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Power Quality Event Detection, Monitoring And Improvement: A Survey

Megha Khatri

School of Engineering & Technology, Ansal University, Gurgaon, India.
meghakhatri@ansaluniversity.edu.in

ABSTRACT: Power Quality has become an important issue of discussion after a decade of inception of power system. The aim of electric power system is to generate electrical energy and to deliver this energy to the end user equipment at an acceptable Level. The power quality detection, monitoring and improvement methods are explained in this paper under various sections. This study will be providing insight to the importance of improved power at user end and also the scope of further implementation of discussed methods in field applications.

Keywords : Power Quality, Fourier Transform, Wavelets, Artificial Intelligence, Fuzzy Logic technique, Neural networks

1 INTRODUCTION

THE network of electrical components combined in different manners used to generate, transmit and distribute the electric power known as power system. Electric Power delivered to user end must be of good in quality[1],[2]. Power quality becomes an important issue in early 1980's.[1] Power Quality is defined as any power problem manifested in voltage, current or frequency deviation that results in failure or disoperation of customer equipment or system itself [2-4].Power Quality problems are classified into different categories based on their occurrence. Power Quality Problem covers the time scales range from tens of microseconds to steady state to describe different events [5]. These events are well discussed in various international standards (IEEE, IEC, EN etc) and also various acceptability curves (CIBMA and ITC) according to amplitude and time frame [5-9]. Further different techniques (RMS method, Fourier Transform, Wavelet Transform, S-transform etc) are implemented for the detection and monitoring of power quality events [10-13]. For Improvement of power quality power electronics based network configuring compensating devices and Fuzzy Logic/Neural Network based controllers are installed at various locations in transmission and distribution systems discussed here under. [14-18]. The application of power electronics to power system for the benefit of a customer or group of customers is called custom power devices [15],[16]. Custom power devices are classified into two main categories; first being networked configuring type and the other is compensating type [17],[18].The former one changes the configuration of the power system network for power quality enhancement[18]. The devices widely used in this category are SSCL (Solid State current limiter), SSCB (Solid state circuit breaker) and SSTS (solid state transfer switch) these types of devices performs rapid transfer of the load from a fault line to an alternative line to protect a sensitive load[19-22]. On the other hand the compensating devices are DVR (Dynamic voltage restorer), DSTATCOM (Distribution static synchronous compensator) and UPQC (Unified power quality conditioner) [20-23]. This study can be further extended to automatic detection, monitoring and improvement of power quality problem within minimum time duration.

2 CLASSIFICATION OF EVENTS

Common Power Quality problems are categorized broadly as Transients, Short duration voltage variations, Long duration voltage variations, Voltage Unbalance, Waveform distortion and Voltage Flickers.[23],[24]. Further these problems are divided into sub categories, their characterization methods and the typical cause of their occurrence as shown in below Table 1. [21],[23],[25-28]

Broad Categories	**Specific Categories**	**Characterization Method**	**Typical Cause**
Transients	**Impulsive**	Peak Magnitude, Rise Time and Duration	Lightning Strike, Transformer Energization and Capacitor Switching
	Oscillatory	Peak Magnitude, Frequency Components	Line or Capacitor or Load Switching
Short Duration Voltage Variation	**Sag**	Magnitude Duration	Ferro Resonant Transformer Single Line to Ground Fault
	Swell	Magnitude Duration	Ferro Resonant Transformer Single Line to Ground Fault
	Interruption	Duration	Temporary (Self Clearing Fault)
Long Duration Voltage Variation	**Under Voltage**	Magnitude Duration	Switching on Load, Capacitor De-Energisation
	Over Voltage	Magnitude Duration	Switching Off Loads Capacitor Energisation
Voltage Unbalance		Symmetrical Components	Single Phase Load,Single Phase Condition

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Waveform Distortion	**Harmonics**	THD, Harmonic Distortion	Adjustable Speed Drives And Non Linear Loads
	Notching	THD, Harmonic Distortion	Power Electronic Converters
Voltage Flickers		Frequency of Occurrence , Modulating Frequency	Arc Furnace , Arc Lamps

Table: 1

2.1 Power Quality Standards and Acceptability Curves

Event Characterization leads to power quality standards due to economic aspects. The events and various standards International Electro technical Commission (IEC) Institute of Electrical and Electronics Engineers (IEEE) and Europe norm (EN) are given in the table:2 and the acceptability curves in table:3 which are used for Quantification of power quality disturbances[27-32].These curves are applicable to 60 Hz 120V supply no studies tell about the curves for 50Hz 220V and are basically used to determine whether the supply voltage to a load is acceptable for the maintenance of a load process. The curves are shown in Figure: 1. [30],[33].

