CHAPTER 1

INTRODUCTION

1.1 GENERAL

The converters in power electronics field converts one form of electrical signal or power source into another form. Generally, converters are be classified into four categories namely rectifier, inverter, chopper and cyclo converter. Converters are used for applications such as rectification of AC to DC, or an inversion from DC to a controlled frequency of AC to supply variable speed AC motor, interfacing DC power source to AC distribution systems such as photoelectric devices, production of DC from AC power for subway applications and controlled DC voltage for speed control of DC motor in various industrial applications etc.

In general, power electronic converters can classified into two sub-categories. They are as follows:

- Indirect Converters - The input is rectified, smoothed by an intermediate DC link capacitor and inverted using an array of power electronic switches.

- Direct Converters - The output is synthesized directly from the input by piecewise sampling of input signal using an array of power electronic switches.
Indirect converter consists of two stages of conversion. The first stage consists of a bridge rectifier, in which, the three phase AC supply is fed to the rectifier so that the rectifier performs the operation of AC to DC conversion. After this conversion, it is fed to the energy storage element which is usually a capacitor. The inverter performs the operation of DC to AC conversion which is provided at the second stage. The intermediate DC-link capacitor used in indirect conversion topologies requires a large space for its installation, which results in bulkier and heavier converter housing. A direct AC-to-AC converter does not contain DC-link capacitor. Converter has a simple structure and many attractive features. The three phase matrix converter is a single stage converter which has nine bi-directional switches, to connect, directly a three phase voltage source to a three phase load. A DC-DC converter is used in power supply systems to provide a regulated output DC voltage.

There are four main types of converters, usually called the Buck, Boost, Buck-Boost and Cuk converters. The buck converter is used for stepping down the voltage level, while the boost converter is used for stepping up the voltage to the desired level. The Buck-Boost and Cuk converters can be used for either stepping-down or stepping-up the voltage level. Normally the DC-DC converters have nonlinear and time invariant system.

The DC-DC converters are type of electronic devices which is used to utilize the DC electrical power efficiently when voltage is transferred from one voltage level to another level. The DC-DC converter is mainly used in a system where a regulated voltage supply is needed to the circuit. The converter controls the DC-link voltage using capacitive energy transfer which results in non-pulsating input and output currents.
1.2 AN OVERVIEW OF POWER FACTOR CORRECTION (PFC)

Obtaining power from the utility power grid can be done in different ways. Most of the electronic equipments connected to the electricity power grid draw high peak discontinuous non-sinusoidal line current rather than smooth sine wave current. This current is composed of number of harmonic currents, which flow through electricity power grid as well as in the equipment itself. For example, single-phase Alternating current-Direct current (AC-DC) bridge rectifier followed by bulk capacitor arrangement draws a discontinuous non-sinusoidal peak current and hence the presence of harmonic currents in the AC-DC rectifier circuit as well as in the power grid to which this converter is connected.

The narrow peak input current occurs due to the short on-time duration of bridge rectifier diodes, as the diodes conduct only when instantaneous input voltage is greater than the output voltage. Thus, a bridge rectifier followed by a bulk capacitor is an inefficient process, which produces a large spectrum of harmonic signals that may interfere with other equipment connected to the same power grid.

1.2.1 Definition of Power Factor

The concept of power factor (PF) is a measure of how well the power from the utility grid is utilized. Its value lies in the range between 0 and 1, and it is computed as the ratio of the real power to the apparent power as given in Equation (1.1).

\[
PF = \frac{\text{RealPower}}{\text{Apparent Power}} \quad (1.1)
\]
Real power is measured in watts and is the power required to do real work. Assuming that the line voltage is perfect sinusoidal, the real power \( P_{\text{real}} \) is defined as the product of the fundamental of the voltage \( V_{\text{rms}} \), the fundamental of the current \( I_{\text{rms}} \) and the cosine of phase displacement \( \cos \Phi \) between these two fundamentals quantities; as given in Equation (1.2).

