Cascaded Multilevel Inverter Based Transformerless Traction Drive for Railway Applications

A Thesis submitted in partial fulfilment of the requirements for the degree of Master of Technology

in

Electrical Engineering

(Power Control & Drives)

By

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Dedicated to my
beloved parents and
my brother Pratik

National Institute of Technology
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CERTIFICATE

This is to certify that the Thesis entitled, "**Cascaded Multilevel Inverter Based Transformerless Traction Drive For Railway Applications**" submitted by "**Minakhi Behera"** bearing **Roll No. 210EE2099** to the National Institute of Technology Rourkela is a bonafide research work carried out by her under my guidance and is worthy for the award of the degree of "**Master of Technology"** in Electrical Engineering specializing in "**Power Control and Drives"** from this institute. The embodiment of this thesis is not submitted in any other university and/or institute for the award of any degree or diploma to the best of our knowledge and belief.

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ABSTRACT

Electric Railway Traction Drive has been introduced as a solution to the environmental problem caused by the diesel or steam engines. Generally, an AC electrified railway system is supplied with 25kV, 50 Hz AC supply. It is fed to the traction motor after stepping down to three phase, 400 V, 50Hz with the help of a transformer. This magnetically coupled transformer lead to high weight, several losses and reduced efficiency. The railway electric traction requires high voltage operation. This is achieved with the help of multilevel inverter. Among the various multilevel inverters, the cascaded multilevel inverter is best suited for railway traction application because of its modular structure and use of low rating devices. The three phase induction motors are widely used in the railway traction drive because of its low cost and weight, better torque characteristics, high reliability and less maintenance due to the absence of brushes. This thesis presents the application of the cascaded multilevel inverter in the transformerless railway traction drive. Cascaded inverters up to eleven level have been simulated to find that THD increases with the increase in the voltage level. Various modulation techniques- Phase Shifted Modulation, Level Shifted Modulation and Selective Harmonic Elimination techniques were implemented in the multilevel inverters to find out the best modulation techniques among them. It was found that SHE technique resulted in low THD. Thus, an IGBT based-cascaded eleven level inverter with SHE method has been modelled to lower the supply voltage to a level convenient for the traction induction motors. This eliminates the need of a transformer in the railway traction drives and also results in the reduction in the Total Harmonic Distortion of the voltage to be supplied to the traction motors.

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NOMENCLATURE

MLI	**– Multilevel Inverter**
CMI	**– Cascaded Multilevel Inverter**
PWM	**– Pulse Width Modulation**
SPWM	**– Sinusoidal Pulse Width Modulation**
PS - PWM	**– Phase Shifted PWM**
LS – PWM	**– Level Shifted PWM**
IPD	**– In Phase Disposition PWM**
POD	**– Phase Opposition Disposition PWM**
APOD	**– Alternate Phase Opposition Disposition**
SHE	**– Selective Harmonic Elimination**
DC	**– Direct Current**
AC	**– Alternating Current**
IM	**– Induction Motor**
THD	**– Total Harmonic Distortion**
VSI	**– Voltage Source Inverter**
EMC	**– Electromagnetic Compatibility**
GTO	**– Gate Turn Off**
IGBT	**– Insulated Gate Bipolar Transistor**
GA	**– Genetic Algorithm**
NR	**– Newton Raphson**
ICE	**– Internal Combustion Engine**
NPC	**– Neutral Point Clamped**
DCC	**– Diode Clamped Converter**

CHB – Cascaded H Bridge

FC – Flying Capacitor

CCC – Capacitor Clamped Converter

emf – electromotive force

SDCSs – Separate DC Sources

HVDC – High Voltage Direct Current

FACTS – Flexible Alternating Current Transmission system

rms – root mean square

Chapter 1

INTRODUCTION

1.1 Overview

Steam and Diesel engines were considered to be a source of environmental disaster on wheels. Thus, there was a desire to improve the efficiency and reliability of the steam traction drive. This lead to the electrification of the railway system [1]. Electric traction drive has now been considered to be an efficient way of transmitting power to the traction motors that can deliver as much as $2\frac{1}{2}$ times the tractive power output of equivalent diesel traction. It has high power-to-weight ratio which results in faster acceleration and higher tractive effort . Because of improved acceleration, extra stations can be served with less time delay and hence, a blessing to the minor stations. There can be a further increase in the efficiency through regenerative braking by recycling the energy of the slowing down train in the descending gradient. While descending a gradient, energy can also be dissipated by the on-board resistors in the form of heat. The improved overall performance and less vibration results in faster, more comfortable, smoother and quieter journeys for the passengers.

The electric traction drives requires medium voltage and high power operation. This can be achieved with the help of multilevel inverters[2]. The traction transformer steps down the catenary voltage to a level convenient for traction motors. This bulky transformer reduces efficiency; add to weight, cost and floor space. In [3], it is shown that the multilevel inverters can be directly connected to the high voltage supply and can step down the voltage. Thus, it eliminates the need of the transformer.

1.2 Research Background

1.2.1 Multilevel Inverter

The changing scenario of the power demand of the world has lead to the development of various new power converters and new power semiconductor devices. One of them is the multilevel converter technology that has been basically introduced for industrial application having medium voltage and high power requirement. In the power industry, the medium voltage is in the range of 2.3 kV to 6.6 kV and high power range is considered to be 1 – 50 MW [2].

A single power semi-conductor cannot be connected to the medium voltage grids (2.3, 3.3, 4.16, 6.9 kV). Hence, this multilevel converter has emerged as a solution to this [4]. Also, several semiconductor devices can be connected in series or parallel to meet this voltage or power requirement. But due to the differences in their inherent characteristics, they distribute the voltages unevenly causing the voltage of the devices to be greater than their blocking voltage and hence affect the devices to a greater extent. To overcome this problem, multilevel converter has been introduced [5]. The three level inverter introduced by Nabae *et al.* lead the use of the term "multilevel'.

In the late 1960s, the multilevel converter technology was introduced. Several H-bridges were connected in series to give multilevel stepped waveform. This was called cascaded H-bridge converter [2,4,5]. In the same year, a low power Flying Capacitor (FC) converter was developed. According to a patent that appeared in 1975, the cascaded inverter synthesized a staircase waveform from several DC sources [4]. In late 1970s, the Diode Clamped Converter (DCC) was introduced [4]. Later, in 1980s, the DCC was called Neutral Point Clamped (NPC) converter. it is because when it was used in a three level inverter, the mid-voltage was called as neutral point [2]. As in 1981, Nabae , I. Takahashi and H, Akagi presented the first NPC PWM converter [5]. The CHB was again reintroduced for the industrial application in the mid- 1990s [2]. Similarly, FCs were used in medium voltage converter in the early 1990s [2]. Recently, many new multilevel inverter topologies are emerging. Some of them are mixed level hybrid multilevel cells, soft switched multilevel inverters , five level H-bridge NPC (5L – HNPC), three level active NPC (3L- ANPC), modular multilevel converter (MMC), cascaded matrix converter (CMC), transistor clamped converter (TCC), hybrid NPC –CHB , hybrid FC - CHB and many more [2].

There are various modulation techniques of the multilevel converters [6]. Some of them are Sinusoidal PWM, Multicarrier PWM, Selective Harmonic Elimination (SHE), Space Vector Modulation (SVM) etc..

Various attractive features of the multilevel converters are as follows [4,7]:

i. Because of the staircase output voltage waveforms, THD and the dv/dt is lowered.
ii. Efficiency is increased because they can be switched at low frequency.
iii. Common mode voltages are reduced and hence the stresses on the motor bearings are reduced.
iv. The input current drawn by them has low distortion.
v. There exists no EMI problem.

But they have a limitation that with the increase in the level, there is an increase in control complexity and the voltage imbalance problem arises [4]. Even though the low voltage semiconductor devices are used, each device should have its own gate circuit, making it expensive and complex. The design of simple and fast modulation techniques are also one of the technological problems [5].

Some of the applications of the multilevel converters include compressors, fans, grinding mills, rolling mills, conveyers, blast furnace blowers, mine hoists, reactive power compensations, high voltage direct current (HVDC) transmission, Flexible Alternating Current Transmission System(FACTS), wind energy conversion, electric traction , railway traction , Hybrid Electric Vehicle. The multilevel converters are not only for high power applications like HVDC etc but also for low power requirements like in renewable energy sources. These converters can be easily interfaced with the renewable energy sources like photo voltaic cells, fuel cells, wind energy conversion [2, 4, 7]. Application of the multilevel inverters in electric railway traction is a recent development. Thus, power electronics is contributing toward a greener and cleaner world.

1.2.2 Electric Railway Traction Drive

According to [8], the class 1822 dual-voltage locomotive of Austrian Railways (OBB) is the first railway traction drive using a three level PWM converter and inverter. Nabae *et al.* introduced the three level inverter . The three level configuration was popular for the high voltage DC operation requirement as a single semiconductor devices cannot be directly connected to high DC voltage of catenaries.

1.2.3 Induction Motor in Railway Traction Drive

In 20th century, the three phase induction motors (IMs) were considered to be ideal for the electric railway traction because of the steep torque-speed characteristics and regenerative capability. The three phase traction system was first implemented in Germany for experimental purpose. It was also used in the Bergdorg – Thun line in Switzerland in the year 1899 and the Cascade tunnel in U S Great Northern Railroad in the year 1909 [9]. And nowadays, the induction motors are used in the inverter-driven electric train. It can withstand the mechanical shock, high temperature and the vibration due to the harmonics present in the supply voltage of the inverter. Due to the absence of the brushes in IMs, the maintenance is low and the weight is reduced. It has better torque characteristics [9]. These favourable characteristics of IMs served as a motivation to use IMs in the traction drive.

1.2.4 IGBT Based Traction Drive

Earlier, the SCRs were used for the voltage regulation of the DC traction motor. Then, the GTO thyristors were developed for three phase induction motor drive. Presently, IGBTs are replacing GTOs to the performance of the drive. The IGBT based traction propulsion system has lesser losses, better controllability, superior performance, high reliability and modular design as compared to the GTO- based system . The Indian Railways has introduced the first fully IGBT based electric locomotive, WAG-9i, type 31248 in the year 2010 [10].

1.3 Motivation

1.3.1 Electric Traction Drive in Railway System

In the 19th century, the steam and diesel tractions were used in the railway vehicles. These proved to be very expensive and polluted form of traction [1]. As a solution to this, electric traction drive has been introduced in the railway system. Not only is it environmental friendly but also cost effective in terms of the fuel cost. With the help of this electric traction drive, the efficiency of the railway system has improved.

1.3.2 Multilevel Inverter

The railway electric traction requires high voltage operation. This can be fulfilled by the series and/or parallel combination of various semi-conductor devices. But because of the differences in their inherent characteristics, it will damage the devices. This limitation can be overcome with the help of multilevel converter [5]. The output voltage of multilevel inverter has low harmonic content (THD) in comparison to that of a two level inverter as shown in Fig.1.1 and Fig. 1.2.

Also with the help of the multilevel inverter, the transformation of the voltage level can be done without the help of the bulky transformer. This results in transformerless traction drives [2]. Thus, the multilevel inverter prevents the motor damage and thereby increases the efficiency of the drive.

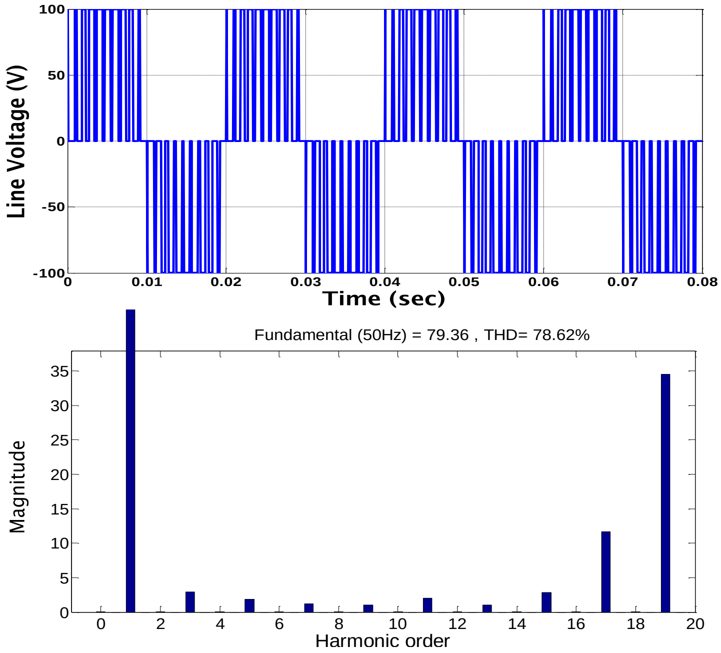


Fig1.1 Line voltage waveform of a two level inverter along with its FFT analysis

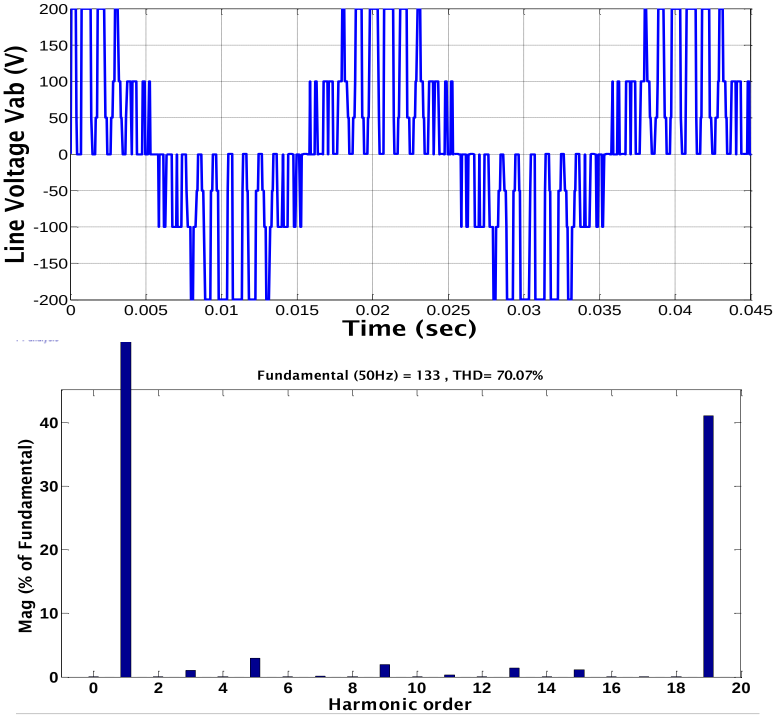


Fig 1.2 Line voltage waveform of a three level inverter along with its FFT analysis

1.3.2.1 Cascaded Multilevel Inverter

The NPC converters requires neutral point control and capacitor voltage balance. With the increase in the output voltage level, the requirement of the clamping diodes increases, the neutral point control and the power circuit become complex [5]. The FC converter balances voltage naturally but the capacitors has to be precharged. Although this converter is modular in structure, but requires large number of flying capacitors as the output voltage level increases and thus adds to the cost. Also the increase in the cell does not guarantee increase in the power rating of the converter [5]. In contrast to this, CHB converters have no voltage balancing problems due to separate DC sources. Its power rating can be increased by the series connection of the cells [2,5]. The NPC converter requires medium-/high voltage devices (like IGCT and medium voltage / high voltage IGBT) whereas CHB converters require low voltage IGBTs. A commercially available CHB converter has more output levels as compared to the three level NPC converter [2]. Its only drawback is the presence of the transformer [5]. But this transformer can be eliminated with the help of cascaded multilevel rectifier and inverter combination. This results in a transformerless system. Thus, it increases the efficiency and reduces the cost of the traction drive. The CHB is suitable for high power applications because of its modular structure, improvement in the power factor reduction in the average device switching frequencies [2].

In CHB converter, each switching devices always conduct for half cycle, hence distributing the current stress equally among the switching devices. It can act as rectifier when it returns the kinetic energy of the motor to the supply if regenerative braking is used and as inverter when it provides supply to motor. The pattern swapping scheme introduced in CHB converter balances voltage naturally [7].

The advantages of the CHB converter can be summarised as below:

i. Modular in structure so packing and circuit layout is easier
ii. No clamping diodes present as in NPC
iii. No voltage balancing capacitors present in FC
iv. Low voltage switching devices required
v. No EMI problem
vi. Less common mode voltage
vii. Less dv/dt
viii. Suitable for medium voltage , high power applications
ix. Separate DC sources eliminates the need of the voltage balancing circuits

x. With the increase in the number of the level, the staircase waveform approximates to a sinusoid

xi. It can work at reduced power level when one of its cell or SDCSs is damaged

xii. Soft switching techniques can be applied to CHB

xiii. No transformer required as in multi-pulse inverters

xiv. It makes Induction Motor more accessible / safer and open wiring possible for most of an induction motor power system.

Because of these advantages, the CHB converter has been used in this traction drive.

1.3.3 Choice of IGBT over GTO based drive

Recently, Insulated Gate Bipolar Transistor (IGBT) based traction propulsion system has been developed for railway system because of its better control ability, superior performance, high reliability, less losses and most importantly , its modular structure [3,10]. Use of IGBT based electric locomotive is found to be more energy efficient than Gate Turn Off (GTO) based locomotives.

1.3.4 Demand of Induction Motor

Earlier DC motors were used as traction motors. But nowadays, three phase induction motors are widely used because of low cost and weight, better torque characteristics, high reliability and less maintenance due to the absence of brushes [8]. Induction motor is smaller in size as compared to the DC motor as shown in Fig. 1.3.

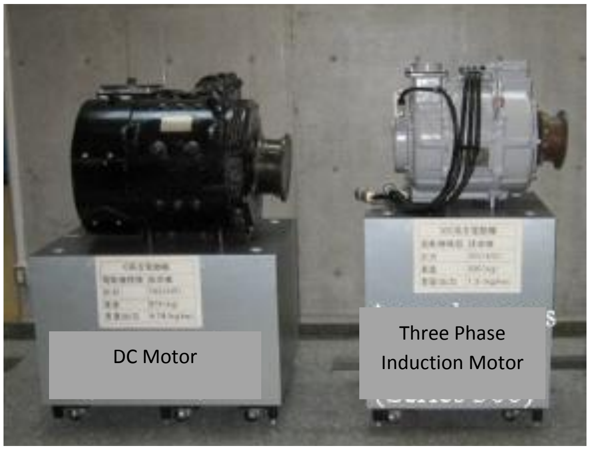


Fig 1.3 DC motor and Induction Motor

1.4 Objective

The objective of the project is to

i. Implement various types of modulation techniques in the IGBT based cascaded multilevel inverter and then finally the best method is to be implemented in the cascaded multilevel rectifier and inverter. the best modulation technique can be obtained after comparing the THD values of each method with one another.

ii. Simulate cascaded three level, five level, seven level, nine level and eleven level inverter to find how the THD is affected by the number of levels.

iii. Design and develop an IGBT based cascaded multilevel inverter drive for electric railway traction.

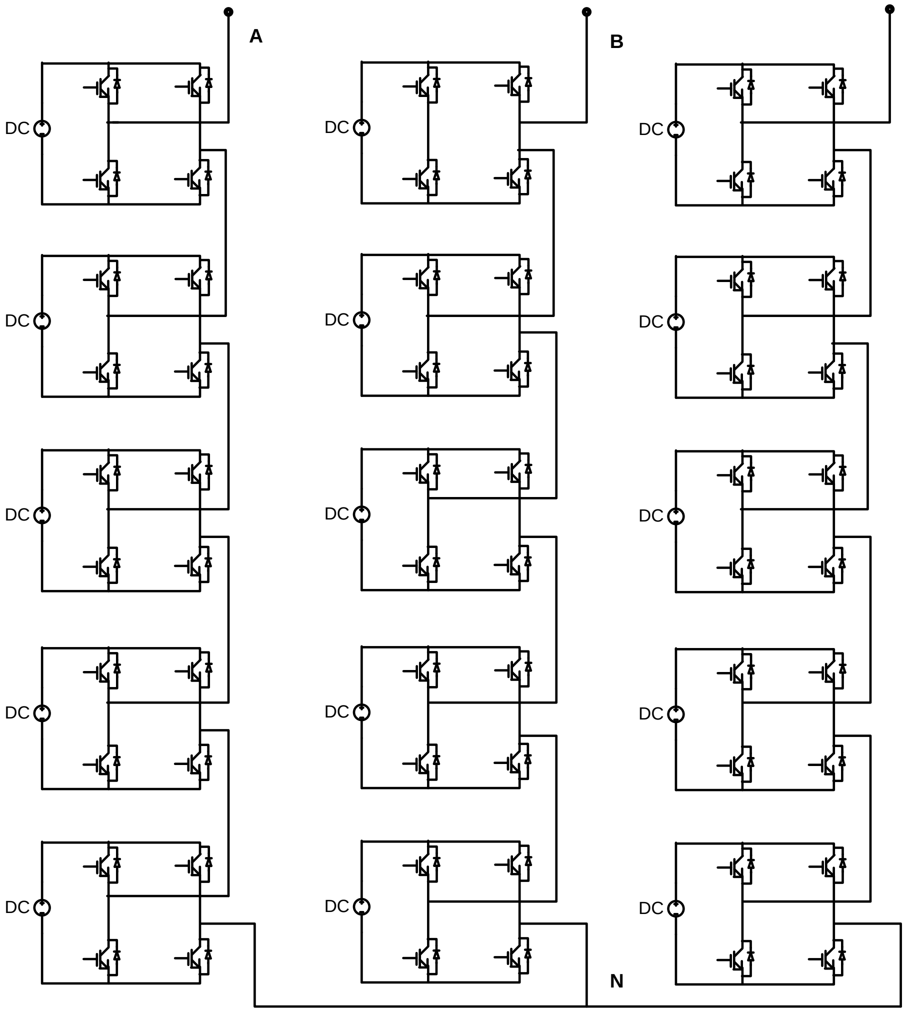


Fig 1.4 Power circuit of three phase cascaded H-bridge eleven level inverter using IGBT

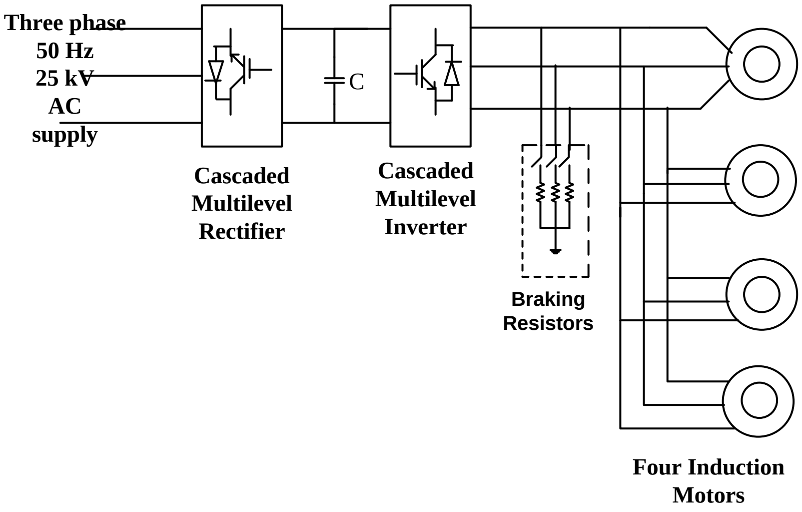


Fig 1.5 Schematic diagram of the drive system of induction motors used in railway traction system

1.5 Thesis Outline

In this thesis, the modelling and the performance of the cascaded multilevel inverter based transformerless railway traction drive has been analyzed. This thesis is divided into six chapters.

Chapter 1 presents the cause for the electrification of the railway system. The introduction of multilevel inverter along with their applications has been discussed. Induction motor drives have been discussed. The advantages and limitations of the cascaded multilevel inverter has been enumerated. The motivation and the objective of this thesis have been presented.

Chapter 2 presents the classical multilevel inverter topologies, their advantages and disadvantages. Various applications of these inverters are also discussed.

Chapter 3 describes the different types of the modulation techniques available for the multilevel converters. A comparison is done to find the modulation technique that is suitable for the cascaded multilevel inverter. Selective Harmonic elimination technique was found to be the best among the discussed modulation techniques and is implemented in the cascaded converter system.

Chapter 4 discusses about the steam traction drive, diesel traction drive and the electric traction drive used in railway systems. The characteristics of the traction motor, the traction mechanics and the speed time curve of a running train is analysed. Preference of induction motor over DC motor is discussed.

Chapter 5 presents the different multicarrier techniques implemented in the three level, five level, seven level, nine level and eleven level cascaded inverter. The modulation techniques and the inverters are compared on the basis of THD. From all the modelled inverters, eleven level inverter is chosen for the drive. Selective Harmonic Elimination Technique was implemented in the eleven level converter systems to reduce the switching losses. This cascaded multilevel inverter is then used in the transformerless railway traction drive and the speed time curve of the train is analyzed. All the simulations are done in MATLAB-Simulink environment.

Chapter 6 draws the conclusion for this thesis and presents the scope for future work.

Chapter 2

MULTILEVEL CONVERTER

MULTILEVEL CONVERTERS

2.1 Introduction

Multilevel inverters comprises of power semi-conductor devices and capacitor voltage sources. These generates stepped or staircase waveforms. The on and off these devices generates voltages in steps which when added gives high voltage at the output. Thus, we get high voltage at the output with low voltage at the semiconductor devices.

