IMPROVEMENT OF POWER QUALITY USING HVDC SYSTEM

DISSERTATION-II

Submitted in partial fulfilment of the
Requirement of the award of

Degree of
MASTER OF TECHNOLOGY
IN
ELECTRICAL ENGINEERING
(POWER SYSTEM)

Submitted by

Registration No:

Under the Guidance of

School of Electronics and Electrical Engineering
Lovely Professional University
Punjab

APRIL-2017

CANDIDATE'S DECLARATION

I **Amar Shukla**, student of M.tech (Electrical Engineering) under school of Electrical and Electronics Engineering of Lovely Professional University, Punjab, hereby declare that all the information furnished in this dissertation report is an authentic record of my own work carried out under the supervision of "**Mrs. Preeti Khurana**" Assistant Professor, School of Electrical and Electronics Engineering. The matter presented in this dissertation has not been submitted to Lovely Professional University or to any other university or institute for the award of any degree.

Signature of the Student
Reg. No. 11501090
Date:

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Signature of the Supervisor

The M.tech Viva-Voce Examination of (Dissertation) has been held on ___________ and found satisfactory/Not satisfactory.

Signature of the Internal Examiner Signature of the External Examiner

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my mentor **“Mrs. Preeti Khurana” (**Assistant Professor) for her guidance, encouragement, and support throughout the course of this work. It was an invaluable learning experience for me to be one of her students. From her, I have gained not only extensive knowledge but also a sincere research attitude. I express my sincere gratitude to **“Mr. Niraj Kishore”** (Assistant Professor) for his invaluable suggestions and constant encouragement all through the research work. My thanks are extended to my teachers; **“Mr. Satish Julakanti Reddi”, “Mr. Mukul Chanakya”, “Ms. Varsha Jaiswal”** and **“Mr. Dara Siva Kumar”** who helped me to make it possible.

I would also like to acknowledge the Head of the School of Electrical and Electronics Engineering and entire teaching and non-teaching staff of the Department for establishing a working environment and for constructive discussions. Finally, I am always indebted to all my family members especially my parents, for their endless love and blessings.

NAME: AMAR SHUKLA

REG. NO: 11501090

CERTIFICATE

This is to certify that the declaration statement made by this student is correct to the best of my knowledge and belief. He is doing Dissertation-II work under my guidance and supervision. The present work is the result of his original investigation, effort, and study. No part of the work has ever been submitted for any other degree at any University. The Dissertation work is fit for the submission and partial fulfilment of the conditions for the award of M.Tech degree in Electrical and Electronics Engineering from Lovely Professional University, Phagwara.

Signature and Name of the Mentor:

Designation:

School of Electronics & Electrical Engineering
Lovely Professional University
Phagwara, Punjab

Date:

ABSTRACT

HVDC technology is used in high power transmission system for interconnection of asynchronous system and/or for bulk power transmission. HVDC link uses rectifier and VSI for the conversion process but it has got some drawbacks such as ripple content present in 12-pulse rectifier and THD present at AC side of inverter and reverse flow of fault signal to the DC link. This dissertation work is primarily focus on reducing the ripple content present in the DC output waveform and THD in AC waveform after inverter.

First is 24-pulse converter which has four 6-pulse converters are connected in parallel and they are supplied by four Phase shifting transformers (PST). PSTs are used to create 15^{o} phase shift between sources of each bridges. It primarily focuses on harmonics reduction. 24-pulse converter is able to reduce 5^{th}, 7^{th}, 11^{th} and 13^{th} which are injected by the use of 6-pulse and 12-pulse converters. However, AC output voltage would have 23^{th} and 25^{th} but it can be simply filtered out.

Second is the use of five-level MLI to reduce the THD from AC output current of MLI. Controlling strategy is done with the help of sinusoidal pulse width modulation (SPWM). Use of MLI interrupt the flow of fault signal to the DC link because MLI is not provide bidirectional power flow.

LIST OF TABLES

LIST OF FIGURES

(b) **(c)**	THD of AC output voltage of phase ‘b’ THD of AC output voltage of phase ‘c’	**60** **61**
Figure 8.5 (a) **(b)** **(c)**	THD of AC output current of phase ‘a’ THD of AC output current of phase ‘b’ THD of AC output current of phase ‘c’	**61** **61** **62**

CONTENTS

CHAPTER-1
INTRODUCTION

1.1 BACKGROUND:

Generally, electric power sector has three sectors which are: generation, transmission and distribution. In generation sector, different kind of energies are converted into electrical energy. Transmission activity is dedicated for transporting electrical energy from sending end to end centers. In distribution activity energy is transferred from utility grid to consumers.

In developing years of electrical technologies, generation is made possible with the help of Edison DC generators, therefore, direct current (DC) transmission system was using in earlier years[1]. Ought to unavailability of technology, electric power is transmitted at low voltage levels. Transmission systems were having high voltage drop and losses because they were working at low voltage levels and it was the main drawback of previous systems. To overcome these problems, inventors went for the AC transmission through which power can be transferred for a long distance. After invention of alternating current, transformer came into picture through which power can be transferred for a long distance by increasing the value of voltage. Although in transmission, AC system has the biggest problem which is synchronization of systems, buses and grids etc. Voltage drop at the load end is also a bigger problem and it comes in the system due line impedance which reduces the load end voltage. Distance is the main problem in transmission system because impedance of the line increases with the increase in distance and it is more severe problem in AC transmission but not in DC transmission because AC transmission require minimum three wire to transmit power and DC require only two wire.

In that time, the main challenge was facing by the inventors is to transmit the power over long distances. In Sweden, consumer centers is far away from hydro plant which is established in north to the centers. In 1940's, in order to transmit power for a very long distance from hydro plant to consumer end Swedish state board was planning which is later divided up into Vattenfall and Svenska Kraftnaft. That transmission line was having a 400KV AC voltage level which was the highest voltage level in the world at that time. After few years later, in 1954, mercury-arc valves was developed which lead to the build of first direct current link between the island of Gotland with the mainland of Sweden [2].

With the advent of thyristors in 1967 mercury-arc rectifiers and thyratron tubes are replaced by thyristors because it has better capability than others. Thyristor word is taken from two words which are Thyratron and Transistors. Greek word "thy" is taken from thyratron which means 'switch' and suffix word "-istor" is taken from transistor which recognize that this device belongs to semiconductor devices [32]. Like diode, it also provides output when it is in forward bias but with trigger pulse. It works only in one direction. It is also named as SCR (Silicon controlled rectifier) which differs it from other similar devices like GTO and TRIAC. It doesn't turn-off until current flow in it goes below to level of holding current of it. It commutated by natural or line-line commutation [30]. Properties of ideal SCRs are:

a) It doesn't have voltage drop across it.
b) During reverse bias, there is no reverse current.
c) Zero holding current.

In 1967, Gotland's HVDC link was made with the help of SCRs and that was the first commercial use of this kind of converter which had SCRs in place of mercury-arc valves.

It is well known that the generation centers and transmission systems established far away from the load centers. The project HVDC system in Itaipu, Brazil, has interconnection between two asynchronous AC systems (50 Hz and 60Hz), with a power rating of 6300 MW, ± 600 kV and around a distance of 800 km. This project shows the maturity of thyristor based HVDC technology.

In United States, currently there are more than 20 DC transmission facilities. 35 DC transmissions across the North American grid as indicated in the map below:

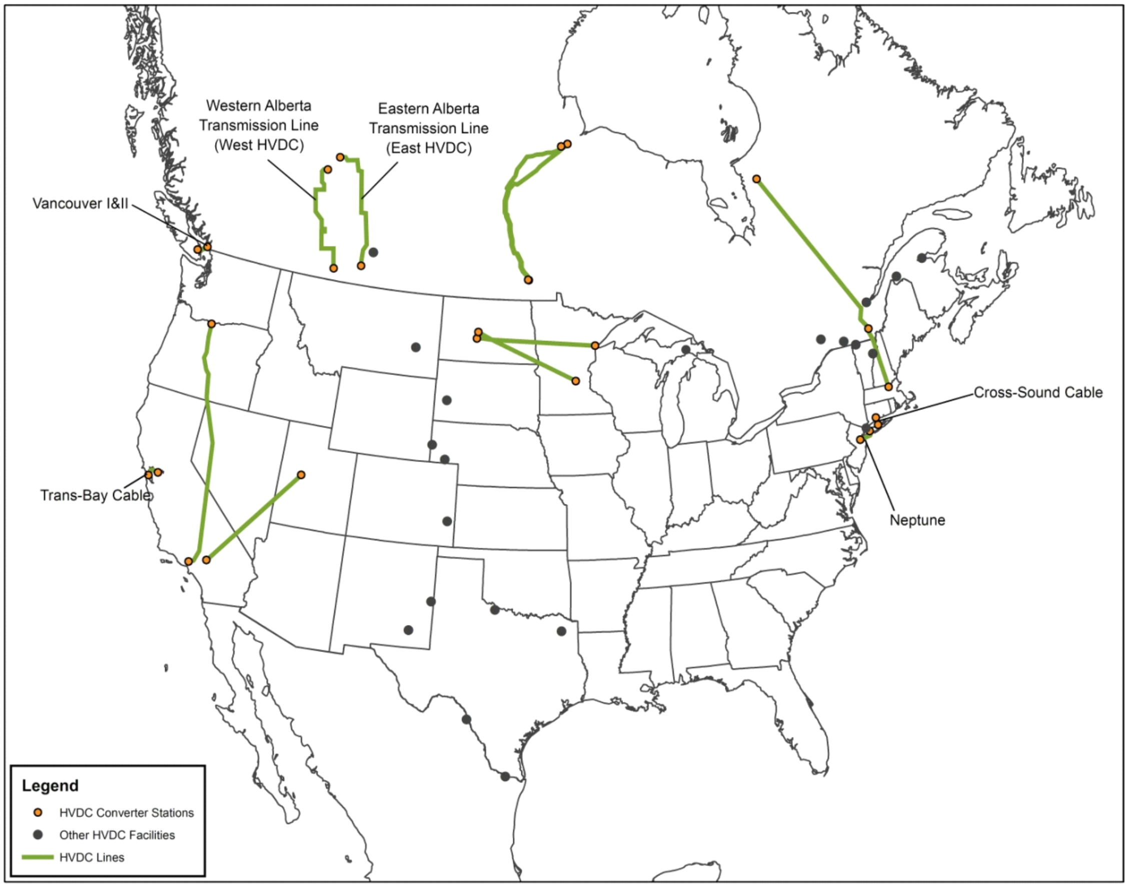


Figure 1.1- DC transmission across the North America.

1.2 HVDC in INDIA:

The India has five different independent regional power grids which are the Northern, Eastern, Western, Southern and Northeastern regions. The HVDC transmission system was chosen because it has advantages over HVAC transmission like lower transmission losses (**R_{ac} = 1.6 R_{dc}**), better power controllability, reduced stresses on cables, connection between asynchronous systems, reduced right-of-way, better stability etc.

India has five HVDC transmission link to enhance the power quality, which are

1. Vindhyachal was commissioned in 1989 (B to B).
2. Rihand-Delhi was commissioned in 1990.
3. Chandrapur-Padghe was commissioned in 1999.
4. Vizag I and Vizag II were commissioned in 1999 and 2002 respectively (B to B).
5. North-East Agra (Stage I in 2014-2015 and Stage II in 2015-2016).

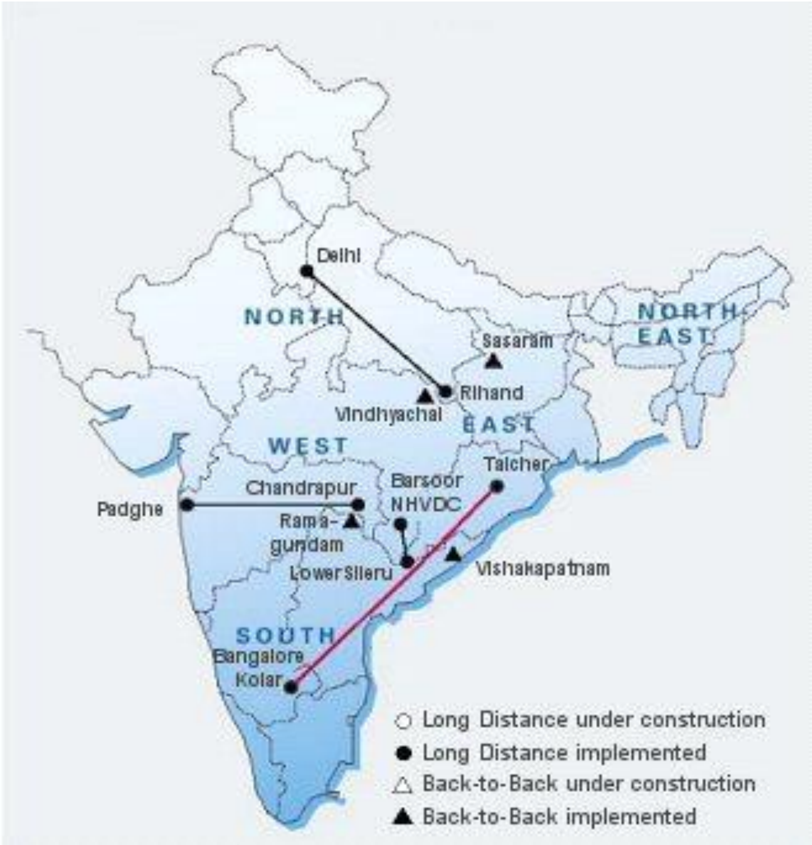


Figure 1.2- HVDC in India.

1.2.1 VINDHYACHAL (1989) - This HVDC back-to-back station is rated with 500MW which connect 400KV AC system with Western regions. It is well known that, the back-to-back link do not have transmission lines and it is used to connect systems having different frequencies. Vindhyachal thermal power plant has three thermal units within a radius of 40km. The three units are: Singrauli (2,000MW), Rihand (2,500MW), and largest Vindhanchal (4,260MW).

Table.1.1- Main data of Vindhyachal.

Commissioning year:	1989
Power rating:	500 MW
No. of poles:	2
AC voltage:	400 kV (both sides)
DC voltage:	70 KV

Type of link	Back-to-back station
Main reason for choosing HVDC:	Asynchronous networks
Application:	Interconnecting grids

Figure 1.3- Vindhyachal HVDC Link.

1.2.2 RIHAND-DELHI (1990) - In India, first HVDC transmission is established in 1990s, which is HVDC Rihand-Delhi. It connects Rihand and Dadri (near Delhi). The HVDC line connects the 3 GW coal-based Rihand Thermal Power Stations in Uttar Pradesh to the Northern region of India. The project has a span of 814 km (506 mi) long bipolar overhead line. The line has 500 KV transmission voltage and maximum transmission power of 1.5 GW and this project was built by ABB and transmitted parallel with existing 400 KV AC lines. On 24 June 1990, during the authorization of the plan, a complete quadrivalve of the Rihand converter station was damaged, and the other two quadrivalve of the same pole got badly damage because of fire which had been occurred due to loose connection on a grading capacitor. That fire was so intense because of that the valve hall was structurally damaged, and the affected converters were taken out of the service for 18 months. Similar incidence has been happened in 1989s on the Itaipu project. These led to CIGRE publishing guidelines on the design of thyristors valves for reducing the fire risks, in 1993s. It is affirmed that the DC transmission are more economically and convenient than AC. In paper [4] or [3], it is mentioned that, the idea of a Trans-European

HVDC grid acting as “Electricity Highways” [3]. The idea of DC lines came for making the tie-line between asynchronous systems. AC lines can only connect the synchronous systems. It helps to transmit bulk power over long distances.

Table.2- Main data of Rihand-Delhi.

Commissioning year:	1990
Power rating:	1,500 MW
No. of poles:	2
AC voltage:	400 kV (both ends)
DC voltage:	±500 kV
Length of overhead DC line:	814 km
Main reason for choosing HVDC:	Long distance, network stability
Application:	Connecting remote generation

Figure 1.4- Rihand-Delhi HVDC Link.

1.2.3 CHANDRAPUR-PADGHE (1999) - The coal is abundant in eastern part of Maharastra state so thermal power plant is situated in that region but power demand is more in western part of state around Mumbai, Nasik and Pune regions. Therefore, there is a HVDC transmission line to connect both regions. The converters which have been used in this system, are manufactured by Bharat Heavy Electrical Limited (BHEL) and ABB (Sweden and India).The 400KV Chnadrapur bus feed 2,700MW of power to the upcoming network. This bus having three 400KV lines between Chandrapur and Mumbai and there is transfer power of 1,200MW.

Table.3- Main data of Chandrapur-Padghe

Commissioning year:	1999
Power rating:	1,500 MW
No. of poles:	2
AC voltage:	400 kV (both ends)
DC voltage:	±500 KV
Length of overhead DC line:	752 km

Main reason for choosing HVDC:	Long distance, network stability, environmental concerns
Application:	Connecting remote generation

Figure 1.5- Chandrapur-Padghe HVDC Link.

1.2.4 VIZAG I and VIZAG II (1999 and 2002)- The consecutive HVDC station Vizag I came into administration in 1999. Powergrid marked an agreement with ABB for Vizag II in September 2002, and the station started working industrially in February 2005. The Vizag II consecutive HVDC station has ostensible DC voltage and current appraisals of 176 kV, 2,841 Ampere. Vizag II is introduced at Gazuwaka, situated close to the city of Vishakhapatnam on India's southeast drift. Sited next to a current HVDC station, it expands the limit with respect to high-voltage control trades by 500 MW. Moreover, the framework gives voltage and recurrence support to both eastern and southern lattices amid power unsettling influences. Vizag I and Vizag

II comprise of two free posts, each with an ostensible power transmission rating of 500 MW. Both establishments utilize air-protected, water-cooled thyristor valves.

Table.4 - Main data of Vizag-I and Vizag-II.

Commissioning year:	2005
Power rating:	500 MW
No. of poles:	1
AC voltage:	400 kV (both sides)
DC voltage:	176 kV
Type of link:	Back-to-back station
Main reason for choosing HVDC:	Asynchronous networks
Application:	Interconnecting grids

Figure 1.6- Vizag I and Vizag II HVDC Link.

1.2.5 NORTH-EAST AGRA - The connection involves four terminals in three converter stations with a 33 percent persistent over-burden rating, empowering an 8,000 MW transformation the biggest HVDC transmission framework ever manufactured. ABB and Bharat Substantial Electricals Ltd. (BHEL) have turnkey duty regarding execution, including framework building, plan, supply and establishment of three HVDC converter stations. Organize one is planned to be operational in 2014-2015, arrange two in 2015-2016. Upper east India has bottomless undiscovered hydropower assets scattered over a vast zone, yet stack focuses are hundreds or even a large number of kilometers away. Control must go through the supposed "chicken neck territory," an exceptionally limit fix of land (22 km width x 18 km of length) in the condition of West Bengal having outskirts with Nepal on one side and Bangladesh on the opposite side.

Table.5- Main data of North-East Agra.

Commissioning year:	2016
Power rating:	6,000 MW (multi-terminal)
No. of poles:	Converter: 4 Line: 2
AC voltage:	400 kV (all stations)
DC voltage:	±800 kV
Length of overhead DC line:	1,728 km
Main reason for choosing HVDC:	Long distance, bulk power
Application:	Connecting remote generation

CHAPTER-2

OBJECTIVES

The main aim of this dissertation-II work is to enhance the energy crises, the world which are facing. India loses 23% power in transmission and distribution. Therefore HVDC system is used to improve power quality which is based on voltage source converter (VSC). Regarding HVDC transmission system, it has been yield that, power can be controlled using DC voltage regulation.

The dissertation-II work has mainly two objectives:

- The first objective of this dissertation-II work is to make a new converter in order to have less harmonics content in DC voltage which in turn reduces the THD. Using multi-pulse converter, output has less ripple content. It means output waveform is smoothed.
- Second objective of this dissertation-II work is to make a multilevel inverter that will give less total harmonic distortion in AC voltage and current to have approximate sine wave.

CHAPTER-3

REVIEW OF LITERATURES

B. gopal et al. (2012), this work proposed power quality improvement for isolated pico-hydropower generation based on an asynchronous generator using conventional electronic load controller (ELC). ELC has a six-pulse uncontrolled bridge rectifier with an auxiliary load and a chopper. It produces harmonic distortion in current and terminal voltage of the generator. A 24-pulse rectifier and a chopper are used in proposed ELC. A polygon wound autotransformer with 24-pulse rectifier is used for reducing the harmonic content to meet the power quality requirement as standardized by IEEE standard 519 [6].

