CHAPTER 1
INTRODUCTION

1.1. INTRODUCTION

Innovation in the field of power electronic technology has brought a great awareness of power quality (PQ) in the distribution system. As per standards, PQ term is defined as the physical characteristics (i.e., magnitude, frequency and wave shape) of the electrical supply delivered under normal operating conditions that will not disturb or disrupt the performance of the end user [1]. However, the term PQ can also be described with different meanings according to the environments and requirements. From the utility point of view, the quality of electrical power supply deteriorates due to increase emergence of the nonlinear loads [2]. Nonlinear loads have increased harmonic distortion and reactive power demand and hence there are serious PQ problems in the utility. From the customer point of view, the life span and performance of load is mostly affected by the distorted electrical supply [3].

The context of the major key issues augment interest on the subject of PQ is explained below:

- In the traditional electric system, the end consumers were found to be simple, robust, non-polluting and insensitive to variations in electrical power supply. Hence, the major contribution in early power system was done in the compensation of the reactive power demand.
- In the modern distribution system, the loads are found to be computers, prototyping platforms, power converters, adjustable motor speed drives, switch mode power supplies (SMPS), uninterrupted power supply (UPS), low power consumption lamps, dimmers, arc welding machines, etc. However, these loads are very sensitive to electric supply variations accompanied by serious PQ problems in the distribution system.
- Increasing penetration of the small/large scale renewable energy system and medium/large scale industries makes the modern power distribution system more susceptible to complex PQ issues.
- Electricity consumers are thoroughly aware of their rights and demand high quality electricity at reasonable cost.

Overall, these issues resulted increased research on optimum compensation of PQ distortions and delivery of quality electrical supply to the end user [4].
1.2. MAJOR POWER QUALITY PROBLEMS

According to IEEE standard 1409, the PQ disturbance can be described as “Any deviation in the voltage and/or current from the nominal sinusoidal waveform at rated amplitude and frequency, resulting in disruption, misoperation, or damage to equipment or processes” [5, 6]. According to IEEE standard 1159, the events of PQ distortions are classified and elaborated in Fig. 1.1.

The common PQ distortions occurring in the distribution system are discussed below:

- **Voltage sag/dip**: The voltage sag is a sudden drop in the voltage magnitude between 10% to 90% of its RMS value. The voltage sag distortion is categorized under the short duration PQ distortion. Time duration of voltage sag occurs between 0.5 cycle to one minute. The voltage sag is a serious PQ distortion that
instantaneously occurs in the distribution system. The voltage dips can be caused by switching on heavy loads, increased load demand, starting of large motors, network and utility faults. The consequences of voltage sags are malfunction in the processor, increases power drop, unnecessary tripping of relay and contractors and economical losses which reduce the efficiency of the system.

- **Voltage swell**: Voltage swell is a sudden increase in voltage magnitude above 110% of RMS value. Typical magnitude of voltage swell is found to be between 110% and 120% of RMS value. The duration of voltage swell appears between 0.5 cycle to one minute and it is classified under short duration PQ distortion. Unlike voltage sag, voltage swell is an uncommon PQ distortion and it is created by under fault conditions, switching off large loads, switching on capacitor banks, load shedding etc. The severity of voltage swells is determined by the fault locations, grounding and system impedance.

- **Interruption**: Interruption is described as the magnitude of source voltage and load current reduced below 10% of its RMS value. The duration of interruptions can be found not to be exceeding one minute. The interruption is resulted from the operation of utility protective device to protect the equipment from the utilitarian view of faulty conditions, equipment failure and controller malfunctions.

- **Transients**: Transient is found to be sudden and non-power frequency change in steady voltage and current or both. The transients can be caused by the switching on/off highly inductive loads, lightning strikes on the distribution line, etc. However, this transient results in shutdown or damage to the equipment.

- **Voltage and current imbalance**: Imbalance in the three phase system is described in percentage of the ratio of magnitude of negative sequence component to the positive sequence component. This definition is common for both voltage and current. Typically, the voltage imbalance in the utility side is less than 3% whereas the current imbalance is found to be more. The effect of voltage and current imbalance is very harmful to the three phase loads.

