SOME INVESTIGATIONS ON VSC BASED HVDC SYSTEMS

A

DISSERTATION

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Candidate's Declaration

I, **Rajat Raj singh**, Roll No. **2K15/PSY/12**, student of **M. Tech (Power system)**, herewith declare that the dissertation entitled "**SOME INVESTIGATIONS ON VSC BASED HVDC SYSTEMS**", under the supervision of Dr. Alka Singh of Electrical Engineering Department, Delhi Technological University, in partial fulfilment of the need for the award of the degree of Master of Technology, has not been submitted elsewhere for the award of any degree.

I herewith solemnly and sincerely affirm that all the particulars declared above by me are true and correct to the best of my knowledge and belief.

Place: Delhi **Rajat Raj Singh**
Date: .07.2017 **2K15/PSY/12**

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Certificate

This is to certify that the dissertation entitled **“SOME INVESTIGATIONS ON VSC BASED HVDC SYSTEMS”** submitted by **Rajat Raj Singh** in completion of major project dissertation for the master of Technology degree in **Power system** at Delhi Technological University is an authentic work carried out by him underneath my superintendence and guidance.

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

Place: Delhi
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ABSTRACT

This thesis presents work on VSC based HVDC systems. Chapter one presents a review of AC systems and various HVDC systems. It explains about various aspects such as components of HVDC system, various configurations used in HVDC systems. Chapter two consists of a synchronous reference theory based control algorithm for two level VSC based HVDC system. The various techniques used for PWM are also explained. The performance of the two level VSC based system under different two cases is observed. Chapter three discusses control algorithm for three level VSC based HVDC system. The dynamic modelling of VSC is also explained. The modeling and operation of three level diode clamped NPC converter is discussed and the generation of PWM gating pulses for the same is observed. Also, the performance of the two level VSC based system is compared with three level VSC based HVDC system. Chapter four presents fault analysis of three level VSC based HVDC system and results have been presented for single line to ground and three phase fault conditions. Chapter five discusses the modeling and control of multi terminal three level VSC based HVDC systems and their dynamic performance.

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LIST OF SYMBOLS, ABBREVIATIONS

S. No	**Symbols/Abbreviations**	**Descriptions**
1.	HVDC	High Voltage Direct current
2.	CSC	Current Source Converter
3.	VSC	Voltage Source Converter
4.	IGBT	Insulated Gate Bipolar Transistor
5.	GTO	Gate Turn-off thyristor
6.	HVAC	High Voltage Alternating current
7.	IGCT	Integrated gate commuted thyristor
8.	PWM	Pulse Width Modulation
9.	THD	Total harmonic distortion
10.	STATCOM	Static Var compensator
11.	MTDC	Multi terminal HVDC
12.	X_{L1} and X_{L2}	converter transformers leakage reactance for VSC1 and VSC2
13.	X_{P1} and X_{P2}	reactance of phase reactors for VSC1 and VSC2
14.	V_{S1} and V_{S2}	AC source phase to ground voltages of AC system 1 and AC system 2
15.	V_{F1} and V_{F2}	phase to ground voltages at the point of common coupling for VSC1 and VSC2
16.	V_{B1} and V_{B2}	the phase to ground voltages at the valves of the VSC converters for VSC1 and VSC2
17.	V_{dc1} and V_{dc2}	the DC side voltages between the 2 poles of the VSC converters for VSC1 and VSC2
18.	I_{dc}	the DC current which flows through the DC line or cable
19.	K_1 and K_2	the proportionality constants for VSC1 and VSC2
20.	FFT	Fast Fourier Transform
21.	P*	the reference values for active and reactive power
22.	Q*	the reference value for reactive power
23.	id* and iq*	dq reference currents

CONTENTS

CHAPTER-1 : INTRODUCTION

1.1 INTRODUCTION

As the demand for electrical energy is increasing day by day, the need for developing new and efficient methods for generating and transmitting this energy to the desired load centres has become a necessity. While designing a power system the location of generating stations is dependent on the energy source and the location of these stations and load centres will decide the transmission distance. For an energy source such as coal, diesel or gas the power plant could be set up near the load centres as these energy sources could easily be transported from a place to another. For power plants such as hydro, tidal, geothermal etc are set up far away from the load centres. Therefore, for such power plants the power generated needs to be transmitted through lines or cables to the load centres. The electrical power system widely used is in the form of three phase ac network. The power plants, transmission and distribution systems are interconnected to form a three phase ac network operating synchronously at a single frequency (50Hz in India).

With increase in demand for electrical energy and also the need for transmission to longer distance has led us to deliver power at higher voltages. All these factors have lead us to find more efficient transmission system at higher power. Increasing transmission voltages above certain value is not feasible as it associates with many problems. For bulk power transfer for longer distance, interconnections between regional grids and for transmission trough cables HVDC is preferred due to its technical performance, economical behaviour and higher reliability than the equivalent AC network for same rated power and voltage [1-4]. HVDC is not general solution for fulfilling the power demand it can only be used for specific purpose of delivering bulk power through longer distances or interconnections.

1.2 INTRODUCTION TO HVDC TRANSMISSION SYSTEM

The HVDC transmission system was first installed between Swedish mainland and the island of Gotland in the year 1954 [3]. It was rated 100 kV and 20MW. In the early stages of HVDC technology the converters were incorporated with mercury arc valves. Around 1970, power semiconductor devices (thyristors) were adopted for the use of converter valves instead of mercury arc valves.

In India, The high-capacity (800-kV, 6,000-MW) HVDC bipole line is being implemented from Bishwanath Chariali in Assam to Agra in Uttar Pradesh through Alipurduar in West Bengal. The high-voltage corridor would facilitate transfer of 24,000 MW from future generation projects in the north-eastern region and Bhutan.

HVDC TRANSMISSION LINES IN INDIA [1-3]

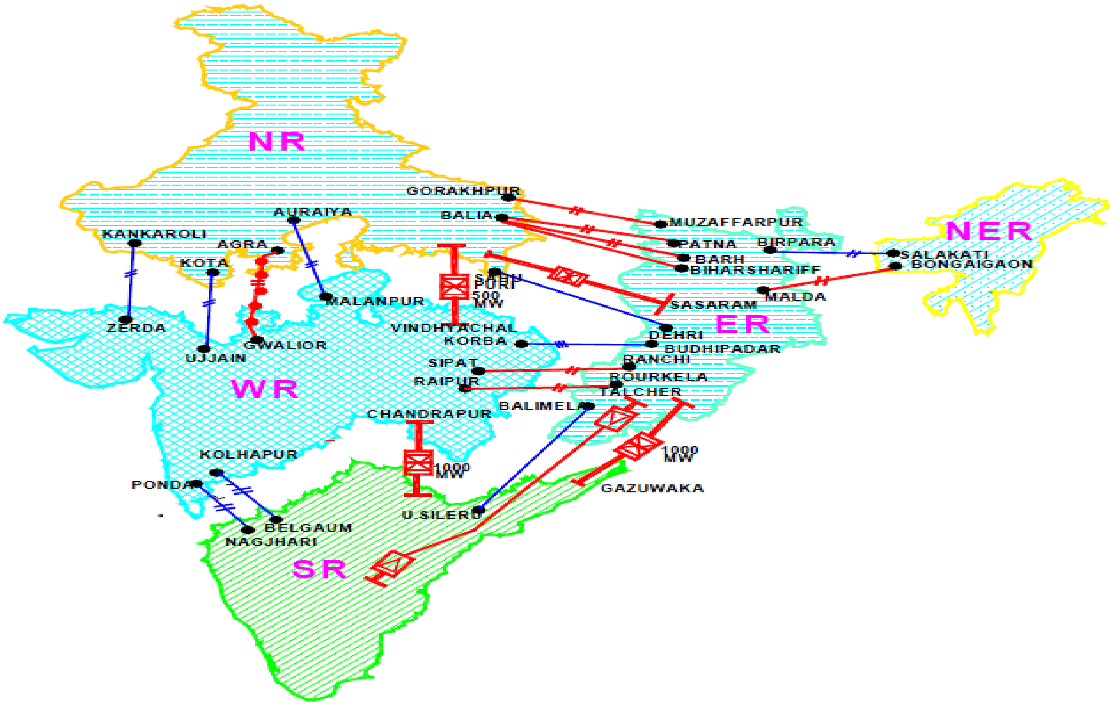


Fig. 1.1: HVDC systems in INDIA

1. Vindhyachal Back-To-Back link connects Northern and Western regions with 2 lines.Transmission Power is 250 MW and the Operational Voltage is 70 KV
2. Chandrapur Back-To-Back link connects southern and western regions with 2 lines.Transmission Power is 500 MW and the Operational Voltage is 140 KV
3. Sasaram Back-To-Back link connects northern and eastern regions. Transmission Power is 500 MW and the Operational Voltage is 140 KV
4. Vizag Back-To-Back link connects southern and eastern regions. Transmission Power is 500 MW and the Operational Voltage is 140 KV
5. Rihand-Dadri: Maximum Transmission Power is 1500 MW and the Operational Voltage is 500 KV. It is a Bipolar Link of length 814 KM in Uttar Pradesh.