Mr S Dinesh Kumar et al. (2015), this work deals with a noon-isolated 24-pulse controlled rectifier. It consist a polygon transformer with it to reduce current harmonic injection in AC mains to meet the requirement as prescribed by the IEEE-519 standard with varying loads. It contains the comparison of 6-pulse, 12-pulse and 24-pulse converter with a set of power quality indices. The proposed converter is capable to suppress up to 21st harmonics in AC mains. Using this proposed converter, system has less than 8% total harmonic distortion (THD) in input current with variable loads [7].

R. Tamiz Nesan, J. Jegadish (2015), this work deals with 24-pulse converter which has four 6-pulse converters are connected in parallel with two three phase transformers for obtaining the desired phase shift. It's primarily focuses on harmonics reduction because the use of converters introduces harmonics in input currents. 24-pulse converter is able to reduce 5th, 7th, 11th and 13th which are injected by the use of 6-pulse and 12-pulse converters. However, AC output voltage would have 23th and 25th but it can be simply filtered out [8].

Alvaro Ortiz Monroy et al. (2012), this work proposed Transformer Rectifier Unit (TRU) which has four 6-pulse converters and four three phase zigzag-star connected windings configuration with phase shifts of 15^{o}, 30^{o}, 45^{o} and 60^{o} respectively. Simulation results are compared with 12-pulse TRU [9].

Chen Xiao-qiang and Qiu Hao (2015), this work deals with a configuration of zigzag connected autotransformer based 24-pulse controlled rectifier, which is used to feed direct controlled torque for induction motor drives. Simulation results shows that it reduces the harmonic content in AC main as well as DC mains. Effect of nature of load and load variation is also described in this. Comparison of 6-pulse, 12-pulse and 24-pulse converters is also done using different set of power quality indices at AC mains as well DC mains [10].

K. Santosh kumar et al. (2013), this work proposed Electronic Load Controller (ELC) for isolated Pico-hydropower generation using Asynchronous generator (AG). ELC has a six-pulse uncontrolled bridge rectifier with an auxiliary load and a chopper. It produces harmonic distortion in current and terminal voltage of the generator. A 24-pulse rectifier and a chopper are used in proposed ELC. A polygon wound autotransformer with 24-pulse rectifier is used for reducing the harmonic content to meet the power quality requirement as standardized by IEEE-519 standard [11].

K. Srinivas (2012), this work proposed that the transformer rectifier unit introduces undesirable harmonic content in line currents which may lead to shut down of devices or may not be tolerated by power sensitive equipment. There is a significant opportunity to use of converters that produce low harmonic contents in AC current main source. It is well known, to increase the number of pulses in converters total harmonic distortion (THD) can be reduced to a greater extent with it power quality is improved. This work describes the effect of increasing the number of pulses on the performance of converters using THD indices [12].

Sonika Raghuvanshi, Nagendra Singh (2014), this work proposed the multi-pulse converters to reduce total harmonic distortion (THD). Phase shift is introduced by zigzag configuration of transformers. This work has 24, 36, 48 and 60-pulse multi-pulse controlled rectifier for reduction of THD which leads to enhance power quality. Resistor is used as load so all the results are obtained for this [13].

Mamta N. Kokate, Preeti V. Kapoor (2013), for high power application, conventional two level inverter has many limitations. The Multi-Level Inverter (MLI) began with three level inverter which has been very popular for high voltage and high power applications. The basic concept behind this is to use of series-parallel combinations of power semi-conductor switches and DC sources for achieving high power capability. Three levels MLI has three levels which has smoother waveform than conventional, this results in reduction of harmonics. This work deals with different topologies of three level MLI and SPWM technique to generate switching pattern for three levels and five levels MLI [14].

Gobinath.K et al. (2013), this work deals with improvement of power extracting methods. From solar cells, MLI is used for effectively extracting power. MLI enhance the wave shape of

AC output voltage waveform. Seven levels with reduced switches topology is used in this paper work. Selective Harmonics Elimination Stepped Waveform (SHESW) technique is used to reduce lower order harmonics which in turn reduces total harmonic distortion (THD). Switches in inverter are controlled by fundamental switching scheme. Appropriate selection of switching angles gives reduction of harmonics. 3^{rd} and 5^{th} harmonics are eliminated in this work. This topology reduces initial cost and complexity [15].

R. Dharmaprakash, Joseph Henery (2014), this work deals with 2-level and 3-level inverter of diode clamped multilevel inverter (DCMLI) configuration. Switching tables is proposed in this dissertation-I work. Sector identification is used for selection of voltage vector from switching table to generate gate signals. The DCMLI can be extended to n-level inverter with new topology. Line to line voltages is compared as well as THD of both inverters is compared. With affecting its simplicity, direct torque control of induction motor can be easily achieved [16].

Carlo Cecati et al. (2010), this work deals with photovoltaic (PV) system with power electronics devices. This paper has two stages: a DC/DC converter and MLI modulated with PWM. The care should be taken due cascading of converters and there may be problem with MPPT. Single phase H-bridge cascade MLI is used with integrated fuzzy logic controller (FLC). This work proposes the use of fully FLC and an H-bridge power sharing algorithm. Improved performance of inverter over 2-level inverter at low-medium power is proposed [17].

Haitham Abu-Rub et al. (2010), this work proposed that, getting high efficiency and minimum total harmonic distortion (THD) at switching frequency with medium-voltage (MV) multilevel inverter (MLI). Industries are facing common problems that are effective power quality with increased power rating of switches by minimizing switching frequency. Common remedy is taken into account by increasing the level of inverter that will give low harmonic distortion at medium voltage at low switching frequency which in turn reduces the device losses and increase life span of devices [18].

Jose Rodriguez et al. (2002), now a day's alternative solution has come to control high power at medium voltage and that is multilevel inverter. This work proposes some important topologies like flying capacitor multilevel inverter (FCMLI), diode-clamped multilevel inverter (DCMLI) and cascaded multilevel inverter. Also new topologies are discussed in this work. This dissertation-I work also proposes most important control technique and modulation techniques like: sinusoidal pulse width modulation (SPWM), space-vector modulation and selective harmonics elimination technique. The need of regenerative loads are supplied by inverter is also discussed in this work. Finally, future development and opportunities regarding power electronic devices at high power, high voltage and high frequency is also addressed [19].

CHAPTER- 4

HIGH VOLTAGE DIRECT CURRENT

4.1 WHAT IS HVDC?

Generally the electric power is produced in ac form and transmission as well as distribution is also in ac form. The power is transmitted from station to the end user via transmission and distribution lines. Generally the transmission lines are long and are done at a very high voltage level. But, the rating of the voltage level is decided by the size of the conductor. HVDC is used to overcome these problems. HVDC transmission system is generally used for bulk power transmission [27].

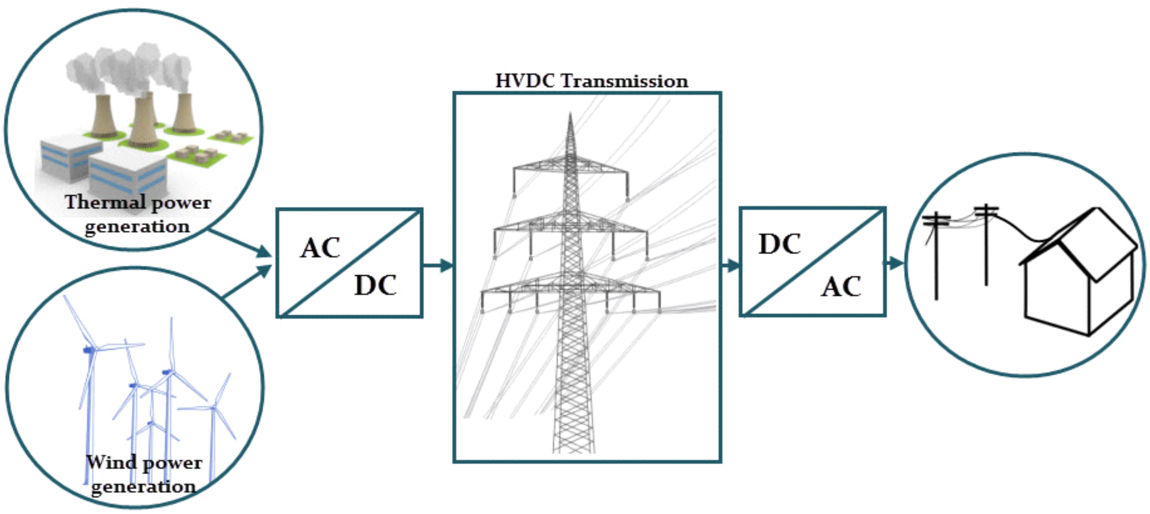


Figure 4.1- General diagram of power system using HVDC [34].

Figure shows that before transmission first ac is converted into dc using controlled rectifier then it is transmitted over long distance. At the end of the transmission, dc power is converted into ac power using inverter. Inversion process helps the system to synchronize with succeeding ac network. Therefore, HVDC system contains three sections which are namely as converter station, transmission station and an inverter station [27].

The converter station may contain of 6, 12, or 24-pulse thyristor bridge controlled rectifier while inverter station contains of similar configuration of thyristor bridges but this operates in inversion mode.

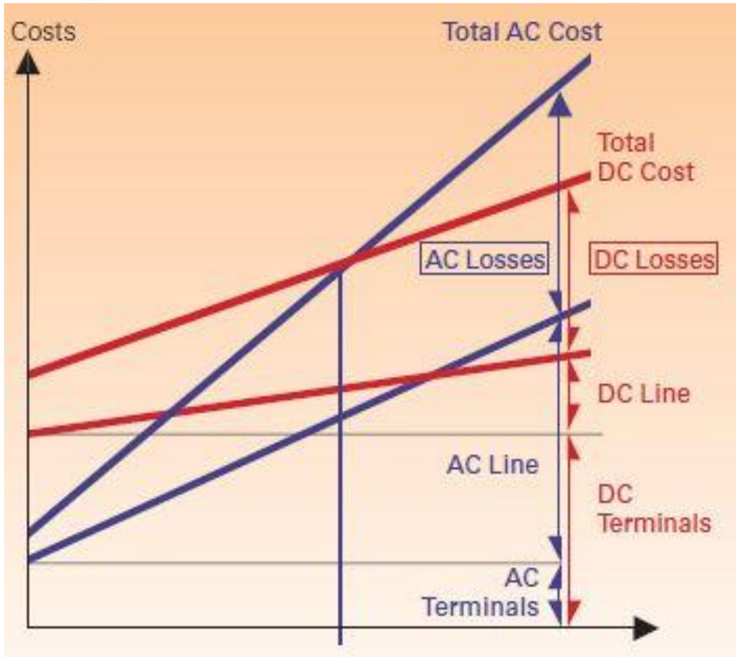


Figure 4.2: Total Cost vs Distance [34].

Advantages of HVDC over HVAC Transmission Systems:

• DC transmission requires only two conductors for a single line while AC requires at least three lines. Using two conductors and ground return, the capacity of the DC line can be doubled while AC line requires at least six conductors for double circuit line.

• The power can be transported economically and efficiently over long distances with reduced transmission losses as compared to AC transmission.

• The DC link does not require maintaining synchronization between both ends while AC links require.

• The power can be easily controlled in DC links using automatic controller.

• The DC links do not require transmission of reactive power, therefore, there is no stability problems.

• No restriction on line length as no reactance in DC lines.

4.2 Components of an HVDC Transmission System:

The essential components of HVDC transmission system are converters, converter transformer, filters at both ends, smoothening reactor, shunt capacitor and DC transmission lines.

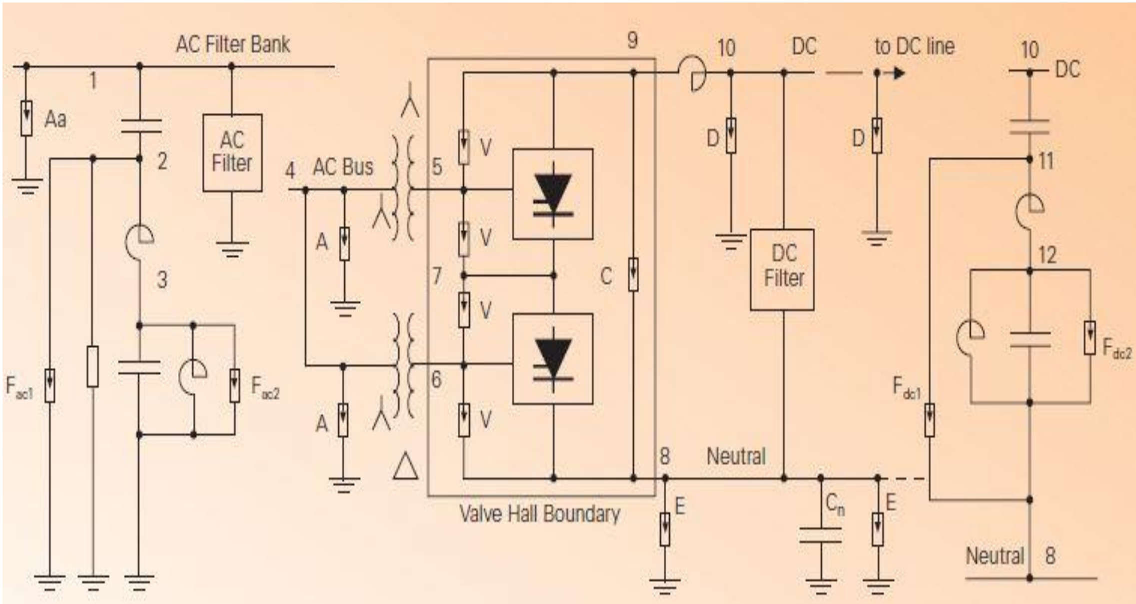


Figure 4.3- Components of HVDC transmission system [34].

4.2.1 Converter Unit-

The converter at the sending end acting as a rectifier which is used to convert AC power to DC power and the converter at the receiving end act as an inverter which is used to convert DC power to AC power. At this time, the converter at the sending end uses 12-pulse rectifier. The configuration can be obtained by connecting the 6-pulse graetz circuit in series. The configuration of thyristor valves may be packaged as single valve or double valve or quadrivalve [27, 34].

There are many things by which thyristor valves can be cooled like as air, water or oil. The converters have firing control circuit, where firing signals are generated and send to all thyristor valves via a fiber optic light guide system. The gate drive amplifiers with pulse transformers are used to convert the light signals into electrical signals. Snubber circuit, gapless surge arrestors and protective firing circuits can be used to protect the valves [5, 34].

4.2.2 Converter Transformers:

The transformers which are used in AC side of HVDC system before the rectification are called as converter transformers. There are many kind of configuration of converter transformer including three phase – two windings, single phase – three windings and single phase – two windings transformers. The configuration star and delta with ungrounded neutral is used to make phase difference 30^0, which is then feed to the rectifier unit. The control transformers used in AC side have different designs such that they can withstand with DC voltage stresses and due to harmonic currents eddy current losses are increased. The harmonics in a converter transformer are much more dominant in compared with the conventional transformer which causes additional leakage flux and it leads to the formation of local hotspots in windings. Using effective cooling arrangement and suitable shunt magnetics, the hotspots can be avoided [27, 34].

Figure 4.4- Converter Transformer during type test [34].

4.2.3 Filters:

Harmonics are generated in the HVDC system because of continuously switching of thyristors. These harmonics are transmitted from DC side to the AC side of the HVDC which causes the overheating of the transformers and equipment as well as interference with communication system. Filters are used to eliminate the harmonics. HVDC include two types of filters:

4.2.3.1 AC FILTERS-

The AC filter is made up of passive elements which provides low impedance shunt path for AC harmonics current. Generally HVDC system uses damped filter as well as tuned filter arrangement [34].

4.2.3.2 DC FILTERS-

Like AC filters, DC filters is also used for eliminating the harmonics content from voltage. DC filter is installed at the DC end. DC filters are less expensive in comparison to the AC filters. The passive part has been removed at the great extent in modern DC filter because it is of active type.

In order to reduce the disturbances caused by harmonics in telecommunication systems, HVDC transmission lines use specially designed DC filters [27].

4.2.3.3 HIGH FREQUENCY FILTERS-

To suppress the high frequency component of currents, the high frequency filters are used. It is installed between converter transformer and the station AC bus. Sometimes high frequency filter is installed in between DC filter and DC line and also on the neutral side [5, 27].

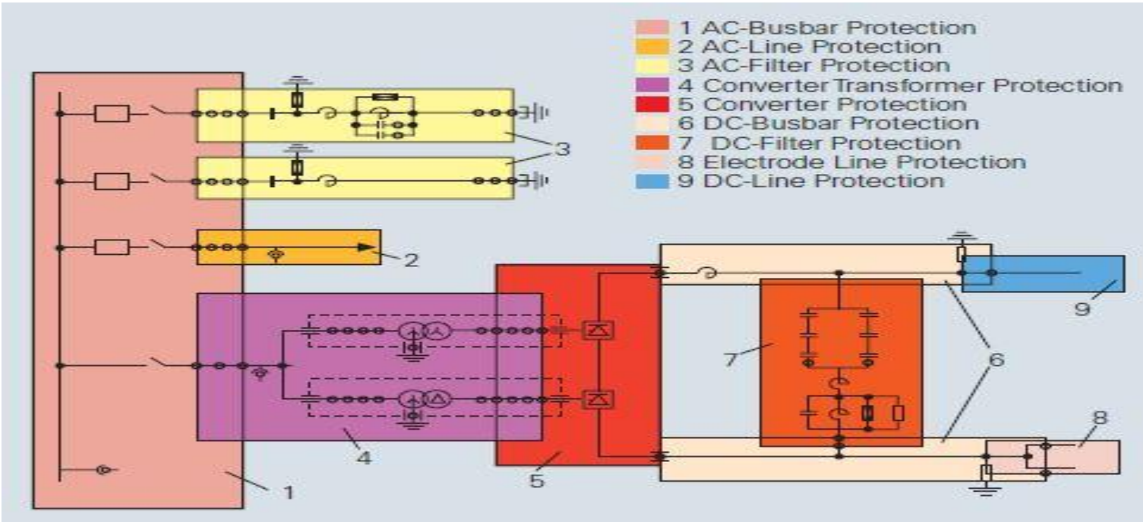


Figure 4.5: Protection zones one pole and one station [34].

4.2.4 Shunt Capacitors or Reactive Compensation:

Reactive power is generated in the conversion process, due to the delay in delay angle of the converter station. Converter does not generate reactive power as well as it does not require reactive power. Therefore, reactive power can be compensated by using shunt capacitors connecting at both the ends [5, 34].

4.2.5 Smoothening Reactor:

Smoothening reactor is a large reactor which is used in current source inverter (CSI). It is used to smooth the DC current as well as protect from the overcurrent. It opposes the sudden change in DC current which comes from converter. It can be connected in three ways, like on the line side, neutral side or at an intermediate location [27, 34].

4.2.6 Transmission Medium or Lines or Cables:

Frequently overhead lines are used for bulk power transmission over land. HVDC system uses two conductors to transfer power from sending end to the receiving end. The DC transmission requires less size of the conductors to handle same as that of AC transmission. DC transmission has no skin effect because of the absence of frequency. High voltage DC cables are mostly of oil filled which has insulation of paper tapes impregnated with high viscous oil. These cables are mostly used in submarine transmission [5, 27].

4.2.7 DC and AC Switchgear:

The switchgear has protection equipment for protecting the entire HVDC system from different kinds of faults and also yields the metering indication. The switchgear contains combination of isolator switches, lightening arrestors, DC breaker, AC breaker, etc [34].

4.3 Types of HVDC Systems:

HVDC systems mainly have three types of link which are given below.

4.3.1 MONOPOLAR LINK—

The DC system with one conductor either positive or negative, which is connected between sending end and receiving end, is called as monopolar link. Generally negative polarity is preferred because of lesser radio interference. It has many return paths like ground or sea water or metallic. Metallic return path uses railway track for returning. Since earth yields less earth resistance in DC in compared with AC [27, 34].

