CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Power electronics is the technology of controlling, conditioning and conversion of electric power from its available form into the desired output form, using high efficiency switching mode electronic devices for a wide range of applications. This technology covers the areas of power converters, power inverters, power semiconductor devices, converter circuits, electrical machines drives and advanced control techniques. Power converter is a device used for converting the AC (alternating current) into DC (Direct current). Adversely, Power inverters is an electronic device or circuitry used for converting DC (Direct current) to AC (Alternating current). Power semiconductor devices such as diodes, MOSFETs, IGBT, SCR, Thyristors, GTO etc., are used as switches or rectifiers for controlling the energy transfer in the power electronic systems.

In this era, the rapid revolution in power semiconductors devices has augmented the employment of power electronic system in the electrical and electronics appliances and there is a great concern towards the improvement of power quality. But the power supplies present in the non-linear loads such as UPS, rectifiers, arc furnaces, electric drills, industrial electronic equipment, VFD’S, DC Motor drives, etc., results in low power factor and introduces harmonics. These harmonics leads to several glitches like noise, heat dissipation, voltage distortion etc., and thereby degrade the performance of the power system, by reducing the efficiency.

Also the non-linearities present in the DC-DC converters is a challenging one, which results in oscillations, noise, overshoot etc., Thus, this research work focuses on the reduction of harmonic distortion, maximization of power factor (Sreenivasa Reddy Mula 2013) for generating power for medium and high power applications, elimination of overshoot, increasing the sensitivity to parameter variations and achieving steady state stability in the power conversion devices like converters and inverters.

1.2 INTRODUCTION TO POWER ELECTRONICS

Power electronics in electrical engineering is the association of Power (electric power), Electronics and control systems, in which power engineering deals with the rotating and static power apparatus for the generation, conveyance and dissemination of the electric power, whereas electronics deals with the investigation of solid state semiconductor power devices and circuits for power conversion. Thus power electronics is a discipline of utilizing the solid state power semiconductor devices for manipulation and conversion of electric power. The Mercury Arc Rectifier is the first power electronic device (Wilson 2000) introduced for power control applications in the year 1900.

Later, the power devices like ignitron, metal tank rectifier, phanotron, thyratron, grid controlled vacuum tube rectifier and magnetic amplifier were developed and used until 1950. The first electronic revolution emerged in the year 1956 with the development of SCR (silicon controlled rectifier) or Thyristor by Bell Lab’s. The second electronic revolution originated in 1958 with the commercial grade Thyristor developed by the General Electric Company (GE). In the modern era, different kinds of power conversion techniques and power semiconductor devices originated as a power electronics revolution. An introduction to various power conversion techniques, total harmonic distortion and power factor correction, which plays a vital role in this thesis are described in the following section.

1.3 POWER CONVERTERS

Power semiconductor devices (Meenakshi Mataray 2012) are realized as the heart of the modern power electronic circuits. They act as switches in the power electronic circuits which does not have any mechanical movements for converting the power from the available form into preferable form. Such power conversion devices are DC-to-AC (inverter), DC-to-DC (chopper), AC-to-AC at the same frequency (AC controller) or different frequencies (Cyclo-converter) and AC-to-DC (rectifier). Since this research work focuses on converters and inverters for generating power, the concepts of converters and inverters are discussed as follows.

1.3.1 DC-DC Converter (Chopper)

A DC-to-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. It belongs to a class of the power converter. There are three types of DC-DC converter. They are

- Boost Converter
- Buck Converter
- Buck-Boost Converter

The above mentioned converters operate in two types of conduction modes, namely Continuous-conduction-mode (CCM) and Discontinuous-conduction-mode (DCM). In Continuous-conduction-mode (CCM), the inductor current never goes to zero between the switching cycles. In Discontinuous conduction mode (DCM) the inductor current goes to zero during the part of the switching cycle. This research focuses only on the continuous conduction modes of the DC-DC converters.

