VOLTAGE SOURCE CONVERTER BASED DC SUB TRANSMISSION AND DISTRIBUTION SYSTEM FOR CITY INFEED

A Dissertation Submitted towards the partial fulfillment of the requirement for the award of the degree of

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IN

POWER APPARATUS SYSTEM

Submitted by

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CERTIFICATE

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This dissertation is a bonafide record of project work carried out by her under my guidance and supervision. Her work is found to be excellent and her discipline impeccable during the course of the project.

I wish her success in all her endeavors.

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ABSTRACT

HVDC utilizes thyristorised converters and inverters for transfer of power from one AC system to another Ac system/loads through single pulse or multipulse per AC cycle. The HVDC systems thus produce huge harmonics and consume very large reactive power for their operation. The requirement of a dynamic DC system has been felt for long to work in tandem for reliable and efficient power system.

In this dissertation, a Multi terminal VSC based DC system has been analysed, modeled, simulated and developed for many nodes. A comprehensive mathematical modeling of VSC based converter and inverter system, their link and Multi Terminal system has been done using SIMULINK and SIMPOWERSYSTEM toolbox under MATLAB environment. A control system has been developed for current control of such MTDC converters, inverters, MTDC systems. The dynamic responses of MTDC systems under various operating conditions such as starting,load perturbations etc is presented to demonstrate the effectiveness of the system.

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CHAPTER 1

INTRODUCTION

1.1 General

A **"WAR OF CURRENTS"** in 1880 placed ad vocation of George Westinghouse and Nikola Tesla over Thomas Edison for adoption of DC. During initial years Edison's DC was the standard for the electricity loads whereas Tesla designed a system for generation, transmission and use of AC power in partnership with Westinghouse to commercialize the system [1] .The drawback with Edison's DC generation and distribution system is the compulsion of proximity of generating station with the loads as the voltage generated is at the same level as been required by the load .However this drawback was well taken care in AC due to transformers which not only allow power to be transmitted at high voltage but also for given flexibility in use of power at dispersed and distanced load centers. Due to these advantages of AC over DC, AC system has totally over powered the DC for centralized power generation and power distribution. The turning point for the acceptance of AC was marked with Tesla's Niagara falls system.

Direct current systems are still universally used in vehicles for engine starting, lighting, ignition and battery charging. Positive twelve DC volt DC is the most common standard in automobiles, though the industry has announced plans to move to positive thirty-six volts DC (nominally forty-two volts at the bus) to reduce wire size requirements as more devices classically driven directly by the engine become all-electric, such as engine valve and air conditioning compressors, and new features such as heated windshields are added. These are other classical examples of the use of DC for distribution such as New York city's subway which continues to be powered by DC till date [1].

Other applications include telephone transmission and switching installations which distribute DC power internally so that local battery banks can instantly assume the loads when external power sources fail. Negative forty-eight volt DC is the usual standard, though much cellular telephone radio equipment runs on positive twenty-four volt DC. Computer systems generally operate with DC power since logic circuits required it.

With the rise of semiconductor technology in power the predominance of alternating current has been altered. The key problem in early evolution of HVDC was how to develop reliable and economic valves that would convert HVAC into HVDC and vice a versa. With the development of thyristor valve for higher power ratings the economics of DC voltage conversion has become somewhat attractive for specialized applications. Though AC predominates, but there exist a number of high-voltage DC transmission lines throughout the world which ports the bulk power. The technology had been found suitable for high voltage systems porting bulk power between two stations. HVDC transmission is widely recognized as being advantageous for long distance bulk power delivery, asynchronous interconnections and long submarine cables crossings.

In today power systems, HVDC transmission makes an important contribution to controlling power transmission, safeguarding stability and containing disturbances. On an HVDC system, the power flow can be controlled rapidly and accurately. Both the power level and direction are determined by control systems.

1.2 History of HVDC Transmission

In early 1881, Marcel Deprez published first theoretical examination of first HVDC power transmission, later in 1882, he transmitted 1.5 KW at 2 KV over a distance of 35 miles. His work was extended by Swiss Engineer Rene Thury with a system of series connected motor generator sets for increased voltage. The first reorganization of ac-dc coexistence has been marked as Moutiers to Lyon HVDC transmission with a final capacity of 20MW at 125KV over a distance of 230km which was used as a reinforcement of an existing AC system. For the practical application of DC power transmission a development of electronic valve was required which was developed by Dr Uno Lamm in Sweden. The development of mercury valve led to the commercial application of a HVDC technology since 1954. Some of the mercury arc based HVDC technology success includes [2]

1. *Sweden-Gotland link (1954)*

A 20 MW, 100KV DC for a distance of 96km that supplies power to Island of Gotland.

2. *English Channel (1961)*

A 160MW, 100KV submarine link over a distance of 64 km

3. *Volgograd-Donbass (1962-1965)*

A 720MW, 400KV over a distance of 470km. The first overhead transmission scheme

4. *New Zealand link 1965*

A 600MW, 250KV over a distance of 570km overhead transmission and 40km submarine link.

Mercury arc schemes has posed great problem of deposition of material throughout the valve which resulted from charged carriers striking the walls during firing and blocking. This affect limited the maximum direct voltage of transmission.

In spite of the successful operation of mercury arch schemes, the incidence of arc-backs, considerable maintenance and voltage limits encouraged the development of thyristors, which in turn led to following incredible progress:

1. *Eel River (1972)*

A 350 MW, 80KV first large HVDC project designed for thyristors valves

2. *Cabora-Bassa (1977-79)*

A 1920MW, 533KV between Zambia river and Johannesburg of 1414km

3. *Inga-Shaba (1981)*

A 560MW, 500KV over a distance of 1700km. also the first case of international bulk power transmission.

4. *Skagerrak (1976-77)*

A 500MW, with interconnections between Norway and Denmark, includes 127km of cable transmission and 113km of overhead line.

With the development of such HVDC projects, the HVDC era started and became global.

1.3 Advantages of HVDC over AC Transmission

The higher voltage levels, mature technology and new converter designs have broadened the potential range of HVDC transmission to include applications for underground, offshore, economic replacement of reliability-must-run generation and voltage stabilization. This broader range of applications has contributed to the recent growth of HVDC transmission.

- Undersea cables, which are not possible with AC transmission due to additional high capacitance losses.
- Without intermediate 'taps', endpoint-to-endpoint long-haul bulk power transmission.
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.
- Power transmission between unsynchronized AC distribution systems.
- For a given power transmission capacity, the profile of wiring and pylons are reduced.
- For connecting remote generating plant to the distribution grid for long distance bulk power delivery using fewer lines with HVDC transmission than with AC transmission.
- Stabilizing a AC power-grid, without increasing maximum prospective short circuit current.
- Reduced Corona discharge (due to higher voltage peaks) for HVAC transmission lines of similar power
- Line cost is lesser in HVDC than with AC due to fewer conductors requirement.

1.4 Applications

HVDC transmission applications can be broken down into different basic categories. The selection of HVDC is economic and only feasible way to interconnect two asynchronous networks, reduce fault currents, utilize long underground cable circuits, bypass network congestion, share utility rights-of-way without degradation of reliability,. In all of these applications, HVDC nicely complements the ac transmission system.

1.4.1 Long-Distance Bulk Power Transmission

HVDC transmission systems provide a more economical alternative to AC transmission for long-distance bulk power delivery from remote resources without limitation. The utilization of HVDC links is usually higher than that for extra high voltage ac transmission, lowering the transmission cost per MWh. This controllability can also be very beneficial for the parallel transmission since, by eliminating loop flow, it frees up this transmission capacity for its intended purpose of serving intermediate load and providing an outlet for local generation. With long-distance transmission, the concept of “break-even distance” frequently arises. This is where the savings in line costs offset the higher converter station costs (Fig 1.1). A bipolar HVDC line uses only two insulated sets of conductors rather than three. This results in narrower rights-of-way, smaller transmission towers, and lower line losses than with ac lines of comparable capacity.

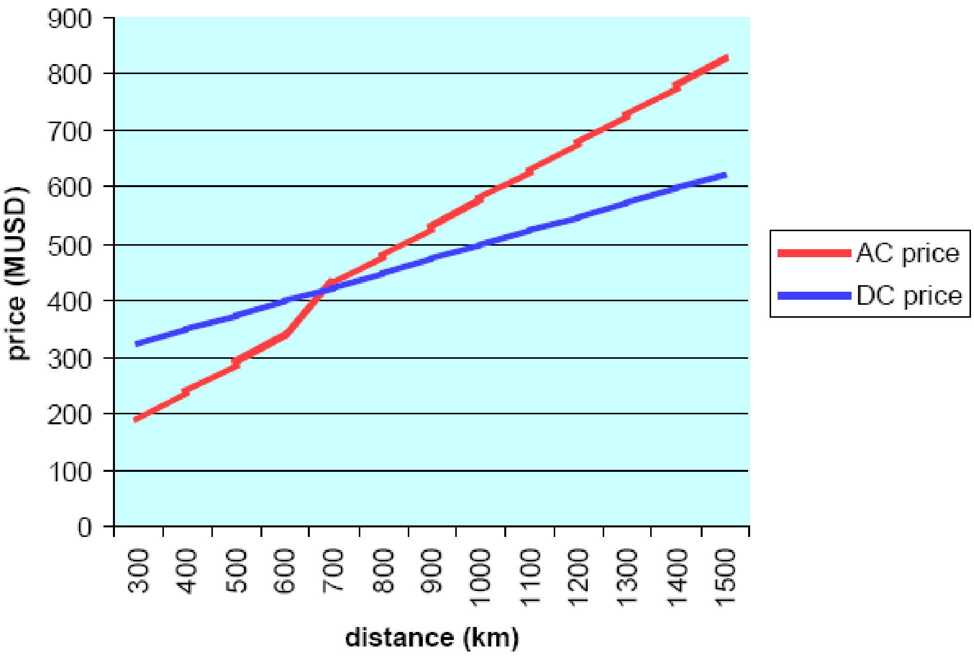


Fig 1.1: Price Variation for AC vs HVDC Transmission

Furthermore, the long-distance ac lines usually require intermediate switching stations and reactive power compensation. This can increase the substation costs for ac transmission to the point where it is comparable to that for HVDC transmission.

1.4.2 Underground and Submarine Cable Transmission

Unlike the case for AC cables, there is no physical restriction limiting the distance or power level for HVDC underground or submarine cables. For underground or submarine cable systems there is considerable savings in installed cable costs and cost of losses when using HVDC transmission. There is a drop-off in cable capacity with AC transmission over distance due to its reactive component of charging current since cables have higher capacitances and lower inductances than AC overhead lines. Although this can be compensated by intermediate shunt compensation for underground cables at increased expense, it is not practical to do so for submarine cables.

For a given cable conductor area, the line losses with HVDC cables can be about half those of AC cables. This is due to ac cables requiring more conductors (three phases), carrying the reactive component of current, skin-effect, and induced currents in the cable sheath and armor.

With a cable system, the need to balance unequal loadings or the risk of post contingency overloads often necessitates use of a series-connected reactors or phase shifting transformers. These potential problems do not exist with a controlled HVDC cable system.

Extruded HVDC cables with prefabricated joints used with VSC-based transmission are lighter, more flexible, and easier to splice than the mass-impregnated oil-paper cables (MINDs) used for conventional HVDC transmission, thus making them more conducive (Fig 1.2). The lower-cost cable installations made possible by the extruded HVDC cables and prefabricated joints makes long-distance underground transmission economically feasible.

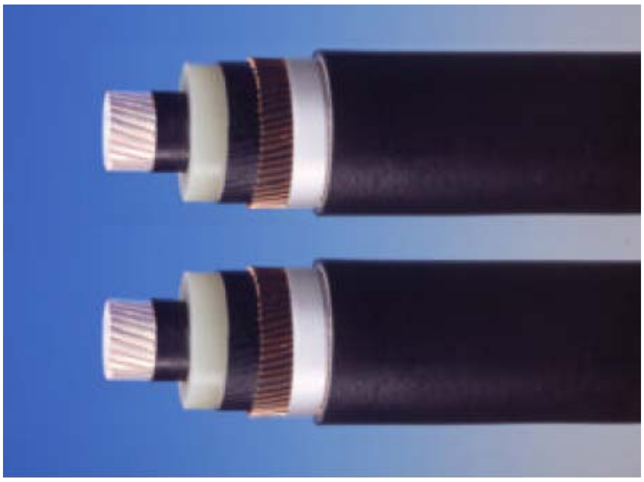


Fig 1.2: Land Cable

1.4.3 Asynchronous Ties

With HVDC transmission systems, interconnections can be made between asynchronous networks (Fig 1.3 and Fig 1.4) for more economic or reliable system operation. The asynchronous interconnection allows interconnections of mutual benefit while providing a buffer between the two systems. Often these interconnections use back-to-back converters with no transmission line. Asynchronous HVDC links act as an effective “firewall” against propagation of cascading outages in one network from passing to another network.

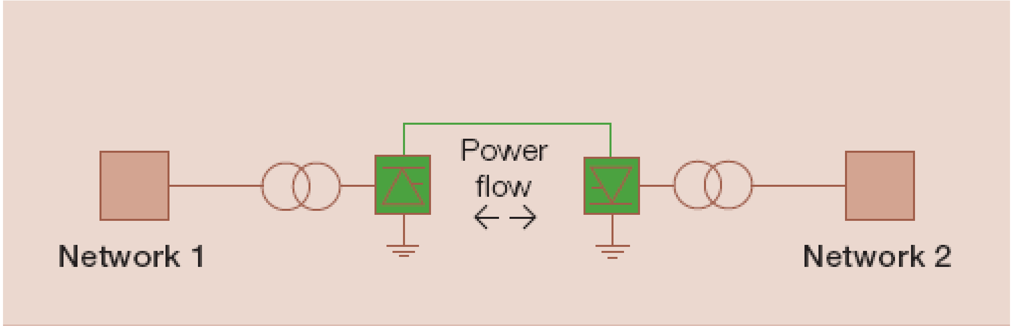


Fig 1.3 : Classic HVDC Scheme for Interconnection

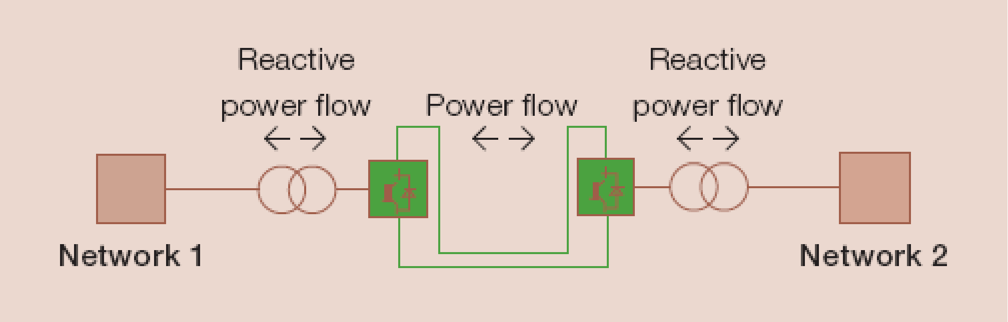


Fig 1.4 : VSC HVDC Scheme for Interconnection

1.4.4 Offshore Transmission

Self-commutation, dynamic voltage control, and black-start capability allow compact VSC HVDC transmission to serve isolated loads on islands or offshore production platforms over long-distance submarine cables. This capability can eliminate the need for running expensive local generation or provide an outlet for offshore generation such as that from wind. The VSCs can operate at variable frequency to more efficiently drive large compressor or pumping loads using high-voltage motors.

Large remote wind generation arrays require a collector system, reactive power support, and outlet transmission. Transmission for wind generation must often traverse scenic or environmentally sensitive areas or bodies of water. Many of the better wind sites with higher capacity factors are located offshore. VSC-based HVDC transmission allows efficient use of long-distance land or submarine cables and provides reactive support to the wind generation complex (Fig 1.5).

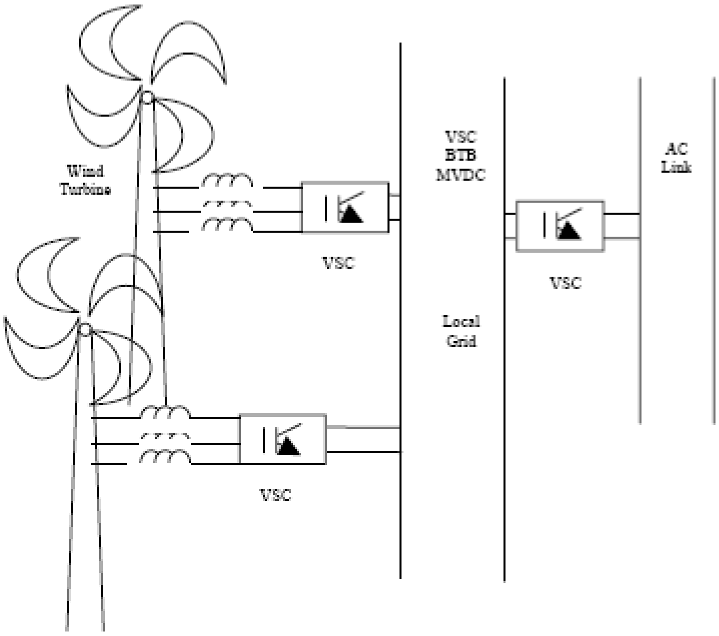


Fig 1.5 : Wind Power Generation Park

1.5 Core HVDC Technologies

Conventional HVDC transmission employs a line commutated 6 pulse current source type converters with thyristor valves. Such converters require a synchronous voltage source at the AC side of converter for proper operation. Most modern HVDC transmission scheme utilizes a 12 pulse configuration to reduce requirements of harmonics filtering as compared to six pulse converters which employs 5th and 7th harmonic filters on AC side and 6th harmonic filter on DC side.

Line commutated converters require a relatively strong synchronous voltage source in order to commutate and can only operate with the ac current lagging the voltage, so the conversion process demands reactive power which is supplied from ac filters ,shunt banks or series capacitors. Any surplus or deficient in reactive power from these local sources must be supplied by the AC power system. The weaker the AC system, the tighter will be the reactive power exchange, to operate within the desired voltage tolerance [3].

The prevalent HVDC technologies employs following types of converters.

1.5.1 Natural Commutated Converters

The converters used for DC-AC and AC-DC conversion is done by the thyristors through there natural commutation. Thyristor are connected in series to form valve which operate at several hundred of KV and at grid frequency. The DC voltage level of the bridge can be changed by means of firing angle control thus enabling the rapid control of transmitted power efficiently.

1.5.2 Capacitor Commutated Converter

Further development has been made in circuit with commutation of thyristors by series connected capacitors. The commutation capacitors are inserted in series between the converter transformer and thyristor valves (Fig 1.6). The configuration is capable of handling of commutational failures which were predominant in case of HVDC converters.

Converters with series capacitors connected between the valves and the transformer were introduced in the late 1990's for weak systems, back to back applications. The series capacitor meets requirements of reactive power automatically through load current and provides part of commutation voltage, and also improves voltage stability.

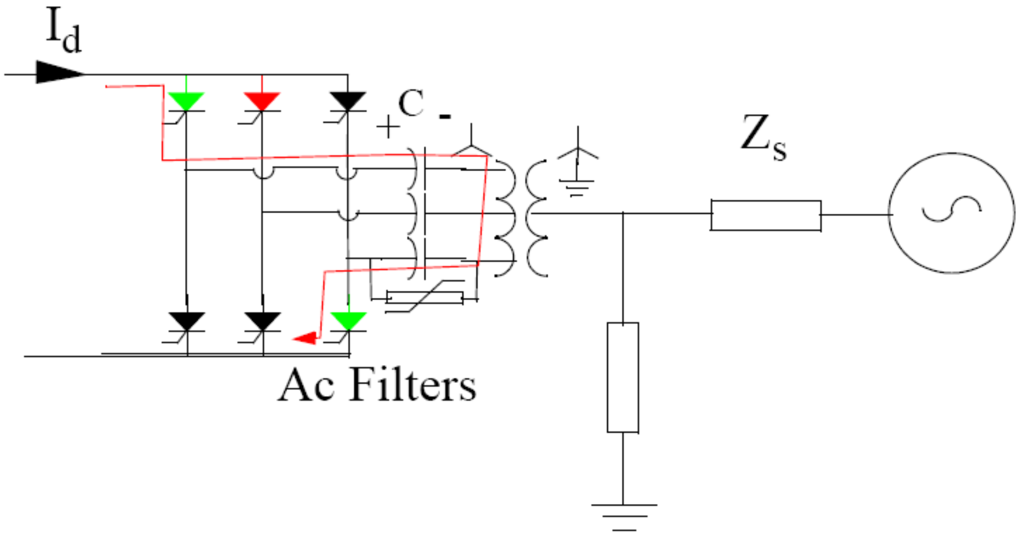


Fig 1.6: Capacitor Commutated Converters

1.5.3 Self Commutated Converters

These converters are also known as VSC converters. The valves of these converters are built up with either GTO or IGBT which has the ability not only to turn on but also to turn off due to inherent self commutation capability, these converters can feed passive network, improves power quality and can control active and reactive power independently.

Unlike conventional HVDC transmission, the converter themselves have no reactive power demand and can actually control the reactive power in AC circuits to regulate AC system voltage.

Though the HVDC made a remarkable progress during this era, it lacks some of the characteristics which enhance a question on its applicability to some specific requirements as the independent control of power, multi terminal ties; coordinated control etc which gave rise to the development of VSC based HVDC.

HVDC transmission using VSCs (Fig 1.7) with PWM (VSC Based HVDC) was introduced in 1997 [4]. The operation of VSC converter is achieved by PWM which can create sinusoidal current wave form at any phase angle or amplitude by changing PWM pattern. This makes PWM voltage source converter an ideal part in the transmission network. These VSC based systems are self commutated with insulated –gate bipolar transistor (IGBT) valves and works very well with solid dielectric extruded HVDC cables. VSC technology can rapidly control both active and reactive power independently at each terminal independent of DC transmission voltage level which gives total flexibility in placement of selection of the converters anywhere in the AC network.

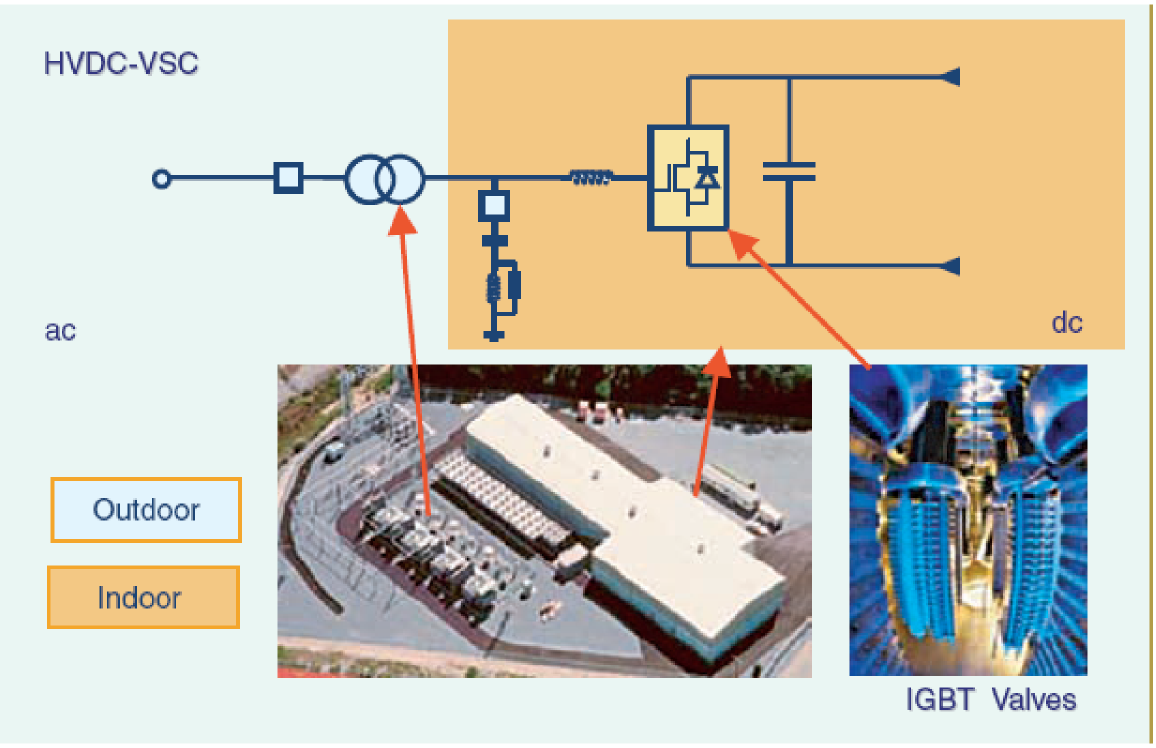


Fig 1.7: HVDC with Voltage Source Converters

1.6 VSC Based HVDC

ABB introduced 1997 a different HVDC technology called VSC based HVDC and is based on VSC transmission technology. This type of converter has the advantage of providing control of active and reactive power independently. Conventional HVDC is DC current based transmission (Fig 1.8) whereas VSC based HVDC operates via the DC voltage and is therefore DC voltage based transmission (Fig 1.9).