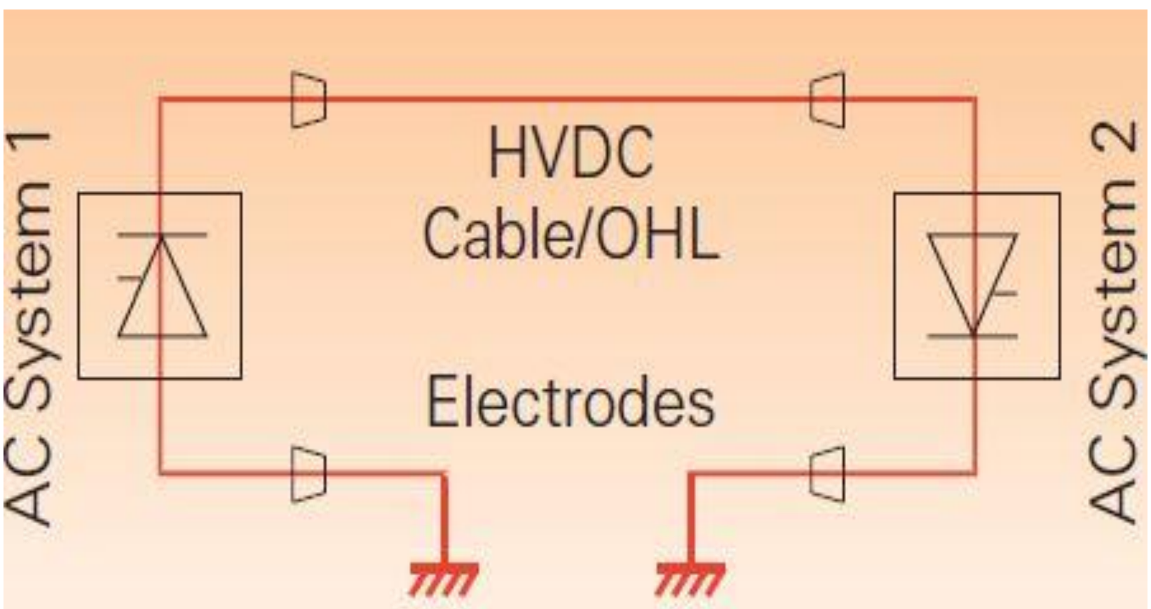


Figure 4.6 (a)- Diagram of monopolar link [34].

4.3.2 BIPOLAR LINK:

Mostly HVDC system uses this kind of configuration for transmission purpose. Bipolar link has two conductors one pole is used for positive conductor and second one is used for negative conductor. The both conductors have same magnitude of ± 650 KV. In bipolar DC link, both sending end and receiving end has two sets of converter with identical specification. Both converters are connected in series on DC side. The points between junction and converters is the neutral point which may be grounded at one or both ends, therefore, this gives the independent operation of poles. DC has zero ground current due to both poles have identical current. This type of system has more reliability than others because if any one conductor will be fail then remaining conductor can supply the half of the rated load with ground return. In this situations, the bipolar link work as a monopolar link [27, 34].

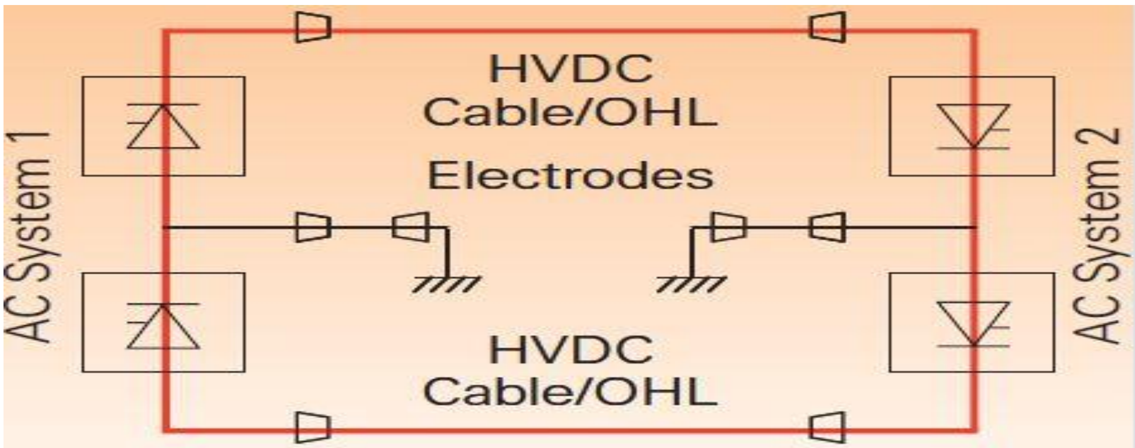


Figure 4.6 (b)- General diagram of bipolar DC link [34].

4.3.3 HOMOPOLAR LINK:

Homopolar link has same polarity of conductors; it may be either positive or negative with metallic return. Mostly negative polarity with ground return is used for transmission because it gives less corona loss as compared with AC lines. In faulty condition converter can be connected with healthy pole for supplying power and it can supply power 50% more than rated power by overloading with increase line losses. But in bipolar link, this is not possible. The continuous ground current should be there for this type of configuration. A use of negative polarity gives advantages to the system which are, less corona loss and les radio interference [27, 34].

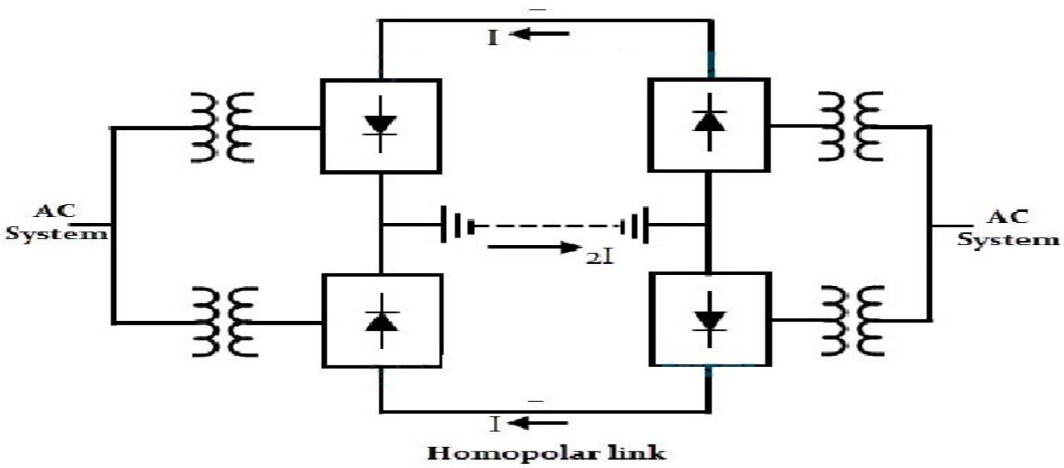


Figure 4.6 (c)- General diagram of homopolar link [34].

4.4 Application of HVDC System:

- It can be used for bulk power transmission.
- It is used for tie line between asynchronous systems.
- It has controlled power because it uses switches for controlling.
- In this, frequency conversion is possible.
- DC is used only for transmission not for distribution.

CHAPTER – 5

RECTIFIER AND MLUTILEVEL INVERTER

5.1 RECTIFIER

In the previous years, according to particle physician point of view, output of the ideal power converter should be the best direct current supplied to the load. The best direct current means that it should have very low ripple content in it and very high stability. So the main aim of the researchers has become to get the best direct current [32]. They are doing it by increasing the number of pulses of rectifier which reduces the dc ripple content from dc current.

In previous years, rectifier was uncontrolled because they were using diode for making the DC to AC and diode is an uncontrolled device. The basic principle of diode is that it works when the forward bias voltage is applied to it. It doesn't require any control signal to on or off. By the invention of thyristor, new area of research has made. Thyristor is a controlled device means it requires some signal to turn on and turn off. When thyristors are used instead of diode the rectifier is known as controlled rectifier. Thyristors require commutation circuit also [33].

5.1.1. Uncontrolled rectifier

5.1.1.1. Single-phase half-wave rectifier- The name has itself the theory about half wave rectifier. This means, rectifier will give output only in one half cycles and that will be dependent on the connection of diode with the source [33]. Figure 5.1 shows the model of half wave uncontrolled rectifier. It doesn't require any control circuit. It allows the current to flow only in one direction when forward bias is applied across it. It doesn't operate in reverse bias. It works as a switch only in active region which is linear after active region, saturation region in which it has constant value of current.

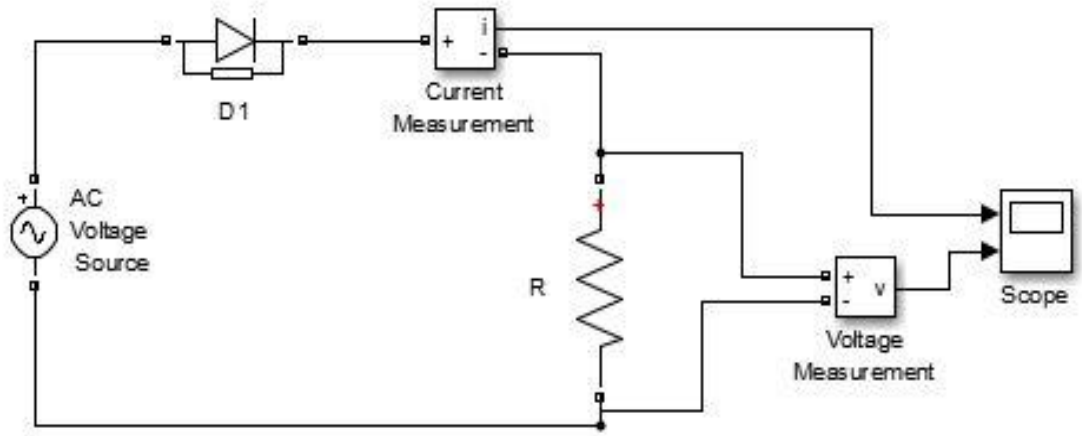


Figure 5.1(a): Simulation model of half-wave diode rectifier.

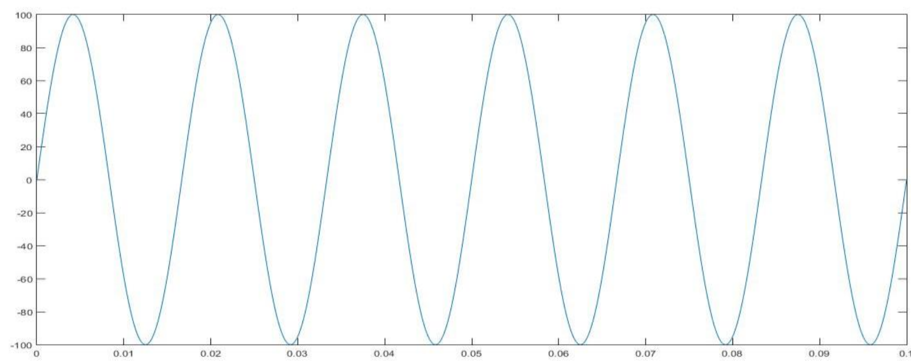


Figure 5.1 (b): AC supply to the rectifier.

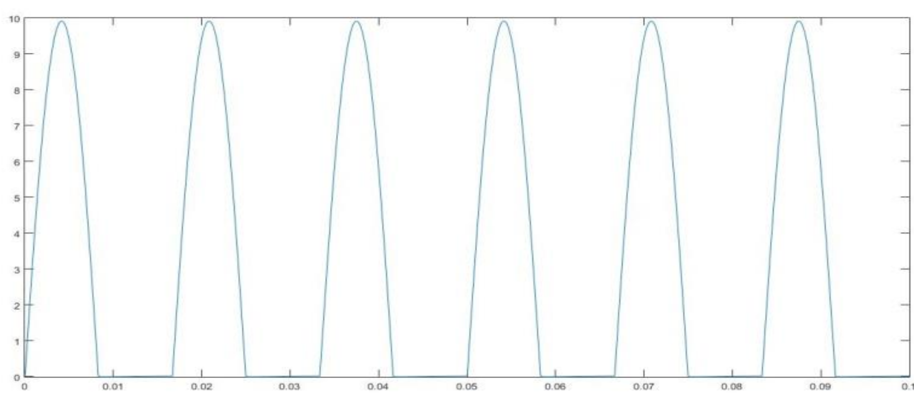


Figure 5.1 (c): Output DC current of rectifier.

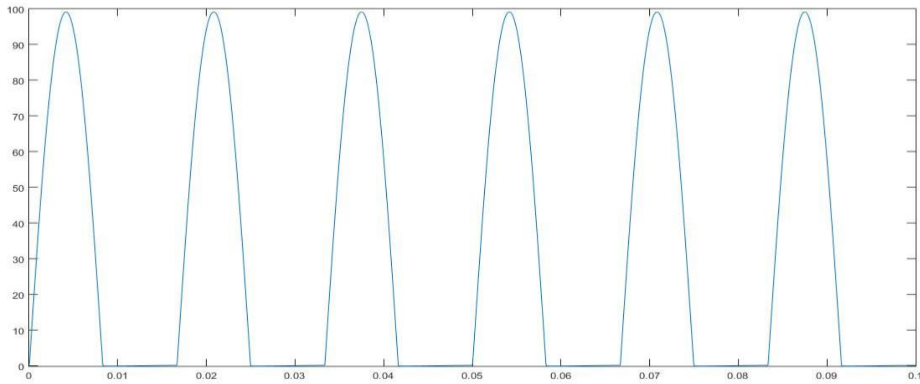


Figure 5.1 (d): Output DC voltage of rectifier.

From above figure it can be seen that the diode is connected with the source in positive half cycle but not in the negative half cycle. When diode is switched in it gives output. Since load is of resistive that's why current and voltage seem to be same because there is no phase difference between voltage and current [33].

5.1.1.2. Single-phase full-wave rectifier- Full wave rectifier is the next progression of rectifier after half wave rectifier. Full wave rectifier means, it rectify AC source in positive half cycle as well as in negative half cycle. It has two type of configuration- (i) Centre-tapped rectifier and (ii) Bridge rectifier. Figure 5.2 shows the diode bridge rectifier with resistive load and their input and output waveforms [33].

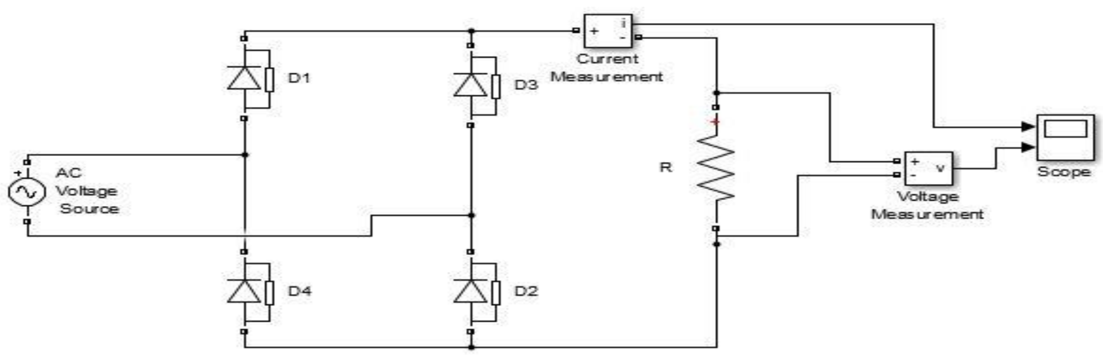


Figure 5.2(a): Simulation model of full wave diode bridge rectifier.

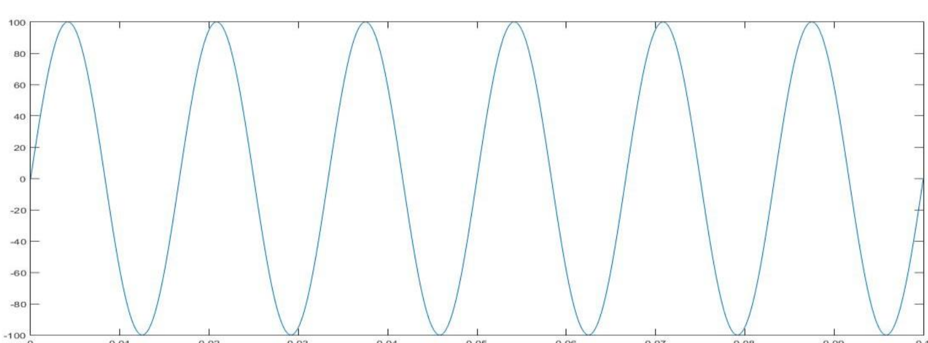


Figure 5.2(b): AC supply to rectifier.

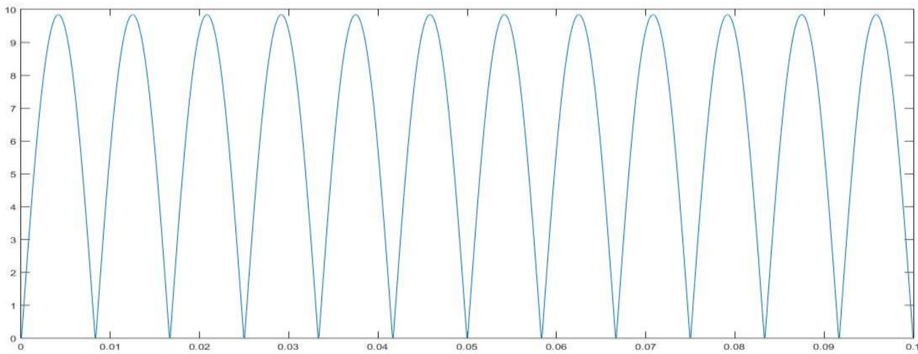


Figure 5.2(c): Full wave DC output current of rectifier.

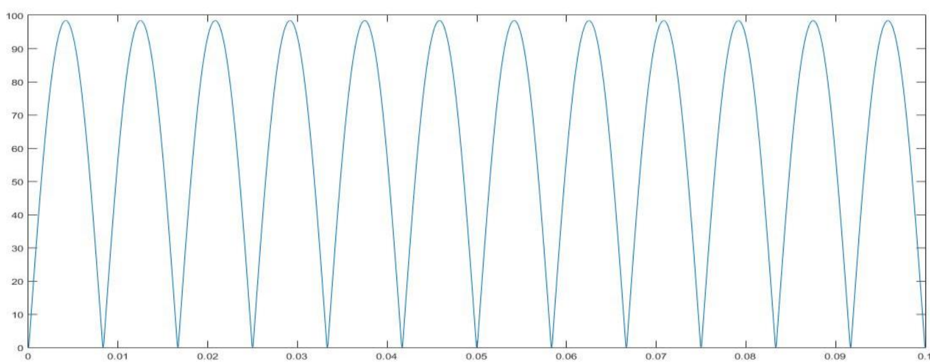


Figure 5.2(d): Full wave DC output voltage of rectifier.

5.1.1.3. Three-phase six-pulse diode bridge rectifier- In a diode bridge rectifier, pulses present in output waveform is equal to the twice of number of phases, i.e., p=2m, where p is the number of pulses and m is number of phases. Diodes are always rated by their peak inverse voltage (PIV). PIV of diode used in bridge rectifier is equal to the half of PIV of diode used in star rectifier [32]. In high power applications, a three phase bridge rectifier is used. It doesn't require transformer for applying AC voltage to the bridge. Transformer may or may not be used with diode bridge rectifier. It has less ripple content in comparison to the half and full wave diode bridge rectifier [31]. It has three legs and each leg has two diode connected in series. The upper diodes work in the positive half cycle and lower diodes work in the negative half cycle. Therefore, they named as positive and negative group respectively. Numbering of diodes is done as the conduction sequences. Figure 5.3 shows the configuration of rectifier. D_1, D_3 and D_5 belong from positive group and D_2, D_4 and D_6 belong from negative group. Each diode conducts for 120°. In a group, a diode conducts after 120° to another diode either in positive or negative group. In a single leg, negative diode conducts after 180° to the positive diode [30].