1.3.1.1 Boost Converter

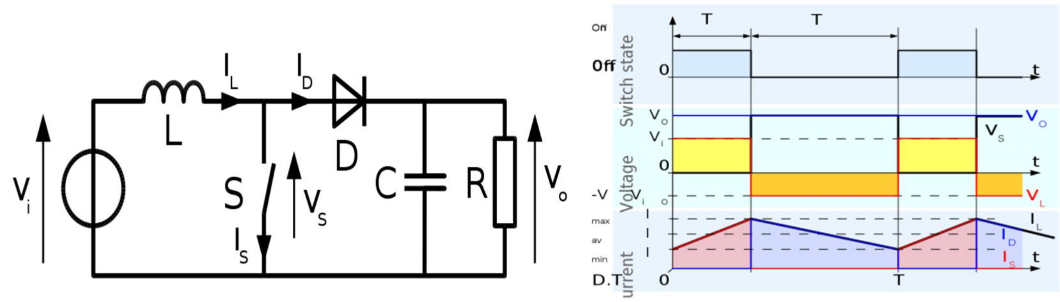
A boost converter (or) step-up converter (Hasaneen & Mohammed 2008) is a kind of DC-to-DC power converter which produces the output voltage always greater than the input voltage. The basic principle that motivates the boost converter is the property of an inductor to resist variations in current by generating and rescinding the magnetic field. When the switch S is closed, the current across the inductor is increased and energy is accumulated in the inductor. When the switch is opened, the energy accumulated in the inductor is transferred to the load through the diode D_1 with a drop in inductor current (I_L). A schematic of a boost converter with its voltage and current waveform in continuous mode are shown in Figure 1.1.

The average output voltage is given by

$$V_o = V_i \left(\frac{1}{1-D}\right) \tag{1.1}$$

Where 'D' is the duty cycle and is given by,

$$D = 1 - \frac{V_i}{V_o} \tag{1.2}$$



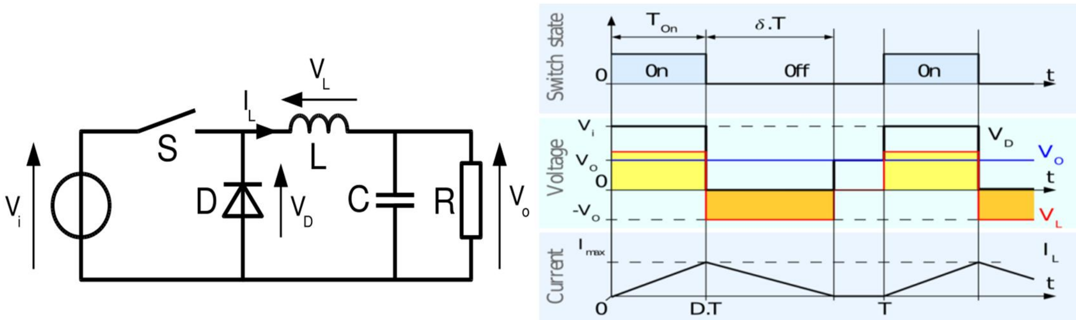
(a) (b)

(Source: Wikipedia)

Figure 1.1 (a) Schematic of a boost converter (b)Voltage and current waveform of Boost converter in continouous mode

1.3.1.2 Buck Converter

A buck converter is a current step up and voltage step down converter. It produces an output voltage always lesser than the DC input voltage. When the switch S is closed, the diode gets reversed biased, causing the inductor current to increase linearly and the corresponding voltage is given by, $V_L=V_i-V_o$. Because of this, there is no current flow from the inductor to load. If it is opened, the diode gets forward biased, causing the inductor current to fall and the voltage is such that, $V_L=-V_o$. A schematic of a buck converter with its Voltage and current waveform in continuous mode is shown in Figure 1.2.



