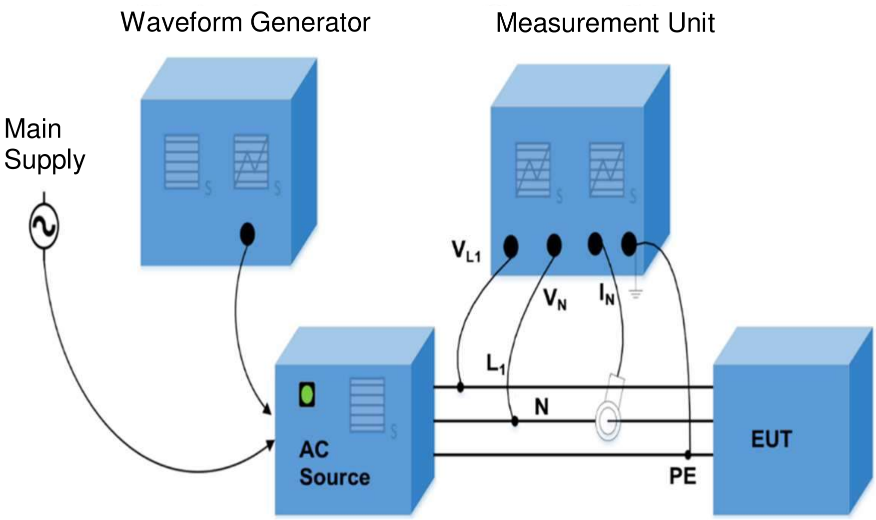

Figure 5. An example of a test setup.

The test generator for this standard must have the ability to generate a 50 Hz or 60 Hz signal frequency to superimpose the required frequencies, e.g., harmonics and frequencies between harmonics. The analyser for harmonics and inter-harmonics must be according to IEC 61000-4-7 for voltage test verification. The example test setup is shown in Fig. 5 (IEC, 2003).

D. CIGRE JWG C4.24

CIGRÉ Study Committee C4 and CIRED established the Joint Working Group (JWG) C4.24: PQ and EMC Issues associated with future electricity networks" in late 2013 to address future power quality issues (CIGRE 719, 2018). In normal practice, the utility companies including transmission and distribution only measure the power quality either in substations or at the Point of Common Coupling (PCC). The future trends will require additional monitoring at the point of connection of renewable energy sources due to their distributed generation and storage along with distribution feeders. Nowadays, the trend of Low Voltage (LV) and High Voltage (HV) side are to measure at every location, both in the control side and revenue side using advanced metering systems. Mostly, these devices do not store data, but there is a need in the future and the potential is already there. Although, the main question is when and what to measure, then its storage and further utilization.

This monitoring requires Intelligent Electronic Devices (IEDs) based on transducers and sensors for current, voltage, temperature, and humidity. Classical transduces work effectively at the fundamental frequency, but they are not suitable for higher frequency ranges (Arrillaga & Watson, 2003). These sensors are quite useful for current and voltage measurements in LV, MV, and HV for protection, operation and monitoring, fault diagnostics, and PQ measurements. Sensors are based on several different phenomena or effects (F. Zavoda, 2009). They have different current and voltage ranges with the possibility of data acquisition, storage, and transmission. Mostly they are used to measure currents and line to ground voltages. However, some of them are compatible with IEC 61000-4-30 and they are used to measure harmonics.

The future devices must be capable of measuring PQ issues like harmonics, inter-harmonics, voltage unbalance, voltage flicker and dip, voltage sag and swell, interruptions, and RVC. There are several proposals for a combination of transducers and IEDs for PQ measurements. Due to the increase of distributed generation and integration, the problems associated with it are also increasing (McDermott & Dugan, 2003). A new set of indices is proposed for a better understanding of these issues (Chicco et al. (n.d.)).

E. IEEE 519-2014 Standard

The standard IEEE 519-2014 (IEEE Power and Energy Society, 2014) is a revision in the previous IEEE 519-1992 standard. The prime goal of these standards is to protect consumers and utilities from the adverse effect of harmonics by keeping the THD in a limit at PCC. In this standard, the individual current limit is 5%, THD is 8% with a new PCC value for voltage ($V \leq 1.0$ kV), and it also defines a new maximum individual value for the 35th to 50^{th} harmonic (Wallace, 2014). The measurement window in this standard, for 60 Hz is 12 cycles (~ 200 ms), and for 50, Hz is 10 cycles on the instrument using DFT. Three statistical limits are defined in this standard, which are as follows:

- For 3 secs, the harmonic current should be less than two times the current distortion limit of the daily 99th percentile.
- For 10 min, the harmonic current should be less one and a half times than the current distortion of the weekly 99th percentile.
- For 10 min, the harmonic current should be less than the current distortion of the weekly 95th percentile

CONCLUSIONS

The advancement in technology has allowed measuring, monitoring, and analysing PQ parameters at higher frequencies and their transmission via wireless technology for accurate evaluation. New sensing equipment is replacing the old one, as we are moving towards higher frequencies, up to 150 kHz or even beyond. This change requires a critical revision of the existing limits and the possibility of their graduation, e.g., super-harmonics, phase angles, and voltage unbalance. Due to the increase in energy-efficient lighting, the harmonics in the system will increase. With the ever-growing measurement data, new system models including both software and hardware are required to get as much information as possible. The live status of the system should be visualized, monitored with the help of flexible and convenient methods.

In future power systems, a balance will be required between conventional PQ analysers, with unconventional devices like controllers and relays, and Advance Metering Interfaces (AMI) with PQ measurement capabilities. The measurement of distortion is a bit tricky; it will require a novel sensor for MV, HV, and EHV systems and it should be done in the planning phase of any new substation. New measurement standards with a new set of parameters are urgently required for the range of 2 kHz to 150 kHz. This must also include both time and frequency domain analysis of these parameters due to special signal characteristics in this range. On the consumer side, the analysis of emissions should also include the monitoring of the contribution of consumer installed devices to voltage quality, rather than only considering current-based measurement methods.

The PQ indices used today were introduced decades ago, but the electricity networks have changed very rapidly. This evolving network needs a new evolving set of PQ indices. The main documents providing information about PQ are IEC 61000-4-30 and IEEE 1159. The currently used measurement units only cover harmonics up to the 50th and calculate the THD and that is not enough. It does not include super-harmonics, so that must be included in future solutions.

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