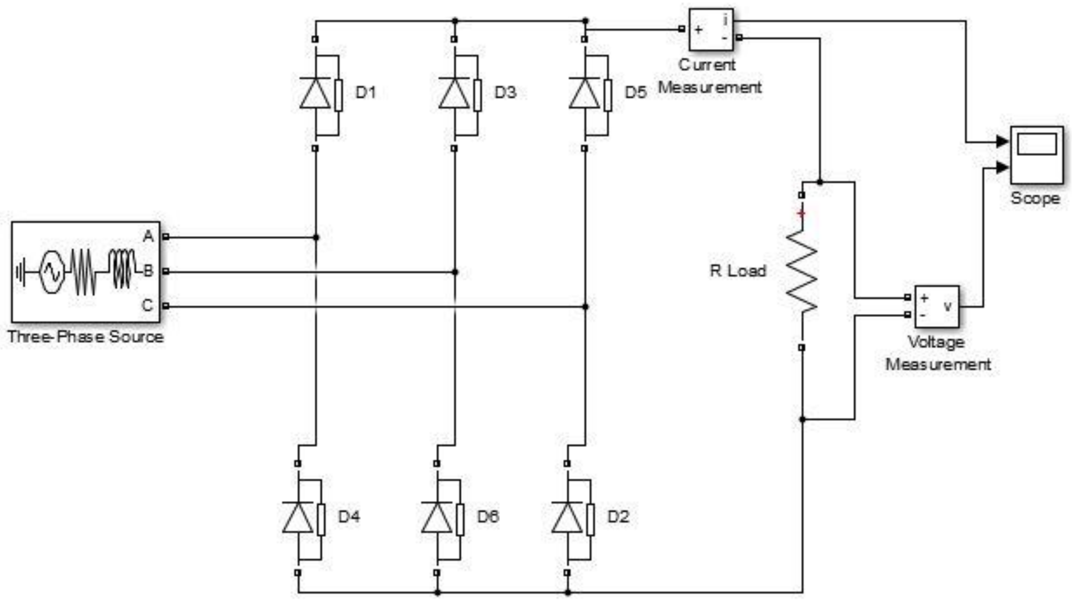


Figure 5.3(a): Simulation model of three phase six pulse diode rectifier.

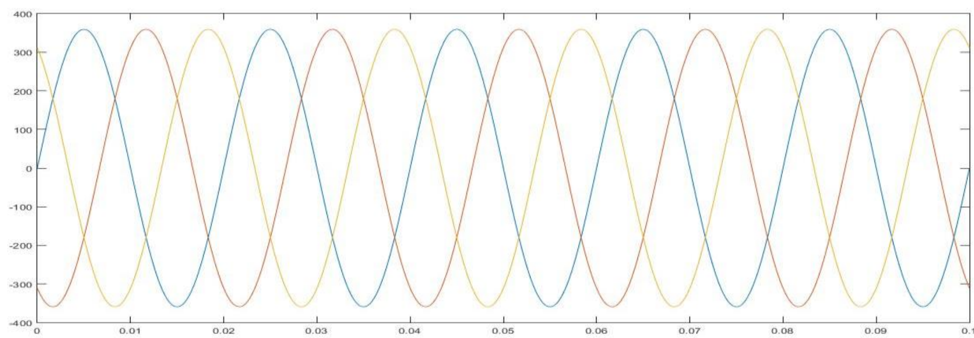


Figure 5.3(b): Three phase AC supply to the rectifier.

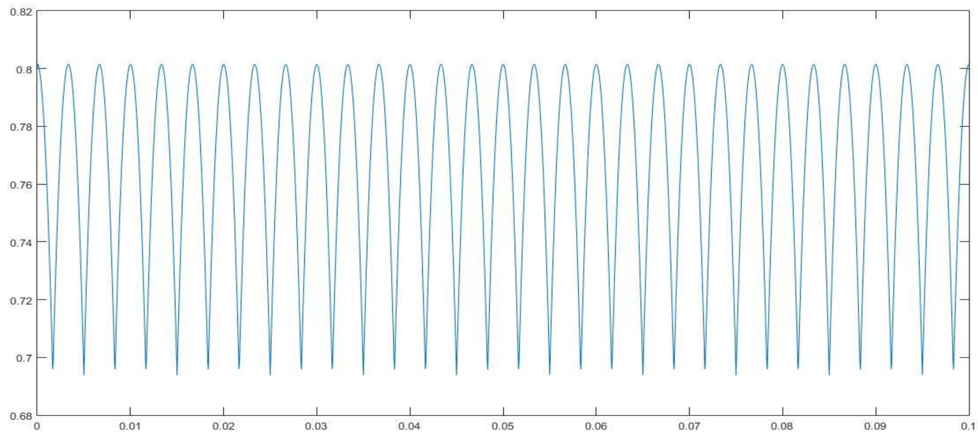


Figure 5.3(c): DC output current of the rectifier.

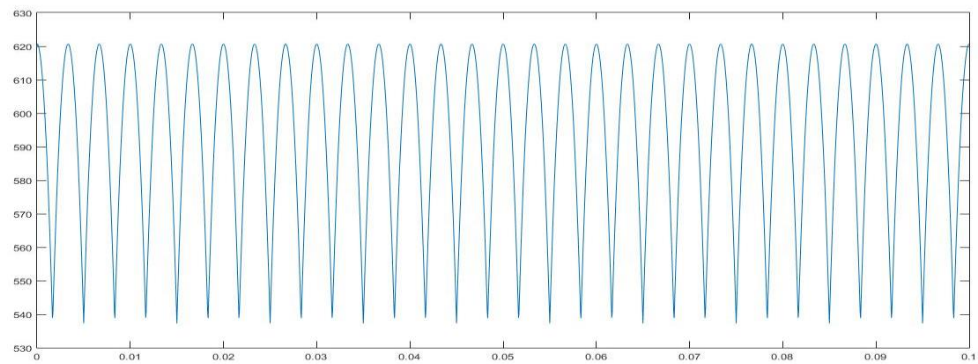


Figure 5.3(d): DC output voltage of the rectifier.

5.1.1.4.Three-phase twelve-pulse diode bridge rectifier- Output DC waveform is improved with the increase in number of pulses per half cycle. Increase in number of pulses per half cycle decreases the ripple content in output DC waveform and further improve the power quality of the circuit. As the pulses increases in output DC waveforms, number of diodes used in rectifier increases [30]. In six pulse rectifier, connection of transformer windings doesn't play important role.

There is four possible combinations of transformer are available. The combinations are Delta-Delta, Delta-Star, Star-Delta, Star-Star. When Delta is at primary side it requires only three main lines and avoids excitation unbalance because there is no neutral. When secondary windings are connected in star configuration then it has some advantages over delta connection. Star connection at secondary side has higher value of voltage in comparison to others with same amount of load current [32]. Simulation model of twelve pulse diode bridge rectifier is shown in figure 5.4.

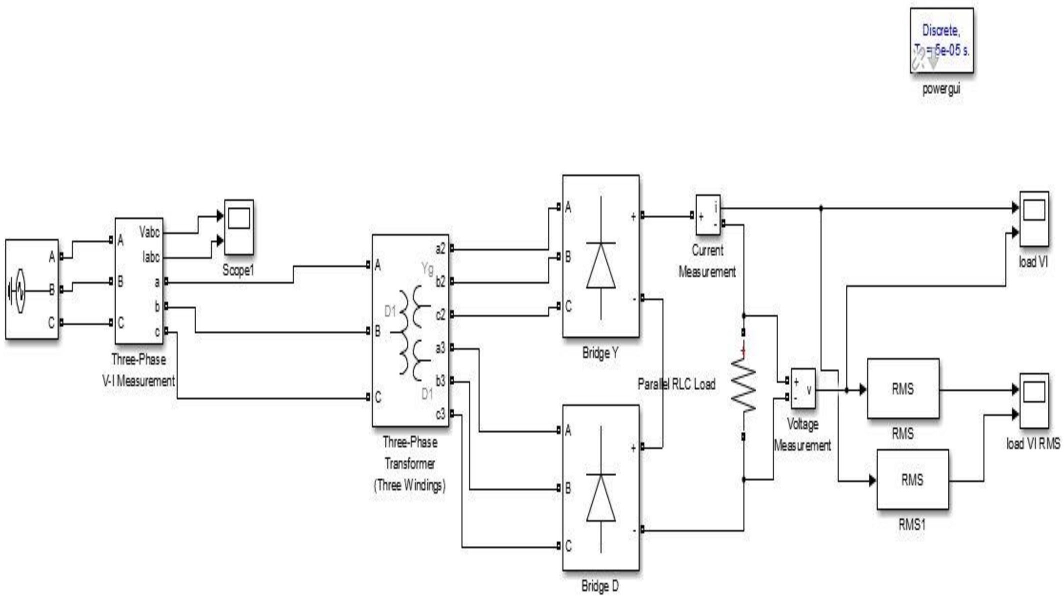


Figure 5.4(a): Simulation model of twelve pulse rectifier.

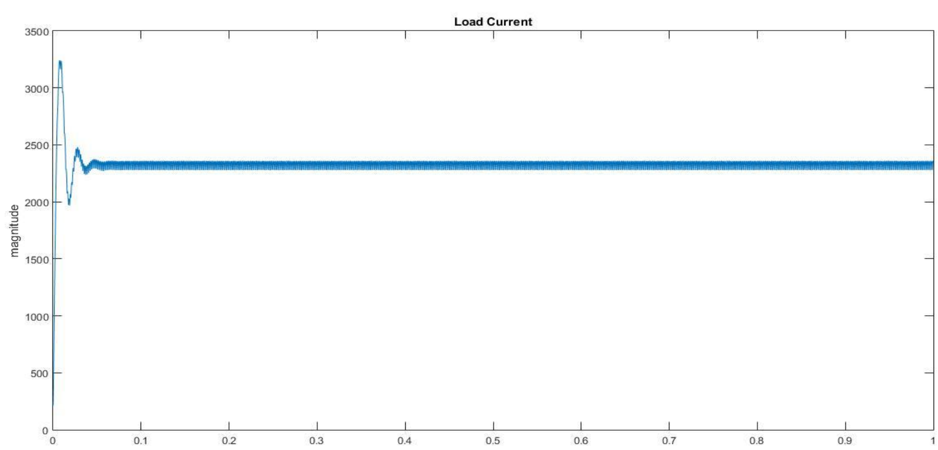


Figure 5.4(b): Output DC current.

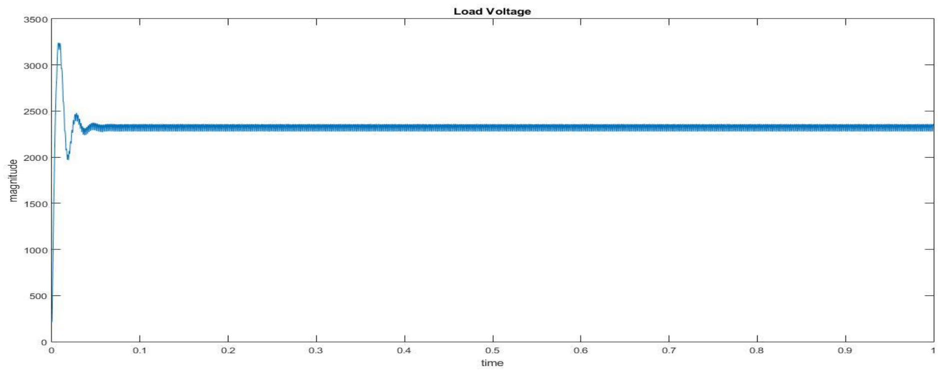
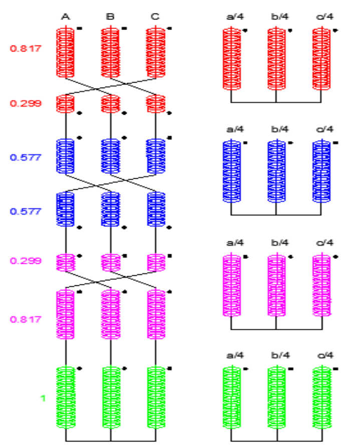
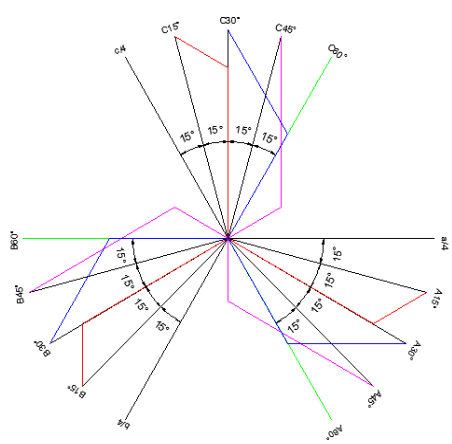


Figure 5.4(c): Output DC voltage.

5.1.1.5. Three-phase twenty four-pulse diode bridge rectifier- 24-pulse diode rectifier means, DC output voltage has 24-pulses per cycle. It has stated before that ripple content decrease in DC waveform with the increase in number of pulses. With this kind of configuration, DC output voltage waveform gets smoothed in comparison to six and twelve pulse [8]. To make 24-pulse rectifier four six pulse rectifier needed. Input to the four graetz bridge should have 15^o phase shift (because phase shift = 360/number of pulses). 15^o phase shift between four secondary of transformers are obtained by using the zig-zag transformer at primary side and star connection at secondary side. Figure 5.5 shows the transformer winding connections and phasor diagram [10].





(a)

(b)

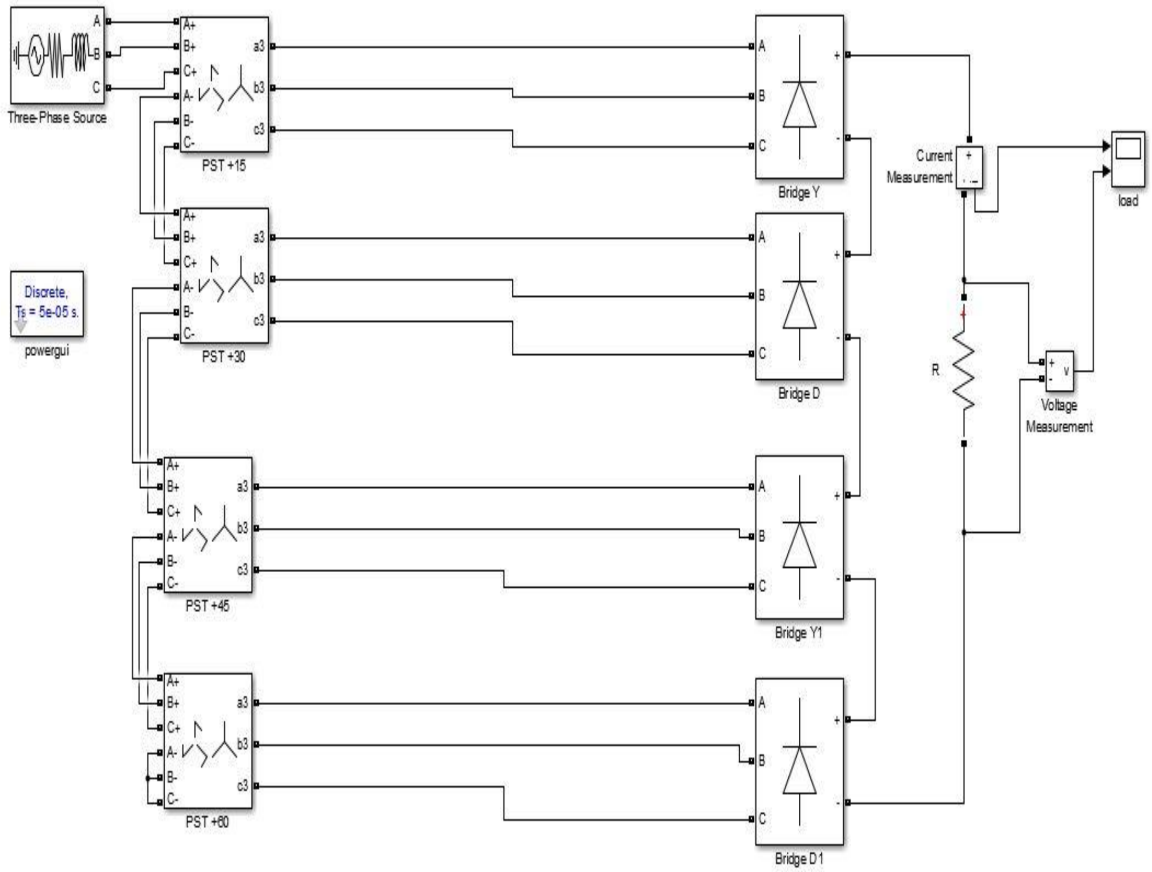


Figure 5.5: (a) Transformer windings connection, **(b)** Phasor diagram [10].

Figure 5.6 (a): Simulation model of twenty four pulse diode rectifier.

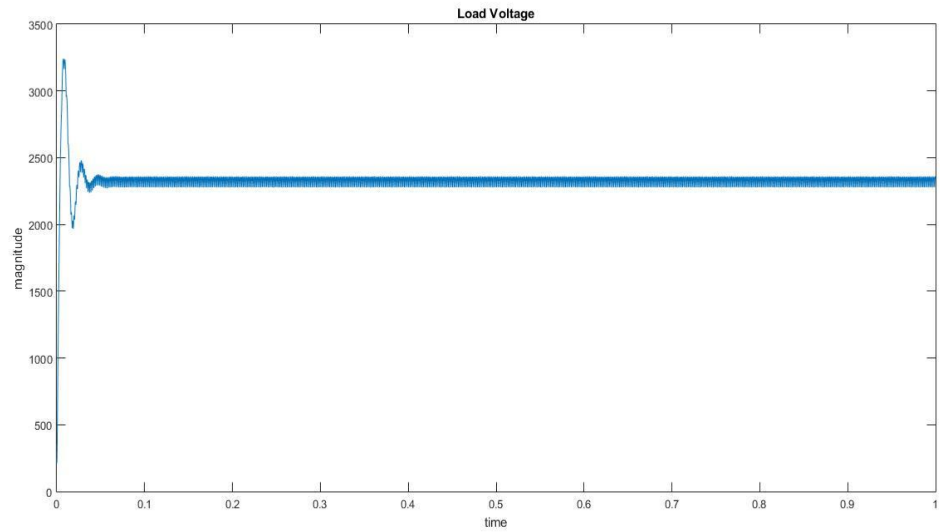


Figure 5.6 (b): DC output voltage of the rectifier.

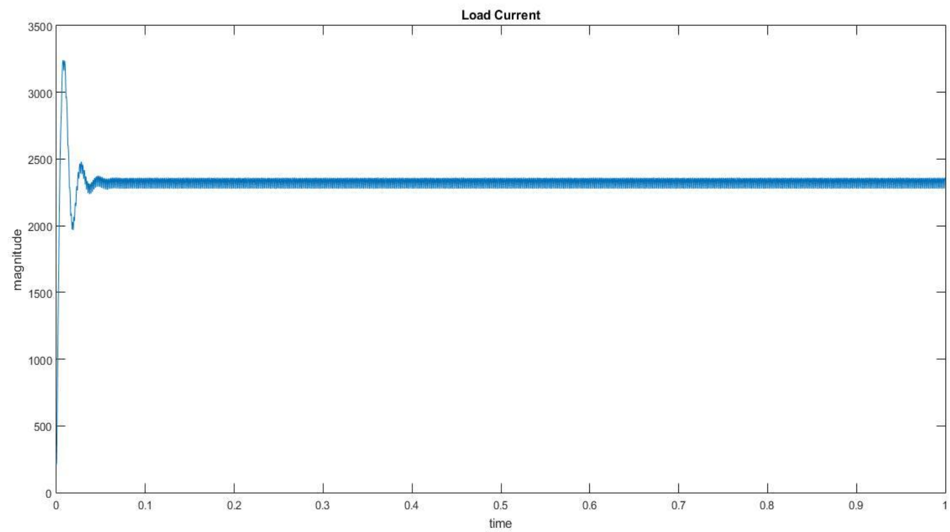


Figure 5.6 (c): DC output current of the rectifier.

5.1.2. Phase Controlled Rectifier: Diode rectifier gives the uncontrolled output DC waveforms therefore, to get controlled DC output waveforms phase controlled rectifier is used. Phase controlled rectifier uses thyristors instead of diode. With the help of thyristors it is possible to get controlled DC voltage from constant AC voltage. Previously mercury-arc rectifiers and thyratron tube were using in rectifiers. But with the advent of thyristors, mercury-arc rectifiers and thyratron tube are replaced by thyristors because it has better capability than others.

Thyristor word is taken from two words which are Thyratron and Transistors. Greek word “thy” is taken from thyratron which means ‘switch’ and suffix word “-istor” is taken from transistor which recognize that this device belongs to semiconductor devices [32]. Like diode, it also provides output when it is in forward bias but with trigger pulse. It works only in one direction. It is also named as SCR (Silicon controlled rectifier) which differs it from other similar devices like GTO and TRIAC. It doesn’t turn-off until current flow in it goes below to level of holding current of it. It commutated by natural or line-line commutation [30]. Properties of ideal SCRs are:

a) It doesn’t have voltage drop across it.
b) During reverse bias, there is no reverse current.
c) Zero holding current.

Phase controlled rectifiers are highly efficient, less expensive and simple therefore, it is mostly used everywhere. In general, efficiency of this rectifier is about 95%. With the help of this, it is widely used in industries where speed control is needed [31].

