CHAPTER 1

INTRODUCTION

1.1 GENERAL

In general, due to the intensive use of power converters and other nonlinear loads in industries and by consumers, an increasing deterioration of the power systems voltage and current waveforms are observed. Most of the electronic equipments used in industrial, telecommunication and residential applications are supplied by utility power and almost all the power is processed through some kind of a power converter. Especially, diode rectifiers are commonly used in the front end of DC-link power converters as an interface with the AC line power. The diode rectifiers are nonlinear in nature and consequently generate harmonic currents in the AC line power resulting in low power factor.

With an increasing demand of this kind of equipment at a high rate, line current harmonics have become a significant problem. The harmonic distortion has several detrimental effects including poor power factor, overheating of the distribution system components, increased power losses which result in low efficiency, interference with communication, protection and control circuit. Arrays of passive and active Power Factor Correction (PFC) techniques have been implemented. Passive filters have the demerits of fixed compensation and large size. The active PFC techniques are used in majority of the applications owing to their superior performance. Switched Mode Power Supplies (SMPS) have been employed as an active PFC to
correct poor power factor and to reduce high harmonic current contents. PFC used for input current shaping should emulate a resistor on the supply side while maintaining a regulated output voltage. In the case of sinusoidal line voltage, the PFC must draw a sinusoidal current from the utility; in order to do that, a suitable sinusoidal current reference is generally needed and the control objective is to force the input current to follow this current reference, as close as possible. In the present work, an attempt has been made to design, simulate and implement an array of linear and nonlinear controllers for single-phase and three-phase PFC circuits.

Brkovic and Ćuk (1992), Lin et al (2008), Ranganathan and Umanand (1999) have reported that boost, Ćuk and SEPIC (Single Ended Primary Inductance Converter) converters are especially suitable to implement PFC due to the presence of an input inductor in series with the bridge rectifier. Huai and Batarseh (1998), Costa and Manoel (2004), Lin and Huang (2007) have suggested that DC-DC Ćuk converter can provide voltage polarity inversion with increase or decrease in the voltage magnitude, good isolation, steady state performance, current limit and short circuit protection when compared to boost converter.

1.2 CONTROL OF DC-DC ĆUK CONVERTER

Due to the nonlinear and time varying nature of the DC-DC Ćuk converter, the design of high performance control is a challenging issue. The control should ensure stability in any operating condition with good static and dynamic performance in terms of input voltage disturbances, load changes and parameter variations (robustness). After a pioneer study, a great deal of effort has been directed in developing the modeling and control of DC-DC Ćuk converters. The classical linear approach of modeling relies on the state averaging techniques. The use of the model reduction method for the higher order state model to produce a reduced order model simplifies the controller
design and reduces the computation efforts so significantly that the robust control can be applied to large system where the computation makes robust control design impractical (John Bay 1998). The transfer function of reduced order model can be easily analyzed and the number of sensors needed for the reduced order model are less.

1.2.1 Digital Predictive Controller

Tse et al (2001) have proposed the two-stage approach which includes a PFC stage and a DC–DC stage. The PFC stage shapes the input current, while the DC–DC stage regulates the output voltage. The converter thereby exhibits high power factor and fast output regulation. Two-stage approaches to PFC and power regulation have been proliferated. Disadvantages of two stage approach are more number of component counts and high cost. Due to these limitations, the power supply industry is presently interested in developing single-stage solutions using low cost digital controllers with the desire to reduce the parts count and cost of the conversion stages. Due to the intensification of digital techniques, more complicated control algorithms are implemented in power electronics circuits by the digital integrated chips, such as microprocessors, microcontrollers and Digital Signal Processors (DSP). The main reason being that digital control is appropriate for realizing complicated algorithms since they have many advantages over analog control including programmability, adaptability and better performance.

As a result, PFC using digital control has been explored by many researchers. Average current mode control, which is one of the analog control strategies, is widely used in digital control PFC. In analog average control mode, the average inductor current, $i_L$, is forced to follow the reference current, $i_{ref}$, which is proportional to the rectified voltage, so that Unity Power Factor (UPF) is achieved.
Buso and Mattavelli (1998) have proposed the digital execution of average current mode control, where the following operations have to be carried out; voltage error calculation, voltage regulation using PI controller, reference current generation, current error calculation and inner current control loop execution. All these operations have to be finished within every switching cycle. The DSP is almost tied up by all these operations and calculations. Therefore, the switching frequency is restricted due to the speed limitation of DSP. This disadvantage is common to all existing digital average current mode control in implementation. Efforts have been made to unravel these problems.