\[
P_{\text{real}} = V_{\text{rms}} I_{\text{rms}} \cos \Phi
\]  

Since only the fundamental component produces real power, while the other harmonics contribute to the apparent power, the actual power factor is well below 1.0. This deviation is represented by a term called distortion factor and is primarily responsible for the non-unity power factor. The general equation governing the relationship between the real power and apparent power is given by the Equation (1.3):

\[
P_{\text{real}} = V_{\text{rms}} I_{\text{rms}} \cos \varphi \cos \theta
\]  

where, \( \cos \theta \) is the distortion factor.

In general, a measure of harmonic content in a circuit is Total Harmonic Distortion (THD) defined as the square root of the ratio of the sum of all of the squared higher-order harmonics to the amplitude of the fundamental harmonic. THD is defined as given in Equation (1.4):

\[
\text{THD} = \sqrt{\frac{I_{2\text{rms}}^2 + I_{3\text{rms}}^2 + \ldots I_{n\text{rms}}^2}{I_{\text{rms}}}}
\]  

where, \( n \) is the order of the \( n^{\text{th}} \) harmonic current.
Therefore, the objective of a power factor correction circuit is to maintain a negligible phase angle between the input voltage and current and to keep the harmonics content to a minimum level.

1.2.2 Compliance and Regulations of Line Current Harmonics

As early as 1980, the efforts made in the various power quality surveys by various utilities research organizations, corporate industrial campus, and commercial building installations (Adams et al 1990 and Coney 1996) revealed that for better understanding of various power quality problems and to provide cost effective solution to specific problems, monitoring of power quality is the first important step. Considering the various effects of harmonics and its issues, the Electricity regulatory commissions and utilities, all over the world have started imposing penalty for harmonics dumped by the user into the supply lines.

In India, Central Electricity Authority through its statutory body Central Electricity Regulatory Commission has notified Institute of Electrical and Electronics Engineers (IEEE) Std. 519-2014(revised version of IEEE Std 519-1992) through legislature, about the allowable limits for harmonics in the electrical system. It is essential for both the utility and user industry to understand the related standard and know the limits specified therein. The IEEE Standard 519 imposes limits on particular harmonics as well as on the THD of the current waveform. Also it provides the recommended practices of harmonic voltage and current limits in detail.

1.2.3 Need of PFC

The rise in the industrial, commercial and residential applications of electronic equipments has resulted in a huge variety of electronic devices requiring mains supply. These devices have rectification circuits, which is the
prominent reason of harmonic distortion. These devices convert AC to DC power supply which causes current pulses to be drawn from the AC network during each half cycle of the supply waveform.

Even if a single device for example, a television neither draw a huge amount of reactive power nor it can generate enough harmonics to affect the supply system significantly, but within a particular phase connection, there may exist several such devices connected to the same supply phase resulting in production of a large amount of reactive power flow and harmonics in line current (Vlad Grigore 2001).

With improvement in the field of semiconductors, the size and weight of control circuits have drastically reduced. This has also affected their performance and thus power electronic converters have become increasingly popular in industrial, commercial and residential applications. However this mismatch between power supplied and power utilized cannot be detected by any kind of meter meant for charging the domestic consumers, and hence, results in direct loss of revenues (Smruti Ranjan Samal & Sanjay Kumar Dalai 2010).

Moreover, since different streets are supplied with different phases, a 3-phase unbalanced condition may also arise within a housing scheme. The unbalance current flows in the neutral line of a star connected network causing undesirable heating and burning of the conductor (Vlad Grigore, 2001, Smruti Ranjan Samal & Sanjay Kumar Dalai, 2010). This pulsating current contains harmonics which results in additional losses and dielectric stresses in capacitors and cables, increasing currents in windings of rotating machinery (e.g., induction motors) and transformers and noise emissions in many equipment. The rectifier used in the AC input side is the prime source of this problem.
Thus, in order to decrease the effect of this distortion, power factor correction circuits are added to the supply input side of equipment used in industries and domestic applications to increase the efficiency of the power usage (Smruti Ranjan Samal & Sanjay Kumar Dalai 2010).