(a) (b)

(Source: Wikipedia)

Figure 1.2 (a) Schematic of a Buck converter (b)Voltage and current waveform of Buck converter in continuous mode

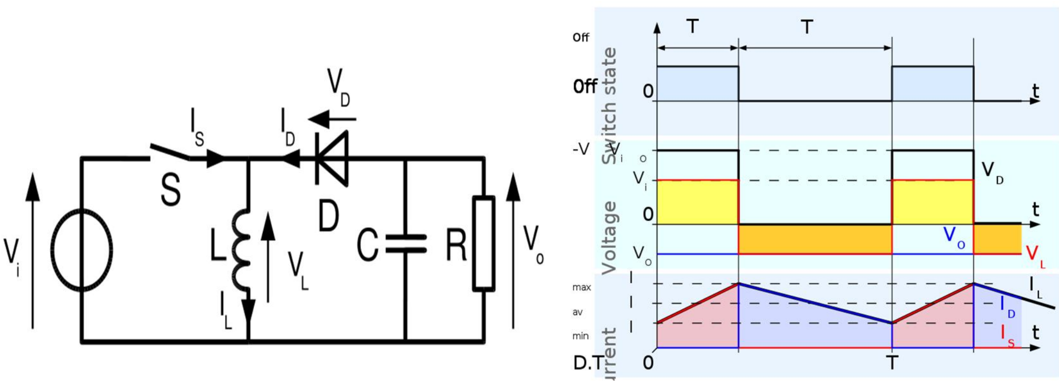
The duty cycle is given by

$$D = \frac{V_o}{V_i} \tag{1.3}$$

From this equation, it is observed that the output voltage significantly differs with the duty cycle for a given input voltage.

1.3.1.3 Buck-Boost Converter

The buck–boost converter is a type of DC-to-DC converter that has both buck (step down) and boost (step-up) operation. This inverted output converter produces the output voltage which is greater or lesser than the input voltage. When the switch is closed, the input voltage is directly connected to the inductor and the energy is accumulated in the inductor. During this time, the capacitor in the circuit provides energy to the load. When it is opened, the inductor is directly connected to the output load and the capacitor provides energy. The schematic of a Buck-boost converter with its Voltage and current waveform in continuous mode is shown in Figure 1.3.



(a) (b)

(Source: Wikipedia)

Figure 1.3 (a) Schematic of a Buck-Boost converter (b) Voltage and current waveform of Buck-Boost converter in continuous mode

The output voltage is given by

$$V_o = V_i\left(\frac{D}{D-1}\right) \quad (1.4)$$

The duty cycle is given by

$$D = \frac{V_o}{V_o+V_i} \tag{1.5}$$

1.4 POWER INVERTERS

The inverter is an electronic device or circuitry that converts DC (Direct Current) to AC (Alternating Current). In power electronics, the Inverter signifies a class of power conversion circuit that converts a DC voltage source or current source, to convert into AC voltage or current. Typical Applications are HVDC, UPS, Traction and Industrial (induction motor) drives. Basically the inverter is categorized into two types. They are Voltage Source Inverter (VSI) and Current Source Inverter (CSI). In Voltage Source Inverter (VSI) the DC voltage is maintained constant; conversely in current source inverter (CSI), the current is maintained constant.

Nowadays, many industrial applications demand for medium to high voltage for their operation. But it becomes difficult when single power semiconductor switch is connected to medium voltage grids. So, Multi-level inverters are established to assist high power and high voltage conditions. Multi-level inverters are nothing but the adaptation of the basic bridge inverters.

1.4.1 Multi-level Inverters (MLI)

The Multi-level Inverter (MLI) (Vinodkumar & Hariprasad 2014) is a capable inverter topology for high power and voltage applications. It synthesizes different DC voltage levels to generate a stepped AC output that approximates the pure sine waveform. It has the advantages such as lower switching frequency, lower harmonic distortion, low switching losses, reduction of stress, lower voltage ratings, high efficiency and high power quality waveforms.

