Chapter 1: Introduction

1.1 General Background

The significant growth of power electronics and widespread usage in variety of power modulators brought in considerable benefits in industrial and commercial use of electrical power. These include development of high power rectifiers/static converters for electrolysis, variable DC output through buck boost converters and inverters for UPS and also variable speed industrial drives. Many of these applications involved multiple power electronic switching devices like diodes, Thyristors, power MOSFETs and IGBTs that operate as non-linear loads as far as the power source is concerned. Consequently, a new set of problems related to power quality was encountered. These problems were mainly prevalent in major industries during the 80-s and 90-s of the previous century and were localized, but have also affected medium and low power distribution networks during the last two decades, due to the widespread use of SMPS, used in a variety of communication equipments apart from laptops, mobile chargers and home appliances.

A general feature of all DC power supplies and nonlinear loads such as SMPS, power electronic converters and computer systems connected to AC mains is the presence of a diode rectifier terminated on a DC link capacitor. The pulsating charging current drawn by the capacitor degrades the quality of supply due to the introduction of harmonics in the source current and leads to distortion of the line voltage waveform, poor power factor, increase in RMS current and electromagnetic interference. It also interferes with and adversely affects the performance of other equipments connected in the power network. Due to these power quality issues, the utility companies have to supply more active and reactive power to the distribution network. The importance of
the power quality issue is evidenced by the wealth of major publications in the topic during the last two decades. A common theme in these research articles [1-4] is the need to maintain the supply side power factor close to unity and minimize the harmonics in voltage and current. Hence, different approaches and schemes to reduce the harmonics within the limits specified by the international standards like IEC61000-3-2, IEEE Standard 519, [5-7] have been developed involving passive and/or active PFC circuits. The advent of various power factor correction circuits have mitigated source current harmonics by shaping the source current to nearly sinusoidal which in turn improves the supply side power factor [8, 9].

Although passive filters for power factor improvement are configuration-wise and function-wise simple, large values of the filter elements required and designed for effectiveness at low line frequency increase their size and weight and also lead to many undesirable effects like supply side resonance. Hence, there is vital need to go in for the development of active power factor correction circuits [10-12]. Since the switching frequency is high in active Power Factor Correction (PFC) Converters, the size of the reactive elements can be made small. Active shaping of the input line current waveform is also possible by using power electronic converters, which control the input current so as to force the current waveform to follow the supply voltage waveform closely. One power circuit configuration that has gained considerable attention is the application of shunt active filter in parallel with the non-linear loads, where the principle of harmonic current injection by the shunt path is aimed as a means of compensation. As an alternative for meeting the regulated low voltage DC output, in addition to input power
factor improvement, development of a DC-DC boost converter in a modular configuration has gained widespread acceptance.

1.2 Active Power Factor Correction for Single Phase System

An ideal PFC used for input current shaping should emulate a resistor on the supply side, while maintaining a regulated DC bus voltage on the load side. Since the supply voltage is normally sinusoidal, the active PFC should draw sinusoidal current from the utility grid. Hence, the objective is to shape the input current to be sinusoidal and maintain good regulation of output DC voltage. This thesis presents a group of control techniques for active PFC using boost converter topology which is applicable to both single-phase and three-phase systems.

In the recent years, various PFC techniques have been developed with different DC-DC converters [13-18]. The boost converter operated in CCM (Continuous Conduction Mode) is the most popular active PFC topology and the same is presented and described in this research work. It provides many advantages over the other types of DC - DC converters. It has excellent features like smooth input current waveform, which reduces filtering requirements and produces less electromagnetic interference. The boost inductor is connected in series with the source so that the inductor current is the replica of source current which makes the control easier. In order to achieve the objectives of input current wave shaping for power factor improvement and output voltage regulation, a nested control configuration is used with outer PI Controller for output voltage regulation and inner current loop, utilizing fixed or variable frequency current controllers for shaping the input current waveform [19-22].
The PFC techniques for single-phase and three-phase systems developed in this work cover the design and implementation of appropriate DC - DC boost converters using Linear and Non Linear Controllers such as Linear Quadratic Controller (LQC), Hysteresis Controller (HC) and Non-Linear Carrier (NLC) Controller. In order to achieve PFC in single-phase systems, sensing of input voltage, inductor current and output load voltage is required. The schematic of front end active PFC as in Figure 1.1 consists of an outer voltage control loop, where the output voltage is scaled down suitably for comparison with a set reference voltage and the error is processed using a PI controller. The output of this controller is multiplied by the rectified input voltage so as to generate reference current template. In the inner current loop, the inductor current is compared with the above reference current for obtaining the instantaneous error signal, which acts as a modulating signal in the PWM circuit of the DC boost converter, thereby determining the duty ratio and forcing the converter to attain the required control objectives.