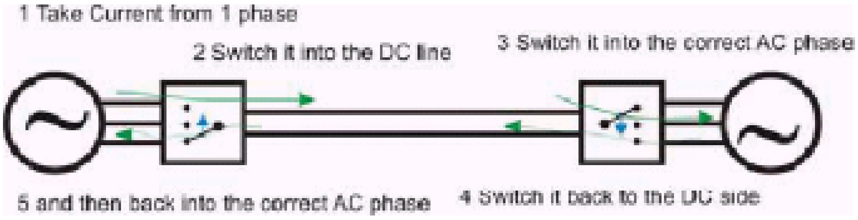


Fig 1.8: Model of Classic HVDC

Fig 1.9: Model of VSC HVDC

In VSC HVDC, Pulse Width Modulation (PWM) is used for generation of the fundamental voltage. Using PWM, the magnitude and phase of voltage can be controlled freely and almost instantaneously within certain limits (Fig 1.10). This allows independent and fast control of both active and reactive power flows. PWM VSC is therefore a close to ideal component in transmission network [5]. From a system point of view, it acts as a Zero inertia motor or generator that can control active and reactive power almost instantaneously. Furthermore it does not contribute to the short circuit power as the AC current can be controlled.

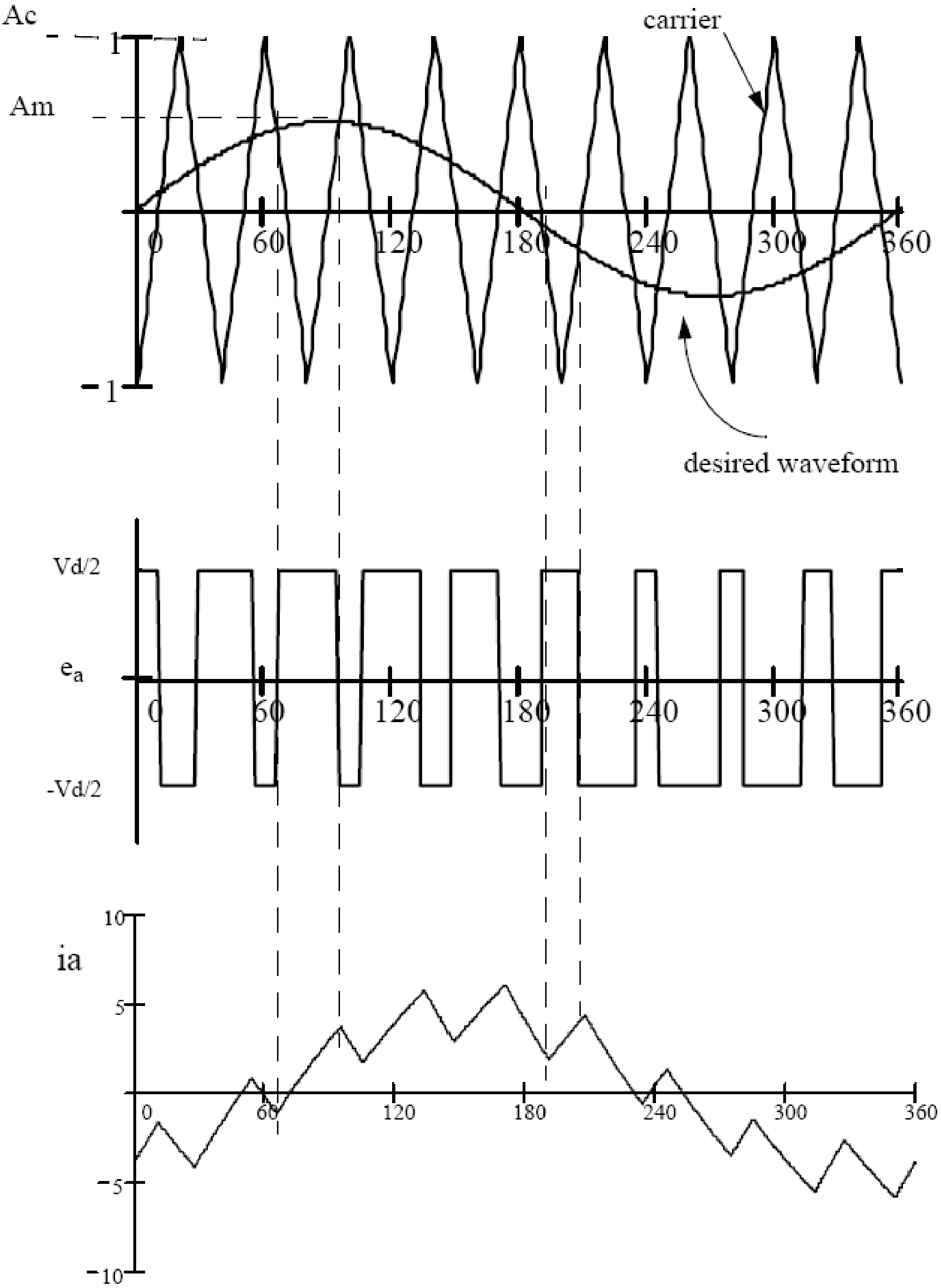


Fig 1.10: Principle of PWM

VSC based HVDC is the successful and environmental-friendly way to design a power transmission system for a submarine cable, an underground cable or back-to-back transmission. In VSC based HVDC, the newly developed IGBT valves replace thyristors. These not only carry out the AC/DC conversion but add new features and flexibility. It is particularly suitable for small scale power transmission application and extends the economical power range to few tens of MW. VSC based HVDC is sometimes called “the invisible power transmission” as it uses underground cables [6].

The advantage of both HVDC and VSC Based HVDC transmission is that they do not contribute to the fault current. The fault free network experiences an interruption of power flow in the DC transmission but no fault current. HVDC transmission with VSCs can be beneficial to over all system performance. Self computational with VSC even permits black start i.e. the converter can be used to synthesize a balanced set of three voltages like a virtual synchronous generator. The dynamic support of the AC voltage at each converter terminal improves the voltage stability and can increase the transfer capability of the sending and receiving end AC system thereby leveraging the transfer capability of DC link.

1.7HVDC vis-à-vis VSC Based HVDC

1.7.1 Short Circuit Power

Classical, thyristor based, HVDC depends on the correct functioning of the AC system. The AC/DC converter requires a minimum Short Circuit Power from the connected AC grid

Classical HVDC cannot feed power into a network which lacks generation completely or which has little or very remote generation. A common measure of the adequacy of this is the Short Circuit Ratio (SCR) [7]

SCR = Short Circuit Power/ Rated Power

VSC based HVDC does not rely on short circuit power to function because the inverter does not require the help of external generators. It can thus energize a “dead” network.

1.7.2 Reactive Power

A great advantage of HVDC is that it does not transmit reactive power.

The classical HVDC converter consumes reactive power; it is therefore common practice to include a reactive power supply in the converter station in form of harmonic filters and shunt capacitor banks.

An VSC based HVDC converter has the ability to generate or consume reactive power within a wide range by control of the IGBT valves without switching filters or shunt banks.

1.7.3 Power Control

Classical thyristor based HVDC transmission can vary the power level from minimum load (b/w 5% and10%) to maximum load (100%). Below minimum load, the transmission can be put in hot standby [7].

VSC based HVDC does not have a minimum power level. It is able to vary power from +100% to -100% progressively.

1.7.4 DC Transmission Circuit

The DC transmission circuit for classical HVDC can be an overhead line or a DC cable. The cables are MIND (mass impregnated) cables (Fig 1.11) with copper conductor. Also majority of these cables are submarines cables.

The DC transmission circuit for VSC based HVDC is made by extruded polymer cables (Fig 1.12) and both for underground and submarine.

Fig 1.11: Mass Impregnated Oil Cables

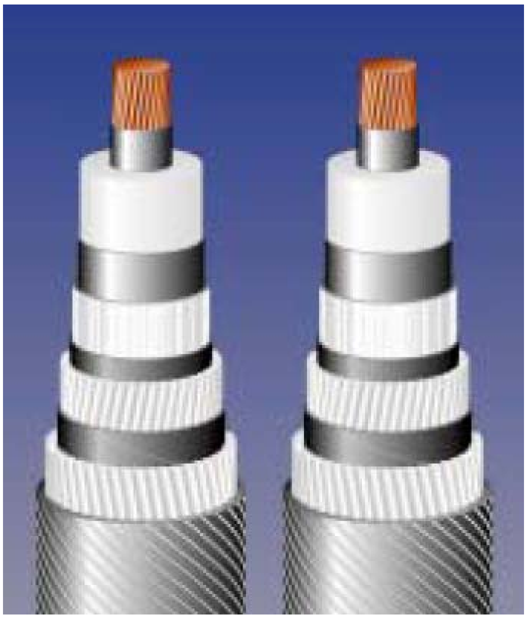


Fig 1.12: Extruded Plastic Cable

1.7.5 Power Reversal

Active power transfer can be quickly reversed by VSC based HVDC without any change of control mode and without any filter switching or converter blocking which is not possible with classical HVDC.

1.7.6 Modular

Classic HVDC is always tailor made to suit a specific application.

VSC based HVDC is based on modular concept. This enables most of the equipment installations in enclosure at the factory itself.

1.7.7 Independence of AC Network

VSC based HVDC is independent of the AC network ability for keeping the voltage and frequency stable. It can feed load into a passive network also.

1.7.8 Independent Power Control

VSC based HVDC inherits a fast switch along with DC voltage source, which can turn on and off the available current and thus can get an average of any voltage between two extremes of DC voltage and with special switching patterns, generation of sinusoidal voltage is possible. Also with slight change in amplitude or phase angel on generated voltage, independent exchange of active and reactive power can be done.

1.7.9 Multi Terminal Configuration

Sometimes more than two AC systems have to be connected via a DC transmission system. The DC connection is realized by a HVDC grid known as multi-terminal configuration.

The structure and controllability of the HVDC grid is much simpler with a VSC based HVDC than with the classic HVDC. Since for the change of power flow direction, polarity reversal of DC voltage is not necessary.

1.7.10 Coordination Control is not required with VSC based HVDC

1.8 Other Benefits of VSC based HVDC

Beyond its black start capability the system offers [8]:

a. AC grid enhancements
b. Reliable power supply
c. Easier permit procedure
    Underground invisible cable systems
    Environmental friendly oil free cables
    Short installation time
d. Flexible, modular systems
    Can easily be built or expanded to multi terminal system
    Modular systems can be staged and installed to meet demand
e. Low operation and maintenance costs

Both HVDC and HVDV light transmission has the advantage that they do not contribute to the fault current: the impact on the fault-free side of the DC transmission is smaller, and on the side with the fault, the fault current is lower than it would be with an AC link. The fault-free network experiences an interruption of power flow in the DC transmission but no fault current.

1.9 Scope of the Work

There are many advantages of AC that makes it superior to DC. Also some characteristics lacked in AC, that has evolved DC globally like bulk power transmission, power control, and reactive power compensation.

The scope of this project is to design a hybrid distribution system that intakes the features of both DC and AC and can thus be further employed for handling common problems faced in both the AC and DC systems. Future energy developments has to face great challenges due to rising world population demands for higher standards of living, less pollution and possible end to fossil fuel. Thus a reliable and flexible distribution system can be developed by hybriding the advantages of AC and DC to deal with DPGs, blackouts, Energy deficit problem and backpane bus. Thus a multi terminal DC system shall be investigated for implementing the above requirement for hybridizing the systems.

1.10 Organization of the Project

Chapter 1	:	**Introduction** This chapter gives a brief about the historical development of AC and DC with their basic advantages and disadvantages. Also illustrates the scope of the project.
Chapter 2	:	**Literature Review** Highlights the workdone on HVDC in the world.
Chapter 3	:	**Multi Terminal Direct Current (MTDC)Systems** Shows the existence and perspective use of MTDC schemes with its present applications.
Chapter 4	:	**Voltage Source Inverters/Converters** This chapter reflects the designing and development of multi level inverter with the introduction of voltage source inverters with their different configurations.
Chapter 5	:	**VSC Based MTDC Systems** Presents the merits, structure of VSC system along with Results and Discussions obtained from the simulink model of Converter, Inverter and DC VSC Based Link and MT Systems.
Chapter 6	:	**Future Scope of the Work**

Chapter 2

CHAPTER 2

LITERATURE REVIEW

2.1 General

The potential range of HVDC transmission have broadened with the higher voltage levels, mature technology and new converter designs. HVDC applications includes underground, offshore, economic replacement of reliability-must-run generation and voltage stabilization concepts. This broader range of applications has contributed to the recent growth of HVDC transmission including power transmission between unsynchronized AC distribution systems, stabilization of AC powergrid, corona discharge reduction for HVAC lines etc.

2.2 HVDC Systems

DC electric power transmission systems are the best reliable form for the bulk transmission in the world today. Till date, HVDC has formed a environmental friendly transmission system and enhances the power flow and its control without complexity. For instance [3]:

- In Itaipu, Brazil HVDC was chosen to economically transmit large amount of hydro power of 6300MW over 800km to supply 50hz power into 60hz system.
- Also to improve stability to the Manila AC network and supply bulk geothermal power across an island interconnection HVDC was the best alternative.
- In India for Rihand Delhi project (Fig 2.1), HVDC transmitted 1500MW power to Delhi. The reason for applicability of HVDC in this case ensures minimum losses, least amount right-of-way and better stability and control.

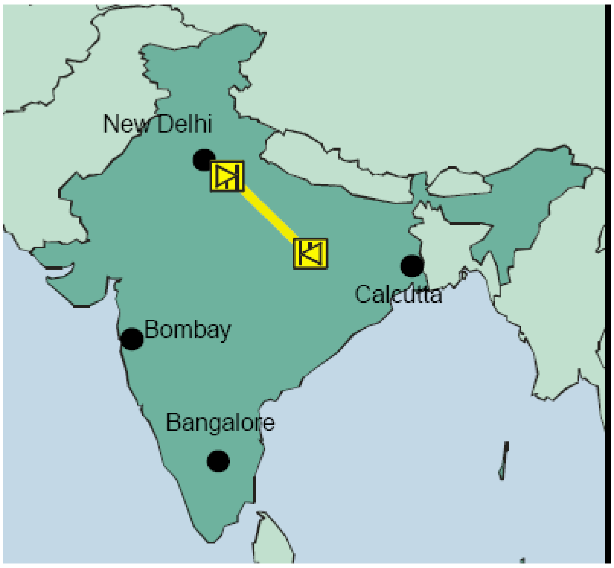


Fig 2.1: Rihand Delhi HVDC Transmission

- For transferring power from Argentina to Brazil, HVDC back-to-back system was selected for supply of 50Hz power to a 60Hz System.
- HVDC was chosen with the capability of environmental sensitivity and power quality in Sweden to connect newly developed wind power site to main city of Visby.
- Also in Queensland, HVDC connected two independent grids since it enables electricity trading between the two systems including change of direction of power flow with reduced construction time.

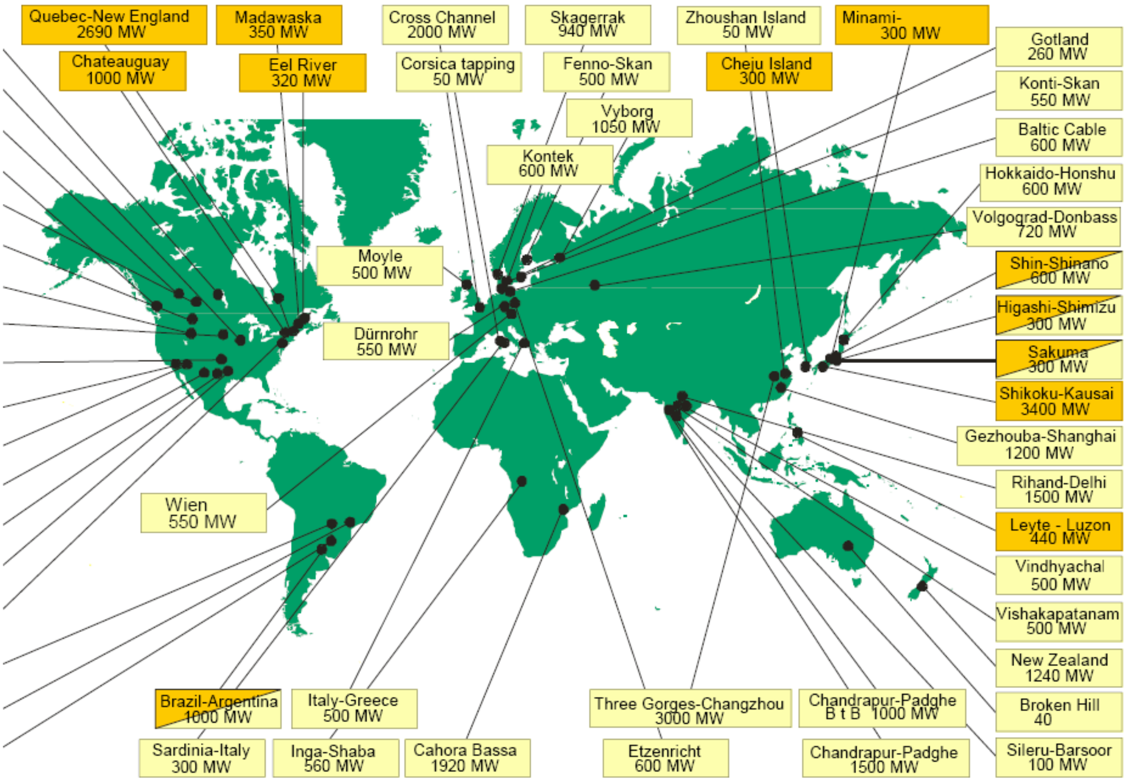


Fig 2.2: World Wide HVDC Projects

Other than these HVDC applications worldwide (Fig 2.2), DC transmission have also helped in preventing outages and in limiting the consequences of major disturbances [5]. Some of these examples from Europe and USA are below;

- On 10th April 1979, within 3 seconds the frequency fell to 48.1Hz in Elsam network where Western Denmark was islanded together with parts of German network. The load on islands was 5000MW and production 3850MW. Part of the load was shed by under frequency protection. The Skagerrak (500MW) and Konti-Skan (250MW) HVDC links from Norway and Sweden remained in service. Skagerrak automatically increase power from 50 to 320MW and Konti-Skan from 0 to 125MW within 3 seconds. The frequency was quickly restored to normal and a blackout was prevented.
- There was a frequency drop to 48.5Hz in Scandiavian network when two 1000MW nuclear stations in Sweden were disconnected. The Skagerrak link was exporting its power of 500MW from Norway to Denmark at that time. Due to frequency drop, reversal of power direction took place and 500MW were injected into Norwegian/Swedish grid. Thus this DC link contributed to 1000MW.
- In Western USA, pacific HVDC Intertie (Fig 2.3) run between Oregon and Los Angeles. Due to high winds, loss of two AC lines north of the Tesla substation occurred which resulted in overloading of other AC lines and splitting of WSCC system into 4 major islands. This lead to the load shedding of 12000MW. That time pacific HVDC Intertie was the only transmission to southern California island and remains in service. It was the one that provided valuable generating support to Southern California and Nevada area thus limited the extent of system outages.

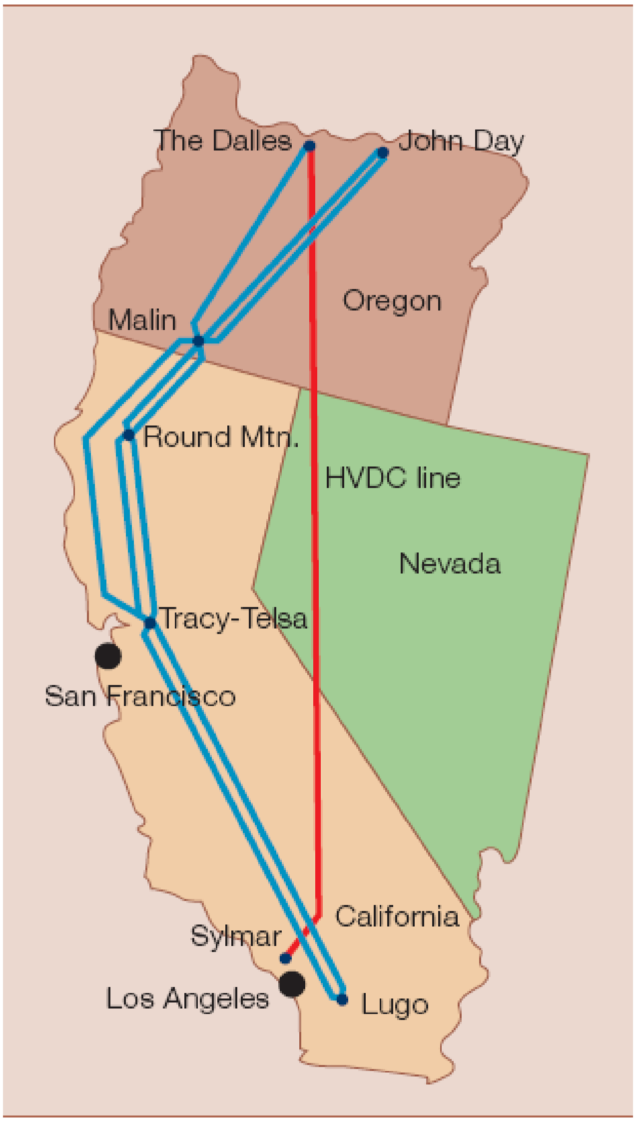


Fig 2.3: Pacific Intertie

These above examples thus explain that power grid system planners and transmission owners should consider HVDC when planning investment in today's ageing transmission system. According to Harrison K Clark [9]: "Segmentation with HVDC can improve reliability while increasing transfer capability by limiting the propagation of disturbances. Also According to Lennart Carlson [5], HVDC is "A Firewall against disturbances in high Voltage grids". Since HVDC not only permit economies through the sharing of reserves but also make the trading of electricity between grids possible. A HVDC link can fully control transmission and does not overload or propagate fault current.

A MTDC system is the one that has more than two converter stations operating either as rectifiers or as inverters. Multiterminal DC system is another big leap on AC systems that makes it easily expandable with the use of tappings. A hybrid HVDC system was first presented by Z Zhao and M R Iravani in 1994. The first application of a MTDC system is the Sardinia-

Corsica-Italy link where a tapping is given at Corsica. This is a 50MW parallel connected tap with two 100kv s ix pulse thyristor bridges connected in series.