Phase controlled rectifier is classified into two types depending upon the input supply [31]:

a) Single-Phase Controlled Rectifier
b) Three-Phase Controlled Rectifier

5.1.2.1. Twelve-Pulse Three-Phase Controlled Rectifier-

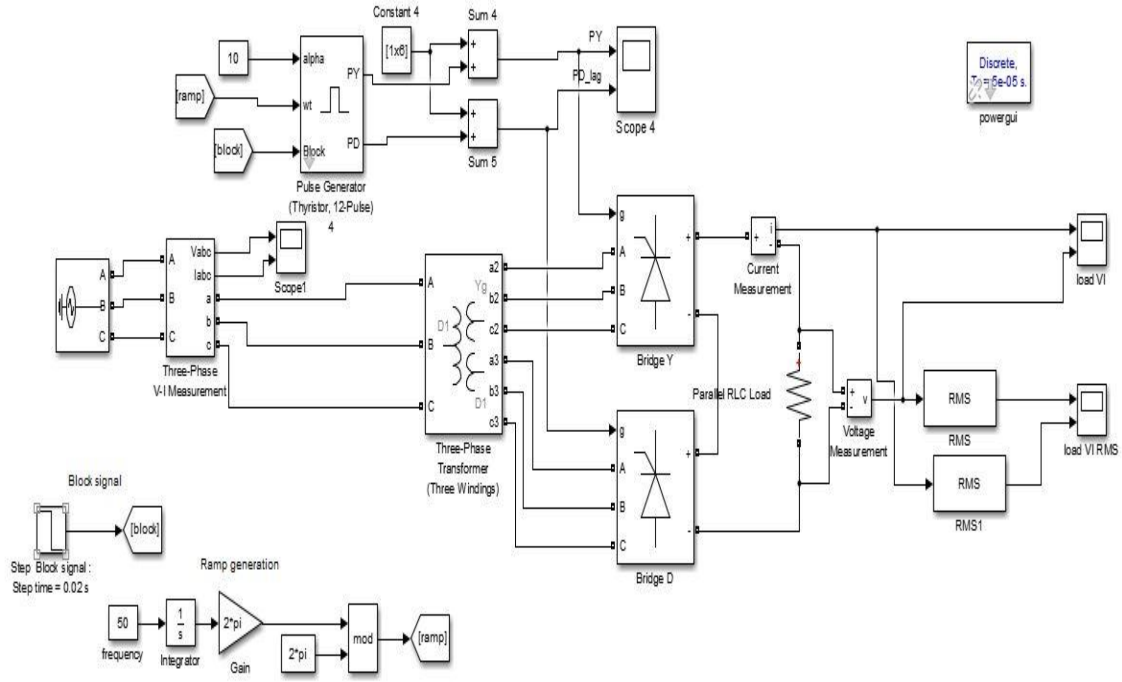


Figure 5.7(a): Simulation model of twelve pulse rectifier.

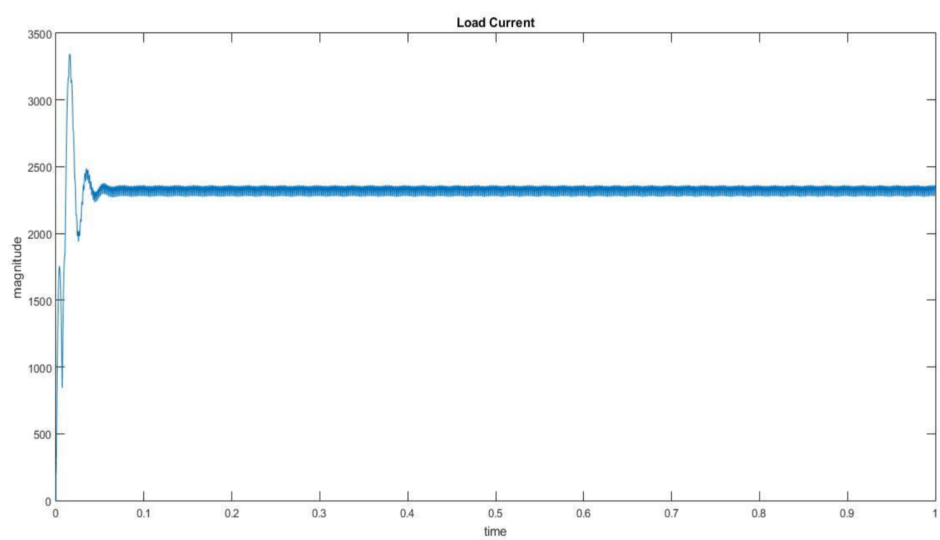


Figure 5.7(b): DC output current of the rectifier.

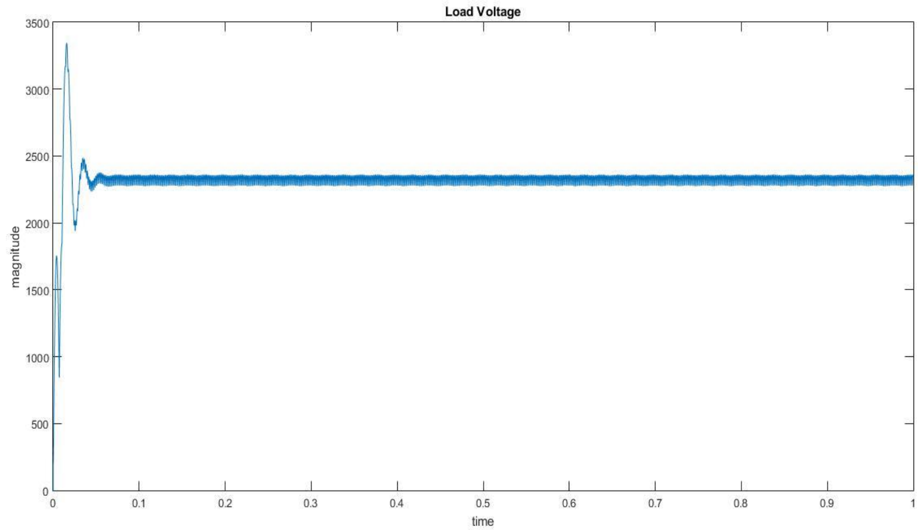


Figure 5.7(c): DC output voltage of the rectifier.

5.2. MULTILEVEL INVERTERS (MLI)

MLI have attracted many utilities and power industries because of their use and advantages. It is well suited for reactive power compensation. It can work with high voltage and high power application with the use of IGBTs. It produce voltage waveform in shape of staircase. Level of voltage is dependent on the number of DC voltage sources are used. Harmonic content present in the voltage waveform decreases with the increase in DC voltage sources [31, 20, 22]. The upcoming topologies of MLI must have these things which are given below:

a) Less switching devices as much as possible.

b) Lower switching frequency.

c) Capable to withstand with very high power and voltage application.

Types of MLI-

1) Diode-clamped MLI (DCMLI)

2) Flying-capacitor MLI (FCMLI)

3) Cascade MLI (CMLI)

5.2.1. Diode-clamped MLI (DCMLI) - In 1981 neutral point DCMLI is proposed by Nabae, Takahashi and Akagi. It was a three level inverter. Then in 1990s, four, five and six-level DCMLI have been proposed by many researchers. From past some decades, they have been used for connection of high voltage system, reactive power compensation, controlling of frequency and variable speed motor drives. The name of this MLI is given as DCMLI because diode is used to clamping the voltage [31, 20-22]. Three level DCMLI is shown below:

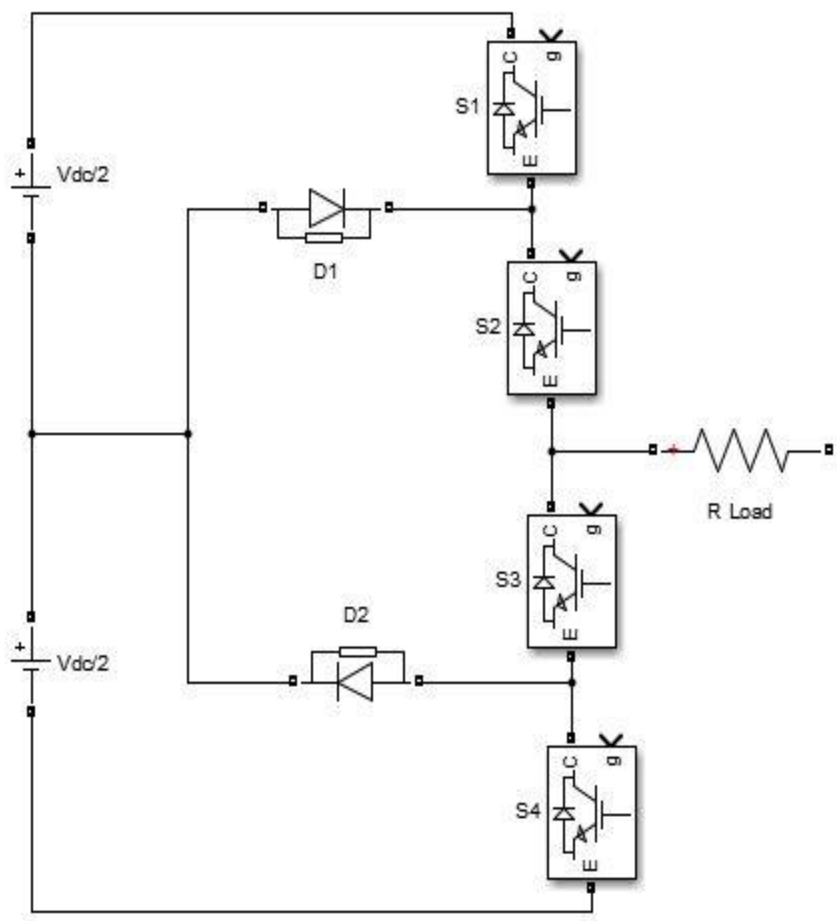


Figure 5.8: Single leg 3-Level DCMLI connected with R load.

An m-level DCMLI has (m-1) DC voltage sources on DC bus, (m-1) (m-2) clamping diodes and 2(m-1) switching devices. Above figure is of three-level DCMLI which has two DC sources having capacity of $V_{dc}/2$. At any particular time, two switches will be on [31].

Advantages:

1) Harmonic content is decreased with the increase in voltage level which reduces the need of filters.

2) All IGBTs switched on at fundamental frequency due to this efficiency of inverter is increased.

3) Simple controlling method.

4) Since DCMLI has common DC link due to this, it reduces the capacitance requirements.

5) Before using capacitor can be charged and then use.

Disadvantages:

1) Requirement of clamping diode is higher when number of level is increases.

2) Control of real power is difficult for a single inverter because without monitoring and control DC level gets discharge and overcharge.

5.2.2. Flying-capacitor MLI (FCMLI) – In 1992 flying capacitor based MLI is proposed by Foch and Meynard. Design structure of FCMLI is same as the DCMLI but it uses capacitor instead of diode. DC side capacitors are arranged in ladder structure in this topology with different voltages as sown in figure 5.9. Level of the voltage is dependent upon the number of capacitors used. One increment in level is determined by the voltage increment in two adjacent capacitors. One main advantages of this MLI that for inner voltage level it has redundancies. It means there may be another combination of switches and capacitors for getting the same level of output voltage [20-22]. FCMLI has more redundancies in comparison to the DCMLI. These redundancies helps to reduce the overcharging and discharging of particular capacitor. Because of this it helps to maintain appropriate voltage level across capacitors and further gives the quality to control real power. An m-level FCMLI needs (m-1)*(m-2)/2 dc link capacitors per phase [31].

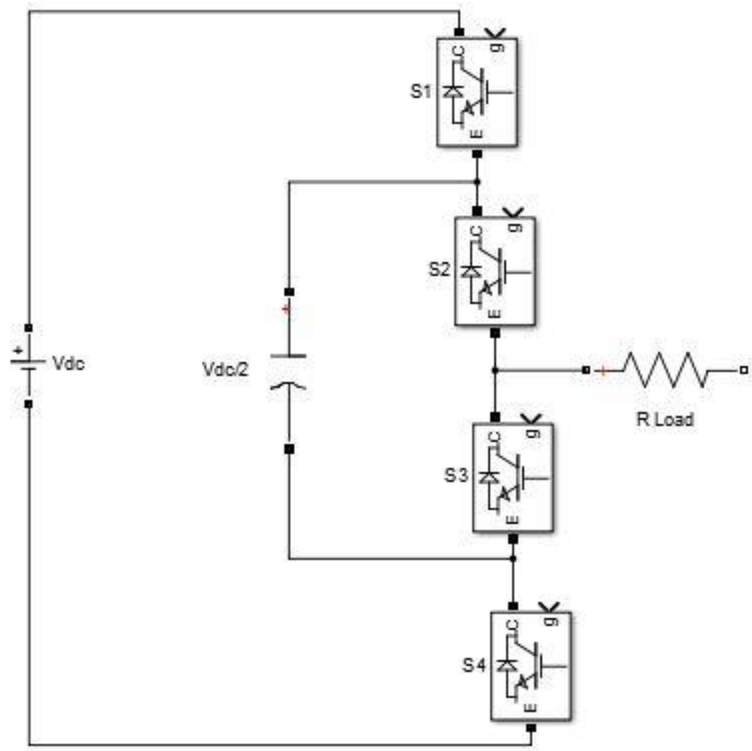


Figure 5.9: Single leg 3-Level FCMLI connected with R load.

Advantages:

1) Voltage levels across each capacitors is maintained due to phase redundancies.
2) Controlling of active and reactive power is possible.
3) FCMLI gives capabilities to inverter, to ride through voltage sag and outages of short duration due to large number of capacitors.
4) Like DCMLI it helps to reduce the need of filters to increase the level of output voltages.

Disadvantages:

1) Requirement of capacitors are increased with the increase in level of output voltages.
2) For high power applications, switching frequency and losses will be high.
3) Controlling of inverters becomes complex.
4) Due to large number of capacitors FCMLI is more expensive and bulky in comparison to DCMLI.

5.2.3. Cascade H-bridge MLI – Cascade MLI contains single phase full bridge inverter which is also known as H-bridge inverter. Single H-bridge has only three-level of output voltage from peak to peak. Number of H-bridge increase with the increase in level of output voltage and they are connected in series. Every H-bridge contains one separate DC sources (SDCS) which can be taken from fuel cell, solar cell or batteries [31]. The ac terminal of each H-bridge is connected in series. Cascade H-bridge does not require any clamping diodes for clamping or capacitors for voltage balancing. An m-level of cascade MLI is shown below, which has (m-1) SDCS and H-bridge. It also can be used for reactive power compensation [20-22].

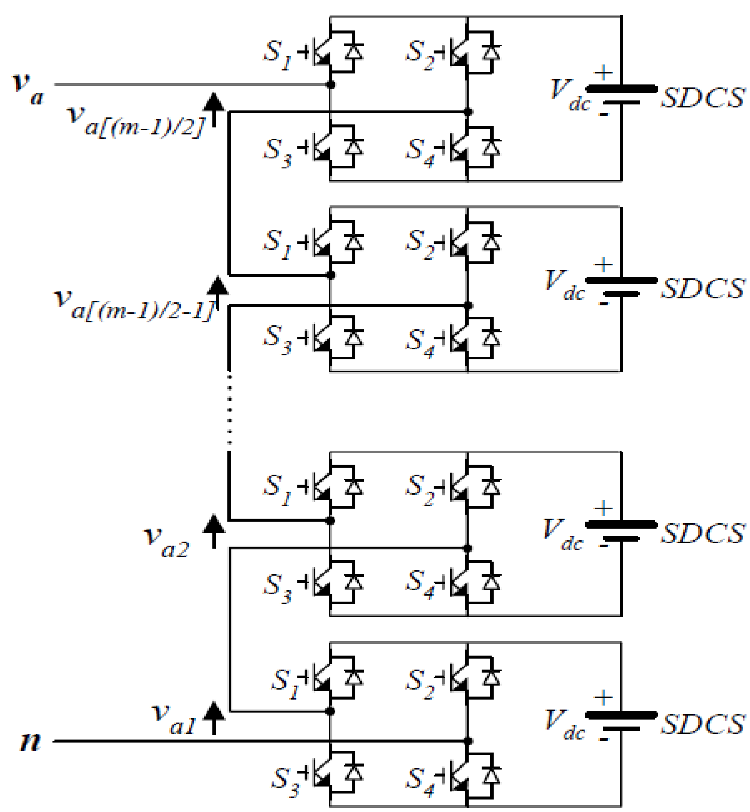


Figure 5.10: m-level cascade MLI.

Advantages:

1) Level of output voltage is twice the number of SDCS ($m=2N_s+1$, where N_s is the number of bridges).

2) It is cheaply and less complex in comparison to DCMLI and FCMLI.

3) To reduce the switching losses and stresses on device, soft switching can be done.

Disadvantages:

1) For active power conversion, SDCS is required.

CHAPTER- 6

CONTROL STRATEGY OF VSC-HVDC

6.1. Introduction

In previous days, conventional HVDC transmission system had the controlling of power but it did not had the controlling of reactive power. While VSC-based HVDC transmission system has the ability to control the active power as well as reactive power. It controls the power in same ways as conventional HVDC systems were using [25]. The controlling is done at the rectifier side to control dc voltage, while at the inverter side active power and frequency can be controlled. Frequency controlling is dependent on the switching time of IGBTs. The controlling of reactive power flow in the system can be done by the ac voltage that is given or by given constant without change in dc voltage. The active power flow controls has two ways to control it. Either by controlling the dc voltage on the dc side or by controlling the frequency of ac side. Thus, by the use of VSC-based HVDC system dc voltage on dc side, reactive power flow at each converter, and active power flow on both sides and frequency of ac side can be controlled [26]. The overall control structure of the system is given below in the figure 6.1.

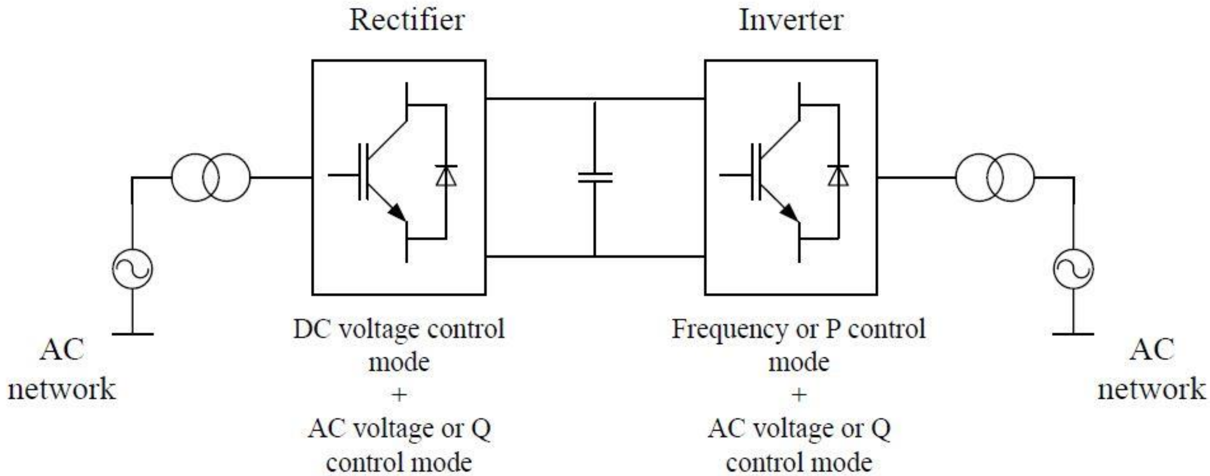


Figure 6.1: Overall control structure of VSC-HVDC system [26].

The appropriate controlling VSCs is needed to improve the efficiency of the VSC-HVDC system as well as the tight coupling between AC system and DC system. The amount of power transfer is dependent upon the precise controlling of dc current and dc voltage. Therefore, here should be a measuring equipment which continuously measure the system quantities like dc voltage, dc current, firing angle (delay angle) α and extinction angle γ for inverter. Inverter is intended to control the dc voltage under steady state conditions. The controlling of dc voltage can be done by maintaining a constant extinction angle γ. By maintaining the constant extinction angle γ dc voltage has droop with the increase in dc current. Therefore, this shows that the extinction angle γ is important and the values of γ must above its minimum setting 18° (60Hz) and 15° (50Hz). The rectifier must control the dc current when inverter is working in these characteristics. The controlling of dc current by the rectifier can be done if the delay angle α is not at its minimum value (5 degree) [26].

The control model for rectifier contains only outer voltage control loop and inner current control loop, while for the inverter both outer voltage control loop and inner current control loop as well as extinction angle control loop are needed. During the faulty conditions, low dc voltage is present in the dc link because of that ac voltage will be depressed at the rectifier or inverter and it will be unable to help weak AC system.