Features of Multi-level Inverter (MLI)

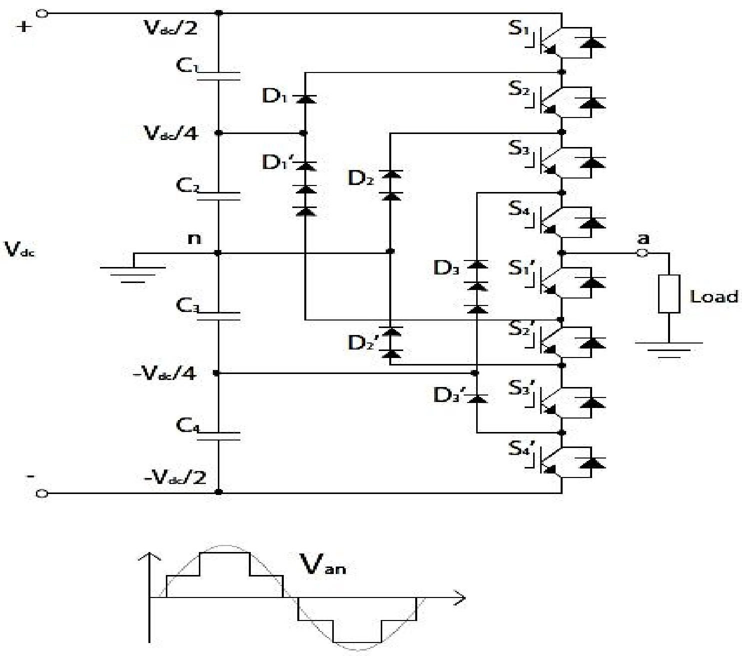
- It has the least number of switching devices.
- It endures very high input voltage for high power applications.
- Each switching device has a lower switching frequency.

Types of Multi-level Inverter

The Multi-level inverter is classified as follows:

1.4.1.1 Diode-clamped (or) Neutral Point Multi-level Inverter

Diode-clamped Multi-level inverter uses diode as a clamping device to clamp the DC voltage to produce stepped AC output voltage. It provides high efficiency because all semiconductor devices are switched at the fundamental frequency. The applications of the device includes High voltage system interconnections, Static VAR compensation, High voltage DC and AC transmission lines and Variable speed motor drives. Figure 1.4 shows the circuit diagram and the output voltage waveform of the Diode-clamped (or) Neutral Point Multi-level Inverter.

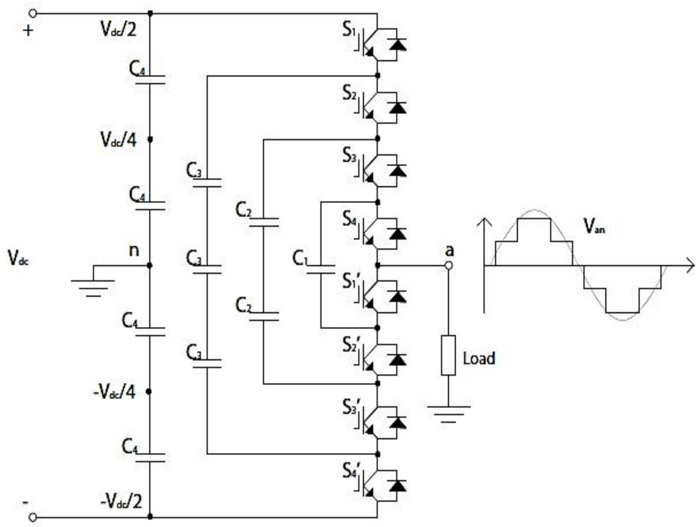


(Source: Andreas Nordvall 2011)

Figure 1.4 Diode-clamped (or) Neutral Point Multi-level Inverter

1.4.1.2 Flying Capacitors (or) Capacitor Clamped Multi-level Inverter

The Flying Capacitors Multi-level Inverter topology (Mahesh kumar et al 2013) utilizes the capacitors as clamping devices, to clamp the DC input voltage to generate the stepped AC output voltage. The size of the voltage steps in the AC output waveform is obtained by the voltage increment between two neighboring capacitors. The applications of the device includes Sinusoidal current rectifiers, Converters with Harmonic distortion capability, AC-DC and DC-AC conversion application, Induction motor control and Static VAR generation. Figure 1.5 shows the circuit diagram and the output voltage waveform of the Flying Capacitors (or) Capacitor Clamped Multi-level Inverter.

