Chapter 1

Introduction

1.1 Introduction

As the title of the thesis suggests, in this research work studies have been carried out on Mixed Power Quality (MPQ) Event Monitoring, which are necessary for smooth and reliable operation of power utility. Before going into the details of the present study as well as the background of the work, an outline of the thesis is given in the following paragraphs.

Monitoring of power quality (PQ) events has two significant aspects or motives:

i) To make proper identification and classification of power quality event by analysing the data obtained through the monitoring module during event.

ii) To develop easy-to-implement power quality event monitoring module with future upgradation facility.

With the advent of microcontroller based modules incorporating signal conditioning techniques, digital signal processing tools are becoming integral part of power quality monitoring setup in order to achieve the aforesaid goals. In the present work different digital signal processing tools are developed and studied for identification of various power quality events. The main application areas of the present study can be broadly classified in three major categories:
a) Identification and classification of Single Power Quality events

b) Identification and classification of Mixed Power Quality events

c) Remote Updating of Power Quality Monitoring Device

The applications (a) and (b) reflect the first aspect of power quality event monitoring (i.e. identification and classification of PQ event from the recoded PQ data) and the application (c) deals with the second aspect of possible future upgradation of the PQ event monitoring module with remote updating facility.

The PQ events affect the quality of power delivered. In order to improve the quality of power, it is required to know the sources of PQ events. Continuous monitoring is needed for proper identification and classification of PQ events. This further helps in mitigating the detrimental effects of PQ events and in maintaining continuity of service. Manual or visual identification is difficult and error prone. So it is desirable to develop sophisticated PQ events identification and classification technique. This identification and classification scheme has to be robust and precise to handle the noisy data collected from power system. The present research work is primarily planned towards the development of digital signal processing tools that require minimal human involvement for analysis or identification and classification of the captured PQ events. It is worth mentioning here that only those processing tools are selected which can be easily incorporated in a microcontroller based module causing low computational burden.

1.2 Background of the Work

1.2.1 Study of Power Quality (PQ) Events

Power quality event study has become very important from both power utility as well as customer point of view. Nowadays, increasing use of electronic equipment, non-linear loads and computer based instruments hampers the quality of power. These equipments inject various types of events in the system like voltage sag, swell, harmonics etc. The primary goal of the electric power utilities is to supply uninterrupted and reliable sinusoidal power within permissible deviations. Therefore, it can be observed that detection and identification of PQ events are important to
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To detect the power quality events, researchers and manufacturers are continuously trying to develop identification algorithm or module based on certain reference or standard and then testing the performance of the developed algorithm with that given in the same reference. In this thesis work, the developed algorithm and module are tested with PQ events as per IEEE Std. 1159-1995 [1]. In the present work, signals i.e., PQ events are generated in two ways: i) using numerical model; ii) employing a real life laboratory setup. These standard wave shapes are used for the development of the identification algorithm.

1.2.1.1 Source of power quality events

Apart from some external sources, power quality events are mainly introduced in the power signals within the system of power utility. The sources of PQ events associated with power utility are Lightning, switching of lines, power factor correction equipment, different types of transmission and distribution network faults etc. Other sources of PQ events include connection of heavy loads, start-up of large motors, uninterupted power supplies, adjustable speed drive, electronic dimming systems, medical equipment, electronic lighting ballasts etc. Noise is introduced in the power signals due to electromagnetic interference from appliances, microwave and radar transmissions, broadcasting of radio and TV signals and improper grounding. Sudden interruption of power supply takes place due to equipment failure, improper coordination or malfunction of protection devices, insulation failure, insulator flashover and natural sources like storm, fire etc. System voltage varies when bulk amount of load is suddenly connected or withdrawn. Voltage unbalance occurs due to operations of single phase load like electric arc furnace, traction load etc. Different types of harmonics are injected in the power signals due to use of arc welding machines, rectifiers, frequency converters, current regulators and increasing use of equipments with non-linear voltage-current characteristics. A sudden change of voltage level from low to high value occurs due to utility switching operations, starting and stopping of heavy equipments etc. These are the major sources of PQ events. Apart from these sources other sources are also there, but their contributions are negligible and hence not considered in this dissertation.
1.2.1.2 Effect of power quality events

