A Research Review on Detection and Classification of Power Quality Disturbances caused by Integration of Renewable Energy Sources

Utkarsh Singh*

September 24, 2020

Abstract- With the increased interest in integrating renewable energy sources (RES) such as wind power and solar into the power systems owing to their zero greenhouse gas emissions and the involvement of power converters for integration in grid, the detection, classification and mitigation of power quality events has become indispensable. For employing an appropriate mitigation technique, it is a pre-requisite to correctly classify the various types of disturbances in power quality. This paper, therefore, presents a detailed research reviews on detection and classification of power quality disturbances caused by the integration of renewable energy sources and associated works present in literature till date. Attempts are also made to highlight the current and future issues involved in the detection, classification and mitigation of PQ disturbances. Best efforts have been made to make this paper serve as a full-fledged reference for the future work in this field. A list of 230 research publications on the subject is also appended for quick reference.

Index terms- power quality, disturbances, detection, time-frequency analysis, feature extraction, classification.

1. Introduction

With the increased concern over global climate change and depletion of fossil fuels, utilization of renewable energy sources such as wind power and solar has grown in the past decades, annually. Integration of these energy sources into the grid has created complexity in the operation of power systems due to their intermittent nature. The major impacts of wind and solar integration are unbalance and voltage fluctuations, voltage and current harmonics, grid islanding protection, and other power quality issues, such as flicker and stress on distribution transformer. Severity of these issues depends on the penetration level of these energy sources, their location and configuration of distribution system.

Before moving on to power quality issues, one should have a clear understanding of ‘Power Quality’. One of the earliest references [1], defines power quality as a tool for describing the conditions at the interface of power sources and loads. To avoid misinterpretation of the term power quality, five different terms were defined [2]: voltage quality, current quality, power quality, quality of supply and quality of consumption. For ease of understanding, it may be said that power quality deals with the deviations in voltage and current waveforms from their respective ideal

* The author is with Artificial Intelligence Lab, Free University of Brussels (VUB), 1050 Brussels, Belgium. Corresponding e-mail: utkarsh.singh@ieee.org
behaviors in a power system, from the point of generation till consumption. These deviations in voltage or current waveforms may be termed as power quality disturbances.

Various types of PQ disturbances or events have been discussed in literature and many techniques for their detection, localization and classification have also been presented. The methods differ in complexity, hardware requirements, computational speed, cost of implementation, suitability and popularity. These techniques range from most innovative ideas (but not effective) to simple methods (yet effective). Due to abundance of such techniques in literature, it is very necessary to categorize which method should be adopted for a particular problem. A survey would be beneficial here, for the researchers in power quality. Fig. 1 gives an approximate research trend ranging from the earliest traceable work to till date. It can be observed from the trend that the interest in power quality has declined in last five years. With the help of this review, it will be shown that there is much more to be uncovered in power quality and classification of disturbances, especially with the emergence of smart grids, micro grids and renewable energy.

Over 200 papers related to PQ and disturbance classification have been compiled in this manuscript. It has not been intended to present a literal chronology of all the work done in this context, because the publication date is generally not indicative of when a particular technique was adopted. It has also been tried to omit papers with reference to a previous work without any significant modification. Author apologizes if one or more important works have been omitted unintentionally. This paper, thus presents a state-of-the-art discussion on PQ analysis and disturbance classification, and has been divided into following segments- Power quality overview, Signal processing techniques, detection and localization, classification techniques and conclusion.

![Fig. 1. Total number of papers per year, since 1967](image)

2. Power quality overview

This section will focus on various aspects of power quality and PQ events. The definition of power quality must not be limited to source-load interactions as it also depends on the interaction between
equipment and electromagnetic environment. This interaction is termed as electromagnetic compatibility (EMC) and the international power quality standards (IEC) are considered as a subset of EMC. Depending on how the power quality disturbances are measured, these can be broadly classified into two types: Variations and Events. Variations are the small deviations (rms or frequency) in voltage or current from their nominal value, e.g. harmonic distortion, voltage fluctuation, voltage and current unbalance and high frequency voltage noise. Variations are measures at a particular time. Events are larger deviations, which occur occasionally e.g. load switching currents or momentary interrupts. Events are measured w.r.t start and end time and deviations crossing a threshold value, e.g. voltage sag, swell interruptions and transients [2]. Power quality disturbances (PQD) may arise due to variations in amplitude, frequency and waveform. Depending upon the duration of existence, events may be classified as short, medium or long type [3]. Different types of classification schemes may be found in literature, but a simplified classification may be divided into the following types [4]: Interruption, under voltage, over voltage, voltage/current unbalance, harmonics (integer harmonics, inter harmonics and sub harmonics), transients (oscillatory and impulsive), voltage sag, voltage swell, flicker, notch and noise. In order to classify a disturbance, it is very necessary to properly understand the pattern of a PQD [5], therefore the nature of commonly used PQDs has been listed in Table 1 [3,4]. The common sources of these disturbances are power electronic devices, IT and office equipments, arcing devices, load switching, large motor starting, embedded generation, sensitive equipments and environment related damage [6]. The equations for modeling the commonly classified events have been given in Table 2, and may also be found in previous works [7-15]. The literature on power quality is increasing but it will not saturate as a research topic due to power system modernization. For detailed knowledge of power quality, readers are encouraged to go through the publications listed in references [16-43].

Table 1: Power quality disturbances and their description [3,4]

| Disturbance                  | Description                                                                 |
|------------------------------|-----------------------------------------------------------------------------|
| Voltage sag                  | Reduction in RMS voltage over a range of 0.1–0.9 pu for a duration greater than 10 ms but less than 1 s. |
| Voltage swell                | Increase in RMS voltage over a range of 1.1–1.8 pu for a duration greater than 10 ms but less than 1 s. |
| Under voltage                | Voltage magnitude is below its nominal value.                                |
| Over voltage                 | Voltage magnitude is above its nominal value.                                |
| Interruption                 | Voltage magnitude is zero.                                                   |
| Flicker                      | A visual effect of frequency variation of voltage in a system.               |
| Voltage/current unbalance    | Deviation in magnitude of voltage/current of any one or two of the three phases. |
| Outage                       | Power interruption not exceeding 60 s duration due to fault or mal-tripping of switchgear/system. |
| Transients                   | Sudden rise of signal which may be impulsive or oscillatory in nature.       |
| Harmonics                  | Equation                                                                 | Parameters                                                                 |
|---------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Non-sinusoidal waveforms   |                                                                         |                                                                           |
| Integer harmonics         | Harmonics with frequency as integer multiple of fundamental frequency.  |                                                                           |
| Inter harmonics           | Harmonics with frequency higher than fundamental frequency, but not integer multiples of it. |                                                                           |
| Sub harmonics             | Harmonics with frequency lower than fundamental frequency.               |                                                                           |
| Notch                     | Non-sinusoidal, periodic waveform distortions.                           |                                                                           |
| Noise                     | Low magnitude electrical signals from a broad frequency spectrum lower than 200 kHz. |                                                                           |

| Disturbance    | Equation                                                                 | Parameters                                                                 |
|----------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Normal         | $x(t) = \sin(\omega t)$                                                  | $\omega = 2\pi \cdot 50 \text{ rad/s}$                                   |
| Sag            | $x(t) = [1 - \alpha (u(t - t_1) - u(t - t_2))] \sin (\omega t)$          | $0.1 \leq \alpha \leq 0.9, T \leq t_2 - t_1 \leq 9T$                     |
| Swell          | $x(t) = [1 + \alpha (u(t - t_1) - u(t - t_2))] \sin (\omega t)$          | $0.1 \leq \alpha \leq 0.8, T \leq t_2 - t_1 \leq 9T$                     |
| Interruption   | $x(t) = [1 - \alpha (u(t - t_1) - u(t - t_2))] \sin (\omega t)$          | $0.9 < \alpha \leq 1, T \leq t_2 - t_1 \leq 9T$                           |
| Flicker        | $x(t) = [1 - \alpha \sin(2\pi \beta t)]\sin (\omega t)$                | $0.1 \leq \alpha \leq 0.2, 5\text{Hz} \leq \beta \leq 20\text{Hz}$      |
| Oscillatory transient | $x(t) = \sin(\omega t) + a\exp\left(-\frac{t-t_1}{\tau}\right)(u(t-t_1) - u(t-t_2))\sin(2\pi f_n t)$ | $0.1 \leq \alpha \leq 0.8, 0.5T \leq t_2 - t_1 \leq 3T, 300\text{Hz} \leq f_n \leq 900\text{Hz}, 8\text{ms} \leq \tau \leq 40\text{ms}$ |
| Harmonic       | $x(t) = \alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t) + \alpha_7 \sin(7\omega t)$ | $0.05 \leq \alpha_3, \alpha_5, \alpha_7 \leq 0.15, \sum(\alpha_i)^2 = 1$ |
| Notch          | $x(t) = \sin(\omega t) - \text{sign}(\sin(\omega t))\sum_{n=0}^{\kappa} [u(t - (t_1 + 0.02n)) - u(t - (t_2 + 0.02n)))]$ | $0.1 \leq \kappa \leq 0.4, 0 \leq t_1, t_2 \leq 0.5T, 0.017T \leq t_2 - t_1 \leq 0.05T$ |
| Spike          | $x(t) = \sin(\omega t) + \text{sign}(\sin(\omega t))\sum_{n=0}^{\kappa} [u(t - (t_1 + 0.02n)) - u(t - (t_2 + 0.02n)))]$ | $0.1 \leq \kappa \leq 0.4, 0 \leq t_1, t_2 \leq 0.5T, 0.017T \leq t_2 - t_1 \leq 0.05T$ |
| Sag with harmonic | $x(t) = \left[1 - \alpha (u(t - t_1) - u(t - t_2))\right] \ast \left[\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t)\right]$ | $0.1 \leq \alpha \leq 0.9, T \leq t_2 - t_1 \leq 9T, 0.05 \leq \alpha_3, \alpha_5 \leq 0.15, \sum(\alpha_i)^2 = 1$ |
| Swell with harmonic | $x(t) = \left[1 + \alpha (u(t - t_1) - u(t - t_2))\right] \ast \left[\alpha_1 \sin(\omega t) + \alpha_3 \sin(3\omega t) + \alpha_5 \sin(5\omega t)\right]$ | $0.1 \leq \alpha \leq 0.8, T \leq t_2 - t_1 \leq 9T, 0.05 \leq \alpha_3, \alpha_5 \leq 0.15, \sum(\alpha_i)^2 = 1$ |
3. Power quality indices (PQI)