1.3 POWER FACTOR CORRECTION TECHNIQUES

As mentioned earlier, due to the proliferation of non-linear loads in the distribution systems, current and voltage harmonics are generated in the power grid. Therefore, there is a need to compensate these undesired distortions and power factor in order to minimize their effects on the distribution system and hence to improve its efficiency. Broadly, two methods have come across to eliminate the harmonic and power factor related problems and to enhance the overall performance of the grid or distribution systems, namely passive method and active method. These two methods are presented and briefly discussed in the following sections.

1.3.1 Passive Power Factor Correction

The Passive power factor correction is the simplest and most reliable way of improving the power factor of a load. Passive PFC approaches can be categorized as either AC side or DC side and post rectifier. PFC techniques can either be passive or active. Passive techniques use passive elements such as inductors and capacitors to improve the power factor and to reduce the harmonic distortions (Parto & Smedley 1999). These passive filters can either be placed at the converter’s input AC side, as shown in Figure 1.1(a) or in the intermediate DC link, as shown in Figure 1.1(b) (Redl & Balogh 1995).
Although passive PFC techniques are simple and inexpensive, they have one significant disadvantage, which is their need for bulky capacitors and inductors. The size of these elements makes passive PFC techniques unsuitable for most applications except for low-power applications with narrow line voltage range.

1.3.2 Active Approaches for Power Factor Correction

Active PFC techniques are much more popular than passive PFC techniques. It is a generally accepted standard practice to implement a second active converter at the front-end of an AC-DC converter to perform input power factor correction. In other words, most AC-DC converters are two-stage converters that consist of an AC-DC front-end converter that performs PFC followed by a DC-DC converter that converts the output of the front-end
converter into the desired output DC voltage. In the following sub sections, two stage and single stage active PFC techniques are presented.

1.3.2.1 Two-stage active PFC technique

The Figure 1.2 shows a simplified block diagram of an input rectifier, an active power factor corrector and a cascaded voltage regulator. This approach achieves a very high power factor, provides energy storage, galvanic isolation and accurate output regulation. Each power stage operates independently of one another through each of their respective control circuits. The PFC controller ensures a near unity power factor and the DC/DC controller ensures regulation and guarantees the required output transient response.

![Two Stage PFC Diagram](image)

Figure 1.2 Conventional two-stage power factor correction block diagram

1.3.2.2 Single-stage active PFC technique

However, with the ever-increasing demand on the design engineer to improve the power density of the converter whilst reducing the cost, one is forced to investigate various methods to electrically integrate the circuits, for example the recent interest in Single-Stage Power Factor Correction (SSPFC).
This concept combines the PFC stage and DC/DC converters into a single converter stage which are cheaper and less sophisticated alternative to conventional two-stage AC/DC converters (Lee et al 2007 & Yao et al 2009).

The Figure 1.3 shows the simplified block diagram of Single-Stage power factor corrector. It is operated with only a single controller to regulate the output DC voltage and PF as they just have one converter stage, which for low-power applications (<200 W) has just a single active semiconductor switch (typically a MOSFET). This is in contrast to conventional two-stage converters that have two controllers – one to regulate the output DC voltage and the other to regulate the intermediate DC bus voltage that is the input to the DC/DC converter. Since single-stage converters do not have a controller to regulate the intermediate DC bus voltage, this voltage can vary considerably as it is dependent on the input line and output load conditions.