If the fault is occur on the inverter side, the ac voltage will decrease and due to this low ac voltage commutation failure persist in the system. Commutation failure happens into the system because of increase in the overlap angle. The reduction of dc current in link is more important in such cases because it reduces the overstress from valve. If the fault is occur on the rectifier side then it will be more severe case because it causes low ac voltage at the rectifier side. Due to this low voltage inverter consume excessive amount of reactive power and it leads to inverter to operate at low power factor. Since these cases are undesirable, therefore, voltage dependent current limit added to the control characteristics to improve the control characteristics of VSC-HVDC which is shown in Figure 6.2 [27].

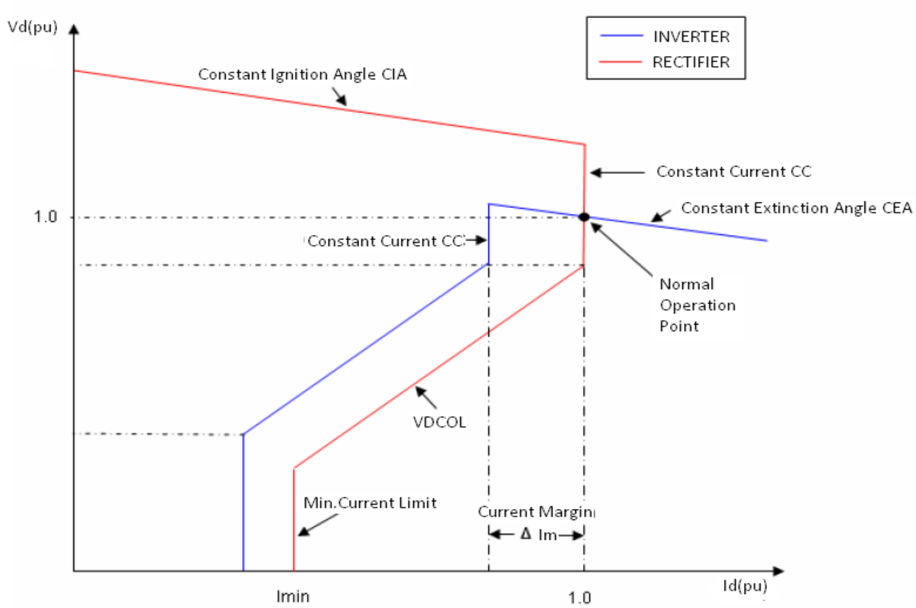


Figure 6.2: VDCOL including control characteristics [27].

The current measured at the mid-point of the cable is used to monitor the dc voltage at the inverter side. This measured voltage is then used to improve the control characteristics by taking it as input to a non-linear gain.

6.2. Control strategies of VSC-HVDC

There are different control strategies to control the active and reactive power flow in the rectifier as well as inverter. Control strategies are:

a) Power angle control.

b) Vector control.

c) Pulse width modulation technique.

6.2.1. Power Angle Control: Power angle control is dependent on power-angle curve and equation as well. This equation gives the relation between power and load angle (θ) which is given below [23],

$$P = \frac{U_1 U_2 \sin\theta}{X}$$

$$Q = \frac{U_1^2 - U_1 U_2 \cos\theta}{X} \qquad (1)$$

Where,

P	=	Active power in ac system.
Q	=	Reactive power in system.
U_1	=	Sending end voltage.
U_2	=	Receiving end voltage.
X	=	Transmission line reactance.
Θ	=	Load angle or phase difference between U_1 and U_2.
$\sin\theta$	=	sine function of load angle θ.
$\cos\theta$	=	cosine function of load angle θ.

The above equation shows that the active power is dependent on phase difference between two end voltages and reactive power is dependent on difference in voltage magnitude. This equation is the most important equation for power-angle control, mean this the base equation. Therefore, from above equation it can be seen that, active power can be control by changing the phase angle difference between two end voltages and reactive power can be control by changing the voltage magnitude. Moreover this control scheme looks simple and beneficial. Until now this scheme has never been used anywhere in HVDC system because it has some severe disadvantages [23, 26]:

a) The controller has limited bandwidth.

b) When the valve current is high then controller will unable to limit that current.

c) It does not has over-current protection features.

6.2.2. Vector Control: This control scheme is the most fashionable control method. VSC-HVDC system uses this control scheme for the controlling of rectifier as well as inverter. In this paper, vector control scheme is used to control the firing angle or delay angle of controlled rectifier which is shown in fig.3.3. The basic principle of this scheme is to control the active and reactive components of grid current [24, 26].

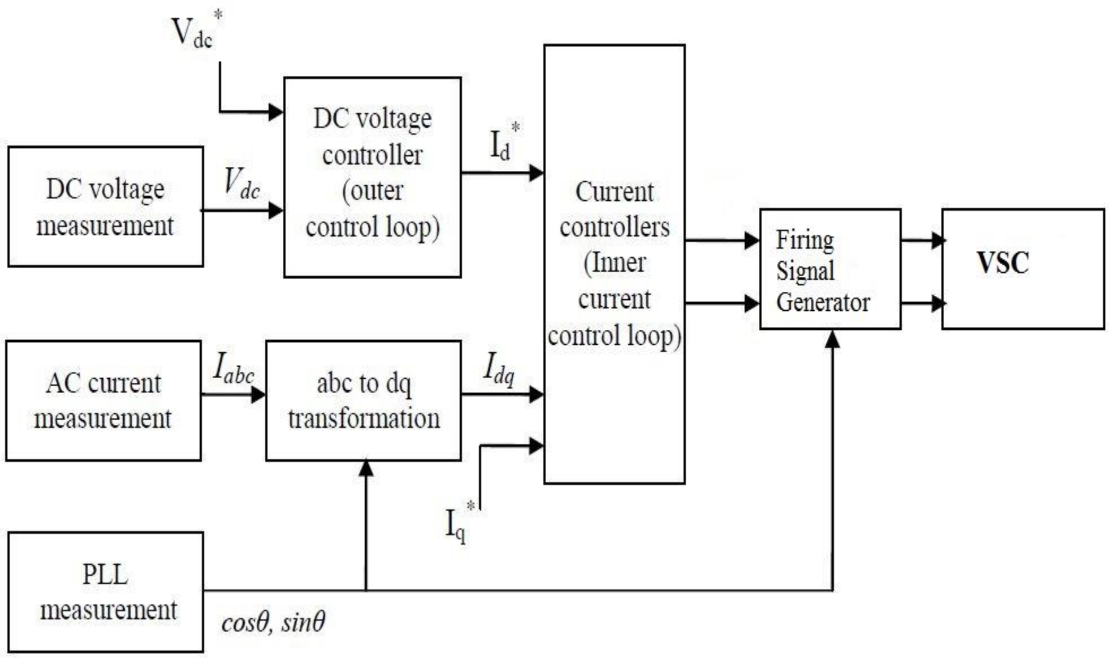


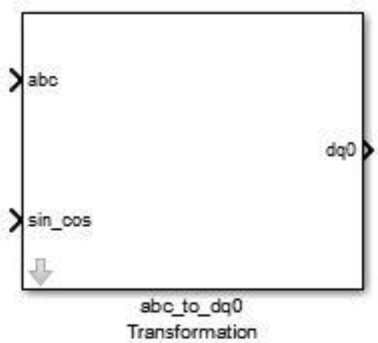
Figure 6.3: Vector control principle [26].

By the use of parks transformation theory in which dq reference frame rotate with synchronous speed, the control of active and reactive components of grid current is made possible. The first park transformation was abc rotating frame to αβ rotating frame and both were rotating with the synchronous speed. Then, second transformation was αβ rotating frame to dq reference frame. The second transformation made possible the conversion of abc to dq frame [26].

In this block two conventions are used by Park transformation:

• At time t = 0, if the d-axis and A-axis are aligned to each other, then this will be consider as cosine-based park transformation. The dqo components are d = 0, q = -1 and zero = 0.

• At time t = 0, if the q-axis and A-axis are aligned to each other, then it will be sine-based park transformation. The dqo components are d = 1, q = 0 and zero = 0.



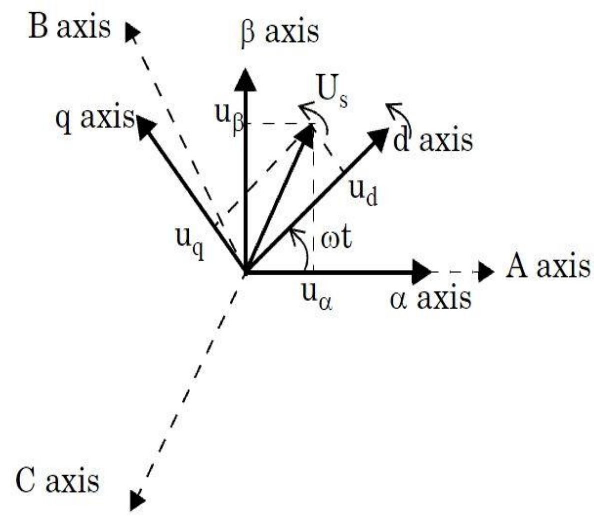


Figure 6.4(a): MATLAB block. **Figure 6.4(b):** Representation of abc, αβ and dq reference frame.

Initially, system voltages and currents are treated as vector and the they are in abc rotating frame. The alignment of A-axis with dq frame decides the abc to dq0 transformation. Here, ωt is the angle between abc frame and dq0 frame which decides the position of frames (where ω is the angular rotation speed of dq frame.

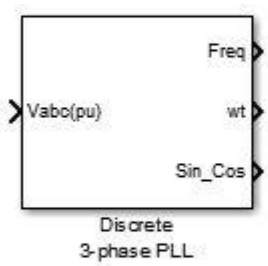
When d-axis is aligned with A-axis,

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - 120°) & -\sin(\theta - 120) & 1 \\ \cos(\theta + 120°) & -\sin(\theta + 120°) & 1 \end{bmatrix} \begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix}$$

And inverse park transformation (dq0-abc) is given by,

$$\begin{bmatrix} U_d \\ U_q \\ U_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120°) & \cos(\theta + 120°) \\ \sin\theta & \sin(\theta - 120°) & \sin(\theta + 120°) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix}$$

6.2.2.1. Phase locked loop- Phase locked loop is the most important and necessary features to connect VSC-HVDC or isolated system with the grid. There are certain conditions for tying with grid such as; voltages and frequency of both the system should be constant at the time of connection. Otherwise it will lead to a severe damage to whole system grid as well as isolated system. In short, PLL is used to synchronize the isolated system with grid by using synchronization algorithm [26]. PLL is used to evaluate the phase angle and frequency of positive sequence component of fundamental system voltage and by using this, system can be synchronized via algorithm [28]. The purpose of PLL is to obtain unity power factor by synchronizing the grid side converter output voltage with the grid voltage. In MATLAB, there are so many PLL blocks but in this paper two types of PLL are used.



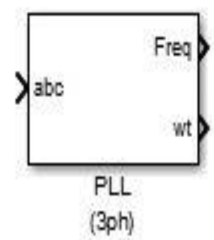


Figure 6.5(a): Simulation block of Discrete 3-phase PLL, **Figure 6.5(b):** 3-phase PLL.

There may be three outputs frequency of the grid voltages, sine-cosine function and weightage signal. Output frequency is used to control the extinction angle of inverter. Sine-cosine function is used to convert the grid voltages (V_{abc}) into (V_d and V_q). Weightage signal is treated as tracked phase angle which is taken as the reference for generating the firing pulses. Cosine-based park transformation (A-axis is aligned with d-axis) is used to realize the phase locking of the system [26].

6.2.2.2. Inner current control loop- Inner current control loop has inputs as measured grid voltages, grid currents and quadrature components of grid current which is generated by outer voltage control loop. Current regulator is used here which work is to generate delay signal (α). In current regulator error signal is generated by comparing measured quadrature components of grid current and reference value, which is then feed to the PI controller and generate delay angle [26].

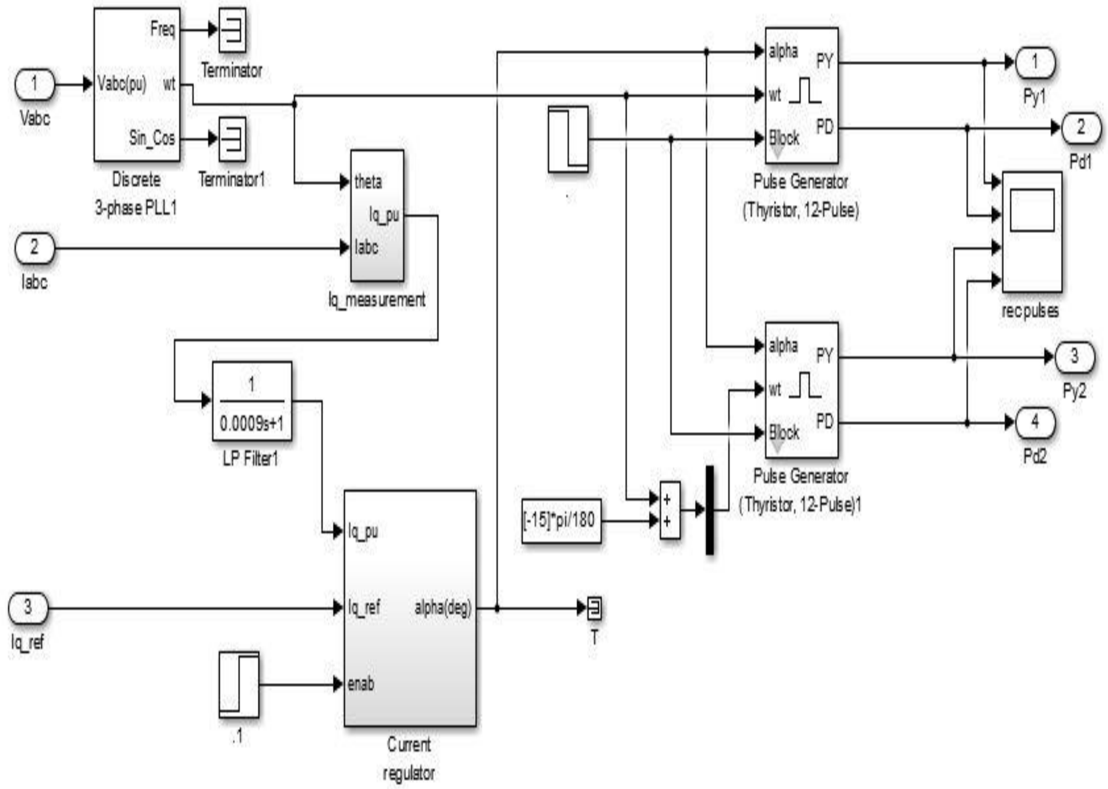


Figure 6.6: MATLAB model of inner current control loop.

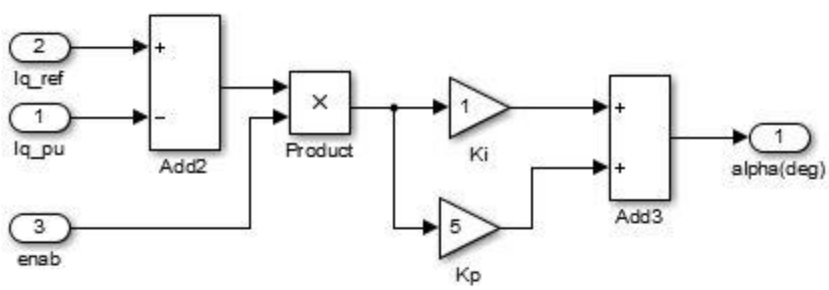


Figure 6.7: MATLAB model of current controller.

6.2.2.3. Outer voltage control loop- Basically it uses the measured grid voltage and from that it takes output as active and reactive components of grid voltages. Then an error signal is generated after evaluation of magnitude of fundamental component voltage reference voltage. This control loop is used to measure the reference grid reactive current (I_q^*) for the inner current control loop [26].

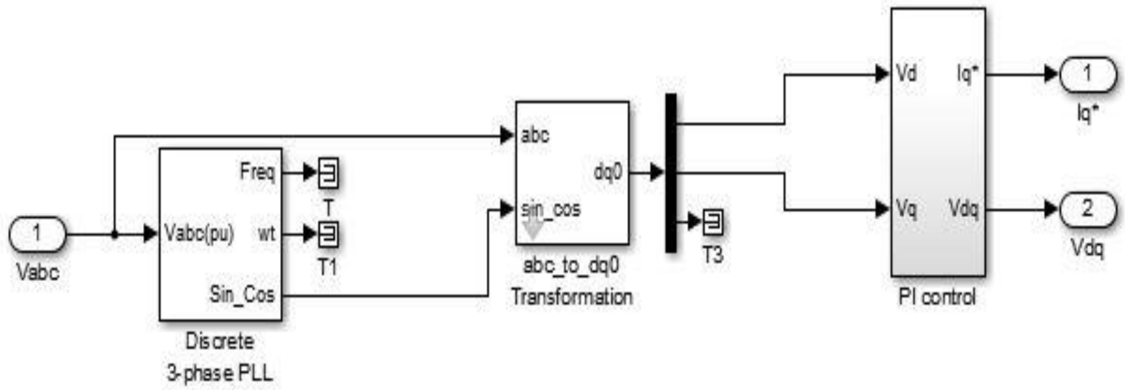


Figure 6.8: MATLAB model of Outer voltage control loop [26, 28].

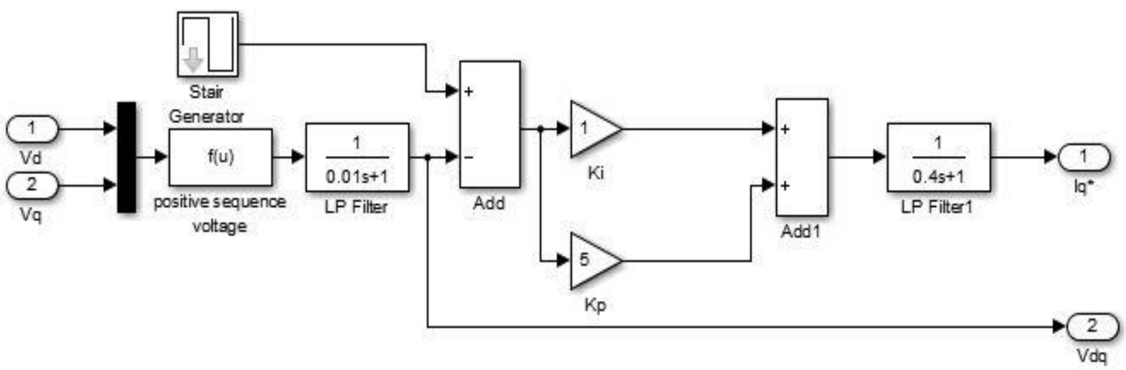


Figure 6.9: MATLAB model of PI control [26, 28].

6.2.3. Pulse width modulation technique- Basically the pulse width modulation is used for the controlling process with constant amplitude pulses. Ideal PWM waveform has zero rise time and fall time. In this time, majority of the electronic and electrical devices have power electronic circuits and they are controlled by PWM signals. Fast switching of power electronic devices is depends upon the fast rising and falling time which minimizes switching transition time and switching losses [29, 30]. The output voltage of inverter is controlled by controlling the width of pulses. Reduction of harmonic content present in the inverter output voltage is depended upon width of pulses. There are so many PWM techniques but here only three techniques are given:

a) Single-pulse modulation
b) Multiple-pulse modulation
c) Sinusoidal-pulse modulation.

PWM inverters require forced commutation. Above three techniques are different from each other by their output voltage and harmonic content present in that. Therefore, the choice of PWM technique is depend upon that which type of output voltage is needed and how much harmonic content should present in the output voltage waveform [30].

6.2.3.1. Single-pulse modulation (SPM) - Single-pulse modulation technique has only one pulse per half cycle and similarly one pulse for anther half cycle. The controlling of output voltage is depending upon the width of pulses [30]. Firing pulses are created by comparing of high frequency carrier wave with low frequency reference wave. Frequency of output voltage is decided by the frequency of reference signal. High frequency carrier wave is of nature of triangular wave and reference wave is rectangular in shape. The ratio of amplitude of reference signal and amplitude of carrier wave is known as modulation index. The output voltage is symmetry with horizontal axis due to this, even harmonics are not present. The shape of output is known as quasi-square wave [30, 31].