6. Chandrapur – Padghe: Maximum Transmission Power is 1500 MW and the Operational Voltage is 500 KV. It is a Bipolar Link of length 753 KM in Maharashtra.
7. Sileru-Barsoor: The Transmission length is about 196 KM and the Transmission Power is 400 MW and the Operational Voltage is 200 KV
8. Biswanath Chariyali –Agra: It is a bipolar Transmission Line of length 1825 KM from Assam to Uttar Pradesh. Maximum Transmission Power 6000 MW and the Transmission Voltage is 800 KV.
9. Talcher- Kolar: It is a bipolar Transmission Line of Length 1376 KM connecting Eastern and Southern regions. Maximum Transmission Power is 2000 MW and operational Voltage is 500 KV.

1.2.1 The Comparison of AC and DC transmission system

The choice of transmission system depends upon the economic considerations, technical performance and reliability [1].

❖ Economic Considerations:

- Capital cost of transmission system
- Cost of energy losses and maintenance
- Needs of future expansion and associated cost.
- Economic aspects related with availability.
- Economic strategy for energy transmission

DC transmission system uses less number of conductors for the three phase ac system to deliver the same amount of power moreover the energy losses and corona are also reduced for a dc transmission system. But the HVDC system incorporates converters and transformers cannot be used for changing the dc side voltages. Therefore, HVDC systems must be used for bulk power transfer to longer distances.

❖ Technical Performance

- Control over power transfer, magnitude and rate of change.
- Stability considerations related with power flow and frequency disturbances
- Reactive power compensation and voltage control.

- Behaviour of system during faults.

  HVDC systems have full control over power transmitted. The fast control used in HVDC systems limits fault currents in DC lines. The HVDC systems have the ability to enhance transient and dynamic stability in associated AC networks. The voltage control in AC lines is also complicated as the voltage profile along the line remains flat only when the system is loaded with SIL. Also, the power transfer capabilities of an AC line are constrained by steady state and transient stability. Power flow capabilities decreases with increase in the transmission distance whereas, it remains the same for a HVDC system.

- Reliability
  - Security of power flow
  - Availability of transmission line
  - Energy availability
  - Transient reliability

  As the use of thyristors as converter valves has increased over mercury arc valves both energy availability and transient reliability has become 95% and above. Moreover the failure rate of thyristor valves is 0.6% per operating year. It shows the HVDC systems are more reliable than AC systems

The comparison between AC and DC transmission systems with considerations of economics of transmission, technical performance and reliability of the system the HVDC systems can be used for:

- Long distance bulk power transfer
- Underground and underwater cables i.e. connections between islands
- Asynchronous interconnection between two or more regional grids operating at different frequency and phase.
- Control and stabilization of power flows in AC ties.

1.2.2 Types of HVDC technologies [2-7]

The main requirement in a power transmission system is the precise control of active and reactive power flow to maintain the system voltage stability. This is achieved through an electronic converter and its ability of converting electrical energy from AC to DC or vice versa. Two types of HVDC systems are used in this days namely Conventional HVDC, which is line commutated, and VSC-HVDC, which is self-commutated. Till recently the traditional HVDC thyristor based, was only used for the conversion of AC to DC and DC back to AC. Different from the HVDC conventional, the new type of HVDC is based mostly on IGBTs and has more advantages over conventional HVDC. The converters are VSCs (Voltage Sources Converters) operating at high replacing frequencies. This new type of HVDC is also called either HVDC Light or HVDC Plus.

1.2.2.1 Current Source Converter (CSC)

Conventional HVDC is a Current Source Converter topology (CSC) where the direction of the current in the DC link does not change. In a Current Source Converter, the DC current is kept constant with a small ripple using a large inductor, thus forming a current source on the DC side. The direction of power flow through a CSC is determined by the polarity of the DC voltage while the direction of current flow remains the same. This technology is realized using thyristors that are either line commutated or forced commutated.

- Advantages of conventional HVDC [2-4]: The conventional HVDC system beside the long transmission of bulk electrical at economical cost, it has also other merits that are not easier to get in conventional AC transmission system, such as:
    - There is no skin effect as much there is in AC system, thus the current density in HVDC transmission might be higher.
    - HVDC links do not suffer stability problem in interconnected power system as they can run independently, plus they do not increase the short circuit current in the link point .thus no need of new calibration of circuit breaker in the existing network.
    - HVDC transmission system does not need shunt compensators, as it is the case for AC long distance transmission lines.

- HVDC system uses less number of conductors when compared to an AC system, thus the construction of transmission system is simple. The line losses are less compared to AC transmission systems.
- In HVDC systems there is less corona and therefore less radio interference and there is not charging current, which put the HVDC system cables away from high dielectric losses.
- HVDC has got the ability to change the magnitude and the direction of power flow easily.

❖ Applications of conventional HVDC:

- The main application of HVDC system was the delivery of bulk electrical power from remote power plant, to the load centres. Most of power plants are located several hundred kilometres from the costumers and far enough for the HVAC transmission to be efficient in terms of losses. Besides that, there are other applications in which can HVDC conventional system be found, like in:
- Interconnections of asynchronous electrical power networks by using back to back configurations. HVDC does not contribute to short-circuit current of the interconnected system.
- Increasing of AC transmitting capacity by either upgrading the latter or by over building new HVDC overhead lines onto the normal AC lines.
- Stabilization of network, with the diversified power electronics equipment that HVDC conventional systems have, they can be used to control the power flow.
- To deliver the power into congested load areas. Where new transmission right of way are impossible to obtain.

1.2.2.2 Voltage Source Converters (VSC) [2-4]

For a VSC, the polarity of DC transmission system remains unchanged in the case of reversal of power. Voltage Source Converters operating with the specified vector control strategy can perform independent control of active/reactive power at both ends. This ability of VSC makes it suitable for connection to weak AC networks, i.e. without local voltage sources. For power reversal, the DC voltage polarity remains the same for

VSC based transmission system and the power transfer depends only on the direction of the DC current.

In Conventional HVDC system, was using current source converters which has thyristor as switch. In VSC based HVDC technology, IGBT's are used as switches for converters that is why the commutation of the valves is not done by the line or network. The commutation is initiated by the polarity change of the AC voltage. As technology goes on developing the introduction of new higher rated power semiconductor like Insulated-Gate Bipolar Transistor (IGBT), Gate Turn Off thyristors (GTO) and integrated gate commutated thyristors (IGCT) had made possible the appearance of voltage source converters (VSC). The THD in AC waveforms at both converter ends is decreased by the use of power width modulation (PWM) techniques. The PWM technique gives the possibility to change the magnitude, phase angle and the waveform of the fundamental component. Those changes can be made instantaneously by the variation of PWM pattern.

In contrast to Conventional HVDC, which was introduced in the1950s, VSC-HVDC is a relatively new technology and the first commercial system was implemented on Gotland in 1999 [4][6-7]. Even VSC-HVDC is less mature than Conventional HVDC, the interest in VSC-HVDC is increasing as it offers several benefits including:

- Technological advantages:
    - Flexibility and controllability of the power flow. Real and reactive power is controlled independently. i.e. Possibility to control the reactive power (consumed or generated by the converter) independently of the active power (to or from the converter).
    - Control of AC voltages is very fast compared to conventional HVDC (almost 20 time faster).
    - No need for fast telecommunication between two station.
    - Power reversal is possible very fast.
    - Operates in all four quadrant of its Capability curve, can be used as STATCOM.
    - Use of PWM minimises harmonics and minimises reactive power demand. Its also makes the response faster.
    - Low complexity-fewer components.
    - It can be used in windmills.