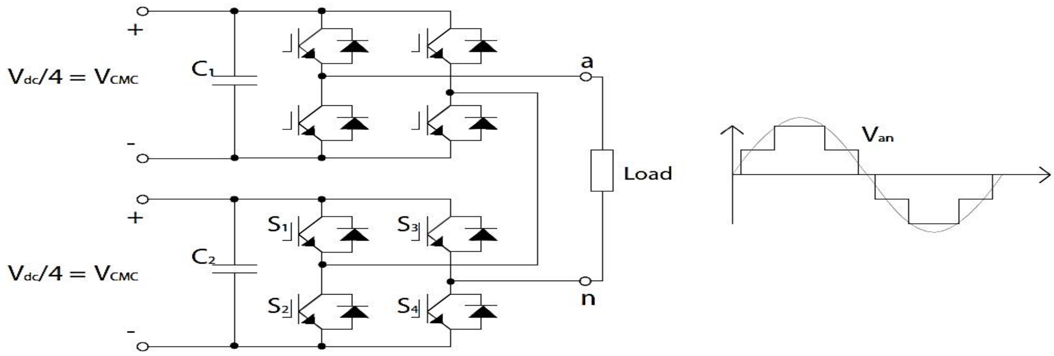


(Source : Andreas Nordvall 2011)

Figure 1.5 Flying Capacitors (or) Capacitor Clamped Multi-level Inverter

1.4.1.3 Cascaded Multi-level Inverters

Cascaded Multi-level Inverters (Zhong Du et al. 2006) uses cascaded H-bridge cells (Full-bridge inverters) with isolated DC-sources, in a segmental setup, to generate the stepped AC output voltage waveform. The H-bridge cells is an integration of capacitor and switch pairs which are provided with three different voltages like zero, negative and positive DC voltages. The applications of the device includes in power factor compensators, electric vehicle drives, motor drives, active filters and frequency link systems. Figure 1.6 shows the circuit diagram and the output voltage waveform of Cascaded Multi-level Inverters.

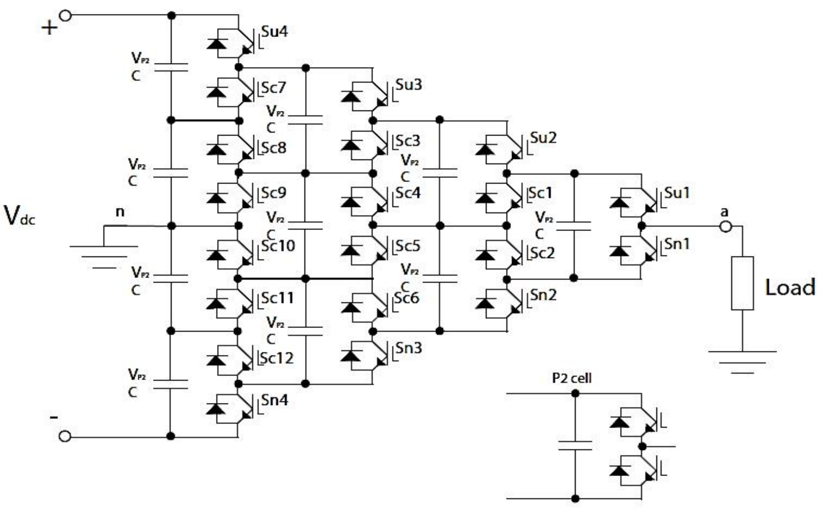


(Source: Andreas Nordvall 2011)

Figure 1.6 Cascaded Multi-level Inverters

1.4.1.4 Generalized P2-cell Multi-level Inverter (GMLI)

The Generalized P2-cell Multi-level Inverter (GMLI) topology depends on the two-level voltage cells known as P2 cells connected in a triangular shape to generate the stepped AC output voltage waveform. The P2 cell is the integration of capacitor and dual switch-diode pairs. This topology has an ability to balance the voltage level by itself devoid of any support from the other circuits. Figure 1.7 shows the circuit diagram of the Generalized P2-cell Multi-level Inverter.