6.2.3.2. Multiple-pulse modulation (MPM) – This technique is an extension of SPM. In this technique, number of pulses per half cycle is more than one. As much as the number of pulses increases lower order of harmonic decreases but higher order of harmonics. Higher order of harmonics is not a big issue because it can easily reduce from low pass filter. In short, reduction of harmonic content in output voltage is depended upon the number of pulses [30, 31]. For generating firing pulses, there is requirement of two signals. One is triangular carrier signal with higher frequency and other is rectangular reference signal with low frequency. Firing pulses are generated by comparing the triangular signal with rectangular signal. The number of pulses per half cycle is depend upon the frequency of reference signal and carrier signal. The output voltage is controlled by modulation index. The ratio of frequency of carrier signal and reference signal is known as frequency modulation index. This kind of modulation index is also called as Uniform pulse-width modulation (UPWM) [31].

6.2.3.3. Sinusoidal pulse-width modulation (SPWM) - The MPM technique has disadvantage that it has equal pulse width over a cycle. To overcome this, SPWM technique has come into picture. SPWM technique also has several numbers of pulses per half cycle as MPM but with different pulse width. In SPWM technique, firing pulses are generated by comparing sinusoidal reference signal with high frequency triangular carrier signal. Modulation index (MI) is the ratio of amplitude of reference signal and amplitude of carrier signal. MI can't be more than unity. If MI is less than one then number of pulses per half cycle is increased in comparison to the MI is greater than one [30]. Comparison of reference signal and carrier signal is shown below:

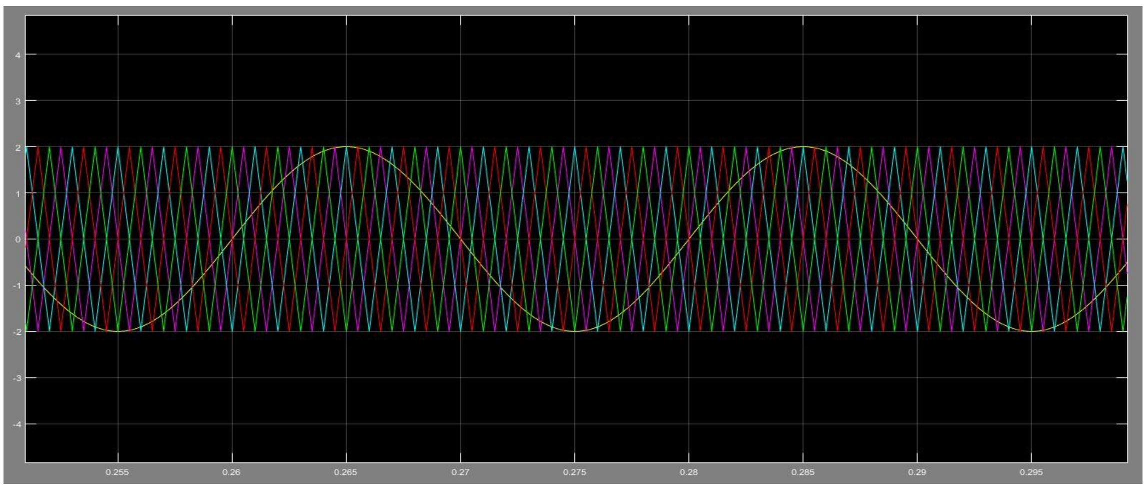


Figure 6.10: Comparison of reference signal and carrier signal.

CHAPTER-7

RESEARCH METHODOLGY

The main aim of this dissertation-II work is to enhance the power quality using multi-pulse converter and multi-level inverter in HVDC transmission link. It is well known that the HVDC link has two converter stations, one is rectifier and other is inverter, AC filter, DC filter, converter transformer, smoothening reactor, switchgear and protection devices.

Rectifier is used to convert AC power into DC power. The output voltage waveform of rectifier has pulses which is dependent on the rectifier configuration that whether it is six-pulse or twelve-pulse. In present time 12-pulse rectifier configuration is using for conversion. But this dissertation work proposes a 24-pulse configuration to convert AC power into DC power which leads to improvement of power quality. The output waveform will have fewer ripple contents in it which causes the lower order harmonics can be eliminated. Then THD will improve. Controlling of rectifier is done by using vector control principle which generate the pulses of rectifier with outer voltage and inner current control loop.

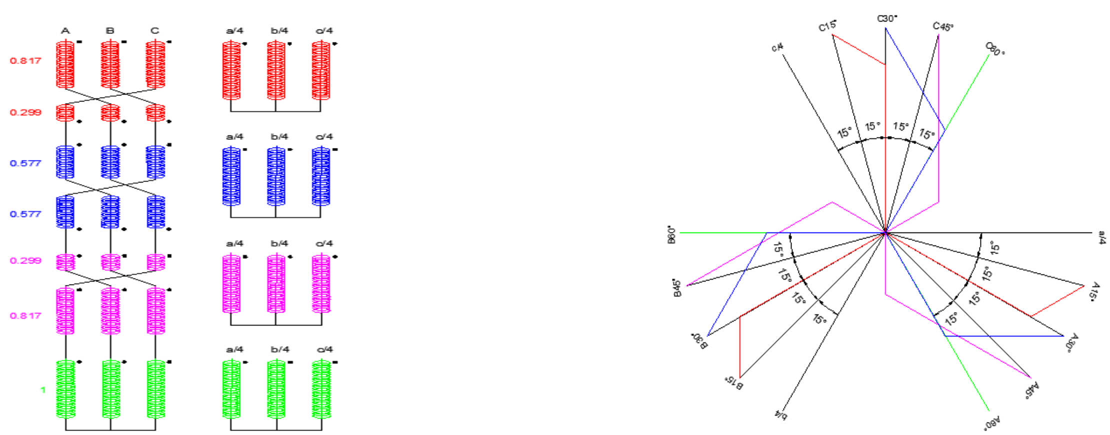
Inverter is used to convert AC power into DC power. The output voltage waveform has levels in it and number of levels is dependent on the type of inverter configuration. The aim of this dissertation work is to use multi-level inverter (MLI) which reduces the THD in the output waveform. Controlling of inverter is done by the use of SPWM.

CHAPTER- 8

SIMULATION MODEL AND RESULTS OF PRESENT WORK

In this paper, two works have been done, first is increasing the number of pulses of controlled rectifier and second is the using MLI with as low as THD. The MLI which is used here gives less THD at load.

8.1. Three-phase twenty four-pulse bridge rectifier- 24-pulse rectifier means, DC output voltage has 24-pulses per cycle. It has stated before that ripple content decrease in DC waveform with the increase in number of pulses. With this kind of configuration, DC output voltage waveform gets smoothed in comparison to six and twelve pulse [8]. To make 24-pulse rectifier four six pulse rectifier needed. Input to the four graetz bridge should have 15^o phase shift (because phase shift = 360/number of pulses). 15^o phase shift between four secondary of transformers are obtained by using the zig-zag transformer at primary side and star connection at secondary side. Fig. 4.6 shows the transformer winding connections and phasor diagram [10].



(a)

(b)

Figure 8.1: (a) Transformer windings connection, and **(b)** Phasor diagram [10].

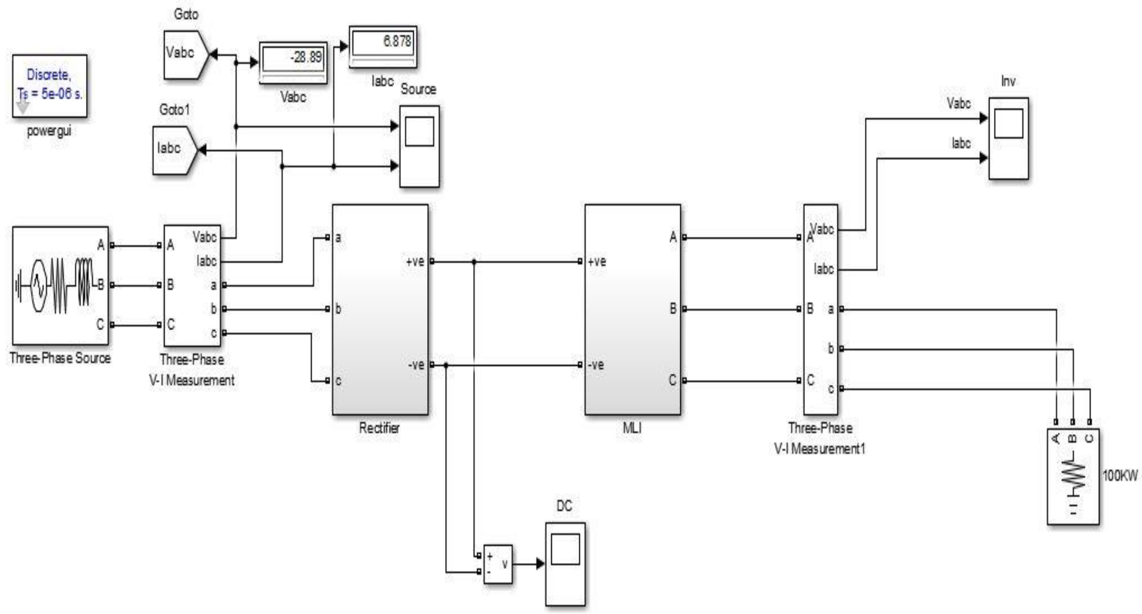


Figure 8.2(a): Simulation model of HVDC system.

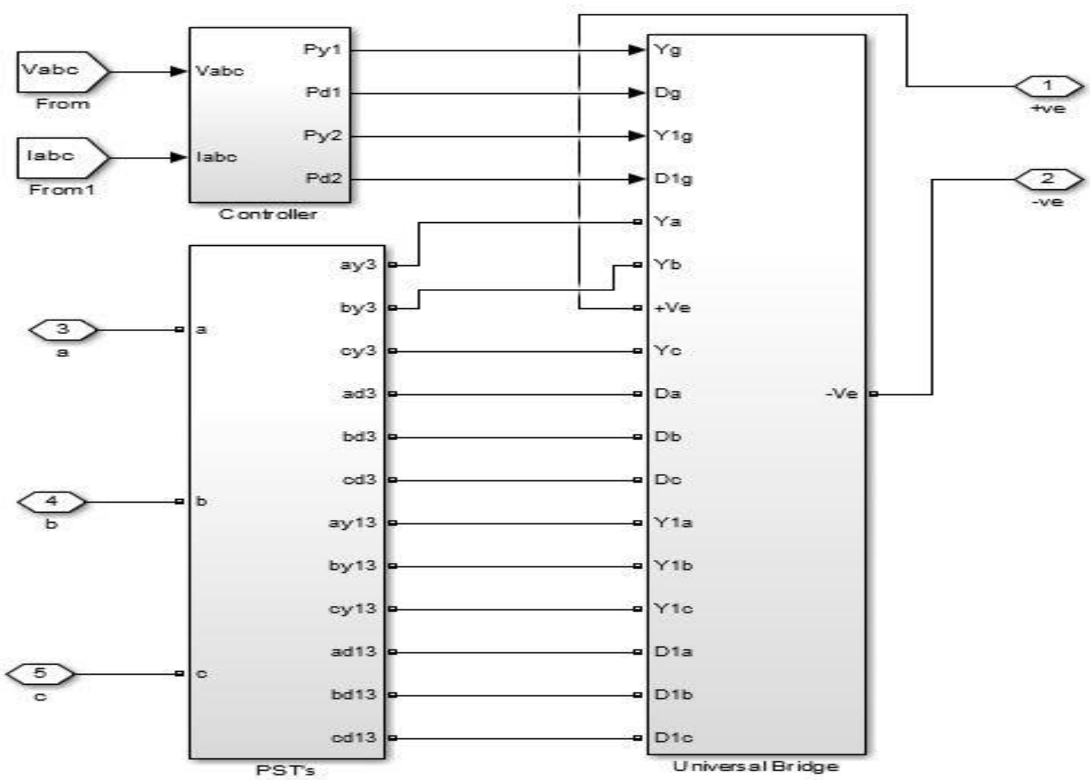


Figure 8.2(b): Subsystem of rectifier.

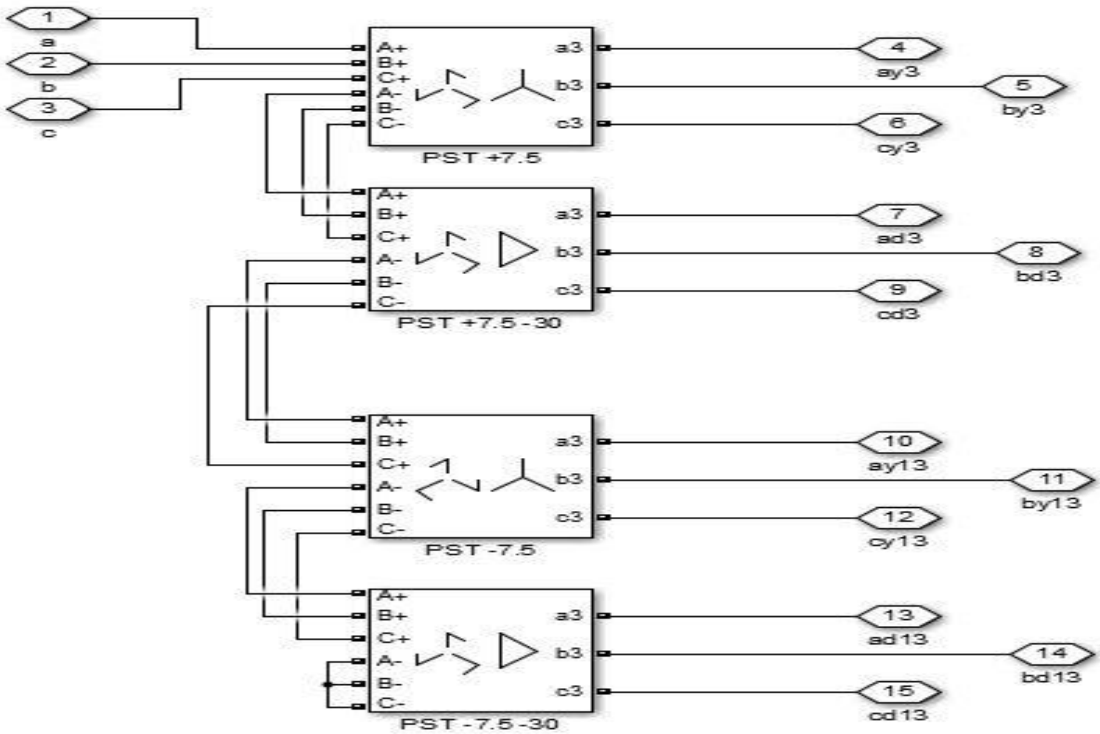


Figure 8.2(c): Subsystem of phase shifting transformer (PST).

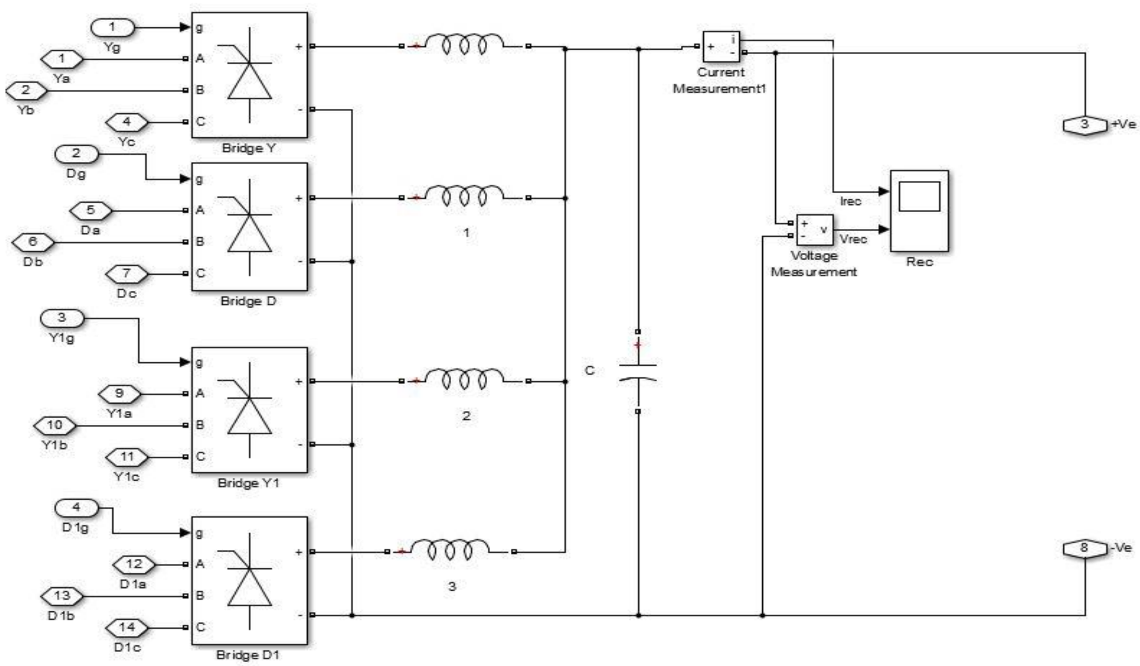


Figure 8.2(d): Subsystem of Universal Bridge.

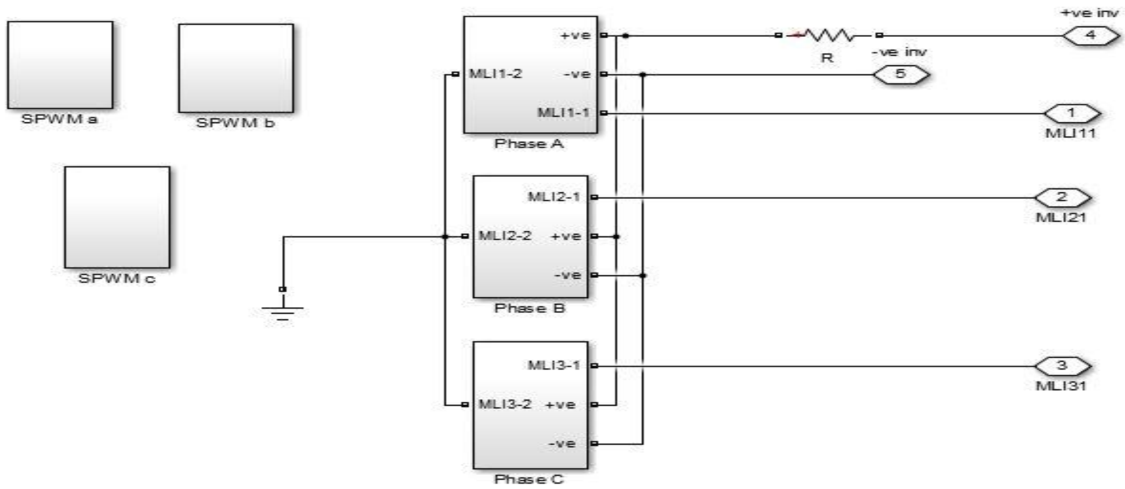


Figure 8.2(e): Subsystem of MLI.

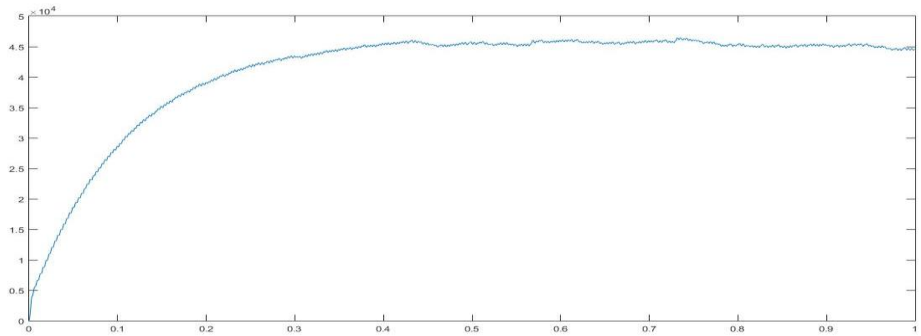


Figure 8.3(a): DC output voltage of the rectifier.

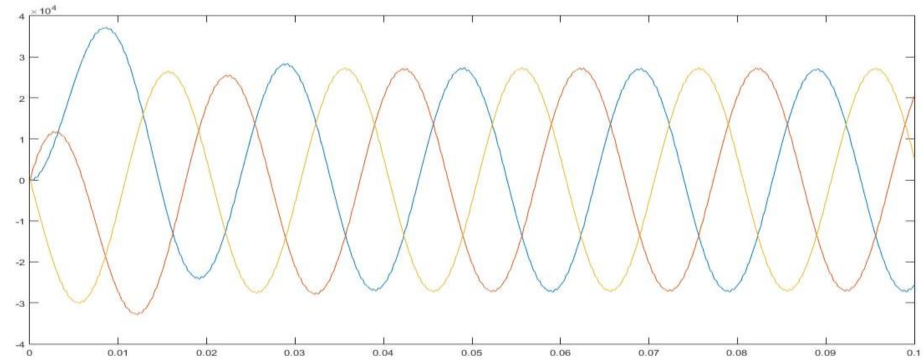


Figure 8.3(b): AC output voltage of MLI at load.