Figure 1.1: Single Phase Front End Active PFC Circuit using Boost Converter
To achieve input current wave shaping which makes the power factor nearer to unity and to obtain a regulated DC output voltage, the Boost Converter is followed by a simple Hysteresis Controller (HC) [23, 24]. The major advantages of this control technique are (a) there is no need of compensation ramp as in peak current mode control and (b) the input current is less distorted. In hysteresis current control, two in-phase sinusoidal current references are generated corresponding to maximum and minimum boundary limits and the switch is turned on when the inductor current goes below the lower reference ($I_{L,\text{ref}}$) and is turned off when the inductor current goes above the upper reference ($I_{U,\text{ref}}$) giving rise to a variable frequency control. To achieve smaller ripple in the input current, a narrow hysteresis band is needed. The potency of the HC is proved by the simulation results. In spite of its simplicity, variable switching frequency operation of this controller requires complicated filter design and generates more chattering noise and increased level of EMI on the operational side.

To overcome the above mentioned problems, a fixed frequency Linear Quadratic Regulator (LQR) is considered in this research work. Linear Quadratic Controller defines the optimal pole location of the control Transfer Function of the Boost Converter based on the cost function. The LQR approach is governed by a set of differential equations, the solution of which evolves the paths of the control variables that minimize the cost function. The aim is to determine the optimal control input so as to minimize the quadratic cost function [25]. The matrices $Q$ and $R$ are selected such that closed loop poles are at the desired location. To achieve perfect wave-shaping of the input current, more weightage is given for inductor current in the selection of state weighting matrix $Q$ and gain matrix $K$ is determined by choosing the values of $Q$ and $R$ matrices
appropriately. The control input $u_c$ has been calculated using K matrix which then adjusts the duty cycle of the boost converter that makes the closed loop system to exhibit desired response [26-31]. The effectiveness of the LQR based controller is verified by simulation results. Although it has many advantages, inaccurate values of Q and R matrices can adversely affect the performance of the system.

In most of the PFC circuits, sensing of input voltage, input current and output DC voltage is essential for reference current generation. This requires more number of sensors which entails additional complexity. The proposed alternative method with Non Linear Carrier Controller eliminates tedious calculations [32-34] and desired performance can be achieved without input voltage and current sensors. In this method also, the DC output voltage is compared with the reference voltage and the resulting error signal is processed by a PI Controller. This produces an actuating signal for the carrier generator from which a periodic non linear parabolic carrier is generated. Further, the switch current is sensed and the integral of the switch current is compared with the non linear carrier waveform and the resulting error signal activates a flip flop circuit for driving the required PWM signal for current wave shaping.

1.3 Active Power Factor Correction for Three Phase Systems

Since most of the high power equipments receive electrical power from three phase supply, the power quality issues can be handled by incorporating three-phase active PFC at the front end [35-41]. Accordingly, this work includes power factor correction of both single phase and three phase systems. The analysis and modelling which are considered for single phase system are extended for three phase systems also.
In order to improve the power factor by input current wave-shaping and to regulate the output voltage, the modular boost converter topology as shown in Figure 1.2 is employed which includes three individual diode rectifiers and boost converters. The DC output voltage is regulated using an outer PI controller and the input current wave shape in each phase is improved by three individual linear or non linear controllers. The proposed modular configuration has been substantiated to be advantageous compared to other topologies [42- 47]. The major advantage of the proposed modular boost converter is module loss operation. Since this modular converter includes three separate single phase modules with common load, the continuity of supply can be maintained as a two-phase/single - phase configuration in case of failure of one/two modules, or even when any one/two phases are disconnected [48- 56].