Events	Standards
Classification of power Quality	IEC61000-2-1:1990 IEC61000-2-5:1995
Monitoring PQ	IEEE1159:1995
Transients	IEC816:1984 IEC 61000-2-1:1990 IEEEC62:41:1991 IEEE1159:1992
Voltage Sag/Swell and Interruptions	IEC6100-2-1:1990 IEEE519:1992 EN50160
Harmonics	IEC61000-2-1:1990 IEEE519:1992
Voltage Flickers	IEC 61000-4-15:1997

Table: 2

Power Quality Curves	
Curves	Year
ITIC(Information Technology industry council)	1996/ Revised in 2000
IEEE Emerald Book	1992
CBEMA(Computer Business Equipment Manufacturer Association)	1978

Table: 3

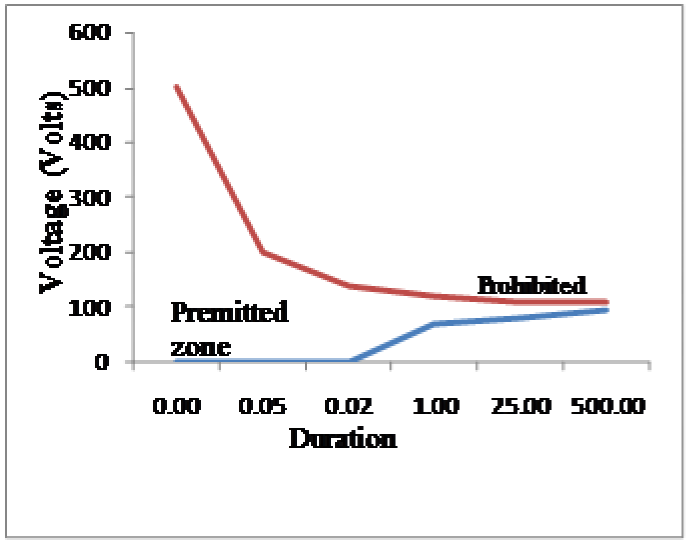

Figure: 1

There is common power quality indices used for quantification of electric power quality. These indices are Total harmonic distortion (THD),power factor, crest factor, unbalance factor, flicker factor etc.[31-34]. In the three phase case these indices can be further delineated into a residual index calculated from the zero sequence components and a balanced index formed by the positive and negative sequence components of voltage or current.[35] In some cases, a breakdown of the even and odd harmonic components of these indices is useful. [35], [36].

3 Detaction And Monitoring

3.1 RMS (Root Mean Square) Method

The root mean square voltage value is mostly applied in power system. This value can be calculated from the time sequenced based on discrete integral [22],[30],[33],[36],[37].
RMS computed in the time domain is the same as in the frequency domain equation shown below

$$RMS = |- \rangle\ x^2(t) = |- \rangle\ |X(f)|^2 = | \rangle\ |-|$$

Whereas $x^2(t)$ is time-domain function and X(f) is frequency-domain function. Despite its simplicity, the RMS-based method is effective in detecting amplitude-related distortions like voltage sags and swell.[37],[38]. This method takes one complete cycle of voltage or current waveform to detect and analyze the type of fault and is applicable for detection of stationary signals i.e. signals either time or amplitude varying only [37-39]. The same method is also applicable for detecting the events in case of frequency domain while the conditions remain same as in time domain systems[39]. The other methods used to detect the distortion in the frequency domain by transforming the time waveform into the frequency waveform are explained in further sections [39-41].