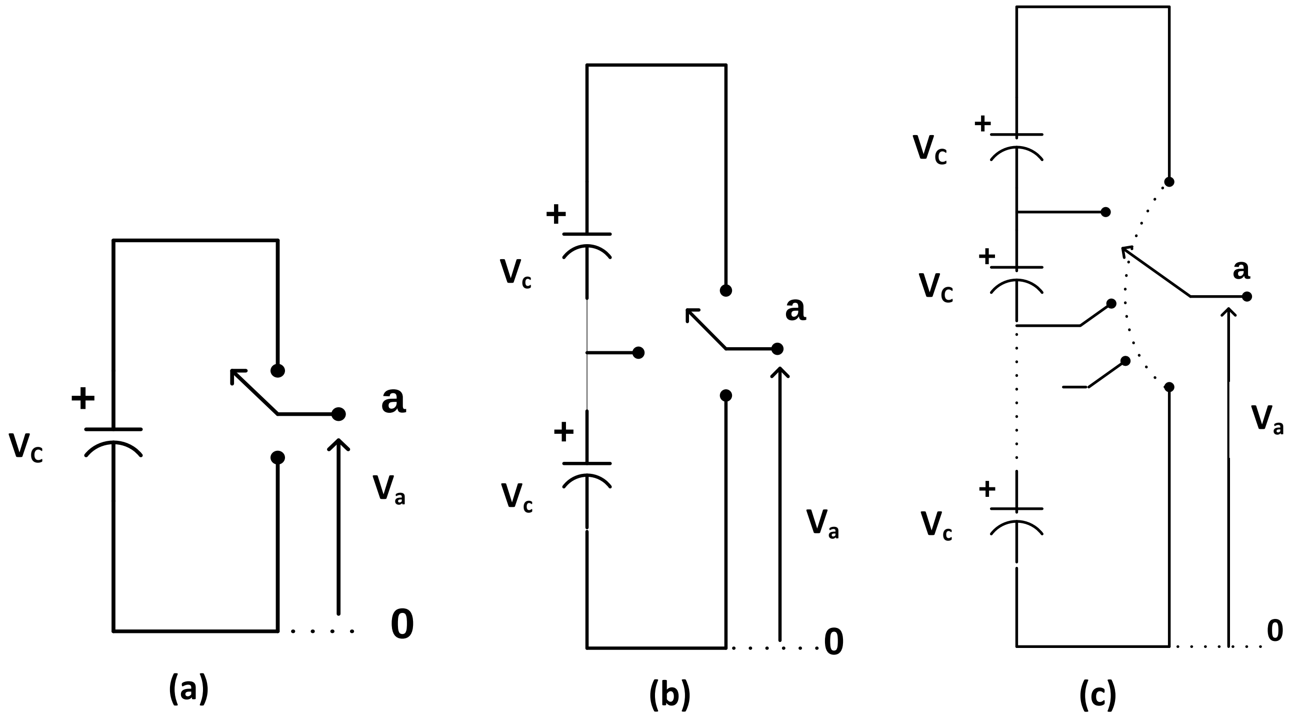


Fig. 2.1 One phase leg of an inverter with (a) two levels (b) three levels (c) n levels

Fig. 2.1 shows the schematic diagram of one phase leg of inverter with different of levels in which the semiconductor device is represented by an ideal switch with several positions.

A two level inverter generates an output voltage with two levels (values) with respect to negative terminal of the capacitor as shown in Fig. 2.1(a) while the tree level inverter generates three level voltages and so on.

Inverter with voltage level greater than two comes under multilevel inverter. The three level inverter was first introduced by Nabae *et al.* it is found that with the increase in the level, the steps increases and the output waveform approaches to be a near sinusoidal waveform. Thus, it reduces the THD with a disadvantage of complex control and voltage imbalance problem.

Some of the remarkable features of the multilevel inverters are [4,7]:

i. Because of the staircase output voltage waveforms, THD and the dv/dt is lowered.
ii. Efficiency is increased because they can be switched at low frequency.
iii. Common mode voltages are reduced and hence the stresses on the motor bearings are reduced.
iv. The input current drawn by them has low distortion.
v. There exists no EMI problem

The multilevel inverters are classified into three types [4,7]:

i. Diode clamped multilevel inverter (Neutral Point Clamped inverter)
ii. Flying Capacitor Multilevel Inverter (Capacitor Clamped Inverter)
iii. Cascaded H-bridge Multilevel Inverter

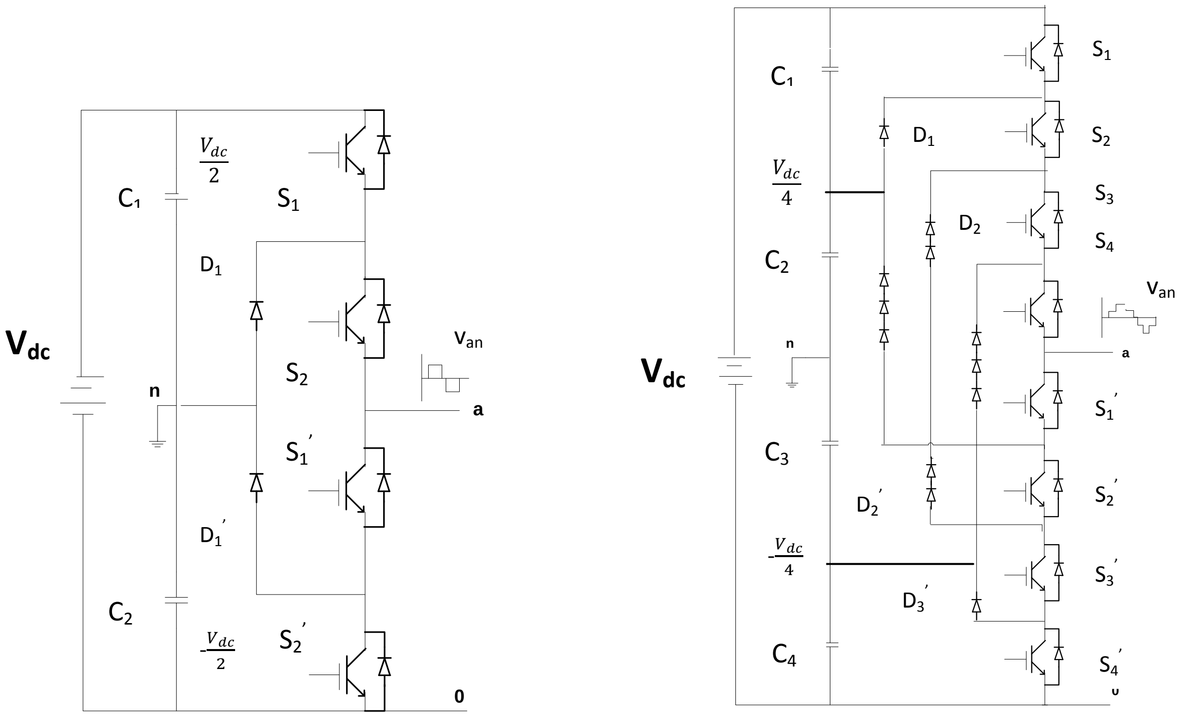
2.2 Diode Clamped Multilevel Inverter

Fig.2.2(a) shows a three level diode clamped inverter in which the two series connected capacitors C_1 and C_2 divide the dc voltage V_{dc} into three output voltage levels v_{an} : $V_{dc}/2$, 0 and -$V_{dc}/2$ by the switching combination as shown in Table 2.1.

The switching state 1 implies the switch is ON whereas state 0 implies that it is OFF.

The two diodes D_1 and D_2' clamp the voltage across the switch to $V_{dc}/2$. When both S_1 and S_2 are turned ON, the voltage across a and 0 $v_{a0} = V_{dc}$. S_1' blocks the voltage across C_1 and S_2' blocks the voltage across C_2. D_1' balances the voltage sharing between S_1' ad S_2'.

The voltage v_{an} is ac whereas voltage v_{a0} is dc. If the output is found between a and 0, then it is a dc-dc converter which has three output voltage levels: V_{dc} , $V_{dc}/2$ and 0.



(a) (b)

Fig. 2.2 Single Phase Neutral Clamped Multilevel Inverter circuit (a) three level (b) five level

Table 2.1 Switching combination for a three level neutral point clamped inverter

Voltage v_{an}	**S_1**	**S_2**	**S_1'**	**S_2'**
$V_{dc}/2$	1	1	0	0
0	0	1	1	0
$-V_{dc}/2$	0	0	1	1

Similarly, Fig. 2.2(b) shows a five level diode clamped converters having four capacitors C_1, C_2, C_3 and C_4. Voltage across each capacitor is $V_{dc}/4$ and each device is required to block a voltage level of $V_{dc}/4$. There are five switch combinations to obtain the output voltage as shown in the Table 2.2.

Table 2.2 Five level Diode Clamped Voltage and Switching States

Output v_{a0}	**Switch State**							
	S_1	**S_2**	**S_3**	**S_4**	**S_1'**	**S_2'**	**S_3'**	**S_4'**
$V_5 = V_{dc}$	1	1	1	1	0	0	0	0
$V_4 = V_{dc}/4$	0	1	1	1	1	0	0	0
$V_3 = V_{dc}/2$	0	0	1	1	1	1	0	0
$V_2 = V_{dc}/4$	0	0	0	1	1	1	1	0
$V_1 = 0$	0	0	0	0	1	1	1	1

Some of the advantages of Diode Clamped Inverter are [2,4,5]:

1. The THD decreases with the increase in the number of levels. Thus avoid the need of filters.
2. It has simple control method for a back-to-back intertie.
3. Since all the devices are switched at the fundamental frequency, the efficiency of the inverter is high.
4. Reactive power flow can be controlled.
5. Capacitors can be pre-charged as a group.
6. Since all the phases share a common dc bus, the capacitance requirements are minimised.

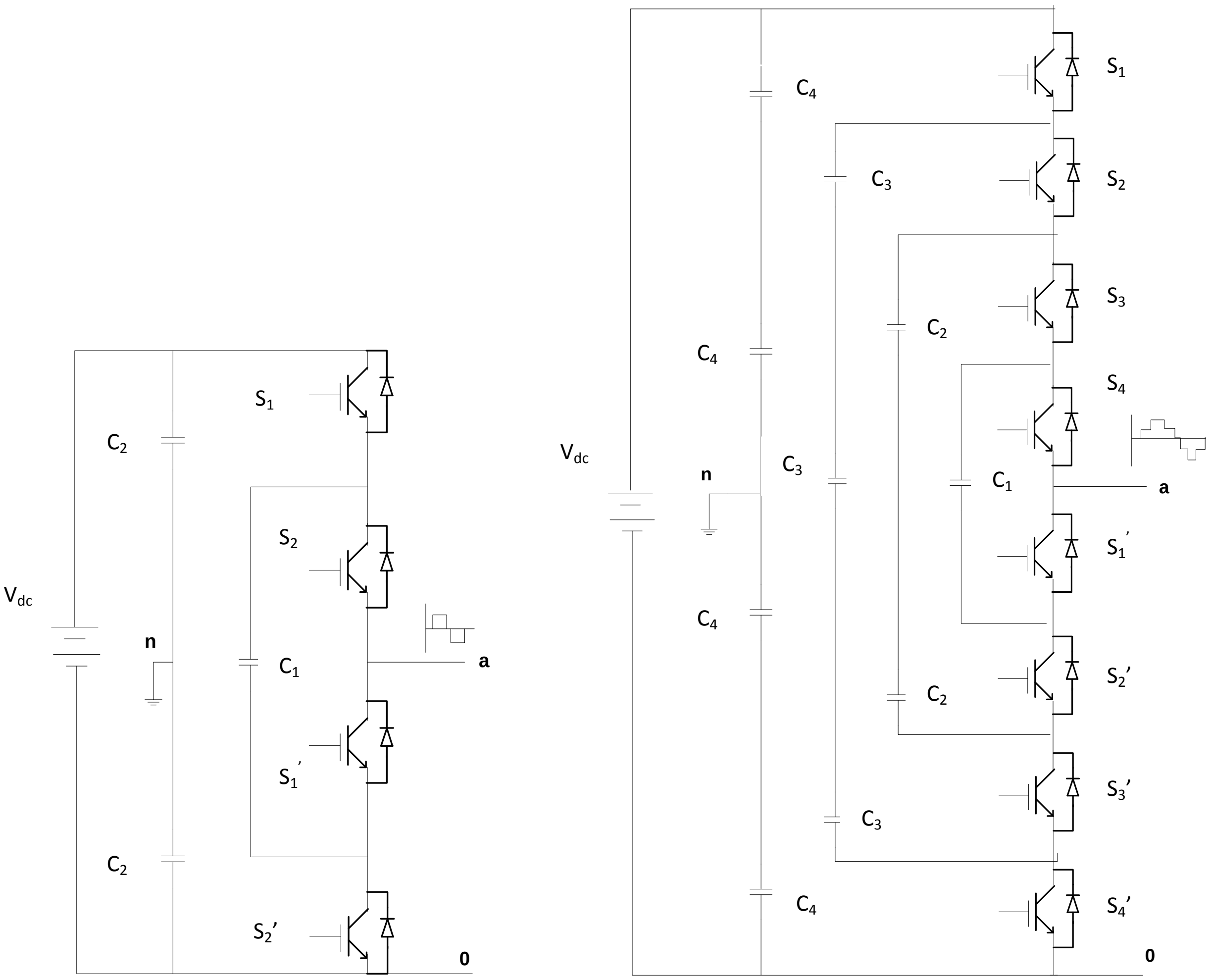
Some of its major disadvantages are:

1. There is a quadratic increase of clamping diodes with the increase in the level.
2. It is difficult to control the real power flow of the individual converter in multi-converter systems as the intermediate dc levels will tend to overcharge or discharge without precise monitoring and control.
3. Even though each active switching device voltage stress is limited to $V_{dc}/(m-1)$, the clamping diodes must have different voltage ratings for reverse voltage blocking.

2.3 Capacitor Clamped Multilevel Inverter:

Fig.2.2(a) shows a three level capacitor clamped inverter. Here instead of diodes, capacitors are used to clamp the device voltage to one capacitor voltage level. The voltage across a and 0 van has three voltage levels v_{an}: $V_{dc}/2$, 0 and -$V_{dc}/2$ by the switching combination as shown in Table 2.3.The switching state ‘1’ denotes that switch is ON and state ‘0’ denotes that switch is OFF.

There are two possible combinations to obtain the voltage level -$V_{dc}/2$.



(a) (b)

Fig. 2.3 Single Phase Capacitor Clamped Multilevel Inverter circuit (a) three level (b) five level

Table 2.3 Switching combination for a three level capacitor clamped inverter

Voltage v_{an}	**S_1**	**S_2**	**S_1'**	**S_2'**
$V_{dc}/2$	1	1	0	0
0	0	0	1	1
$-V_{dc}/2$	1	0	1	0
	0	1	0	1

Let us consider the one leg of the five level inverter as shown in Fig.2.3(b). The dc rail 0 can be considered as the reference point for the output phase voltage. There are various switching combinations to generate the five level voltages. One of the possible combinations is as in Table 2.4.

Table 2.4 Switching combination for a five level capacitor clamped inverter

Output V_{a0}	Switch State							
	S_1	S_2	S_3	S_4	S_1'	S_2'	S_3'	S_4'
$V_5 = V_{dc}$	1	1	1	1	0	0	0	0
$V_4 = 3V_{dc}/4$	0	1	1	1	1	0	0	0
$V_3 = V_{dc}/2$	0	0	1	1	1	1	0	0
$V_2 = V_{dc}/4$	0	0	0	1	1	1	1	0
$V_1 = 0$	0	0	0	0	1	1	1	1

Fig. 2.4 shows the stepped output phase voltage waveform of a flying capacitor inverter.

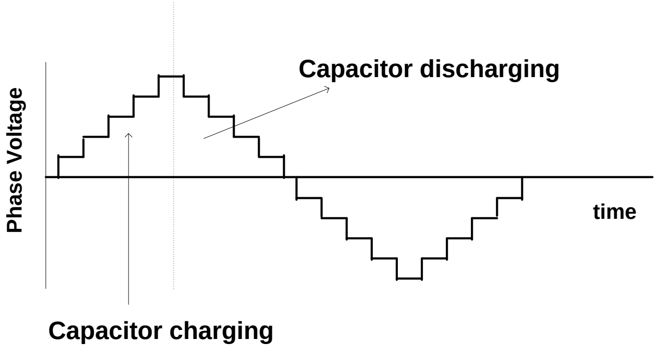


Fig. 2.4 Stepped Output Waveform Of Flying Capacitor Inverter

Some of its advantages can be summarized as follows:

1. Switching redundancy helps to balance different voltage levels.
2. THD is lowered with the increase in the level as in NPC .
3. Both the real and reactive power flow can be controlled.
4. Large amounts of storage capacitors provide ride through capability during power outages.
5. By proper selection of capacitor combination, the capacitor charge can be balanced.

Some of its disadvantages can be summarized as follows:

1. Large numbers of capacitors are required to clamp the voltage. This makes it bulky, expensive and difficult in packaging.
2. Its control is complicated.
3. It is less efficient for real power transmission as the switching frequency and switching losses are high.
4. Precharging of all the capacitors too the same voltage level is complex.

2.4 Cascaded H Bridge Multilevel inverters

It is the series connection of the single phase H-bridge units with separate DC sources (SDCSs). These SDCSs may be batteries, fuel cells or solar cells [1]. Each unit produces three voltages at the output: + V_{dc}, 0 and – V_{dc}. The number of these units is decided by the operating voltage and manufacturing cost [2].

Fig. 2.5 shows a phase leg of a five level cascaded inverter. It consists of two H-Bridge inverter units with two isolated and equal DC sources. When switches S_{11} , S_{21} and switches S_{12} , S_{22} conduct, the output voltage of the H Bridges H_1 and H_2 is $v_{H1} = v_{H2} = E$ and the resultant inverter phase voltage is $v_{AN} = v_{H1} + v_{H2} = 2E$.

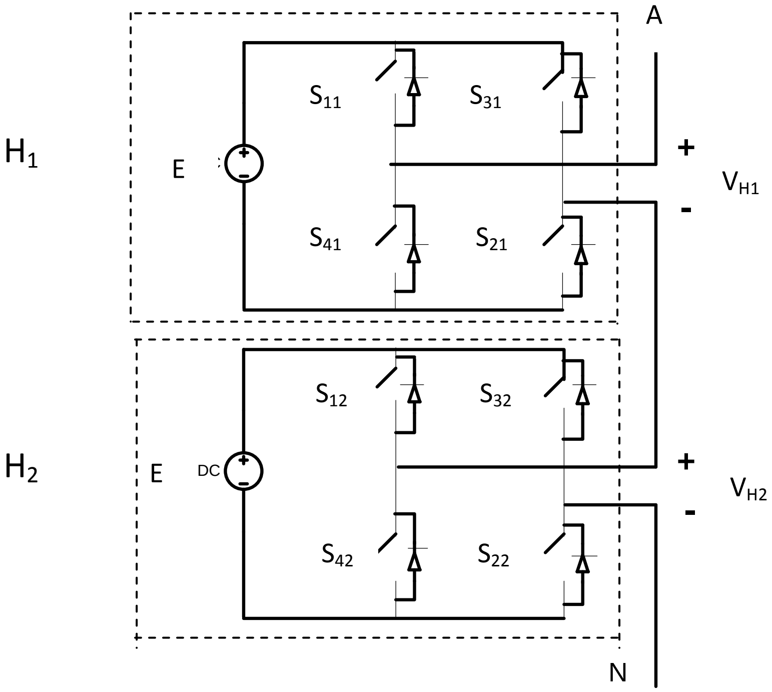


Fig. 2.5 Cascaded multilevel inverter topology

Sometimes, more than one switching state results in the same voltage level. This switching state redundancy provides a greater flexibility for switching pattern design, particularly in space vector modulation technique [2].

The number of the output line voltage level is found by $m = (2H + 1)$ where H is the number of H-bridges in each phase leg. Unlike other multilevel inverters, only odd number of voltage level is obtained in CHB. The total number of active switches used in CHB is given by $N_{sw} = 6(m - 1)$.

Fig.2.6 shows an IGBT based three phase eleven level cascaded inverter which is used in the modeling of the traction drive. Fig. 2.7 shows the output phase voltage waveform of an eleven level inverter.

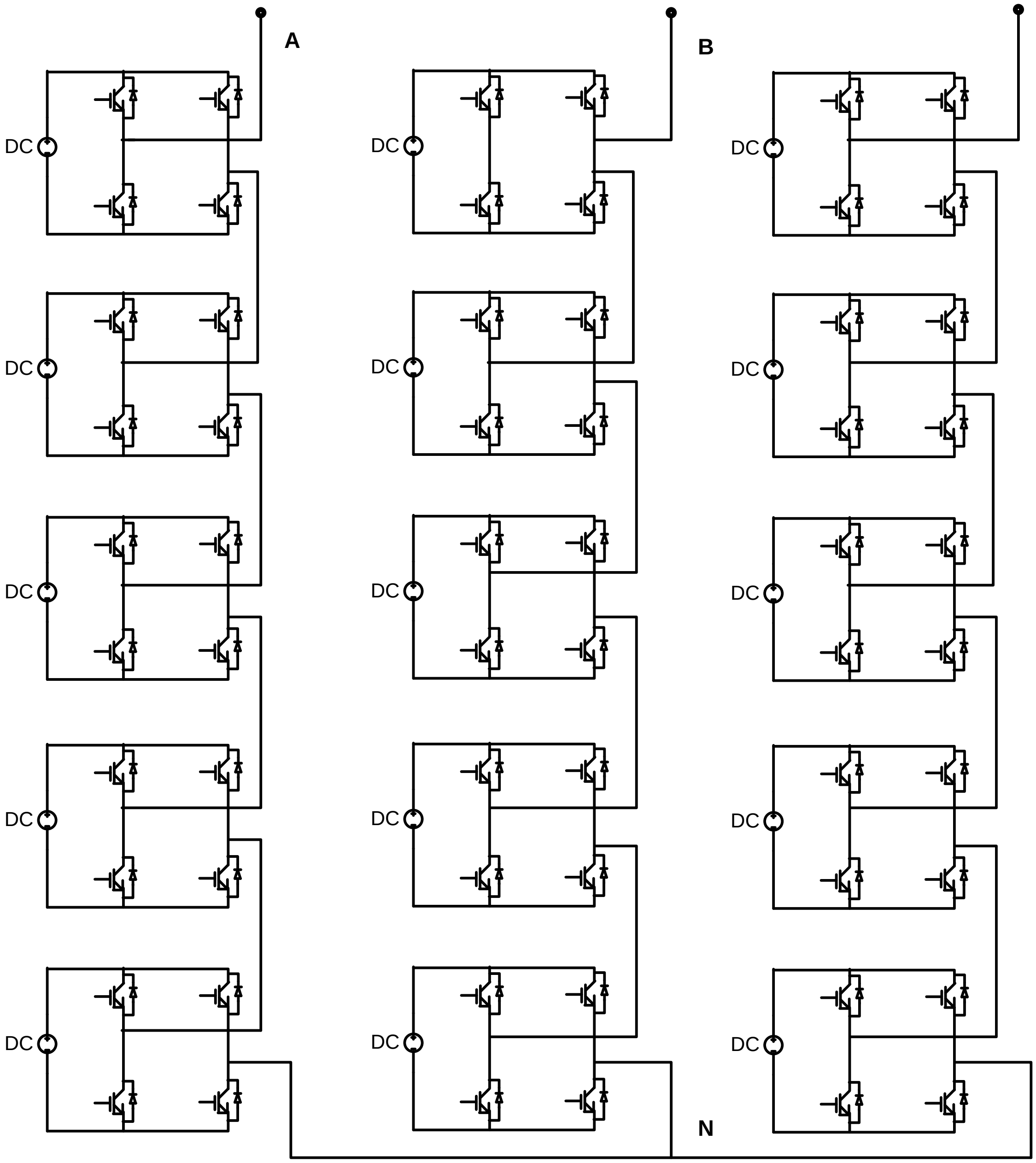


Fig 2.6 An eleven level cascaded inverter

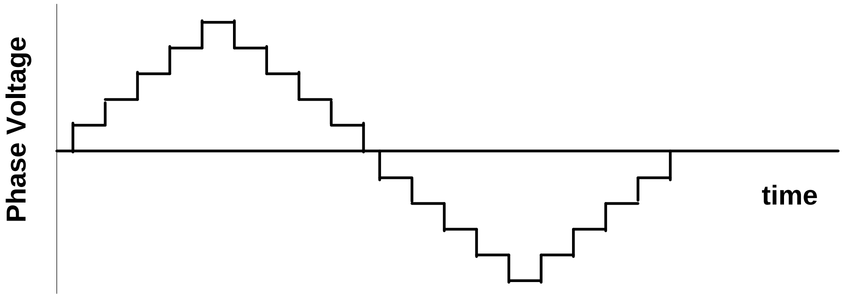


Fig. 2.7 Output phase voltage waveform of an eleven level cascaded multilevel inverter

Some of the advantages of the CHB converter can be summarized as below:

xv. Modular in structure so packing and circuit layout is easier
xvi. No clamping diodes present as in NPC
xvii. No voltage balancing capacitors present in FC
xviii. Low voltage switching devices required
xix. No EMI problem
xx. Less common mode voltage and less dv/dt
xxi. Suitable for medium voltage , high power applications
xxii. Separate DC sources eliminates the need of the voltage balancing circuits
xxiii. With the increase in the number of the level, the staircase waveform approximates to a sinusoid
xxiv. It can work at reduced power level when one of its cell is damaged
xxv. Soft switching techniques can be applied to CHB
xxvi. No transformer required as in multi-pulse inverters
xxvii. Number of possible output voltage levels is more than twice the number of DC sources $(m = 2s + 1)$

Its major disadvantage is the requirements of separate DC sources. It is thus limited to the applications where SDCSs are already present.

In Table 2.5, the three types of multilevel inverter have been compared on the basis of the component requirement.