Sudden and short duration interruptions of power supply causes unnecessary tripping of protection devices, malfunction of data processing equipment, damage of sensitive equipment etc. If interruptions persist for long duration, it stops all equipments and ongoing automatic process. A very fast voltage variation from low to high value affects the insulation of many equipment and data recording process. Harmonics present in the power signals causes additional losses in capacitors and rotating machines, neutral overloading, overheating of conductor and cables, unwanted tripping of protective equipments, malfunctioning of signal receivers or other equipment. The effect of noise is usually not destructive but it affects the operation of sensitive electrical equipment and causes data loss in data processing systems. From the above discussion it can be observed that the causes of PQ events ultimately result in financial loss. The financial losses related to PQ events are mainly divided into two parts, one is direct cost and another is indirect cost [2]. The direct loss includes damage of equipment, loss of production, loss of raw materials, reduction of equipment life etc. Some of the effects of PQ events are not directly related to the cost. But it hampers the production process of the company. The company may not fulfill the deadline of delivery. As a result, they may loose some financial benefit for completing the task within a specific date. Also they may not receive further order in the near future. Some of the effects of PQ events are seldom related to the cost, e.g. distortion of communication signal, radio signal etc.

1.2.1.3 Remedial measures of power quality events

Different types of compensating device are used for compensation of PQ events [2]. Dynamic Voltage Restorer (DVR) and Constant Voltage Transformers (CVT) are used for improvement of power signal from voltage dip and abnormal rise of voltage. These two devices are used to maintain the constant voltage at load terminals. Transient Voltage Surge Suppressors (TVSS) is a device which diverts the surge and clamps the overvoltage to a safe value. In this way it protects the power line from unwanted surge. Noise Filters and harmonic filters are used for elimination of noise and unwanted harmonics from the power signal. Static VAR Compensators are used in transmission line to maintain the constant voltage at the load terminals by controlling the reactive power.
Active power line conditioner is used to maintain the quality of power. It is basically a combination of series and shunt power converters that share a single DC link. Pulse Width Modulation technique (PWM) is used to control series and shunt converters. Hence, these two converters are simultaneously used for harmonic compensation in load current and supply voltage. The equipment has been known as unified power quality conditioner (UPQC).

1.2.2 Identification and classification of Power Quality Events

Ensuring quality of electrical power that is delivered to the consumers is a much discussed issue over several years. In recent times, the quality of power is degraded due to the presence of different types of non-linear load. This load may introduce power quality events like sag, swell, harmonic, transient, notches etc. If these events are not mitigated properly it can cause interruption or failure of different electrical equipments which are necessary for providing clean and reliable power. It is desirable to detect and identify the power quality events present in it to provide quality power to the consumers. It is desired to monitor power signal continuously by power utility for remedial measures. By analysing the recorded power signals researchers have proposed different methods for automatic detection and identification of power quality events [3]-[35]. The identification and classification of PQ events has two aspects i.e. identification and classification of single power quality event and identification and classification of mixed power quality events.

1.2.2.1 Identification and classification of single power quality events

Power quality study follows two major steps[3] monitoring the power signals and extracting the events from it. These extracted events are compared with previously recorded events in order to determine if there is any pattern match with the known events. The monitoring and identification are the main features of power quality study which has significantly improved over the years.

Ghosh et al [3] have described an artificial neural network (ANN) based approach for identification of PQ events. Two different neural network topology, feed-forward neural network (FFNN) and time delay
neural network (TDNN) were tested. The reported test results showed that TDNN had higher identification rate compared to FFNN. ANNs are popular identification tool because of their pattern recognition capabilities and their ability to handle noisy data. But it requires large number of training cycles and high computational burden. Figure 1.1 shows the ANN based identification scheme of PQ events [3].