Unless some means is used to limit this voltage, it can reach to levels of up to 1000V in converters that are operating under high input line and light load conditions. The excessive level and the variability of the DC bus voltage results in the need for components that can handle high peak voltage stresses and that can operate under a very wide range of operating conditions. The commonly used topologies as DC-DC converter in active
PFC converter are boost, buck, buck-boost, sepic or cuk topologies (Rustom & Batarseh 2003, Qiao & Smedley 2001, Garcia et al 2003). Among the different topologies, PFC cuk converter has been utilized in this thesis to maintain the input power factor and to reduce the source current THD to within the permissible limit. The cuk converter offers several advantages in PFC applications, like easy implementation of transformer isolation, natural protection against inrush current at start or overload current and lower input current ripple.

1.4 BRIDGED AND BRIDGELESS PFC CONVERTERS

Now of all the active PFC techniques, mentioned in above with reference to implementing a bridged PFC approach. This means there was a need for a rectifier before the DC-DC converter; however, bridged PFC is not necessarily the best way to achieve high power factors efficiently (Jovanovic & Jang 2005). Bridgeless PFC is a viable solution that is introduced a long time ago, but designers are just now showing more interest in the technology (Jovanovic & Jang 2005). The technology eliminates the need for the rectifier bridge stage of the power factor correction process and uses only the DC-DC converters mentioned to provide the PFC. The non-isolated converters such as buck, boost, buck boost, sepic and cuk are capable of providing bridgeless PFC.

Bridgeless PFC is a beneficial alternative to bridged PFC because the technique reduces the number of semiconductors contributing to switching losses (Fardoun et al 2010). The bridgeless boost over the regular boost reduces overall conduction losses from the elimination of the rectifier (Jovanovic & Jang 2005). However the bridgeless boost requires more complex control circuitry, has a higher startup in-rush current, and increased common mode noise because there is a direct connection of switches (Jovanovic & Jang 2005). The common mode noise however for the
bridgeless buck-boost does not change with respect to the bridged version (Wang et al 2008). One problem that is associated with the bridgeless technique is with input voltage sensing. Some methods taken to compensate for the input voltage sensing are using a line frequency transformer, optical coupler, or resistor divider networks (Wang et al 2008).

All non-isolated topologies are capable of becoming bridgeless with the switches existent within the topologies being utilized in a rectification fashion. The SEPIC and Cuk converters are other possibilities with bridgeless and makes use of the method to excel past their bridged counterparts. For both topologies, they offer easy implementation of transformer isolation, natural protection of inrush current at startup, lower input current ripple and less EMI (Fardoun et al 2010). The converters also allow easy control with PWM signals, which greatly simplifies their cost and size (Fardoun et al 2010 & Ismail 2009). The SEPIC unfortunately, when operated in DCM mode results in a high output ripple and also requires an additional gate drive transformer (Ismail 2009).

The benefits of bridgeless methods are very important in simplifying power supply design because when correcting power factor in one stage, the volume, size and final cost of the converter are reduced (Tsorng-Juu et al 2007). Hence this thesis mainly deal with novel bridgeless PFC cuk converter with driving motor for power factor correction at the AC side and also to reduce the source current THD within the permissible limit.

1.5 DC BRUSHED AND BRUSHLESS MOTORS

The DC brushed motors consist of a permanent magnet or a fixed electromagnet for a field system and a set of armature windings. The current conducted to the windings through a set of slip-rings and brushes. The brushes make mechanical contact with a set of electrical contacts on the rotor
(Commutator), forming an electrical circuit between the DC electrical source and the armature coil-windings. As the rotating armature turns to align with the stationary magnetic field, the stationary brushes come in contact with different sections of the rotating commutator reversing the direction of the current in each set of windings in the rotating armature. The commutator and brush-system form a set of electrical switches, each firing in sequence, such that electrical-power always flows through the armature coil closest to the stationary stator (permanent magnet).