The Multi Terminal HVDC System was built for Quebec-New England project. The power is generated at La Grande II hydro power station, converted in to DC at the Radisson converter station and transmitted over MT system to load centres in Montreal and Boston

The multiterminal VSC based HVDC has covered all the drawbacks originating from HVDC classic. There are no true multiterminal HVDC schemes at present however two existing schemes, the Nelson River and Kingsnorth include control characteristics which are virtually multiterminal. A MTDC schemes may provides a considerable improvement in the dynamic performance of an integrated AC-DC power system, due to the fact that fast power modulation account to selected control strategies can be implemented at more than one terminal.

With VSC based HVDC technology number of commercial projects already exists which include Gotland VSC based HVDC transmission, the Tjaereborg VSC based HVDC project, direct link in Australia and Eagle Pass of mexician transmission system.

Hongbo Jiang et al [10] has reviewed that in terms of cost and performance, a multiterminal HVDC might be an interesting alternative to conventional HVAC system. Also introduction of multiterminal HVDC system offers power quality and less disturbances in comparison. With Weixing Lee [11] the concept of multiterminal HVDC system based on IGBT VSC is proposed as an alternative to an AC cable system. This will enhance uninterrupted quality power to sensitive loads. Digital simulation in his work has shown that severe disturbances such as loss of generation sources are transparent to sensitive loads but the VSC multiterminal HVDC offers a DC bus back-bone by which alternate generation sources can be integrated to electric utility added with benefits like improved safety, environmental acceptability, compactness and lower cost.

Not only this but a performance analysis of hybrid multiterminal HVDC system carried by X F Yuan et al [12] has proved that the faults on AC system of VSC converter have little effects on the DC transmission network of the hybrid MTDC system and that the VSC converter can work in hybrid MTDC system either as rectifier or as inverter.

Chapter 3

CHAPTER 3

MULTI TERMINAL DIRECT CURRENT (MTDC) SYSTEMS

3.1 Introduction

A MTDC scheme may provide a considerable improvement in the dynamic performance of AC-DC power systems due to the fact that fast power modulation according to selected control strategies can be implemented at more than one terminal. A MTDC system is the one that has more than one converter, some acting as a rectifier and others as a inverter. With the availability of fast communication, the expected performance has greatly improved. It has now been recognized that the limitation to the speed of response in MTDC systems is not only because of control systems but involves characteristics of main circuit and telecommunicational delays [2].

There are three distinct potential applications for HVDC (Multi Terminal) MT schemes [13].

1. Bulk Power Transmission
2. AC Network Interconnection
3. Reinforcement of an AC Network

3.2 Classification of MTDC System

The MTDC systems can classified in to three types [12]:

1. Current Source Converter (CSC) MTDC systems, in which all the AC/DC converter stations consists of CSCs
2. Voltage Source Converter (VSC) MTDC systems, in which all the AC/DC converter stations consists of VSCs
3. Hybrid MTDC systems, in which some AC/DC converter stations consists of CSCs, and other converter stations consists of VSCs.

3.2.1 CSC MTDC Systems

The CSC MTDC systems are based on conventional HVDC transmission which uses voltage polarity reversal to reverse the power direction. Polarity reversal requires no special switching arrangement for a two-terminal system where both terminals reverse polarity by control action with no switching to reverse power direction. Special DC side switching arrangements are needed for polarity reversal in a multiterminal system, however, where it may be desired to reverse the power direction at a tap while maintaining the same power direction on the remaining terminals. For a bipolar system this can be done by connecting the converter to the opposite pole.

The CSC MTDC systems can be configured into the following three types:

- Parallel or Radial Tappings
- Meshed or Ring Systems
- Series Connections

3.2.1.1 Parallel or Radial Tappings

In parallel systems, the current in all the converter stations are adjusted to the power requirements except one converter station which operates as a voltage setting terminal at constant angle or voltage [13].

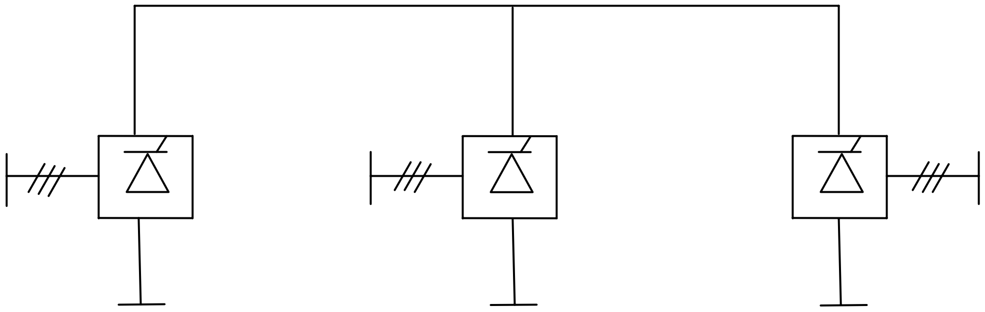


Fig 3.1 : Parallel System

The connection permits tappings of nonpolar or bipolar lines without the redundancy affordable by mesh connection.

In such systems, disconnection of one segment of transmission results in interruption of power from one or more station. The loss of a bridge in on current station requires disconnection of bridge in all stations or disconnection of the affected station.

As compared with separate point to point interconnections the parallel MT system has severe limitations which includes

- Loss of whole systems can be caused by the loss of DC line
- A whole or larger part of the system is affected by disturbances like line fault or communication failure
- Communication failure at one of the invertor can draw current from the other terminal
- Mechanical switching is required for reversal of voltage
- Disconnection of any part of the DC line reduces the transmission capacity of system by atleast MW ratings of one convertor station pole.

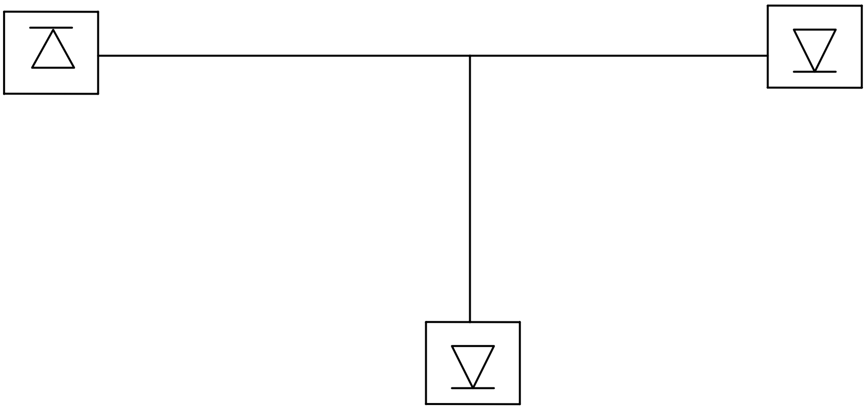


Fig 3.2 : Parallel System

3.2.1.2 Meshed or Ring systems

Meshed or Ring Systems are part of parallel systems only. The only distinctive features with ring systems is that in the case of ring system each converter station is connected to more than one line and therefore the loss of a line has a lesser effect on transmission capability.

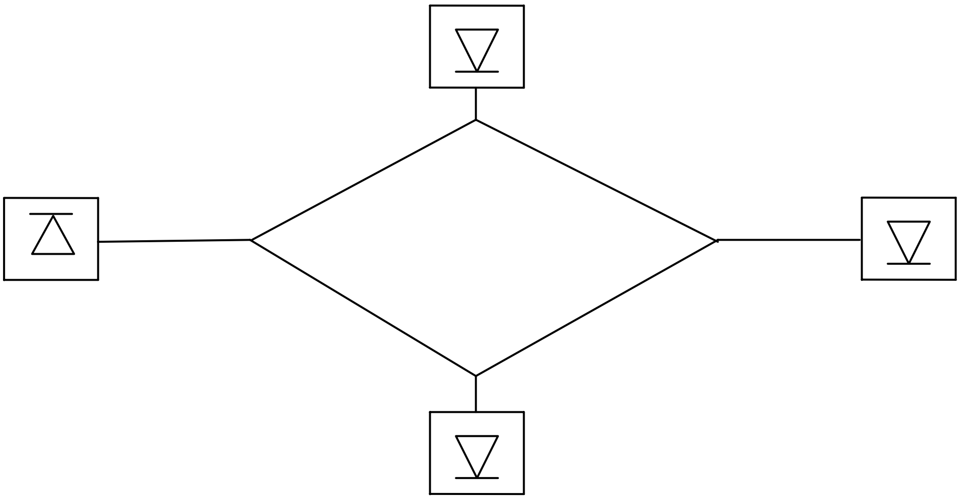


Fig 3.3: Meshed or Ring System

HVDC ring systems provide flexible power interchange with neutral DC load flow for minimizes the losses together with increased reliability compared with radial tappings. It corresponds to either the tapping of a double circuit bipolar line or the double on field per pole at each terminal from 2 or more directions. It provides the fastest recovery from a transient or sustained DC line fault. It relies on the overload capability of the remaining lines without the need for reallocation of power interchange.

3.2.1.3 Series Connection

In the figure, the concept of series connection of convertors in two terms monopolar operation is geographically extended into multi terminal system.

Fig 3.4 : Series Connection

The series connection offers advantage in allowing flexibility of size of tapped station and for some small ratings of the tap, may be an attractive alternative. The series connection is restricted to certain station locations in comparison with a mesh network, line losses are higher and a double circuit line is required to provide the same reliability as one pole.

Fast reversal is achievable without polarity reversing switches at each terminal and the recovery from system disturbances is similar to the conventional point to point links i.e. in most cases does not affect the remaining systems. An overall control system is still necessary for optimized operation of the system. Insulation coordination requires special attention for series connection.

Communication between terminals is required for optimization of line loadings to minimize losses but this can be achieved with relatively slow communication. In a series connected multiterminal scheme, current is controlled by one terminal and also other terminals operates against a firing angle limit current control [14].

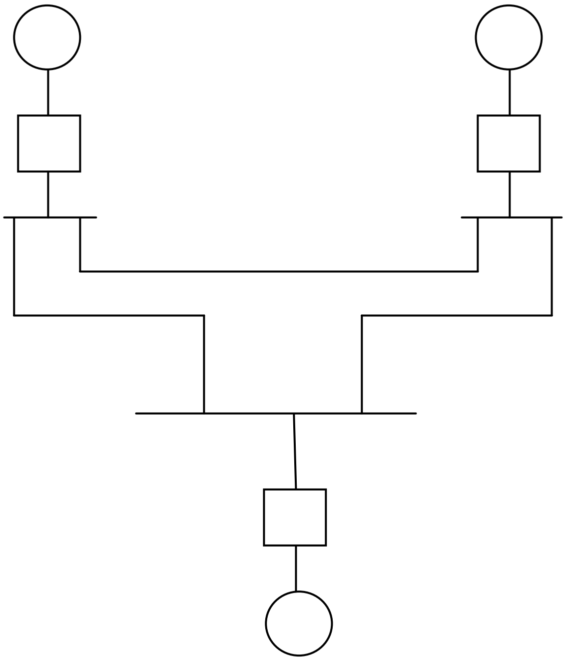


Fig 3.5 : Series Connection

3.2.2 Comparison between the Series and Parallel Configuration

- High speed reversal of power is not possible in parallel systems without mechanical switching and is possible with series systems.
- Valve rating in series system is related to power rating while current rating in a parallel system is related to power. Thus series connection is cheaper for small power ratings of tap and parallel connections has staged development in converter stations
- In series systems, insulation coordination is a problem as the voltage along the line varies
- In series system, the losses in line and valves are more comparative to parallel connected system
- Any permanent fault in series connection lead to complete shutdown while for radial it leads to only the shutdown of converter system connected to line
- In parallel system, reduction in AC voltages and communication failures in an inverter leads to overloading of converters which can be a severe problem if rating of inverter is relatively small
- Extension of parallel system is not straight forward and leads to increased communication requirement and problem in recovery from commutation failure

With the above comparative measures it can be concluded that series connection is appropriate for taps of rating less than 20% of major inverter terminal and parallel connection is appropriate for AC systems [13].

3.2.3 VSC MTDC Systems

Conventional HVDC consists of line commutated current source converter (CSC) stations, which are sensitive to the disturbances of ADC power systems, and are less favorable for the weak AC power systems. With the development of fast, high self-commutated power electronic devices, such as GTO, IGBT, it is possible to realize new powerful HVDC systems which are based on forced commutated voltage source converter (VSC). The VSC has the advantages of quickly control the active and the reactive power independently, regardless of the AC power system conditions. For this reason it is widely recognized that application of the VSC to the HVDC system is very advantageous. Feeding AC systems with low short circuit power or even passive networks with no local power generation, and STATCOM functionally, i.e. continuously adjustable reactive power support to the AC system to control AC bus voltage and improve stability. VSC HVDC transmission, however, reverses power through reversal of the current direction rather than voltage polarity. Thus, power can be reversed at an intermediate tap independently of the main power flow direction without switching to reverse voltage polarity [7].

Also Multi-Terminal High Voltage Direct Current (VSC-M-HVDC) Transmission has the possibility of being an attractive alternative to AC transmission in city centers where underground cable transmission is preferred for safety and environmental reasons. In regards to cable transmission, DC transmission has the advantages of compactness and cost. Even with the cost of the converter stations, DC transmission begins to be competitive when the cable length is short.

According to Weixing Lu Multi-Terminal HVDC has the technical capability to implement premium quality power parks. The added value, which comes from providing premium quality power, offsets the costs of the VSCs in an underground cable system based on Multi-Terminal HVDC.

VSC designs are composed of two basic configurations [15]

- Shunt connected VSC system
- Series connected VSC system

The VSC configurations have similar electrical design features for the equipment, installation and service conditions, although some differences exist in equipment ratings, control, protection schemes and other aspects.

3.2.3.1 Shunt Connected VSC

In this case, the VSC is connected to the power system via a shunt connected transformer. By varying the amplitude and the phase of the output voltage produced, the active power and the reactive power exchange between the converter and the AC system can be controlled in a manner similar to that of a rotating synchronous machine [15]. The reactive power exchange between the VSC and the power system can be controlled by varying the amplitude of the output voltage. If the amplitude of the output voltage is increased above that of the AC system voltage, the VSC generate reactive power to the power system. If the amplitude of the output voltage is decreased below that of the AC system voltage, the VSC absorbs reactive power from the power system. The real power exchange between the VSC and the power system can be controlled by altering the phase angle between the output voltage and the AC system voltage. An energy supply or absorbing device is required for real power exchange. This role is played by another VSC or a DC energy storage device like battery or a superconducting magnet. The Volt Ampere (VA) rating of the VSC is determined by the product of power system voltage and the maximum output current.

3.2.3.2 Series Connected VSC

In this case, the VSC is connected to the power system in series via a series connected transformer. By varying the amplitude and the phase of the output voltage produced, the magnitude and the angle of the injected voltage can be controlled. The VSC output voltage injected in series with the line acts as an AC voltage source [15]. The current flowing through the VSC corresponds to the line current. The VA rating of the VSC is determined by the product of maximum injected voltage and the maximum line current. If the injected voltage is controlled with a quadrature relationship to the line current, the VSC provides only reactive power to the AC power system and there is no need for another VSC or energy storage device on the DC terminal. If the injected voltage is controlled in a four quadrant manner to the line current, the VSC provides both real and reactive power to the AC power system and another VSC or energy storage device is needed for real power exchange on the DC terminal.

Theses VSC based systems designs leads to rapid response to system disturbances and provides smooth voltage control over a wide range of operating conditions. It automatically reconfigures to handle certain equipment failure and improved system reliability and availability through the inherent modularity [15].

3.3 Conclusions

Thus the Multi Terminal HVDC Transmission based on VSC’s in MTDC schemes has been found suitable for many applications without any question. These applications may include:

- Systems interconnection using an HVDC-VSC back-to-back tie
- Grid connection of offshore wind farms
- Grid connection of otherwise autonomous systems such as islands and oil platforms
- City centre infeed

Chapter 4

CHAPTER 4

VOLTAGE SOURCE INVERTERS/CONVERTERS

4.1 Introduction

A voltage source inverter is an inverter where desired output voltage is achieved by applying a fixed input DC voltage, using appropriate switching's methods. These are conventional inverters which are fed by DC supply and the rms value of the output AC voltage is a function of on-time of the switches.

Following are the three conventionally used Voltage Source Inverter (VSI):

- Conventional 3-phase inverter
- 12 pulse inverter
- Multi-level inverter

4.1.1 Conventional 3-Phase Inverter

A basic three phase inverter consists of three single phase inverter switches each connected to one of the three load terminals (Fig 4.1). For the most basic control scheme, the operation of the three switches is coordinated so that one switch operates at each 60 degree point of the fundamental output waveform. This creates a line-to-line output waveform that has six steps. The six step waveform has a zero voltage step between the positive and the negative sections of the square wave such that the harmonics that are multiples of three are eliminated as described above. When carrier based PWM techniques are applied to six step waveforms, the basic overall shape, or envelope, of the waveform is retained so that the 3^{rd} harmonic and its multiples are cancelled.

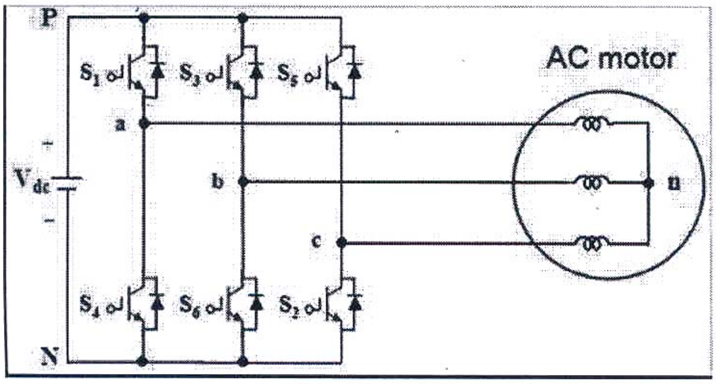


Fig 4.1: Conventional 3 Phase Inverter Feeding A Motor

4.1.2 Twelve Pulse Inverters

A twelve pulse inverter is obtained from a six pulse inverter by using 2 six pulse inverters and two three phase transformers, one being of Y-Y
△

configuration and one with Y-   configuration, so as to introduce a 30 degree phase shift, and then adding the two to achieve a 12 pulse output waveforms (Fig 4.2).

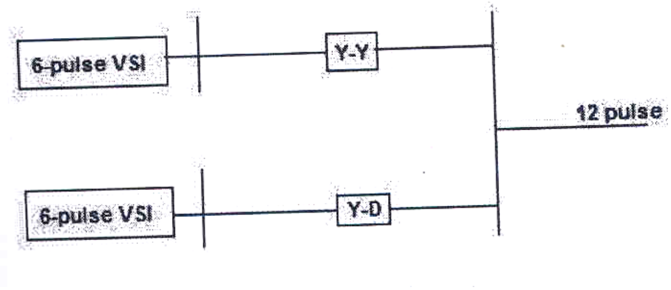


Fig 4.2: Pulse Inverter

4.1.3 Multi Level Inverters

Multilevel inverters are a different class of inverters where more than two levels of voltage of applied DC voltage (i.e. + V_{dc} or – V_{dc}) are obtained. Theses inverters use different techniques to split the applied DC voltage into different voltage levels and then using a firing scheme these different voltage levels appear in the output AC waveform, thus making the output multi-level.

Multilevel inverters include an array of power semiconductors and capacitor voltage sources; the output of which is voltage with stepped waveforms. The permutation of switches permits the addition of the capacitor voltages, which reach high voltage at output, while the power semiconductors must withstand only reduced levels.

By increasing the number of levels in the inverter, the output voltages have more steps generating a staircase waveform, which has a reduced harmonic distortion. The major multilevel topologies are: cascaded, diode clamped, capacitor clamped and generalized topology. However, for a high number of levels in the output voltage, the former three multilevel converters require either isolated DC power sources or a complicated voltage balancing circuit and control to support and maintain each voltage level. In this aspect, these three multilevel converters are neither operable nor complete for real (active) power conversion because they all depend on outside circuit for voltage balancing.

The most attractive features of multilevel inverters are as follows:

1. They can generate output voltages with extremely low distortion and lower dv/dt
2. They draw input current with very low distortion

3. They generate smaller common ode (CM) voltage, thus reducing the stress in the motor bearings. In addition, using sophisticated modulation methods, CM voltages can be eliminated.
4. They can operate with a lower switching frequency

4.2 Three Level Diode Clamped Inverter

A three level diode clamped inverter is shown in Fig 4.3. In this circuit, the DC bus voltage is split into three levels by two series-connected bulk capacitors, C1 and C2 [17]. The middle point of the two capacitors can be defined as neutral point. The output voltage has three states: $V_{dc}/2$,0,-$V_{dc}/2$. The key components of this circuit are diodes D1 and D1'. These two diodes clamp the switch voltage to half the level of the DC bus voltage. When both S1 and S2 are turned on, the voltage across a and 0 is V_{dc} [18]. In this case D1' balances out the voltage sharing between S1' and S2' with S1' blocking the across C1 and S2' blocking the voltage across C2. The output voltage V_{an} is AC and V_{a0} is DC. The difference between V_{an} and V_{a0} is the voltage across C2, which is $V_{dc}/2$.

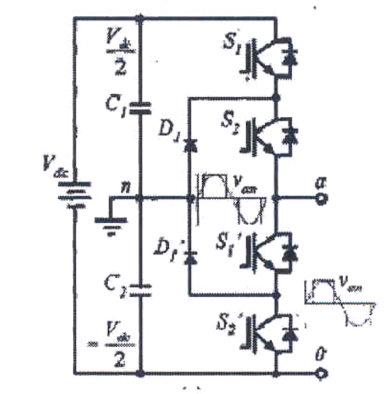


Fig 4.3: Three Level Diode Clamped Inverter

4.3 Three Level Flying Capacitor Inverter

Fig 4.4 illustrates the fundamental building block of a phase leg capacitor clamped inverter. The circuit has been called the flying capacitor inverter with independent capacitor clamping the device voltage to one capacitor voltage level (19). The inverter in Fig 4.4 provides a three level output across a and n, i.e. $V_{an} = V_{dc}/2$, 0 or $–V_{dc}/2$ [1]. For voltage level $V_{dc}/2$, switches S1 and S2 need to be turned on; for $–V_{dc}/2$, switches S1 and S2 need to be turned on; for $–V_{dc}/2$, switches S1' and S2' need to be turned on; and for the zero level, either pair (S1, S1') or (S2, S2') need to be turned on [17]. Clamping capacitor C1 is charged when S2 and S2' are turned on.

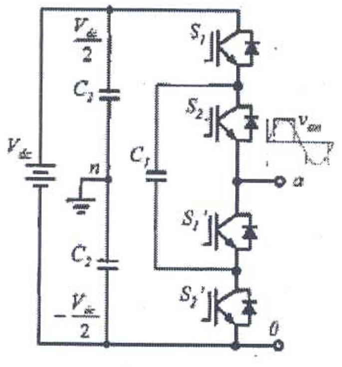


Fig 4.4: 3 Level Flying Capacitor Inverter

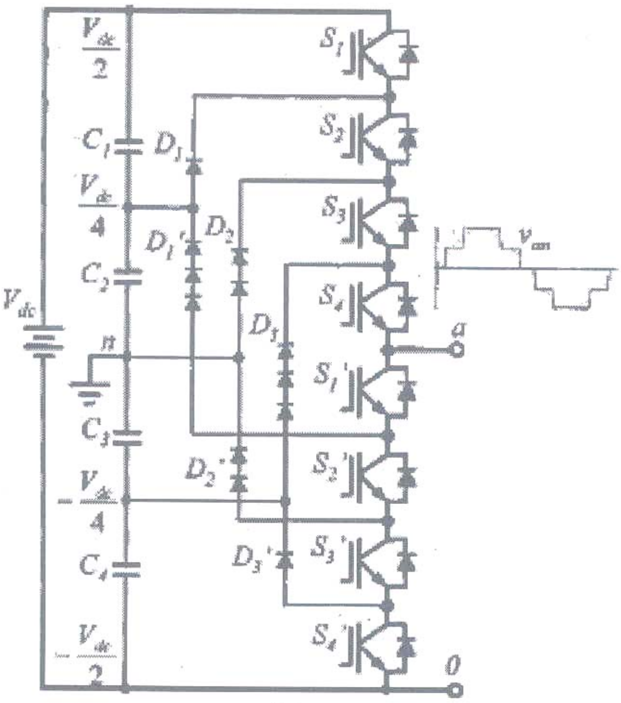
4.4 Five Level Diode Clamped Inverter

Fig 4.5 shows a five level diode clamped converter in which the DC bus consists of four capacitors, C1,C2,C3 and C4. For DC bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/4$, and each device voltage stress will be limited to one capacitor voltage level $V_{dc}/4$ through clamping diodes [17].