- It is robust with respect to AC network faults, fault-ride through capability.
- Multi terminal configurations.
- Fast response in case of disturbances.
- No risk of commutation failures in the converter.
- Ability to connect to weak AC networks, or even dead networks.

❖ Economical advantages:

- It is economical even in low power range
- No or less filters required
- A standard transformer design can be used without special requirements to withstand DC voltage or harmonic currents.
- The converter does not produce any significant high frequency noise, so outdoor installation of AC- and DC reactors (if necessary) and switchgear is feasible.
- The modular rack-type converter arrangement provides flexibility with respect to building height versus -length. It allows to lower building height compared to conventional HVDC converters
- The converter modules are operated with a low replacing frequency resulting in low converter losses.
- Minimal environmental impact.

1.2.3 COMPONENTS OF HVDC SYSTEM

A HVDC system has various components that work together to sufficiently transfer the desired amount of power under certain conditions. An HVDC system can be seen in Figure:

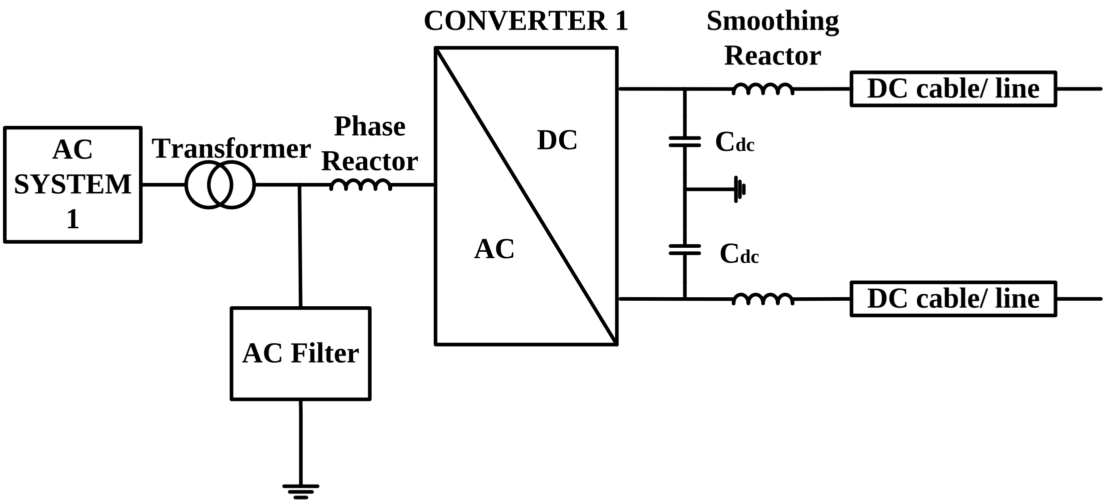


Fig. 1.2: Components of a HVDC system [2-3]

The AC voltage level from the bus bar is transformed and filtered using transformer and AC filters and is converted into dc and passed through smoothing reactors to remove current ripple from the dc current. At inverter end, reverse process is done at the receiving end and DC is brought back into AC.

1.2.3.1 AC System

An AC system in a HVDC system is a combination of a generator station providing power at rated voltage level, electrical loads. The generator station full fills both active and reactive power demand generated by the loads and the converters or any other electrical machine.

1.2.3.2 Harmonic Filters

Harmonics are generated by the no-linear loads that draw a non-linear sinusoidal current from AC sources. HVDC system constitutes of converters which behaves as nonlinear loads so the harmonic current is drawn from the AC system which is not advisable. Harmonics has very adverse effect on electrical machinery, sometimes they lead to overheating of the machine and electrical motor produces fluctuating torque due to harmonics. That’s why it is necessary to limit harmonic content in current and voltage.

Harmonics are limited or minimized use various methods:

- Increasing the pulse number of the converters i.e. by using multilevel converters.
- Use of Active and passive filters.

Since increasing the pulse number of converters makes the control complex it is not advisable to use more than 12 pulse converter. So, we are left with the option of harmonic filters. It’s not economical to use active filters to full fill the whole demand of reactive power as active power filters use controller and power electronic switches which increases the cost of installation. So, passive filters made from combination of R, L and C elements are installed in the HVDC system. There are majorly three types of filters used in HVDC system:

- AC Filters: The AC side quantities of the converter consist of harmonics which are injected by the converter in the system. these harmonics are removed from current and voltage by using AC tuned filters and High pass filter. Ac tuned filters are the combination of R,L and C elements tuned for a particular harmonic frequency such as 5th or 7th harmonic. For high order harmonics such as 23rd and above that a single high pass filters is used.
- DC Filters: The DC side of the converters also has ripple in current and voltage. To remove these ripples and make DC side quantities smooth DC side filters are used. DC filters are same as AC filters. DC filters are tuned to certain DC harmonics frequencies. These are connected between the DC link and ground in shunt so that the tuned DC harmonic frequency elements do not pass through the DC line and diverted to ground.
- High frequency (RF/PLC) filters: these are connected between the converter transformer and the AC system as to minimize any high frequency current.

1.2.3.3 Converter Transformers

A converter transformer is connected between the AC system and the converter. Converter transformer transforms the AC system voltage to the desired voltage at the AC end of the converters. The converter transformer is different from a conventional transformer as it had to deal with the harmonic current injected by the converter valves, DC voltage appearing at the valves and commutating short circuit pulse.

The design of converter transformer winding depends upon the type of converter used in HVDC system:

- For a 6 pulse CSC converter either a star-star or star-delta configuration is used.
- For 12 pulse CSC converter we have to use either 2 converter transformers in which one is star-star and the other one is star-delta or we can use a three winding transformer with primary in star, secondary in star and tertiary in delta. This configuration of transformer winding for a CSC based 12 pulse converter is to proved 12 phase with 30 phase difference in each one.
- For VSC based system the designing depend upon the level of converter.

Some special Design features of Converter transformer:

- The transformer can sustain high amount of harmonic content.
- Converter side windings of the transformer are subjected to DC voltages and therefore both AC and DC voltages are present on the transformer windings.
- Converter transformers have high short circuit strength.
- In comparison with a power transformer converter transformers can deal with higher stresses.

1.2.3.4 Smoothing Reactors

Smoothing reactor is a series inductor connected on the DC side of the converter. An inductor does not allow current flowing trough it to change suddenly. The major functions of a smoothing reactor are:

- Smoothing reactors reduce the incidence of commutation failure in inverter caused by dips in the AC voltage at the converter bus.
- They prevent consequent commutation failures in inverter by reducing the rate of rise of DC current, smooth the ripples, decrease harmonic voltage and current, limit the crest current in rectifier etc.
- They prevent intermittent current, limit the DC fault currents and prevent resonance in the DC circuits.

1.2.3.5 Converters

Converters are most important and major component of a HVDC system. Converters can be used as rectifier for conversion of AC to DC and can also be used as inverter for conversion of DC to AC. These converters are designed using power electronic switches in such a fashion that they can be used for bi directional power flow. Both converter station work irrespective of each other i.e. both converter can have different AC side voltages, frequency or current. Now a day’s, we are using thyristors as switches in CSC based HVDC converters and IGBT’s for VSC based HVDC system. The use of power electronic switches allows us for rapid and reliable control of the HVDC system. According to the commutation process used for the switches in the converter, they can be categorised into two categories:

Types of CSC based converters based on their commutation technique:

- Line Commutated Converters (LCC):

  These are the most widely used converter technology in HVDC systems. This sort of converter uses thyristor as switches. Thyristors has high current carrying capabilities as well as they have the ability to block high voltages. Series and parallel connections of thyristors can be used to increase the overall current and voltage rating and the whole system of series parallel connected thyristors is known as thyristor valve. Thyristors are the controlled switches which could be turned on and off as per the system requirement. When a thyristor is turned off, the path of current flow changes and this is called as commutation of the thyristor. In LCC converters, the reverse voltage applied by the alternating line voltages makes it possible for thyristors to commutate. Since the thyristor are commutated automatically without any external commutation circuit this type of converter configuration is also known as natural commutated converters. Thyristor valves are controlled by changing the firing angle and LCC converters are made to operate at constant rated frequency (50or 60 Hz) to convert desired power quickly and efficiently. Besides the high power rating of line commutated converters, the configuration is still vulnerable to various problems associated with commutation failure when connected to weak networks. So a new configuration of the Capacitor Commutated Converters, which use the commutation capacitors can be used. By this method the weakness of line commutated converter are reduced even in presence of weak networks.