Many of the limitations of the classic commutator DC motor are due to the need for brushes to press against the commutator. The drawbacks are as follows:

- At higher speeds, brushes have increasing difficulty in maintaining contact.
- Brushes may bounce off the irregularities in the commutator surface, creating sparks, which limits the maximum speed of the machine.
- The current density per unit area of the brushes limits the output of the motor.
- The imperfect electric contact also causes electrical noise.
- Brushes eventually wear out and require replacement, and the commutator itself is subject to wear and maintenance.
- The commutator assembly on a large machine is a costly element, requiring precision assembly of many parts.
All problems in brushed technology are eliminated in DC brushless motors (also known as BLDC). A brushless dc motor is a dc motor turned inside out, so that the field is on the rotor and the armature is on the stator. The brushless dc motor is actually a permanent magnet ac motor whose torque-current characteristics mimic the dc motor. Instead of commutating the armature current using brushes, electronic commutation is used. This eliminates the problems associated with the brush and the commutator arrangement, for example, sparking and wearing out of the commutator-brush arrangement, thereby, making a BLDC motor more rugged as compared to a dc motor. Having the armature on the stator makes it easy to conduct heat away from the windings, and if desired, having cooling arrangement for the armature windings is much easier as compared to a dc motor.

It introduces the need of an electronic drive controller to generate torque, which means more complex and sometimes expensive systems. The controller can use position information of the rotor, plus the desired direction for the motor, to determine the next coil to which a current should be applied. Some of the designs use Hall Effect sensors to detect the position of the rotor and provide it to the controller.

The other way to measure the back EMF in the undriven coils to infer the rotor position, thus eliminates the need for separate Hall Effect sensors, and therefore are often called “sensorless” controllers. There are basically two possible configurations for brushless DC motors according to their structure: inner-rotor motors and outer-rotor motors. The outer-rotor motors have much more magnetic material than the inner-rotor ones. This means that they are capable of more flux when the identical materials are used in both structures. However, because of its higher rotor diameter, outer rotor motors offer higher rotor inertia and so slower acceleration, which sometimes can be beneficial to system performance in some applications, such as computer disk drives or cooling fans etc.
1.6 MOTIVATION OF RESEARCH

The mismatch between power supplied and power utilized at the consumer end results in power losses due to the presence of the reactive elements in the load side. This power losses would in turn affect the power factor and also leads to increase in the supply current THD. This scenario affects the supplier with direct loss of revenue. Thus, in order to decrease the effect of this distortion and power loss, power factor correction circuits are added to the supply input side of equipments used in industries and domestic applications to increase the efficiency of power usage as discussed in (Shalini & Murthy 2014).

However, with advancement in the field of semiconductors, the size and weight of components have drastically reduced. This has an impact on the performance of the system and thus power electronic converters have become increasingly popular in industrial, commercial and residential applications. The number of power utility devices present in converter plays a vital role in the switching losses, cost and size of the overall system. It is observed from the literature that with higher number of power utility devices, the switching losses are observed to be higher with higher cost.

Thus, designing a converter with reduced number of power utility devices is a challenging and essential task for improving the overall performance of the system. In recent years, permanent magnet synchronous motors have been widely used in industry, agriculture, transportation and electronics, aerospace and other areas. Due to the increasing requirement of smaller size, higher efficiency, lower maintenance and lower cost, controlling the speed and torque of BLDC motor based on the stator current is a challenging task as described in (Enrique 2006).
1.7  **OBJECTIVES OF THE RESEARCH**

The objectives of the research work are as follows:

1. To design and analyze a novel bridgeless cuk converter for power factor correction and source current harmonics reduction at the AC input side.

2. To implement the proposed cuk converter fed VSI operated BLDC motor with Proportional and Integral (PI) controllers.

3. To enhance the operation of BLDC motor in terms of peak overshoot in DC-link voltage and settling time of the speed, the conventional PI controller is replaced with Fuzzy Logic Controller (FLC).