To explain how the staircase voltage is synthesized, the neutral point n is considered as the output phase voltage reference point. There are five switch combinations to synthesize five level voltages across a and n.

- Voltage = $V_{dc}/2$, upper switches S1-S4 are turned on
- Voltage = $V_{dc}/4$, upper switches S2-S4 are turned on and so on

Four complementary switch pairs exist in each phase. The complementary switch pair is defined such that turning on one of the switches will exclude the other from being turned on. In this example, the four complementary pairs are (S1,S1’), (S2,S2’), (S3,S3’), (S4,S4’).



(b)

Fig 4.5: 5 Level Diode Clamped Inverter

4.5 Five Level Flying Capacitor Inverter

The voltage synthesis in a five level capacitor clamped converter has more flexibility than a diode clamped converter [17]. Using Fig 4.6 as the example, the voltage of the five-level phase-leg a output with respect to the neutral point n, V_{an} can be synthesized by the following switch combinations.

- For voltage level $V_{dc}/2$, turn on all upper switches S1-S4
- For voltage level $V_{dc}/4$, there are three combinations:
  S1,S2,S3,S1’
  S2,S3,S4,S4’
  S1,S3,S4,S4’
- For voltage level =0 there are six combinations:
  S1,S2,S1’,S2’’
  S3,S4,S3’,S4’
  S1,S3,S1’,S3’
  S1,S4,S2’,S3’
  S2,S4,S2’,S4’
  S2,S3,S1’,S4’ and so on

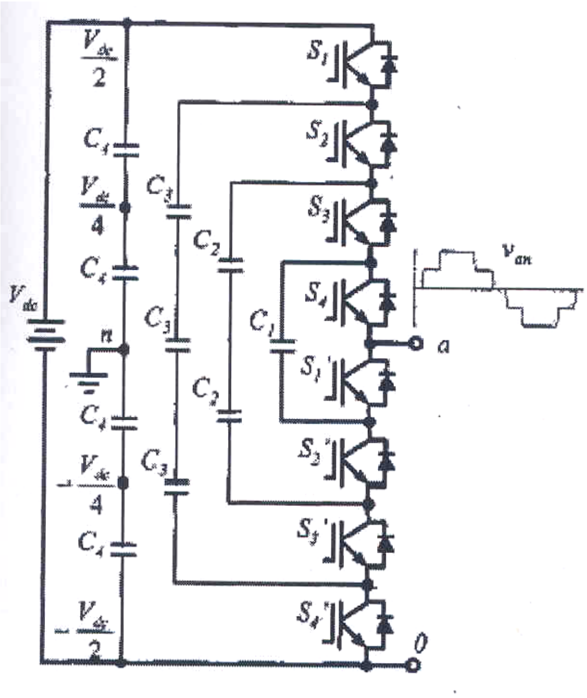


Fig 4.6: 5 Level Flying Capacitor Inverter

4.6 Cascaded Multi-Cell Inverter

This topology is based on the series connection of single-phase inverters with respect to DC sources [20]. Fig 4.7 shows the power circuit for one phase leg of a nine level inverter with four cells in each phase. The resulting phase voltage is synthesized by the addition of the voltages generated by the different cells. Each single phase cell generates three voltages at output: $+V_{dc}$, 0 and $-V_{dc}$. This is made possible by connecting the capacitors sequentially to the AC side via the four power switches. The resulting output AC voltage swings from $-4V_{dc}$ to $+4V_{dc}$, with nine levels, and the staircase waveform is nearly sinusoidal, even without filtering [21].

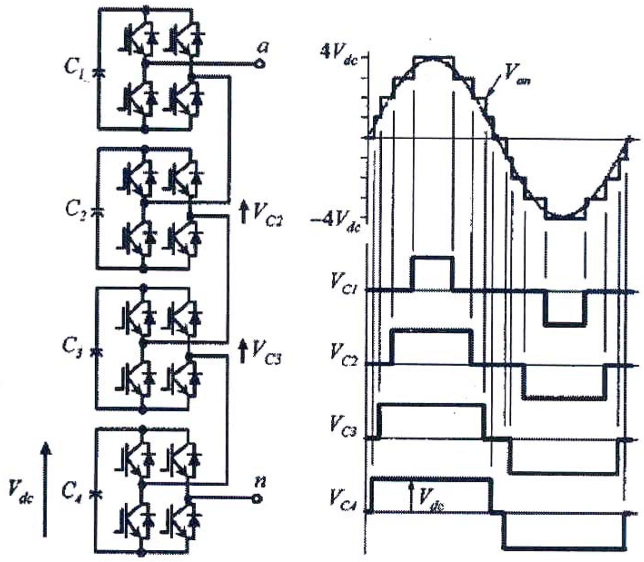


Fig 4.7: Cascaded Inverter Circuit Topology and its Associated Waveform

4.7 Generalized P2 Cell Multi-Level Inverter

The generalized multilevel inverter topologies can balance each voltage level by itself regardless of inverter control and load characteristics. Any inverter with any number of voltage levels including the conventional two level inverter can be obtained from this generalized topology as shown in Fig 4.8.It is evident that a m level inverter can be constructed by the basic cell as shown. Since the basic cell is a two level phase leg, this generalized multi level inverter is called the P2 multi level inverter.

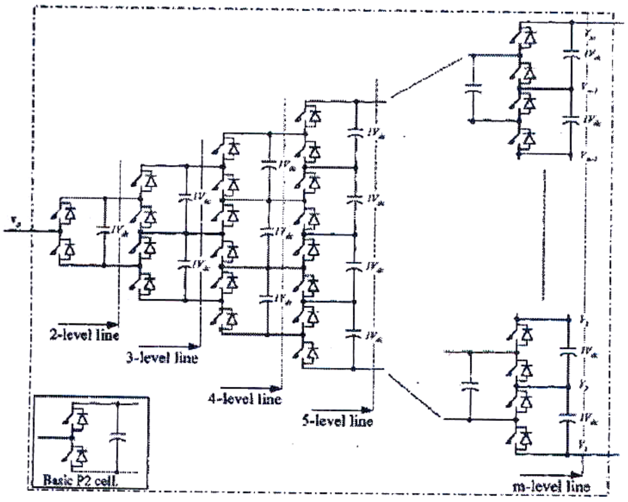


Fig 4.8: Generalized m Level Inverter

4.8 Basic P2 Cell

The basic P2 cell consists of a capacitor in parallel to 2 switches. One of the two switches is always on. The output is taken from the mid point of the connection between the switches. Depending on the charge stored by the capacitor, the polarity of output voltage reversed when switching changes from upper-lower or vice versa. On similar ideas, P3D and P3C cells can also be developed which will have less number of devices being used. A cascade multilevel inverter can be further configured using the P2 H-bridge or P3 H-bridge or a combination of P2H bridge and P3 H bridge inverter cells [22].

4.9 Five Level Generalized Topology

This topology is derived from the generalized P2 multilevel topology. The output levels in the voltage are five and hence the generalized topology reduces to designing to five levels as shown in Fig 4.9. In the P2 m level converter, the number of required switching devices is m*(m-1) and the number of required capacitors is m*(m-1)/2 (23). These numbers are easily obtained by pyramid structure.

The immediate use of the generalized multilevel converter topology may include switched-capacitor DC to DC converters and voltage multipliers [24] [25]. For these applications, the component count is actually minimal and less than traditional ones.

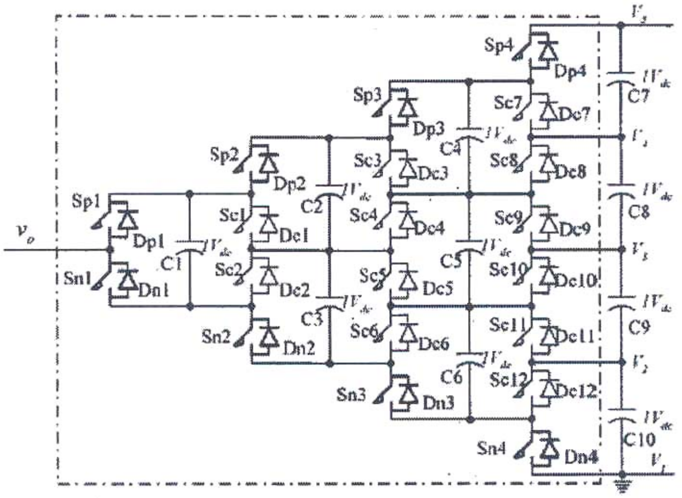


Fig 4.9: Generalised Five Level Inverter

4.10 Results and Discussion

4.10.1 Three Level Diode Clamped Inverter

4.10.1.1 For Open Circuit

The output voltage and current waveforms for the 3 level diode clamped inverter are given in the Figure 4.10. For V_{dc} = 100V, Fourier analysis of fundamental and harmonics of voltage waveform gives:

- Fundamental frequency voltage: 48.91V
- 3rd harmonic voltage: 7.1V
- 5th harmonic voltage:12.05V
- 7th harmonic voltage: 1.85V
- Output voltage: 37 V rms
- Total harmonic distortion (THD) : 0.374

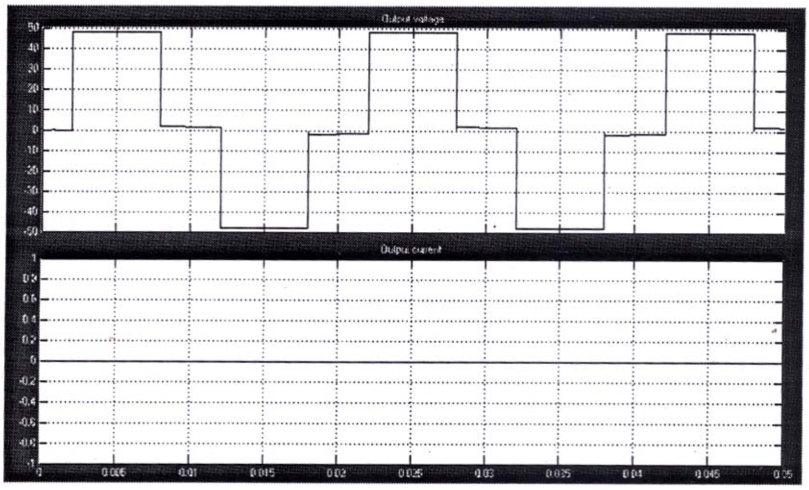


Fig 4.10: Output Voltage and Current for 3 Level Diode Clamped Multilevel Inverter for Open Circuit

4.10.1.2 For Highly Inductive Load

The output voltage and current for 3 level diode clamped multilevel inverter for highly inductive load are given in the Figure 4.11. V_{dc} = 100V. Fourier analysis of fundamental and harmonics of current waveform gives the following results:

- DC component of current: 0.12mA
- Fundamental frequency current: 0.15mA
- 3rd harmonic current: 7.5µA
- 5th harmonic current: 8µA
- 7th harmonic current: 1µA

- rms output current: 0.16mA
- Mean output current: 0.115mA

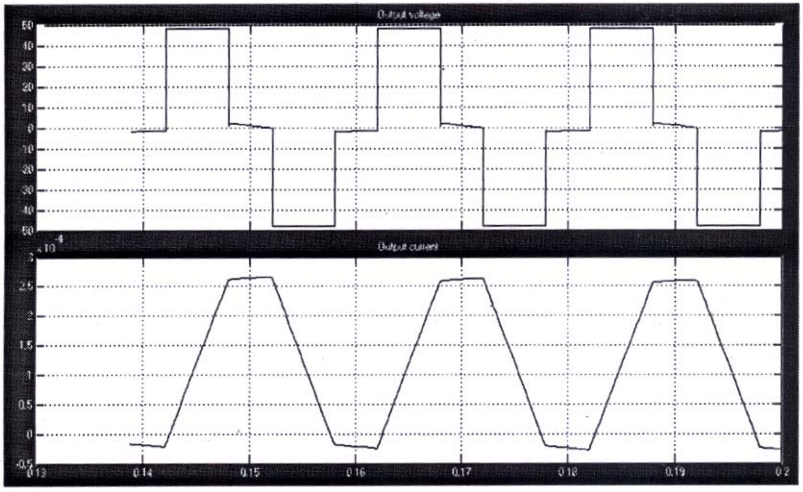


Fig 4.11: Output Voltage and Current for 3 Level Diode Clamped Multilevel Inverter for Highly Inductive Load

4.10.2 Three Level Capacitor Clamped Inverter

4.10.2.1 For Open Circuit

The output voltage and current waveforms for 3 level flying capacitor multilevel inverter during open circuit are given in Fig 4.12. For V_{dc} = 100V, Fourier analysis of fundamental and harmonics of voltage waveform gives:

- DC output voltage: 0.03V
- Fundamental frequency voltage: 510V
- 3^{rd} harmonic voltage: 74V
- 5^{th} harmonic voltage: 12.7V
- 7^{th} harmonic voltage: 18.5V
- Output voltage : 385 V rms
- Total harmonic distortion (THD) : 0.371

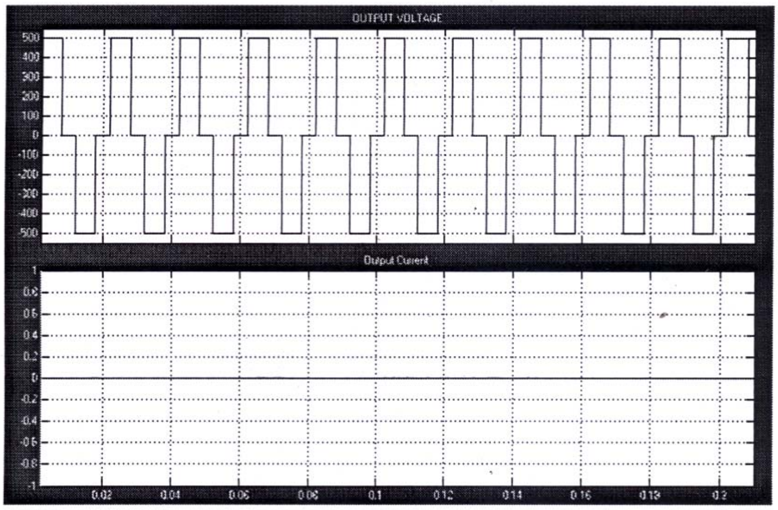


Fig 4.12: Output Voltage and Current for 3 Level Flying Capacitor Multilevel Inverter at Open Circuit

4.10.2.2 For Highly Inductive Load

The output voltage and current for 3 level flying capacitor multilevel inverter for highly inductive load are given in Fig 4.13. V_{dc} = 100V. Fourier analysis of fundamental and harmonics of current waveform gives:

- Fundamental frequency current: 1.65mA
- 3rd harmonic current: 0.1mA
- 5th harmonic current: 85 micro A
- 7th harmonic current: 97 micro A
- rms output current: 1.15mA

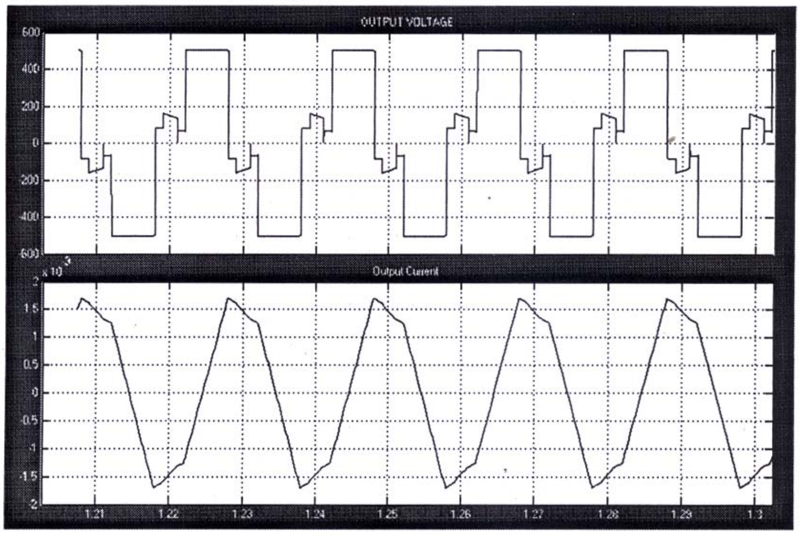


Fig 4.13: Output Voltage and Current for 3 Level Flying Capacitor Multilevel Inverter for Highly Inductive Load

4.10.3 Five Level Diode Clamped Inverter

4.10.3.1 For Open Circuit

The output voltage and current for 5 level diode clamped multilevel inverter at open circuit are given in Fig 4.14. For V_{dc} = 100V, Fourier analysis of fundamental and harmonics of voltage waveform gives:

- Fundamental frequency voltage: 43.5 V
- 3rd harmonic voltage: 9.25 V
- 5th harmonic voltage:3.5 V
- 7th harmonic voltage: 2.3 V
- Output voltage: 39 V rms
- Total harmonic distortion (THD) : 0.21

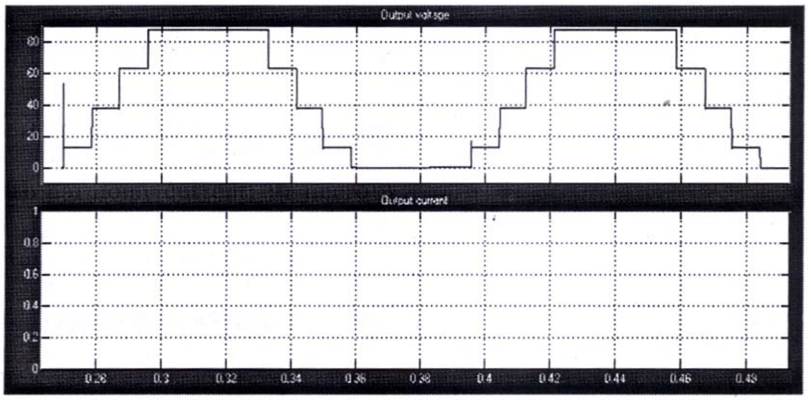


Fig 4.14: Output Voltage and Current for 5 Level Diode Clamped Multilevel Inverter at Open Circuit

4.10.3.2 For Highly Inductive Load

The output voltage and current for 5 level diode clamped multilevel inverter for highly inductive load are given in Fig 4.15. For V_{dc} = 100V, Fourier analysis of fundamental and harmonics of voltage waveform gives:

- Fundamental frequency voltage: 87V
- 3rd harmonic voltage: 18.5V
- 5th harmonic voltage: 7V
- 7th harmonic voltage: 4.6V
- Output voltage: 78V rms

- Total harmonic distortion (THD) : 0.21

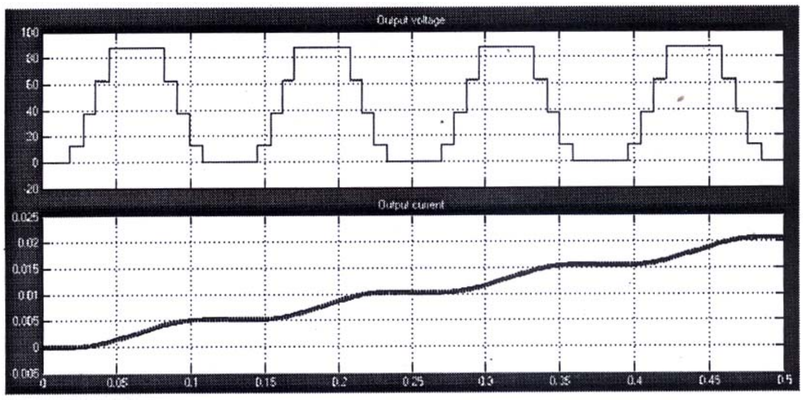


Fig 4.15: Output Voltage and Current for 5 Level Diode Clamped Multilevel Inverter for Highly Inductive Load

4.10.4 Generalized Single Phase Five Level Inverter

4.10.4.1 For Open Circuit

The output voltage and current for 5 level generalized inverter at open circuit are given in Fig 4.16. For V_{dc} = 650V, Fourier analysis of fundamental and harmonics of voltage waveform gives:

- Fundamental frequency voltage: 325 V
- 3rd harmonic voltage: 42 V
- 5th harmonic voltage: 23 V
- 7th harmonic voltage: 12 V
- Output voltage: 327 V rms
- Total harmonic distortion (THD) : 0.24

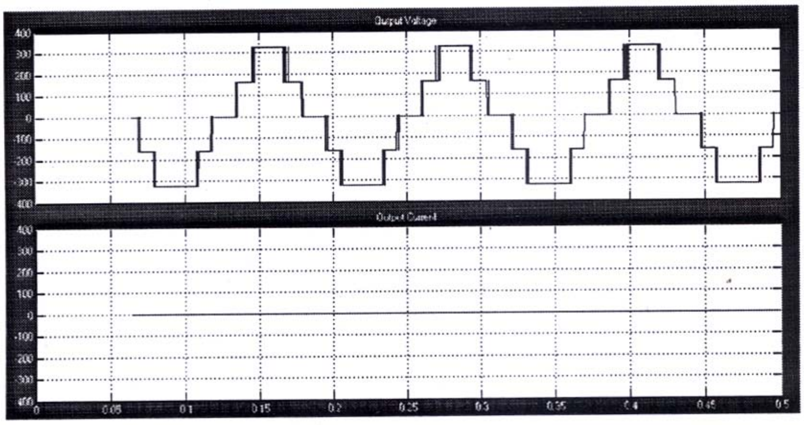


Fig 4.16: Output Voltage and Current for 5 Level Generalized Inverter at Open Circuit

4.10.4.2 For Highly Inductive Load

The output voltage and current waveforms for generalized 5 level inverter for highly inductive load are given in Fig 4.17. Fourier analysis of fundamental and harmonics of current waveform gives:

- Fundamental frequency current: 2mA
- 3rd harmonic current: 0.68mA
- 5th harmonic current: 0.4mA
- 7th harmonic current: 0.3mA
- rms output current: 0.71mA
- Total harmonic distortion (THD) : 0.355

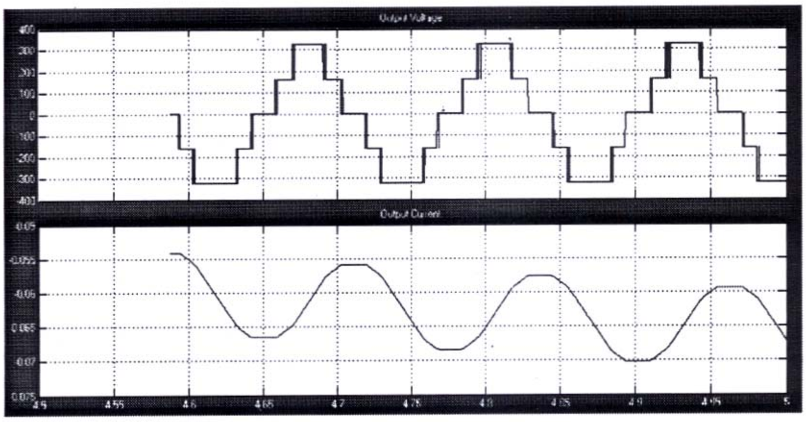


Fig 4.17: Output Voltage and Current for Generalized 5 Level Inverter for Highly Inductive Load

4.10.5 Generalized Three Phase Five Level Inverter

4.10.5.1 For Open Circuit

The phase to neutral voltage for 5 level generalized inverter at open circuit is given in Figure 4.18, and phase to phase voltage is given by Figure 4.19.