- Forced Commutated Converters:

  This type of converter either uses the voltage controlled switches such as IGBT's or GTO's or the uses an external commutation circuit. Forced commutated converters are further classified in two categories one is circuit commuted converter and the other one is self commutated converters.

  - Circuit Commutated Converters: Sometimes, the ac line voltage is insufficient, distorted or the requirement for the early commutation before the natural commutation instant leads us to use and external commutation circuit which uses a capacitor known as commutation capacitor. The ac line voltage, DC line voltage or an auxiliary voltage can be use to charge the commutation capacitor and this capacitor holds this voltage temporarily until it is required to commutate a certain valve. Various commutation circuits used are:
    - Series capacitor circuits
    - Parallel capacitor circuits
    - Dc line side commutated circuits
  - Self Commutated Converters: They uses semiconductor switches which not only have the ability to control the turn processes but also have the ability to control the turn off process and this is the major difference these converters has from the LCC converters. Insulated gate bipolar transistor (IGBT's) or Gate turn-off thyristor (GTO) are the power electronic switches which are mostly used in this sort of converters. They are also known as Voltage Source Converters (VSC). As the power electronic switches used in this configuration can be operated at high frequencies Pulse Width Modulation (PWM) is used to turn on and off these switches. PWM provides VSC converters the ability to control the variation of phase angle and amplitude within a certain range and hence control active and reactive power of an individual converter independent of other converter parameters. Since they have high commutation frequency, the ability to control active and reactive

power independently and efficiently they can be used to support a very weak AC system.

There are various configuration used for designing of 3 phase HVDC Converters. Most of the VSC based HVDC converters are classified on basis of levels:

- Two levels converters:

  The two levels VSC based converters are designed from two levels half-bridge circuits which has six valves, as it can be seen on Fig.. Each valve uses an IGBT and an anti-parallel diode. Since the converter provides Two voltage level +/- Vdc/2 on the DC side of the converter that’s why this converter configuration is called two level. Two half bridge VSC may be connected in parallel on their DC side to make a two level full bridge, called also H-bridge converter. The advantage in doing that is the AC voltage is now twice of the half bridge AC voltage. For two levels converters replacing, various Pulse Width Modulation (PWM) are used.

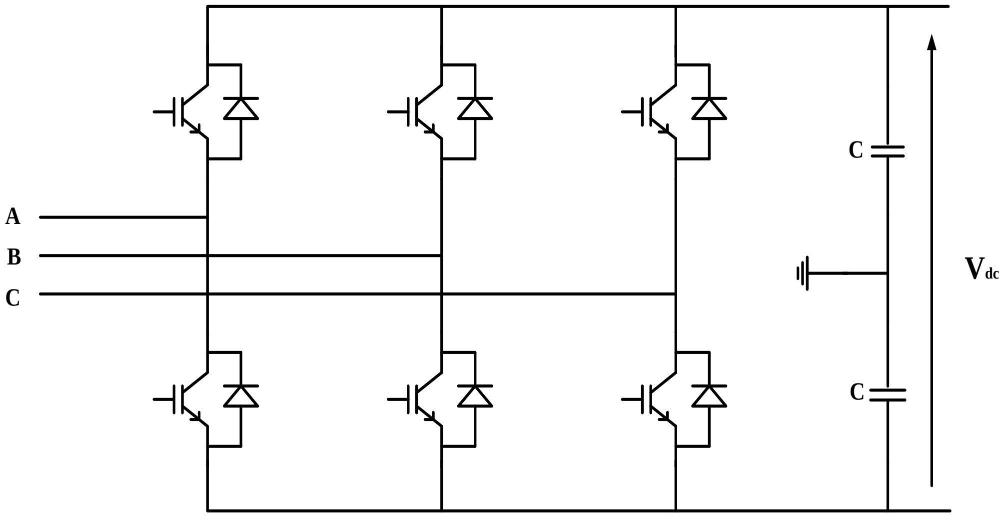


Fig. 1.3: Two level three phase VSC converter

- Three level converters:

  This configuration of VSC based HVDC converters are designed using 2 two level converters. It uses 12 IGBT switches with anti parallel diodes. Since it provides 3 voltage levels (+Vdc,0,-Vdc) on the DC side of converter that’s why this configuration is known as three level VSC. As it has three levels, when we use PWM techniques on these converters the reactive power demand as well as the THD of AC side Voltages and current reduces and is comparatively lower than the two level VSC based converters. As the no of switches increased in this configuration the control of these converters is complex in comparison with the two level converters.

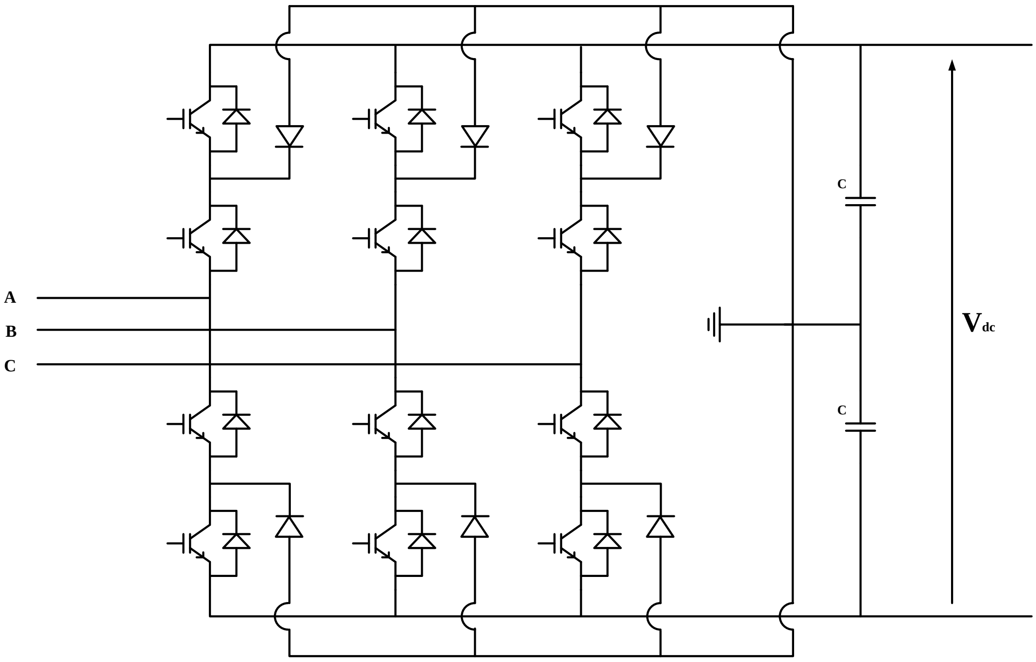


Fig. 1.4: Three level three phase VSC converter

- Multilevel converters:

This sort of configuration of vsc based HVDC converters is designed by using a high number of switches in series and parallel combination. The number of level defined for these converters is the number of steps the AC side voltages or currents waveform consists. It requires a number of series of power semiconductor switches with various voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Thus a number of different voltage levels at the AC side are possible to get. Multilevel converters have got improved performance than two level converters and they are as well very complex and onerous than the two level converters Figure.2.7 represents the schematic diagram of multilevel VSC. There are three configurations of multilevel VSC:

- ➢ H-bridge-based multilevel VSC
- ➢ Diode-clamped multilevel VSC.
- ➢ capacitor-clamped multilevel VSC

With increase in the number of level the associated DC power supplies and also the number of switches increases and with increase in the number of switches the control of such converters become complex.

1.2.4 HVDC SYSTEM CONFIGURATIONS [2-3][6-7]

The configuration of a HVDC system can be identified on the basis of pole and earth return. Pole refers to the conductor having a constant voltage with reference to the earth return and the DC current flows through it.