Certain indices (known as power quality indices) have been prepared to minimize the dissimilarity of results while monitoring power quality using different techniques. The power quality indices (PQI) include parameters such as rms, magnitude, phase, frequency or energy of signals. The deviation in these indices during a disturbance as compared to their nominal or threshold values may be then used in accordance with the standards [38,44] for detection or categorization of PQDs. Other standards for measurement of parameters for detection of power quality events have been mentioned in [35,45,46]. Mathematical representations of these PQI can be found in [47].

4. Detection

Power quality indices or features of a power signal are used for detection of power quality disturbances or events. Signal segmentation is a necessity for reduced data handling and it also helps in categorizing the events as pre- and post-fault events. Wavelet transform can be used along with threshold check for detection and time estimation of disturbances [48-52]. Use of adaptive linear combiner (ADALINE) with wavelet transform may help in residual detection and reduce the burden of training [53,54]. Authors have emphasized on the necessity of test sample size and calculation time reduction for real time power quality analysis [55,56]. Fundamental voltage component provides high precision level and works well even in presence of DC decaying components. Peak voltage does not provide much detail about PQD but is a cheaper option from detection perspective. RMS voltage is suitable for harmonic and flicker detection. Fundamental voltage component is good for detection of sag, swell and interrupts. Peak voltage based detection has been suggested for impulses and surges [57]. It was found that one window length is suitable for short duration disturbance detection. Time at level analysis was suggested as an improvement to the conventional RMS based detection techniques where RMS estimation was done using a moving window. Time at level curves is suitable for comparison with standard curves like CBEMA and ITIC [58]. Preset threshold advantage was presented in an easy VI program [59]. RMS per unit, waveform distortion, harmonic and interharmonic distortions are suitable indices for PQD detection using rule based systems [60]. Higher order cumulants and Phase locked loop (PLL) are good for transient detection and differentiating between long and short transients [61-63]. Spectral sincfit algorithm was given as a robust method for harmonic detection [64]. Generalized likelihood ratio test (GLRT) detector shows better performance in sag detection as compared to RMS, wavelet, kalman filtering, peak voltage and missing voltage based detection techniques [65]. Various methods have been discussed in literature for sag/swell and rms based detection [56-58,60,66-68]. Effect of noise and harmonics on detection has also been discussed in some of these cases. Some other variants with simplified approach were: Fuzzy expert system [69], Space vector representation [70], neural network based detection [56,71,72], Phase Space Embedding [73], 2D wavelet transform [74], Phase space representation [75], Continuous wavelet transform [76], Adaptive filtering [77], Symmetrical components [78], Multiresolution morphological gradients
Sparse signal decomposition [80] and Hilbert-Huang transform [81]. Phase space representation based techniques were found to perform better than window based techniques.

5. Signal processing techniques

Signal processing is the most vital part of PQD classification. It is very important to analyze the time and frequency components of a power signal to accurately detect and classify the events. Many techniques evolved in the course of time, out of which Wavelet transform and Stockwell transform gained huge popularity. Though these techniques can be event specific such as: parametric (fixed number of parameters) and non-parametric (parameters grow with the amount of training data) or according to the signals: stationary (frequency content does not change over time) and non-stationary (frequency content changes over time), but it is better to list the pros and cons of these methods so that the researchers can choose a technique accordingly.

Important techniques available in literature include: Short Time Fourier Transform (STFT) [82-84], Wavelet Transform (WT) [85-117], Stockwell Transform (ST) [118-135], Hilbert/Hilbert-Huang Transform (HT/HHT) [81,136-141], Gabor/Gabor-Wigner Transform (GT/GWT) [142-145], Cohen’s class [146-151], Filters [46,152-157], Prony Analysis (PA) [158-163], Phase Space Embedding [73], Phase Locked Loop [63,164,165], Parametric Methods [166-171]. Application of some of these techniques for disturbance detection has already been discussed in the previous section. The description and mathematical definitions of these techniques have been properly tabulated in [172]. To avoid any inconvenience to the readers, the key findings of the references used in this segment may be summarized as follows:

- Fourier transform is a powerful tool for frequency analysis but is incapable of detecting the sudden changes. STFT solves this problem by using a small window, so that these types of disturbances can be considered as stationary during analysis.
- STFT, GT, Filter banks, WT, ST, PA, Cohen’s class and parametric methods are well suited for non-stationary signal analysis.
- STFT is simple in implementation but has limited time-frequency resolution.
- DWT offers simultaneous time-frequency analysis. Multi Resolution Analysis (MRA) makes it possible to break a signal into continuous high-low frequency components. Performance of this technique depends on the choice of mother wavelet and the level of decomposition. Debauchies-4 (Db4) wavelet has been found to be most suitable for PQD classification. Wavelet transform is affected by the presence of noise and has cross-term problem. High decomposition levels increases the computational burden.
- ST is capable of localizing the real and imaginary components of spectrum in time. It is a phase corrected form of continuous wavelet transform with a Gaussian window. Cross-term problem can be avoided with this method. This technique is not suitable for harmonics. Use for real time applications is also not recommended, due to high computational complexity and execution time.
- HHT is helpful in obtaining and preserving the instantaneous frequency data, and hence it is suitable for real-time applications. Both non-stationary and non-linear signals can be analyzed using this technique. It is limited in distinguishing different components in narrow signals.
- GT is a special case of STFT. It offers good time-frequency resolution and signal-to-noise ratio (SNR). It has the ability to zoom into the segment of interest in a signal. Computational complexity in this technique is proportional to sampling frequency and it is not suitable for analyzing high frequency events. Addition of Wigner's distribution function may help further improvement of time-frequency resolution but window width plays a very critical role in this case.
- Cohen's class offers different tools for achieving high time-frequency resolution (Spectrogram, Wigner-Ville distribution, Choi-Williams distribution and reduced interference distribution). Proper kernel selection may reduce the interference problem.
- Filter banks help in frequency sub-banding and computational complexity is lesser. Inaccurate harmonic prediction and frequency band overlapping are common problems with this technique.
- Kalman filter (KF) is suitable for real-time harmonic and transient detection. It also offers good SNR. With Extended Kalman Filter (EKF), changes in the parameters of distorted signal can be detected. It is not capable of simultaneous time and frequency decomposition.
- PA does not require frequency information before filtering and additional frequency estimators. It is suitable for analysis of transients, harmonics and oscillations. Slight mismatch in model may result in incorrect estimation of an event.
- Phase space embedding represents the parameters of a dynamic system in phase space. It is suitable for real-time application as it requires current sample and a quarter cycle ago sample. It also provides noise immunity to a great extent.
- PLL provides accurate measurement of phase and frequency. It is also capable of synchronizing with the input signal. Harmonic and interharmonic estimation is inconvenient with this technique.
- Parametric methods such as MUSIC, Yule-Walker and Auto-Regressive (AR) models give outstanding time-frequency resolution. Though these methods maintain essential signal information but require large model order and sufficient time for accurate prediction. Proper assumption of statistical distribution of signal is a pre-requisite.

