CHAPTER 1
INTRODUCTION

1.1 GENERAL

With the growth and development of technologies, power distribution systems and the loads, have increasingly concentrated on the quality of power supply. In the recent years, various highly sensitive medical equipments, high-speed motors, and computer-controlled processing plants, require the power source of high quality and good reliability. Over the last decade, substantial research has been carried out on power distribution systems to overcome most severe power disturbances such as harmonics elimination, mitigation of voltage sags, load balancing, voltage regulation and interruptions of renewable resources [1]. The required techniques have been developed to analyze, predict, and mitigate these disturbances in system-equipment interactions [2]-[3]. To assess and to maintain the good quality of power in power distribution systems, presently electrical supply industries are becoming efficient without compromising the quality of power supply service [4]-[5]. Providing new solutions for this newly power quality paradigm in distribution systems by custom power devices (CPDs) has reduced the complexity, costs and has increased the reliability of power supply [6]-[11].

In addition, the demand for electricity is increasing due to urbanization and growth of population. Renewable energy resources integration is playing an important role to meet the demand in distribution systems. However, issues of power delivery quality of the supply voltage or current from the sinusoidal waveform with the amplitude at rated frequency, have deviated the quality of waveforms.
1.2 STATE OF THE ART ON POWER QUALITY

The power quality problems in the distribution systems are mainly due to the proliferation of different types of nonlinear loads, unplanned expansion of the distribution system, etc [12]-[13]. Therefore, power quality is quantified in terms of voltage, current, or frequency deviation of the supply system, which may result in failure or mal-operation of customer's equipment [8]. The degradation of power quality leads to low power factor, low efficiency, over heating of transformers, and so on. In distribution systems, the power quality problems can reduce the power supplied to the customers from its nominal value. The utility and the users are responsible in polluting the supply network due to operating large loads [14]-[15]. Power quality has taken an increasing importance in view of the widespread use of power electronic equipment [16]-[18]. Power quality problems related to the voltage, are voltage harmonics, surge, sag/dip, spikes, notches, unbalance, swell, fluctuations, and so on at the point of common coupling (PCC) where various loads are connected. However, some power quality problems related to the currents drawn from the AC mains, are poor power factor, reactive power burden, harmonic currents, unbalanced currents, and an excessive neutral current in poly-phase systems due to unbalancing and harmonic currents generated by some nonlinear loads. In distribution systems, power quality issues related to voltage and current drawn from AC mains at point of common coupling (PCC) like unbalanced voltages supply, active and reactive power demands, are affecting performance of customer equipment [19]-[21]. A power quality problem is any occurrence manifested in voltage, current, or frequency deviations, which are major impacts to a distribution system that result in failure of customer equipment [22]-[27]. These aspects become important when power supply is not ideal
i.e., it deals with unbalance, harmonics, faults and fluctuations in frequency [28], [29]. The mitigation of power quality issues has been provided by filters such as passive, active and hybrid in series, shunt or combination of both [30]-[50]. Power electronics based controllers have played a vital role to enhance the quality and reliability of power delivered by electric distribution system. These devices can be shunt connected, series connected or a combination of both series and shunt connected at PCC [51]-[61]. A number of international standards are developed by various organizations such IEEE (Institute of Electrical and Electronics Engineers) and IEC (International Electrotechnical Commission) to specify the permissible limit of power quality problems and to provide guidelines for the end users, manufacturers and utilities to improve the quality of power [62]-[68]. The critical and sensitive loads are protected from power quality problems by monitoring these power quality events. The objectives of power quality monitoring, are prediction of performance of the load and the selection of power quality mitigation system [69]-[79].

Further, with the deregulation of the power industry, competitive pressure forces electric utilities to cut cost, which sometimes affects power quality and reliability. Hence, it must be ensured by suitable regulations that customers do not suffer from reduced power quality and reliability.