Table 2.5 Comparison of component requirement per leg of three types of multilevel inverter

Converter Type	Diode-clamp	Flying capacitors	Cascaded inverter
Main switching devices	(m-1)*2	(m-1)*2	(m-1)*2
Main diodes	(m-1)*2	(m-1)*2	(m-1)*2
Clamping diodes	(m-1)*(m-2)	0	0
DC bus capacitors	(m-1)	(m-1)	(m-1)/2
Balancing capacitors	0	(m-1)*(m-2)/2	0

2.5 Applications of Multilevel Inverter

Since the diode clamped and cascaded multilevel inverters have separate DC sources, they find applications in real power conversion. The capacitor clamped inverter is not suitable for reactive power conversion as they cannot balance voltage in case of only reactive power conversion [4]. Since separate Dc sources are used in the cascaded multilevel inverter, it is best suitable for harmonic compensation, reactive power compensation and other utility applications [4]. The Cascaded multilevel inverter is mostly used in FACTS and STATCOM applications. Neutral point Converter can also be used in FACTS and STACOM. A three port Universal Flexible Power Management (UNIFLEX-PM) System was proposed using Cascaded Multilevel Inverter [2]. Multilevel converters are used in train traction, ship propulsion and automotive applications also. The three level NPC in back to back configuration has been used in train drive systems, particularly in Transrapid maglev train [2]. The back-to-back three level NPC has been used in permanent magnet synchronous generator wind turbine [2]. A CHB-based and an NPC-based multilevel mutlistring photovoltaic topology have been developed [2]. Hydro-pumped energy storage is one of the recent applications of multilevel converters. FC based converters have limited applications in photovoltaic topology, automotive applications, active filters, UPFC etc.

2.6 Summary

The NPC converters requires neutral point control and capacitor voltage balance. With the increase in the output voltage level, the requirement of the clamping diodes increases, the neutral point control and the power circuit become complex [5]. The FC converter balances voltage naturally but the capacitors has to be precharged. Although this converter is modular in structure, but requires large number of flying capacitors as the output voltage level increases and thus adds to the cost. Also the increase in the cell does not guarantee increase in the power rating of the converter [5]. In contrast to this, CHB converters have no voltage balancing problems due to separate DC sources. Its power rating can be increased by the series connection of the cells [4,5]. The NPC converter requires medium-/high voltage devices (like IGCT and medium voltage / high voltage IGBT) whereas CHB converters require low voltage IGBTs. A commercially available CHB converter has more output levels as compared to the three level NPC converter [7]. Its only drawback is the presence of the transformer [5]. But this transformer can be eliminated with the help of cascaded multilevel rectifier and inverter combination. This results in a transformerless system. Thus, it increases the efficiency and reduces the cost of the traction drive. The CHB is suitable for high power applications because of its modular structure, improvement in the power factor reduction in the average device switching frequencies [4].

Chapter 3

MODULATION TEHCNIQUES

3.1 Introduction

This chapter describes various modulation techniques to control the output voltage of the multilevel voltage source inverter. Broadly, these control techniques can be classified into Pulse Width Modulation (PWM), Selective Harmonic Elimination (SHE) Modulation and Optimised Harmonic Stepped Waveform (OHSM) [11]. The PWM technique can be open loop type like sinusoidal PWM, Space Vector Modulation, sigma delta and closed loop type like hysteresis current controller, linear current controller etc.

PWM can be considered to be an efficient modulation technique as it does not require additional components and also the lower harmonics can be eliminated or minimised leaving higher order harmonics which can be easily filtered out whereas the requirement of SCRs in this technique with low turn-on and turn-off times makes it expensive.

Sinusoidal Pulse Width Modulation (SPWM) is the simplest technique that can be implemented in both two level and multilevel inverters [12]. Basically, in SPWM, two signals - a sinusoidal reference signal and a high frequency carrier signal (triangular signal) are compared to give two states (high or low). The amplitude of the fundamental component of the output voltage of the inverter can be controlled by varying Modulation Index (M_I). Modulation Index is defined as the ratio of the magnitude of the reference signal (V_r) to that of the magnitude of the carrier signal (V_c). Thus, by keeping V_c constant and varying V_r, the modulation index can be varied.

3.2 SPWM of a Single Phase H-Bridge Inverter

The basic SPWM techniques are unipolar pulse width modulation and bipolar pulse width modulation which are used in a single phase H –bridge inverter to vary its output voltage [13].

3.2.1 Bipolar Pulse Width Modulation

In this modulation, the gate pulses are obtained by comparing a sinusoidal modulating signal or reference signal with a high frequency carrier signal.

3.2.2 Unipolar Pulse Width Modulation

The unipolar modulation normally requires two sinusoidal modulating waves, which are of same magnitude and frequency but 180 degree out of phase. The inverter output voltage switches either between zero and $+V_d$ during the positive half-cycle or between zero and $-V_d$ during the negative half-cycle of the fundamental frequency. This modulation is also possible with two triangular carrier waves and one sinusoidal modulating signal.

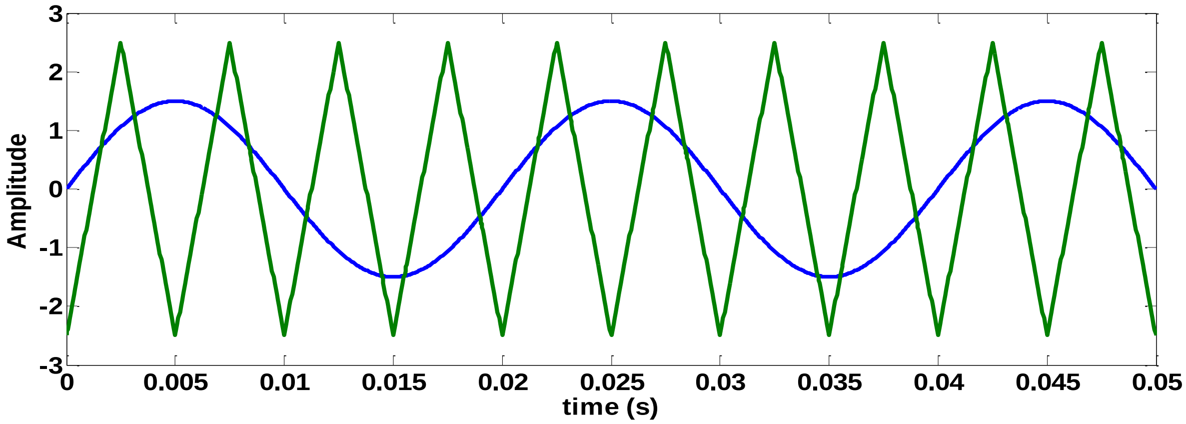


Fig 3.1 Bipolar Pulse Width Modulation

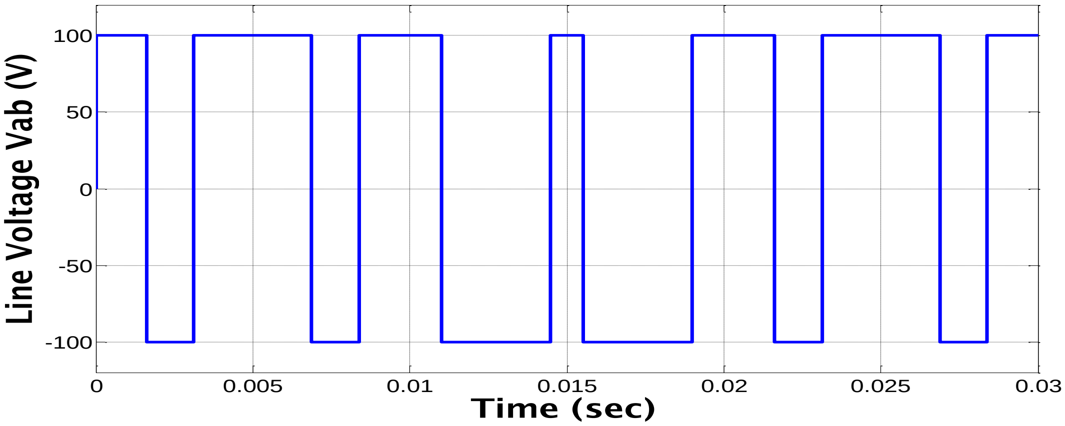


Fig 3.2 Output line voltage waveform for bipolar modulation

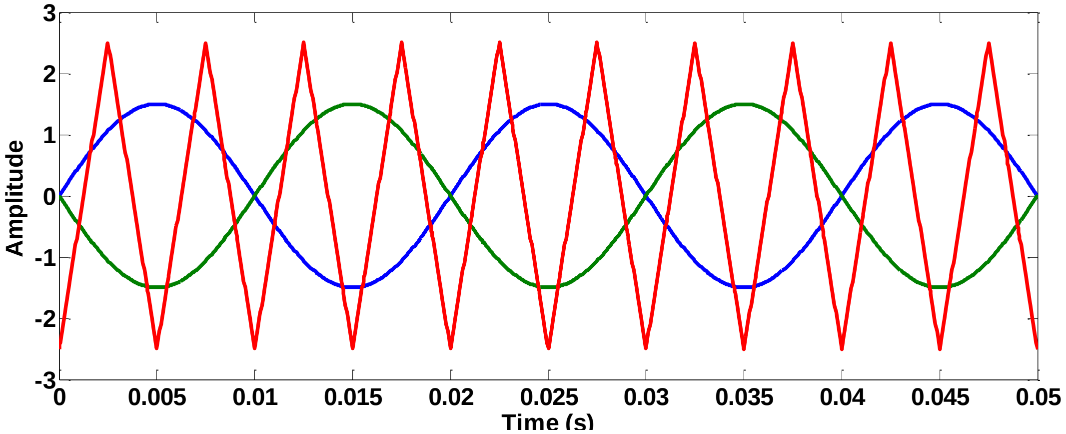


Fig 3.3 Unipolar Pulse Width Modulation

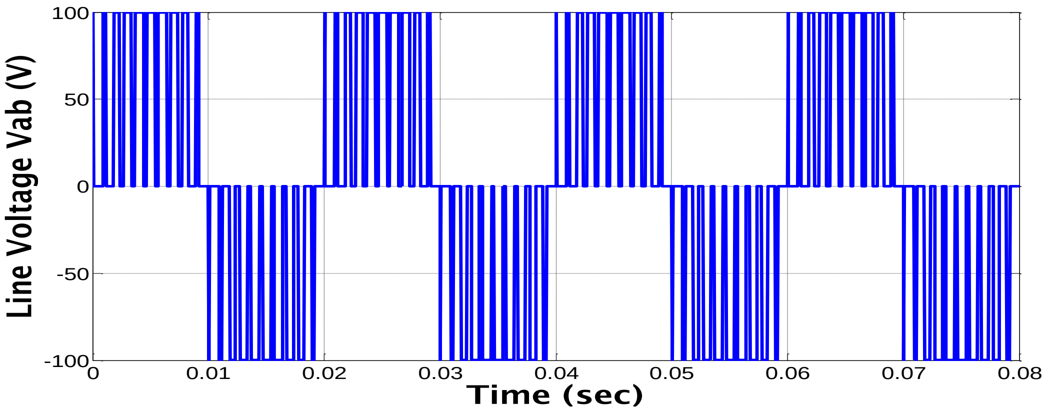


Fig 3.4 Output voltage waveform for unipolar modulation

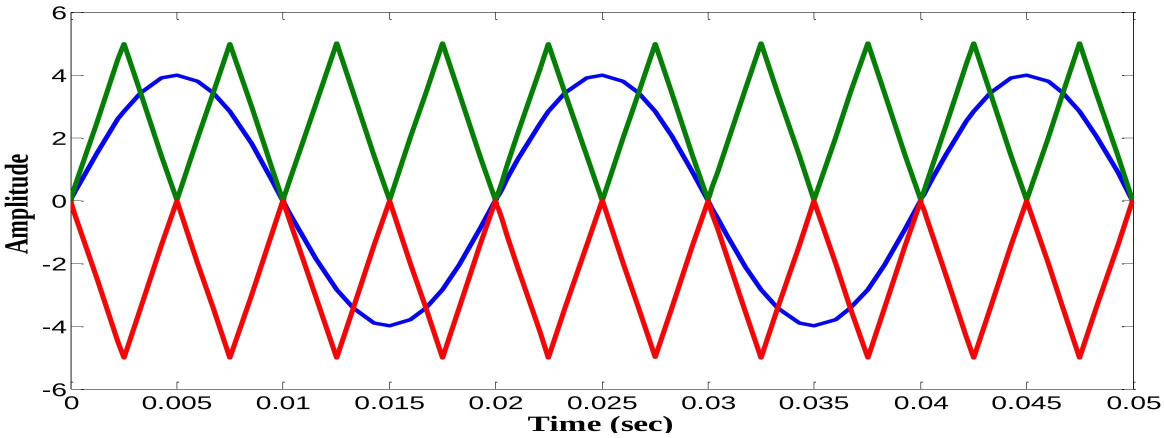


Fig 3.5 Unipolar Pulse Width Modulation

3.3 Multicarrier Pulse Width Modulation Techniques

The carrier based PWM techniques for cascaded multilevel inverter can be broadly classified into : phase shifted modulation and level shifted modulation [13]. In both the techniques, for an m level inverter, (m-1) triangular carrier waves are required. And all the carrier waves should have the same frequency and the same peak to peak magnitude.

3.3.1 Phase Shifted Multicarrier Modulation

In phase shifted PWM (PS-PWM), there is a phase shift of ϕ_{cr} between the adjacent carrier signals. The phase shift is given by

$$\phi_r = \frac{360^{\circ}}{(m-1)} \tag{3.1}$$

For a three phase inverter, the modulating signals should also be three phase sinusoidal signals with adjustable magnitude and frequency.

For this modulation scheme, the frequency modulation index m_f and the amplitude modulation index m_a is given by

$$m_f = \frac{f_{cr}}{f_m} \tag{3.2}$$

And

$$m_a = \frac{\widehat{V_{mA}}}{\widehat{V_{cr}}} \tag{3.3}$$

Where f_{cr} and f_m is the frequency of the carrier and the modulating signals respectively and $\hat{V}_{cr}$ and $\hat{V}_{mA}$ are the peak amplitudes of the carrier and the modulating signals respectively. The amplitude modulation lies in the range of 0 to 1.

The switching frequency of the device can be calculated as $f_{dev} = f_{cr} = f_m \times m_f$ .The switching frequency of the inverter can be found from the device switching frequency as $f_{inv} = (m-1)\, f_{dev}$

Consider the case of a seven level inverter. Here, m=5. So it requires (m-1) i.e. 4 number of carrier waves of the same frequency and having the same peak to peak magnitude as shown in Fig. 3.6.

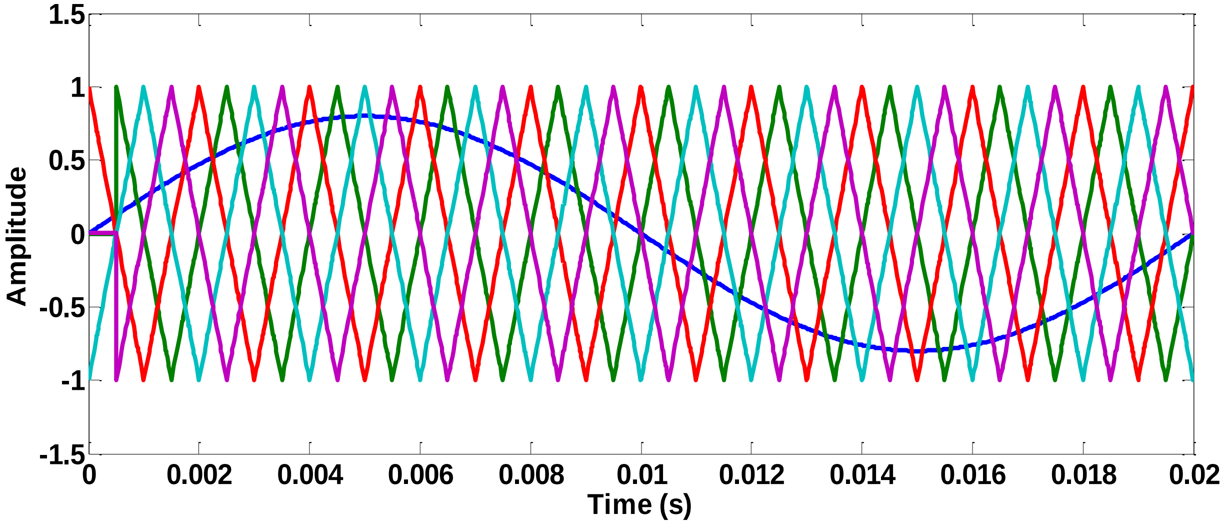


Fig 3.6 Phase-shifted PWM for five level CHB inverters

3.3.2 Level Shifted Multicarrier Modulation:

In Level Shifted PWM (LS –PWM), the triangular waves are vertically displaced such that the bands occupy are contiguous. The frequency modulation is given by $m_f = \frac{f_{cr}}{f_m}$ and amplitude modulation index is $m_a = \frac{V_{mA}}{(m-1)V_{cr}}$, where f_m and f_{cr} are the frequencies of the modulating and carrier waves and V_{mA} and V_{cr} are the peak amplitudes of modulating and carrier waves respectively. The amplitude modulation lies in the range of 0 to 1. Depending upon the disposition of the carrier waves, level shifted PWM can be In Phase Disposition PWM (IPD – PWM), Phase Opposition Disposition PWM (POD – PWM) and Alternate Phase Opposition Disposition PWM (APOD – PWM).

IPD PWM:

In this modulation, all the triangular carrier waves are in phase as shown in Fig 3.7.

POD PWM:

The carrier waveforms are in all phase above and below the zero reference value; however there is 180 degrees phase shift between the ones above and below zero respectively as shown in the Fig 3.8.

APOD –PWM:

The carrier waves have to be displaced from each other by 180 degrees alternately as shown in Fig 3.9.

In this modulation, the inverter switching frequency and the device switching frequency is given by $f_{inv} = f_{cr}$ and $f_{dev} = \frac{f_{cr}}{(m-1)}$ respectively.

In [12], it was found that LS-PWM can be implemented in all types of multilevel inverters, but it is best suitable for NPC. It is do because each carrier signal can be related to each semiconductor devices. It is not suitable for CHB as there is an uneven distribution of power because each vertical shift relate to each carrier and output level to a particular bridge.

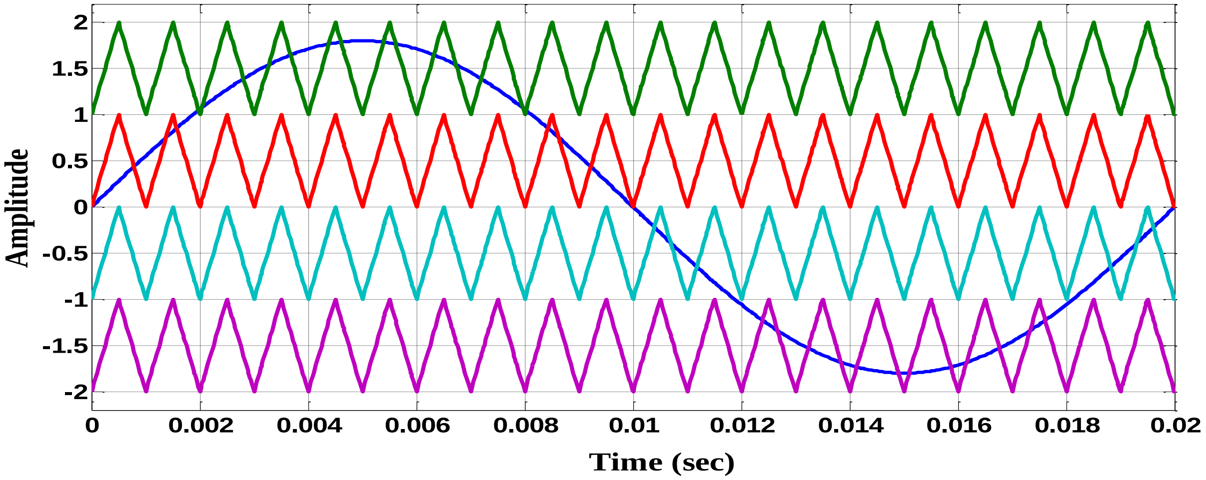


Fig 3.7 In Phase Disposition PWM for five level CHB inverter

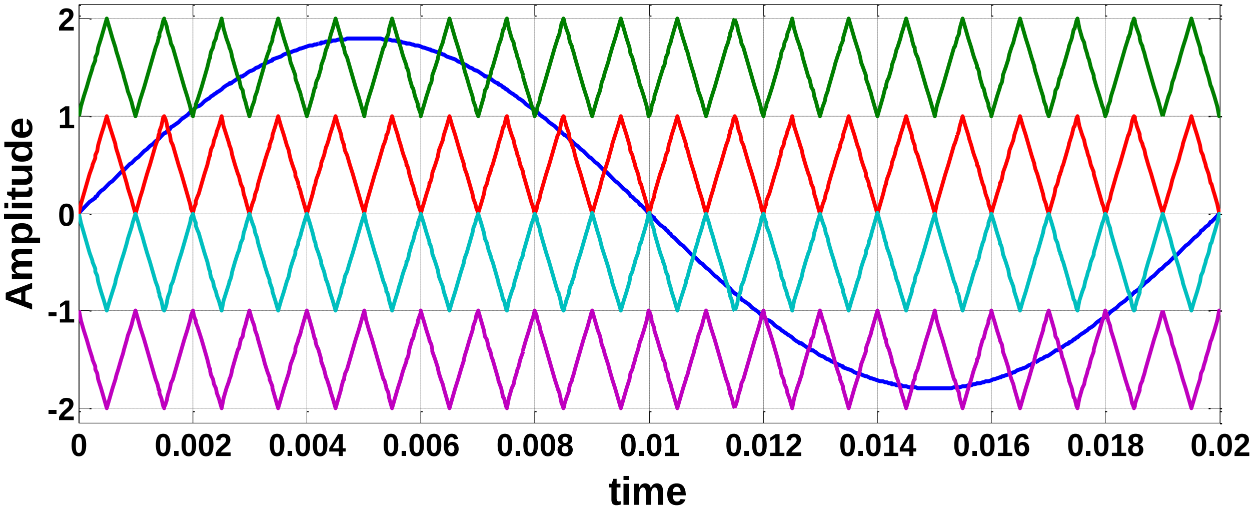


Fig 3.8 Phase Opposition Disposition PWM for five level CHB inverter

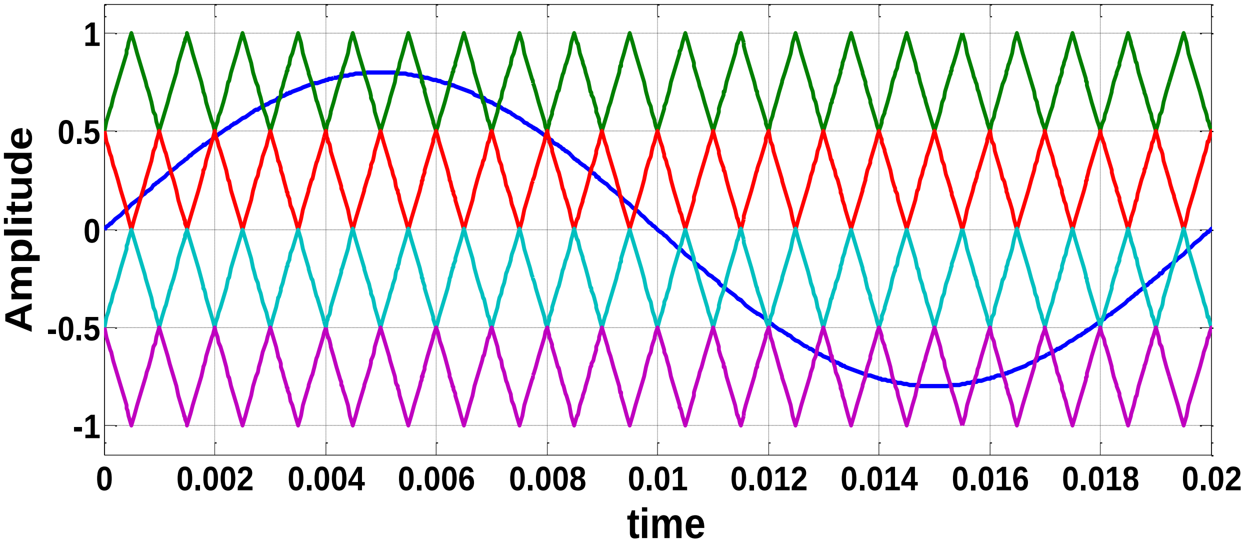


Fig 3.9 Alternate Phase Opposition Disposition PWM for five level CHB inverter

In LS-PWM, each carrier is associated with the gating signals of NPC converter whereas in PS-PWM, a pair of carriers is associated with each cell of the CHB and FC converters. Because of the phase shifting of the carriers, power is evenly distributed among the cells which results in the smooth operation of CHB and the natural voltage balancing of the FC. Therefore, LS-PWM is mainly used for NPC converter whereas PS-PWM is practically used for CHB and FC converter. Even though IPD PWM results in low THD as compared to PS-PWM, the small difference in the high frequency content can be filtered out [5,14].