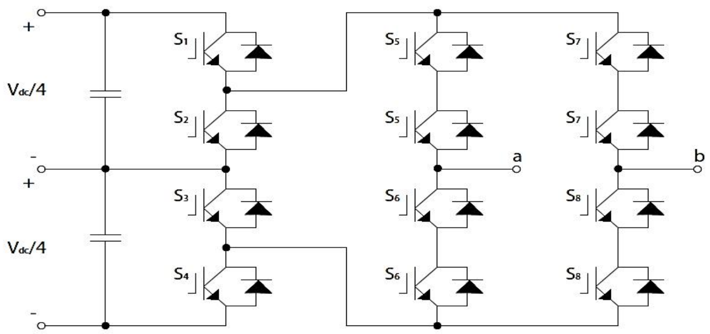


(Source: Andreas Nordvall 2011)

Figure 1.7 Generalized P2-cell Multi-level Inverter

1.4.1.5 Reversing Voltage Multi-level Inverter (RVMLI)

The Reversing Voltage Multi-level Inverter topology (Najafi et al. 2008) is utilized to generate Multi-level stepped positive half-wave voltages with less number of DC sources. The full bridge associated to the inner (or) first inverter, reverses the positive half wave voltage in each half cycle to generate the AC sinusoidal voltage. The full-bridge is controlled by low frequency switching, whereas inner inverter is controlled by the high frequency switching. This topology helps in minimizing the switching power dissipation and switching transitions reduction. Figure 1.8 shows the circuit diagram of the Reversing Voltage Multi-level Inverter.

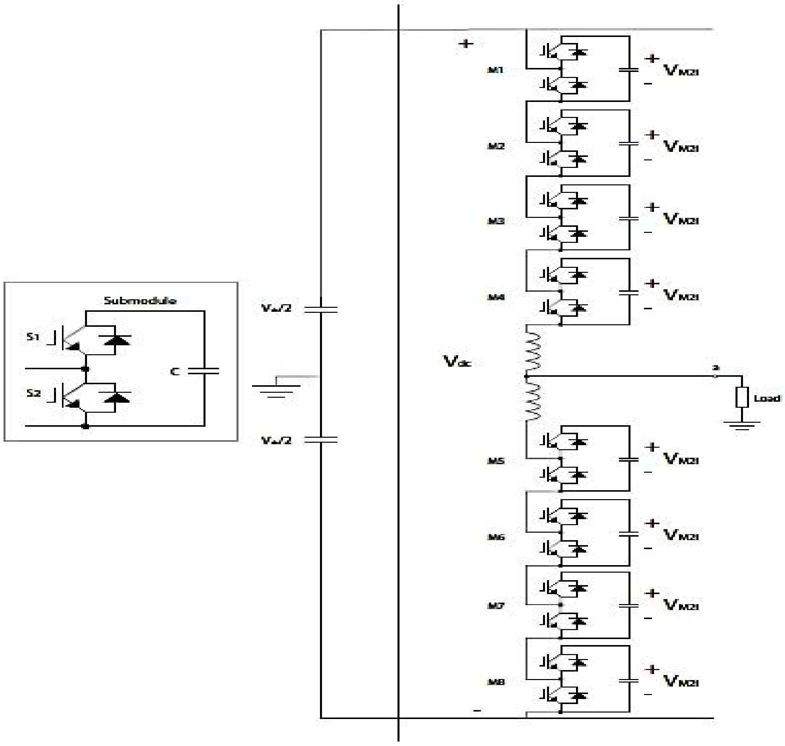


(Source: Andreas Nordvall 2011)