3.2 Fourier Transform (FT) Method

Signal transformation helps us in analyzing the signals from another side. Fourier Transform is a powerful analyzing tool for extracting the frequency contents of the recorded signals [40],[41]. The standard equations shown below in time domain and frequency domain signals respectively are used for the

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voltage and current signals as Sine and Cosine functions[41-44].

$$f(x) = a_0 + \sum^{\infty} \left(a_n \cos \frac{n\pi x}{\,} + b_n \sin \frac{n\pi x}{\,}\right)$$

and

$$F(s) = \int f(x) e^{-2\pi j s x}\, dx$$

Whereas FT is not efficient technique for capturing short term transients like impulses and oscillatory transients in the power system[44]. Also, the time-evolving effects of the frequency on non-stationary signals have not been considered in FT analysis. Although the STFT can partly alleviate the problem, it has the limitation of fixed window length [45-47]. A Discrete Fourier Transform (DFT) is simply the name given to the Fourier Transform when it is applied to digital (discrete) rather than an analog (continuous) signal.[46] Whereas Discrete-Time Fourier Transform (DTFT) represents the discreteness on time domain while DFT represents the discreteness on frequency domain of power signals. An FFT (Fast Fourier Transform) is a faster version of the DFT that can be applied when the number of samples in the signal is a power of two.[45-47], [49] An FFT computation takes approximately N * log2 (N) operations and DFT takes approximately N^2 operations, where N is number of samples [47],[48]. Thus the FFT is significantly faster, While these are having fixed window length i.e. the minimum and maximum limits on time as well as magnitude to identify the event and analyze the same [49-51]. The types of windows one can choose to apply STFT, DTFT, DFT and FFT are Rectangular window, Hann-window, Blackman-Harris window, Gaussian window etc defined by the renowned scientist in this field.[43],[44],[45]

3.3 Wavelets Transform and S –Transform

The signal-processing techniques such as wavelets applicable to automatic detection and monitoring of power quality events. Wavelet theory is an advanced mathematical tool that uses multi-resolution techniques to analyze waveform and images.[34],[35]. The wavelet transform is the projection of a discrete signal into two spaces: the approximation space and a series of detail spaces. The Implementation of the projection operation is done by discrete time sub band decomposition of input signals using filtering followed by down sampling [36],[39]. Various software packages are available for wavelet analysis the MATLAB is one of them where wavelet toolbox wavemenu provides platform for wavelet transforms [38]. The drawback of wavelet transform is choice of window function and another one is the use of ranges of frequency [40]. The S-transform is an extension of wavelet transforms also known as modified wavelet transform and is based on moving and scalable localizing Gaussian window and has characteristics superior to either of the transforms [24],[33]. The superior properties of the S- transform are due to the fact that the modulating sinusoids are fixed with respect to the time axis while the localizing scalable Gaussian window dilates and translates [34]. It is noted that the frequency dependant resolution of the S-transform allows the detection of high frequency bursts and shows good frequency resolution on the long period signals[38]. Various tests are performed where S-transform provides significant tool for detecting and analyzing the PQ events [39], [40].

3.4 Artificial Intelligence (AI)

A broad definition of AI can be the automation of activities that are associated with human thinking, such as decision making, problem solving, learning, perception and reasoning [47].
The AI tools of interest to the electric power community include fuzzy logic (FL), adaptive fuzzy logic (AFL),expert system(ESs),artificial neural networks(ANNs) and genetic algorithms(GAs) [50-55].

3.4.1 FL and AFL Applications

FL and AFL are very powerful AI techniques. Some Applications of these tools in PQ have been developed in the literature includes:[51],[52],[55].

- Diagnosing and classification of PQ problems
- Allocating capacitor banks while maintaining harmonic distortion levels within acceptable limits
- Estimating power quality indices using fuzzy constraints.
- Automating the identification of abnormal system operation using adaptive fuzzy techniques.
- Predicting system abnormal operation
- Automating system VAR control for improved voltage stability and better voltage profiles.

3.4.2 Expert Systems Applications

Although expert systems are expensive and time consuming in their development, some research involved the application of expert systems in Power Quality because of its advantageous approach like[12],[47],[53].