6. Feature extraction

In earlier reviews, feature extraction has not been discussed in particular. So this segment has been dedicated to feature extraction. A feature, in reference to power signals, can be defined as the distinctive attribute of a power signal which later assists in the classification of power quality events. A feature vector can hence be defined as a set of such features. Feature extraction refers to the process of selection of important features from a signal which can be used for classification. The foundation and applications of feature extraction have been elucidated in [173]. In [74], 60 features were generated using number, location and amplitude of local maximum points in 2D...
wavelet transform spectrum. Energy extracted from coefficients of multi resolution analysis has been used as a prime feature in wavelet transform based works [89,103,113,174,181]. Binary features can be developed in wavelet transform by using five different types of indices: duration index, interruption index, flat index, rising index and falling index [100]. RMS and THD based features are very helpful in harmonic detection and classification [104]. In [131], five different types of energy measures have been shown. Some other papers on wavelet transform present additional set of features for distinguishing PQ events, such as: fundamental component, total harmonic distortion (THD), number of peaks in wavelet coefficients, phase angle shift, oscillation number of missing voltage, lower harmonic distortion and oscillation number of rms variations [175,179]; time duration and peak based features [178]; mean, standard deviation, skewness, kurtosis, RMS, form factor, crest factor and fast fourier transform based features [181]; number of samples in a particular range of amplitude or beyond that range [183]. Magnitude and argument coefficients obtained from continuous wavelet transform have been used as features to extract desired band of transient signal for disturbance detection [111,182]. In [184], 64 feature vectors were developed using mean and standard deviation out of which 8 optimal feature vectors were identified based on principal component analysis. Amplitude factor, maximum/minimum values of signal, standard deviation of magnitude and phase contour are suitable features to be extracted from Stockwell transform (ST) [125,176]. If the coefficients of a transform possess sufficient information for distinguishing between one or more events, they can be directly used to form a feature vector as shown in [136,184]. Parallel feature extraction in time and frequency domain speeds up the computational process significantly [185]. While feature extraction, it should be noted that features should not be correlated and should be able to distinguish between various PQDs. If the feature values are not uniform, data must be normalized. Various methods for feature vector normalization may be found in [186]. Irrelevant and redundant features must always be rejected which do not provide any useful information. Hence, optimal selection of features based on their relevance is very necessary. Techniques for optimal feature selection have been discussed in [187-189].

7. Classification

To avoid the ill effects of PQDs on power system and the equipments within, mitigation is required. Mitigation measures are taken according to the type of disturbance. This calls for the classification of PQDs. In this segment various classification methods available in literature will be discussed and the important aspects will be summarized. Bayesian classifiers use maximum likelihood (ML) criteria for PQD classification along with probability density functions of features [82,190-193]. In [190], a rule based approach has been presented for time characterized classification and wavelet transform (WT) - hidden markov model (HMM) for frequency characterized classification. Nearest neighbor (NN) classifiers have been covered in [82,174,194,195]. In [174], NN based pattern recognition has been shown for online application. Artificial neural network (ANN) has already been proved in past for their optimization, pattern recognition and data clustering capabilities. Use of ANN for PQD classification has been shown in
Common types of ANN, which have been widely implemented for classification are: Back propagation neural network (BPNN), Multi-layer perceptron (MLP) and Radial basis function neural network (RBFNN). BPNN is suitable for training multi layered feed forward networks. MLP offers good recognition ability. However, a proper scheme or optimization is required for proper selection of number of hidden layers and nodes. While MLP is slow, RBFNN offers fast learning and detection advantages. The membership of a particular PQ event to a class may be characterized by using fuzzy classifier [82,103,165,175,207,210,212-214]. The performance can be further improved by using neuro-fuzzy [175,212] or genetic-fuzzy combinations [207]. These hybrid schemes are used to improve the rule base of fuzzy classifier. Some rule based expert systems (ES) have been presented in literature [82,157,206,207,209,215-218], out of which fuzzy-expert system is most successful. Rule based decision trees are used in ES. A binary feature matrix scheme for classification has been presented in [215]. Support vector machine (SVM) is a very useful technique for auto-classification of disturbances. Use of SVM and its variants like multi-class SVM, fuzzy-SVM, directed acrylic graph SVM has been shown in [15,170,202,217,219-225]. Dynamic time warping classifier has been presented in [226], which is suitable for automated monitoring and provides superior speed and accuracy as compared to neural network and fuzzy classifiers. Important findings to assess the performance and abilities of these classifiers have been summarized as follows:

- Bayesian classifiers are suitable for functions with Gaussian probability density, which should be known beforehand. Large computational cost is a disadvantage in this case.
- Nearest neighbor classifiers are very accurate in classifying mixed event problems. Noise hinders the performance of these classifiers.
- ANN is appropriate for real time classification, but the performance depends on the network architecture. Noise reduction techniques must be used to avoid any effect on accuracy.
- Fuzzy logic classifiers offer easy modeling but an additional training set is required for a new PQ event.
- Expert systems do not rely much on the amount of input data available. These classifiers are slow and costly. Moreover, the classification may be affected in a case where a particular event does not match any of the rules.
- SVM classifiers have high learning capability. It can handle large number of features and is suitable for quadratic optimization problems. Good classification accuracy can be achieved only with proper training.

8. Conclusion

This paper provides an absolute review for the classification of power quality disturbances (PQD). All the important terms related to power quality and PQD classification have been properly defined. The role of power quality indices has been focused upon to obtain comparable performance with different detection and classification tools. An extended literature has also been
provided for the readers to understand the power quality standards. This paper covers almost all the important aspects of detection, signal processing, feature extraction and classification with respect to power quality problems. Mathematical models of commonly investigated power quality events have also been presented in this paper for the ease of use. Feature extraction plays a key role in PQD classification; therefore, a dedicated segment has been presented in this paper, which was absent in earlier reviews. Summarized points in signal processing techniques and classification segments will help the researchers to easily assess the pros and cons of a technique without going through extensive literature.

From this review, it is clear that the main causes of poor quality are dips, surges, transients and momentary interrupts. Early detection and characterization schemes offered by power quality monitoring standards IEEE 61000-4-30 and IEEE 1159 were based on RMS voltage. The performance of these methods depends on window length, which is not suitable for transients. Several other techniques are popular for PQI estimation such as WT and filter banks. But there is a need for new set of standards keeping in view the estimation and classification of transients and harmonics. Singular point (start and end points of a disturbance) detection has recently emerged as a new area of interest. The conventional singular point detection schemes such as High Pass Filter and RMS method introduce time delay, are susceptible to noise and do not work well under frequency changes. With the advent of near perfect reconstruction (NPR) filter banks and improvement in design of digital filters, the accuracy of harmonic measurement has significantly improved. Among the signal processing techniques WT and ST have been used extensively, but these methods have the respective disadvantages of noise susceptibility and large computational burden, which makes them unsuitable for real time operation. Other techniques, which offer good time-frequency resolution are either very costly or fail to analyze the harmonic and transients disturbances properly. Rule based expert systems, fuzzy classifiers, artificial neural network (ANN) and support vector machines (SVM) are the common classifiers based on artificial intelligence. The SVM has become a preferred choice over the ANN recently. The main advantages of SVM are simple geometric interpretation and existence of global minima in all cases. In context of modern grids (smart and micro), it can be suggested that there is a need to monitor the nature of PQ events on these sites and prepare detection/classification schemes accordingly. A proper scheme is still required which offers speed, accuracy, uses minimum resources, less training and is adaptable to new disturbances. The various stages involved such as detection, signal processing, feature extraction and classification already increase the computational burden. Therefore, optimal feature selection is also indispensable to reduce the memory usage and computational time.

Substantial progress has been made in the area of PQ disturbances covering analysis, simulation, and hardware development and testing for identification, classification and mitigation etc. However, many problems and issues, especially those related to development of real time automated detection, classification and mitigation schemes etc., still need to be addressed for
appropriate system planning and operation of power system to supply a good quality and reliable electric power.