For 650V DC applied, Fourier analysis of phase to phase AC voltage gives:

- DC component of voltage: 8.38V
- Fundamental frequency voltage: 538 V
- 3rd harmonic voltage: 10.1V

- 5th harmonic voltage: 31.75V
- 7th harmonic voltage: 6 V
- rms output voltage: 410 v ph-ph
- Total harmonic distortion (THD) : 0.106

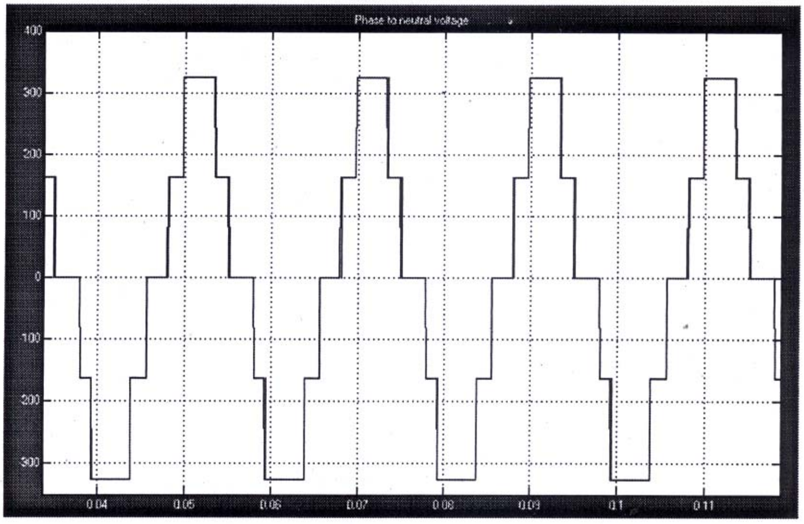


Fig 4.18: Output Phase to Neutral Voltage for 5 Level Generalized Inverter at Open Circuit

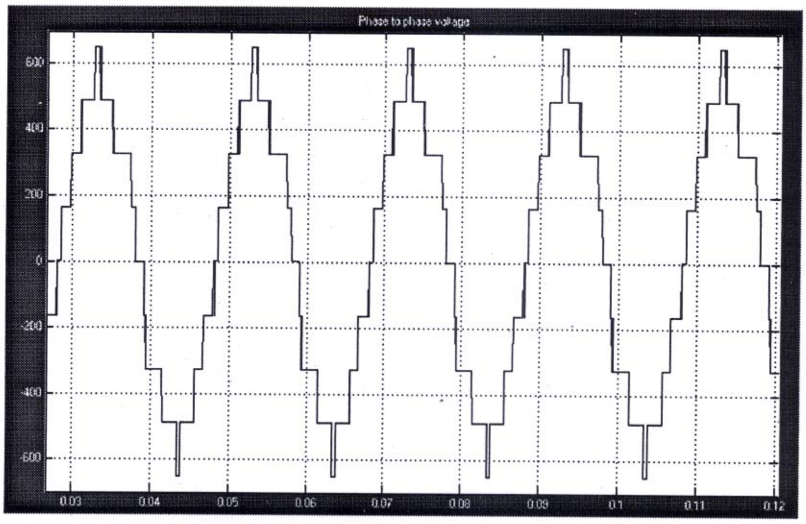


Fig 4.19: Output Phase to Phase Voltage for 3 Phase, 5 Level Generalized Inverter at Open Circuit

4.10.5.2 For Highly Inductive Load

The output phase to phase voltage and current waveforms for generalized 3 phase 5 level inverter for highly inductive load are given in Fig 4.20. The three phase quantities are shown in Fig 4.21.

- DC component of current: 1.084A
- Fundamental frequency current: 18.32A
- 3rd harmonic current: 0.097A
- 5th harmonic current: 0.202A
- 7th harmonic current: 0.04A
- rms output current: 19.15A
- Total harmonic distortion (THD) : 0.0715

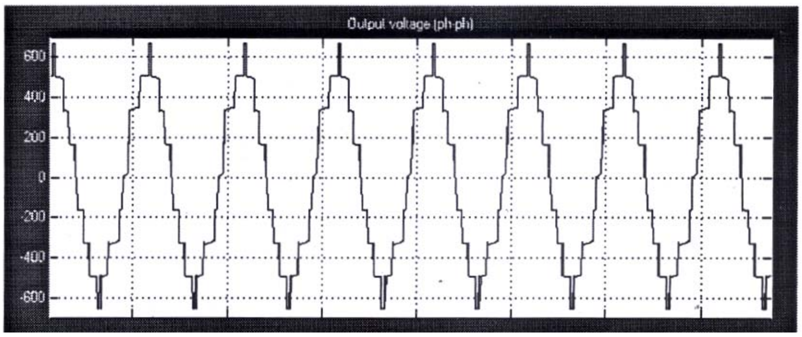


Fig 4.20: Output Phase to Phase Voltage for Generalized 3 Phase, 5 Level Inverter for Highly Inductive Load

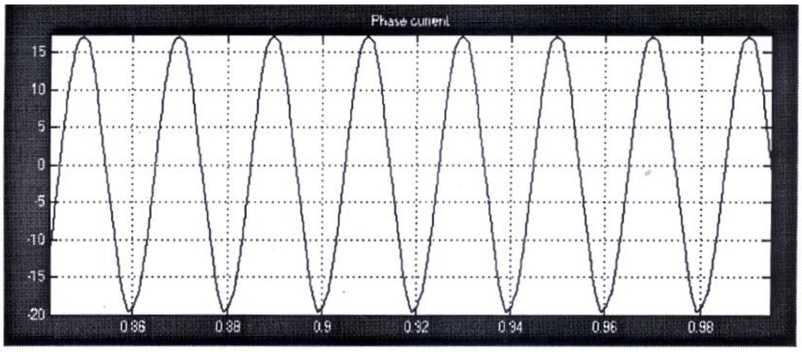


Fig 4.21: Output Phase to Phase Current for Generalized 3 Phase, 5 Level Inverter for Highly Inductive Load

4.11 Conclusion

Multilevel inverters can be used to generate output that has a low harmonic content. A low THD of 0.07 was obtained.

When sinusoidal PWM firing is used, the voltage across the capacitors which are used remains nearly constant for high switching frequency of PWM and hence the output voltage achieved has less distortion.

Chapter 5

CHAPTER 5

VSC BASED MTDC SYSTEMS

5.1 General

The main shortcomings of Line Commutated Capacitor (LCC) are large reactive power requirements, injection of low order harmonic currents, risk of inverter commutation failures and their dependence on reasonably strong AC systems to provide the commutating voltages. These problems can be eliminated in self commutated conversion by use of more advanced switching devices. The present DC technology favours the use of IGBT based VSC, combined with higher switching frequencies carried out by PWM.VSC transmission offers more flexibilities and does not rely on the AC system voltages for the valves commutation.

5.2 Merits of VSC Based Systems

With reference to power transmission, self commutating VSC offers the following advantages over conventional LCC-CSC

1. Each end of the link can be controlled to absorb or generate reactive power independently of the active power transfer.
2. The DC link can be converted to a weak and even passive AC network.
3. VSC transmission has no minimum AC limits.
4. VSC transmission can be designed to provide a variety of ancillary services to the interconnected AC systems, such as reactive power compensation, harmonic and unbalanced voltage compensation, filter elimination etc.

5.3 Structure For End Connection Of VSC Link

The structure of each terminal in a VSC transmission link is shown in Fig 5.1. This VSC transmission link comprises of the various components:

5.3.1 AC System Circuit Breaker

Its main function is to disconnect the AC system from the DC link during faults. This circuit breaker is required since the VSC transmission has no inherent capability to clear DC faults. In this case the DC capacitor will discharge and the fault current will flow through the diodes until the circuit breaker opens. Also when the DC capacitor is charged from the AC system by switching the station breaker, the latter requires the assistance of a resistor which helps in reducing the inrush currents of the transformers and filters during station energisation.

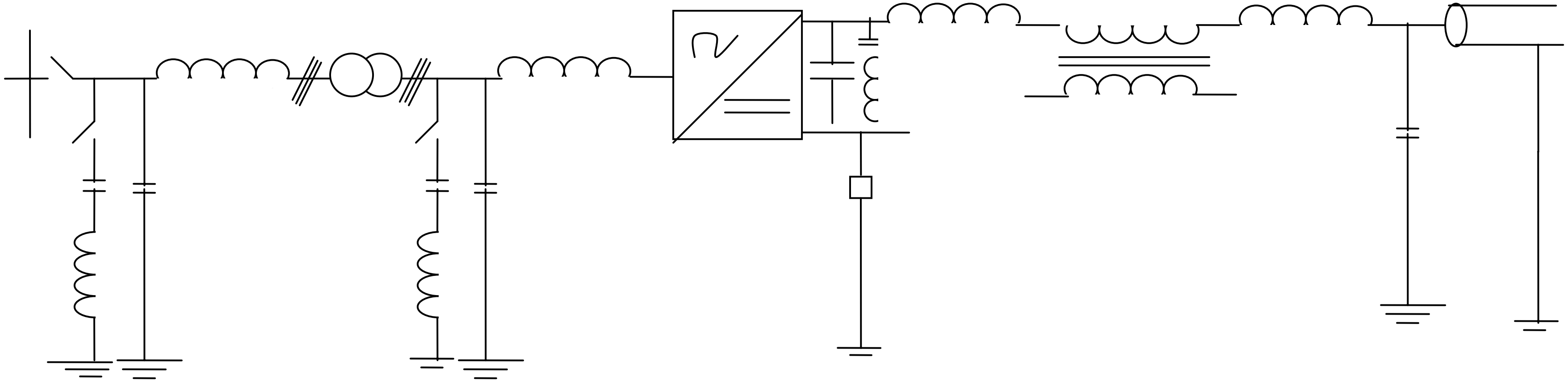


Fig 5.1 Structure For End Connection Of VSC Link

5.3.2 AC Side Harmonic Filter

These are cheaper and more compact in the case of VSC. The use of PWM only produces high frequency harmonics and therefore a high pass filter is required.

5.3.3 AC Side Radio Frequency Interference Filter

This is required to reduce the penetration of high frequency harmonics into the AC system.

5.3.4 Interface Transformer

It is required to adapt the converter voltage and provide reactance between the AC and converter unit in order to control the AC output current.

5.3.5 Converter Output Harmonic Filter

These are even harmonic filters. These are generally tuned at 6th harmonic frequencies and are used to filter out ripple currents.

5.3.6 High Frequency Blocking Filter

These filters are used to block the flow of higher order harmonics in the DC systems.

5.3.7 VSC Converter Unit

These are IGBT based three phase two level or multilevel bridge converters used for AC-DC or DC-AC conversion .These converter ensure power transfer at unity power factor from mains and vice-versa.

5.3.8 DC Side Capacitor

This is the DC storage shunt connected capacitor which keeps the DC voltage within tight limits and controls the DC voltage ripple. A DC link will require an independent DC capacitor at each end in order to maintain a stable DC voltage.

5.3.9 Neutral Point Grounding

Grounding at one point in the DC side is needed to define the potential of the DC circuit.

5.4 VSC Based DC System Control

The common feature of all VSC configuration is the generation of a fundamental frequency AC voltage from a DC voltage and its control in both phase and magnitude. The active power transfer is controlled by shifting the fundamental frequency voltage produced by converter. The power transfer can be in either direction depending on the sign of the phase angle difference. In the multipulse and multi level configuration, with valves switching at fundamental frequency, the magnitude of generated AC voltage will be directly proportional to the DC capacitor voltage.

The latter can be varied by means of small variations in the phase angle difference between the AC and the converter voltage. When power is fed into the capacitor, voltage increases and when power is taken from it the voltage decreases. The charging of large DC capacitor takes lot of time which leads to the disadvantage of controlling AC voltage using DC voltage level.

Now the control of AC voltage is done by using PWM keeping the DC voltage nominally constant. In this control the AC output voltage is varied by means of a modulation index signal defined as the ratio of the required AC voltage magnitude to the maximum AC voltage. If the modulation index is close to 1, converter voltage is greater than AC system voltage and reactive power is transferred to the system otherwise converter absorbs reactive power. The modulation index is implemented either by direct control (Fig 5.2) or vector control (Fig 5.3).

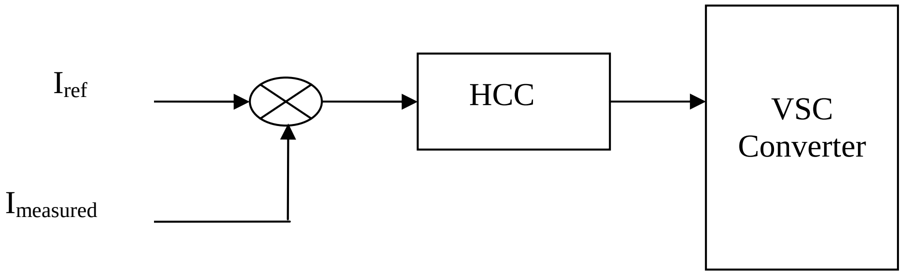


Fig 5.2 Direct Control Method

5.4.1 AC Voltage Control

By regulating the magnitude of the fundamental frequency component of the AC voltage produced by VSC on the converter side either by varying DC capacitor voltage or modulation index, the AC voltage is controlled. If VSC feeds into the isolated load, AC voltage controller automatically controls the power going into the load.

5.4.2 Frequency Control

When VSC link supplies power to an isolated load ,the frequency control of the oscillator is necessary since it determines the valve pulse firing sequence. When VSC is connected to an active power system, VSC controls the system frequency by regulating the power delivered to or from the AC system.

5.4.3 Active Power Control

The phase angle of the fundamental frequency component of AC voltage generated by converter is regulated for the active power control transfer. The transfer of the active power through the link requires coordination at both the ends of the link. Fast power control is required for the improvement of transient stability.

5.4.4 Reactive Power Control

The reactive power control by the VSC is controlled by the magnitude of the converter AC voltage source and is determined by the modulation index.

5.4.5 DC Voltage Control

DC voltage control is achieved by regulating the extra power required to charge or discharge the DC capacitor to maintain the specified DC voltage level through the proportional or proportional integral controller.

5.4.6 AC Control

Current control ensures that the converter valves are not overloaded and is achieved either through direct or vector control where the control of current is the intermediate step in control.

The converters at both the ends of a point-to-point link must be controlled to work together in order to transfer active power which requires setting of appropriate phase angles for the AC volt ages at the converter sides.When the VSC feeds into an active AC system, the frequency is fixed by the synchronous generators and load frequency Control, the VSC regulates the power delivered to or taken from AC system. Under normal operation, each station controls its reactive power independently of the other and the active power flow of sending end station must equal receiving end station plus the losses in the DC system.

5.5 Control Capability of VSC Transmission

Following three factors influences the capability of VSC transmissions in terms of stability

1. Maximum current through IGBTs. This relates the multiplication of maximum current and actual AC voltage in the power plane with the drop in AC voltage. MVA capability reduces
2. Maximum DC current through the cable
3. Maximum DC voltage level. If reactive power is high the difference between the maximum DC voltage and the Ac voltage will be low.

5.6 MVDC Link

A VSC based DC sub transmission link can be created via multi terminal in feeds from AC transmission systems and multiple outlets to AC distributions system. The converters in the ring can operate as both inverters or rectifiers and thus facilitates the exchange of active and reactive power according to the load and source requirements. The power sharing requirement of the converters connected to the ring could be achieved by a droop control strategy so that the power allocation among the rectifiers is proportional to their power rating. The power is fed into link from various AC grids. These all sources are connected to the DC bus via VSCs or directly in case of DC source. The best economical, technical and environmental benefits can thus be obtained by the hybridization of both the systems through voltage source converter with independent control of active and reactive power. It is possible to operate the distribution system with satisfactory stability regardless of the AC power system condition. Also VSC based systems are very advantageous in feeding AC distribution systems with low short circuit power or even passive networks with no local power generation. The various loads here are presented in terms of industries, distribution systems and other local loads. A typical configuration of MTDC sub transmission system is shown in Fig 5.4. however, for present study, only one source has been selected.

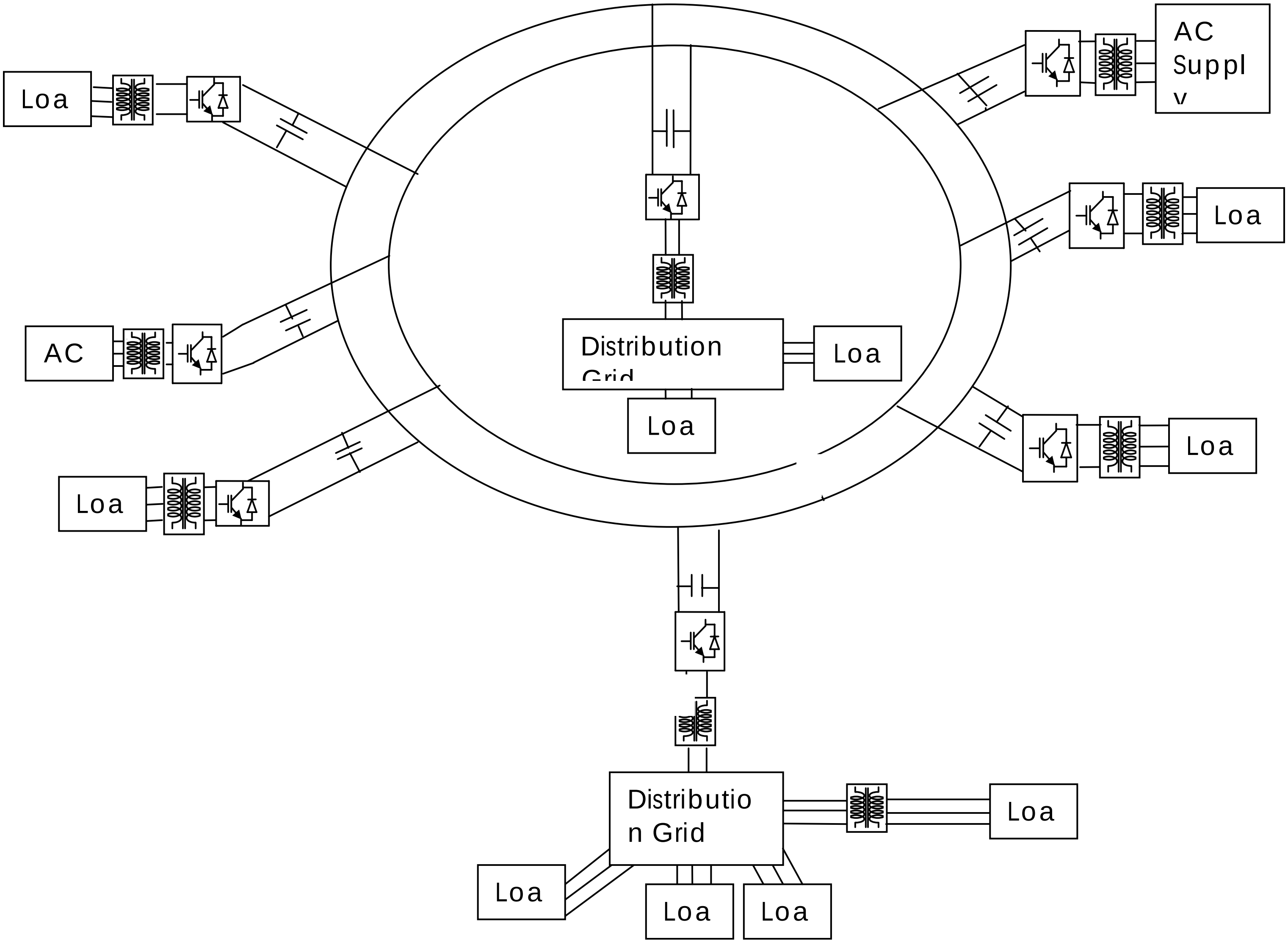


Fig 5.4 MTDC Sub Transmission System

5.7 Current Control Scheme of MTDC Systems

A current control technique has been adopted to control these VSCs for power flow management and provide multiple connectivity on the dam through DC bus voltage control. The proposed DC power dam includes connectivity to various loads and the main AC source. The block diagram of the control scheme is shown in Fig 5.5.

In this current control scheme the voltage across DC bus is measured (V_{dcm}) and the reference voltage (V) is compared and given to PI controller which generates a current i. This component corresponds to the control of the DC bus. Also nominal value of current (I_{nom}) is given to time based selector which computes i'. This component is related to the selection of input power. Also the voltage across AC side, V_{abc} is transformed into dq components from which V_d is extracted and compared with the voltage measured, V and if fed to PI controller which computes current, $i_{d'}$ .This component of current corresponds to the compensation of AC side voltage. All the three components i, i'and $i_{d'}$ are finally compared and limited by a limiter. This limited value of current component computes the d component of current i_d.

Similarly for reactive power management, the current at AC side I_{abc} is sensed, transformed into dq components. This transformed i_q component is given to multi port selector along with the reactive component of the current calculated through v_q and i_q parameters. This component through limiter is given to transformation block of dq to abc. Thus i_d and i_q component is transformed back into abc components and is given to the input of HCC which is then given to VSC controller.

Therefore a current component for the HCC is computed through the DC bus control, compensation of AC side voltage and active and reactive power control.

5.8 Multi Terminal Direct Current Components

The simulation models have been developed in MATLAB environment. Along with SIMULINK , the SIMPOWERSYSTEM blockset has been extensively used for the purpose of simulation. SIMULINK is an interactive tool for modeling, simulating and analyzing dynamic systems. The MATLAB provides extensive tools for testing and debugging the desired system before going for final hardware implementation. This section of the chapter describes the model of MTDC components, VSC based DC link and multi terminal system developed in MATLAB environment. All the models are developed in discrete time domain with sampling time Ts= 5e-06 s.

5.8.1 Two Level Converter

A 3 phase 1 volt, 50 Hz AC is supplied to a DC side load of 200 KW. The voltage obtained at the DC terminal is compared with a reference value, selected here as 500 Volts. The DC bus contro; has been obtained by PI controller and is making an estimate of current required at DC load side.

A hysteresis current control is employed for controlling the voltage source converter so that the output current generated follows closely the reference current waveform.

Two capacitors of 10,000 μf in series are placed across the Dc bus. The sample time of the controller is 5e-06. PI controller computes the required current to flow through the DC bus such that the desired voltage is maintained across it. This magnitude of current is obtained with unit template to get the reference current for input to HCC. PLL is used to compute the unit template corresponding to phase voltage at the time of common coupling.