- Classifying distorted voltage and current waveforms into defined categories
- Analyzing harmonics using expert system technology
- Automatic Fault Location
- Identifying and managing power quality events through a scalable system

3.4.3 Neural Network Application

In Artificial neural network two common types of learning that are often mentioned are supervised learning and unsupervised learning [48], [49]. One often understands that in supervised learning, the system is given the desired output, and it is required to produce the correct output for the given input, while in unsupervised learning the system is given only the input and the objective is to find the natural structure inherent in the input data [53], [55]. We, however, suggest that even with unsupervised learning, the information inside the input, the structure of the input, and the sequence that the input is given to the system actually make the learning "supervised" in some way [42], [51], [54],[56]. ANNs have extensive use in power quality its main applications include [8]

- Identifying PQ events from non power quality ones
- Modeling the patterns of harmonic production from individual fluorescent lighting systems
- Identifying high impedance faults, faults like loads and normal load current patterns

3.4.4 Genetic Algorithm (GA)

Genetic Algorithms are considered to be an excellent intelligent paradigm for optimization using a multi point, probabilistic, random, guided search mechanism. Some applications are documented as follow[47], [50].

- Developing an alarm processing system and diagnose system for a power grid using AI tools

- Using Fault tree induction Algorithm for classification of power quality waveforms
- Integrating AI and advanced communication technologies in substation intelligent electronic devices (IED)

The research is advanced in assessing the power quality events by Empirical mode decomposition (EMD) introduced by Huang together with Hilbert transform for extracting instantaneous amplitude and frequency from multi component non stationary signals [33]. The other emerging technique probabilistic neural network (PNN) is a supervised neural network that is widely used in the area of signal pattern recognition.[52] The following features are distinct from other networks in learning process.[33-36], [52].

- It is implemented using probabilistic model, such as Bayesian Classifiers
- No Learning Processes are required
- The inference vector and the target vector are not used to modify the weights of the network.

4 IMPROVEMENT OF POWER QUALITY

The situation of power distribution networks become alarming rather than transmission systems due to extensive use of power electronics based household appliances and several AC and DC drives in almost all areas which could make the point of common coupling highly distorted [13],[14],[27],[35].Various compensating devices are used for improvement of power quality are employed briefly reviewed here under.

4.1 Distribution Static Synchronous Compensator

The DSTATCOM configuration consists of a two level Voltage Source Converter (VSC), a dc energy storage device and a coupling transformer connected in shunt with the ac system [23-26]. The VSC converts the dc voltage across the capacitance, which is coupled to the ac system through the reactance of the coupling transformer [19],[20-24]. Suitable adjustment of the storage device is used to convert dc into a set of three phase ac output voltages in phase and magnitude of the DSTATCOM output voltage, which allows effective control of real and reactive power exchanges between the DSTATCOM and the ac system [22],[23]. The voltage source converter connected in shunt with the ac system provides a multifunctional topology, which can be used for distinct purposes like [23],[26],[50], [57]. Voltage regulation and compensation of reactive power. Correction of power factor Elimination of current harmonics.

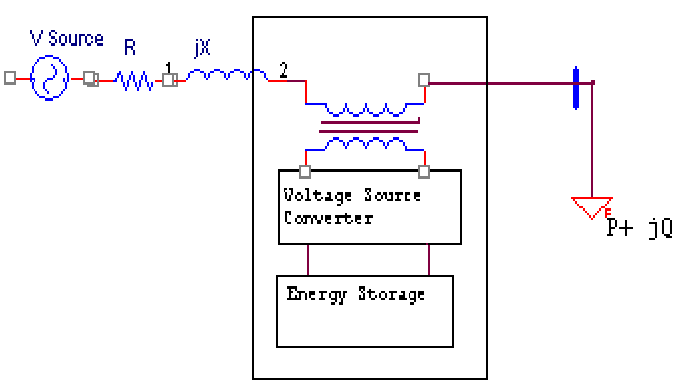

Figure: 2 *Diagrammatic representation of DSTATCOM*

The working limits of the D-STATCOM are determined by following steady state equations where V is the source voltage at its terminals , is the phase difference and P,Q are the active and reactive power delivered by it respectively. The active power generation capability of a D-STATCOM can be increased by adding energy storage system to its DC side, such as batteries, flywheels. Thus results in smoothening of output power, electromechanical oscillation damping and in frequency control or inertia emulation [17], [19], [40].