- **Waveform distortion**: The waveform distortion is a steady state PQ distortion defined as deviation from the ideal sinusoidal waveform. The waveform distortion is characterized under five primary issues such as DC offset, harmonics, interharmonics, notching and noise.
**Harmonics:** Harmonics is the frequency of AC voltage and current containing integer multiples of fundamental frequency usually 50 Hz or 60 Hz. Harmonic distortion is defined as ideal sinusoidal wave distorted by the combination of fundamental frequency and harmonics. The major source for harmonic distortion in the power distribution system is power electronic devices and nonlinear loads and equipments. High harmonic distortions cause malfunction and system failure besides creating additional power losses, overheating in neutral wire, additional acoustic noise in the motor and electronic apparatus, interference in telephone line and reduction of overall system efficiency.

**Interharmonics:** Interharmonic phenomenon is described as AC voltage and current signals containing non integer multiplication of fundamental frequency. Cycloconverters, static frequency converters, arcing devices and induction furnace and the applications whose control cannot be synchronized with the power line frequency are the major sources for interharmonic distortions.

**Notching:** Notching PQ distortion is created by the normal operation of power electronic converters. The notching distortions are characterized under steady state PQ distortion that contains both transients and harmonic distortions. The severity of notching PQ distortion depends on isolation inductance used in the converters and source inductance.

**Voltage fluctuation:** Voltage fluctuation phenomenon is described as random variations or systematic changes on the magnitude of voltage which does not exceed the voltage range from 0.95 p.u. to 1.05 p.u. The most common source for voltage fluctuations in the distribution system is arc furnace. Lamp flicker is the best example for voltage fluctuation problems.

**Power frequency variation:** The variation in power frequency of the system from its nominal value is termed as power frequency variation. The rotating speed of generators directly determines frequency of the power system. The frequency at any instant in the distribution system depends on balance between available generation capacity and total load demand. Small instantaneous changes on power frequency are due to switching ON/OFF loads. The variation in power frequency above the accepted limit is caused by the faults on bulk power transmission system, sudden drop of large source and blockage by large loads.
1.3. LITERATURE SURVEY ON POWER QUALITY PROBLEMS

The defects in PQ were first reported by Kusko in 1967 [7]. Kusko stated that defected electrical power delivered to the modern loads such as computers and logic control systems resulted in error reading together with dangerous and very expensive failure. These power quality defects can be classified according to the magnitude and time durations. The impact of PQ problems on critical loads can be reduced by placing compensation equipment across loads and by redesigning the utility system.

Key et al. diagnosed the impact of PQ problems on the development of computers. At that time of evaluation of computers, people gain more attention on the PQ problems. Intermittent PQ disturbances have the capability to disturb/disrupt the function of sensitive electronic system in industrial, government and commercial activities [8].

McNeill et al. analyzed PQ for a photovoltaic based residential system. The model was developed by the authors to estimate the THD and power factor as the function of photovoltaic parameters. From the overall analysis, the authors concluded that the photovoltaic based residential power system significantly injected harmonic distortions in the distribution system [9].

Key et al. summarized various views on PQ problems from both the utility and industrial end user’s point of view [10]. Hall conducted a huge research on the PQ in the distribution system [11]. And the authors stated that the electromagnetic problems were enhanced by the increasing use of power electronic converters, controllers and drives in industrial applications. These electromagnetic problems disseminated into PQ distortions in the power distribution system.

Jewell made analysis on the impact of power quality problems on equipments installed in the hospital [12]. The author discussed the kind of PQ disturbances injected in the power system and measures taken to enhance the quality of power supplied.

Krishnaswamy Srinivasan et al. conducted research on transient and steady state PQ distortions. From the research, it was concluded that voltage sag, unbalanced three phase, RMS fluctuation and waveform distortions were the major PQ problems. And also responsibilities between utility and customers for sharing the compensation of PQ distortion were addressed [13]. Lakshmikanth et al. developed a methodology to monitor the PQ of the system [14].
Mladen Kezunovic et al. developed a new concept for PQ studies using software prototyping implemented in Matlab [15]. This novel concept incorporated modeling of power system, classifying the power quality events, analyzing equipment sensitivity to the PQ disturbances and locating point of occurrence of power quality distortions. Eduard Muljadi et al. investigated the PQ issues in the integration of wind power plant and diesel generator. However, the wind power plant was seen reducing pollution generated by diesel generator. But the problem of power fluctuation in wind power plant resulted in serious PQ issues such as voltage fluctuation, poor reactive power compensation and harmonic distortion [16].

Zhuo Sun et al. developed simulation and a prototype model for investigation on electrified railways traction substation [17]. From this investigation, the major PQ issues generated in the traction substation were found to be negative sequence current, harmonic distortion and reactive power consumption.