3.4 Simulation results of a Single Phase H-Bridge Inverter

The following voltage waveforms have been obtained by simulating a single phase H bridge inverter using different types of modulation techniques:

A. Bipolar Modulation

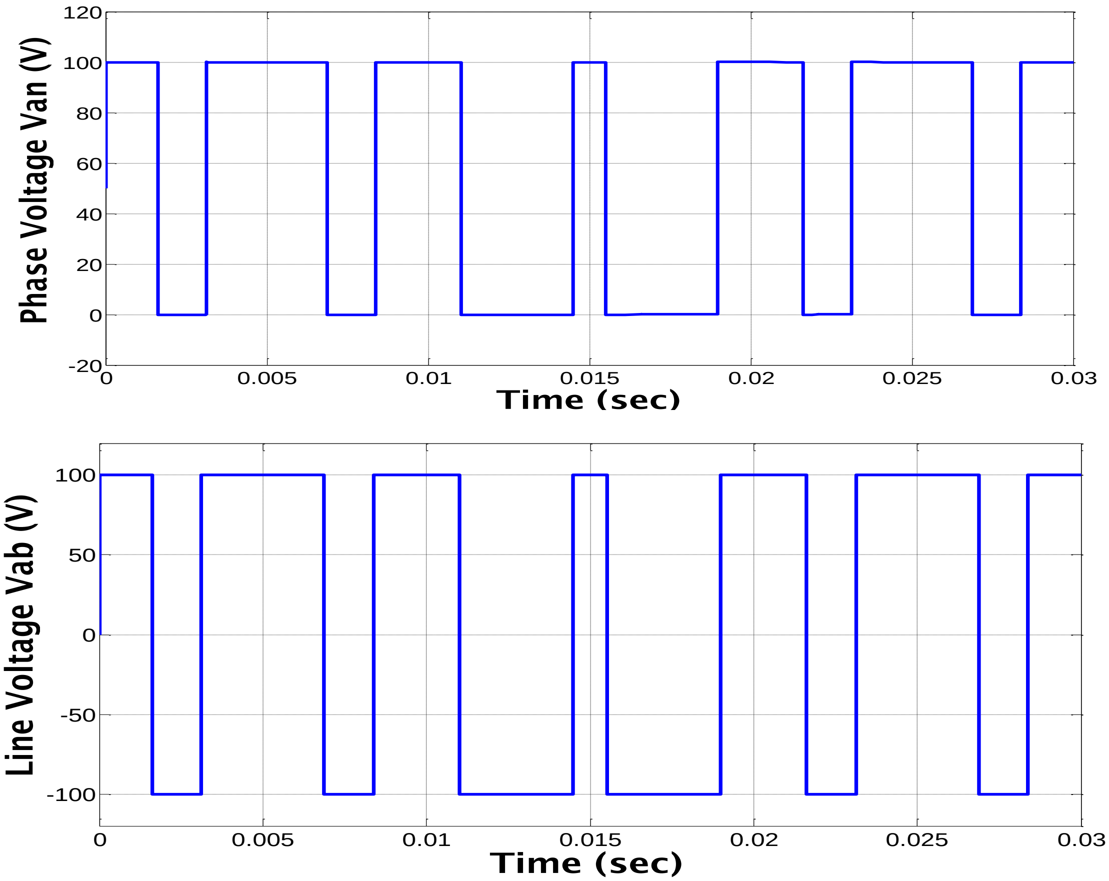


Fig 3.10 Output phase and line voltage waveform for bipolar modulation

B. Unipolar Modulation

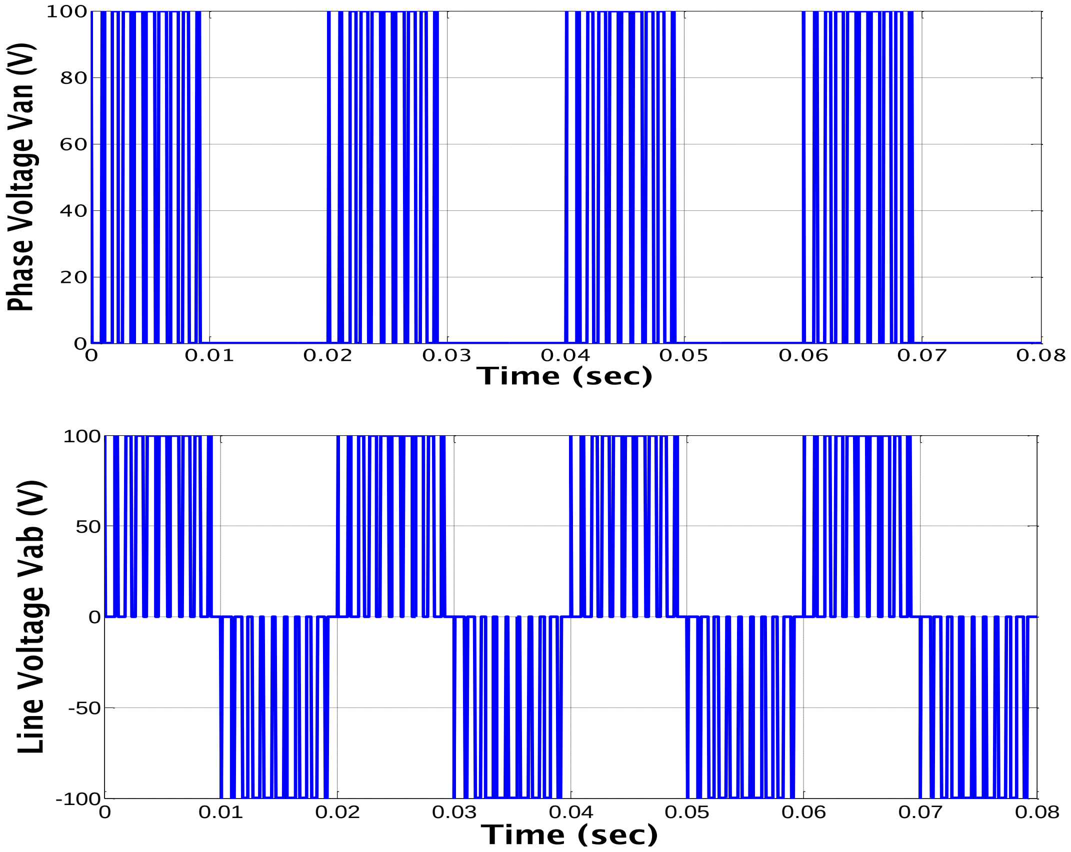


Fig 3.11 Output voltage waveform for unipolar modulation

3.5 THD values of Single Phase Two Level Inverter

On implementing the unipolar and bipolar modulation technique in the single phase two level inverter, the following THD values are obtained. It can be found from Table 3.1 that the unipolar modulation technique results in lower THD as compared to the bipolar modulation .

Table 3.1 Comparison of THD values of the line voltage of a single phase two level inverter using different modulation techniques

Modulation Technique	**THD (in %)**
Bipolar Modulation	215.50
Unipolar Modulation	78.62