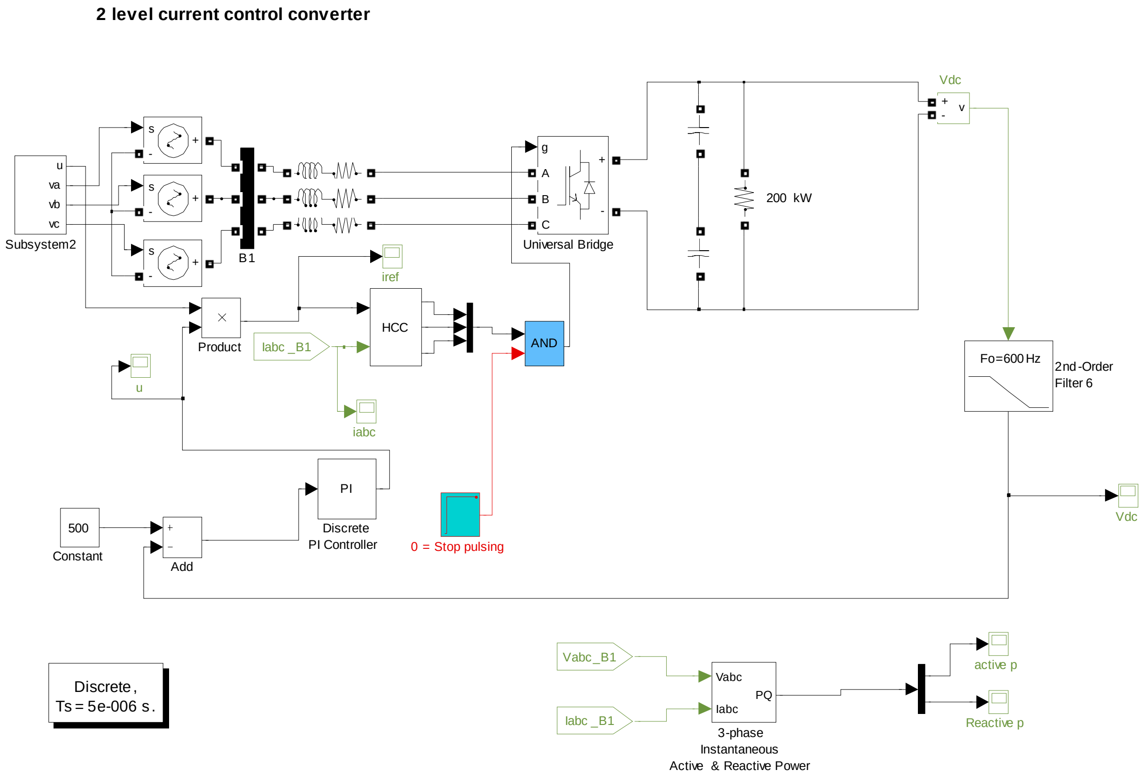


Fig 5.6 Two Level Current Control Converter

5.8.2 Two Level Inverter

A 500 V DC supply is applied across a three phase RL load with R = 14 Ohms and L= 4 mili henry. Same current control technique is utilised here also .The voltage obtained at the three phase load, vabc is transformed to dq and this transformed value of voltage, vd through low pass filter is compared with a refernce value of 230 V and is then fed to PI controller. Thus the obtained value of current, id is taken as idref. Here the value of the voltage is computed to maintain the desired current across the load. This value of idref is utilised in hysteresis current controller for the reference signal generation. The simulink model of the same is shown in Fig 5.7.

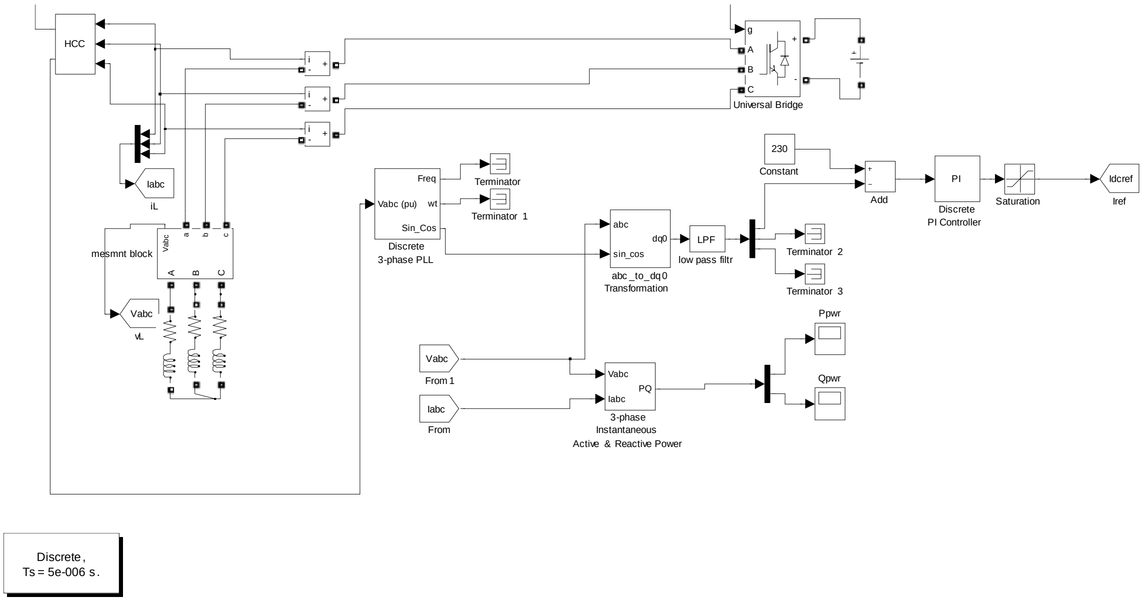


Fig 5.7 Two Level Inverter

5.8.3. Multiterminal Direct Current (MTDC) Link

A multi terminal Direct link is formed with the above converter and inverter. The VSC controller works as rectifier at the sending end and is linked to the other controller at the receiving end via a DC cable of 25 km length. The schematic diagram of this type is shown in Fig 5.8.

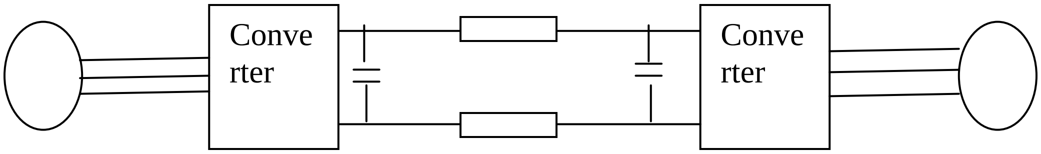


Fig.5.8 VSC Based DC Link For Power Exchange Between The Two Converters

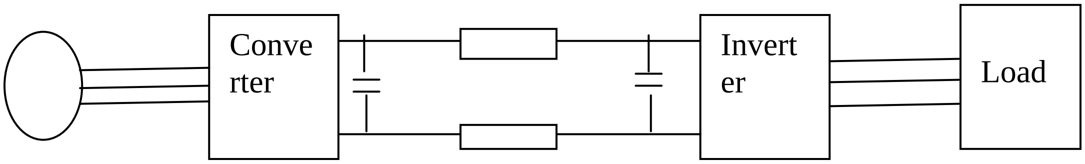


Fig.5.9 VSC Based DC Link For Power Transfer

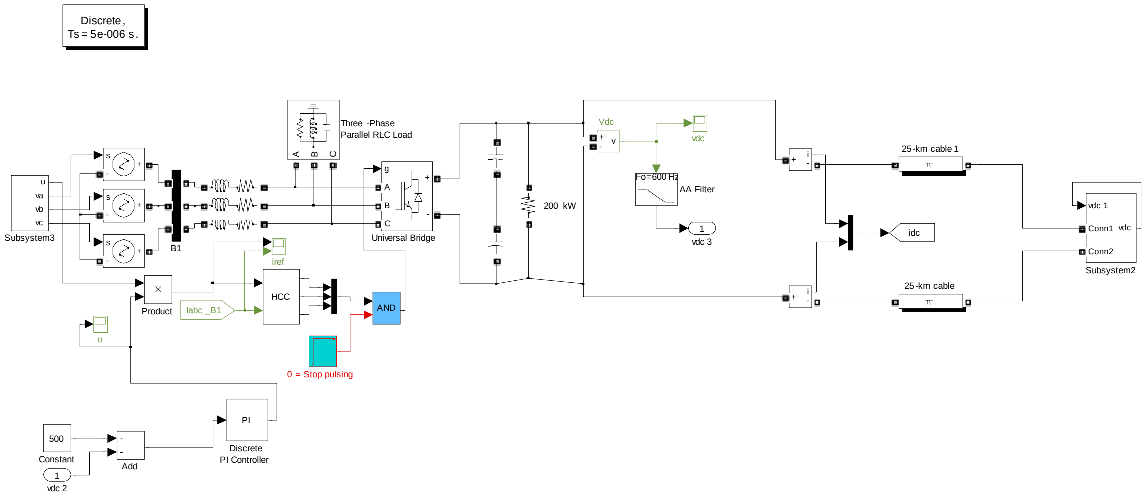


Fig 5.10 The Simulink Model for Power Exchange

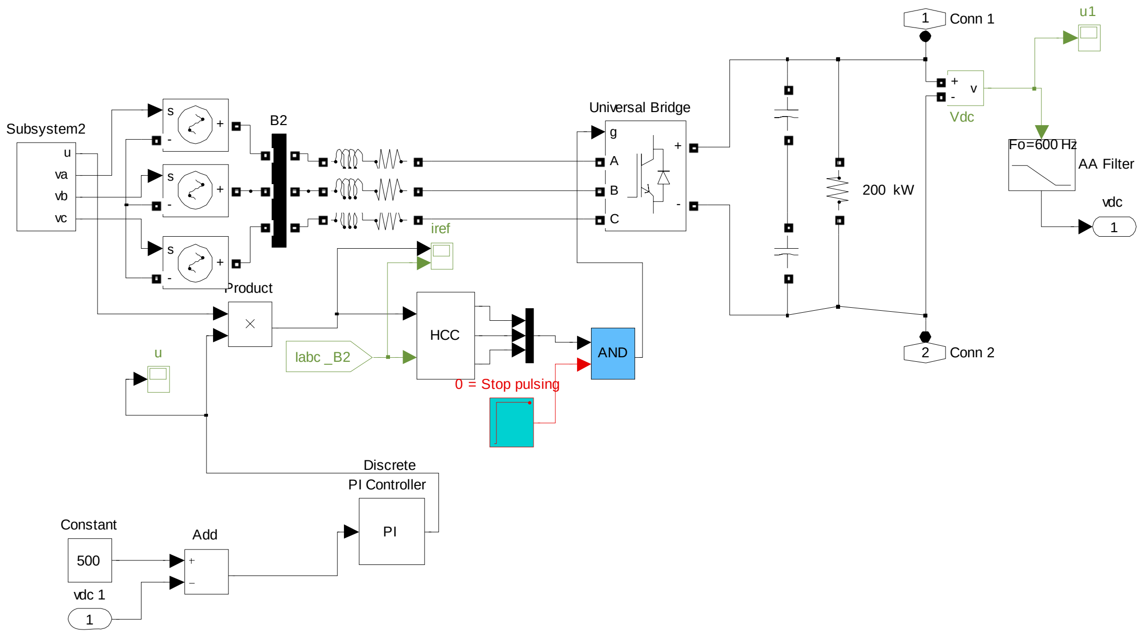


Fig 5.11 The Subsystem of the Simulink Model for Power Exchange

The converters on either sides are controlled through current control with a flexibility of quantizing the reactive component on the AC side of the system. The control keeps track of DC bus voltage across the capacitor and the bus voltage is maintained in a way to control the flow of real power to/from the DC bus. A hysteresis based control is adopted for switching of converters with a limit to the maximum switching frequency to prevent the system to enter limit cycles. In the Fig 5.9, a three phase RL load is also connected at the converter side. The Fig 5.10 illustrates the simulink model of the VSC Based DC Link for Power

Exchange Between the Two Converters. The two converters for power exchange are connected via a DC bus of length 25 km. The voltage V_d is maintained at the DC side.

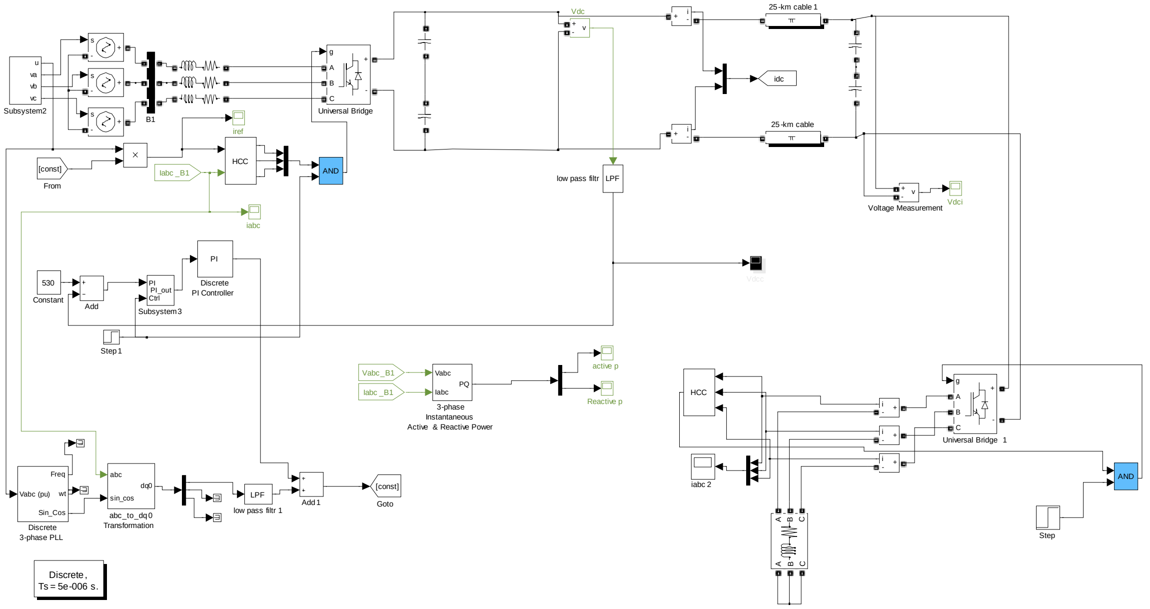


Fig 5.12 The Simulink Model for Power Transfer

The simulink model for power transfer is shown in Fig 5.12. the model is simulated for sampling time of 5e-06 seconds. Here the inverter is switched at 0.1 s and the DC cable is allowed to charge and settled. The converter is then switched at 0.2 s. The DC voltage maintain itself at a reference value of 550 V.

5.8.4 Multiterminal System

A multi terminal system is formed with the same components the VSC controller are utilized to work as inverter or converter according to the requirement. A 1V, 50 Hz, AC supply is provided at the converter side and a RL load is also incorporated. Through a link of DC cable of 50 km length another converter is provided with the RL load. The DC cable is tapped at the centre to provide a RL load at 60 Hz frequency. This forms a multi terminal system and on the same basis more components can be added to the DC cable, either rectifier or converter, to form multi terminal sub transmission system. The schematic diagram of the model is shown below:

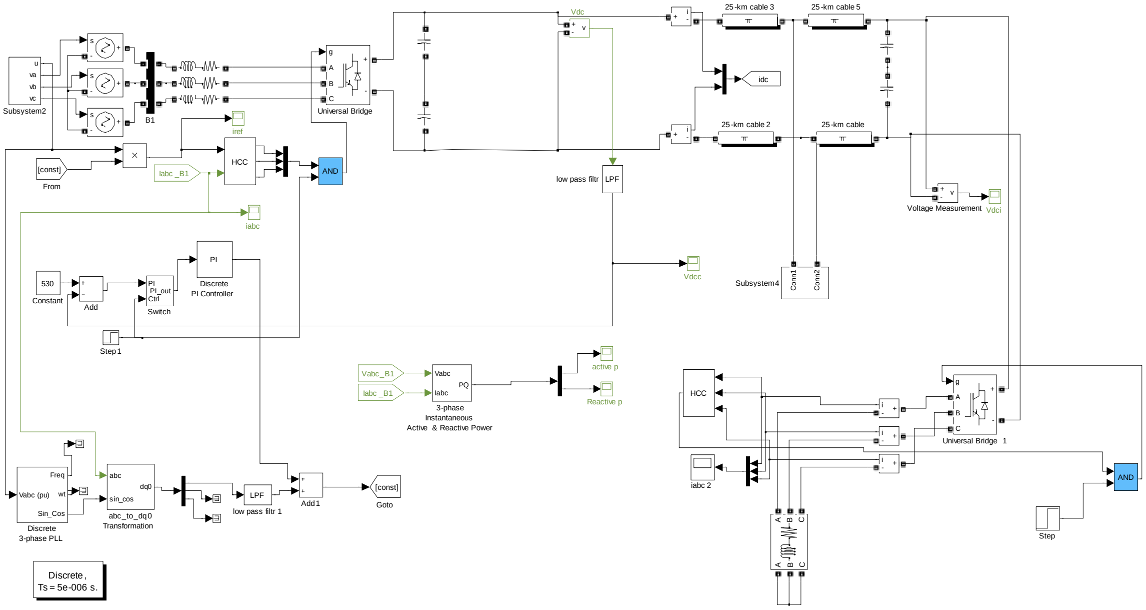


Fig 5.13 The Simulink Model for Power Transfer

5.9 Results and Discussions

The performance of the multi terminal system is simulated using developed mathematical model in MATLAB environment along with SIMULINK and SIMPOWERSYSTEM blockset. The discrete system has been executed at sampling interval of 0.5μs.

5.9.1 Converter

The performance for the converter is being shown in Fig 5.14 to Fig 5.17. The DC bus as shown is settled and the reactive and active power at the converter side is also shown. Initially the three phase current is distorted but when the converter switches at 0.05 it became sinusoidal. The load perturbation is also shown and found that DC bus restores itself and settled with the active and reactive power.