![Figure 1.1: ANN based PQ events identification scheme [2]](image)

Santoso et al [4] presented a power quality (PQ) event identification technique using wavelet-based neural classifier. Different PQ events can be effectively classified using the frequency-selective feature of wavelet transform. Here, wavelet transform is used for feature extraction and ANN is used as a classifier. In [4] six types of power quality events were considered and most of these events were recorded during monitoring of power distribution feeders. It was reported that identification accuracy rate of PQ events is more than 90% for the testing data.

Dash et al [5] described the PQ event identification using fuzzy expert system and Fourier linear combiner. They have shown that the reported method was much simpler and efficient compared to wavelet based neural approach with respect to computational time and operational burden. In [5] PQ events were simulated using EMTP software package.

In [6], an automated event identification technique, based on wavelet-multiresolution analysis and pattern recognition techniques was presented. For classification of wavelet based extracted feature, the authors used minimum Euclidean distance, k-nearest neighbor and ANN
classifiers. Test results reported in [6] showed that the performance of the ANN classifier was better with respect to both error rate and noise level. In this paper [6] the authors identified five PQ events including two mixed PQ events. All these events were simulated using MATLAB® software and contained white Gaussian noise.

Huang et al [7] presented a neural-fuzzy based identifier for detection of PQ events. Total 13 types of PQ events were used to judge the performance of the proposed classifier. Figure 1.2 shows the PQ events waveform and corresponding feature vectors extracted from PQ events. The identification accuracy obtained in this method was reported to be 93%.

The authors of [8]-[12] reported identification results based on S-transform. Here, S-transform is used for feature extraction, pattern recognition of power signal and identification of PQ events therein. The S-transform is a modified form of wavelet transform. S-transform can provide frequency dependent resolution of time-frequency domain and also provides the local phase information. The authors have shown that S-transform provides pattern that closely resembles the non-stationary event type. Therefore, features obtained from S-transform are very powerful and it requires simple identification procedure. Figure 1.3 shows the 3-D representation of a particular PQ event. This 3-D plot provides magnitude, frequency and time information which is useful for identification of the PQ event. The studies on PQ event identification using the above mentioned methods showed that more than 98% accuracy can be obtained for ten number of power quality events. However, in the presence of noise identification accuracy is reduced.

Youssef et al in [13] described PQ event identification utilizing dynamic time warping (DTW) identifier. This algorithm is supported by the vector quantization (VQ) and the fast match (FM) techniques to speed up the identification process. The Walsh transform and the FFT are used as feature extraction tool for this work. The authors of [13] performed the identification of six events successfully with 97% accuracy. Authors in [14] have applied inductive inference algorithm for identification of PQ events. They found that identification of PQ events can be successfully done with 91% accuracy of total events.
Authors in [15] have applied extended fuzzy reasoning scheme for identifying six types of PQ events using wavelet based features. The main idea of this method was to map the PQ event features into a real valued number through extended fuzzy reasoning. In order to show the

Figure 1.2: a) Waveforms with PQ events. b) Feature vectors [6].
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The effectiveness of the proposed method, simulated waveforms were generated using ARENE program from EDF, France. The typical simulated waveforms are shown in Figure 1.4.

Lin et al in [16] proposed an adaptive wavelet network (AWN) for power quality detection and identification in power system. In their work, AWN is composed of two-subnetwork architecture, consisting of morlet wavelet and adaptive probabilistic network. In [16], wavelet is used for feature extraction and adaptive probabilistic network is used for identification of PQ event based on the features extracted by wavelet. This method has a dynamic and fast adaptation algorithm with continually adding or deleting features by automatically tuning the target. The studies on PQ event identification using above mentioned methods showed that it had better detection accuracy, robustness and identification performance. Figure 1.5 shows the architecture of the AWN.