3.6 Simulation results of Cascaded Multilevel Inverters using Phase Shifted Modulation Technique:

a. Three Level Inverter

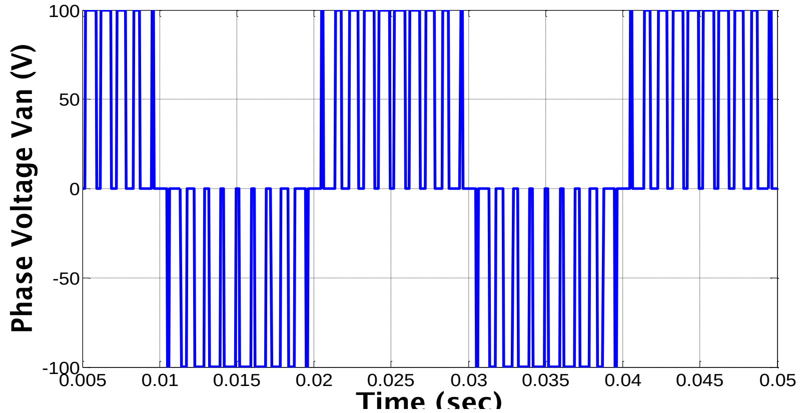


Fig 3.12 Outpu/t phase voltage waveform of a three level inverter

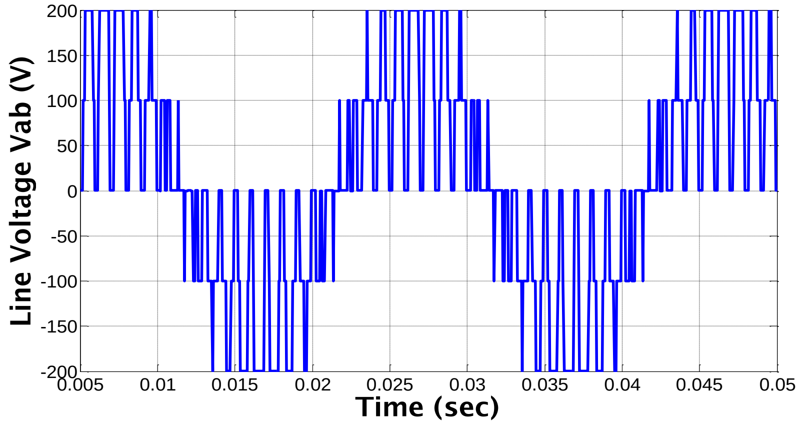


Fig 3.13 Output line voltage waveform of a three level inverter

b. Five Level Inverter

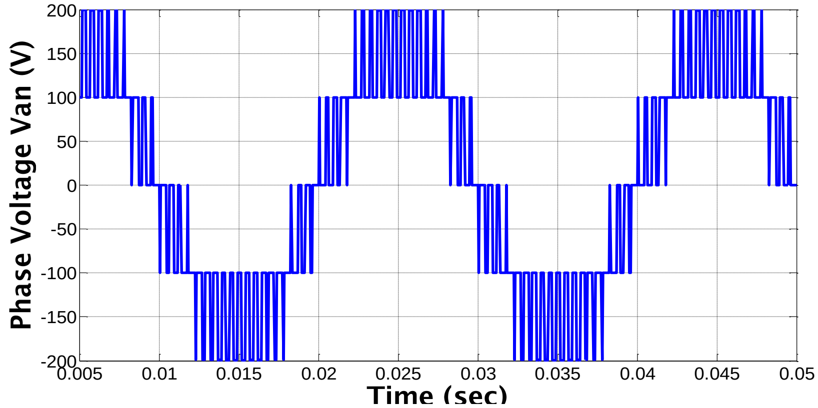


Fig 3.14 Output phase voltage waveform of a five level inverter

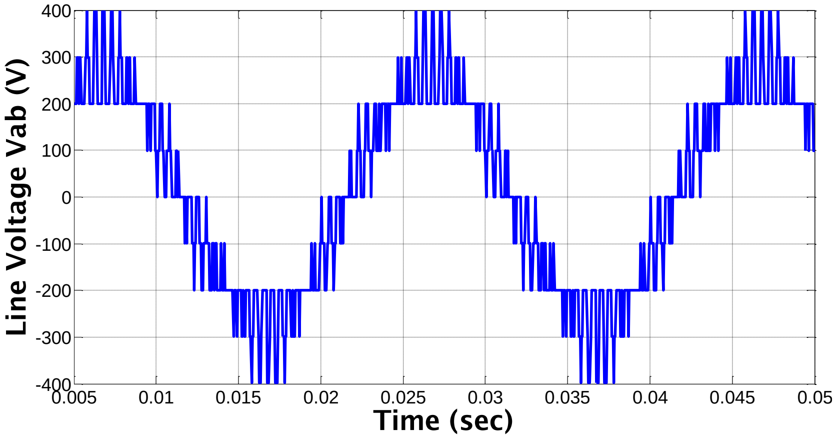


Fig 3.15 Output line voltage waveform of a five level inverter

c. Seven Level Inverter

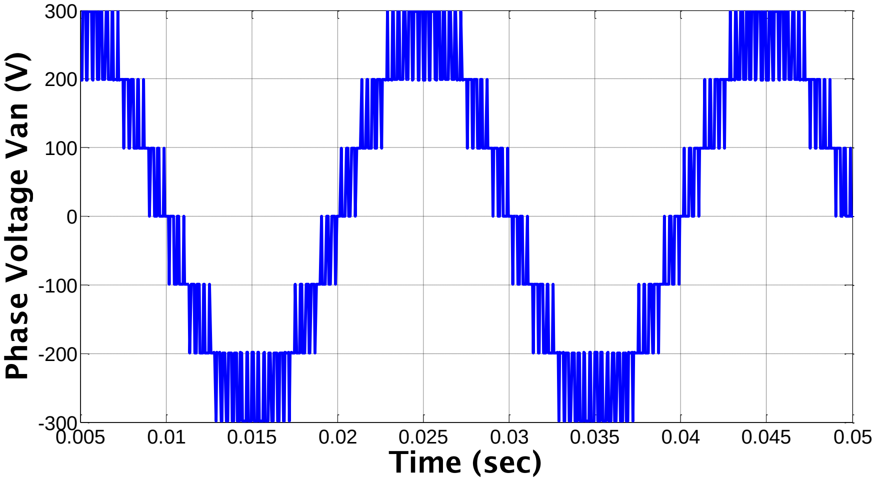


Fig 3.16 Output phase voltage waveform of a seven level inverter

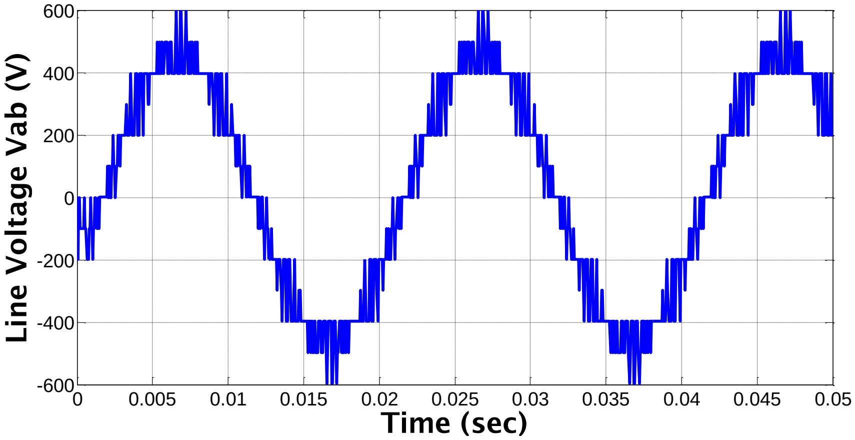


Fig 3.17 Output line voltage waveform of a seven level inverter

d. Nine Level Inverter

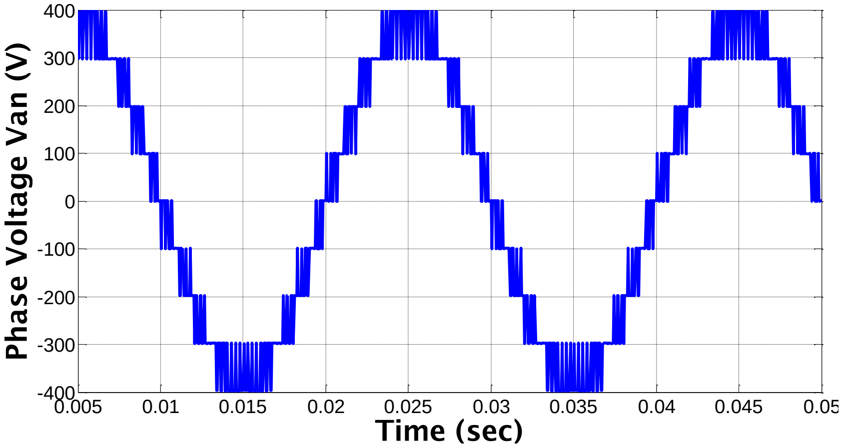


Fig 3.18 Output phase voltage waveform of a nine level inverter

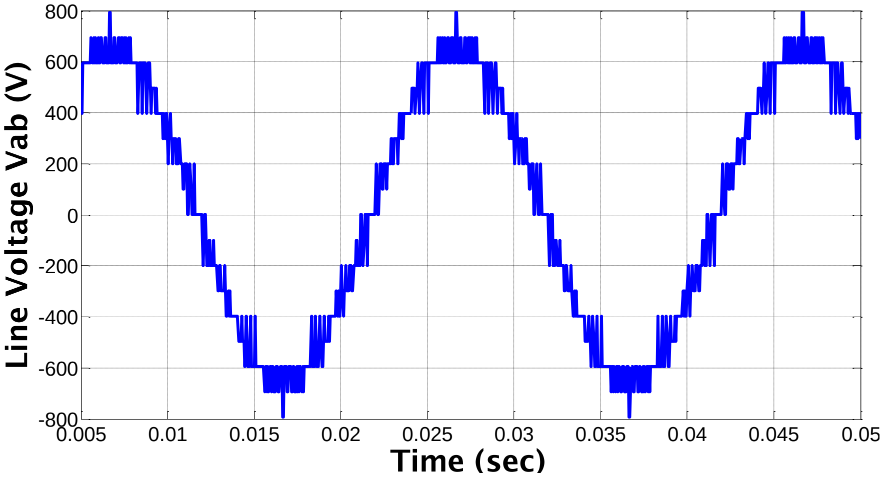


Fig 3.19 Output line voltage waveform of a nine level inverter

e. Eleven Level Inverter

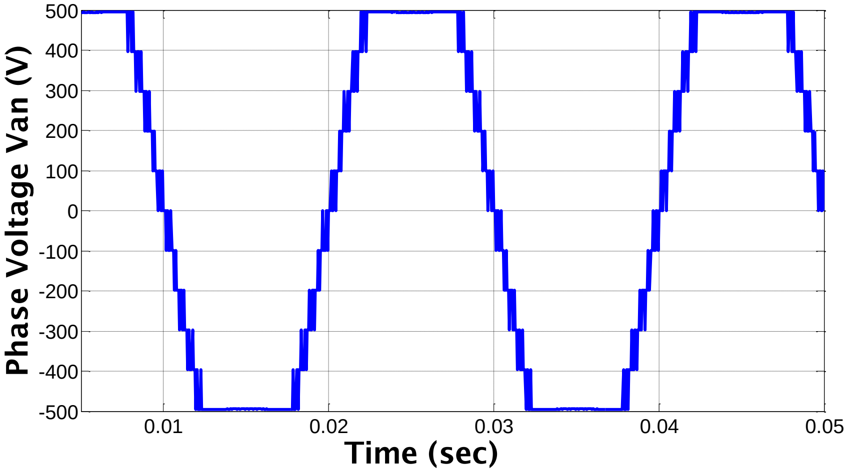


Fig 3.20 Output phase voltage waveform of an eleven level inverter

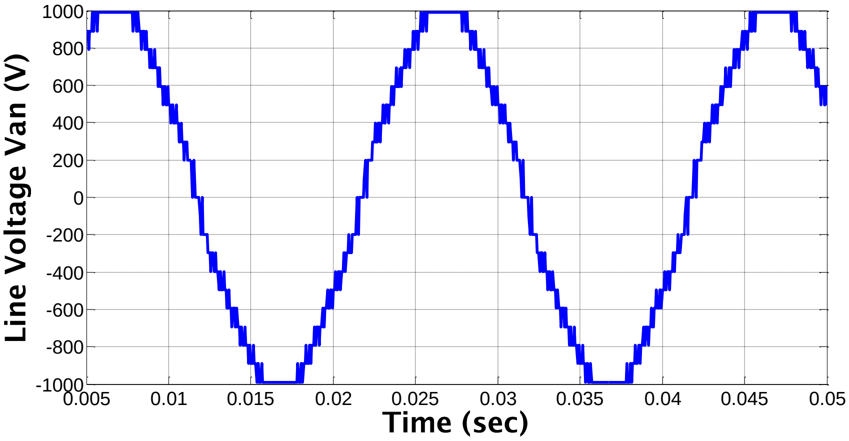


Fig 3.21 Output line voltage waveform of an eleven level inverter

3.7 Simulation results of Cascaded Multilevel Inverters using In Phase Level Shifted Modulation Technique:

a. Three Level Inverter

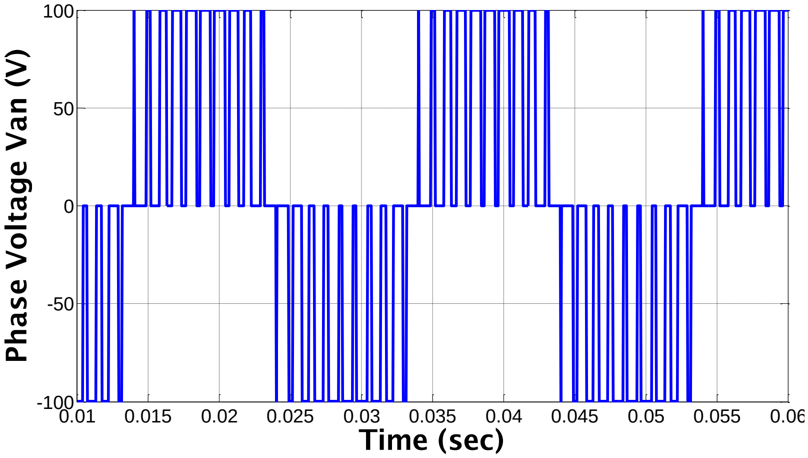


Fig 3.22 Output phase voltage waveform of a three level inverter

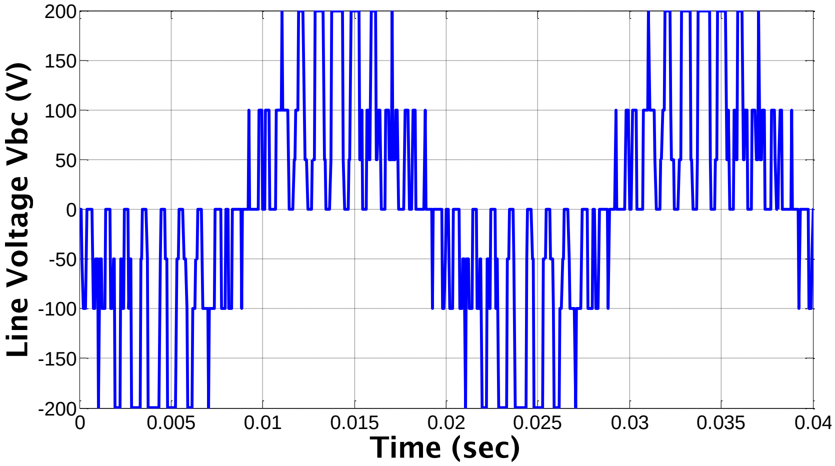


Fig 3.23 Output line voltage waveform of a three level inverter

b. Five Level Inverter

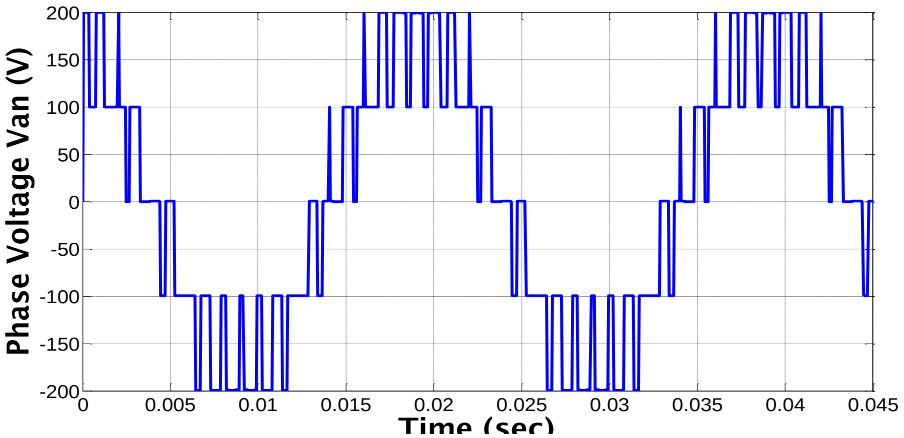


Fig 3.24 Output phase voltage waveform of a five level inverter

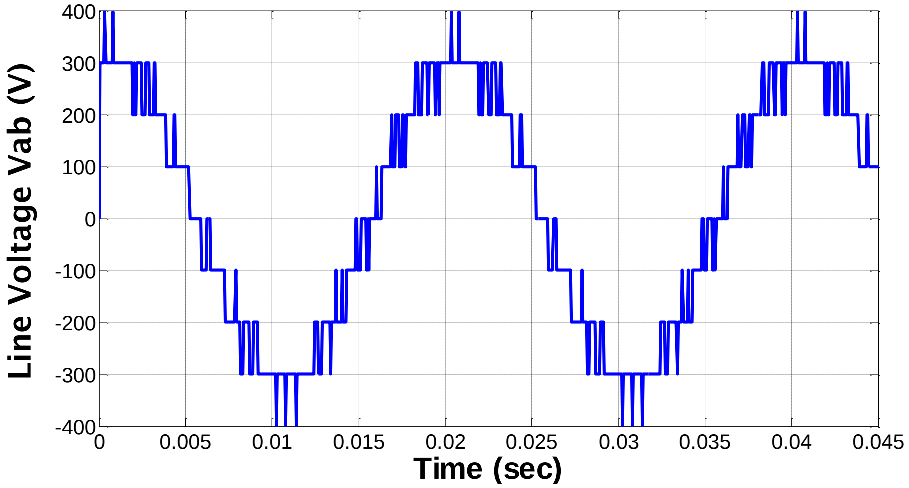


Fig 3.25 Output line voltage waveform of a five level inverter

c. Seven Level Inverter

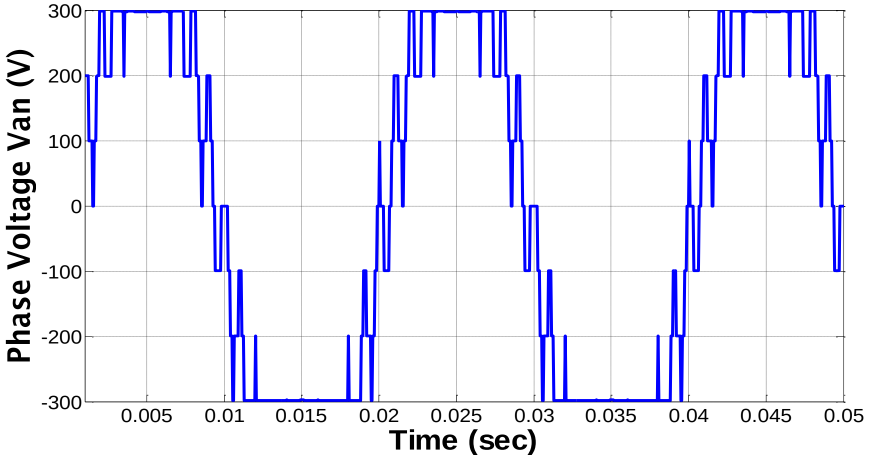


Fig 3.26 Output phase voltage waveform of a seven level inverter

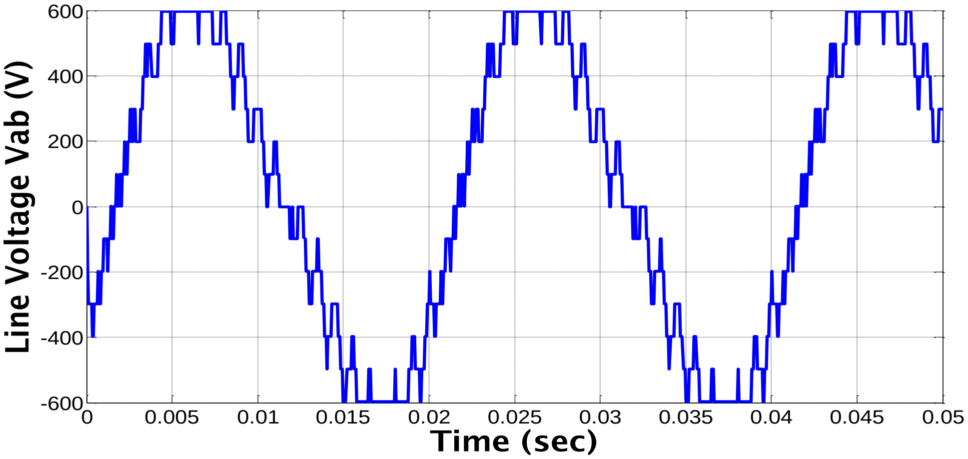


Fig 3.27 Output line voltage waveform of a seven level inverter

d. Nine Level Inverter

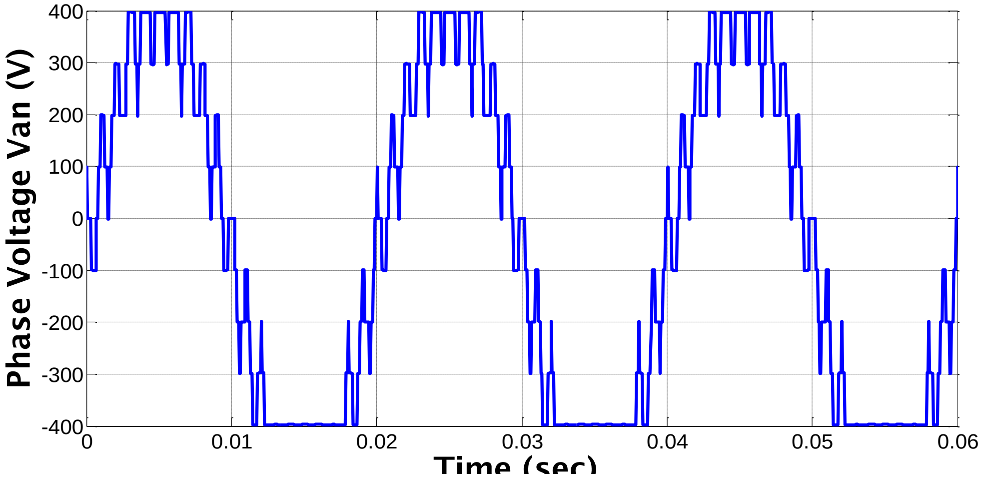


Fig 3.28 Output phase voltage waveform of a nine level inverter

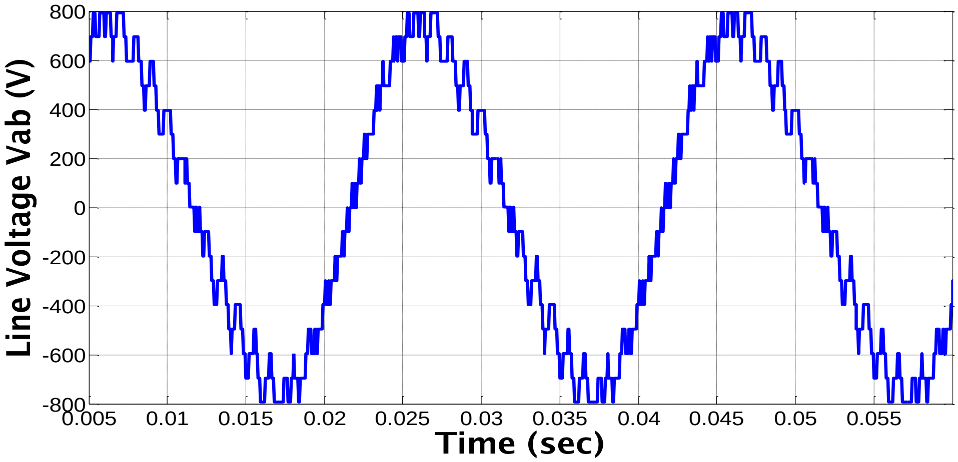


Fig 3.29 Output line voltage waveform of a nine level inverter

e. Eleven Level Inverter

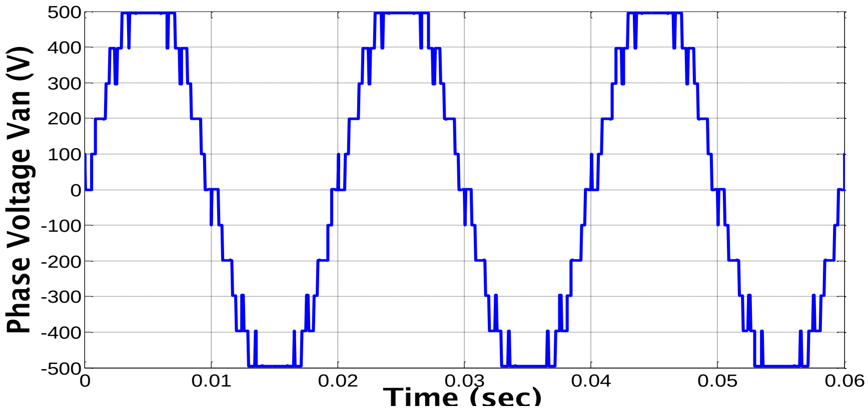


Fig 3.30 Output phase voltage waveform of an eleven level inverter

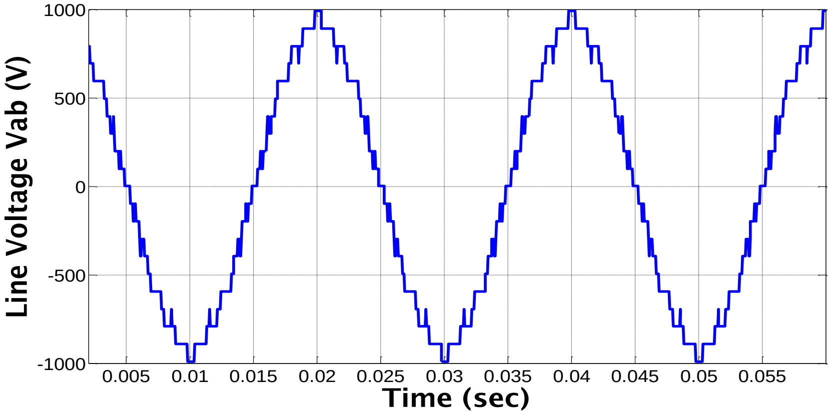


Fig 3.31 Output line voltage waveform of an eleven level inverter

3.8 Simulation results of Cascaded Multilevel Inverters using Phase Opposition Disposition Level Shifted Modulation Technique

a. Three Level Inverter

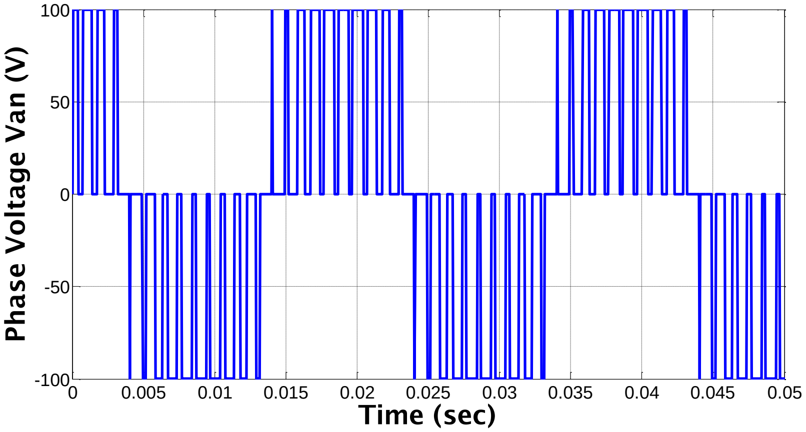


Fig 3.32 Output phase voltage waveform of a three level inverter

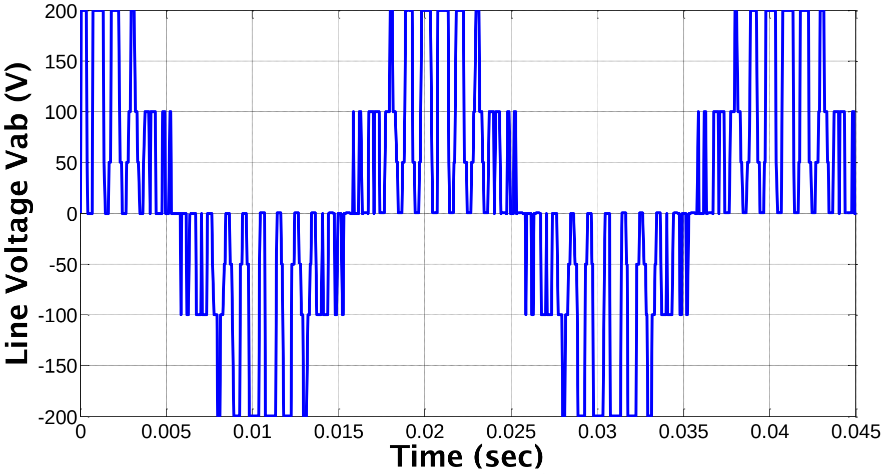


Fig 3.33 Output line voltage waveform of a three level inverter

b. Five Level Inverter

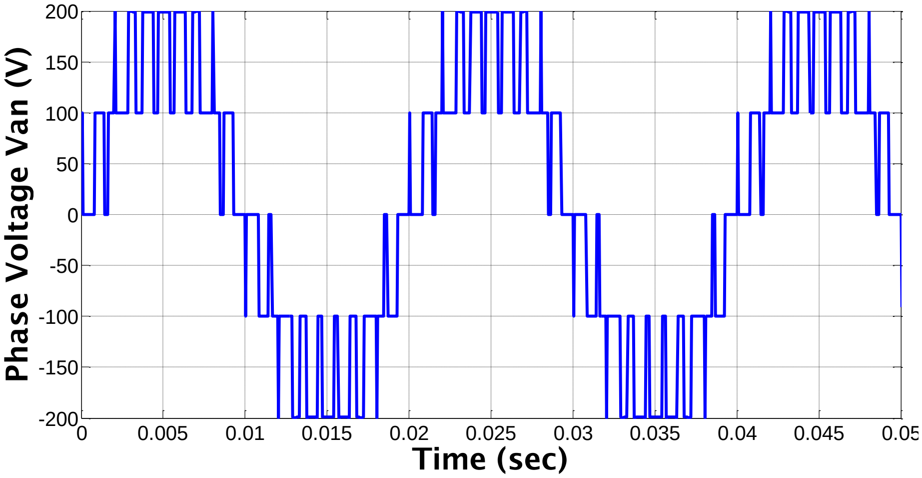


Fig 3.34 Output phase voltage waveform of a five level inverter

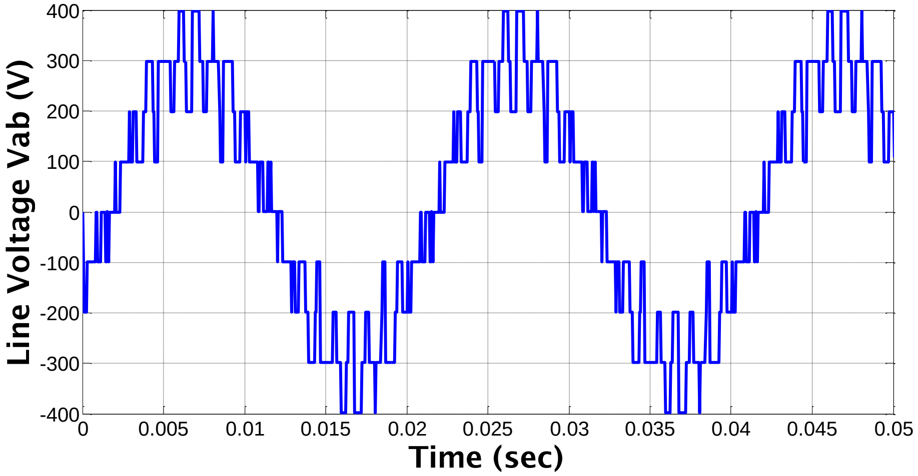


Fig 3.35 Output line voltage waveform of a five level inverter

c. Seven Level Inverter

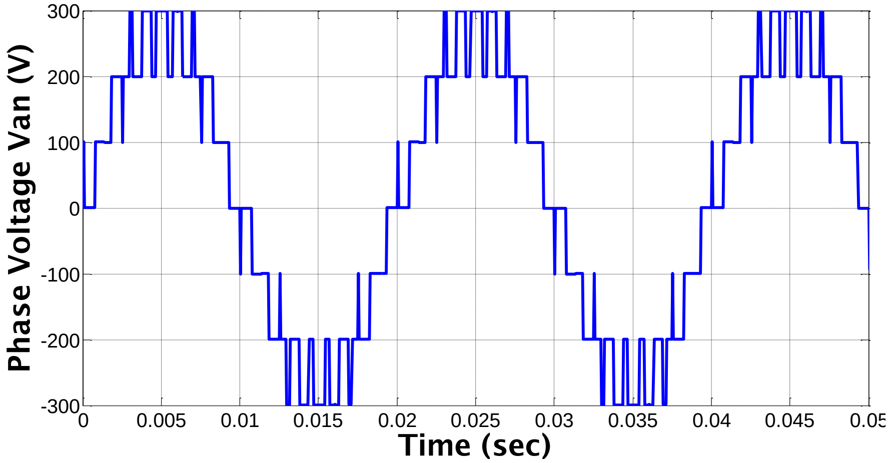


Fig 3.36 Output phase voltage waveform of a seven level inverter

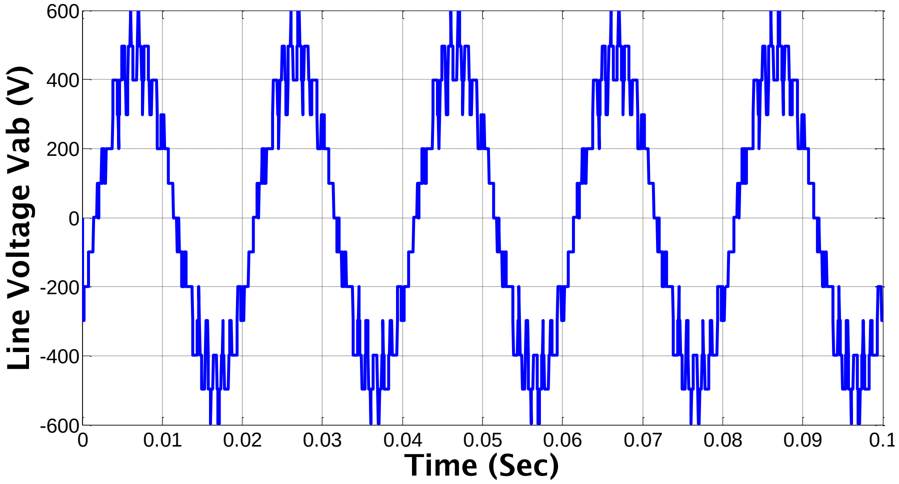


Fig 3.37 Output line voltage waveform of a seven level inverter

d. Nine Level Inverter

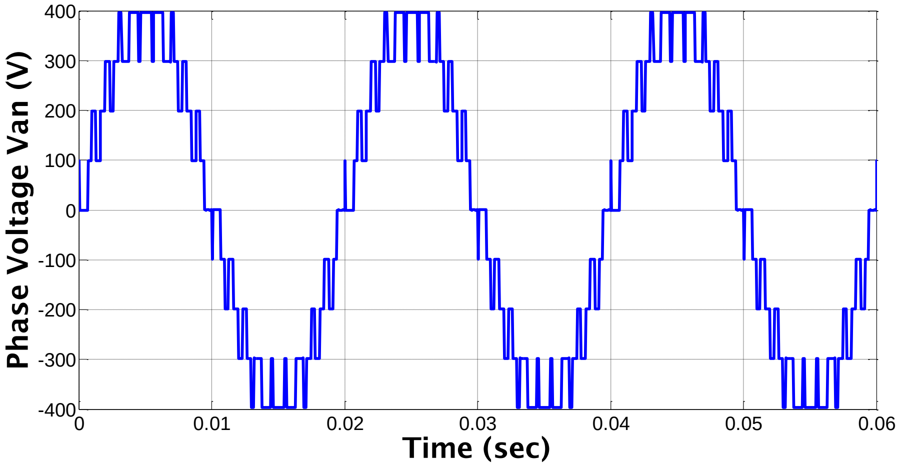


Fig 3.38 Output phase voltage waveform of a nine level inverter

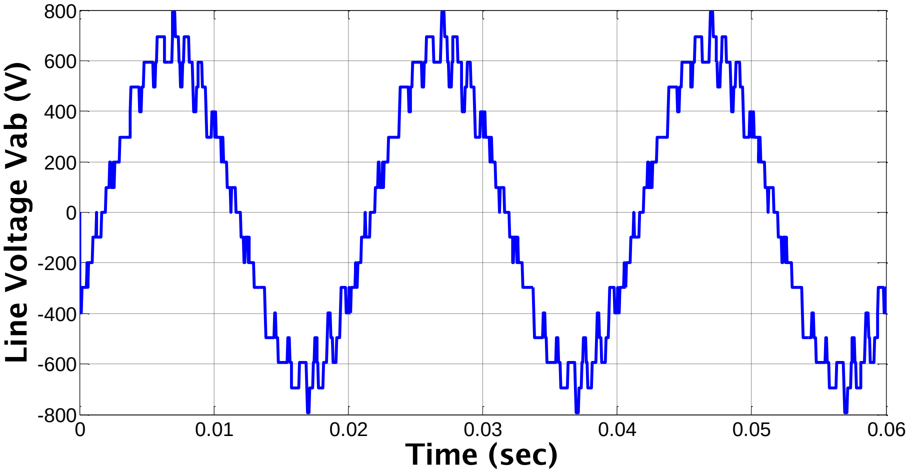


Fig 3.39 Output line voltage waveform of a nine level inverter

e. Eleven Level Inverter

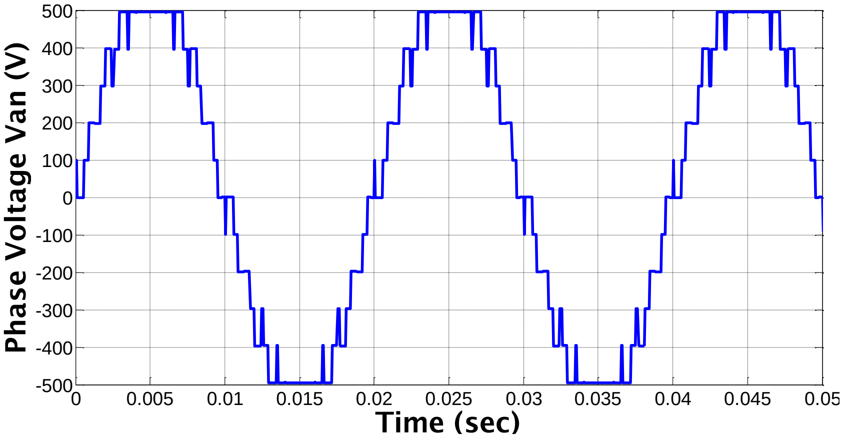


Fig 3.40 Output phase voltage waveform of an eleven level inverter

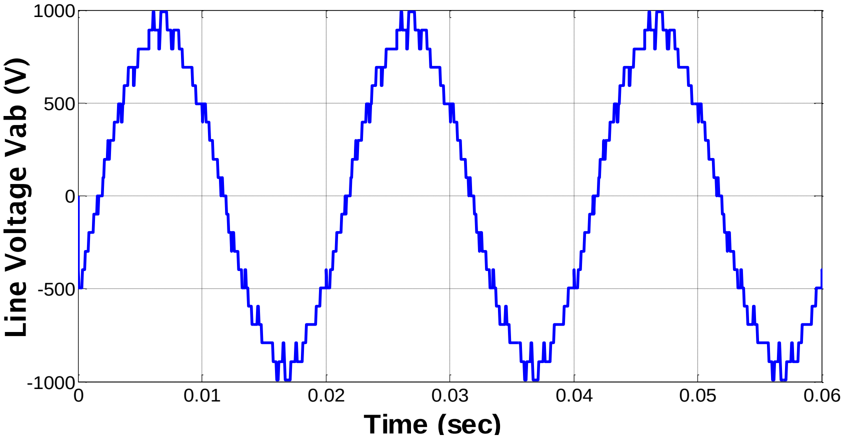


Fig 3.41 Output line voltage waveform of an eleven level inverter

3.9 Simulation results of Cascaded Multilevel Inverters using Alternate Phase Disposition Level Shifted Modulation Technique