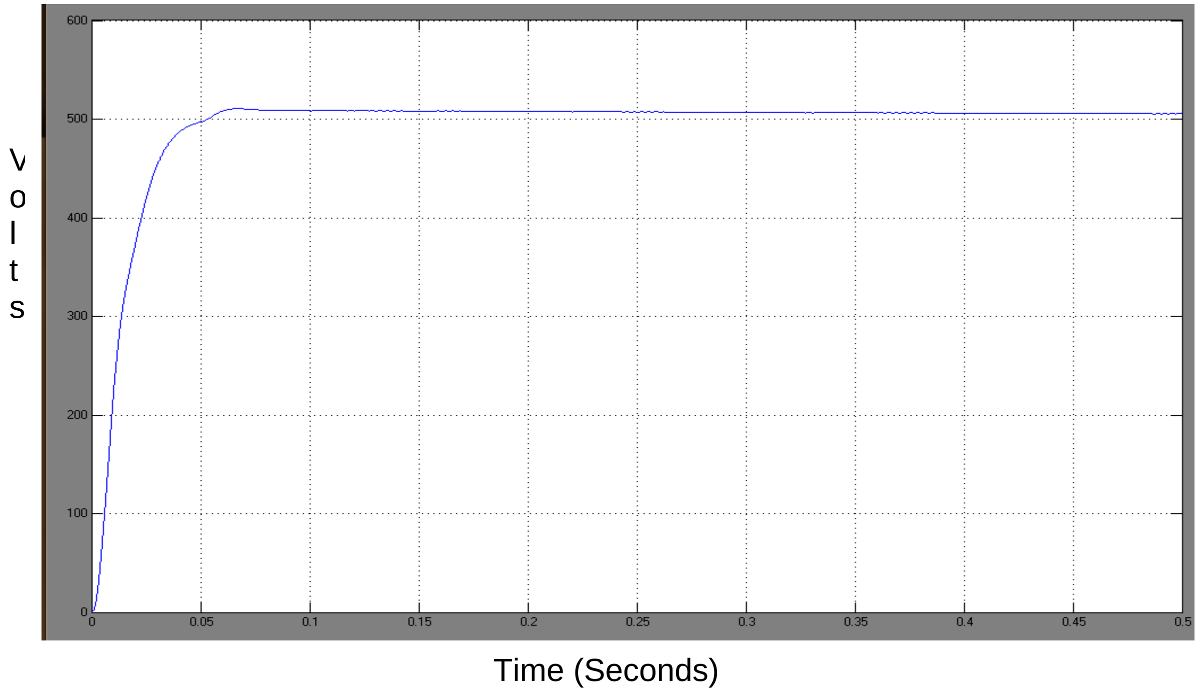


Fig 5.14: DC Bus Voltage across the Load

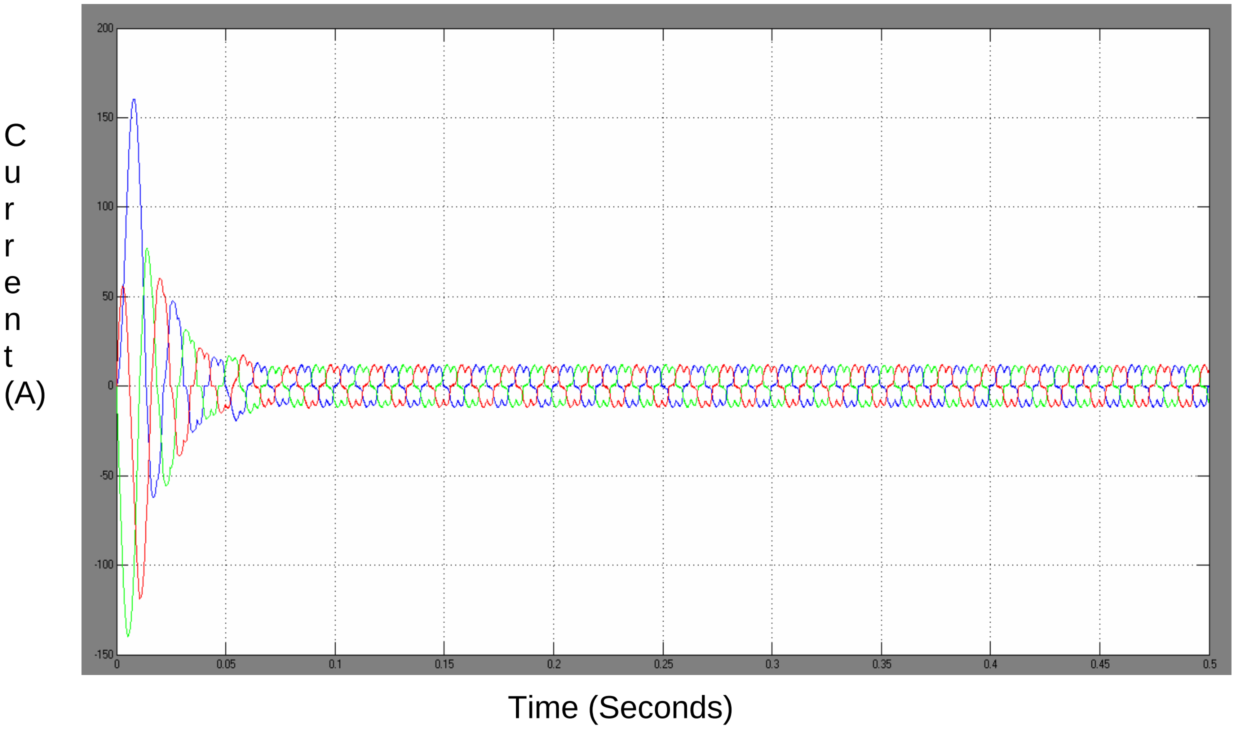


Fig 5.15: Three Phase Current Waveform at the AC Supply

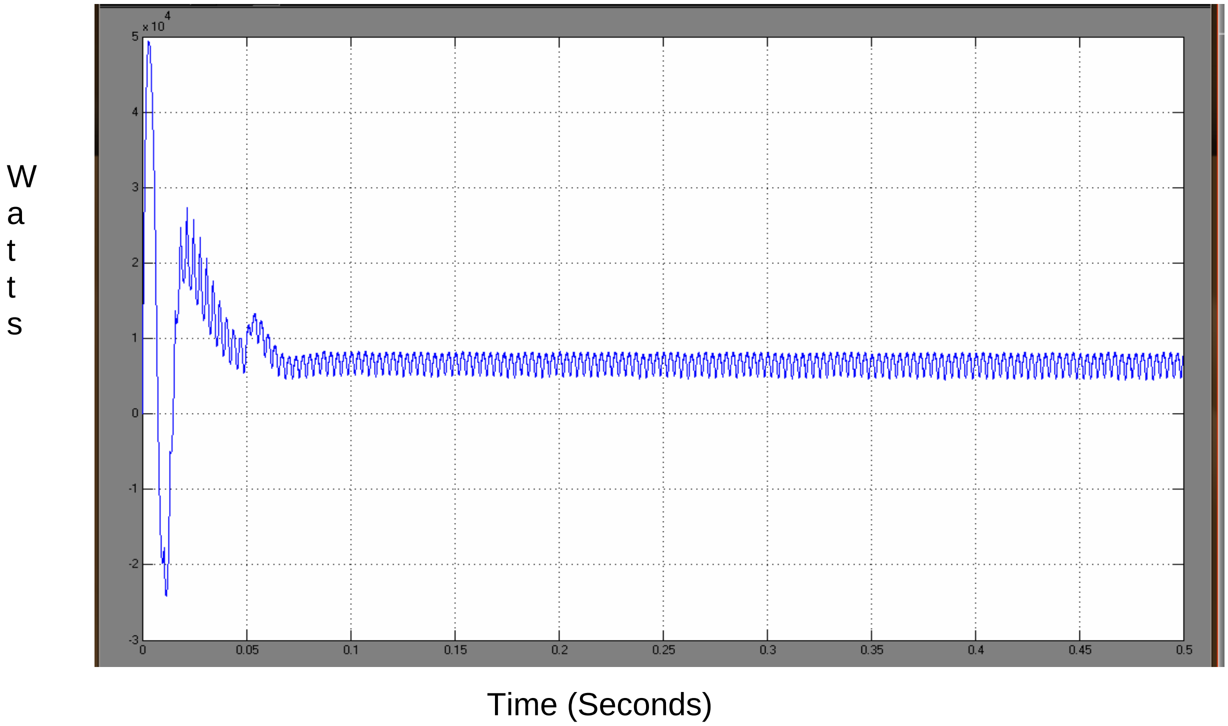


Fig 5.16: Active Power at the AC Side

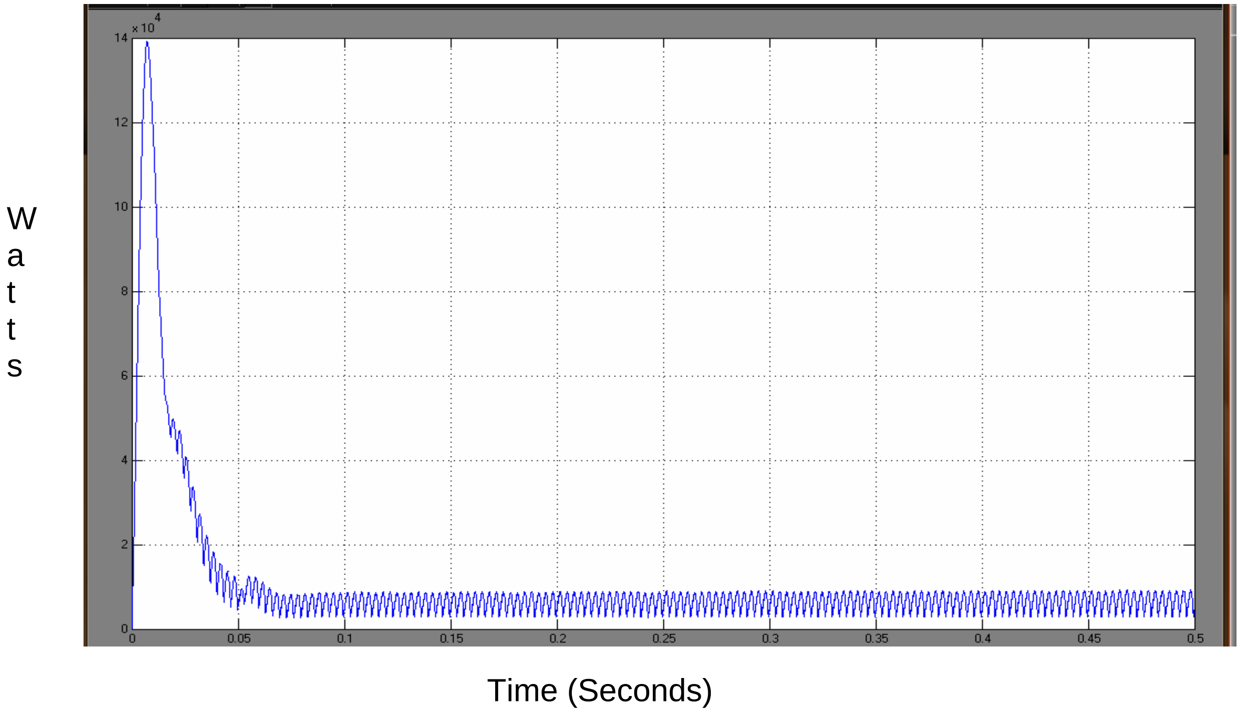


Fig 5.17: Reactive Power at the AC Side

5.9.1.1 Load Perturbation

In the converter mode the load is switched at 0.3s after the switching of the converter at 0.05s. The following results are obtained and it is being shown that the voltage across the DC is stabilizing with the active and reactive power .The three phase current is sinusoidally maintained and are shown below.

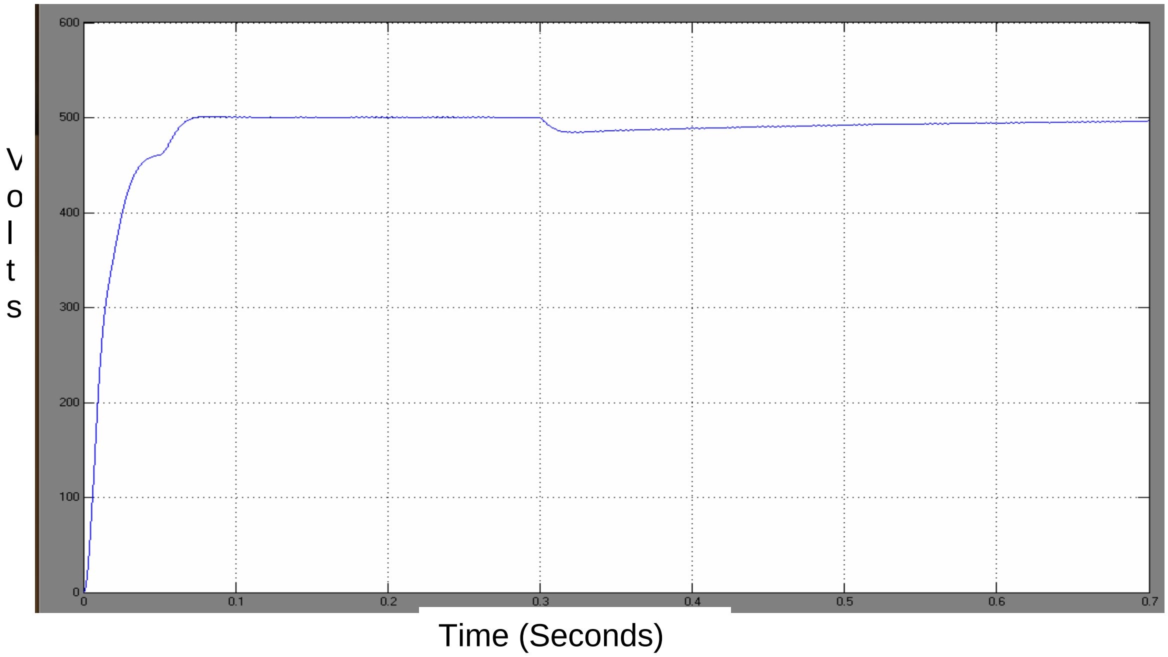


Fig 5.18: Voltage across the DC Cable

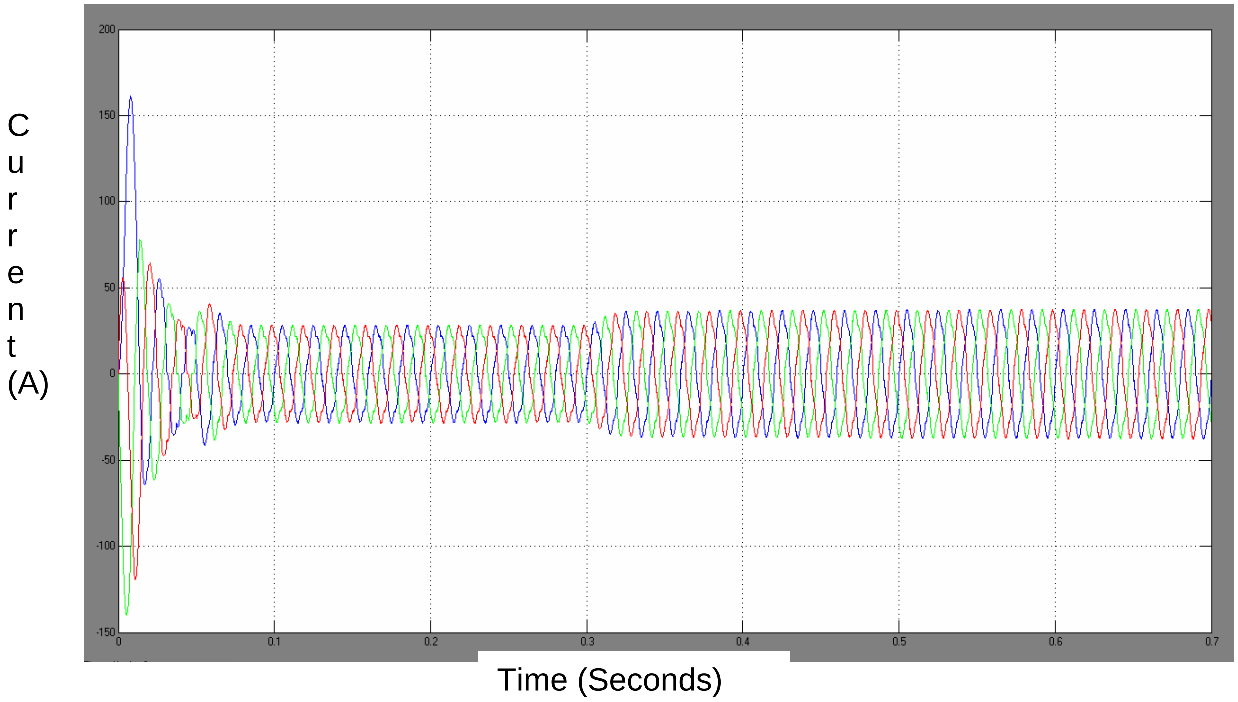


Fig 5.19: Three Phase Current across the AC

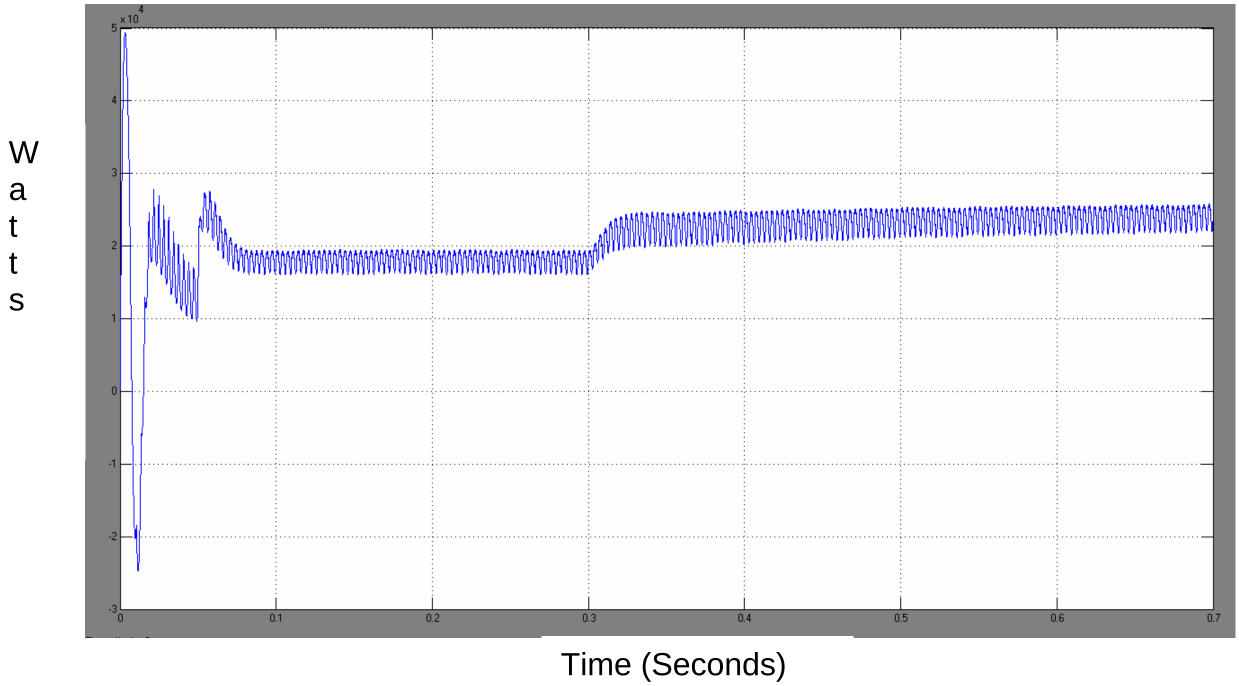


Fig 5.20: Three Phase Active Power at the AC Supply

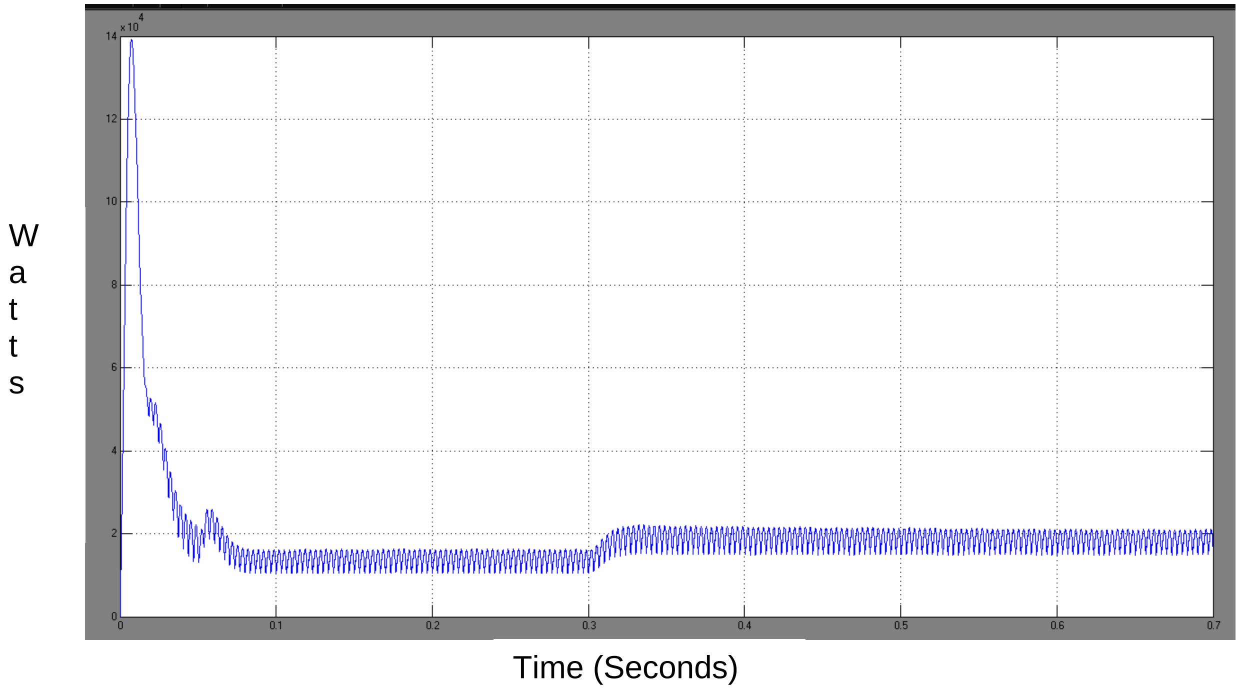


Fig 5.21: Three Phase Reactive Power at the AC Supply

5.9.2 Inverter

The Result of the simulink model of inverter is shown in Fig 5.22 to Fig 5.26. The DC voltage of 500 V is supplied to a RL load. The three phase current and the three phase voltage at the load are shown, also the active and reactive power at the output side are shown.