Digital current programmed control using predictive algorithm has been described by Chen et al (2003) and the duty cycle, D(k+1), has been calculated based on the value of the present duty cycle, D(k) and sensed inductor current, input voltage and output voltage. The problem is that, the duty cycle calculation requires the duty cycle value in previous switching cycle. Therefore, if there is an error in the calculated value of D(k), this error will affect the value of D(k+1). Bibian and Jin (2001) have reported a DSP based digital predictive deadbeat control that does not update the duty cycle in every switching cycle and the cost of the DSP is also high.

A variable-frequency predictive current control technique, which can achieve the target current in just one switching cycle using boost converter has been proposed by Praneet Athalye et al (2004) and the control algorithms rely on precise high-speed inductor current sensing. The variable switching frequency causes excessive power losses, electromagnetic interference generation and filter design complication. Souvik Chattopadhyay et al (2003), Zhang et al (2004) have proposed the digital control PFC algorithm using DSP. The duty cycles required to achieve UPF
in a half line period are calculated in advance by using a predictive algorithm. A Boost converter controlled by these pre-calculated duty cycles can achieve sinusoidal current waveform. Mather and Dragan Maksimovic (2011) have also implemented boost PFC based on digital pulse width modulator. But in boost converter, the output voltage is always higher than the input voltage and also isolation is not possible.

Abedi et al (2008) have reported a predictive control strategy for the Sheppard–Taylor based PFC rectifier. The input voltage feed forward compensation provides the sinusoidal input current as well as regulated output voltage. The disadvantage of this method is difficulty in controlling the two MOSFET switches. The DSP combined with an analog controller chip UC3854 to achieve PFC has been reported by Ahmed Mitwalli et al (1996). DSP only handles the outer voltage loop and it provides the reference current signal to the analog control IC. The analog IC takes care of inner current loop and provides PWM signals to the switches. However, its control structure is complicated and the cost is also high due to the usage of analog and digital controllers.

In this work, an attempt is made to design a PFC Ćuk converter employing constant digital predictive control scheme using a low cost PIC microcontroller for source current shaping. It consists of two loops an outer voltage loop employing Proportional Integral (PI) controller and an inner current control loop which uses predictive algorithm. The PI controller constants $K_p$ and $K_i$ are obtained from the small signal model of DC-DC Ćuk converter (Erickson and Maksimovic 2004) using Zeigler-Nichols tuning method. The inner current loop implements digital predictive control strategy. In predictive algorithm, duty cycle calculation is based on the sensing of transfer capacitor voltage, input inductor current and rectified voltage. However, implementation of predictive control strategy requires sensing of
more number of parameters. A simple hysteresis controller is designed in order to overcome the above disadvantage.

1.2.2 **Hysteresis Controller**

Recently there has been growing interest in Hysteresis Control (HC) for PFC applications due to its simple implementation (Siyuan Zhou and Gabriel A. Rincon Mora 2006, Castilla 2008, Luca Corradini et al 2009, Kisun Lee et al 2009, Williams et al 2010). Typical advantages of the standard hysteresis controller include simplicity and no limitations in the switch conduction time. The controller is comprised of an inner current loop which uses HC for shaping the source current and an outer voltage control loop using PI controller to regulate the output voltage. The values of PI controller gains $K_p$ and $K_i$ are found by Ziegler-Nichols tuning method.

The input inductor current is continuously compared with reference current waveform. The hysteresis controller turns ON the switch when the inductor current goes below the lower reference and turns OFF the switch when the inductor current goes above the upper reference giving rise to a variable frequency control. The standard hysteresis controller also has some drawbacks. Because of delay, the output voltage ripple is always higher than the fixed window of the hysteretic comparator. The major problem exist in the hysteresis controller is that the switching frequency of DC-DC converters varies according to the hysteresis bandwidth. The variable switching frequency causes excessive power losses, Electro Magnetic interferences (EMI) and filter design complications. To alleviate these problems, it is proposed to introduce constant frequency Reduced Order Linear Quadratic Regulator (ROLQR) control.
1.2.3 Reduced Order Linear Quadratic Regulator Controller

The classic Linear Quadratic Regulator (LQR) approach (K. Ogata 1998 and Leung et al 1991, 1993) deals with the optimization of a cost function or performance index. Thus, the designer can weigh which states are more important in the control action to seek for appropriate performance. The choice of the cost function parameters can be used to minimize the ripple present in the feedback signal. For a continuous time system, the state-feedback law \( u = -Kx \) minimizes the quadratic cost function \( J = \int (x^T Q x + u^T R u) dt \).