Figure 1.8 Reversing Voltage Multi-level Inverter

1.4.1.6 Modular Multi-level Inverter(M2I)

The Modular Multi-level Inverter (M2I), is the new topology that has sectionalized setup of sub modules, basically half bridge that are coupled and bypassed to produce the AC output voltage. Each sub module has capacitor and dual switch-diode pairs with isolated DC source. It is advantaged by high quality output, Low switching frequency and reduced voltage steps in the switches. Figure 1.9 shows the diagram of the Modular Multi-level Inverter.



(Source: Andreas Nordvall 2011)

Figure 1.9 Modular Multi-level Inverter

1.5 POWER FACTOR AND TOTAL HARMONIC DISTORTION

Power factor (PF) is defined as the ratio between the real power to apparent power (or) cosine (for pure sine wave for both current and voltage) of the phase angle between the voltage and current waveforms. The main concept behind power factor is to measure how efficiently the converter employs the AC input power. It is expressed as

$$\text{Power FACtor} = \frac{\text{Real Power}}{\text{Apparent Power}} \quad (1.6)$$

Real power (P_{Real}) is defined as the product of the voltage fundamental (V_{RMS}), the current fundamental (I_{1_RMS}) and the phase displacement (cos ø) between these voltage and current fundamentals. It is measured in watts. It is given by

$$P_{Real} = V_{RMS} I_{1\_RMS} \cos ø \qquad (1.7)$$

Apparent power (P_{App}) is the product of the RMS(Root mean square) voltage (V_{RMS}) and RMS(Root mean square) current (I_{RMS}).It is measured in volt-amps(Volt-Ampere). It is given by

$$P_{App} = V_{RMS} I_{RMS} \qquad (1.8)$$

By dividing the Equations (1.7) and (1.8),

$$PF = {I_{1\_RMS}}/{I_{RMS}} \cos ø \qquad (1.9)$$

But,

$$PF = K_d K_\theta \qquad (1.10)$$

Therefore,

$$K_d = {I_{1\_RMS}}/{I_{RMS}} \qquad (1.11)$$

Where,

$$K_\theta = \cos ø \qquad (1.12)$$

The distortion factor K_d, is the ratio of the fundamental RMS (Root mean-square) current (I_{1_RMS}) to the total RMS(Root mean- square) current I_{RMS}.

The displacement power factor, K_θ is the cosine of the displacement angle between the fundamental input voltage and the input current.

Total harmonic distortion

Total harmonic distortion (THD) is defined as the square root of the ratio of the sum of all the squared higher-order harmonics to the amplitude of the fundamental harmonic. It is given as

$$THD = \frac{\sqrt{I_{2\_RMS}+I_{3\_RMS}+\cdots\ldots\ldots I_{n\_RMS}}}{I_{1\_RMS}} \tag{1.13}$$

Where 'n' is the order of the n^{th} harmonic current.

The relationship between the THD and the PF for nonlinear load is given by ,

$$PF = \frac{1}{\sqrt{1-THD^2}} \cos \phi \tag{1.14}$$

Therefore, the main goal is to correct the power factor of the input voltage so as to reduce the harmonic content present in the circuit. For power factor correction, different topologies are utilized and are discussed as follows.

1.6 POWER FACTOR CORRECTION TECHNIQUES

Power factor correction topologies (VijethaInti et al. 2013) can be broadly classified into two types based on the type of elements used. They are,

1. Passive Power factor correction
2. Active Power factor correction

Passive power factor correction includes the utilization of passive elements such as capacitors and inductors as filters for the compensation of reactive power in the circuit. But these topologies has some drawbacks. They are

- Expensive and Bulky circuit.
- Lack of Voltage regulation.
- Imperfect Dynamic response.
- Input current shape dependency based on load.