He et al [17] have efficiently identified seven types of power quality

![Figure 1.3: S-transform plot of voltage sag [10]](image)
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events with the help of wavelet based self-organizing learning array (SOLAR) system. In order to reduce the feature dimension, energy at each decomposition level was used as feature instead of detail and approximate coefficient. SOLAR is an improved version of ANN and uses a feed forward network (FF) structure with all neurons arranged in a multiple layer. For training and testing of the reported method, simulation data were generated in MATLAB with Gaussian white noise.

Reaz et al. [18] proposed an expert system for PQ events identifier. In this method, discrete wavelet transform (DWT) was used for feature extraction from the software generated signals and utility sampled disturbance events. For detection and identification of features both artificial neural networks (ANN) and fuzzy logic were used. The studies

![Image](image.png)

**Figure 1.4**: Six typical event waveforms: (a) Low-frequency capacitor switching, (b) High-frequency capacitor switching, (c) Voltage sag, (d) Impulsive transient, (e) Transformer energizing, (f) Perfect sine waveform. [14]
on PQ events identification using the above mentioned methods showed that the identification accuracy was 98.19% for five PQ events.

In [19], researchers presented automatic identification of PQ events using wavelet packet transform (WPT) and fuzzy k-nearest neighbor (FKNN) based algorithm. The features were extracted using WPT by decomposing the signal up to fourth level. The extracted features were identified by FKNN based identifier. In order to decrease the operational burden, the dimension of the extracted features was reduced by genetic algorithm. The reported method was tested with the data obtained from parametric model and also laboratory setup.

In recent years, the support vector machine (SVM) has been successfully used as identification tool in various applications [20]-[26]. Janik et al applied SVM identifier to identify the PQ events using suitable features extracted from the space phasor [24]. The authors of [24] have reported that SVM identifier showed better identification results compared to radial basis function (RBF) networks. The authors of [25]-[26] reported identification results of PQ events using wavelet features aided

![Architecture of AWN](image)

Figure 1.5: Architecture of AWN [15]
SVM. In [25], they presented wavelet multiclass support vector machine (WMSVM). The structure of proposed WMSVM is shown in Figure 1.6. The proposed architecture had effectively detected PQ events using WT and MSVM techniques [25]. Using wavelet based SVM, Eristi et al was able to detect and identify PQ events with 98.51% accuracy [26].

![Figure 1.6: Structure of the proposed WMSVM [24]](image)

Authors of [27] have applied probabilistic neural network-based feature selection (PFS), for PQ events identification. In [27] multilayer perceptron, K-nearest neighbor and adaptive PNN based identifier were used to judge the viability of selected features. The reported results showed that PFS was capable of efficiently identifying the features to improve the performance of the identifiers even in noisy environments.

### 1.2.2.2 Contributions of the present study in relation to single power quality events

In the present study, a scheme based on rough set theory is presented. The proposed method uses minimum set of features for identification of
PQ events. The presented methodology can be implemented in a general purpose microcontroller for embedded applications. Correlation based method is used for feature extraction because of its low computational burden, which is desirable for microcontroller based system, as it has limited space in program memory. For selecting an optimal set of extracted features as well as to identify them, Rough-Set based approach is used in this work. The Rough Set Theory (RST) is appropriate where the knowledge of features is limited or it contains redundant information [28]. RST minimizes the data of a decision support system keeping required information intact [28]. Detailed description of this method is presented in Chapter 2 and Chapter 3. The performance of the scheme is studied on both numerical model as well as real life power signal data. Result show that the developed method can successfully classify the single PQ events with 97.1% accuracy. Moreover, the performance of the scheme exhibits acceptable accuracy even with the presence of noise. Crosscorrelation technique is used in this method as feature extraction tool because it minimizes the effect of random noise present in the signal and also offers low computational burden. Rough set theory is not only used as identifier but is also used as an optimizer to select an optimal set of feature.