References

[1] Kusko, Alexander. "Quality of Electric Power." Industry and General Applications, IEEE Transactions on 6 (1967): 521-524.
[2] Bollen, M. H. J. "What is power quality?." Electric Power Systems Research 66.1 (2003): 5-14.
[3] Chattopadhyay, Surajit, Madhuchhanda Mitra, and Samarjit Sengupta. Electric power quality. Springer Netherlands, 2011.
[4] Widlund, Emanuel. "Power Quality Disturbances in Production Facilities." (2012).
[5] Koval, Don O. "Power system disturbance patterns." Industry Applications, IEEE Transactions on 26.3 (1990): 556-562.
[6] Stones, John, and Alan Collinson. "Power quality." Power Engineering Journal 15.2 (2001): 58-64.
[7] Hooshmand, R., and A. Enshaee. "Detection and classification of single and combined power quality disturbances using fuzzy systems oriented by particle swarm optimization algorithm." Electric Power Systems Research 80.12 (2010): 1552-1561.
[8] Kaewarsa, Suriya, Kitti Attakitmongcol, and Thana Chai Kulworawanichpong. "Recognition of power quality events by using multiwavelet-based neural networks." International Journal of Electrical Power & Energy Systems 30.4 (2008): 254-260.
[9] Uyar, Murat, Selcuk Yildirim, and Muhsin Tunay Gencoglu. "An effective wavelet-based feature extraction method for classification of power quality disturbance signals." Electric Power Systems Research 78.10 (2008): 1747-1755.
[10] Hu, Guo-Sheng, Feng-Feng Zhu, and Zhen Ren. "Power quality disturbance identification using wavelet packet energy entropy and weighted support vector machines." Expert Systems with Applications 35.1 (2008): 143-149.
[11] Uyar, Murat, Selcuk Yildirim, and Muhsin Tunay Gencoglu. "An expert system based on S-transform and neural network for automatic classification of power quality disturbances." Expert Systems with Applications 36.3 (2009): 5962-5975.
[12] Abdel-Galil, T. K., et al. "Power quality disturbance classification using the inductive inference approach." Power Delivery, IEEE Transactions on 19.4 (2004): 1812-1818.
[13] He, Haibo, and Janusz Starzyk. "A self-organizing learning array system for power quality classification based on wavelet transform." Power Delivery, IEEE Transactions on 21.1 (2006): 286-295.
[14] Lee, Chun-Yao, and Yi-Xing Shen. "Optimal feature selection for power-quality disturbances classification." Power Delivery, IEEE Transactions on 26.4 (2011): 2342-2351.
[15] Moravej, Z., A. A. Abdoos, and M. Pazoki. "Detection and classification of power quality disturbances using wavelet transform and support vector machines." Electric Power Components and Systems 38.2 (2009): 182-196.
[16] E. Acha, M. Madrigal, Power System Harmonics, Computer Modelling and Analysis, Wiley, Chichester, 2001.
[17] E. Acha, V.G. Agelidis, O. Anaya-Lara, T.J.E. Miller, Power Electronic Control in Electrical Systems, Newnes, 2002.
[18] P.M. Anderson, Analysis of faulted power systems, IEEE Press, 1995.
[19] J. Arrillaga, D. Bradley, P.S. Bodger, Power System Harmonics, Wiley, London, 1985.
[20] J. Arrillaga, B.C. Smith, N.R. Watson, A.R. Wood, Power System Harmonic Analysis, Wiley, Chichester, 1997.
[21] M.H.J. Bollen, Understanding Power Quality Problems: Voltage Sags and Interruptions, IEEE Press, New York, 2000.
[22] R.C. Dugan, M.F. McGranaghan, H.W. Beaty, Electric Power Systems Quality, McGraw-Hill, New York, 1996.
[23] G.T. Heydt, Electric Power Quality, Stars in a Circle Publications, West LaFayette, 1991.
[24] W.E. Kazibwe, M.H. Sendaula, Electric Power Quality Control Techniques, Van Norstad Reinhold, New York, 1995.
[25] G.J. Wakileh, Power Systems Harmonics- Fundamentals, Analysis and Filter Design, Springer, 2001.
[26] D. Blume, J. Schlabbach, T. Stephanblome, Voltage Quality in Electrical Power Systems, IEE, 2001.
[27] IEC 61000-2-8, Voltage dips and short interruptions on public electric power supply systems with statistical measurement results, in preparation.
[28] IEC 61000-3-2, Limits on harmonic current emissions (equipment input current ≤16 A per phase).
[29] IEC 61000-3-4, Limits on harmonic current emissions for equipment with rated current greater than 16 A.
[30] IEC 61000-3-6, Assessment of emission limits for distorting loads in MV and HV power systems.
[31] IEC 61000-3-7. Assessment of emission limits for fluctuating loads in MV and HV power systems.
[32] IEC 61000-4-7, General guide on harmonic distortion and interharmonics measurement and instrumentation, for power systems and equipment connected thereto.
[33] IEC 61000-4-11, Voltage dips, short interruptions and voltage variations immunity tests.
[34] IEC 61000-4-15, Flickermeter- functional and design specifications.
[35] IEC 61000-4-30, Power quality measurement methods, in preparation.
[36] IEEE Std. 493, Recommended practice for the design of reliable industrial and commercial power systems.
[37] IEEE Std. 1100, Recommended practice for powering and grounding sensitive electronic equipment.
[38] IEEE Std. 1159, Recommended practice for monitoring electric power quality.
[39] IEEE Std. 1250, Guide for service to equipment sensitive to momentary voltage disturbances.
[40] IEEE Std. 1346, Recommended practice for evaluating electric power system compatibility with electronics process equipment.
[41] IEEE Std. 1453, Voltage flicker, in preparation.
[42] IEEE Std. 1564, Voltage sag indices, in preparation.
[43] Hunter, Ian. "Power quality issues: a distribution company perspective." Power Engineering Journal 15.2 (2001): 75-80.
[44] European Standard EN 50160: ‘Voltage characteristics of electricity supplied by public distribution systems’, 2002.
[45] Broshi, Amir. "Monitoring power quality beyond EN 50160 and IEC 61000-4-30." Electrical Power Quality and Utilisation, 2007. EPQU 2007. 9th International Conference on. IEEE, 2007.
[46] Bollen, Math H., and Irene Gu. Signal processing of power quality disturbances. Vol. 30. John Wiley & Sons, 2006.
[47] Caramia, Pierluigi, Guido Carpinelli, and Paola Verde. Power quality indices in liberalized markets. John Wiley & Sons, 2009.
[48] Ukil, Abhisek, and Rastko Živanović. "Adjusted Haar wavelet for application in the power systems disturbance analysis." Digital Signal Processing 18.2 (2008): 103-115.
[49] Dash, P. K., et al. "Power quality disturbance data compression, detection, and classification using integrated spline wavelet and S-transform." Power Delivery, IEEE Transactions on 18.2 (2003): 595-600.
[50] Daponte, P., M. Di Penta, and G. Mercurio. "TransientMeter: a distributed measurement system for power quality monitoring." Power Delivery, IEEE Transactions on 19.2 (2004): 456-463.
[51] Dwivedi, Umakant Dhar, and S. N. Singh. "Denoising techniques with change-point approach for wavelet-based power-quality monitoring." Power Delivery, IEEE Transactions on 24.3 (2009): 1719-1727.
[52] Li, Yan, et al. "Automatic disturbance signal monitoring method for on-line detection and recognition." Computer Application and System Modeling (ICCASM), 2010 International Conference on. Vol. 15. IEEE, 2010.
[53] Chen, Cheng-I., and Yu-Ting Fu. "Hybrid power quality event detection method with wavelet and ADALINE." Power System Technology (POWERCON), 2010 International Conference on. IEEE, 2010.
[54] Valtierra-Rodriguez, Martin, et al. "Detection and classification of single and combined power quality disturbances using neural networks." Industrial Electronics, IEEE Transactions on 61.5 (2014): 2473-2482.
[55] Kapoor, Rajiv, and Manish Kumar Saini. "Detection and tracking of short duration variations of power system disturbances using modified potential function." International Journal of Electrical Power & Energy Systems 47 (2013): 394-401.

[56] Lv, Ganyun, and Xiaodong Wang. "Voltage Sags Detection and Identification Based On Phase-Shift And RBF Neural Network." Fuzzy Systems and Knowledge Discovery, 2007. FSKD 2007. Fourth International Conference on. Vol. 1. IEEE, 2007.

[57] Wang, Z. Q., and S. Z. Zhu. "Comparative study on power quality disturbance magnitude characterization." Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference on. Vol. 1. IEEE, 2002.

[58] Deckmann, S. M., and A. A. Ferrira. "About voltage sags and swells analysis." Harmonics and Quality of Power, 2002. 10th International Conference on. Vol. 1. IEEE, 2002.

[59] Ferrero, Alessandro, and Simona Salicone. "An easy VI program to detect transient disturbances in the supply voltage." Instrumentation and Measurement, IEEE Transactions on 54.4 (2005): 1471-1474.

[60] Abdullah, Abdul Rahim, et al. "Detection and classification of power quality disturbances using time-frequency analysis technique." Research and Development, 2007. SCOREd 2007. 5th Student Conference on. IEEE, 2007.

[61] De-La-Rosa, Juan-Jose González, et al. "Characterization and classification of electrical transients using higher-order statistics and neural networks." Computational Intelligence for Measurement Systems and Applications, 2007. CIMSA 2007. IEEE International Conference on. IEEE, 2007.

[62] Sierra-Fernandez, Jose Maria, et al. "Adaptive detection and classification system for power quality disturbances." Power, Energy and Control (ICPEC), 2013 International Conference on. IEEE, 2013.