Y. Liu et al. proposed real time hardware in loop simulation for PQ analysis on navy electric ships [18]. In electric ship, major sensitive PQ issues are generated by variable speed motor drives. The power frequency variations, voltage sag and THD are the PQ distortions generated in electrical ship application. David B. Vannoy et al. made a road map for the development of PQ standards. PQ standards provide recommended limit between the utilitarian and end user customers [19].

Josep M. Guerrero et al. investigated on power quality on energy storage and AC/DC microgrid. Grid connected microgrid normally compensates voltage related PQ problems such as voltage sag, swell, interrupt and imbalance [20]. Prakash K. Ray et al. classified the power quality disturbances produced by distribution generators not only by means of load changes but also by environmental characteristics such as wind and radiation changes [21].

Prakash K. Ray et al. analyzed the PQ issues on penetration of the distribution generators in the traditional distribution system [22]. The voltage sag, swell, notches and harmonic distribution were the various PQ disturbance resulted from these penetrations. Carlos R. Baier et al. researched on a single phase non-regenerative power cell using a multilevel converter [23]. Different input/output frequencies and poor decoupled behavior of the DC link resulted in interharmonics that caused harmful effect in the power distribution transformer and reduced the life span of the equipment and created serious power quality distortions at the point of common coupling (PCC).
Zheng Zeng et al. investigated the PQ issues of microgrid using multifunctional grid tied inverters [24]. Harmonic distortion, maintaining of real and reactive power and voltage fluctuations are the major PQ issues in microgrid. Matthew K. Gray et al. investigated the power quality issues on the impact of electrical vehicles such as plug-in hybrid and battery vehicles in the power distribution system [25]. Both the types resulted in voltage related power quality problems over voltage, under voltage and voltage imbalance.

1.4. CLASSIFICATION ON POWER QUALITY PROBLEMS

In general, the power quality problems are broadly classified into voltage related and current related. Any deviations in voltage from the nominal value or any distortions present in the utilitarian/source side are termed voltage related PQ distortion. Increasing penetration of small and large scale renewable energy, sudden

![Fig. 1.2 Pictorial view of voltage related PQ problems](image-url)
increase in load demand, network faults, switching ON/OFF large loads and capacitor banks, overloading of distribution transformers etc., causes voltage related PQ distortions. The voltage related PQ problems are voltage sag/swell, interrupt, over voltage, under voltage, unbalance voltage, harmonic distortion, etc., [26]. The pictorial representation of the voltage related PQ distortions is shown in Fig. 1.2.

Fig. 1.3 Pictorial view of current related PQ problems

Imperfections in the current or distortions originating on the customer’s side are labeled as current related PQ distortions. The current related PQ problems are generated by penetration of power electronic applications, prototyping platform based control applications in industries, nonlinear/high inductive loads, uninterrupted power supply (UPS), power rectifier/inverters, single phase loads, air conditioners and washing machines etc. The current related PQ problems are harmonic distortion, reactive power demand loads, unbalanced loads, interharmonics, DC offset and
negative sequence current [27]. The pictorial view of the current related PQ distortions is shown in Fig. 1.3.

1.5. NEED FOR MITIGATION OF POWER QUALITY PROBLEMS

The voltage related PQ distortions cause disastrous consequence in the industrial sector by tripping or damaging sensitive equipment which can lead to unexpected outcomes or shutdown of complete production unit. These outcomes cause huge economical damage to the end user. To avoid huge economical loss, the customers need to install compensation devices in order to protect their own plant from the voltage related PQ distortions [28].

Increasing the use of power electronic applications in commercial as well as industrial sector is quite common. Most of the power electronic applications use a diode bridge rectifier followed by a front end capacitor. However, these topologies are often insensitive to the voltage distortion but draw highly distorted current in nature. This distorted current is termed as current related PQ distortion. Moreover, recent studies show that the current related PQ distortions significantly deteriorate the supply voltage. The plants producing current distortions do not experience direct impact but they are the main source in deteriorating the quality in electrical supply delivered to the neighbour-customer. Also there may be many similar types of loads used in the same feeder. Hence, pollution in the distribution system increases rapidly and the electrical supplier can no longer support them. Presently, government has recognized this problem and provides certain limits imposed to restrict these distortions within the limit. The customers are forced to pay massive penalty if they fail to maintain distortions within the limit. To comply with the limit, the end user has to install compensation device at the point of common coupling (PCC) to minimize the pollution created by their own loads [29].