1.2.2.3 Identification and classification of Mixed Power Quality (MPQ) events

According to the opinion of utility engineers, presence of non-linear loads may frequently introduce MPQ events in power network for short duration of time [29]. The efficiency of the system reduces with occurrence of MPQ events. However, in most of the research work emphasis are not given to the identification of mixed power quality (MPQ) events occurring simultaneously.

Abdelmageid et al [30] proposed a method for identification of single and mixed power quality events. This method was based on discrete wavelet transform (DWT) and adaptive neuro-fuzzy inference system (ANFIS). Here, DWT and Parseval’s theorem were employed to extract feature from PQ events. In total twelve PQ events including four mixed PQ events were efficiently identified by this method. Five stages of classifier were required to identify the PQ events.

In [31], the modified Gaussian window was reported to improve the
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detection and identification of PQ events. The Gaussian window together with S-transform produced the time-frequency contours for feature extraction. The feature vectors were clustered using fuzzy-C means algorithm. The efficacy of the fuzzy-C means algorithm was enhanced by optimizing the cluster centers using adaptive particle swarm optimization. Total nine disturbances including four mixed PQ events were considered for this research work. Results showed that identification accuracy of the reported method was comparable with the methods presented earlier researchers. The structure of fuzzy C-means tree is shown in Figure 1.7

\[ \text{Figure 1.7: Fuzzy C-means tree [30]} \]

The authors of [32] reported a method for the detection and identification of single and mixed PQ events using fuzzy logic and particle swarm optimization (PSO) algorithm. The fuzzy system was employed for detection and identification of PQ events whereas, the PSO algorithm was used for optimization of membership function parameters related to the fuzzy systems. The window discrete Fourier transform (WDFT) and wavelet transform (WT) were used for feature extraction from the PQ events. The reported algorithm for detection and identification is shown in Figure 1.8. The authors of [32] have considered eight MPQ events for the present study. They found that average rate of correct identification was 96% for both single and mixed PQ events under noisy conditions.
Biswal et al [33] described a PQ event detection scheme based on a fast dyadic S-transform (FDST) algorithm for feature extraction and a fuzzy decision tree (FDT) for identification of various PQ events. Various single as well as six mixed PQ events have been simulated to validate the effectiveness of the proposed technique. In the proposed scheme FDT based method was not only used as an identifier, but also to select optimal set of features removing dispensable features, thereby reducing the computational burden. The simulation results showed that the proposed identifier provided significant accuracy while identifying mixed PQ events.

Kumar et al [34] presented a method for recognizing the single and mixed PQ events using S-transform based ANN identifier and rule based decision tree. In this research work, eight single and four mixed PQ events were simulated in MATLAB to validate the performance of the proposed method. Here, S-transform was used for feature extraction and two layer feed forward neural network was used for identification of extracted features.

1.2.2.4 Contributions of the present study in relation to mixed power quality events

The objective of the present study is to detect and classify the mixed PQ events in noisy conditions. In majority of the literature, mixed PQ events are not considered. But, it is reported that mixed power quality events occur at the same period of time in many cases and the signals are basically superposition of more than one PQ events [35]. In this work, the cross-wavelet spectra are found from various mixed power quality events. From those spectra some specific features are selected by using Fischer Linear Discriminant Analysis (FLDA) that are given in Chapter 4. The scheme is well suited for detecting simultaneous occurrence of mixed PQ events. The proposed method has the capability of finding out a smaller set of uncorrelated features from higher order statistical data. Smaller set of features means low computational burden. Hence, this analysis is well suited for microcontroller based applications. Moreover, the scheme is immune to real life uncorrelated noises due to incorporation of XWT in the feature extraction process. For identification and classification of the extracted features, a linear support vector machine
(SVM) based identifier is found to be sufficient. This is because FLDA maps the original high-dimensional feature space onto a reduced low-dimensional feature space. The entire scheme has been implemented in a low-cost general purpose microcontroller. Results show that the developed standalone module is capable of sensing simultaneous occurrence of mixed PQ events with reasonable accuracy even with noise contamination.