4. To develop an experimental setup of proposed cuk converter fed VSI operated BLDC motor with electronic commutation.

The main aim of this research work is to design a novel bridgeless PFC cuk converter with reduced number of power utility devices. This work also investigates the functionality of the bridgeless cuk converter with variable DC voltage based on the corresponding speed error. This proposed cuk converter helps in improving the input power factor and to reduce the source current harmonics.

The proposed bridgeless cuk converter has been mainly employed to maintain the DC-link voltage of three-leg Voltage Source Inverter (VSI) based BLDC motor. The main objective of this research work is to analyze BLDC with electronic commutation through efficient controlling methods that enable handling output parameters like peak overshoot and settling time. The control of the front-end PFC converter generates the Pulse Width Modulation (PWM) pulse for the PFC converter switch ‘S’ for DC link voltage control
with PFC operation at AC mains. The PWM pulse for the proposed cuk converter is accomplished by employing two PI controllers.

The first PI controller is a speed controller which is mainly employed to track the reference speed. The output of this PI controller is the equivalent reference DC-link voltage of the proposed bridgeless cuk converter. This reference DC-link voltage and the sensed voltage are processed through the second PI controller which generates the necessary PWM pulse for the proposed cuk converter fed VSI operated BLDC motor in order to improve the power factor and to reduce the source current harmonics at the AC mains.

In order to improve the operation of the BLDC motor, the peak overshoot of the DC-link voltage of three-leg VSI has to be reduced and the settling time of the speed needs to be improved. This can be achieved by means of replacing the DC-link voltage PI controller (second PI controller) with a well-known intelligent technique called Fuzzy Logic Controller (FLC). The simulation results of proposed PFC cuk converter fed VSI operated BLDC motor with fuzzy controller is compared with the conventional PI controller. From the obtained results, the FLC employed for generating the PWM pulse for the proposed cuk converter is found to be superior when compared with conventional PI controller employed proposed cuk converter. Hence, the experimental setup has been developed for proposed FLC employed PFC cuk converter fed VSI operated BLDC motor and measurements are taken to validate the simulation studies.

1.8 ORGANIZATION OF THESIS

The first chapter clearly discusses about the background of Converter design and its functionalities. An overview about the BLDC motor is discussed in this chapter. The importance of Power Factor Correction
(PFC), objective and research contribution have also been discussed in
detailed.

The second chapter deals with the study of existing approaches
available in the literature related to cuk converter design. PFC cuk converter
based approaches have been investigated in this chapter. Moreover, the
techniques related to load side applications like BLDC motor have also been
discussed in detailed. This chapter summary the important points that have to
be carried out to develop an efficient PFC cuk converter design.

The third chapter presents the first proposed methodology called
the ‘Novel PFC Cuk Converter Design’. This chapter discusses in detail about
the overall proposed methodology which utilizes lesser power utility devices.

The fourth chapter discusses about the second proposed
methodology called Novel PFC cuk converter fed VSI operated BLDC motor
applications with PI controllers. The performance of the proposed cuk
converter design is validated with the BLDC motor. The importance of PI
controller has been thoroughly analyzed in this chapter.

The fifth chapter describes the use of proposed PFC cuk converter
for BLDC motor with fuzzy logic based controller. This work explains the
utilization of the fuzzy logic approach for minimization of settling time and
speed error.

The sixth chapter discusses about the experimental results and
performance evaluation. This chapter evaluates the overall performance of the
proposed approaches based on the experimental verification.
The seventh chapter concludes the thesis with the findings from the proposed approaches. Moreover, the future scope for enhancement is also discussed in this chapter.

1.9 SUMMARY

This chapter is started with fundamental information about the converters. Then it is followed by an overview of the power factor correction and need for the power factor correction in motor application is briefly analyzed. A brief overview of the power factor correction techniques, bridged and bridgeless PFC converters and DC brushed and brushless motor are also discussed in this chapter. Also the motivation, objectives, contribution and organization of the present research work have been discussed.