[63] Cataliotti, Antonio, Valentina Cosentino, and Salvatore Nuccio. "A phase-locked loop for the synchronization of power quality instruments in the presence of stationary and transient disturbances." Instrumentation and Measurement, IEEE Transactions on 56.6 (2007): 2232-2239.

[64] Radil, Tomáš, and Pedro M. Ramos. "Power quality detection and classification method for IEC 61000-4-30 Class A instruments." 2010 IEEE Instrumentation&Measurement Technology Conference Proceedings. 2010.

[65] Moschitta, Antonio, Paolo Carbone, and Carlo Muscas. "Performance comparison of advanced techniques for voltage dip detection." Instrumentation and Measurement, IEEE Transactions on 61.5 (2012): 1494-1502.

[66] Ning, Ding, et al. "Voltage sag disturbance detection based on RMS voltage method." Power and Energy Engineering Conference, 2009. APPEEC 2009. Asia-Pacific. IEEE, 2009.

[67] Wan, Junli, et al. "Study of the detection and analysis methods of power quality." Electrical and Control Engineering (ICECE), 2010 International Conference on. IEEE, 2010.
[68] Thakur, Padmanabh, Asheesh K. Singh, and Ramesh C. Bansal. "Novel way for classification and type detection of voltage sag." Generation, Transmission & Distribution, IET 7.4 (2013): 398-404.

[69] Kezunovic, Mladen. "Advanced assessment of the power quality events." Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on. Vol. 3. IEEE, 2000.

[70] Meena, P., K. Uma Rao, and Ravishankar Deekshit. "A simple algorithm for Fast detection and quantification of Voltage deviations using Space Vectors." IPEC, 2010 Conference Proceedings. IEEE, 2010.

[71] Singh, Harapajan, Manjeevan Seera, and Ahmad Puad Ismail. "Condition monitoring of electrical supply voltage quality to electrical machines using RBF neural network." Power and Energy (PECon), 2010 IEEE International Conference on. IEEE, 2010.

[72] Liao, Wei, Hua Wang, and Pu Han. "Neural network-based detection and recognition method for power quality disturbances signal." Control and Decision Conference (CCDC), 2010 Chinese. IEEE, 2010.

[73] Ji, T. Y., Q. H. Wu, and Y. S. Xue. "Disturbances location and classification in the phase space." Power and Energy Society General Meeting, 2010 IEEE. IEEE, 2010.

[74] Mollayi, N., and H. Mokhtari. "Classification of wide variety range of power quality disturbances based on two dimensional wavelet transformation." Power Electronic & Drive Systems & Technologies Conference (PEDSTC), 2010 1st. IEEE, 2010.

[75] Ji, T. Y., et al. "Disturbance detection, location and classification in phase space." IET generation, transmission & distribution 5.2 (2011): 257-265.

[76] Tan, Rodney HG, and V. K. Ramachandaramurthy. "Real time power quality event detection using continuous wavelet transform." Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on. IEEE, 2011.

[77] Chen, Cheng-I., Hung-Lu Wang, and Yuan-Chieh Chin. "A simple rule-based approach for detection and classification of voltage sag, swell, and interruption in power systems." Power Electronics and Drive Systems (PEDS), 2011 IEEE Ninth International Conference on. IEEE, 2011.

[78] Kumar, Raj, Bhim Singh, and D. T. Shahani. "Symmetrical components based technique for power quality event detection and classification." Power Electronics, Drives and Energy Systems (PEDES), 2014 IEEE International Conference on. IEEE, 2014.

[79] Zhu, Junan, et al. "Detection and classification of power disturbances using mathematical morphology with trapezoid structuring elements and signal envelopes." Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES. IEEE, 2014.

[80] Manikandan, M. Sabarimalai, S. R. Samantaray, and Innocent Kamwa. "Detection and Classification of Power Quality Disturbances Using Sparse Signal Decomposition on Hybrid Dictionaries." Instrumentation and Measurement, IEEE Transactions on 64.1 (2015): 27-38.
[81] Önal, Yasemin, Doğan Gökhan Ece, and Ömer Nezih Gerek. "Hilbert–Huang Transform Based Approach for Measurement of Voltage Flicker Magnitude and Frequency." Electric Power Components and Systems 43.2 (2015): 167-176.

[82] Choong, Florence, M. B. I. Reaz, and Faisal Mohd-Yasin. "Advances in signal processing and artificial intelligence technologies in the classification of power quality events: a survey." Electric Power Components and Systems 33.12 (2005): 1333-1349.

[83] Wright, Paul S. "Short-time Fourier transforms and Wigner-Ville distributions applied to the calibration of power frequency harmonic analyzers." Instrumentation and Measurement, IEEE Transactions on 48.2 (1999): 475-478.

[84] Nuruzzaman, Abul, Ozdal Boyraz, and Bahram Jalali. "Time-stretched short-time Fourier transform." Instrumentation and Measurement, IEEE Transactions on 55.2 (2006): 598-602.

[85] Mallat, Stéphane. A wavelet tour of signal processing. Academic press, 1999.

[86] Rioul, Olivier, and Martin Vetterli. "Wavelets and signal processing." IEEE signal processing magazine 8.LCAV-ARTICLE-1991-005 (1991): 14-38.

[87] Huang, Shyh-Jier, Cheng-Tao Hsieh, and Ching-Lien Huang. "Application of wavelets to classify power system disturbances." Electric Power Systems Research 47.2 (1998): 87-93.

[88] Yilmaz, A. Serdar, et al. "Application of lifting based wavelet transforms to characterize power quality events." Energy conversion and management 48.1 (2007): 112-123.

[89] He, Haibo, Xiaoping Shen, and Janusz A. Starzyk. "Power quality disturbances analysis based on EDMRA method." International Journal of Electrical Power & Energy Systems 31.6 (2009): 258-268.

[90] Dehghani, H., et al. "Power quality disturbance classification using a statistical and wavelet-based Hidden Markov Model with Dempster–Shafer algorithm." International Journal of Electrical Power & Energy Systems 47 (2013): 368-377.

[91] Latran, Mohammad Barghi, and Ahmet Teke. "A novel wavelet transform based voltage sag/swell detection algorithm." International Journal of Electrical Power & Energy Systems 71 (2015): 131-139.

[92] Pillay, P., and A. Bhattacharjee. "Application of wavelets to model short-term power system disturbances." Power Systems, IEEE Transactions on 11.4 (1996): 2031-2037.

[93] Gaouda, A. M., M. M. A. Salama, and M. R. Sultan. "Automated recognition system for classifying and quantifying the electric power quality." Harmonics and Quality of Power Proceedings, 1998. Proceedings. 8th International Conference On. Vol. 1. IEEE, 1998.

[94] Angrisani, L., et al. "A measurement method based on the wavelet transform for power quality analysis." Power Delivery, IEEE Transactions on 13.4 (1998): 990-998.

[95] Kopparapu, Chakravarthy, and A. Chandrasekaran. "A study on the application of wavelet analysis to power quality." System Theory, 1998. Proceedings of the Thirtieth Southeastern Symposium on. IEEE, 1998.

[96] Angrisani, L., P. Daponte, and M. D'Apuzzo. "A method based on wavelet networks for the detection and classification of transients." Instrumentation and Measurement Technology Conference, 1998. IMTC/98. Conference Proceedings. IEEE. Vol. 2. IEEE, 1998.
[97] Huang, Shyh-Jier, Cheng-Tao Hsieh, and Ching-Lien Huang. "Application of Morlet wavelets to supervise power system disturbances." Power Delivery, IEEE Transactions on 14.1 (1999): 235-243.

[98] Lin, Tao, Mineo Tsuji, and Eiji Yamada. "Wavelet approach to power quality monitoring." Industrial Electronics Society, 2001. IECON'01. The 27th Annual Conference of the IEEE. Vol. 1. IEEE, 2001.

[99] Gaouda, A. M., et al. "Wavelet-based signal processing for disturbance classification and measurement." IEE Proceedings-Generation, Transmission and Distribution 149.3 (2002): 310-318.

[100] Xiangxun, Chen. "Wavelet-based detection, localization, quantification and classification of short duration power quality disturbances." Power Engineering Society Winter Meeting, 2002. IEEE. Vol. 2. IEEE, 2002.

[101] Xiangxun, Chen. "Wavelet-based measurement and classification of power quality disturbances." Precision Electromagnetic Measurements, 2002. Conference Digest 2002 Conference on. IEEE, 2002.

[102] Kim, Hongkyun, et al. "Power quality monitoring system using wavelet-based neural network." Power System Technology, 2004. PowerCon 2004. 2004 International Conference on. Vol. 1. IEEE, 2004.