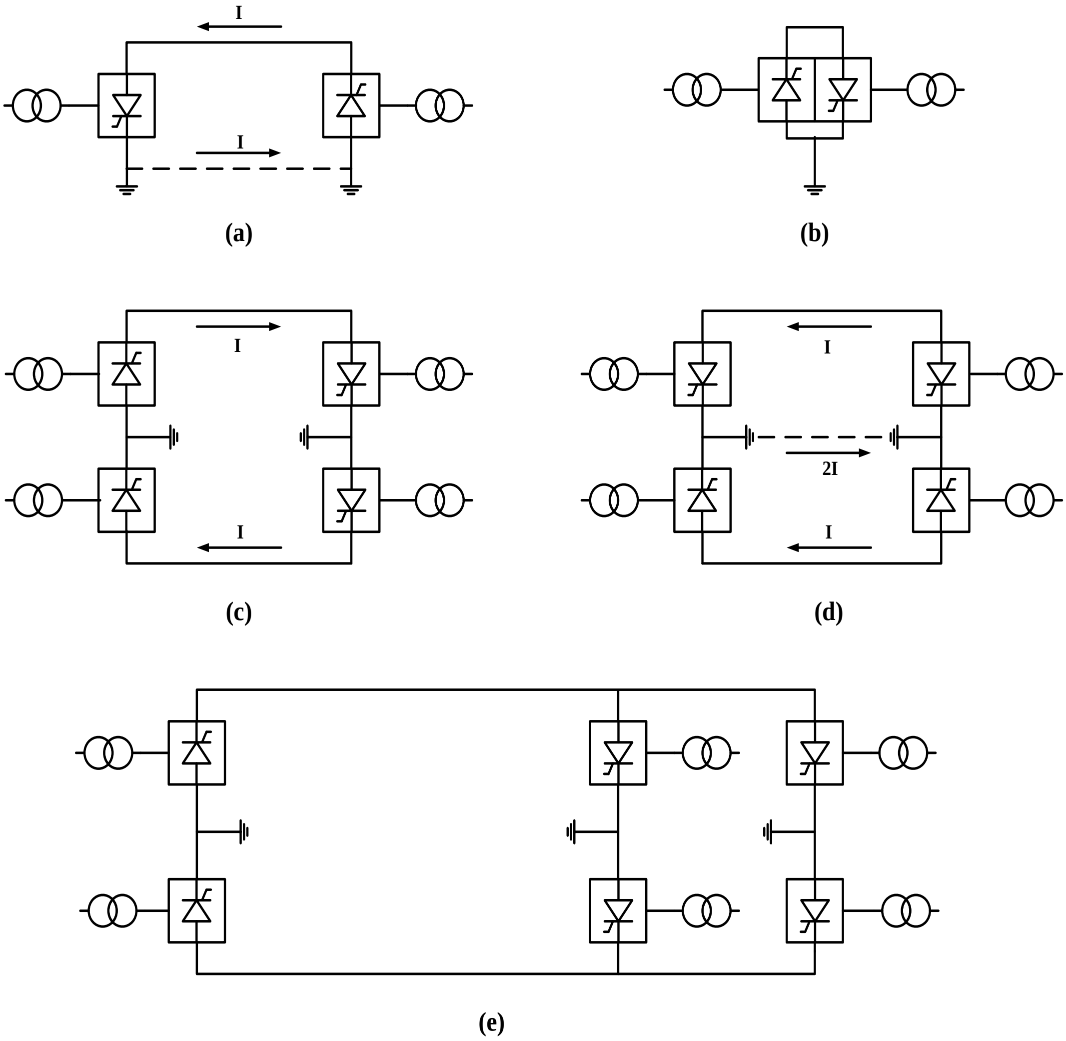


Fig. 1.5: Different types of HVDC configuration (a) Monopolar (b) Back-to-Back(c) Bipolar (d) Homopolar (c) Multiterminal

There are various configurations for HVDC system are as follows:

1.2.4.1 Monopolar HVDC system

This configuration of HVDC system consists of one pole and other terminal is ground on both rectifier and inverter side. The pole is usually charged from negative voltage with the ground as to minimize the corona effect. The pole conductor transmits DC current and the ground works as a return. The ground electrodes are designed for continuous full rated current capacity and also for a slight overload capability for a specific condition. Monopolar HVDC system has low power rating and they can later be converted into bipolar for increased power rating by adding an extra pole to the system.

1.2.4.2 Bipolar HVDC system

This configuration of HVDC system consists of two poles and one terminal is ground on both rectifier and inverter side. In bipolar HVDC system, one pole is charged from positive voltage and other from negative voltage with the ground that is why the rating of these systems is depicted as +/- Vdc. The positive pole conductor transmits DC current from rectifier to inverter and the negative pole conductor returns the dc current from inverter to rectifier. This configuration has a small ground current which flows due to out of balance of the ground terminals of two converters. Bipolar HVDC system has twice the power transfer capability as of Monopolar HVDC system. Because of the advantages of operating the HVDC system without any ground current makes the bipolar HVDC system most desirable of the all configuration.

1.2.4.3 Homopolar HVDC system

This configuration of HVDC system consists of two poles and one terminal is ground on both rectifier and inverter side. In homopolar HVDC system, both the poles are charged from same polarity which is usually negative as to reduce the insulation level as well as corona effect in conductor. Both pole conductors transmits DC current from inverter to rectifier and the ground terminals has twice the pole conductor current which returns from rectifier to inverter.

1.2.4.4 Back-to-Back HVDC system

This configuration of HVDC system is used for interconnection of two AC systems which have different frequency or phase. Back to back HVDC system provides isolation between two AC systems and moreover this type of system can also transfer power from one AC system to another AC system if required. The DC line or cable length in such configuration is zero. The rectifier and inverter both are placed in a single housing unit.

1.2.4.5 Multiterminal HVDC system

A multiterminal HVDC system consists of more than 2 AC systems. These AC systems are interconnected through a single DC link. This configuration is similar to Bipolar HVDC system as it also has 2 poles at each converter station and out of the two poles one is positively charged and other is negatively charged. The only difference they have is that multiterminal HVDC system has more than 2 converter station in connection to DC link. These systems are used mainly when one of the AC systems has large amount of power which is supplied to the rest of the AC system. Power in such HVDC systems can be transferred quickly and efficiently and moreover it prevent from the problem of power blackout.

1.3 LITERATURE REVIEW

In the beginning of industrialized era, the advancement in electrical components increased the use of electrical energy over the steam energy that was serving for long period. The electricity available or generated at the moment was direct current. At first a DC generator was used, so the first electrical power transmission system was based on DC at that moment. The use of alternating current finally surpassed DC due to two major reasons:

- The introduction of induction motors,
- The availability of transformer with its easier ability of changing voltage level i.e. stepping up or down the voltage according to generation, transmission or distribution levels.

Hence, the AC became useful commercially and domestically [1-4][6][7].

As it was recognized early in the 1920's that there was advantages in the use of DC transmission in more challenging applications, the idea of transmitting electrical power in DC emerged again, but stacked due to the lack of necessary technologies in AC/DC vice versa conversion. The problem was resolved by the invention of high voltage mercury rectifier valves and especially by the introduction of thyristors valve into HVDC applications, around 1970 [5-8]].

Various topologies were introduced for the HVDC systems. The overview of HVDC system, various topologies, configurations of HVDC system, the effectiveness of HVDC system, various components of HVDC system are explained by various authors such as M. P. Bahrman, V. Sood, Nikolas Flourentzou, Vassilios G. Agelidis, Georgios D. Demetriades. K. R. Padiyar, Nagesh Prabhu, Vladimir Blasko and Vikram Kaura explained the modelling of VSC based HVDC systems [9-15].

The dq theory for the control of VSC based hvdc system is the most popular. It was first proposed by Robert H. park in 1929. The conversion of three phase quantities to DC quantities helped in the use of PI controller for HVDC system. Ana-Irina Stan, Daniel-Ioan Stroe and Rodrigo da Silva used a mathematical approach for the disen of the controllers in [16]. Many other researchers such as K.R. padiayar, N. Prabhu, C. Du, M. H. J. Bollen, E. Agneholm, and A. Sannino used dq theory to design controller such as DC link controller, Active power controller, Reactive power controllers to implement them on VSC based HVDC system[17-18][21-29][41]. These controllers are used for the purpose their name suggests. Also, space vector control was approached for VSC HVDC systems by T. Nakajima, M. Saeedifard, H.Nikkahajoei in [19-20].