a. Three Level Inverter

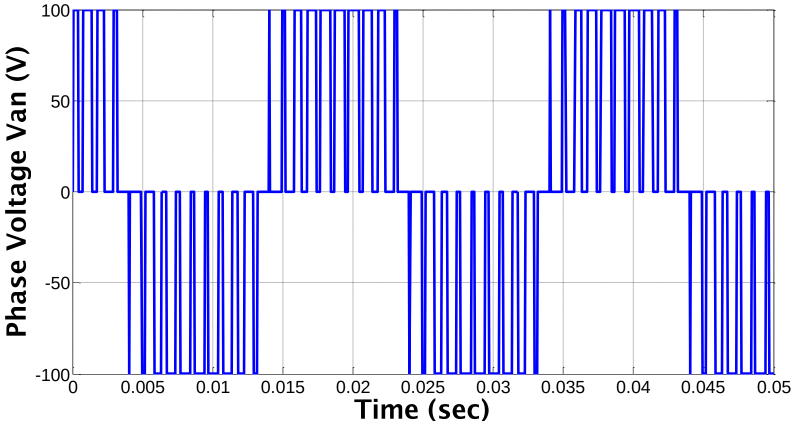


Fig 3.42 Output phase voltage waveform of a three level inverter

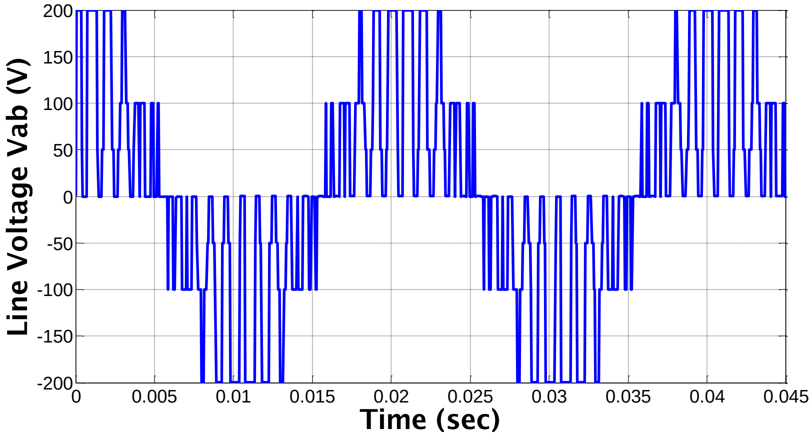


Fig 3.43 Output line voltage waveform of a three level inverter

b. Five Level Inverter

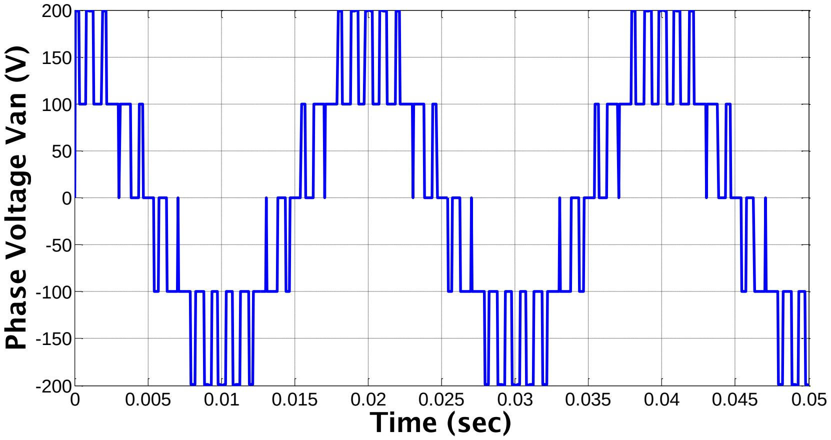


Fig 3.44 Output phase voltage waveform of a five level inverter

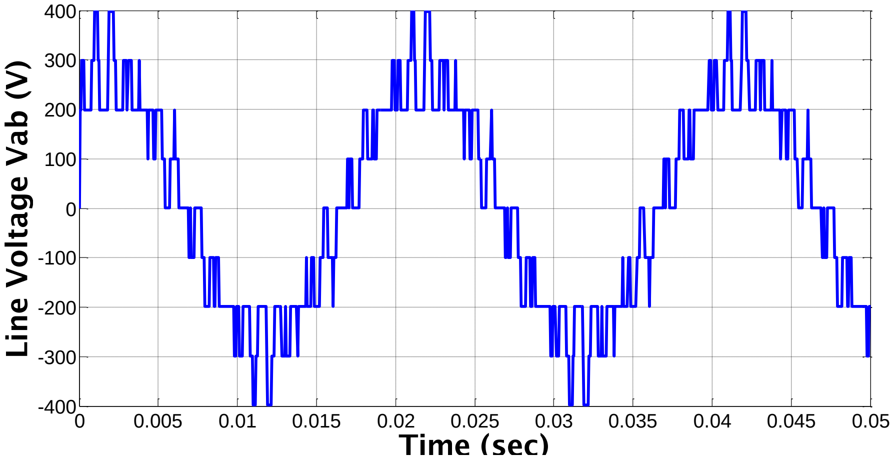


Fig 3.45 Output line voltage waveform of a five level inverter

c. Seven Level Inverter

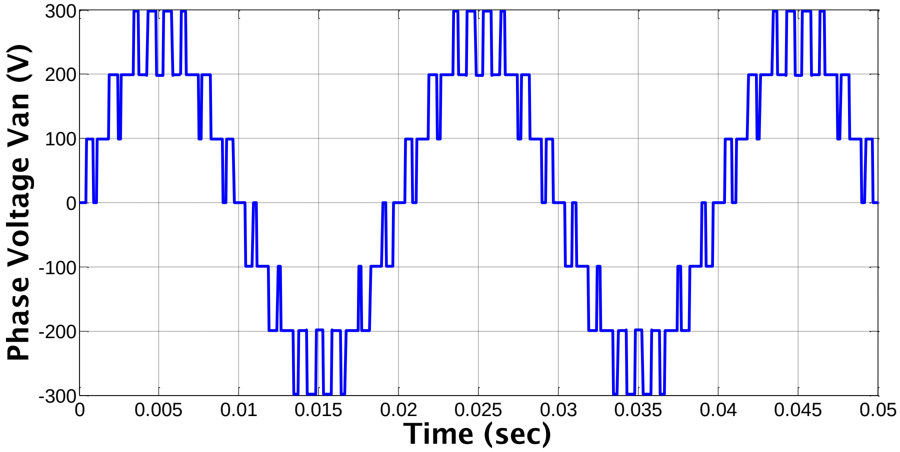


Fig 3.46 Output phase voltage waveform of a seven level inverter

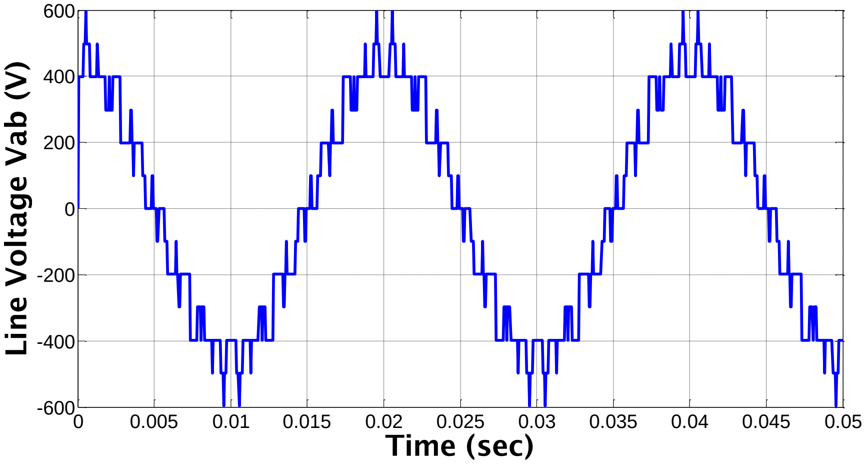


Fig 3.47 Output line voltage waveform of a seven level inverter

d. Nine Level Inverter

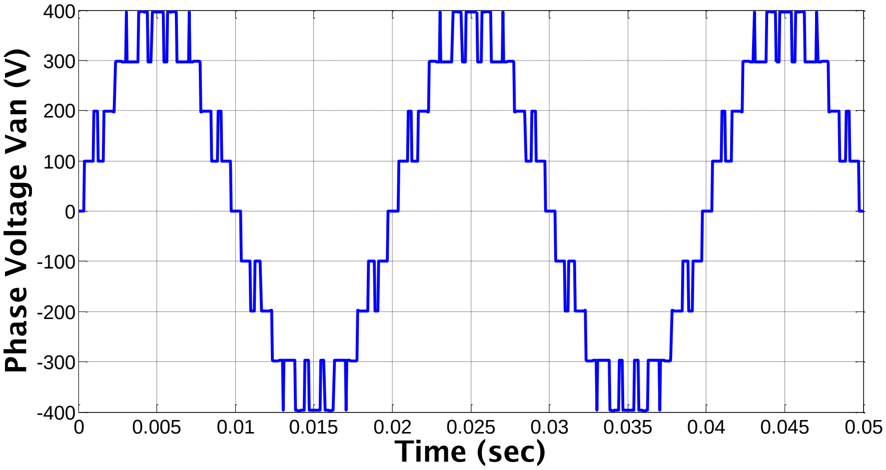


Fig 3.48 Output phase voltage waveform of a nine level inverter

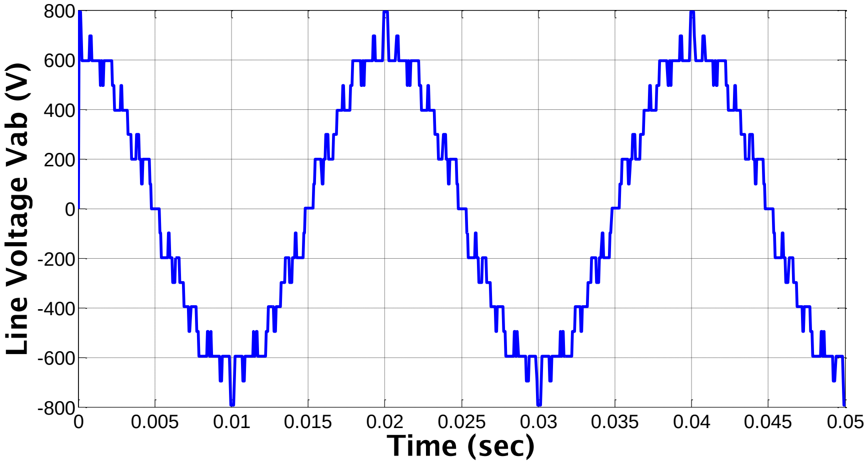


Fig 3.49 Output line voltage waveform of a nine level inverter

e. Eleven Level Inverter

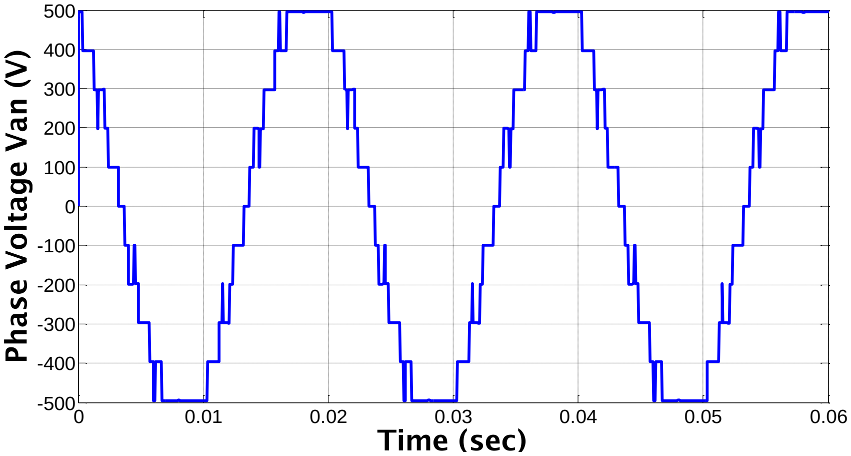


Fig 3.50 Output phase voltage waveform of an eleven level inverter

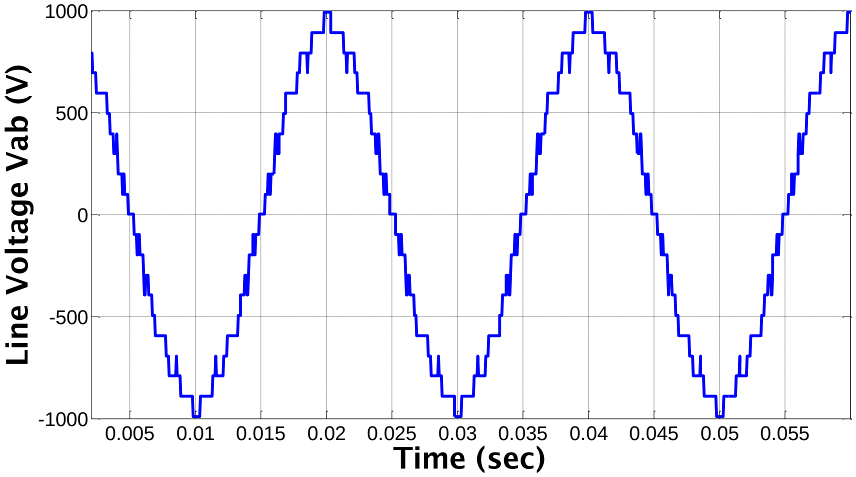


Fig 3.51 Output line voltage waveform of an eleven level inverter

3.10 THD values of the Multilevel Inverters

The value of THD so obtained for various modulation techniques implemented to various multilevel inverters is tabulated as Table 3.2.

Table 3.2 Comparison of THD values (in %) of line to line voltage of several cascaded multilevel inverter obtained by implementing carrier based modulation techniques

LINE VOLTAGE LEVEL	LEVEL SHIFTED MODULATION			PHASE SHIFTED MODULATION	REMARKS
	APOD	POD	IPD		
3 Level	79.5	79.5	70.61	69.21	IPD modulation results in reduced THD
5 level	30.49	31.87	30.82	31.20	
7 Level	20.11	20.11	19.75	19.74	
9 Level	14.59	15.21	14.45	14.47	
11 Level	9.11	9.32	8.34	9.77	

3.11 Selective Harmonic Elimination Technique

The multilevel inverter generates a staircase output voltage waveform by switching on and off the switches in the inverters once during one fundamental cycle. This minimizes the switching losses of the devices. Even if the switching frequencies reduce and certain higher order harmonics eliminates, low order harmonics still exists [11,12].

There are two ways to eliminate low frequency harmonics- i) by increasing the switching frequency in SPWM and SVM in case of two level inverters or in multicarrier based phase shift modulation for multilevel inverters or ii) by computing the switching angles using SHE techniques.

This first method is limited by the switching losses and the availability of the voltage steps [11].

The SHE techniques includes the mathematical modelling of output waveform and solving them for switching angles of based on the characteristics of the output waveform of the inverter, the amplitude of the fundamental wave of the output voltage and the order and number of the eliminated harmonics [15].

Thus, in SHE, the lower order harmonics are either eliminated or minimised while the higher order harmonics are filtered out. The transcendental equations reflecting each harmonics are solved to compute the switching angles of the inverter. Being highly non-linear in nature, these SHE equations are difficult to solve. Also it may produce single, multiple or even no solutions for a particular modulation index.

In [16,17,18], to solve these equations, various iterative numerical techniques have been used with a proper initial guess and starting values of modulation index. In [19], a sequential homotopy based computation has been done to solve for the switching angles. In [20,21], theory of resultants of polynomials, the theory of symmetric polynomial and the resultant theory has been proposed to solve the polynomial equations obtained from the transcendental equations. But the computation becomes high as the order of the polynomials become very high with the number of H-bridges connected in series. In [22], the SHE equations were solved by using Genetic Algorithm (GA). But it requires proper selection of certain parameters such as population size, mutation rate etc. to eliminate all these problems. In [22], the Newton Raphson method has been used in solving these equations. The switching angles can be found with negligible computation effort for any initial guess. Switching angles can be computed to produce the desired fundamental voltage $V_I = m_I (4sV_{dc}/\pi)$ while eliminating 5th, 7th, 11th and 13th harmonics.

Solving the transcendental equations with *n* number of unknowns is a tedious job. But the switching angles can be calculated offline to eliminate the specific low order harmonics and also switching takes place at the fundamental frequency and hence minimizes the switching losses. In other words, in SHE, few commutations takes place in one cycle and hence increases efficiency and enables air cooling [13,14]. The computation of the switching angle increases with the increase in the voltage level [14]. With a limitation for the switching angles to be within (π/2), it provides a narrow range of modulation index [15]. This method is limited to open-loop applications [5,15] and low-dynamic-performance demanding applications [5].

3.11.1 Mathematical Modelling of Switching Angles and SHE Equations for Cascaded Multilevel Inverter

The Fourier series expansion of the staircase output voltage waveform of the multilevel inverter as shown in Fig.3.52 is given by

$$V(\omega t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{n\pi} \left(\cos(n\theta_1) + \cos(n\theta_2) + \cdots + \cos(n\theta_s)\right) \tag{3.4}$$

Where V_{dc} is the magnitude of the dc voltage source and

s is the number of dc sources in each phase.

For a desired fundamental voltage V_1, the switching angles $\theta_1, \ldots, \theta_n$ are to be determined so that $V(\omega t) = V_1 \sin(\omega t)$ satisfying the following condition : $0 \leq \theta_1 < \theta_2 \ldots < \theta_s \leq \pi/2$ as shown in Fig.3.52.

Here, the first harmonics is made equal to the desired fundamental voltage $V_1$and specific higher harmonics of $V(\omega t)$ equal to zero, i.e

$$\frac{4V_{dc}}{\pi} \left(\cos(\theta_1) + \cos(\theta_2) + \cdots + \cos(\theta_s)\right) = V_1 \tag{3.5}$$

$$\cos(n\theta_1) + \cos(n\theta_2) + \cdots + \cos(n\theta_s) = 0 \tag{3.6}$$

Where n = 5, 7, 11, 13….

Hence, among the s number of switching angles, one is used for fundamental voltage and the remaining (s-1) for the predominating lower order harmonics elimination [14]. In three phase system, the triplen harmonics cancels out automatically in the line to line voltages [2]. The 5th , 7th, 11th, 13th order harmonics has to be cancelled as they affect the THD vastly.

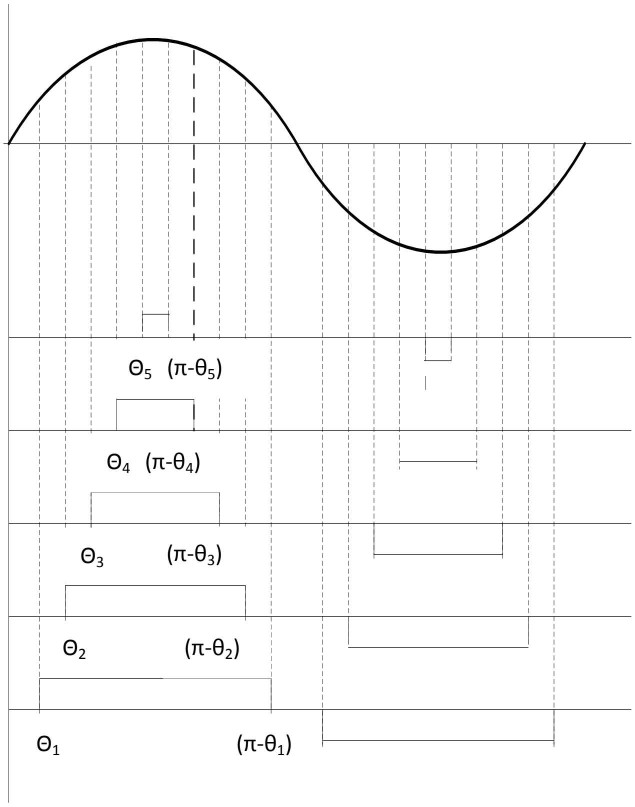


Figure 3.52 Selective Harmonic Elimination technique for eleven level inverter

Thus, the following equations are to be solved:

$$\cos(\theta_1) + \cos(\theta_2) + \cdots + \cos(\theta_s) = \frac{(m-1)}{2} M_I \tag{3.7}$$

$$\cos(5\theta_1) + \cos(5\theta_2) + \cdots + \cos(5\theta_s) = 0 \tag{3.8}$$

$$\cos(7\theta_1) + \cos(7\theta_2) + \cdots + \cos(7\theta_s) = 0 \tag{3.9}$$

$$\cos(11\theta_1) + \cos(11\theta_2) + \cdots + \cos(11\theta_s) = 0 \tag{3.10}$$

$$\cos(13\theta_1) + \cos(13\theta_2) + \cdots + \cos(13\theta_s) = 0 \tag{3.11}$$

Where M_I is known as Modulation Index and is equal to the ratio of the fundamental output voltage V_1 to the maximum obtainable fundamental voltage V_{1max}.

Fundamental voltage $V_{1max} = \frac{4sV_{dc}}{\pi}$ and $s = \frac{(m-1)}{2}$ where m is the m level of the inverter output voltage.Thus, the equations (7) to (11) can be written as

$$F(\theta) = H_M \tag{3.12}$$

3.11.2 Algorithm for Newton Raphson Method for finding out the switching angles of an Eleven Level Cascaded Inverter:

The step by step procedure to solve the SHE equations is as follows:

1. Define a switching angle matrix

   Note: all switching angle must lie within 0 to (π/2)

   $X_{old} = [\, x_1 \quad x_2 \quad x_3 \;\; x_4 \quad x_5 \,]$

2. Specify the value of modulation index $\boldsymbol{M_I}$ and the number of line voltage level $\boldsymbol{m}$.
3. Define a non-linear matrix F as below:

$$F = \begin{bmatrix} \cos(\theta_1) + \cos(\theta_2) + \cdots + \cos(\theta_s) \\ \cos(5\theta_1) + \cos(5\theta_2) + \cdots + \cos(5\theta_5) \\ \cos(7\theta_1) + \cos(7\theta_2) + \cdots + \cos(7\theta_5) \\ \cos(11\theta_1) + \cos(11\theta_2) + \cdots + \cos(11\theta_5) \\ \cos(13\theta_1) + \cos(13\theta_2) + \cdots + \cos(13\theta_5) \end{bmatrix}$$

4. Define the corresponding harmonic amplitude matrix as

$$H_M = \begin{bmatrix} \frac{(m-1)M_I}{2} & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

5. Define dervF which is the derivative of the matrix F with respect to x_1, x_2, x_3, x_4, x_5.
6. Initial values for the switching angles are entered as $X_{old\_}0 = [\, x_{10} \quad x_{20} \quad x_{30} \;\; x_{40} \quad x_{50} \,]$
7. Solve for F and dervF at the initial values of X_{old_0}

   As on linearizing the equation (3.12), we get

$$F + (dervF * DelX) = H_M \tag{3.13}$$

   Where *DelX* is the change in the switching angle.

8. Solve for *DelX* from equation (3.13) as

$$DelX = INVERSE\ (dervF) * (T - F)$$

9. Update the value of the switching angle

$$X_{new} = X_{old} + DelX$$

10. The process is repeated until the desired condition is satisfied.

On solving the above equations, using Newton Raphson method, with m=11 and M_I =0.8 for an eleven level inverter, the values of x_1 , x_2 , x_3 , x_4 , x_5 were found.Thus, the switching angles are$\theta_1 = 6.57°, \theta_2 = 18.94°, \theta_3 = 27.18°, \theta_4 = 45.15°, \theta_5 = 62.24°$.

On solving these equations in MATLAB, the following results were obtained as in Table 3.3.

Table No. 3.3 The values of the switching angles obtained using the SHE algorithm

Iteration	X_{old} (in degree)	F	DelX (in degree)	X_{new} (in degree)
0	5	4.1082	-0.1419	4.8581
	20	-0.2806	1.9920	21.9920
	25	-0.2694	-1.0478	23.9522
	40	0.5683	5.7090	45.7070
	60	0.6284	2.6641	62.6641
1	4.8581	3.9951	1.9104	6.7686
	21.9920	0.0976	-7.6242	14.3678
	23.9522	-0.0840	7.8179	31.7701
	45.7070	0.0748	-0.5339	45.1731
	62.6641	0.7206	-0.4292	62.2348
2	6.7686	3.9827	-0.4447	6.3238
	14.3678	0.1716	4.0250	18.3928
	31.7701	0.7249	-3.9744	27.7958
	45.1731	0.4084	0.3727	45.5458
	62.2348	-1.0186	-0.1212	62.1136
3	6.3238	3.9955	0.2400	6.5638
	18.3928	0.0405	0.5262	18.9189
	27.7958	0.1373	-0.5918	27.2039
	45.5458	0.0325	-0.4081	45.1377
	62.1136	0.0515	0.1327	62.2463
4	6.5638	3.9999	0.0060	6.5698
	18.9189	0.0012	0.0212	18.9401
	27.2039	0.0026	-0.0206	27.1833
	45.1377	0.0028	-0.0019	45.1358
	62.2463	-0.0031	-0.0038	62.2425
5	6.5698	4.0000	0.0140e-4	6.5698
	18.9401	0.0000	0.4082e-4	18.9402
	27.1833	0.0000	0.4261e-4	27.1833
	45.1358	0.0000	0.0341e-4	45.1358
	62.2425	-0.0000	0.0120e-4	62.2425

3.12 Simulation Results

The single phase H-bridge inverter was studied by implementing the bipolar and unipolar modulation techniques. The three phase three level, five level, seven level, nine level and eleven level cascaded inverters were simulated in MATLAB Simulink environment. The multicarrier modulation schemes – level shifted and phase shifted modulation were implemented in these inverters. It was found that as the number of the level increases, the output voltage waveform appears to be more sinusoidal and also the THD decreases. Hence, among all the simulated cascaded inverters, the eleven level inverter was chosen for the traction drive. SHE technique was also implemented in the eleven level inverter and compared with carrier based modulation technique. This was done to find the best modulation technique among the three. SHE was found to be the best and hence was used in the cascaded rectifier and inverter configuration to be used in the traction drives.

The following voltage waveforms have been obtained by simulating eleven level cascaded inverter using Selective Harmonic Elimination techniques:

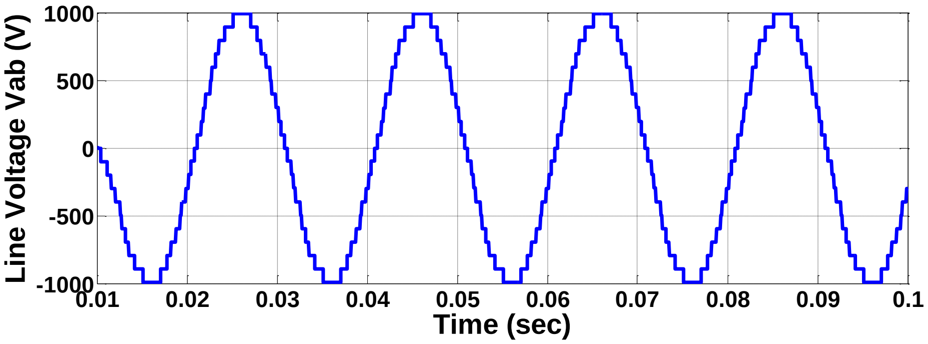


Fig 3.53 Output phase voltage waveform of an eleven level inverter

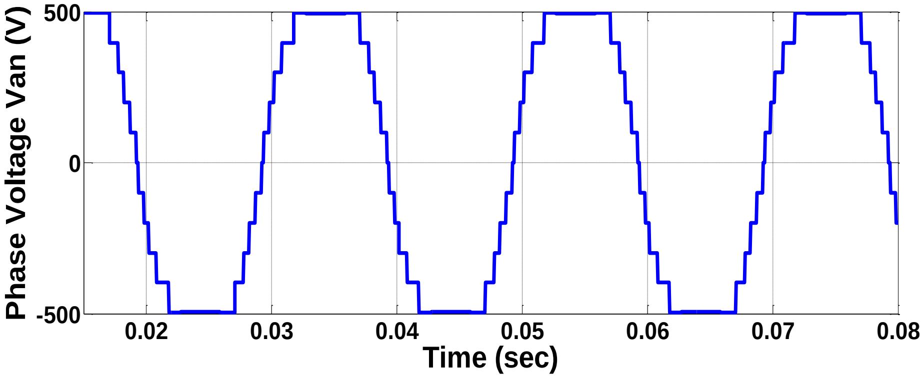


Fig 3.54 Output line voltage waveform of an eleven level inverter

3.13 THD values of cascaded eleven level inverter

The value of THD so obtained for various modulation techniques implemented in a cascaded eleven level inverters is tabulated as in Table 3.4.

Table 3.4 Comparison of THD values (in %) of line to line voltage of eleven level cascaded inverter obtained by implementing various modulation techniques

MODULATION TYPE	THD (in %)	REMARKS
Phase Shifted	9.77	Selective Harmonic Elimination is better with low THD
Level Shifted (IPD)	8.34	
Selective Harmonic Elimination	4.56	

3.14 Cascaded Rectifier Inverter configuration (ac-dc-ac converter)

The following voltage waveforms were obtained with three types of eleven level rectifier inverter configuration - one employing level shifted PWM, other Phase shifted PWM and the last one SHE Modulation. This was done to find the best modulation suitable for the traction drive. The THDs of the voltages were compared to choose the best among the three configurations.