The impact of PQ distortions is studied from both the utility and customer sides. The voltage and current characteristics for different loads such as R load, RL load and rectifier load are shown in Fig. 1.4 (a), Fig. 1.4 (b) and Fig. 1.4 (c) respectively. For R load, it is found that current varies linearly with respect to voltage since the voltage and current are found to be inphase with each other. Hence no compensation device is needed for R load. For RL load, it is found that current varies oval shape with respect to voltage since the current lags the voltage. Compensation device is needed for RL load to compensate the load reactive power demand.
For rectifier load, it is found that current varies nonlinearly with respect to voltage since the current response is highly distorted. For the rectifier load, compensation device is needed to compensate harmonic distortions and reactive power demand [30].

As discussed early, the power electronic devices behave like nonlinear loads and create unwanted PQ distortion but interestingly, power electronic devices themselves provide solution for PQ distortions. At the present scenario, single compensation device has to develop as it plays dual role to protect the sensitive loads from voltage related PQ distortion simultaneously it protects utility form load side imperfections [31].
1.6. ROLE OF CUSTOM POWER DEVICE

Rapid growth of power electronic technologies and its applications have dramatically changed the characteristics in the distribution system. The power-electronic-devices based equipments/loads act as nonlinear components that generate unwanted serious PQ problems in the modern distribution system [32]. Interestingly, power electronic technologies have the ability to protect both utility and load from the PQ problems. Power electronic compensation devices installed in the power system are broadly classified into flexible AC transmission system (FACTS) and custom power device (CPD) [33]. The FACTS technology incorporates power electronic controlled storage devices installed on the transmission side to improve the power transfer capability. Some of the FACTS devices are thyristor-switched capacitors (TSC) and thyristor-switched reactors (TSR), static VAR compensators (SVC), STATCOM, static series compensator (SSC) or dynamic voltage restorer (DVR) and unified power flow controller (UPFC). However, these devices play major role on the transmission side for optimum control of real and reactive power flow [34-36].

The custom power device is a power electronic controlled compensation device installed in the distribution system [37]. Alexander Domijan et al. done simulation study on various custom power devices and addressed the compensation done various custom power quality devices [38]. The major custom power devices utilized in the distribution side are categorized as series active power filter (APF), shunt APF and unified power quality conditioner (UPQC). The series APF topology is shown in Fig. 1.5 (a) and it is designed using a voltage source inverter (VSI) with a DC link capacitor. In series APF, the VSI is connected in series with the source and the load through the series coupling transformer. Zhaoan Wang et al. made a detailed analysis on the series APF and it is found that the series APF compensates voltage related power quality problems i.e., it protects load from the utility side disturbances [39]. But it fails to compensate the current related power quality problems i.e., fails to protect utility from the penetration of current imperfections.

The topology of shunt APF is shown in Fig. 1.5 (b) and it is designed using a VSI with a DC link capacitor and it is connected in parallel between the source and the load. Bhim Singh et al. carried out a detailed analysis on shunt APF and found that shunt APF compensated current related PQ distortion i.e., it protected utility from the current imperfections [40]. Parag Kanjiya et al. applied shunt APF to solve the problems produced by the nonlinear load and reactive load under normal and distorted
It has been found that the shunt APF fails to compensate voltage related PQ distortions i.e., it fails to protect load from the voltage related distortion.

In the present scenario, the series APF and shunt APF alone do not meet the requirement for compensating the PQ distortions. The unified power quality conditioner (UPQC) is a promising custom power device that combines both series APF and shunt APF with a common DC link capacitor and its topology is shown in Fig. 1.5 (c). The UPQC has the ability to compensate both voltage and current related PQ distortions [42]. The UPQC has the capability to protect sensitive loads from the utility side disturbances as well as it protects utility from the penetration of current imperfection.

1.7. OVERVIEW ON TRADITIONAL CONTROL SCHEMES

Simultaneous compensation of voltage and current related PQ distortions using UPQC is achieved by proper controlling of series VSI and shunt VSI. The control scheme designed in the UPQC is broadly classified into series control technique and shunt control technique. The roles of the series control schemes are accurate generation of reference voltage signal and controlling pulse for the series inverter. The shunt control technique is designed to generate reference current signal and controlling pulses for the shunt VSI and to regulate the DC link voltage at the desired level [43].
From the various literature surveys, the control schemes are broadly classified on the basis of generation of reference signals are instantaneous reactive power theory, synchronous reference frame technique, power angle control technique and unit vector template generation (UVTG) technique [44,45]. These techniques used fixed gain proportional integral (PI) controller to regulate the DC link voltage. The DC link voltage is the voltage across the DC link capacitor. The popular PWM method is used to generate the firing pulses to the inverters and the duty cycle of the firing pulse are controlled using hysteresis band control, space vector modulation, triangular carries pulse generation [46,47].