[103] Zhu, T. X., S. K. Tso, and K. L. Lo. "Wavelet-based fuzzy reasoning approach to power-quality disturbance recognition." Power Delivery, IEEE Transactions on 19.4 (2004): 1928-1935.

[104] Tuntisak, S., and S. Premrudeepreechacharn. "Harmonic detection in distribution systems using wavelet transform and support vector machine." Power Tech, 2007 IEEE Lausanne. IEEE, 2007.

[105] Hua, Liu, Zhao Baoqun, and Wang Guangjian. "Application of wavelet network for automatic power quality disturbances recognition in distribution power system." Control Conference, 2007. CCC 2007. Chinese. IEEE, 2007.

[106] Hua, Liu, and Fan Feng. "Simulation Study of Power Quality Disturbance in Distributed Power System Using Complex Wavelet Network." Electronic Measurement and Instruments, 2007. ICEMI'07. 8th International Conference on. IEEE, 2007.

[107] Shanlin, Kang, Song Yuhai, and Kang Yuzhe. "Application of Adaptive Wavelet Network for Power Quality Disturbance Recognition and Analysis." Electronic Measurement and Instruments, 2007. ICEMI'07. 8th International Conference on. IEEE, 2007.

[108] Costa, F. B., B. A. Souza, and N. S. D. Brito. "A wavelet-based algorithm to analyze oscillographic data with single and multiple disturbances." Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, IEEE, 2008.

[109] Hua, Liu, Zhao Baoqun, and Zhang Hong. "Recognition and classification of power quality event in power system using wavelet transformation." Control Conference, 2008. CCC 2008. 27th Chinese. IEEE, 2008.
[110] Faisal, M. F., and A. Mohamed. "Comparing the performance of various mother wavelet functions in detecting actual 3-phase voltage sags." Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International. IEEE, 2008.

[111] Kang, Shanlin, Huanzhen Zhang, and Yuzhe Kang. "Simulation analysis of time-frequency based on waveform detection technique for power quality application." Control and Decision Conference (CCDC), 2010 Chinese. IEEE, 2010.

[112] Masoum, M. A. S., Shahram Jamali, and N. Ghaffarzadeh. "Detection and classification of power quality disturbances using discrete wavelet transform and wavelet networks." IET Science, Measurement & Technology 4.4 (2010): 193-205.

[113] Christy, J., X. Jeno Vedamani, and S. Karthikeyan. "Wavelet based detection of power quality disturbance - a case study." Signal Processing, Communication, Computing and Networking Technologies (ICSCCN), 2011 International Conference on. IEEE, 2011.

[114] Singh, Bhim, D. T. Shahani, and Ravindra Kumar. "Recognition of power quality events using DT-DWT based Complex Wavelet Transform." Power India Conference, 2012 IEEE Fifth. IEEE, 2012.

[115] Tuljapurkar, Madhura, and A. A. Dharme. "Wavelet Based Signal Processing Technique for Classification of Power Quality Disturbances." Signal and Image Processing (ICSIP), 2014 Fifth International Conference on. IEEE, 2014.

[116] Liu, P. Pillay, P. Ribeiro, J. "Wavelet analysis of power systems transients using scalograms and multiresolution analysis." Electric Machines & Power Systems 27.12 (1999): 1331-1341.

[117] Dwivedi, Umakant Dhar, and S. N. Singh. "A wavelet-based denoising technique for improved monitoring and characterization of power quality disturbances." Electric Power Components and Systems 37.7 (2009): 753-769.

[118] Stockwell, Robert Glenn, Lalu Mansinha, and R. P. Lowe. "Localization of the complex spectrum: the S transform." Signal Processing, IEEE Transactions on 44.4 (1996): 998-1001.

[119] Stockwell, Robert Glenn. "A basis for efficient representation of the S-transform." Digital Signal Processing 17.1 (2007): 371-393.

[120] Dash, P. K., B. K. Panigrahi, and G. Panda. "Power quality analysis using S-transform." Power Delivery, IEEE Transactions on 18.2 (2003): 406-411.

[121] Xiao, Xianyong, Fangwei Xu, and Honggeng Yang. "Short duration disturbance classifying based on S-transform maximum similarity." International Journal of Electrical Power & Energy Systems 31.7 (2009): 374-378.

[122] Suja, S., and Jovitha Jerome. "Pattern recognition of power signal disturbances using S Transform and TT Transform." International journal of electrical power & energy systems 32.1 (2010): 37-53.

[123] Salem, Mohammad E., Azah Mohamed, and Salina Abdul Samad. "Rule based system for power quality disturbance classification incorporating S-transform features." Expert Systems with Applications 37.4 (2010): 3229-3235.
[124] Lee, Ian WC, and Pradipta K. Dash. "S-transform-based intelligent system for classification of power quality disturbance signals." Industrial Electronics, IEEE Transactions on 50.4 (2003): 800-805.

[125] Panigrahi, B. K., and S. K. Sinha. "Detection and classification of non-stationary power disturbances in noisy conditions." Power Electronics, Drives and Energy Systems, 2006. PEDES'06. International Conference on. IEEE, 2006.

[126] Quan, Huimin, and Yuxing Dai. "Power Quality Disturbance Classification Using S-Transform and Decision Tree." Computational Intelligence and Industrial Application, 2008. PACIIA'08. Pacific-Asia Workshop on. Vol. 2. IEEE, 2008.

[127] Mishra, Sukumar, C. N. Bhende, and B. K. Panigrahi. "Detection and classification of power quality disturbances using S-transform and probabilistic neural network." Power Delivery, IEEE Transactions on 23.1 (2008): 280-287.

[128] Kaewarsa, Suriya. "Detection of power quality events using DOST-based support vector machines." Computer Science and its Applications, 2008. CSA'08. International Symposium on. IEEE, 2008.

[129] Kaewarsa, Suriya. "Classification of power quality disturbances using S-transform based artificial neural networks." Intelligent Computing and Intelligent Systems, 2009. ICIS 2009. IEEE International Conference on. Vol. 1. IEEE, 2009.

[130] Reddy, M., and Dusmanta Kumar Mohanta. "Detection, classification and localization of power system impulsive transients using S-transform." Environment and Electrical Engineering (EEEIC), 2010 9th International Conference on. IEEE, 2010.

[131] Huda, N. H. T., A. R. Abdullah, and M. H. Jopri. "Power quality signals detection using S-transform." Power Engineering and Optimization Conference (PEOCO), 2013 IEEE 7th International. IEEE, 2013.

[132] Reddy, Maddikara Jaya Bharata, Kalpna Sagar, and Dusmanta Kumar Mohanta. "A multifunctional real-time power quality monitoring system using Stockwell transform." Science, Measurement & Technology, IET 8.4 (2014): 155-169.

[133] Jayasree, T., D. Devaraj, and R. Sukanesh. "Power quality disturbance classification using S-transform and radial basis network." Applied Artificial Intelligence 23.7 (2009): 680-693.

[134] Moravej, Z., A. A. Abdoos, and M. Pazoki. "New combined S-transform and logistic model tree technique for recognition and classification of power quality disturbances." Electric Power Components and Systems 39.1 (2011): 80-98.

[135] Hasheminejad, S., S. Esmaeili, and S. Jazebi. "Power quality disturbance classification using S-transform and hidden Markov model." Electric Power Components and Systems 40.10 (2012): 1160-1182.

[136] Jayasree, T., D. Devaraj, and R. Sukanesh. "Power quality disturbance classification using Hilbert transform and RBF networks." Neurocomputing 73.7 (2010): 1451-1456.

[137] Shukla, Stuti, Sukumar Mishra, and Bhim Singh. "Empirical-mode decomposition with Hilbert transform for power-quality assessment." Power Delivery, IEEE Transactions on 24.4 (2009): 2159-2165.
[138] Afroni, Mohammad Jasa, Danny Sutanto, and David Stirling. "Analysis of nonstationary power-quality waveforms using iterative Hilbert Huang transform and SAX algorithm." Power Delivery, IEEE Transactions on 28.4 (2013): 2134-2144.

[139] Cai, Zhixiong, et al. "Power quality signal analysis for the smart grid using the Hilbert-Huang transform." Communications, Computers and Signal Processing (PACRIM), 2013 IEEE Pacific Rim Conference on. IEEE, 2013.

[140] Biswal, Biswajit, et al. "Automatic classification of power quality events using balanced neural tree." Industrial Electronics, IEEE Transactions on 61.1 (2014): 521-530.

[141] Kumar, Raj, Bhim Singh, and Dilip Tekchand Shahani. "Recognition of Single-stage and Multiple Power Quality Events Using Hilbert–Huang Transform and Probabilistic Neural Network." Electric Power Components and Systems 43.6 (2015): 607-619.

[142] Qian, Shie, and Dapang Chen. "Discrete gabor transform." Signal Processing, IEEE Transactions on 41.7 (1993): 2429-2438.