Figure 1.8: Algorithm for detection and identification of PQ events. [31]
1.2.3 Importance of remote updating for identification and classification of Power Quality events

From literature survey, it is found that for identification and classification of PQ events research works can be divided in two parts. Firstly, the authors have focused on feature extraction and identification algorithm for better identification accuracy and lesser processing time. Secondly, researchers have given attention to number of PQ events that will be identified by the specific algorithm. Thus, for a change in algorithm or change in number of events, in many cases the firmware of the existing module needs to be updated without altering its hardware. The updating process is a specialized job in which either the module is taken back to the manufacturer or a qualified technical person needs to attend the module on site. However, both the methods are manual, time consuming and also it is difficult if larger number of instruments need to be updated within a short time. Remote updating is a good alternative to overcome this difficulty. A number of methods for remote updating have been proposed by researchers [36]-[39]. But most of the implemented schemes are complex and require high end processors. In the present study a remote updating scheme is proposed based on general purpose 8 bit microcontroller. The proposed scheme utilizes the voice communication channel in any existing cellular network. The proposed scheme is implemented in the developed “PQ monitoring module” for firmware updation in varied working conditions.

1.3 Organization of thesis

Chapter2 describes the brief explanation of PQ events that are studied in this thesis work. In PQ event monitoring, data files are important in the training process of the proposed scheme. An experimental setup for generation of PQ events according to IEEE Std.1159-1995 [1] is discussed in this chapter. Apart from experimental setup, emphasis is also given to development of PQ event monitoring module employing a PIC24F series microcontroller.

The identification of PQ event is the main objective of PQ event monitoring. Correlation based technique and Rough Set Theory (RST) are used for identification and classification of single PQ event. Correlation based method is used for feature extraction because of its low
computational burden, which is desirable for microcontroller based system. In correlation based method, two different signals were compared to measure the degree to which the two signals are similar. For selecting an optimal set of extracted features as well as to identify them, Rough-Set based approach is used in this work. Chapter 3 deals with the basic theory of correlation technique and includes a detailed explanation of Rough Set theory (RST). The performance of the proposed method shows that correlation technique and RST together identify the single PQ events efficiently in the presence of noise.

Chapter 4 of the thesis presents a scheme for identification and classification of both single and mixed PQ events. Cross-Wavelet transform (XWT) based feature extraction method is used for feature extraction from mixed PQ events. Selection of features is important for proper identification and classification of the events. Moreover, if the features are not suitably selected it may contain redundant information which increases analysis time. Fischer linear discriminant analysis (FLDA) is used for feature selection because this method is well suited for non-stationary mixed PQ events. A linear support vector machine (SVM) is used for identification and classification of the mixed PQ events based on FLDA selected features. In this chapter an elaborate description of XWT, FLDA and SVM has been presented. The performance of the proposed method shows that cross-wavelet (XWT) transform aided Fischer linear discriminant analysis (FLDA) can identify the mixed PQ events efficiently in the presence of noise.

In varied working condition, addition and alterations are required for developed PQ monitoring module. The advantage of a microcontroller based module is that, the module can be upgraded by changing the firmware, without altering the deployed hardware. Chapter 5 describes the remote updating process of developed PQ monitoring module.

The concluding chapter gives the summarization of the present work and future scope of work

1.4 Originality of the Thesis

To the best of knowledge of the author, the following are the original contributions of the present work:
1. Development of a method based on Rough Set Theory (RST) which is capable of minimizing the set of features for PQ event identification and classification. This method is capable of identification and classification of a single PQ event and can be run on a standalone microcontroller based PQ monitoring module.

2. Development of cross-wavelet (XWT) transform aided Fischer Linear Discriminant Analysis (FLDA) Scheme for Mixed Power Quality events identification and classification and is effective for a standalone microcontroller based PQ event monitoring module.

3. Development of a scheme to incorporate new events in the developed PQ event monitoring module which is located far away from controlling centre through remote updating process. This remote updating scheme is applicable for any topologically similar problems.