1.3 TRANSITION TO SMART POWER DISTRIBUTION SYSTEMS

With the help of intelligent custom power devices (CPDs) in distribution systems such as distribution static compensators (DSTATCOMs), dynamic voltage restorers (DVRs), and unified power quality conditioners (UPQCs), power quality problems arising due to various disturbances in the system or due to the presence of various
nonlinear loads such as furnaces, uninterruptible power supplies (UPSs), and adjustable speed drives (ASDs), which have evolved inherently, can be monitored and mitigated. These intelligent CPDs make the power distribution systems smart [30]-[36]. Intelligent CPDs use experiential knowledge about the process that generally produces a model in terms of input–output behaviour. The acceptable controller to mitigate current related power quality problems at distribution level is distribution static compensator (DSTATCOM), which is also named as an active shunt compensator or filter [52]-[61]. The DSTATCOM is used for mitigation of current related power quality problems such as harmonics distortion, poor power factor, load unbalancing and voltage regulation etc. Tremendous progress in the field of power semiconductor devices and signal processing, has made the cost effective implementation of DSTATCOM [50]-[58]. The research in this area has led to the developments in the area of different configurations and control algorithms for control of the shunt compensator. The DSTATCOM is configured based on the number of switching devices, the use of isolation transformer and the use of type of transformer for neutral current compensation. Mainly DSTATCOM configurations are divided into two major categories such as three phase three wire and three phase four wire [69]-[79].

1.3.1 Limitations of CPDs

The ability of the DSTATCOM as a compensator is impaired by control algorithms of the following steady-state and dynamic-state limitations. The control algorithm should have fast response and stable operation in both steady state and dynamic conditions. The selection of a control algorithm depends upon processing time,
mathematical complexity, fast response, stable operation and easy implementation. The primary objectives of the DSTATCOM in a distribution system are:

- **DC link voltage control**: Maintaining desired level of voltage, prevention of transient under dynamic condition of load and fast response under steady state.
- **Power flow control**: Increased power factor, minimization of loop flows and voltage regulation.
- **Load balancing**: During, transient, steady-state and dynamic state.
- **Harmonics elimination**: Reduction in losses, reduction in overload capacity and increase in efficiency of utility equipments.

### 1.3.2 Concept of Intelligent CPDs

The modeling of intelligent CPDs to be computationally efficient to deal with the power quality problems is related to the current drawn from the AC mains. There are three basic approaches to intelligent controls [80].

- **Knowledge-based systems**
- **Fuzzy logic**
- **Neural networks**.

Knowledge-based systems utilize a collection of information in different forms such as facts, heuristics, common sense and other forms of knowledge and use reasoning methods to inferences. In this approach, measurements, process modeling and control can never be exact for real and complex processes. Moreover, there are uncertainties such as incompleteness, randomness, and ignorance of data in the process model [81]-[85].
Fuzzy logic can incorporate certain types of unknown nonlinearity from imprecise and incomplete information by giving definitions to vague terms and allowing construction of knowledge-base in form of rules [86]-[89].

Neural network based control has received considerable interest over the last two decades because neural networks have been shown to be able to approximate any nonlinear function defined on a compact set of data to a specified accuracy and secondly most control systems exhibit certain types of unknown nonlinearity, which suits neural networks as an appropriate control technology [85]-[95].

1.4 SCOPE OF THE WORK

After carrying out a brief literature survey on control algorithms of the CPDs like UPQC, DVR and DSTATCOM, it has been identified that the advanced intelligent control of DSTATCOM builds the distribution system smart and intelligent. The aspects of advanced intelligent control strategies comprise of different issues that include the speed of response, convergence, computational burden, complexity, static error, robustness and stable operation in the steady state and dynamic conditions with verification by an experimental prototype.

The main objectives of the proposed research work are as follows:

- To design and develop a prototype configuration of three-phase distribution system with DSTATCOM in the laboratory.
- To develop the mathematical model of the proposed control algorithms and their experimental realization through the digital signal processor (DSP).
- To investigate the implication on real-time application to mitigate the power quality issues of the configuration taken under consideration.
To assess the effectiveness of the developed advanced intelligent control algorithms based on neural network and nonlinear adaptive filter under different operating conditions.