4.2 Dynamic Voltage Restorer (DVR)

The DVR is a powerful controller that is commonly used for alleviation of voltage sag at the point of common connection [18],[19] .The DVR employs the same blocks as that of coupling transformer in series with the ac system, as shown in figure 3. [20] The main functions of DVR are [20],[21],[22],[23],[57].

Voltage Regulation.

Compensation of voltage sags and swells. Unbalance compensation for current and voltage (for a 3 phase system)

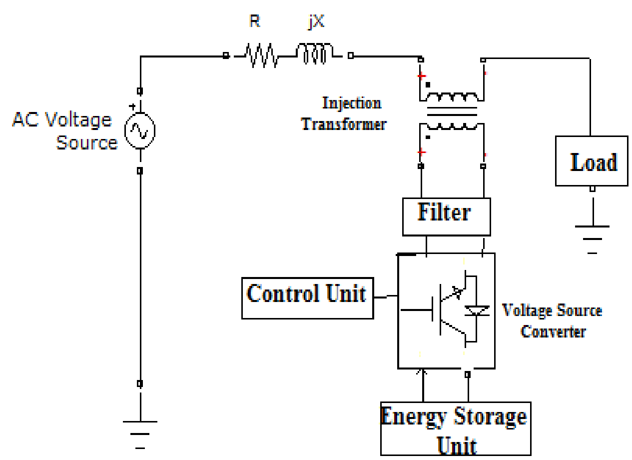

Figure: 3 *Diagramatic representation of DVR.*

The VSC generates a three-phase ac output voltage which is controllable in phase and magnitude [21]. This Voltage is injected into the ac distribution system in order to maintain the load voltage at the desired voltage reference [22], [29].

4.3 Unified Power Quality Conditioner (UPQC)

UPQC allows the alleviation of voltage and current disturbances that could affect sensitive electrical loads while compensating the load reactive power. UPQC consists of combined series and shunt active power filters [13], [14]. The passive filters have drawbacks like dependence of filtering characteristics on source impedance, detuning, parallel/series resonance between power system components, high no load losses, bulky size and fixed compensation.[41],[42],[53],[57].To overcome these difficulties with the passive filters, active filters have been developed, which provide dynamic and adjustable solutions to power quality issues.[17],[19]. This device deals with both load current and supply voltage imperfections [16],[25]. The UPQC can further be classified based broadly on its application as physical structure and voltage compensation [58-60].

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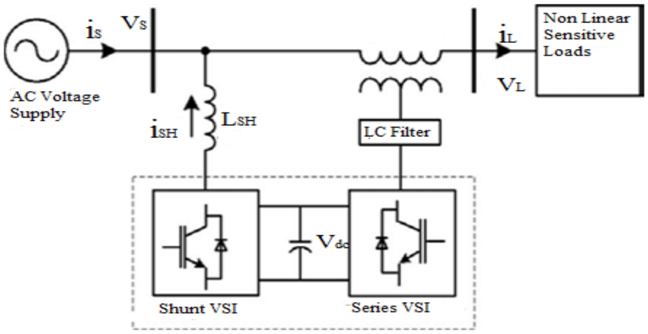

Figure:4 *Diagrammatic representation of UPQC*

The main functions of UPQC include

- Compensation of short duration faults in minimal possible time duration
- Simultaneously current and voltage compensation
- Applicable in Grid Control systems, Distributed Generation and in transmission lines

5 CONCLUSION AND FUTURE SCOPE

In this paper classification of events, their detection, monitoring as well as improvement methods are briefly documented .It is found from the classification of events the most common events occur due to the single line to ground fault in power system are voltage sag / swell and due to increase in communication networks and power electronic industrial loads harmonics mainly the odd ones in voltage and current arises commonly which affect the quality of power in power system adversely. Various methods with different combinations are given above to detect and analyze these events are discussed. Empirical mode decomposition (EMD) introduced by Huang together with Hilbert transform is the latest one, whereas research is still going on to find the method which takes minimum time to detect the event and power grids can be saved from blackouts or failures. Distribution System is studied in the improvement of power quality section because of increase in small-scale industries and usage of electronic based home appliances. The application of active filters to develop Unified Power Quality Conditioner (UPQC) for distribution systems and Unified Power Flow Controllers (UPFC) for the transmission systems are having disadvantage of effecting the operation of sensitive loads leads to further research in their controlling methods for the improvement.

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