Later, Fuzzy logic controllers were designed for the control of HVDC systems []. Various designs and implementation of these controllers in HVDC system is done by Akshaya Moharana, Jagath Samarabandu, Rajiv K. Varma, Chamorro H. R, N.L. Diaz, J.J Soriano, H.E Espitia [30-35]. Also, some new hybrid controllers [21][36] which were made with the help of PI controllers and Fuzzy controllers were proposed by GengYuancheng, Li Zhixiong, Zhang Jiangcheng. The Implementation of Fuzzy Adaptive PI Controller in VSC-HVDC Systems by Haifeng Liang, Gengyin Li, Ming Zhou, Chengyong Zhao explains the fuzzy PI parameter self-adapting module combined with the PI control is designed to weaken the influence of system fluctuations on control effectiveness [33]. The PI parameter will be self-adjusting in response to different running conditions when the system is running.

With growth in the power generation from renewable sources the need for delivering that power to the load centres has lead us to use various control strategies. VSC based HVDC proves to be very efficient for such situations and the control algorithms for such VSC bade HVDC systems were explained and implemented by N. M. Kirby, Lie Xu, M. Luckett, W. Siepmann, P. Breseti, W. L. Kling, L. Ran, D. Xiang in [37-40].

Faults analysis for a VSC based system is an important aspect to study. C. Du, M. H. J. Bollen studied various faults on HVDC system in [47]. Lie Xu, B. R. Andersen and P. Cartwright showed the performance of VSC based HVDC systems under unbalanced AC conditions in [43]. Some other researchers A. K. Khaimar, P. J. shah, Weixing Lu also presented the performance of VSC based HVDC system under faults [42][44-46].

Georgious Stamatiou and Massimo Bongiorno suggested power-dependent droop based control stratergy for multi-terminal HVDC transmission systems. Some active power control stratergies were also proposed by Javier Renedo, Aurelio Garalia for Multi-terminal VSC based HVDC systems.

1.4 MOTIVATION OF THE THESIS

- VSC based HVDC becomes superior choice over CSC based HVDC systems. This has motivated to develop a two level VSC based HVDC system and providing a closed loop control system for the same.
- The closed loop control for VSC based HVDC system can be designed with the help of dq theory. It provides the reference dq currents and these currents are further used for generating reference three phase voltages which are compared with a high frequency triangle wave to provide PWM gate pulses.
- This is followed by three level VSC based system and the performance of the same with closed loop control with different cases and strategies is analyzed.
- The next problem is to investigate the effect of different faults on such system and remedy for controlling the system in such cases in different fault locations and situations.

- Multi-terminal VSC based HVDC is efficient for Bulk power transfer to various loads centres and its advantage over AC systems motivates for designing os such system and propose a control scheme for the same.

1.5 OBJECTIVE OF THE THESIS

- To design two level and three level VSC based HVDC systems and develop control algorithms for these systems.
- Using dq theory generate the reference currents and later reference voltages.
- Designing and implementation of various controllers such as DC link Controllers, Active power controller and reactive power controller which provides fast and accurate responses.
- With the help of these controllers form a stable and rigid HVDC system which performs as desired.
- Simulate both two level and three level VSC based HVDC system in MATLAB/SIMULINK and analyse their performance and compare.
- Subject the VSC based HVDC system to various faults such as single line to ground fault and three phase to ground fault at both the converters of the HVDC system for 5 cycles of AC signal and analyse the system response.
- Propose changes in the control for multi-terminal three level VSC based HVDC systems and investigate its performance.

1.6 OUTLINE OF THE THESIS

The chapters included in this thesis are organised as follows-

- CHAPTER 1 presents the basic introduction and gives an overview of the HVDC systems and also explains the problems associated with AC system. Various types or topologies, components of HVDC systems, configuration of HVDC sytems and the comaprision between VSC and CSC based HVDC system are also expined in this chapter. literature review is also presented in this chapter.
- CHAPTER 2 presents introduction to two level VSC based HVDC system and its power transfer characteristics. It also discuss about various PWM techniques used for VSC systems. Later in this chapter synchronous reference dq theory

control algorithm for VSC based system was proposed and simulated on MATLAB and performance of various parameters is studied.

- CHAPTER 3 comprises of introduction to three level VSC based HVDC system and its dynamic modelling. It also discusses about three level VSC converter and PWM gating pulse generation for the same. Later in this chapter synchronous reference dq theory control algorithm for three level VSC based system was proposed and simulated on MATLAB and performance of various parameters is studied. Also the simulation results of two level and three level VSC based HVDC system are compared in this chapter.

- CHAPTER 4 presents analysis of three level VSC based HVDC systems under single line to ground fault and three phase fault either the rectifier or inverter. In this chapter the PQ characteristics of three level VSC based HVDC systems are also discussed.

- CHAPTER 5 presents some investigations on VSC based HVDC systems. In this chapter multi-terminal VSC based HVDC systems are discussed and control for the same is discussed. Also the dynamic performance of such systems is studied.

- CHAPTER 6 gives the future scope of work.

CHAPTER-2 : TWO LEVEL VSC BASED HVDC SYSTEM

2.1 INTRODUCTION

With the recent development in the field of power electronic switches in the past decades, there has been an increased interest of manufacturers and researchers towards the designing and development of HVDC systems using Self commutating switches such as Insulated Gate Bipolar Transistor (IGBT) and Gate turn off thyristors (GTO). Thereby, a more versatile, rapid, flexible and reliable VSC based HVDC system has been developed. The CSC based HVDC system requires AC line voltages for the commutation of thysistor based converter valves. The VSC based HVDC concept explains transmitting a high voltage direct current from one VSC converter to another VSC converter. These VSC converters use self commutating switches such as (IGBTs). VSC based HVDC systems allows the flow of active power in either direction at both the converter poles. Additionally there is control over the reactive power at both VSC converters independent of each other. The VSC based HVDC system with all its major components is shown in Fig. 2.1.

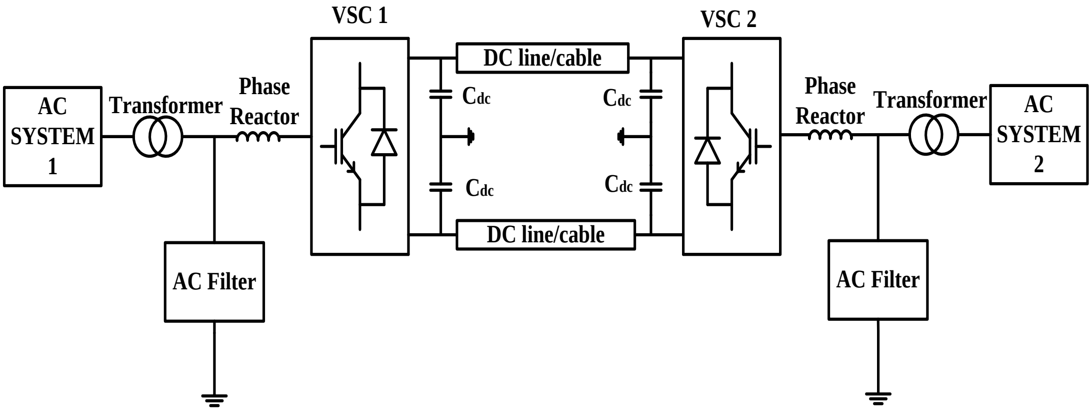


Fig. 2.1: Basic VSC based HVDC system

The VSC converters are connected to an AC system through three phase transformers and phase reactor connected in each phase. These VSC converters are connected to each other through DC lines or cables. As per today, Bipolar HVDC system is widely used. Active power flows from one VSC converter to another converter using the DC lines or cables as shown in Fig. 2.1.

Self commutation of VSC based HVDC is only offered with the use of PWM (Pulse width modulation) technology developed by ABB and is also known as HVDC light []. HVDC light provides high controllability over power and also the reactive power control at each station is maintained independent of active power through that station. This is only feasible through the use of PWM technology. The high frequency switching of VSC based HVDC converter also leads to higher switching losses in comparison with the CSC based HVDC system.

This Chapter explains about the power transfer capabilities of a VSC based HVDC. In this chapter, the modelling and simulation of a 2-level VSC based system using MATLAB/SIMULINK is carried out and the performance of various parameters of the VSC based HVDC system are analyzed. Also, the control algorithm for the 2 level VSC based system is designed and explained. This chapter also includes various PWM techniques used in VSC based HVDC system.