The proposed research work has been carried out as follows:

**1.4.1 Control Strategy for DSTATCOM**

The control strategy for DSTATCOM is implemented in three stages, which are required for implementing developed control algorithms. In the first stage, current and voltage signals are sensed using Hall Effect sensors (LEM make) to take system parameters. In the second stage, developed model of control algorithms on MATLAB Simulink platform, are used to drive the DSTATCOM to deliver current compensation signals in order to mitigate current related issues of power quality. In the third and last stage, the gating signals for controlled switches (IGBTs) are driven using hysteresis current controller (HCC) logic based pulse width modulation (PWM) control technique. To design the control part in real time, digital signal processor (DSP) based on dSpace-1104 is used. Earlier this work has been carried out through complex analog and digital circuits.

**1.4.1.1 Sensing of signals**

For implementing control algorithm, instantaneous voltage and current signals are sensed. These signals are used to evaluate various parameters like THDs, power factor, crest factor, active and reactive power, etc. The Hall Effect voltage sensors (LV-25P) are used to sense the voltage signals such as phase voltages of AC supply at PCC and DC bus voltage of VSC based DSTATCOM. The Hall Effect current sensors (LA-25) are used to sense current signals such as load currents, supply currents at PCC. Current and voltage
signals have to be filtered to avoid any noise or interference problems using R-C series low pass filter (LPF). The required levels of sensed signals are maintained by dSPACE, which has DSP based platform, by passing through power conditioning circuits. In hardware, the ripple filters are designed using analog circuit.

1.4.1.2 Reference currents generation

The generation of the reference currents comprises of extracted fundamental active and reactive current components of the load current, respectively. The switching has been initiated by taking the error of sensed and reference fundamental currents that results into injecting compensating current signals. To draw compensating current signals, some control algorithm based on either frequency domain or time domain has to be designed.

In frequency domain, Fourier analysis is generally used to extract fundamental current components, for which switching frequency for the device is kept twice of highest frequency component for accurate and effective compensation. Fourier transform has a disadvantage of producing large response time in the system.

In time domain, instantaneous values of compensation currents or voltages are generally derived from polluted currents or voltages signals. Here, a number of control methods have been derived such as synchronous reference frame, instantaneous active and reactive power theory, adaptive filter based techniques etc.

1.4.1.3 Switching pulse generation

The error signal of fundamental current is passed to PWM based hysteresis current control method that generates required gate signals at a frequency of around 10 kHz.
1.4.2 Fast Multilayer Neural Network Based Control Algorithm

The back-propagation learning has various drawbacks such as slowness in learning, stuck in local minima, and requires functional derivative of aggregation and threshold functions to minimize error function. Various researchers have suggested a number of improvements in simple back-propagation learning algorithm [96]-[120]. On the primary objectives of advanced intelligent control, fast multilayer neural network based control algorithm is developed that has enhanced the convergence speed of the developed backpropagation (BP) algorithm in three-phase three-wire distribution system using three-leg VSC for reactive power compensation, harmonics eliminations, and load balancing. The developed algorithm is validated experimentally in the laboratory on the developed prototype of DSTATCOM.

1.4.3 Generalized Neural Network based Control Algorithm

In the available ANN based algorithms, the sigmoid threshold function and ordinary summation or product as aggregation functions in the existing models, fail to cope with the nonlinearities present in the AC supply current or voltage sinusoidal waveforms. To deal with such nonlinearities, the proposed generalized neuron has both sigmoid and Gaussian functions with weight sharing. The generalized neuron has flexibility at both the aggregation and threshold function level to cope with the nonlinearity present in the sinusoidal waveforms [121]-[145]. This new concept has reduced the complexity of multilayer into single layer, which reduces the computational time. GNN has reduced network problem and learning complexity on training of input signals in three-phase three-wire distribution system using DSTATCOM for reactive power compensation,
harmonics eliminations, and load balancing. The developed algorithm is validated experimentally in the laboratory on the developed prototype of DSTATCOM.