3.14.1 Rectifier Inverter configuration with phase shifted modulation technique

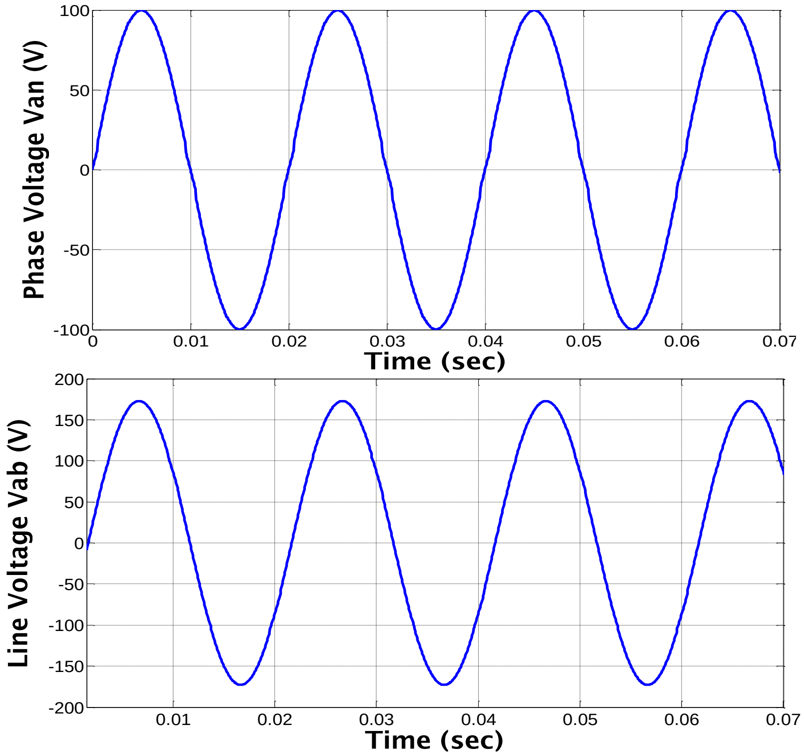


Fig. 3.55 Output phase and line voltage waveform of eleven level cascaded rectifier inverter configuration with phase shifted modulation technique

3.14.2 Rectifier Inverter configuration with level shifted modulation technique

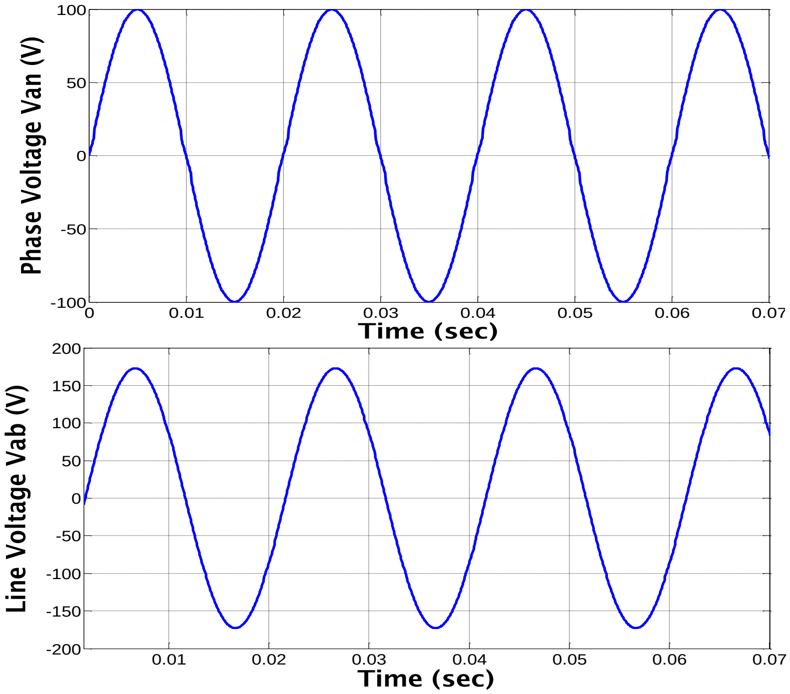


Fig. 3.56 Output phase and line voltage waveform of eleven level cascaded rectifier inverter configuration with level shifted modulation technique

3.14.3 Rectifier Inverter configuration with SHE modulation technique

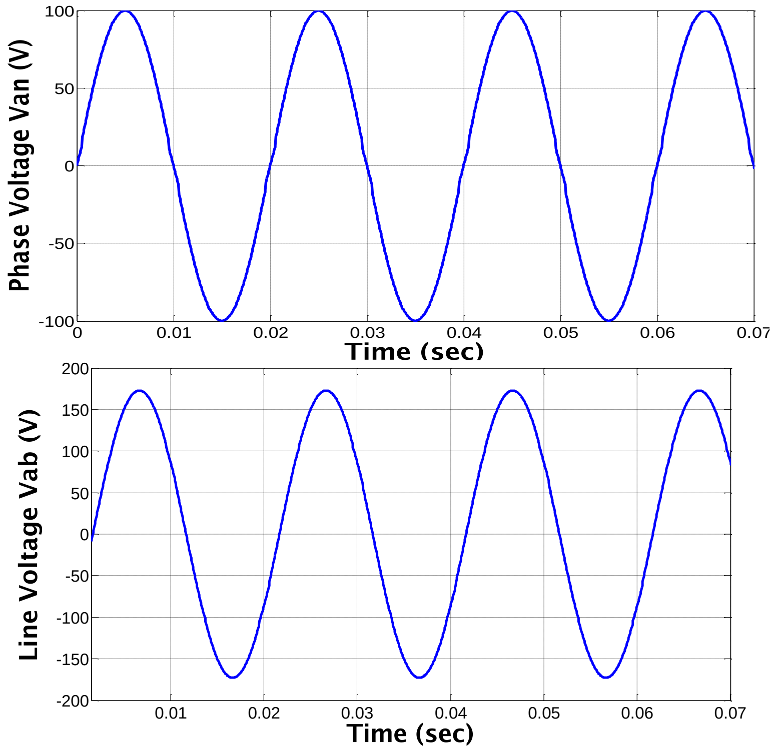


Fig. 3.57 Output phase and line voltage waveform of eleven level cascaded rectifier inverter configuration with Selective Harmonic Elimination modulation technique

3.15 THD values of cascaded eleven level rectifier and inverter

The THD values of the cascaded eleven level rectifier and inverter with different modulation techniques were compared as in Table 3.4.

Table 3.5 Comparison of THD values (in %) of line to line voltage of eleven level cascaded rectifier inverter configuration obtained by implementing various modulation techniques

MODULATION TYPE	THD (in %)	REMARKS
Phase Shifted	0.49	Selective Harmonic Elimination is better with low THD
Level Shifted	0.51	
Selective Harmonic Elimination	0.27	

3.16 Summary

There are various control strategies of multilevel inverters. In this chapter, the multicarrier modulation techniques were implemented in the cascaded multilevel inverter and it was found that the In Phase Disposition Level Shifted Modulation technique has lower THD in comparison to the Phase Shifted Modulation technique. To reduce the switching losses, the Selective Harmonic Elimination Technique was implemented in the cascaded eleven level inverter. The switching angles were calculated offline at the fundamental frequency. The THD of the cascaded eleven level inverter was found to be less than 5% and that of the cascaded rectifier and inverter was found to be 0.27%. Hence, the SHE technique was implemented in the cascaded eleven level inverter in the modeled traction drive.

Chapter 4

ELECTRIC TRACTION

4.1 Introduction

In this chapter, the railway electrification and its traction drive has been discussed. Comparison of the steam and diesel traction drive has been done with the electric traction. Different traction units have been discussed. Traction motor, traction mechanics and various other issues has been studied here.

Traction system can be broadly classified into two groups:

i. One which do not use electrical energy at any stage like steam engine, diesel engine and ICE, and
ii. One that uses electrical energy at some stage or another like electric drive.

In earlier days, the steam engine drives and the diesel engine drives were used [1]. Their characteristics and drawbacks are discussed below.

4.2 Steam Engine Drive

Some of the important features of the rail traction employing steam engine drive are:

1. Simple in construction
2. It does not involve electrification of railway track and hence Low initial cost
3. Easy to maintain
4. Easy speed control
5. No Electromagnetic interference

But it has the following limitations:

1. Even though the train may be idle, the fire has to be banked. This results in low thermal efficiency.
2. It requires adequate supply of feed water at regular interval. Also the supply of water and coal add to the cost.
3. To put the steam engine into operation, steaming time is required.
4. The steam engine is greatly influenced by the firing rate of the coal.
5. Power weight ratio is low.
6. Its centre of gravity is high due to the presence of boiler.
7. It causes environmental disaster with high carbon emissions.

8. The man power requirement is more as compared to the electric drive.
9. It cannot be used in underground railways because of the smoke.

4.3 Diesel Engine Drives

This drive has nearly the same characteristics and limitation as that of the steam engine. It does not have a starting torque and thus requires an external means to start the engine.

4.4 Electric Drive

This involves use of the electric motors fed from overhead distribution system.

Some of its remarkable features are:

1. It is the cleanest form of drive.
2. It has high starting torque.
3. It has high power to weight ratio.
4. It enables quicker acceleration.
5. Railway electrification leads to rural electrification which is the most important industrial development.
6. It requires less maintenance.
7. It does not consume time to start
8. Smooth braking is possible with electric braking
9. No coal and water required and hence saves money.

Every coin has two sides. Similarly, the electric drive too has some limitations. These include:

1. High capital cost is required for electrification
2. Power failure can affect the railway system.
3. There is problem of electromagnetic interference due to the presence of both the communication lines and power lines.

4.5 Railway Electric Traction Drive

At the end of the nineteenth century, railway electrification emerged as a means of traction [24]. The advent of power electronics concept has proved to a blessing in the field of traction. It supplies the energy of the catenaries to traction motors in a controlled manner [25].

There are mainly three types of traction units. These are:

1. DC traction units: these units draw Direct Current from either a conductor rail or an overhead line.
2. AC traction units: these draw alternating current from an overhead line.
3. Multi-system unit: These units operate under several different voltages and current types.

In 1925, electric traction at 1.5kV DC was introduced in India. Later, in 1957, 25kV, 50 Hz, AC was used for electric traction in India [26]. Figure 4.1 is an illustration of an electric locomotive. It can be seen that it consists of the transformer, the main rectifier, the main inverter and the three phase AC motors [27]. This thesis is mainly concerned with the main rectifier, main transformer, an inverter and three phase AC motors. So these are discussed here in brief.

Main transformer is used to step down the supply voltage before it can be used by the train. Main rectifier is mainly used for the conversion of AC to DC. Main Inverter is mounted on the trains to provide alternating current from direct current. It is used for three phase drives. Three phase AC motors are used to generate tractive force to provide accelerate to the train. Earlier DC motors were used but nowadays, three phase AC motors are used.

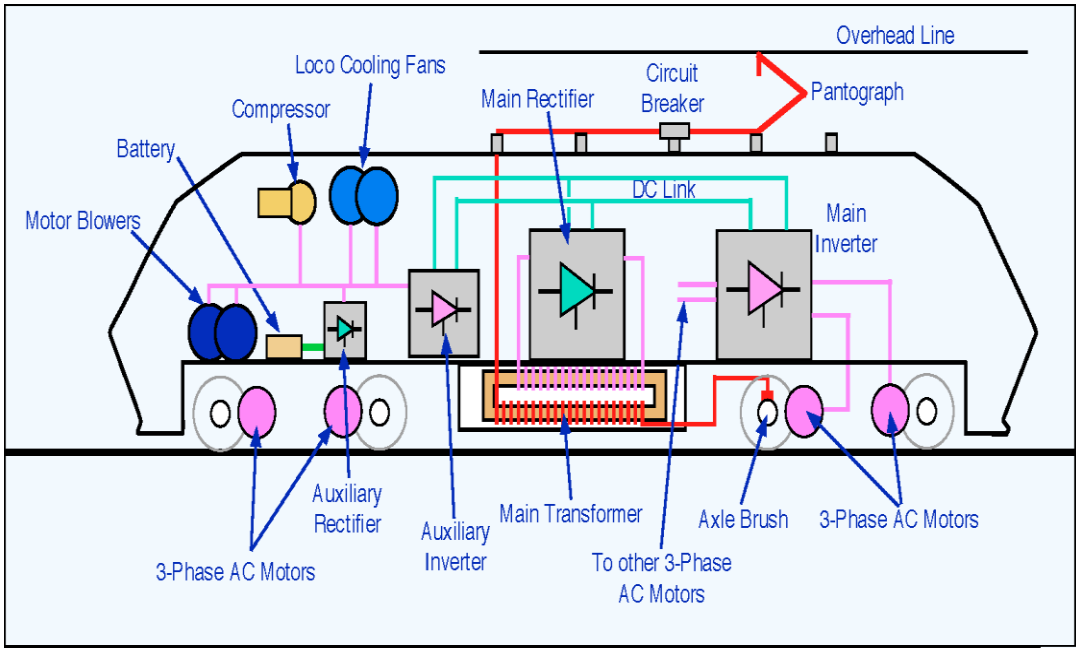


Fig. 4.1 Schematic layout of an electric locomotive

4.6 Tractive Effort

"Tractive effort developed by the traction unit is the force provided at the wheel rims for moving the unit and the train"- as defined in [28].

It performs the following things:

i. It provides necessary acceleration
ii. It overcomes the train resistance
iii. It overcomes the gradient
iv. It provides the necessary effort to overcome the curvature.

4.7 Train Movement

The study of the train movement is done with the help of a speed time curve. The speed time curve of a train running on a main line is shown in Fig. 4.2.

There are five different periods in the run [28]:

1. Notching Up period (t_0=0 to t_1=0.05hr): During starting, motor fluctuates. Therefore, the torque developed by the motor and tractive effort also fluctuates. Since the average tractive effort remains same, the acceleration also remains constant and the speed time curve is therefore a straight line.

2. Acceleration on speed curves (t_1=0.05hr to t_2=0.15hr): Here the acceleration decreases with speed.

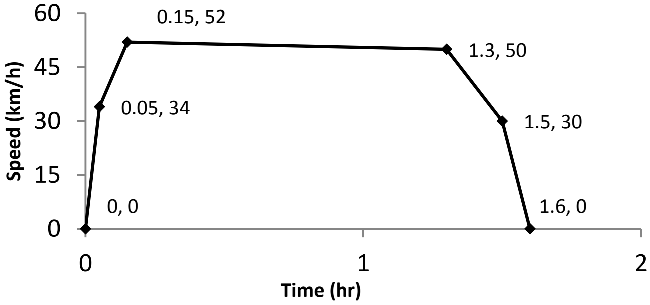


Fig. 4.2 Speed-time curve of a train

3. Free running period (t_2=0.15hr to t_3=1.3hr): During this period, train runs at constant speed.

4. Coasting Period (t_3=1.3hr to t_4=1.5hr): During this period, supply to motors is cut off and train is allowed to run under its own momentum. The speed of the train gradually decreases because of its own resistance.

5. Braking Period (t_4=1.5hr to t_5=1.6hr): At the end of the coating period, brakes are applied to stop the train.

The traction motor determines the acceleration and free running periods of the train. The train resistance determines the coasting period whereas the braking retardation decides the braking period. Practically, the shape of the speed-time graph is different as the distance covered by the train involves various gradients. In some cases like in short suburban service, the free running period may be totally absent. Similarly, in main line service, free running period will be more whereas the starting period will be negligible. The speed time curve is the most important part while electrifying a track. The scheduled train speed and the energy consumption can be determined from this curve.

4.8 Traction Motors

A good traction motor should have the following features:

i. Simple speed control
ii. Better speed torque characteristics
iii. High starting speed
iv. It should be suitable for dynamic or regenerative braking
v. The commutations should be good even the supply voltage fluctuates.
vi. It should be robust and withstand continuous vibration due to the high speed.
vii. It should have less weight and small size.
viii. They should be protected from dirt and dampness.

All these above requirements are not fulfilled by any single motor. For DC system, DC series and compound motors are used. For single phase AC system, AC series motor is used and for three phase system, induction motors are used [28].

DC series motors have high starting torque and variable speed characteristics. For this reason, it is very much used for electric traction. But because of presence of brushes and commutation problem, three phase induction motors are used.

Nowadays, the three phase induction motor is generally used as traction motor [9] because of the following reasons:

i. Absence of brushes.
ii. Robustness and reliability with low maintenance
iii. Simple cooling arrangement with enclosed frames
iv. High uniform torque with inherent overload management

v. High power to weight ratio
vi. High voltage operation
vii. Low cost to power ratio
viii. High maximum speeds
ix. Inherent regenerative braking capability
x. Steep torque speed characteristics

4.9 Converters and Transformers in Traction Drive

Earlier, thyristor were used in the converters. But nowadays, IGBTs are replacing GTO thyristor and are commonly used in the cascaded multilevel inverter as it is smaller and requires less current to operate the switching sequences [27]. It offer low on-resistance and require very little gate drive power [29]. Its switching takes place easily and with low power loss [30]. Also it can handle the high power required by the motor drives. The Indian Railways has introduced the first fully IGBT based electric locomotive, WAG-9i, type 31248 in the year 2010. The IGBT based traction propulsion system has lesser losses, better controllability, superior performance, high reliability and modular design as compared to the GTO- based system [10].

The transformer used in the electric locomotive is the most heavy and expensive equipment. It causes several losses and reduces efficiency. It requires a large floor space. Due to the saturation of the transformer, it leads to dc magnetising and dc overvoltage of the inverters [31]. Harmonic currents in the transformer lead to increase in temperature because of the losses. The alternating magnetic field caused by the harmonic current lead to unwanted noise and vibration [32]. Thus, making it uncomfortable for the passengers. But with the help of the cascaded multilevel inverter, this magnetically coupled bulky transformer can be eliminated and the multilevel inverter can be used for stepping down the voltage. This transformerless drive increases efficiency and reduces the cost of the traction drive.

4.10 Electric Braking While Stopping

When the supply is cut off from the motors, the speed decrease and gradually come to rest. So in order to bring the motor to rest quickly, brakes has to be applied [28,33]. Brakes can be either mechanical or electrical brakes. Because of the frequent wear of the mechanical brakes, high maintenance is required. To avoid this, electrical braking is done to have smooth and quick braking with low maintenance cost.

There are three types of electrical braking: plugging, rheostatic and regenerative braking.

Plugging in induction motor occurs when any of the two stator phases are reversed. The direction of the rotating field reverses. The direction of the rotor and stator are opposite in nature and the slip is greater than unity.

Rheostatic braking or DC dynamic braking of induction motor takes place, when the supply of an IM is cut off for braking. It will draw the magnetising current from the supply and no voltage could be generated. However, if a DC current is passed through the stator, a steady flux will be generated in the air gap and the rotation of the short circuited rotor in this flux produces an emf. Thus, a sufficient current is produced for the braking torque. In the case of slip ring IMs, extra resistance is added to the rotor circuit for braking. During the braking period, the rotor current is in opposite direction to the one in normal running condition. Fig. 4.3 shows the different types of stator connections during DC rheostatic braking.

Regenerative braking of induction motor takes place when the rotor and stator rotates in the same direction and the speed is above the synchronous speed. It usually takes place in the downward motion of the hoist mechanism. Here the kinetic energy of the rotating part is fed to the supply.

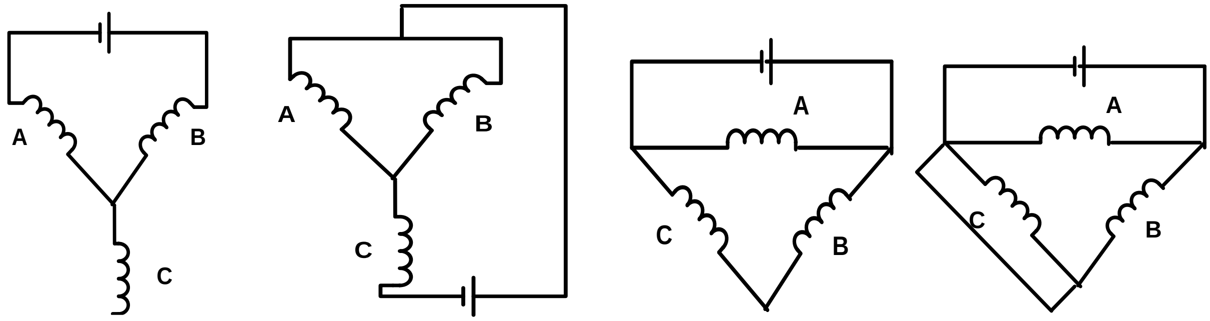


Figure 4.3 Different types of stator connections during DC rheostatic braking

Comparison of different braking methods of induction motor [33]:

Plugging or reverse current braking is a simple control scheme with a relay to stop. There is uniform current loading in all the three phases. But there is a significant amount of losses, heating of the machines, motor running in reverse direction due to the malfunction of the relay and also the appearance of the high voltage at the slip rings.

Regenerative braking takes place only at high speeds (super synchronous speeds). It is applicable in hoisting type mechanisms or with a multi speed squirrel cage motor.

DC rheostatic braking is the most preferred method as the braking can take place even at low speed and also there is no possibility of the reversal of the motor. We can have automatic control of this braking process by means of closed loop.

So, a transformerless railway traction drive with DC dynamic braking has been modelled using an IGBT based eleven level cascaded converter systems.

4.11 Simulation Results of Railway Traction Drive

The traction drive was simulated in MATLAB/SIMULINK using IGBT based eleven level cascaded converter feeding to four number of squirrel cage induction motors connected in parallel. On comparing the multicarrier SPWM with Selective Harmonic Elimination modulation technique, the latter was found to be an efficient technique with lower THD and lower switching losses. Hence, Selective Harmonic Elimination technique was implemented in the converter system.

A three phase, 25kV, 50Hz supply of the catenary voltage is stepped down to three phase, 400kV, 50 Hz to be used by the induction motors. Four numbers of 5 HP induction motor are used to generate the tractive force required by the railway traction. The specification of the induction motors are given in Appendix I. DC dynamic braking is used for electrical braking in the motors.

From Fig. 4.4, it can be seen that the supply voltage of 25kV has been reduced to 400V which is the rated voltage of each motor. When supply was cut off, the voltage gradually becomes zero and during braking a constant DC supply was used

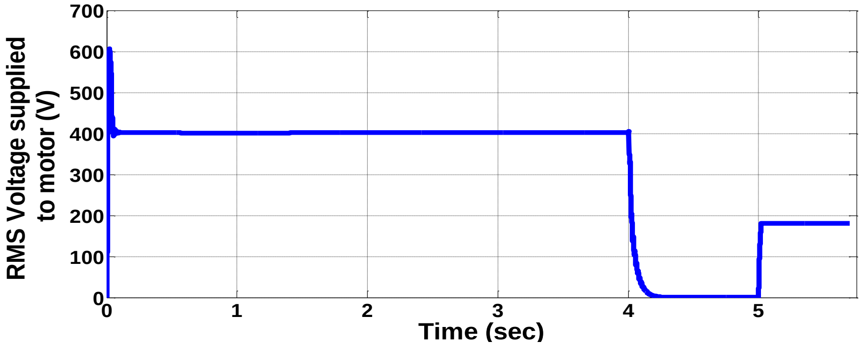


Fig. 4.4 rms voltage fed to the induction motor

Using this rectifier inverter configuration in the railway traction drives, the speed time curve was obtained as shown in Fig. 4.5.In the speed –time curve, the five regions can be seen: notching up period from 0 to 1 sec, acceleration from 1 to 2.2 sec, free running period from 2.2 to 4 sec, coasting period from 4 to 5sec and braking period from 5 to 5.7 sec.

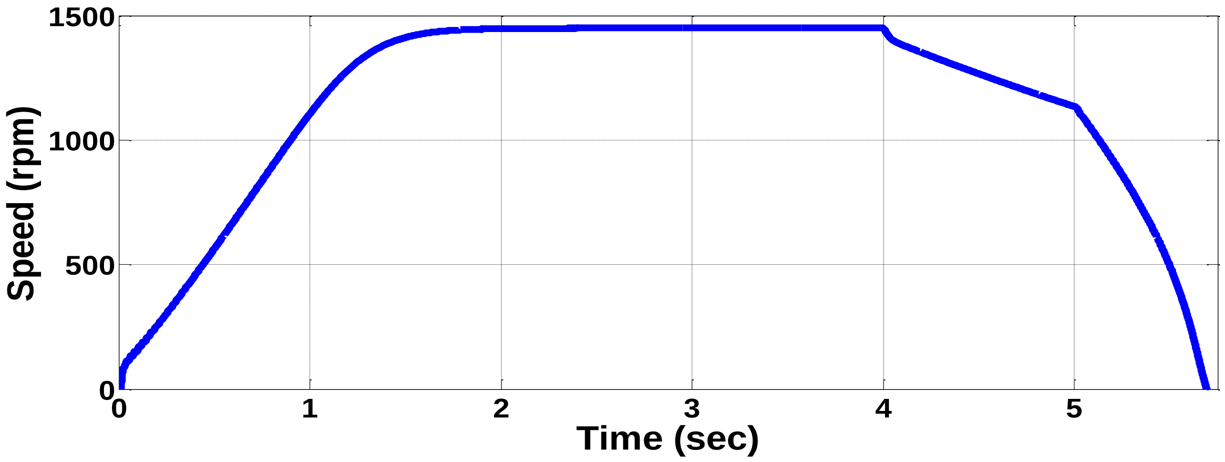


Fig. 4.5 Speed time curve of the train

The electromagnetic torque developed by the induction motor drive can be seen in Fig. 4.6.At starting, a high torque was developed. At time=4 sec, the supply was cut off, hence torque approaches zero after a negative value. At time = 5 sec, DC dynamic braking was applied and the torque became negative and this is the braking torque.

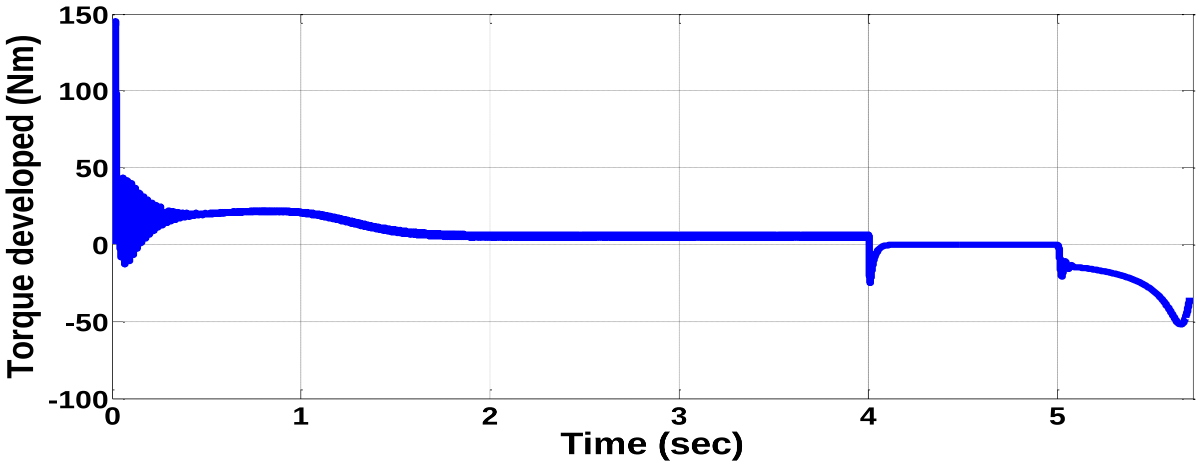


Fig. 4.6 Torque developed by the induction motor

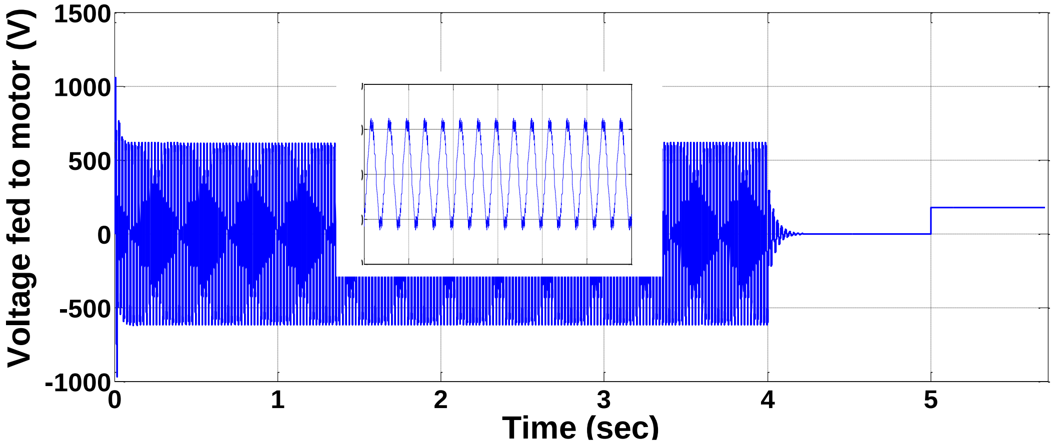


Fig. 4.7 Output voltage of the inverter fed to the motors

Fig.4.8 shows the output rms current of the inverter that is supplied to the induction motor. Fig. 4.9 and Fig. 4.10 shows the rotor current and stator current of the induction motor. It can be seen that when a DC supply is given to the IMs, the stator current is also a DC.