[143] Huang, S. J., C. L. Huang, and C. T. Hsieh. "Application of Gabor transform technique to supervise power system transient harmonics." Generation, Transmission and Distribution, IEE Proceedings-. Vol. 143. No. 5. IET, 1996.

[144] Cho, Soo-Hwan, Gilsoo Jang, and Sae-Hyuk Kwon. "Time-frequency analysis of power-quality disturbances via the Gabor–Wigner transform." Power Delivery, IEEE Transactions on 25.1 (2010): 494-499.

[145] Naderian, Sobhan. "Detection and Classification of Power-Quality Events Using Discrete Gabor Transform and Support Vector Machine.", Power Electronics, Drives Systems & Technologies Conference (PEDSTC), 2015.

[146] Wright, Paul S. "Short-time Fourier transforms and Wigner-Ville distributions applied to the calibration of power frequency harmonic analyzers." Instrumentation and Measurement, IEEE Transactions on 48.2 (1999): 475-478.

[147] Shin, YongJune, et al. "Time-frequency analysis of power system disturbance signals for power quality." Power Engineering Society Summer Meeting, 1999. IEEE. Vol. 1. IEEE, 1999.

[148] Wang, Min, and Alexander V. Mamishev. "Classification of power quality events using optimal time-frequency representations-Part 1: theory." Power Delivery, IEEE Transactions on 19.3 (2004): 1488-1495.

[149] Wang, Min, Gabriel Rowe, and Alexander V. Mamishev. "Classification of power quality events using optimal time-frequency representations-Part 2: application." Power Delivery, IEEE Transactions on 19.3 (2004): 1496-1503.

[150] Abdullah, Abdul Rahim Bin, Ahmad Zuri Bin Sha Ameri, and Auzani Bin Jidin. "Classification of power quality signals using smooth-windowed Wigner-Ville distribution." Electrical Machines and Systems (ICEMS), 2010 International Conference on. IEEE, 2010.

[151] Kamarulafizam, I., et al. "Time-Frequency analysis of power signal: Application to substation monitoring and management system." Computers, Communications, & Signal
[152] Lin, Tao, and Alexander Dom. "On power quality indices and real time measurement." Power Delivery, IEEE Transactions on 20.4 (2005): 2552-2562.

[153] Radil, Tomáš, Pedro M. Ramos, and Fernando M. Janeiro. "PQ monitoring system for real-time detection and classification of disturbances in a single-phase power system." Instrumentation and Measurement, IEEE Transactions on 57.8 (2008): 1725-1733.

[154] Chen, Z., and P. Urwin. "Power quality detection and classification using digital filters." Power Tech Proceedings, 2001 IEEE Porto. Vol. 1. IEEE, 2001.

[155] Dash, P. K., and M. V. Chilukuri. "Hybrid S-transform and Kalman filtering approach for detection and measurement of short duration disturbances in power networks." Instrumentation and Measurement, IEEE Transactions on 53.2 (2004): 588-596.

[156] Reddy, J., et al. "Fast tracking of power quality disturbance signals using an optimized unscented filter." Instrumentation and Measurement, IEEE Transactions on 58.12 (2009): 3943-3952.

[157] Bollen, Math HJ, et al. "Classification of underlying causes of power quality disturbances: deterministic versus statistical methods." EURASIP Journal on Applied Signal Processing 2007.1 (2007): 172-172.

[158] Hauer, John F., C. J. Demeure, and L. L. Scharf. "Initial results in Prony analysis of power system response signals." Power Systems, IEEE Transactions on 5.1 (1990): 80-89.

[159] Qi, Li, et al. "Prony analysis for power system transient harmonics." EURASIP Journal on Applied Signal Processing 2007.1 (2007): 170-170.

[160] Andreotti, A., et al. "Adaptive prony method for the calculation of power-quality indices in the presence of nonstationary disturbance waveforms." Power Delivery, IEEE Transactions on 24.2 (2009): 874-883.

[161] Peng, Jimmy C-H., and Nirmal-Kumar C. Nair. "Adaptive sampling scheme for monitoring oscillations using Prony analysis." Generation, Transmission & Distribution, IET 3.12 (2009): 1052-1060.

[162] O'Shea, Peter. "The use of sliding spectral windows for parameter estimation in power system disturbance monitoring." Power Systems, IEEE Transactions on 15.4 (2000): 1261-1267.

[163] Shea, Peter. "A high-resolution spectral analysis algorithm for power-system disturbance monitoring." Power Systems, IEEE Transactions on 17.3 (2002): 676-680.

[164] Lin, Tao, and Alexander Domijan. "Real time measurement of power disturbances: part 1. Survey and a novel complex filter approach." Electric power systems research 76.12 (2006): 1027-1032.

[165] Teke, Ahmet, K. Bayindir, and M. Tümay. "Fast sag/swell detection method for fuzzy logic controlled dynamic voltage restorer." IET generation, transmission & distribution 4.1 (2010): 1-12.
[166] Alkan, Ahmet, and Ahmet S. Yilmaz. "Frequency domain analysis of power system transients using Welch and Yule–Walker AR methods." Energy conversion and management 48.7 (2007): 2129-2135.

[167] Ou-yang, Hua, and Zheng-guo Wu. "A Method for Interharmonic Measurement Based on DQ Transform and MUSIC Algorithm." Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific. IEEE, 2012.

[168] Bollen, Math HJ, Emmanouil Styvaktakis, and Irene Yu-Hua Gu. "Categorization and analysis of power system transients." Power Delivery, IEEE Transactions on 20.3 (2005): 2298-2306.

[169] Huang, Jiansheng, Michael Negnevitsky, and Thong D. Nguyen. "A neural-fuzzy classifier for recognition of power quality disturbances." Power Delivery, IEEE Transactions on 17.2 (2002): 609-616.

[170] Moravej, Z., S. A. Banihashemi, and M. H. Velayati. "Power quality events classification and recognition using a novel support vector algorithm." Energy Conversion and Management 50.12 (2009): 3071-3077.

[171] Osowski, S. "SVD technique for estimation of harmonic components in a power system: a statistical approach." IEE Proceedings-Generation, Transmission and Distribution 141.5 (1994): 473-479.

[172] Granados-Lieberman, David, et al. "Techniques and methodologies for power quality analysis and disturbances classification in power systems: a review." Generation, Transmission & Distribution, IET 5.4 (2011): 519-529.

[173] Guyon, Isabelle, et al., eds. Feature extraction: foundations and applications. Vol. 207. Springer, 2008.

[174] Gaouda, A. M., S. H. Kanoun, and M. M. A. Salama. "On-line disturbance classification using nearest neighbor rule." Electric Power Systems Research 57.1 (2001): 1-8.

[175] Liao, Yuan, and Jong-Beom Lee. "A fuzzy-expert system for classifying power quality disturbances." International journal of electrical power & energy systems 26.3 (2004): 199-205.

[176] Salem, Mohammad E., Azah Mohamed, and Salina Abdul Samad. "Rule based system for power quality disturbance classification incorporating S-transform features." Expert Systems with Applications 37.4 (2010): 3229-3235.

[177] Lv, Ganyun, et al. "PQ Disturbances Identification based on Phase-shift and LS Weighted Fusion Combining Neural Network." Neural Networks and Brain, 2005. ICNN&B’05. International Conference on. Vol. 1. IEEE, 2005.

[178] Hu, Guo-Sheng, Jing Xie, and Feng-Feng Zhu. "Classification of power quality disturbances using wavelet and fuzzy support vector machines." Machine Learning and Cybernetics, 2005. Proceedings of 2005 International Conference on. Vol. 7. IEEE, 2005.

[179] Dwivedi, U. D., and S. N. Singh. "A robust energy features estimation for detection and classification of power quality disturbances." Power India Conference, 2006 IEEE. IEEE, 2006.
[180] Kim, Hongkyun, et al. "Power disturbance classifier using wavelet-based neural network." Power Electronics Specialists Conference, 2006. PESC'06. 37th IEEE. IEEE, 2006.

[181] Weili, Huang, Hua Zixiang, and Du Wei. "Neural network model-based training algorithm for transient signal analysis." Mechatronics and Automation, 2009. ICMA 2009. International Conference on. IEEE, 2009.

[182] Milchevski, Aleksandar, and Dimitar Taskovski. "Improvement of wavelet based methods for classification of power quality disturbances." Harmonics and Quality of Power (ICHQP), 2010 14th International Conference on. IEEE, 2010.

[183] Masoun, M. A. S., Shahram Jamali, and N. Ghaffarzadeh. "Detection and classification of power quality disturbances using discrete wavelet transform and wavelet networks." IET Science, Measurement & Technology 4.4 (2010): 193-205.

[184] Imtiaz, Hafiz, and Tahsina Farah Sanam. "Frequency domain feature extraction for power quality disturbance classification." Informatics, Electronics & Vision (ICIEV), 2013 International Conference on. IEEE, 2013.