1.7.1. Instantaneous Reactive Power Theory

The instantaneous reactive power theory was proposed by Akagi et al. and it is also termed as three phase p-q theory [48]. The concept of the theory is instantaneous three-phase voltage and current which are transformed to \(\alpha-\beta-0\) coordinates using clark-park transformations. From the voltage and current in \(\alpha-\beta-0\) coordinates, instantaneous real and reactive powers are computed. The next stage is to compute fundamental and harmonic quantities from the real and reactive powers. The load reactive power and harmonic active power are to be compensated. Hence the fundamental component of load active power is subtracted from the instantaneous total load real power using low pass filter (LPF) and high pass filter (HPF). The voltage and current in \(\alpha-\beta-0\) coordinates are computed from the compensation power. Finally, the reference signals to the UPQC are generated by transforming the voltage and current from \(\alpha-\beta-0\) coordinates to three-phase axes using inverse clark-park transformation.

However, this technique works properly for three phase balanced sinusoidal supply whereas it poorly exhibits under distorted environment. Another issue is that this technique utilizes clark-park transformation, inverse clark-park transformation, LPF and HPF [49]. These transformations and filters required linear and nonlinear mathematical operand. And these occupy more memory space in the processor and reduce processing speed.

1.7.2. Synchronous Reference Frame Technique

The synchronous reference frame (SRF) technique was proposed by Bhattacharya et al. and is known as d-q theory [50]. In the SRF method, compensation component is directly extracted from voltage and current. For the shunt inverter, the
three-phase distorted source current is transformed to $\alpha$–$\beta$–0 coordinates in stationary frame. The stationary quantities are transformed to the synchronous frame using phase lock loop (PLL). The PLL generates the sine and cosine functions that support to synchronous with supply system and the fundamental and harmonic components are separated using HPF and LPF similar to PQ theory. After separation, the reference signal for the shunt VSI is generated. For series VSI, the reference signal is generated from voltage in the synchronous frame [51]. This scheme works better even under distorted environment. But the problem is that more mathematical operands are used that result in processor slow down.

1.7.3. Power Angle Control Technique

The power angle control (PAC) was proposed by Vinod Khadkikar et al. [52]. The control technique was introduced to overcome the drawbacks like poor utilization of series APF and high rating of shunt APF. In PAC, the major work is contributed on the series part of the UPQC. The shunt part of the UPQC is designed using either PQ theory. In PAC, the optimum power angle is computed as the function of load reactive power demand. The power angle is introduced in the reference load voltage. The actual load is forced to track the reference load voltage such that the power angle is successfully injected into the load voltage. Before the power angle injection, the load reactive power demand is completely delivered by the shunt APF. After power angle injection, series APF shares the compensation of load reactive power demand with the shunt APF i.e., both series APF and shunt APF deliver the load reactive power demand. Overall, the advantage of this technique is minimizing KVA rating of the shunt APF and it results in better compensation of harmonic distortion.

1.7.4. Unit Vector Template Generation Technique

The unit vector template generation (UVTG) was designed by Vinod Khadkikar [53]. The UVTG is a simple prominent control technique with minimum mathematical operands. The principle of UVTG is to compensate the PQ distortions by controlling the DC link voltage at the desired level. The shunt UVTG estimates the fundamental current directly from the difference of reference and actual DC link voltage using PI controller. The reference source current signal is generated from the product of estimated reference current and three-phase unit sine vectors. The compensation components of current related PQ distortions are determined by difference of reference and actual source current [54]. In series UVTG, reference load
voltage signal is the product of predetermined rated voltage magnitude and three-phase unit sine vectors. The compensation components of voltage related PQ distortions are determined by direct difference of reference and actual load voltage. From various control techniques, UVTG seems to be simple control technique and it is flexible to implement in the digital processor. However, this technique utilizes the fixed gain PI controller to regulate DC link voltage at constant reference value which resulted in constant voltage across the DC link capacitor. Under distorted environment, the fixed gain PI controller exhibits poor control of DC link voltage that results in poor compensation capability of UPQC.