2.2 POWER TRANSFER CHARACTERISTICS

The basic configuration of a VSC based HVDC system has two VSC converters and these VSC converters are connected to AC systems consisting of phase reactor, converter transformers and a three phase AC grid or generation unit. The VSC based converters does not allow the change the change in voltage on the DC side of the VSC converters. Hence, the direction of power flow is monitored by the direction of the DC current. The converter transformers have leakage reactance which is denoted by X_L and the fundamental voltage V_B at the converter is directly proportional to the DC voltage V_{dc} as shown in Fig. 2.2. The two VSC converters are connected to each other through a DC cable or line in which the DC current flows. The DC line or cable is represented using resistance R_{dc} and inductance L_{dc}.

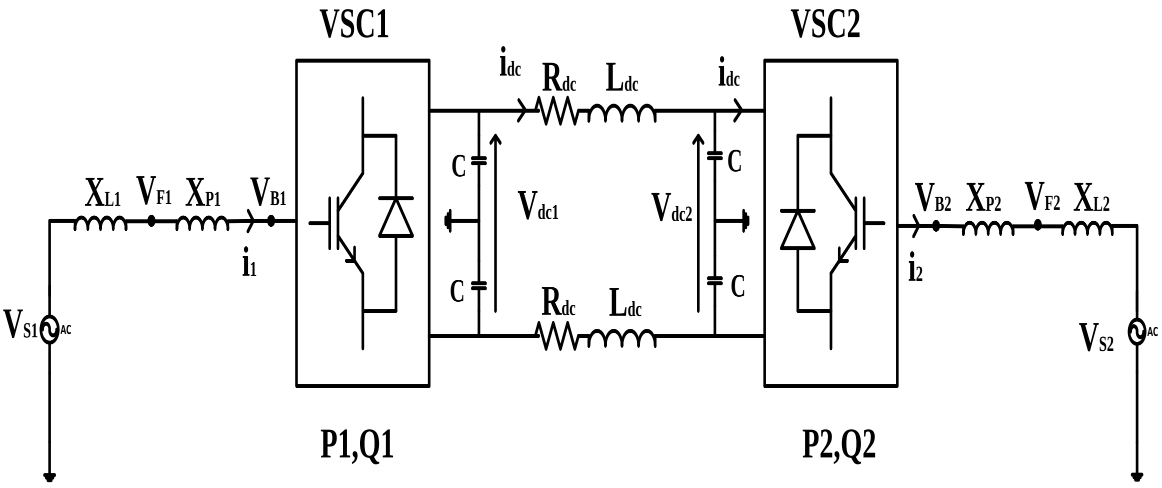


Fig. 2.2: Equivalent circuit for VSC based HVDC system

In the Fig. 2.2

- X_{L1} and X_{L2} represent the converter transformers leakage reactance when they are considered as ideal for VSC1 and VSC2 respectively.
- X_{P1} and X_{P2} represent the reactance of phase reactors for VSC1 and VSC2 respectively.
- V_{S1} and V_{S2} are the AC source phase to ground voltages of AC system 1 and AC system 2 respectively.
- V_{F1} and V_{F2} are the phase to ground voltages at the point of common coupling for VSC1 and VSC2 respectively.
- V_{B1} and V_{B2} are the phase to ground voltages at the valves of the VSC converters for VSC1 and VSC2 respectively.
- V_{dc1} and V_{dc2} are the DC side voltages between the 2 poles of the VSC converters for VSC1 and VSC2 respectively.
- I_{dc} is the DC current which flows through the DC line or cable.

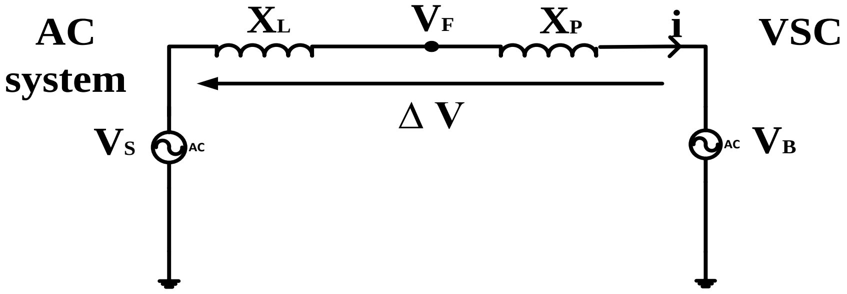
The fundamental voltage V_B at the converter is directly proportional to the DC link voltage V_{dc}. The relationship between the DC link voltages and fundamental voltage at the AC side of the bridge for both VSC is shown in equation (2.1) & (2.2) respectively.

$$V_{B1} = K_1 V_{dc1} \tag{2.1}$$

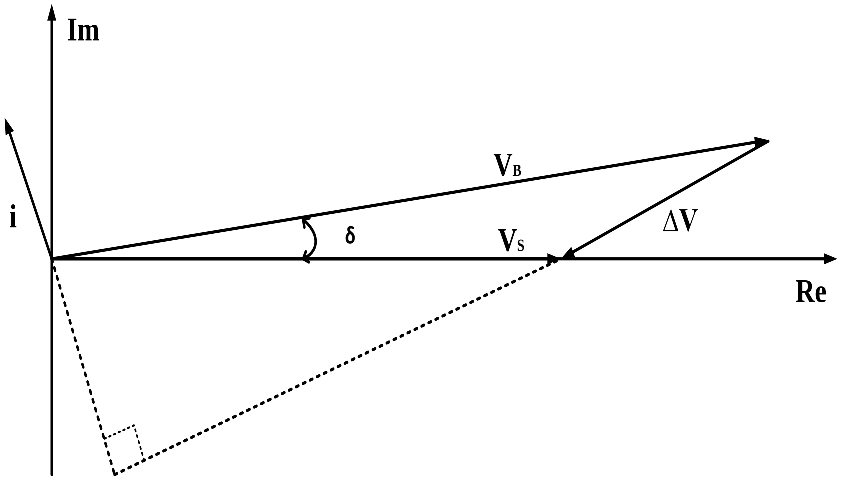
$$V_{B2} = K_2 V_{dc2} \tag{2.2}$$

where K_1 and K_2 are the proportionality constants for VSC1 and VSC2 respectively. These constants depends on various factors such as modulation index, pulse width modulated gate pulses used for controlling the VSC system.

For determining the magnitude of active and reactive power an equivalent diagram of the AC side of the VSC converter can be drawn in reference with Fig. 2.2. Also, a phasor diagram can be drawn using the equivalent diagram of AC side of the VSC converter. While drawing the phasor diagram it is assumed that the active power and reactive power is flowing from VSC converter to AC system. That's why, the magnitude of V_B is higher than that of V_S and also V_B is leading V_S by an angle δ. The equivalent and the phasor of the equivalent for the AC side of the VSC converter is shown in Fig. 2.3 (a) and Fig. 2.3 (b).



(a)



(b)

Fig. 2.3: (a) AC equivalent for VSC based HVDC system & (b) its phasor diagram

From the Fig.2.3 the magnitude of active power and reactive power for certain points in VSC based HVDC system is found out as follows in equation (2.3),(2.4)and (2.5) by assuming the transformer and phase reactors as ideal (i.e. assuming resistance is 0).

$$P_{AC} = \frac{V_S V_B}{X_L + X_P} \sin(\delta) \tag{2.3}$$

$$Q_{SF} = \frac{V_S \left(V_S - V_F \cos\left(\delta^{'}\right)\right)}{X_L} \tag{2.4}$$

$$Q_{SB} = \frac{V_S \left(V_S - V_B \cos(\delta)\right)}{X_L + X_P} \tag{2.5}$$

Where From equation (2.3), (2.4) and (2.5) the PQ characteristics for a VSC based system can be drawn as unit circle where negative active power shows that it is working in inversion mode and are shown in Fig.2.4.