[185] Krishna, Brahmadeasam V., and Kaliaperumal Baskaran. "Parallel computing for efficient time-frequency feature extraction of power quality disturbances." IET Signal Processing 7.4 (2013): 312-326.

[186] Suarez-Alvarez, Maria M., et al. "Statistical approach to normalization of feature vectors and clustering of mixed datasets." Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences. The Royal Society, 2012.

[187] Koller, Daphne, and Mehran Sahami. "Toward optimal feature selection." (1996).

[188] Somol, Petr, Pavel Pudil, and Josef Kittler. "Fast branch & bound algorithms for optimal feature selection." Pattern Analysis and Machine Intelligence, IEEE Transactions on 26.7 (2004): 900-912.

[189] Peng, Hanchuan, Fuhui Long, and Chris Ding. "Feature selection based on mutual information criteria of max-dependency, max-relevance, and min-redundancy." Pattern Analysis and Machine Intelligence, IEEE Transactions on 27.8 (2005): 1226-1238.

[190] Chung, Jaehak, et al. "Power disturbance classifier using a rule-based method and wavelet packet-based hidden Markov model." Power Delivery, IEEE Transactions on 17.1 (2002): 233-241.

[191] Bollen, Math HJ, et al. "Classification of underlying causes of power quality disturbances: deterministic versus statistical methods." EURASIP Journal on Applied Signal Processing 2007.1 (2007): 172-172.

[192] Santoso, Surya, et al. "Power quality disturbance waveform recognition using wavelet-based neural classifier. I. Theoretical foundation." Power Delivery, IEEE Transactions on 15.1 (2000): 222-228.

[193] Karimi, Masoud, Hossein Mokhtari, and M. Reza Iravani. "Wavelet based on-line disturbance detection for power quality applications." Power Delivery, IEEE Transactions on 15.4 (2000): 1212-1220.
[194] Panigrahi, B. K., and V. Ravikumar Pandi. "Optimal feature selection for classification of power quality disturbances using wavelet packet-based fuzzy k-nearest neighbour algorithm." IET generation, transmission & distribution 3.3 (2009): 296-306.

[195] Gaouda, A. M., et al. "Pattern recognition applications for power system disturbance classification." IEEE Transactions on Power Delivery 17.3 (2002): 677-683.

[196] Jafarabadi, S. Esmaeili, and H. Rastegar. "Contribution to automatic detection and diagnosis of wide variety range of power quality disturbances using combined wavelet transform and neural network methods." Universities Power Engineering Conference, 2004. UPEC 2004. 39th International. Vol. 2. IEEE, 2004.

[197] Oleskovicz, Márió, et al. "Power quality analysis applying a hybrid methodology with wavelet transforms and neural networks." International Journal of Electrical Power & Energy Systems 31.5 (2009): 206-212.

[198] Perunicić, B., et al. "Power quality disturbance detection and classification using wavelets and artificial neural networks." Harmonics and Quality of Power Proceedings, 1998. Proceedings. 8th International Conference On. Vol. 1. IEEE, 1998.

[199] Carpinelli, G., Elio Chiodo, and Davide Lauria. "Indices for the characterisation of bursts of short-duration waveform distortion." Generation, Transmission & Distribution, IET 1.1 (2007): 170-175.

[200] Cho, Soo-Hwan, Gilsoo Jang, and Sae-Hyuk Kwon. "Time-frequency analysis of power-quality disturbances via the Gabor–Wigner transform." Power Delivery, IEEE Transactions on 25.1 (2010): 494-499.

[201] Borras, Dolores, et al. "Wavelet and neural structure: a new tool for diagnostic of power system disturbances." Industry Applications, IEEE Transactions on 37.1 (2001): 184-190.

[202] Janik, Przemyslaw, and Tadeusz Lobos. "Automated classification of power-quality disturbances using SVM and RBF networks." Power Delivery, IEEE Transactions on 21.3 (2006): 1663-1669.

[203] Hoang, T. A., and D. T. Nguyen. "Improving training of radial basis function network for classification of power quality disturbances." Electronics Letters 38.17 (2002): 976-977.

[204] Gaing, Zwe-Lee. "Wavelet-based neural network for power disturbance recognition and classification." Power Delivery, IEEE Transactions on 19.4 (2004): 1560-1568.

[205] Lin, C-H., and M-C. Tsao. "Power quality detection with classification enhancible wavelet-probabilistic network in a power system." IEE Proceedings-Generation, Transmission and Distribution 152.6 (2005): 969-976.

[206] Reaz, M. B. I., et al. "Prototyping of wavelet transform, artificial neural network and fuzzy logic for power quality disturbance classifier." Electric Power Components and Systems 35.1 (2007): 1-17.

[207] Reaz, Mamun Bin Ibne, et al. "Expert system for power quality disturbance classifier." Power Delivery, IEEE Transactions on 22.3 (2007): 1979-1988.
[208] Ghosh, Atish K., and David L. Lubkeman. "The classification of power system disturbance waveforms using a neural network approach." Power Delivery, IEEE Transactions on 10.1 (1995): 109-115.

[209] Monedero, Inigo, et al. "Classification of electrical disturbances in real time using neural networks." Power Delivery, IEEE Transactions on 22.3 (2007): 1288-1296.

[210] Wijayakulasooriya, J. V., G. A. Putrus, and P. D. Minns. "Electric power quality disturbance classification using self-adapting artificial neural networks." IEE Proceedings-Generation, Transmission and Distribution 149.1 (2002): 98-101.

[211] Gaouda, A. M., et al. "Power quality detection and classification using wavelet-multiresolution signal decomposition." IEEE Transactions on Power Delivery 14.4 (1999): 1469-1476.

[212] Elmitwally, A., et al. "Proposed wavelet-neurofuzzy combined system for power quality violations detection and diagnosis." Generation, Transmission and Distribution, IEE Proceedings-. Vol. 148. No. 1. IET, 2001.

[213] Reaz, M. B. I., et al. "Prototyping of wavelet transform, artificial neural network and fuzzy logic for power quality disturbance classifier." Electric Power Components and Systems 35.1 (2007): 1-17.

[214] Duan, Xiangying, et al. "Synthetic evaluation of power quality based on fuzzy cluster analysis." Power System Technology, 2006. PowerCon 2006. International Conference on. IEEE, 2006.

[215] Nguyen, Thai, and Yuan Liao. "Power quality disturbance classification utilizing S-transform and binary feature matrix method." Electric Power Systems Research 79.4 (2009): 569-575.

[216] Abdel-Galil, T. K., et al. "Power quality disturbance classification using the inductive inference approach." Power Delivery, IEEE Transactions on 19.4 (2004): 1812-1818.

[217] Zhao, Fengzhan, and Rengang Yang. "Power-quality disturbance recognition using S-transform." Power Delivery, IEEE Transactions on 22.2 (2007): 944-950.

[218] Dash, P. K., R. K. Jena, and M. M. A. Salama. "Power quality monitoring using an integrated Fourier linear combiner and fuzzy expert system." International Journal of Electrical Power & Energy Systems 21.7 (1999): 497-506.

[219] Kezunovic, Mladen, and Yuan Liao. "A novel software implementation concept for power quality study." Power Delivery, IEEE Transactions on 17.2 (2002): 544-549.

[220] Panigrahi, Bijaya K., Pradipta K. Dash, and J. B. V. Reddy. "Hybrid signal processing and machine intelligence techniques for detection, quantification and classification of power quality disturbances." Engineering Applications of Artificial Intelligence 22.3 (2009): 442-454.

[221] Zang, Hongzhi, and Yishu Zhao. "Intelligent identification system of power quality disturbance." Intelligent Systems, 2009. GCIS'09. WRI Global Congress on. Vol. 1. IEEE, 2009.
[222] Hu, Guo-Sheng, Feng-Feng Zhu, and Zhen Ren. "Power quality disturbance identification using wavelet packet energy entropy and weighted support vector machines." Expert Systems with Applications 35.1 (2008): 143-149.

[223] Lin, Wei-Min, et al. "Detection and classification of multiple power-quality disturbances with wavelet multiclass SVM." Power Delivery, IEEE Transactions on 23.4 (2008): 2575-2582.

[224] Ekici, Sami. "Classification of power system disturbances using support vector machines." Expert Systems with Applications 36.6 (2009): 9859-9868.

[225] Li, Zhi-yong, and Wei-lin Wu. "Classification of power quality combined disturbances based on phase space reconstruction and support vector machines." Journal of Zhejiang University SCIENCE A 9.2 (2008): 173-181.

[226] Youssef, A. M., et al. "Disturbance classification utilizing dynamic time warping classifier." Power Delivery, IEEE Transactions on 19.1 (2004): 272-278.