1.8. **RESEARCH MOTIVATION**

The main challenge of the research work is to develop UPQC with an optimum compensation capability to protect both utility and sensitive loads simultaneously from the wide range of PQ distortions. The optimum compensation capability of UPQC is achieved by the control strategies. In traditional control technique, fixed gain PI controller is designed to control the DC link voltage at constant reference value. Under distorted environment, fixed gain PI controller exhibits poor control of DC link voltage. This issue results in poor compensation capability of the UPQC. Under poor compensation capability, UPQC itself acts as source for PQ distortions. The performance of conventional schemes shows the dependency of (abc to dq0) transformation, saturation limit, low pass filter and high pass filter. However, these models require linear and nonlinear mathematical expressions, which fail to satisfy the objective function under parameter variations and nonlinear load disturbances. Moreover, these models increase mathematical operands in the control scheme which results in prototyping complexity and increases processor memory size and slows down the processor speed. These limitations motivated the researcher to carry out research work on proposing an appropriate control technique for obtaining better compensation capability, wide range operating condition of UPQC and flexibility in the real time implementation.

1.9. **RESEARCH OBJECTIVES**

The main objective of this research work is to develop an appropriate control technique for UPQC, in order to achieve optimum compensation capability and wide range of operating conditions. An appropriate control technique is chosen which exhibits robust control of DC link voltage, effective utilization of series and shunt
APFs, and flexibility in implementation. These considerations constitute the objectives of the research and they are enumerated below:

- To identify the source and effect of PQ problems in the power distribution system.
- To design a unified power quality conditioner for compensating PQ distortions.
- To develop an adaptive control technique with a view to achieve optimum compensation capability of the UPQC.
- To examine the performance of the proposed adaptive control technique using analytical method and artificial intelligence technique.
- To validate in real time, the proposed algorithm implements in the Xilinx system generator.
- To perform feasibility investigation on PQ enhancement at PCC using proposed UPQC in the distribution system.

1.10. METHODOLOGY AND CONTRIBUTIONS

The objective of this thesis is on protection of utility and customer from a wide range of power quality distortion using unified power quality conditioner. To accomplish the highlighted objectives, important methods have been followed which are sketched below:

- The power circuit for the unified power quality conditioner is constructed using two voltage source inverters with a common DC link capacitor with appropriate passive filters.
- Design of suitable control technique to the unified power quality conditioner for better compensation capability and a wide range of operating conditions.
- Implement of control algorithm in real time Xilinx system generator.
- Enhancement of power quality in the distribution system using proposed UPQC.

Specific contributions to formulate appropriate control strategy are as follows:

- Study on conventional fixed-gain PI controller.
- Proposed MRAS based online self-tuning PI controller.
- Proposed analytical method based DC link voltage estimator and power angle estimator.
- Proposed ANFIS based DC link voltage controller.
Proposed ANFIS based DC link voltage estimator and power angle estimator.
Proposed Xilinx PI controller.
Proposed Xilinx based DC link voltage estimator and power angle estimator.

1.11. ORGANIZATION OF THE THESIS

The research work has reported in the thesis is organized into seven chapters. Each chapter deals with a study, contribution and highlights of the merits and inference.

A general introduction to the PQ problems is presented here. A thorough literature survey on the PQ problems is reported. The role of custom power device for PQ enhancement is highlighted. The main objectives and outline of the dissertation are also presented.

The unified power quality conditioner topology and system configuration are elaborately discussed in chapter 2. The UPQC basics and principle of compensation of PQ distortions are explained in detail, which serve the foundation of this research work.

In chapter 3, the compensation capability of the UPQC is analyzed using analytical based ACT. The simulation studies are carried out on online self-tuning PI controller, variable DC link voltage control and power angle estimator. The advantages of maintaining variable voltage across the DC link capacitor are also highlighted.

In chapter 4, special attention is given to the development of an ANFIS based ACT. An ANFIS training procedure, selection of neural learning algorithm and identification of suitable membership function are drafted in this section. The simulation analysis conducted on ANFIS based UPQC to ensure the enhancement of compensation capability is compared with other schemes.

The procedure for implementing control algorithm in the real time Xilinx system generator is reported in chapter 5. The process of using Matlab/Simulink as co-simulation for FPGA rapid prototyping using a XSG is also presented.

In chapter 6, the proposed UPQC is applied to enhance the PQ profile at PCC in existing and microgrid distribution system.

The major conclusions of the research work and recommendation for future work are reported in chapter 7. Finally, the list of reference and appendices are provided at the end of the thesis.