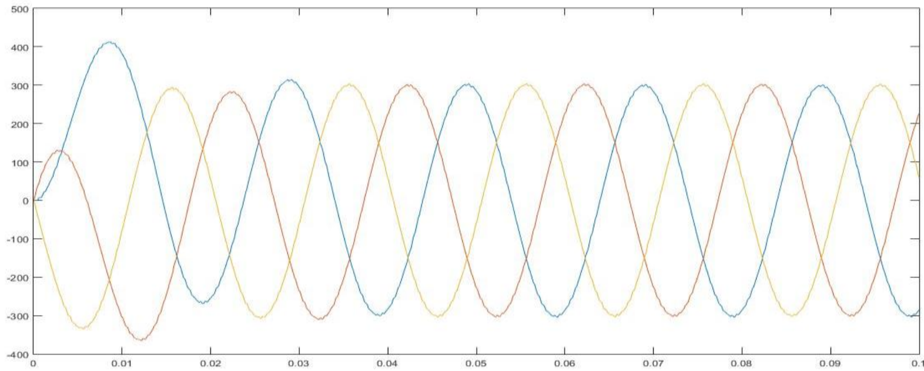


Figure 8.3(c): AC output current of MLI at load.

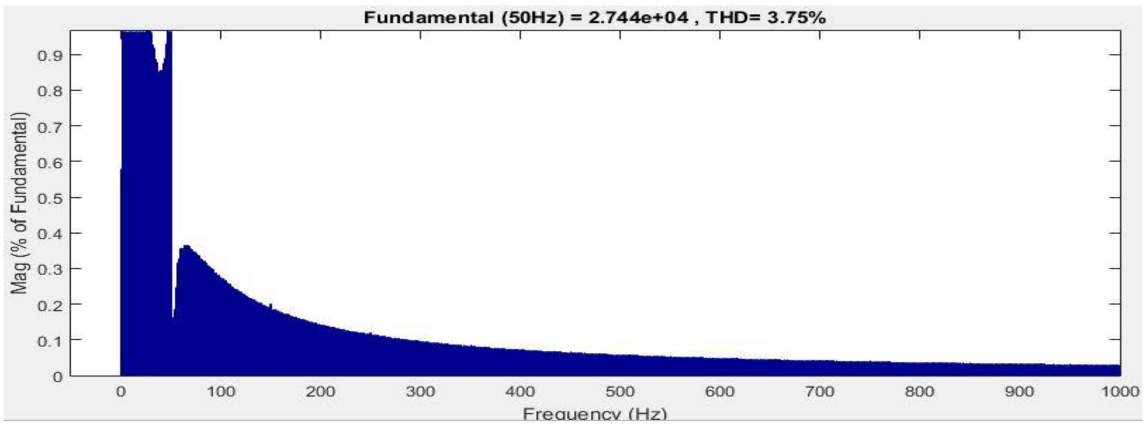


Figure 8.4(a): THD of AC output voltage of phase 'a'.

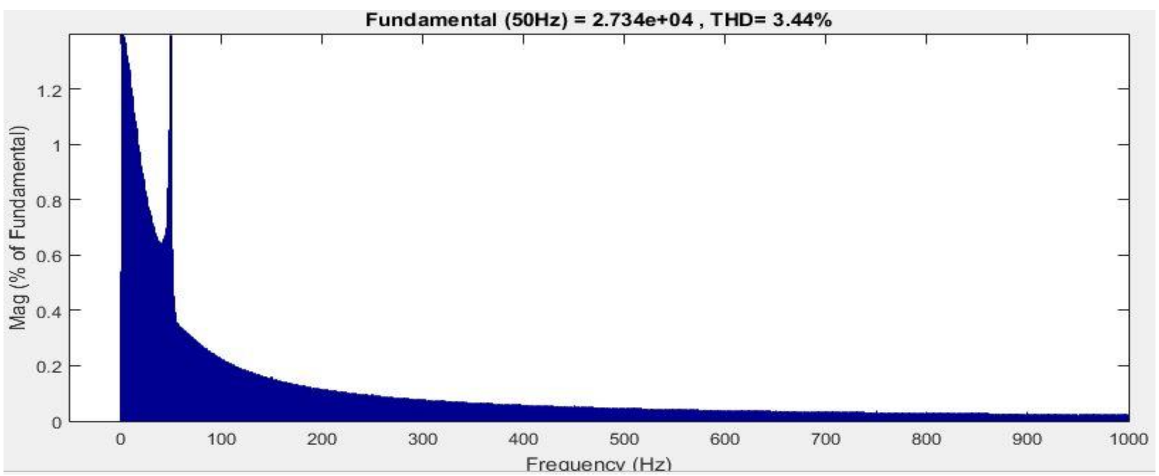


Figure 8.4(b): THD of AC output voltage of phase 'b'.

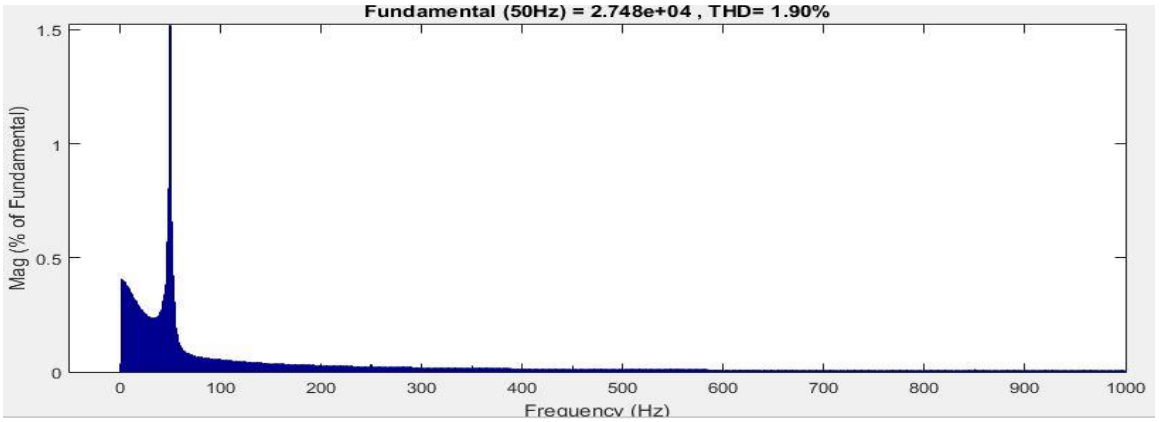


Figure 8.4(c): THD of AC output voltage of phase 'c'.

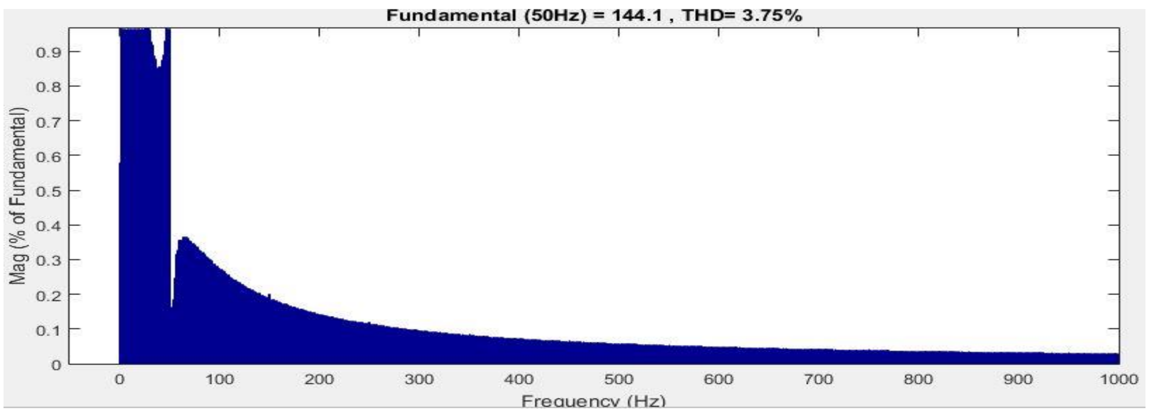


Figure 8.5(a): THD of AC output current of phase 'a'.

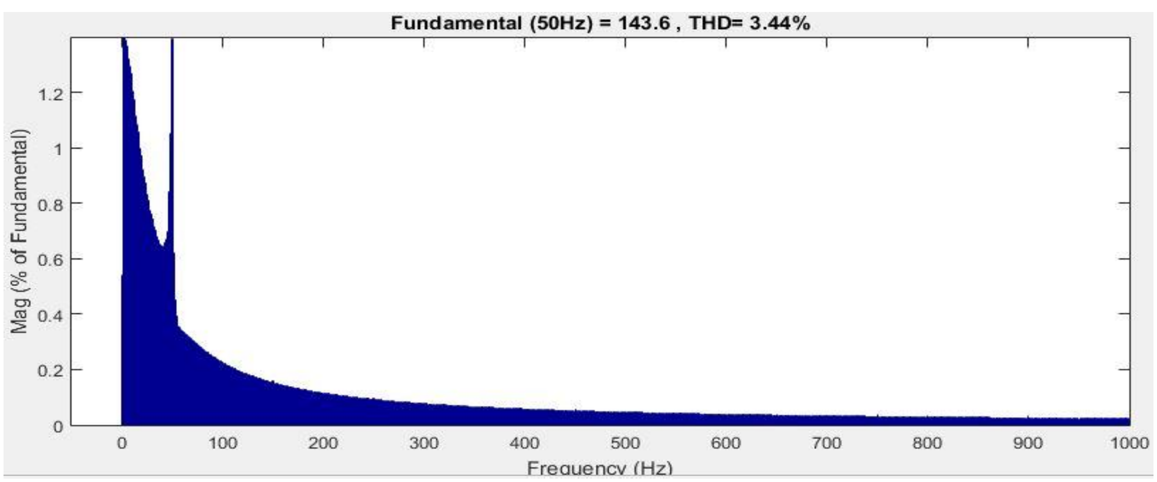


Figure 8.5(b): THD of AC output current of phase 'b'.

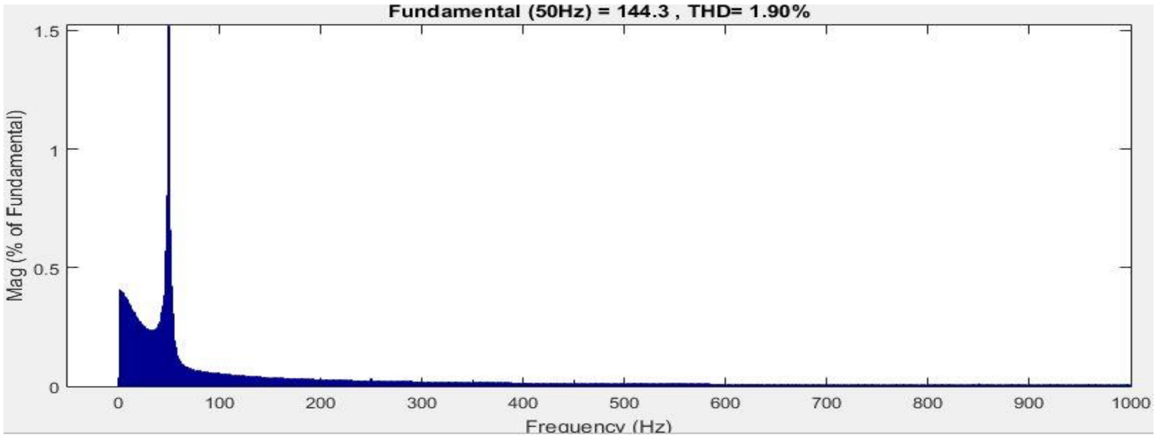


Figure 8.5(c): THD of AC output current of phase 'c'.

CHAPTER-9

CONCLUSION

Until now there are various multi-pulse structure and generally they are simulated using MATLAB/SIMULINK software and their result have been shown. In this paper, main objective is to increase number the number of pulses of controlled rectifier to have less ripple content in DC waveform of the rectifier and as well as reduces the total harmonic distortion(THD) of AC output waveform using five-level MLI. This paper proposed a HVDC link which has low THD in AC output voltage as well as in current after MLI.

Table 9.1 Ripple Content Observed results:

No. of pulses	Ripple Factor
6	4.447
12	2.049
24	0.2975

Table 9.2 Total Harmonic Distortion at R load:

Phases	THD in Voltage	THD in Current
A	3.75	3.75
B	3.44	3.44
C	1.90	1.90

CHAPTER-10

FUTURE SCOPE

In Future, HVDC technology will have many future application. Although, it has reached to a greater extent but still it has so much area of research. In HVDC, research can be done on controlling of rectifier and inverter, DC circuit breaker and improved topology of rectifier and inverter. If the size and cost of HVDC system will reduce then it can be used in offshore wind farm, hybrid renewable energy sources as well as in power conditioning circuit (PCS). There is some point on which basis application of HVDC link is limited which are:

➢ **Power Semiconductor Devices;** the use of light trigger thyristor will give astonishing improvement because it uses microprocessor and computer memory and with use of these equipment, work can be done beyond what many thought.

- **Cable and Insulation;** all things are happening at higher voltage level so there should be a cable with proper insulation which can withstand with these voltage level.
- **Control System;** since HVDC system needs continuous controlling and monitoring therefore, HVDC system should have much more precise and effective controlling technique.
- **DC circuit breaker;** HVDC system are facing heavy problem in interrupting DC current or switching of DC current. New advancement in circuit breaker will give better use of HVDC system.

REFERENCE

1. Robert Rudervall, J.P. Charpentier, Raghuveer Sharma, "High Voltage Direct Current (HVDC) Transmission Systems Technology Review Dissertation-I work," in *Energy Week 2000*, Washington, D.C, USA, March 2000.
2. ABB, "The early HVDC development," available from: http://www05.abb.com/global/scot/scot221.nsf/veritydisplay/8cf1c44dbc5226 85c12574e9006051a5/$File/The%20early%20HVDC%20development.pdf.
3. German Aerospace Center, Institute of Technical Thermodynamics, Section System Analysis and Technology Assessment, "Trans-Mediterranean Interconnection for Concentrating Solar Power," Available from: http://www.dlr.de/tt/trans-csp.
4. EWEA, "Oceans of Opportunity," Available from: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Offshore_ Report_2009.pdf, September 2009.
5. Abhay Kumar, Mats Lagerkvist, Mårten Eklund, Yuan QingYun, Three Gorges – Changzhou HVDC: Ready to Bring Bulk Power to East, October 2003.
6. B.Gopal1, P.Krishna Murthy2, G.N.Srinivas3, Power Quality Improvement using 24 Pulse Bridge Rectifier for an Isolated Power Generation, IJAIR, 2012.

7. Mr S Dinesh Kumar1, Abhilash Dwivedi2, Pranshita Gupta3, Shubham Sachan4, DESIGN AND ANALYSIS OF 24 PULSE AC-DC CONVERTER, JETIR, May 2015, Vol.2.
8. R.Tamizh Nesan, J.Jegadhish, Designing and Harmonic analysis of a new 24-Pulse Rectifier using diodes with Phase Shifting Transformer, IJSETR, Vol. 4, February 2015.
9. Sewan Choi* Prasad N. Enjeti * Derek A. Paice **, NEW 24-PULSE DIODE RECTIFIER SYSTEMS FOR UTILITY INTERFACE OF HIGH POWER AC MOTOR DRIVES, IEEE, 1996.
10. Alvaro Ortiz Monroy Hoang Le-Huy Claude Lavoie, Modeling and Simulation of a 24 pulse Transformer Rectifier Unit for More Electric Aircraft Power System.
11. Chen Xiao-qiang and Qiu Hao*, Zigzag Connected Autotransformer-Based 24-pulse AC-DC Converter, IJEEPS, 2015.
12. K. Santhosh kumar1, K. Anji babuK2, N. Uday kumar3, M. Soma Sekhar, Power Quality Improvement through 24 -pulse Diode Bridge Rectifier in Pico Hydro Power Generation, IJETAE, Vol. 3, March 2013.
13. K.Srinivas, Analysis and Implementation of Multi Pulse Converter for HVDC System, IJETAE, Vol. 2, April 2012.
14. Sonika Raghuvanshi 1, Nagendra Singh, Comparative analysis of 36, 48, 60 pulse AC-DC Controlled Multipulse Converter for Harmonic, IJARCET, Vol. 3, April 2014.
15. Mamta N. Kokate, Comparison of simulation results three level and five level H-bridge inverter and hardware implementation of single leg H- bridge three level inverter, IJIRS, Vol. 2, April 2013.
16. Gobinath.K1, Mahendran.S2, Gnanambal. I, NEW CASCADED H-BRIDGE MULTILEVEL INVERTER WITH IMPROVED EFFICIENCY, IJAREEIE, Vol.2, April 2013.
17. R.DHARMAPRAKASH, 2JOSEPH HENRY, SWITCHING TABLE BASED 2-LEVEL INVERTER AND 3-LEVEL DIODE CLAMPED INVERTER, JTAIT, Vol.60, Feb. 2014.
18. Carlo Cecati, Fabrizio Ciancetta, and Pierluigi Siano, A Multilevel Inverter for Photovoltaic Systems With Fuzzy Logic, *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 57, NO. 12, DECEMBER 2010*.
19. Haitham Abu-Rub, Joachim Holtz,Jose Rodriguez, and Ge Baoming, Medium-Voltage Multilevel Converters—State of the Art, Challenges, and Requirements in Industrial

Applications, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 57, NO. 8, AUGUST 2010.

20. José Rodríguez, Jih-Sheng Lai,and Fang Zheng Peng, Multilevel Inverters: A Survey of Topologies, Controls, and Applications, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 49, NO. 4, AUGUST 2002.
21. Dr. Keith Corzine, **Operation and Design of Multilevel Inverters,** Developed for the Office of Naval Research December 2003.
22. Pablo Correa, *Student Member, IEEE*, Mario Pacas, *Senior Member, IEEE*, and José Rodríguez, *Senior Member, IEEE*, Predictive Torque Control for Inverter Fed Induction Machines, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 54, NO. 2, APRIL 2007.
23. L. Zhang, "Modeling and Control of VSC-HVDC Links Connected to Weak AC Systems," Doctor of Philosophy, School of Electrical Engineering Electrical Machines and Power Electronics, Royal Institute of Technology, Stockholm, 2010.
24. J. Svensson, "Grid-Connected Voltage Source Converter- Control Principles and Wind Energy Applications," PhD thesis, Department of Electric Power Engineering, Chalmers University of Technology, Goteborg, 1998.
25. S. Meier, "Novel Voltage Source Converter based HVDC Transmission System for Offshore Wind Farms," Department of Electrical Engineering Electrical Machines and Power Electronics, Royal Institute of Technology, Stockholm, 2005.
26. Tatjana Kalitjuka, “Control of Voltage Source Converter for Power System Applications,” Master thesis, Department of Electric Power Engineering, Norwegian University of Science and Technology, 2011.
27. K. R. Padiyar, “HVDC Power Transmission Systems,” Third Edition, New Age International Publications, 2015.
28. Bhim Singh and R. Saha, “Modeling of 18-Pulse STATCOM for Power System Applications,” Journal of Power Electronics, Vol. 7, No. 2, April 2007.
29. Jian Sun, “Pulse Width Modulation,” Department of Electrical, Computer and System Engineering, Springer-Verlag London Limited 2012.
30. P. S. Bhimra, “Power Electronics,” Fourth Edition, Khanna Publishers, 2012.

31. Muhammad H. Rashid, “Power Electronics Circuits, Devices and Applications,” Third Edition, PEARSON, 2004.
32. R. Visintini, “RECTIFIERS,” Elettra Synchrotron Light Laboratory, Trieste, Italy.
33. Kurt A. Young, Comparative Analysis of Multi-Pulse Phase Controlled Rectifiers in Continuous Conduction Mode with a Two-Pole LC Filter for Surface Ship DC Applications,” Master thesis, Naval Post-Graduate School, March 2013.
34. High Voltage Direct Current Transmission-Proven Technology for Power Exchange, SIEMENS.