![Figure 1.2: Three Phase Modular Boost Converter](image-url)
In three phase PFC circuits, instantaneous symmetrical component theory and \( pq \) theory are employed for the reference current generation [57- 61] in the inner current loop under balanced supply voltage conditions utilizing Linear Quadratic Controller. The extended versions of \( pq \) theory such as sinusoidal current control method, Fryze current control method and extended synchronous detection methods [62, 63] such as equal current strategy, equal power strategy and equal impedance strategy are used for reference current generation under unbalanced supply voltage conditions with Hysteresis Controller. The Non Linear Carrier Controller is suitable for both balanced and unbalanced supply voltage conditions where there is no need of any separate reference current generation technique. PI controller is retained in the outer control loop for regulating the DC output voltage as a common feature in all the control schemes.

The working of this modular boost converter with linear and non linear controllers under balanced/unbalanced supply conditions is verified and simulation results are obtained using MATLAB/SIMULINK and the same is validated by experimental results using a prototype model controlled by dSPACE processor. The simulation and experimental results show the effectiveness of the controller which ensures well regulated DC output voltage and power factor nearer to unity for a wide range of load variations.

1.4 Objectives of the Thesis

- To perform small signal modelling and stability analysis of the Boost Converter.
- To develop systematic methodology for the analysis and design of Hysteresis Controller (HC), Linear Quadratic Regulator (LQR), Non Linear Carrier (NLC) Controller.
➢ To construct simulation models of single phase boost PFC converter with HC, LQR and NLC schemes for achieving
   - DC output voltage regulation
   - Nearly unity power factor by source current wave-shaping and
   - Servo tracking of output voltage

➢ To develop simulation models of three-phase modular boost PFC converter based on HC, LQR and NLC schemes to achieve
   - DC output voltage regulation
   - Nearly unity power factor by source current wave-shaping and
   - Servo tracking of output voltage
   under balanced/unbalanced supply conditions.

➢ To confirm the feasibility of each of the controllers with experimental results carried out on a fabricated three phase prototype model.

1.5 Outline of the Thesis

The Thesis is organized in the following manner and prepared in 8 chapters

Chapter 1 describes the general background and objectives of the research work. This chapter provides an overview, principles of the single-phase and three-phase active PFC schemes using linear and non-linear controllers, along with their advantages and limitations.

Chapter 2 covers the literature review of various PFC converters with respect to alternative topologies and control techniques. This provides a historical background and recent research innovations in PFC converter control techniques.
Chapter 3 discusses the working, design, small signal modelling and state space analysis of boost converter. The implementation of power factor correction and voltage regulation using boost converter with outer voltage mode and inner current mode control for single phase system is described. A PI based voltage controller achieves regulation of DC output voltage and the input current wave shaping for power factor improvement is achieved with HC, LQR and NLC Controller. Simulation results have been obtained using MATLAB/SIMULINK.

Chapter 4 explores the design and analysis of three phase modular boost converter for PFC and load voltage regulation under balanced and unbalanced supply voltage conditions. The output voltage regulation is achieved with a common PI controller and source current wave-shaping is achieved with HC, LQR. The three - phase reference currents are generated using \( pq \) theory and extended \( pq \) theory for balanced and unbalanced supply conditions respectively. The extended \( pq \) theory includes two schemes such as Sinusoidal Current Control method and Fryze Current Control method. The potency of the controller with various reference current generation techniques is verified by simulation results and is confirmed experimentally with help of prototype developed along with dSPACE 1104 digital signal processor.

Chapter 5 focuses the analysis and working of three phase modular boost PFC converter with symmetrical component theory and extended synchronous detection methods as reference current generation techniques. The synchronous detection method includes Equal Current Strategy, Equal Impedance Strategy and Equal Power Strategy. The simulation results are obtained using LQR and HC for balanced and unbalanced
supply conditions respectively and verified with the experimental results obtained on a prototype model.

Chapter 6 addresses the analysis and working of three phase boost converter with NLC Controller under balanced and unbalanced supply conditions. The control scheme requires less number of sensors and there is no need of reference current generation algorithm involving tedious calculations. Simulation and experimental studies are carried out and results are presented.

Chapter 7 deals with the extended applications of the proposed topology in low power Wind Energy Conversion Systems (WECS) for effective source utilization, power quality improvement related to powering Low Voltage DC (LVDC) grid applications and power factor improvement in case of non linear loads in a conventional AC system.

Chapter 8 wraps up all the results and summarizes the conclusions from the various chapters spanning the thesis. The uniqueness of the work is highlighted and a performance comparison is also made. Finally, the scope for future work and suggestions in this regard are presented.