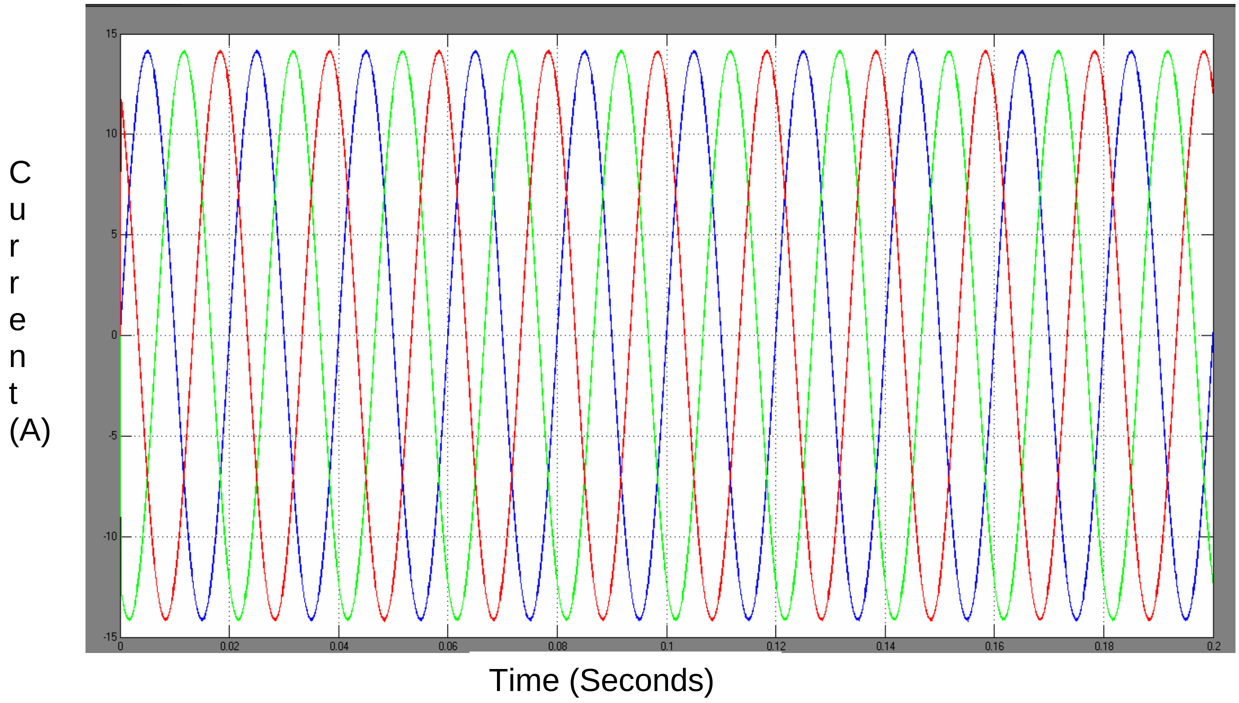


Fig 5.22: Three Phase Current Waveform at the Load Side

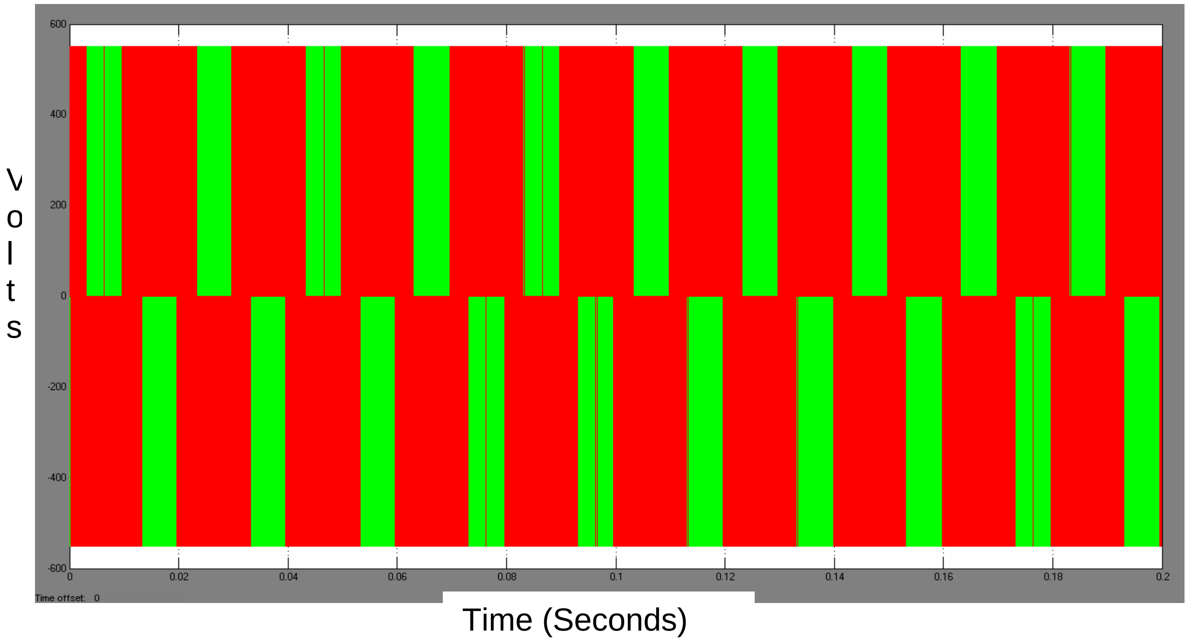


Fig 5.23: Three Phase Voltage Waveform at the Load Side

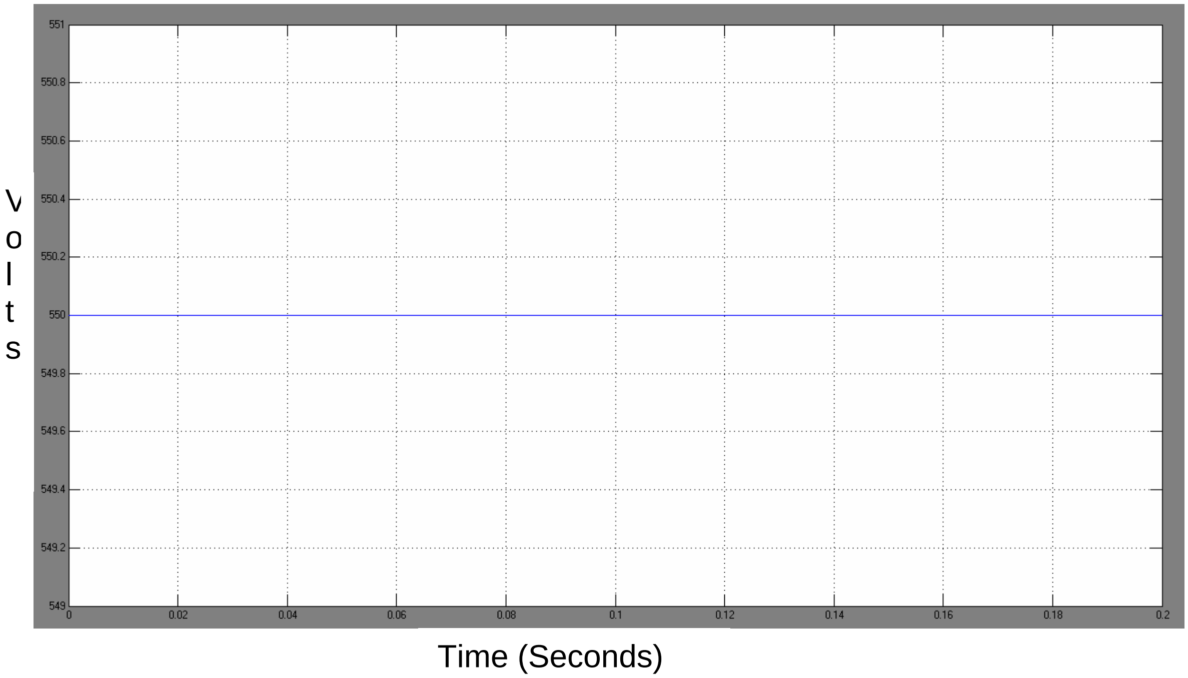


Fig 5.24: The DC Voltage Supplied at Inveter

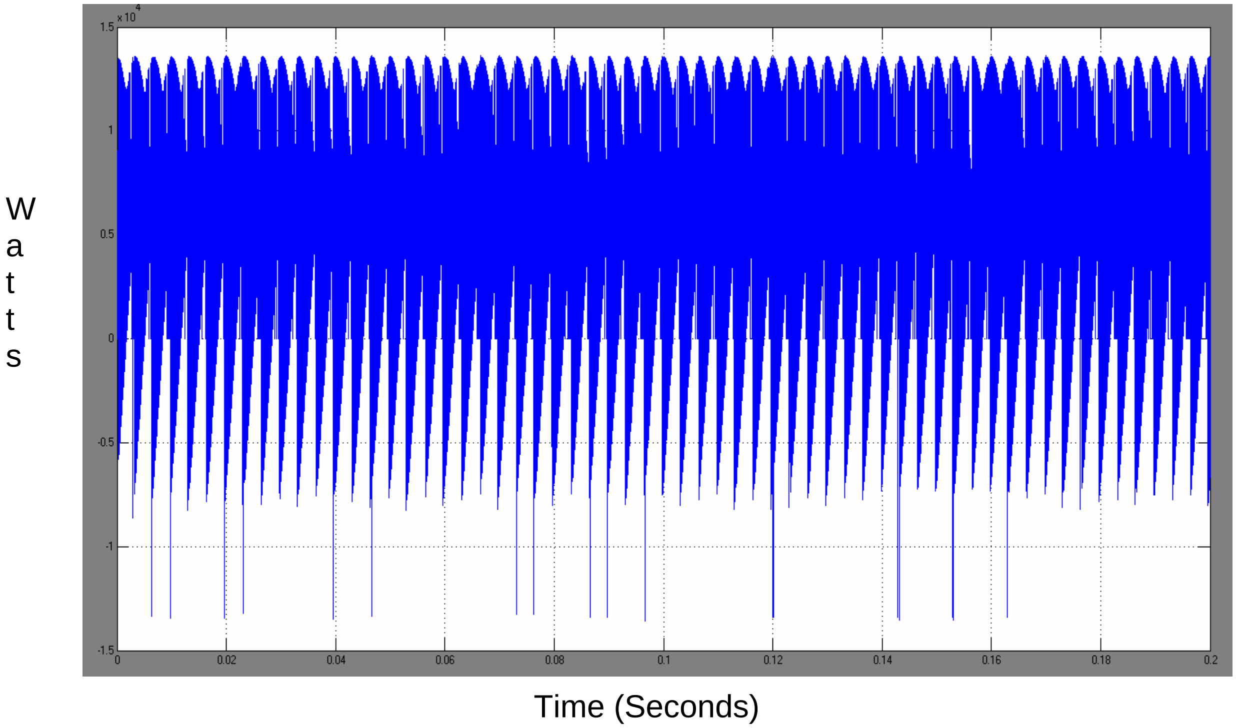


Fig 5.25: Active Power at the Load Side

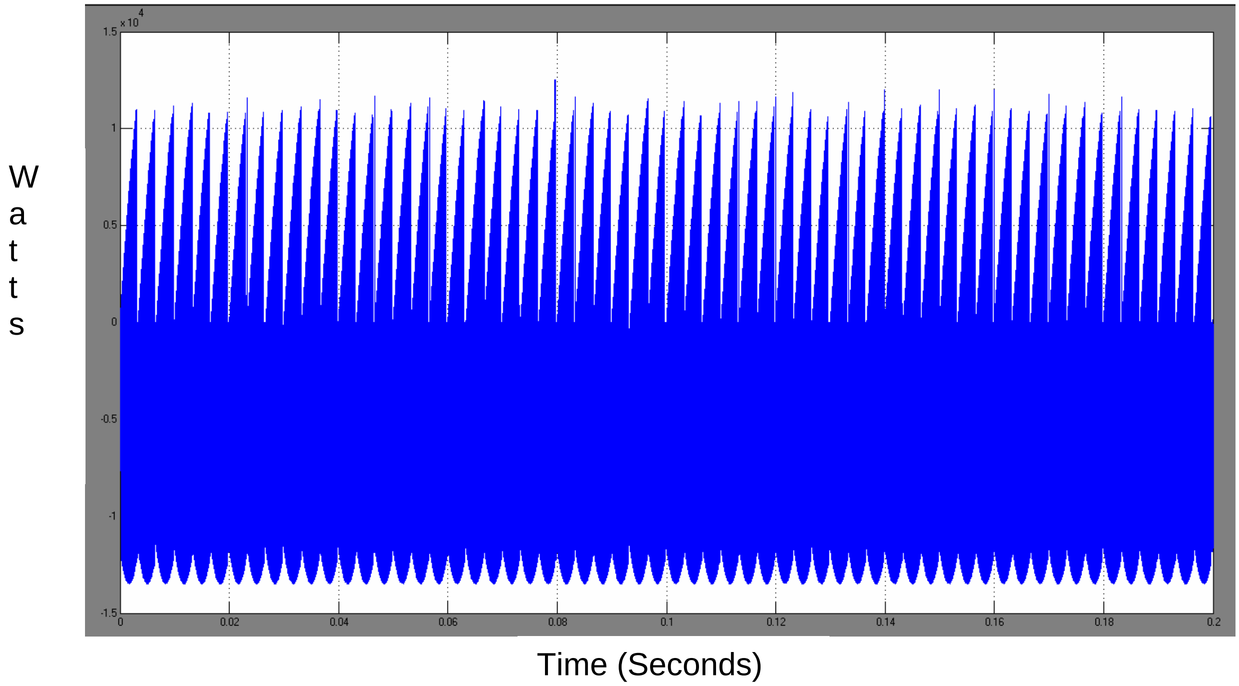


Fig 5.26: Reactive Power at the Load Side

5.9.3 Multi Terminal Link

The result of Multi Terminal Link are shown in Fig 5.27 to Fig 5.32. The DC Bus is initially allowed to charge and the Inverter is switched at 0.1s as shown below in the DC Voltage graph. After the DC Voltage is settled, the converter is switched at 0.2s . The voltage here slightly increases and tries to maintain its value at a reference value of 550V. This could be referred in the figure below.

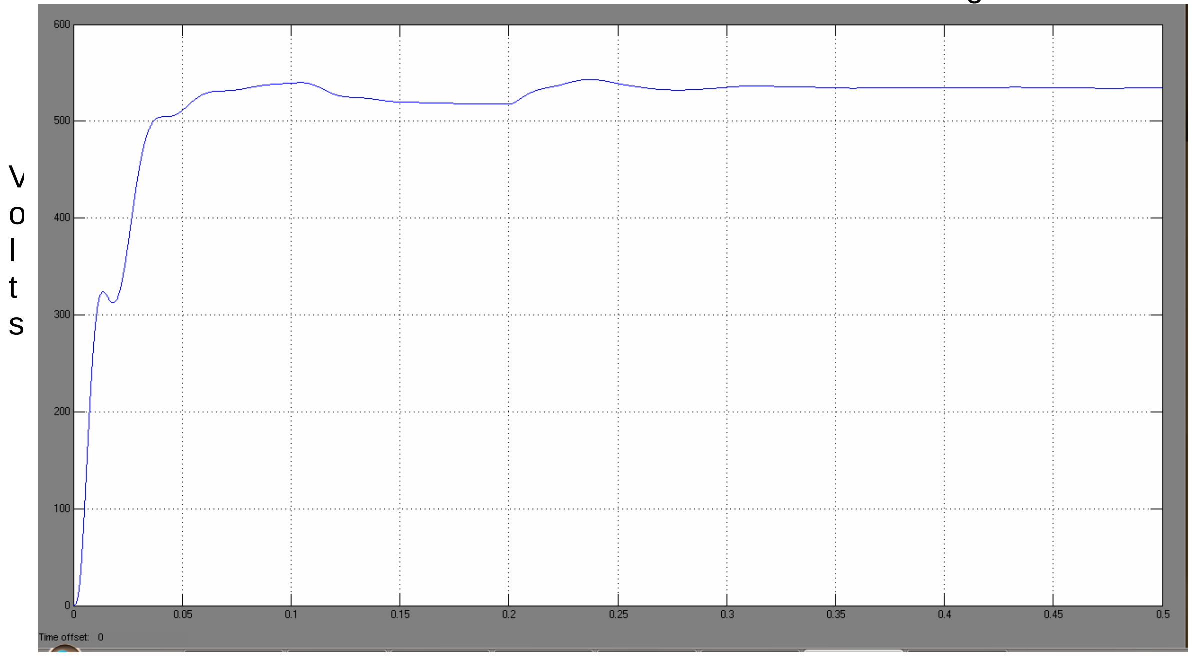


Fig 5.27: Voltage across the DC Cable

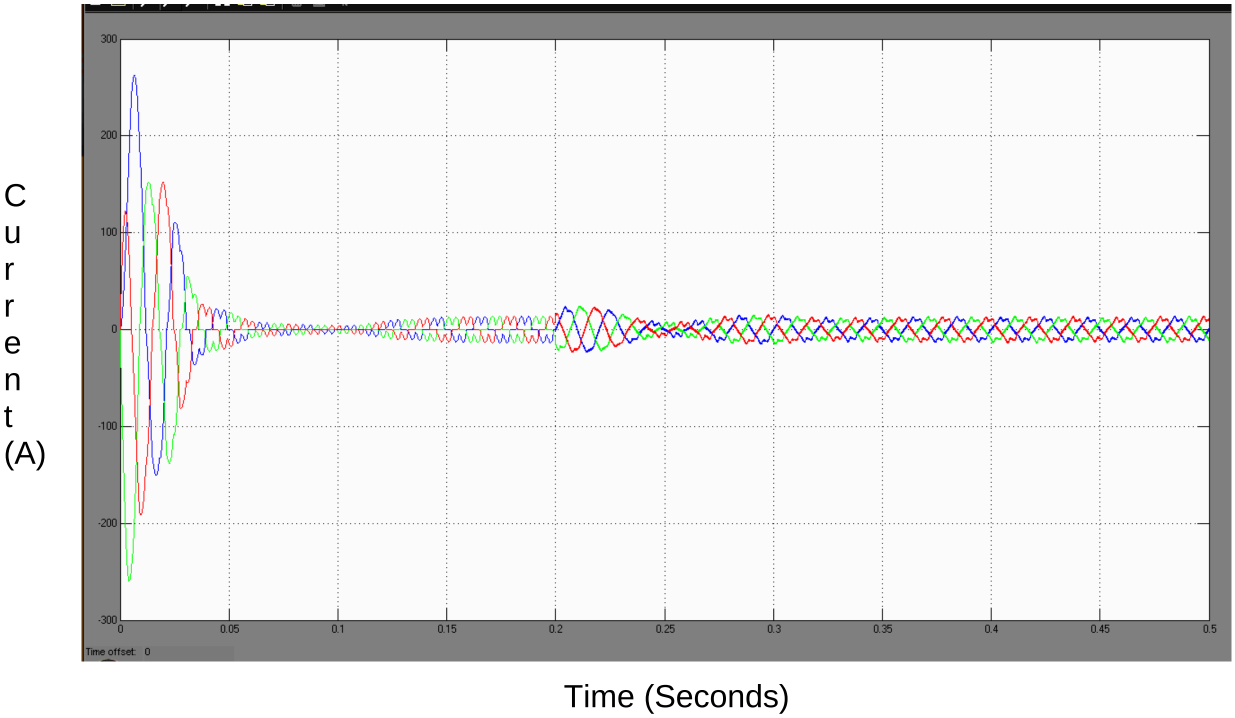


Fig 5.28 : Waveform of Current at the Converter Side

Since the Inverter is switched at 0.1s ,the waveform of the current shows the rectification phenomenon. At 0.2s ,the conversion mode is switched on and the disturbances created in the waveform can be seen in the above Fig. This tries to settled down to maintain constant DC across the DC Cable.

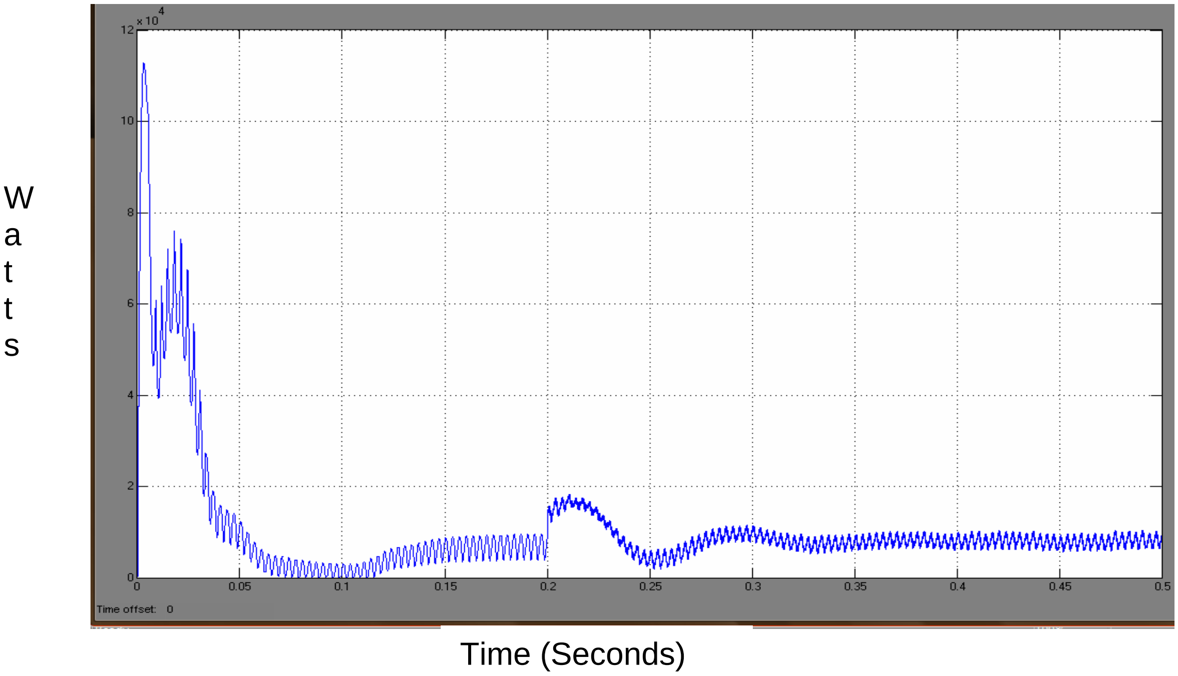


Fig 5.29 : Waveform of Active Power at the Converter Side

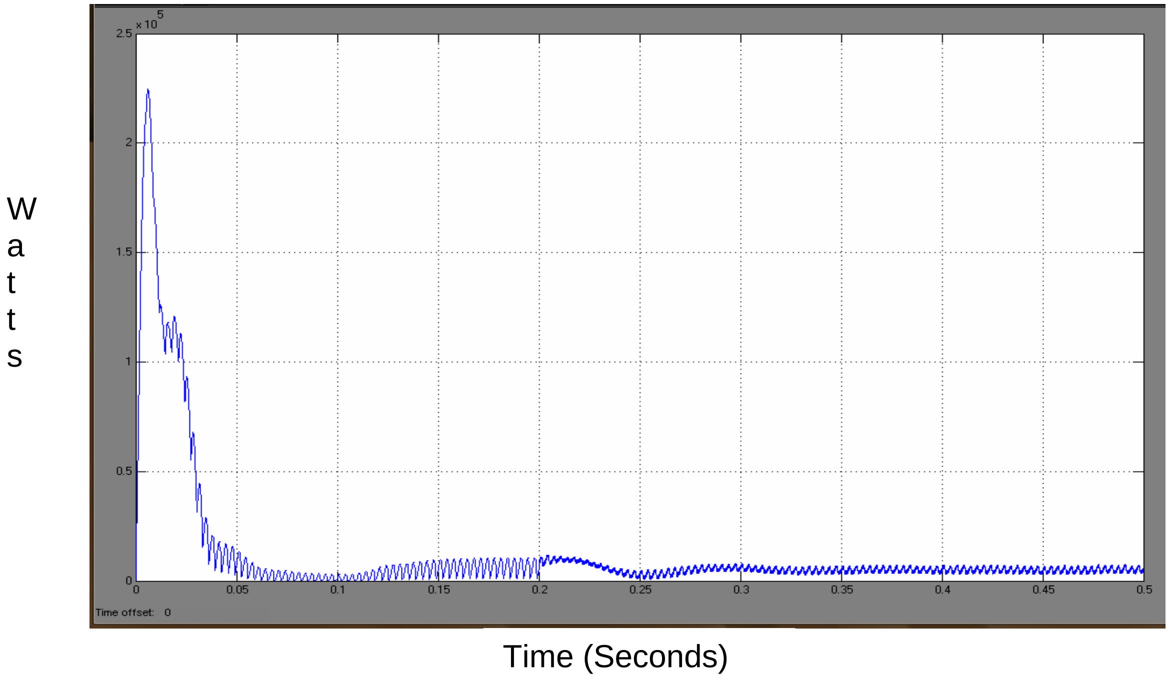


Fig 5.30 : Waveform of Reactive Power at the Converter Side

After the switching of inverter at 0.1s and converter at 0.2s , both the Active and Reactive power try to maintain the constant level as can be seen above.

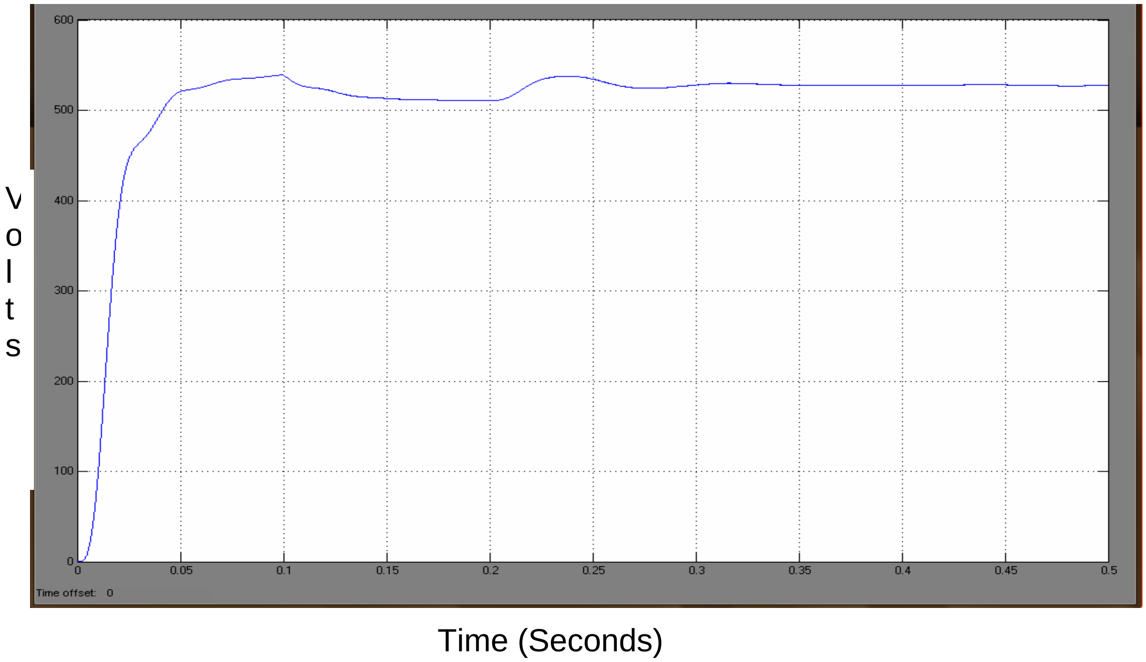
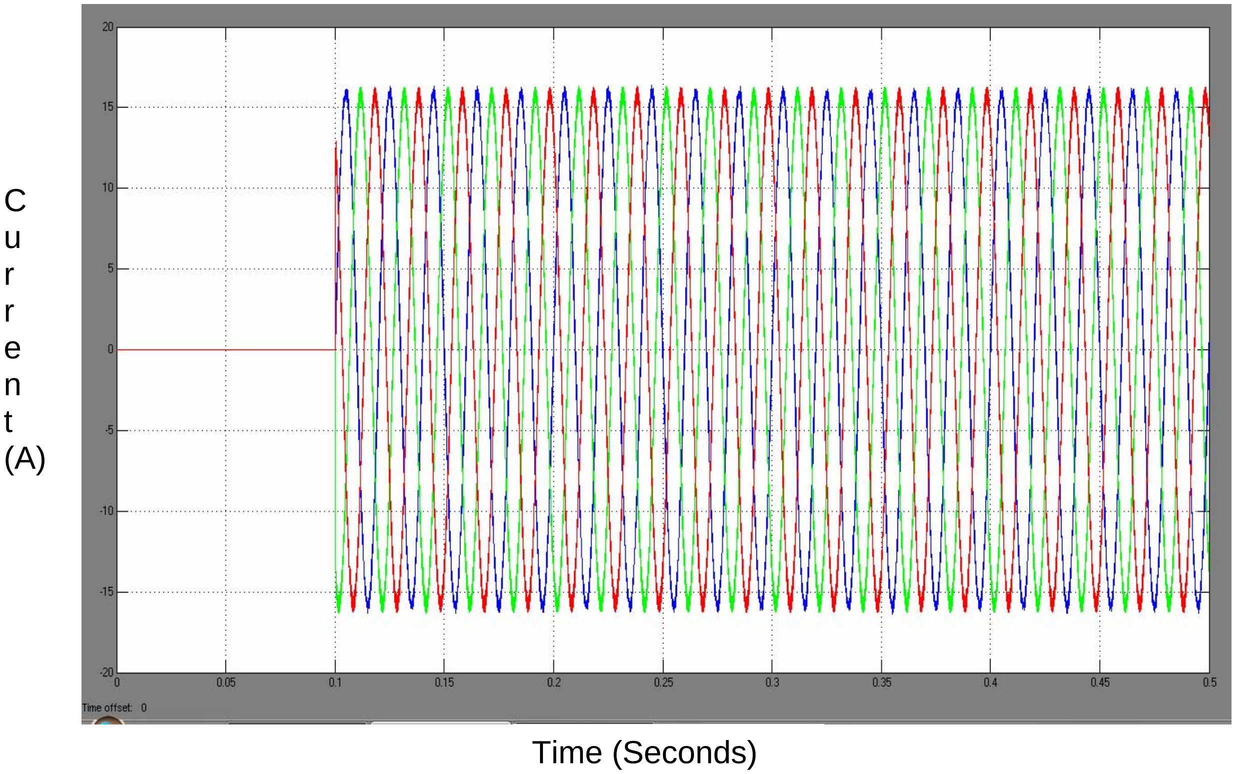


Fig 5.31 : DC Voltage at the Inverter Side



5.9.4 Multiterminal System

A multi terminal system is simulated. An inverter is tapped in between the DC cable. The results of the simulink model of power transfer is shown below:

5.10 Conclusions

The following are the conclusions drawn from the simulink results and discussion.

1. A new control schemes of current control is being developed which is a simplified technique and is easy to implement for power transfer and power flow analysis.
2. A multi terminal system is being modeled, simulated under dynamic conditions.

Chapter 6

CHAPTER 6

FUTURE SCOPE OF THE WORK

6.1 General

The main objective of the thesis has been aimed towards the modeling, simulation and analysis of converters, inverters, HVDC link and its multi terminal configurations.

The MATLAB SIMULINK model of the above said systems are modeled under various conditions in MATLAB environment and simulated results obtained were discussed and found appropriate regarding the DC bus control and other perspectives.

6.2 Future Scope of the Work

There are certain aspects required for further investigations. Some of them are listed below:

1. The system may be investigated by incorporating multiple input sources and power exchange may be studied between such sources.
2. Often industries require VSD (Variable Speed Drive) for which DC source is required. The system may be studied for supplying power through AC and DC modes.
3. The basic structure of MTDC systems has the advantage of polarized DC link thus increasing the possibilities of connecting battery banks for storage of power and better power management.
4. The MTDC system can be further analysed for its utility with DPG (Distributed Power Generations) and stand by power system for various loads.

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