The LQR method determines the gain matrix \( K \) by appropriately choosing values of \( R \) and \( Q \) (weight matrix). This feature of LQR control has initiated several researchers to apply successfully this technique in the field of power converters. Leung et al (1991, 1993) have suggested a method to find out the performance indices using pole placement technique. Gezgin et al (1997) have proposed a method for deriving the cost function from an initial controller, which was obtained by frequency domain methods. Optimal control provides a systematic way of designing a LQR controller and the controller design does not depend on the exact location of closed loop poles and is robust to parameter and load variations.

In constant frequency Reduced Order Linear Quadratic Regulator (ROLQR) control, the main objective is to shape the input source current and to regulate the output voltage of the DC – DC Ćuk converter. The converter requires sensing of four state variables, which is not acceptable from practical point of view. In order to reduce the complexity in controller design, the fourth order model of a Ćuk converter is reduced to a second order model. The reduced order model is obtained from the original higher order state-space averaged model of the DC-DC Ćuk converter. The model reduction
technique used is Pade’s approximation technique, wherein the two dominant poles of the system i.e, the input inductor current, $i_{Li}$ and the output capacitor voltage, $v_{Co}$ are retained and the effects of the transfer capacitor $C_{t}$ and the output inductor $L_{o}$ are neglected. Hence it becomes sufficient to regulate these two variables $i_{Li}$, $v_{Co}$ using the ROLQR control strategy.

In constant frequency ROLQR control, depending on weighing matrices, the closed loop system will exhibit a different response. Hence, inaccurate values of weighing matrices will affect the system performance. To solve these problems, nonlinear controller such as Reduced Order Sliding Mode Control (ROSMC) under Current Mode Control (CMC) can be implemented.

### 1.2.4 Reduced Order Sliding Mode Controller

Since DC-DC converters are inherently variable structured, a variable type Sliding Mode Control (SMC) has been proposed by Knight et al 2006. In particular, the converter switches are driven as a function of the instantaneous values of the state variables in such a way so as to force the system trajectory to stay on a suitable selected surface on the phase space called the sliding surface. The most remarkable feature of SMC is its robustness. The SMC method is particularly suitable for handling nonlinear systems with uncertain dynamics and disturbances due to its order reduction property, which relaxes the burden of the necessity of exact modeling. Taking advantage of these properties, SMC has also been applied to the DC-DC Ćuk converters.

SMC for Variable Structure Systems (VSS) offers an alternative way to implement a control action which exploits the inherent variable structure nature of DC-DC converters. In most of the previous research, the sliding surface co-efficients were chosen by trial and error method. Here the
sliding surface co-efficient design is done using the reduced order model obtained by Pade’s approximation model reduction method.

Many studies in the literature have reported the implementation of SMC to different applications (Sanchis et al 2005, Siyuan Zhou et al 2006, Knight et al 2006 and Oettmeier et al 2009). The small-signal analysis of DC-DC converters for SMC control has been addressed by Mattavelli et al (1993), Domingos S´avio Lyrio Simonetti et al (1997), He and Luo (2006). The small-signal analysis of DC-DC converters for SMC control has been addressed by Hung-Chi Chen et al (2010). Small-signal analysis cannot predict the dynamics of a switching converter in a saturated region and can be used optimally for specific conditions only. Lin et al (2005), Cheng et al (2007), Hsu et al (2009) and Cao and Cao (2009) have proposed a fuzzy logic controller based SMC for DC-DC converters. Fuzzy logic systems need a time consuming trial and error tuning procedure and also the control design is purely heuristic.

In SMC, a converter will switch at infinite frequency with its phase trajectory moving on the sliding line. This is undesirable as high switching frequency will result in excessive switching losses, inductor and transformer core losses and EMI noise issues. To solve these problems, hysteresis band with the boundary conditions method has been described by Sira-Ramirez et al (1997), Luis Martinez-Salamero et al (1998), Donoso-Garcia et al (1998), Wai et al (2008) and Castilla et al (2008). Few papers have reported the design procedure of a practical SMC for buck converter (Siew Chong et al (2005). The design approach uses complicated mathematical expressions, and has not provided generalized design procedures applicable to different topologies of switching converters.
Hence, a simple design procedure for finding out the sliding surface co-efficients to implement Reduced Order Sliding Mode Control (ROSMC) is proposed. In this work, an attempt is made to carry out extensive simulation studies for single-phase PFC Ćuk converter to verify the validity of predictive control, HC, constant frequency ROLQR scheme and ROSMC using MATLAB/SIMULINK. Also experimental investigations have been carried out to validate the simulation results.