Active Power Factor Correction embraces reactive elements in combination with Active switches, such as IGBTs, MOSFETs and Thyristors, that are switched at a frequency which is preset earlier. This topology improves the power factor of the system in addition to controlled output voltage. Based on the switching frequency of the active devices, active power factor correction can be categorized as:

1. Low Frequency active power factor correction.
2. High Frequency active power factor correction.

In Low Frequency active power factor correction, switching devices such as MOSFETs and IGBTs are used to obtain the ideal power factor and harmonic reduction. But it lags due to the bulky reactive elements and low output voltage regulation.

In high frequency active power factor correction, a diode bridge and a DC/DC converter are used to get unity power factor and to minimize the harmonics.

1.7 MOTIVATION

Power factor correction, harmonic distortion reduction and high output power generation are the challenging issues in the power electronic systems. Power factor is the ratio of active power to the apparent power (or) the ratio of the power drawn from the main supply to the consumed power. It is mandatory to get corrected and to utilize the power efficiently, that is drawn from the supply (Suja C Rajappan et al. 2013). For the power factor correction, several converters were introduced, but their performance in getting power factor nearer to the unity fails. Furthermore, harmonics caused due to the nonlinear relationship between the current and voltage across the switching devices revealed a negative impact over power generation, particularly for high power applications. Additionally, harmonics causes more stress, heat, noise and Electro-Magnetic Interference (EMI) (Najafi et al. 2012). Moreover, the sensitivity to parameter variations is a major concern. Motivated by these facts, this work utilizes a methodology in converters and inverters, for getting high power output with less total harmonic reduction, good power factor, good output voltage regulation and to achieve steady state stability.

1.8 OBJECTIVES

The objective of this research work is to Design and implement a novel converter fed inverter topology for medium and high power applications with minimum Total Harmonic Distortion and a Power Factor close to unity. It is also proposed to develop novel control technique to reduce undesirable sensitivity and to eliminate the overshoot in the system response and hence to produce steady-state output voltage. It is necessary to analyze suitable, efficient pulse width modulation control techniques to achieve minimum total harmonic reduction in multi-level inverters.

1.9 THESIS ORGANIZATION

This thesis is organized into 6 chapters including this introduction (**Chapter 1**). Conclusion of the chapters is presented in this section.

The rest of this thesis is organized as follows,

Chapter 2 briefly discusses the reviews on various Multi-level inverter, power factor correction methods and various compensators for DC-DC converters along with the work done by other researchers.

Chapter 3 focuses on the Bridgeless PFC Boost converter with cascaded H bridge reverse voltage Multi-level inverter.

Chapter 4 deals with the Hybrid Posicast control techniques that has been proposed to solve the sensitivity issues in the Buck-Boost converter.

In **Chapter 5**, the concept of Reverse voltage technique for a novel Multi-level inverter is briefly discussed and also presents the comparison of various PWM control methods.

Chapter 6 draws out the conclusion of various topologies investigated in this thesis and also gives the future work for further development.

1.10 CONCLUSION

This chapter provides the background of this thesis work. A brief introduction about the power electronics is initially presented. The areas that the power electronics study involved are power semiconductor devices, converters, inverters and their control techniques are discussed. The working, advantages, applications and symbol of Power semiconductor devices such as diodes, BJT, MOSFETs, IGBTs are presented. The operation of Power converter circuits and their respective resultant output in converting AC (Alternating Current) to Direct current (DC) are explained. Subsequently, Power inverters circuits, which are responsible for obtaining the AC (Alternating Current) at high power and voltage level from Direct current (DC) are discussed. PWM Techniques which are used for controlling the switches in the circuits for obtaining the controlled AC output voltage are presented. The power factor correction which helps in efficient utilization of power and total harmonic distortion are defined. The power factor correction techniques such as Passive Power factor correction and active Power factor correction methods are discussed. Finally, the motivation behind this research work, objectives and the organization of the research work are presented.