1.4.4 Nonlinear Adaptive Filter based Control Algorithm

In the literature survey, the applications of non-linear filter based control algorithms for DSTATCOM, are rarely available. However, linear filter based control algorithms, are effective in a variety of performances improvement of DSTATCOM [146]-[165]. Moreover, in nonlinear signal processing where linear filters do not give satisfactory performance, nonlinear filtering techniques are able to provide better performance. Performance of these control algorithms are analyzed in three-phase three-wire system using three-leg VSC for reactive power compensation, harmonics eliminations and load balancing.

1.5 OUTLINE OF CHAPTERS

This thesis consists of seven chapters including introduction, literature review, design and development of DSTATCOM in a three phase distribution system, which deals with the control strategy for DSTATCOM, realization of developed advanced intelligent control algorithms such as fast multilayer neural network based control of DSTATCOM, generalized neural network based control of DSTATCOM, nonlinear adaptive Volterra second order filter (AVSF) based control of DSTATCOM, main conclusions and suggestions for further work followed by references.

Chapter-1: This chapter covers introductory concepts of power quality issues and their mitigation in a distribution system and transition to smart power distribution system integrated with custom power devices and their control techniques. The scope of work includes advanced intelligent control algorithms for improving power quality problems
such as harmonics, reactive power and load unbalancing. This classification of control algorithms, includes fast multilayer neural network based control algorithm, generalized neural network based control algorithm, and nonlinear adaptive filter based control algorithm.

**Chapter-2:** The brief literature review on power quality standards, issues, monitoring and their mitigation in the distribution system, is described in this chapter. Further, a comprehensive literature review on multifunction operation and control of DSTATCOM is also reported in detail. The performance of DSTATCOM on configurations and control algorithms for load compensation, is also discussed in this chapter. Based on the exhaustive literature review, identified research areas are presented at the end of this chapter.

**Chapter-3:** This chapter deals with the design and development of DSTATCOM in a three phase distribution system. Mathematical modeling and selection of various components of DSTATCOM such as VSC, DC bus voltage, DC bus capacitance, interfacing inductors, and ripple filter are presented. Design and testing of voltage sensor circuits, current sensor circuits, and gate driver circuits with signal conditioning for generation of pulses for control of VSC, are discussed here. In addition, the interfacing inductors are also designed in the laboratory for the hardware of prototype of DSTATCOM.

**Chapter-4:** This chapter addresses the mathematical modeling and analysis of the proposed fast multilayer neural network based control algorithm for DSTATCOM. Mathematical formulation, MATLAB modeling and DSP based implementation of the proposed control algorithms, are discussed in detail. Simulation and test results of the
proposed algorithm are also given in detail. Test configuration of DSTATCOM, has been simulated and validated with the experimental results for linear/nonlinear loads under various conditions.

Chapter-5: This chapter presents a generalized neural network (GNN) based control algorithm and its mathematical formulation for DSTATCOM. Investigations on the performance of GNN based control algorithms include power factor correction and zero voltage regulation modes of DSTATCOM. Mathematical formulation and MATLAB models have been developed for real time applications on a developed prototype of DSTATCOM. The control algorithm investigated, is validated using simulation as well as experimental results obtained on a developed prototype of DSTATCOM at linear/nonlinear loads under various conditions.

Chapter-6: In this chapter, the nonlinear adaptive Volterra second order filter (AVSF) based control algorithm for DSTATCOM is presented and its mathematical formulation is given in detail. The performance of the proposed nonlinear adaptive theory based algorithm such as Volterra second order filter, is demonstrated. Mathematical formulation and MATLAB models, have been developed for real time applications on a developed prototype of DSTATCOM using DSP. Simulation and test results of this algorithm, are given in detail. Performance of the DSTATCOM has been studied through simulation results and validated with the experimental results on developed prototype at linear/nonlinear loads under various conditions.

Chapter-7: This chapter provides a summary of conclusions drawn from the different aspects of the developed control algorithms proposed for DSTATCOM and highlights its
feasibility. Some suggestions are also presented for further work in the areas covered in the thesis at the end of this chapter.