1.3 CONTROL OF THREE-PHASE PFC ĆUK CONVERTER

Recently, there is a growing awareness of line pollution and deteriorating power factor due to the usage of pervading inductive and nonlinear loads. Although many solutions were offered for single-phase PFC, three-phase active PFC was seldom considered. As all high power equipments derive electrical power from three-phase mains, incorporating an active three-phase PFC front end can contribute significantly in improving the overall power factor and reducing the line pollution. A three-phase single switch PFC topology has been reported by Huang-Jen Chiu et al (2008), Luiz and Ivo (2009), Spiazzi and Lee (1997), Prasad et al (1991), Dalessandro et al (2008). A three-phase single switch PFC topology has the merits of simple control and few components. This type of converter suffers due to discontinuous conduction, causing high current stresses on the power devices.

The widely used PFC rectifier for high-power applications in a three-phase system is Pulse Width Modulation (PWM) six switch Boost rectifier. Advantages of this type of rectifier are high efficiency and good current quality and it permits bidirectional power flow. Three-phase boost rectifiers for power quality problem has been suggested by Souvik Chattopadhyay and Ramanarayanan (2004, 2005), Rajesh Ghosh and Narayanan (2008), Wu et al (2008) and Peng Xiao et al (2008). However, the
three-phase PWM Boost rectifier has more component counts and it is too expensive for medium power applications and moreover, it is not suitable for buck operation.

In modular form, buck and boost rectifiers used for three-phase PFC have been addressed by Mustafa Al-Saffar et al (2009). Usage of buck rectifier modules has been reported by Baumann Kolar et al (2007). It has some attractive features than boost rectifier such as inherent short circuit protection and low voltage output. However, the conduction loss is high in buck rectifier compared to boost rectifier. The three-phase boost rectifier proposed by Pan and Liao (2008) suffers by the lack of isolation between the input and output and the output voltage is always higher than the input voltage.

A derived version of buck boost converter is a Ćuk converter which can invert the voltage polarity and can also simultaneously increase or decrease the voltage magnitude. It has excellent features such as capacitive energy transfer, magnetic components integrability, full transformer utilization and good steady-state performance. It also provides smooth input and output currents due to the presence of inductors in the input and output side (Singh and Singh 2012). A three-phase three-switch topology composed of three modified single-phase single-switch modules has been proposed for PFC by Eric Ho et al (2000) and Sangsun Kim and Prasad N. Enjeti (2003). The advantages of this method are easy control, continuous operation of the system in case of one or two module failure. However, no detailed solution was addressed for unbalanced supply voltages.
Many methods for generating the reference template were proposed by many researchers. Akagi and Nabae (1993), Peng and Lai (1996) and Huang and Jinn (1999) have presented the instantaneous reactive power theory (i.e. p-q theory) for calculating the reference currents. The above algorithm fails miserably if the source voltage is unbalanced. The unbalanced input supply voltages lead to the appearance of even order harmonics at the DC output and odd order harmonics in the input currents. Mahesh Mishra et al (2001) have addressed the extended versions of p-q theory to derive a more general vector equation for calculating the reference currents. Chen and Hsu (2000) described the final formulation of the extracted reference current using synchronous detection methods. It is simple and free from various definitions of the active and reactive powers (Mahesh Mishra et al 2007). Maurfuó Aredes and Edson H. Watanabe (1995) have reported the general equation for deriving the reference current which relates the new concept of instantaneous active and reactive theory, but no detailed information was given for DC bus voltage compensation. Kamnarn and Chunkag (2009), Chunkag and Kamnarn (2010), have proposed the PFC using Ćuk rectifier modules and reference current was generated using power balance control technique.

In this thesis, an attempt is made to develop a three-phase PFC Ćuk converter based on HC, constant frequency ROLQR control, ROSMC schemes for achieving voltage regulation and power factor nearly equal to unity under balanced supply voltage conditions. The instantaneous symmetrical component theory / p-q theory is used for calculating the reference template under balanced supply conditions. Extended synchronous detection methods such as equal current criterion, equal power criterion, equal impedance criterion and extended versions of p-q theory such as constant instantaneous power control method, sinusoidal current control method and Fryze current control methods are used for reference current generation under
unbalanced supply conditions. Simulation and experimental studies using HC scheme are carried out under unbalanced supply conditions.