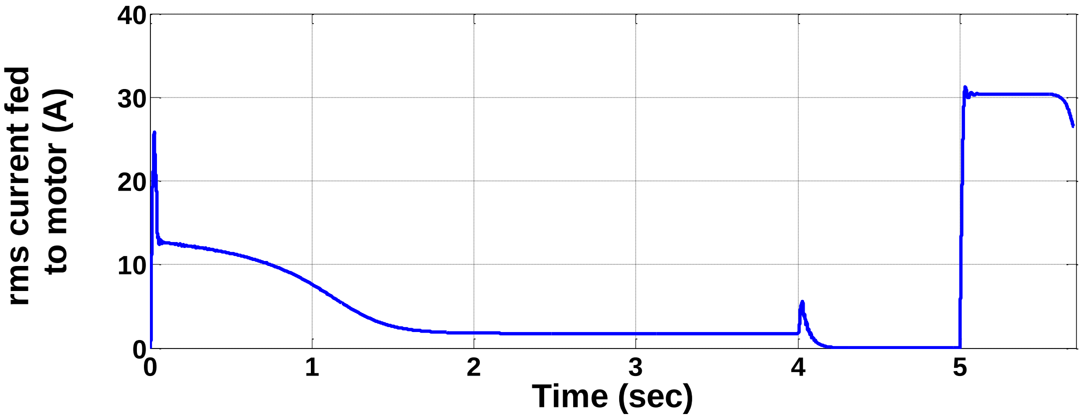


Fig. 4.8 rms current fed to the motor

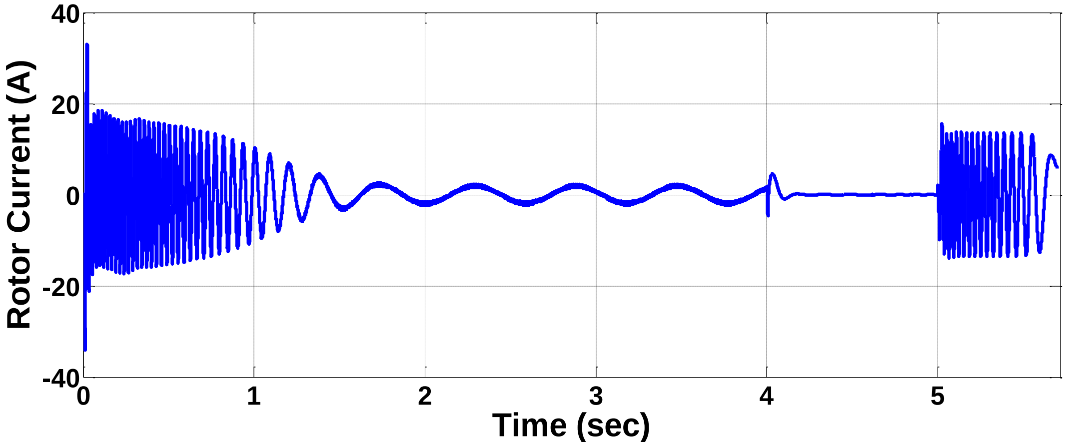


Fig. 4.9 Rotor current of each induction motor

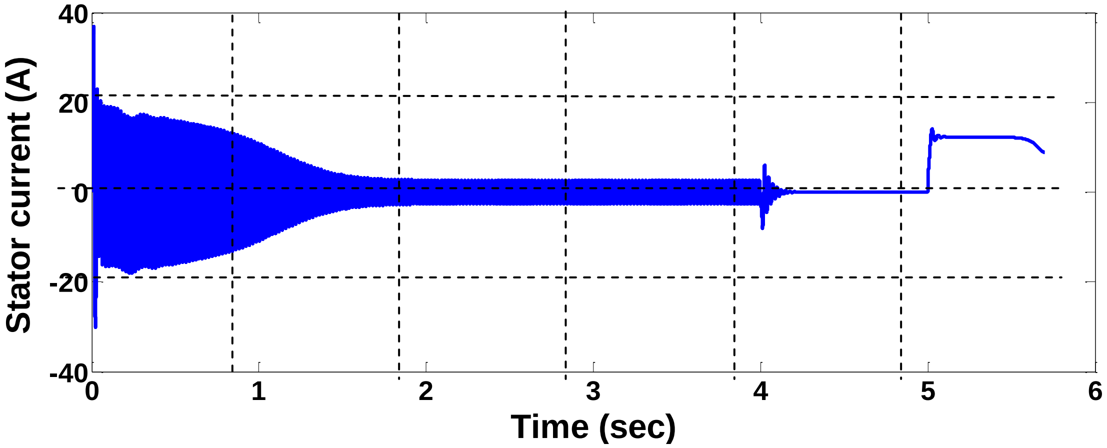


Fig. 4.10 Stator current of each induction motor

The active and reactive power consumption by the induction motors can be seen in Fig. 4.11 and Fig. 4.13 respectively.

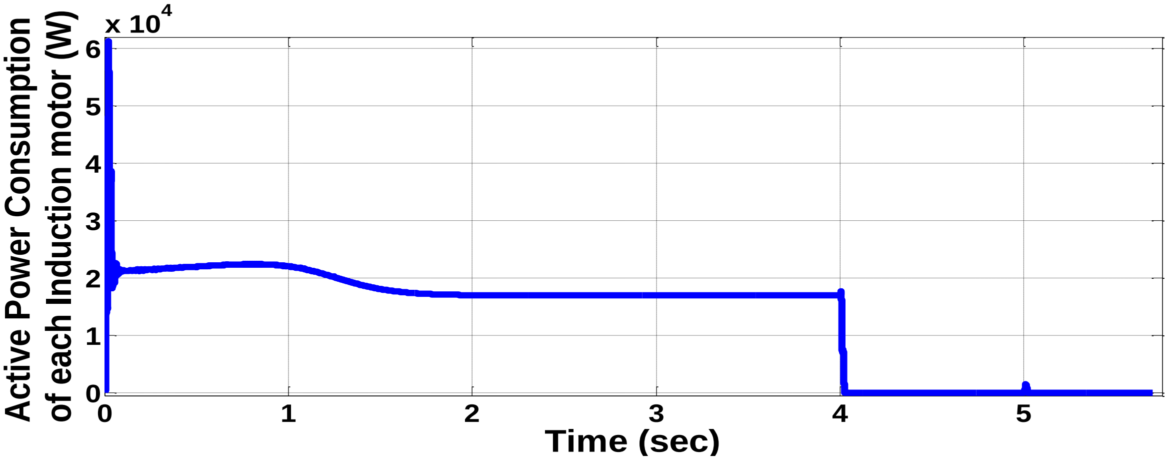


Fig. 4.11 Active Power consumption by each induction motor

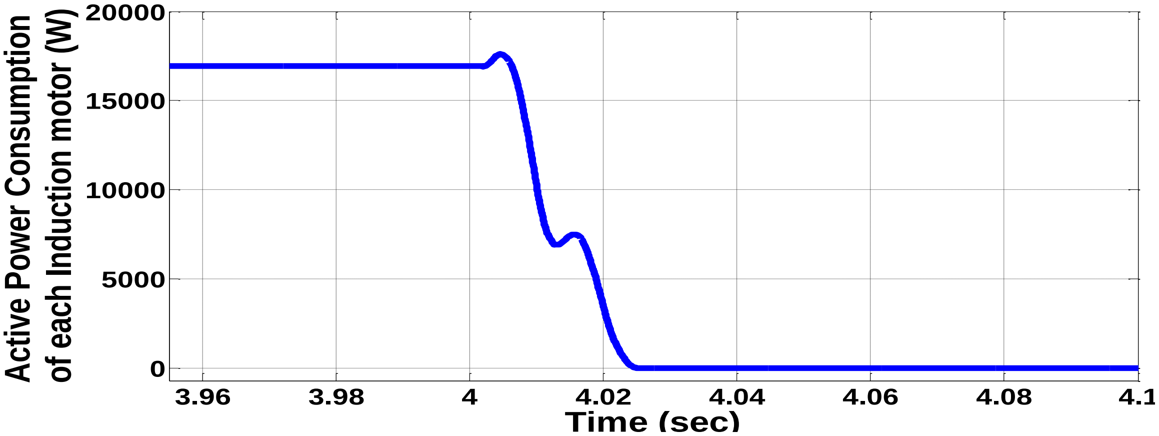


Fig. 4.12 Active power consumption during the coasting period

From Fig. 4.12, it can be seen that there is an overshoot in the active power consumption when the supply is cut off. It is because the induction motor draws small amount of power from the supply to meet the losses taking place in the motor. Initially, on no-load, the starting current is high. Also it draws high reactive component of current i.e. magnetizing current for flux generation. Hence the active and reactive power is large during starting as shown in Fig. 4.11 and Fig. 4.13.

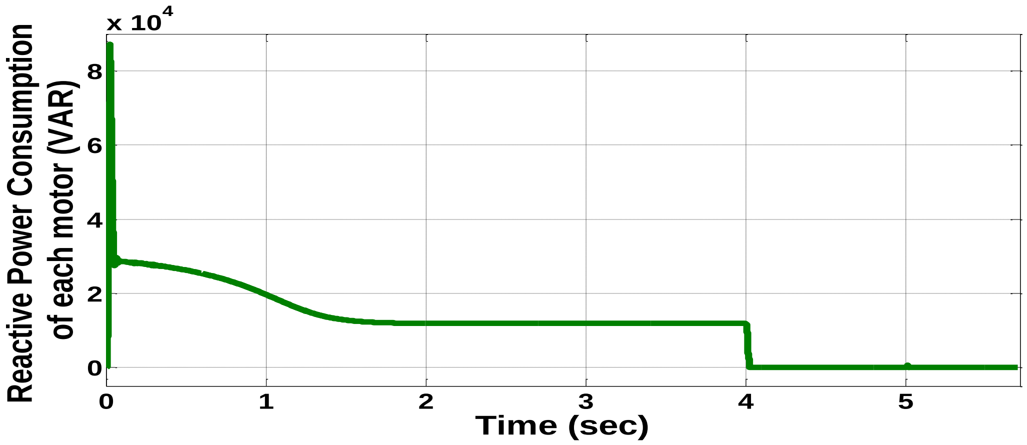


Fig. 4.13 Reactive Power Consumption of each induction motor

During the coasting period, the reactive power gradually decreases to zero as in Fig. 4.14.

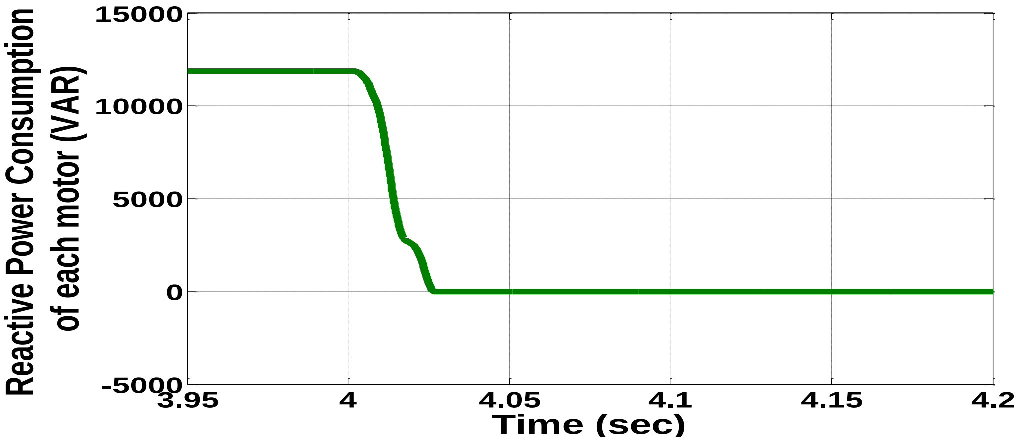


Fig. 4.14 Reactive power consumption of each induction motor during coasting period

In order to bring the train to stop, DC dynamic braking was applied at time= 5 sec. a DC supply of 200 V was applied. The braking current obtained after applying DC dynamic braking is shown in Fig. 4.15. The negative value implies braking is applied.

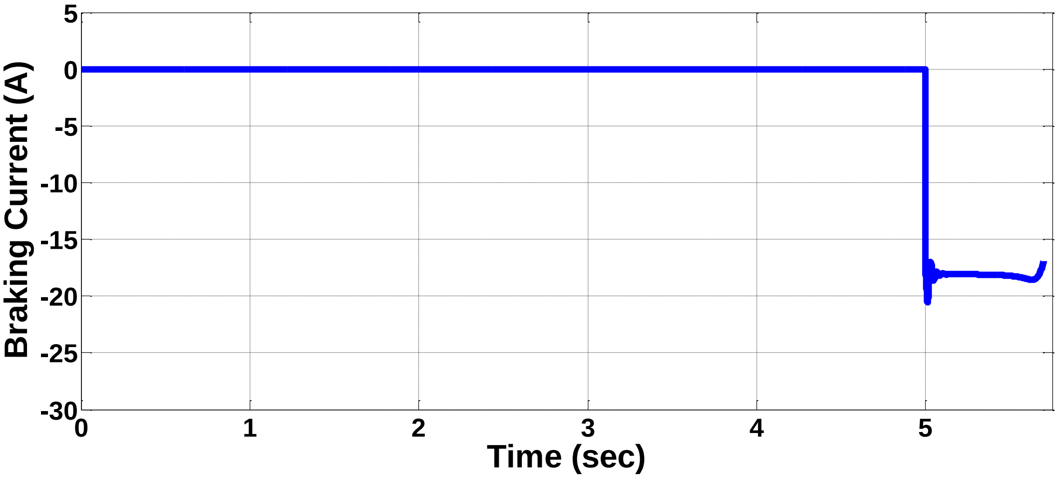


Fig. 4.15 Braking current through the braking resistors when the DC dynamic braking is applied

4.12 Summary

It was found that the cascaded multilevel rectifier and inverter can be used in the traction drive of the railway system. It can step down the supply voltage to the rated voltage of the Induction motor. Hence, it eliminates the need of the transformer. This leads to a transformerless railway traction drive.

Chapter 5

CONCLUSION

AND

SCOPE FOR FUTURE WORK

5.1 Conclusion

The three level, five level, seven level, nine level and eleven level cascaded H-bridge inverters were simulated in MATLAB-Simulink environment. Two types of Multicarrier Pulse Width Modulation – Level Shifted Modulation and Phase Shifted Modulation were implemented for the cascaded multilevel inverter. Bipolar modulation and unipolar modulation techniques were used for a two level H-bridge inverter. The following things can be concluded about the modulation techniques and the multilevel inverters:

1. Unipolar Modulation technique is better than Bipolar Modulation technique. It is because:
    a. The output voltage switches between either between zero and $+V_d$ during the positive half-cycle or between zero and $–V_d$ during the negative half-cycle of the fundamental frequency. So the voltage stress across the switches of the inverter is less as compared to that of the bipolar modulation.
    b. The value of THD obtained in case of unipolar modulation is less than that of the bipolar modulation.
2. Among the Level Shifted Modulation techniques, the In Phase Disposition (IPD) modulation is better in terms of THD.
3. Level Shifted Modulation was found to have better THD values as compared to Phase Shifted Modulation.
4. As the number of levels of the output voltage of the inverter increases, the synthesized waveform has more steps, which produces a staircase wave that approximates to a sinusoidal waveform.
5. Also as the level of the output voltage increases, the harmonic distortion of the output wave decreases.
6. Selective Harmonic Elimination (SHE) Modulation Technique is found be better in comparison to the above mentioned modulation techniques. The THD of the output line voltage of the eleven level inverter is comparatively low (less than 5%).

Thus, on comparison it was found that SHE technique is best suitable for the cascaded eleven level inverter. Hence, this technique was implemented in cascaded rectifier also. The cascaded rectifier inverter configuration with SHE modulation was used in the railway traction drive. It was found that the cascaded rectifier inverter configuration gave sinusoidal output waveform. This converter system can meet the power or voltage requirement of the traction drive. The cascaded eleven level converter system modeled in this project can be used in traction drive consisting of four induction motors for stepping down the catenary voltage to the rated voltage of the induction motors. Thus, this model eliminates the necessity of the transformer in railway traction and hence lowers the cost and floor space and increases the efficiency of the traction drive.

5.2 Scope for Future Work

The following are the scope for the future work that can be performed for this traction drive:

1. Space Vector Modulation technique can be implemented for the cascaded rectifier inverter configuration used in the transformerless traction drive.
2. Direct Torque Control strategy can be employed in the transformerless inverter traction drive

REFERENCES

[1] H. Partab, Modern Electric Traction,4th ed., Dhanpat Rai and Co. , 2003, pp. 1-10,65-68.

[2] Samir Kouro, Mariusz Malinowski *et. al.*, "Recent Advances and Industrial Applications of Multilevel Converters", *IEEE Transactions on industrial electronics*, vol.57, no.8, pp. 2553-2580, Aug 2010.

[3] Farhad Shahnia and B.B.Sharifian, "Harmonic analysis and modelling of transformerless electric railway traction drives," *13th International conference on Electrical Drives and Power Electronics (EDPE),* Dubrovnik, Croatia, 26-28 Sep 2005.

[4] Jose Rodriguez, Jih-Sheng Lai and Fang Zheng Peng, "Multilevel Inverters: a survey of topologies, controls, and applications," *IEEE Transactions on Industrial Electronics*, vol. 49, pp. 724-738, 2002.

[5] Leopoldo G. Franquelo, Jose Rodriguez, *et. al.*, "The Age of Multilevel Converters arrives", *IEEE Industrial Electronics Magazine*, vol. 2, Issue 2, pp. 28-39, June 2008.

[6] V.Kumar Chinnaiyan, Dr. Jovitha Jerome, J. Karpagam, and T. Suresh, "Control techniques for Multilevel Voltage Source Inverters," in *Proceedings of The 8th International Power Engineering Conference (IPEC 2007),* Singapore, pp. 1023-1028,3-6 Dec 2007.

[7] Muhammad H. Rashid, "Power Electronics Circuits, Devices and Applications, 3rd ed. , PEARSON publication, 2009.

[8] R. J. Hill, "Traction Drives and Converters", *2nd IEE Residential Course on Railway Electrification Infrastructure Systems, IEE Digest*, vol. 2005, Issue 1087, Canterbury, UK, 23-27 May 2005.

[9] R. J. Hill, "Electric railway traction Part 2 Traction drives with three-phase induction motors", *Power Engineering Journal*, pp. 143-152, Jun 1994.

[10] www.clw.indianrailways.gov.in

[11] Jin Wang and Damoun Ahmadi, "A Precise and Practical Harmonic Elimination Method for Multilevel Inverters", *IEEE Transactions on Industry Applications*, vol. 46, no. 2, pp. 857-865, Mar-Apr 2010

[12] S. H. Hosseini, M. Ahmadi, S. Ghassem Zadeh, "Reducing the output harmonics of Cascaded H-bridge Multilevel Inverter for Electric Vehicle Applications" , *8th International Conference on Electrical Engineering/ Electronics, Computer Telecommunications and Information Technology (ECTI-CON 2011)*, Thailand, pp. 752-755, 17-19 May 2011.

[13] Bin Wu, High Power Converters and AC Drives, IEEE Press, Wiley-Interscience, A John Wiley and Sons Inc., Publications, 2006.

[14] V. Naga Bhaskar Reddy, V. Narasimhulu, Dr. Ch. Sai Babu, "Control of Cascaded Multilevel Inverter by using carrier based PWM technique and implemented to Induction Motor drive," *International Journeal on Automatic Control and System Engineering (ICGST-ACSE Journal),* vol. 10, Issue 1, Dec 2010.

[15] Wenyi Zhang, Qiang Zhang, Wensheng Chen and Liuzhong Zhang, "Analyzing of Voltage Source Selective Harmonic Elimination Inverter," *in Proceedings of the 2011 IEEE*

Internation Conference on Mechatronics and Automation , Bejing, China, pp. 1888-1892, 7-10 Aug 2011.

[16] F. Z. Peng, J. W. McKeever and D. J. Adams, "Cascade Multilevel Inverters for Utility Applications", *in Proceedings of Industrial Electronics Conference (IECON),* vol. 2, pp. 437-442, 1997.

[17] L. M. Tolbert, F. Z. Peng and T.G. Habetler, "Multilevel converters for large electric drives", *IEEE Transactions on Industry Applications,* vol. 35, no. 1, pp. 36-44, Jan/Feb 1999.

[18] R. Lund, M. D. Manjrekar, P. Steimer , T. A. Lipo, "Control strategies for a hybrid seven-level inverter", *in Proceedings of the European Power Electronic Conference*, Lausanne, Switzerland, Sep 2009.

[19] Toshiji Kato, "Sequential Homotpy-Based Computation of Multiple Solutions for selected Harmonic Elimiantion in PWM Inverter", *IEEE Transaction on Circuits and Systems-I: Fundamental Theory and Applications,* vol. , no. 5, pp. 586-593, May 1999.

[20] John N. Chiasson, Leon M. Tolbert, Keith J. McKenzie, Zhong Du, "Control of a Multilevel Converter using Resultant Theory", *IEEE Transaction on Control Systems Technology,* vol. 11, no. 3, pp. 345-353, May 2003.

[21] John N. Chiasson, Leon M. Tolbert, Keith J. McKenzie, Zhong Du, "A new approach to solving the harmonic elimination equations for a multilevel converter", *in Proc. IEEE Industry Applications Society Annual meeting*, Salt Lake City, UT, pp. 640-645, Oct. 12-16, 2003.

[22] Burak Ozpineci, Leon M. Tolbert, John N. Chiasson, "Harmonic Optimisation of Multilevel Converters using Genetic Algorithms", *IEEE Power Electronics Letters,* vol. 3, no. 3, pp. 92-95, Sep 2005.

[23] Jagdish Kumar, Biswarup Das, and Pramod Agarwal, "Selective Harmonic Elimination technique for a Multilevel inverter," in *Proc. of 15th National Power Systems Conference (NPSC),* IIT Bombay, pp. 608-613, 16-18Dec 2008.

[24] http://en.wikipedia.org/wiki/Railway electric_traction

[25] Mauro Carpita, Mario Marchesoni, Marc Pellerin, and David Moser, "Multilevel Converter for Traction Application: Small Scale Prototype tests Result", *IEEE Transaction on Industrial Electronics,* vol. 55, no. 5, pp. 2203-2212, May 2008.

[26] H. D. Awasty, "Railway Electrification in in India", *in Proceedings of IEE* , vol III, no. 12, pp. 2071-2074, May 2008.

[27] www.railway_technical.com

[28] N. V. Suryanarayan, "Utilisation of electric power including electric drives and traction", New Age International (P) Limited, 2005.

[29] K. Thiyagarajah, V. T. Ranganathan, B. S. Ramakrishna Iyengan, "A high switching frequency IGBT PWM rectifier / inverter system for AC motor drives operating from single phase supply", *IEEE Transactions on Power Electronics,* vol. 6, no. 4, pp. 576-584, Oct. 1991.

[30] A.K.Verma, P.R.Thakur, K.C.Jana, and G.Buja, “Cascaded multilevel inverter for Hybrid electric vehicles,” *2010 India International Conference on Power Electronics (IICPE),* New Delhi, 28-30 Jan 2011.

[31] P. G. Song, E. Y. Guan, L. Zhao, S. P. Liu, “Hybrid Electric Vehicles with a multilevel cascaded converter using Genetic Algorithm” , *2006 1st IEEE Conference on Industrial Electronics and Applications,* 24-26 May 2006.

[32] Adrian David Cheok, Shoichi Kawamto, Takeo Matsumoto and Hideo Obi, “ High power AC/DC converter and DC/AC inverter for high speed train applications”, in *Proceedings of IEEE TECON 2000,* vol. 1, pp. 423-428, 24-27 Sep 2000.

[33] S. K. Pillai, A first course on electrical drives , 2nd ed., New Age International Publishers, 2004.

APPENDIX I

The specification and the parameters of the induction motor is :

Power = 5HP, line-line voltage=400V, frequency = 50Hz, speed= 1445 rpm, Stator resistance R_s = 7.34, leakage stator inductance L_{ls} =0.021 H, mutual inductance L_m = 0.5H,Rotor resistance R_r = 5.64 Ω, leakage rotor inductance L_{lr} = 0.021 H, moment of inertia J=0.16 kg-m^2, frication factor B=0.035 kg-m^2/s.