1.4 OBJECTIVES OF THE THESIS

The main objectives of the thesis are as follows:

- To design the predictive controller, HC, constant frequency ROLQR control, ROSMC for the single-phase PFC Ćuk converter. Simulation models and prototype of single phase PFC Ćuk converter are to be constructed and tested to achieve UPF and output voltage regulation.

- It is also proposed to develop simulation models and a prototype of three-phase PFC Ćuk converter based on HC, ROLQR and ROSMC schemes for achieving voltage regulation and power factor nearly equal to unity under balanced supply conditions. It is also planned to construct simulation and experimental models for three-phase PFC Ćuk converter using HC scheme under unbalanced supply conditions.

1.5 ORGANISATION OF THE THESIS

The thesis is divided into six chapters. The organization of each chapter is briefly described below. Chapter 1 presents the general introduction to the problems and previous investigations reported in the literature. This chapter discusses the principle of PFC and various types of control techniques for PFC in single-phase and three-phase systems. It concludes with the statement of the main objectives of the work presented in the thesis.
Chapter 2 considers the analysis and design of a PFC Ćuk converter employing digital predictive control for source current shaping and output voltage regulation. It is proposed to calculate the duty cycles in advance using predictive algorithm to achieve UPF. Since the proposed algorithm requires only the updating of the duty cycle at every switching instant, a microcontroller is selected for implementation. The duty cycles required to achieve UPF are calculated in advance using predictive algorithm. The proposed control method uses the sampled input inductor current, input voltage and transfer capacitor voltage to calculate the duty ratio for the next switching cycle so that the error between the reference current and the actual inductor current is reduced to zero. To regulate the output voltage, a PI compensator is selected. The design of the outer voltage regulator makes use of the control to output transfer function of the DC-DC Ćuk converter. A prototype was constructed in order to experimentally test the proposed control method.

Chapter 3 focuses on the derivation of state model, reduced order model and design of HC and ROLQR for single-phase PFC Ćuk converter. The reduced order model is obtained from the original higher order state-space averaged model of the DC-DC Ćuk converter. The model reduction method used here is Pade’s approximation technique. Reduced order model makes the implementation of control technique easier and requires less computation time. The closed loop system is comprised of an outer voltage control loop to regulate the output voltage and an inner current loop for source current shaping. HC and ROLQR controllers are used individually for source current shaping and an outer voltage loop using PI controller for load voltage regulation. Experimentation is carried out by using dSPACE (DS 1104) signal processor and the experimental results are compared with the simulation results.
Chapter 4 discusses the analysis and design of ROSMC. The control law for ROSMC is derived by using Filippov’s method and parameters of the PI controller are found by Zeigler-Nichols tuning method. The performance of ROSMC is tested with the dynamic model of the DC-DC Ćuk converter developed using SIMULINK for step load variations. Prototype model is tested by using dSPACE signal processor for the proposed ROSMC algorithm.

Chapter 5 presents the analysis and design of a single stage three-phase PFC Ćuk converter for achieving voltage regulation and power factor improvement for the balanced and unbalanced supply conditions. The proposed scheme uses a single stage converter for both PFC and voltage regulation. The proposed controller guarantees the continuous operation of the system even in case of module failure. The p-q theory is used for calculating the reference template under balanced supply conditions. Extended versions of p-q theory such as sinusoidal current control method, constant instantaneous power control method and Fryze current control method are used for reference current generation under unbalanced supply conditions. The control strategy uses an outer voltage control loop and three inner hysteresis current controllers. A prototype controlled by dSPACE signal processor is set up in order to experimentally test the proposed control method.

Chapter 6 considers the analysis and design of a three-phase PFC Ćuk converter to achieve UPF and output voltage regulation. Two methods of reference current generation techniques are employed. In the first scheme, reference current is generated using instantaneous symmetrical component theory for the balanced supply voltage conditions and in the second scheme, extended synchronous detection methods such as equal current criterion, equal power criterion and equal impedance criterion are used for the
unbalanced supply voltage conditions. The control strategy uses three different types of controllers such as HC, constant frequency ROLQR, and ROSMC individually for source current shaping and an outer voltage loop using PI controller for load voltage regulation under balanced supply conditions and their performances are compared. HC scheme is also extended for unbalanced supply conditions. To validate the proposed method, a prototype controlled by dSPACE signal processor is set up. Simulation results are validated with experimental results.

In chapter 7, a review of the work reported in the thesis and major contributions are presented. This chapter also briefly presents the future work that can be carried out in this area. The results reveal that DC-DC Ćuk converters are suitable for PFC. Three-phase PFC Ćuk converters are viable alternative to boost rectifiers for medium power applications. The proposed method can be used for UPS and SMPS applications.