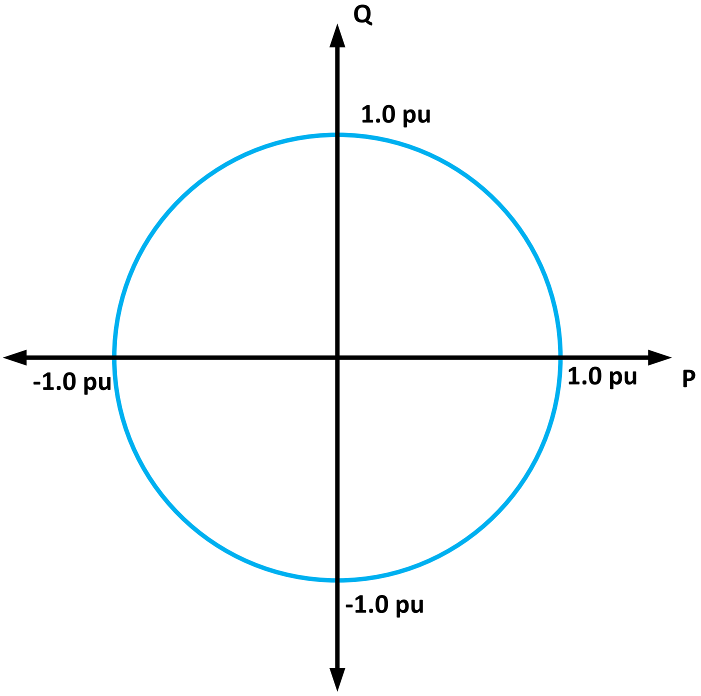
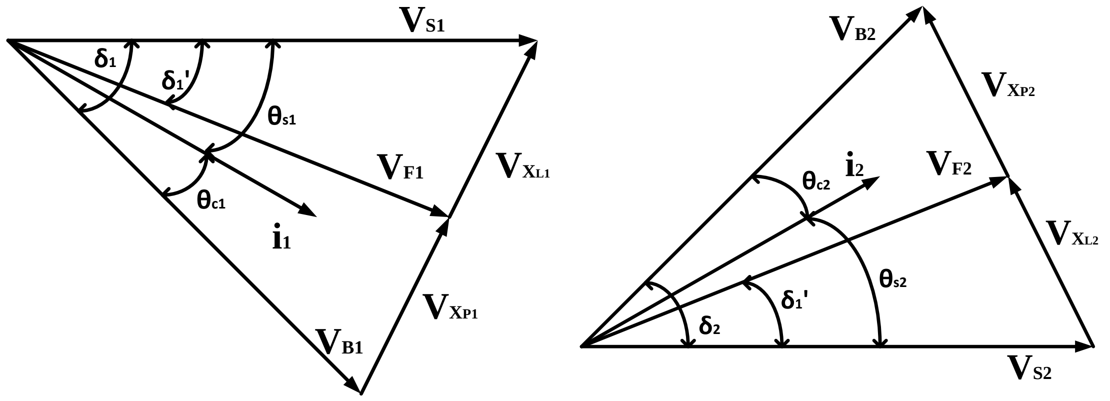


Fig. 2.4: Ideal PQ characteristics for VSC based HVDC system

Furthermore, the phasor diagrams for both the VSC converters can be drawn with reference to Fig.2.2. While drawing these phasor diagrams VSC1 is assumed to be working in rectification mode and VSC2 is assumed to working in inversion mode.

Phasor diagram for VSC1 is in Fig.2.5 (a) and Phasor diagram for VSC2 is in Fig.2.5.(b)



(a) (b)

Fig. 2.5: Phasor diagram for (a) VSC1& (b) VSC2

- From the Fig.2.5 (a) following equations can be stated and the active and reactive power at various points of VSC1 are:

$$\overrightarrow{V_{S1}} = \overrightarrow{V_{B1}} + \overrightarrow{\Delta V_1} = \overrightarrow{V_{F1}} + \overrightarrow{V_{X_{L1}}} \tag{2.6}$$

$$\overrightarrow{\Delta V_1} = \overrightarrow{V_{X_{L1}}} + \overrightarrow{V_{X_{P1}}} \tag{2.7}$$

$$\overrightarrow{V_{F1}} = \overrightarrow{V_{B1}} + \overrightarrow{V_{X_{P1}}} \tag{2.8}$$

$$P_1 = \frac{V_{S1}V_{B1}}{X_{L1}+X_{P1}}\sin\left(\delta_1\right) = \frac{V_{S1}V_{F1}}{X_{L1}}\sin\left(\delta_1^{'}\right) = \frac{V_{F1}V_{B1}}{X_{P1}}\sin\left(\delta_1-\delta_1^{'}\right) \tag{2.9}$$

$$Q_{SB1} = \frac{V_{S1}\left(V_{S1}-V_{B1}\cos\left(\delta_1\right)\right)}{X_{L1}+X_{P1}} \tag{2.10}$$

$$Q_{SF1} = \frac{V_{S1}\left(V_{S1}-V_{F1}\cos\left(\delta_1^{'}\right)\right)}{X_{L1}} \tag{2.11}$$

- Similarly, from the Fig.2.5 (b) following equations can be stated and the active and reactive power at various points of VSC2 are:

$$\overrightarrow{V_{B2}} = \overrightarrow{V_{S2}} + \overrightarrow{\Delta V_2} = \overrightarrow{V_{F2}} + \overrightarrow{V_{X_{P2}}} \tag{2.12}$$

$$\overrightarrow{\Delta V_2} = \overrightarrow{V_{X_{L2}}} + \overrightarrow{V_{X_{P2}}} \tag{2.13}$$

$$\overrightarrow{V_{F1}} = \overrightarrow{V_{S1}} + \overrightarrow{V_{X_{L1}}} \tag{2.14}$$

$$P_2 = \frac{V_{S2}V_{B2}}{X_{L2}+X_{P2}}\sin\left(\delta_2\right) = \frac{V_{S2}V_{F2}}{X_{L2}}\sin\left(\delta_2^{'}\right) = \frac{V_{F2}V_{B2}}{X_{P2}}\sin\left(\delta_2 - \delta_2^{'}\right) \tag{2.15}$$

$$Q_{SB2} = \frac{V_{S2}\left(V_{S2} - V_{B2}\cos\left(\delta_2\right)\right)}{X_{L2}+X_{P2}} \tag{2.16}$$

$$Q_{SF2} = \frac{V_{S2}\left(V_{S2} - V_{F2}\cos\left(\delta_2^{'}\right)\right)}{X_{L2}} \tag{2.17}$$

From the above equations (2.6) to equation (2.17) it can be concluded that in a VSC based HVDC system, active power at each VSC converter can be easily controlled by changing the angle δ and reactive power can be controlled by changing the magnitude of the voltage (V_B) on AC side of the VSC converter. Also, the reactive power required at each converter is independent of the other converter. By the use of PWM gating signals it is very easy and feasible to control both active power and reactive power at both the VSC converter station effectively and efficiently.

2.3 PWM TECHNOLOGY

Pulse width modulation method is one of various methods which can be used for providing high frequency gate pulses to the VSC converters. PWM allows the converters to reduce harmonics from the ac currents and voltages. With the use of PWM for gate pulses, the low order harmonics are eliminated from the converter AC currents and voltages but harmonics near the frequency of carrier wave and its integer multiple are amplified. There are various PWM techniques which have been developed to achieve an efficient control over the VSC HVDC system [4]. Some of the most popular PWM techniques are:

1. Selective Harmonic Elimination PWM (SHE PWM). Selective Harmonics elimination PWM technique was first introduced by Turnbull in the year 1964. Later, in 1970's it was implemented in the thyristor based inverters by Patel and Hoft. This method was developed for two and three levels inverter harmonic's elimination but through recent developments and faster DSP's this method can now days be used for multilevel inverters. SHE PWM concept is based on the devices

replacing time evaluation and the replacing sequences such that the harmonics of certain order are suppressed from the synthesized output voltage waveform. This method is efficient in eliminating harmonics of specific order or harmonics in a specific band of frequencies.

2. Space vector PWM (SVPWM): The space vector PWM method is actually finding its way in power converters replacing, during the last decade several works were published and it has been seen as the most efficient but on the hand is complex. SVPWM is a digital technique consisting in developing pulses voltages based on space vector theory using Clarke transform as platform. Compared to the other PWM techniques SVPM is getting more attention due to its efficient use of supply voltage and low harmonic distortion in both output voltage and current. But the merits it has got are shaded by the complexity associated to its circuit.

3. Sinusoidal PWM (SPWM): In this technique a sinusoidal (sine wave) signal is compared with a carrier signal. For amplitude of sine higher than carrier signal amplitude the PWM output is 1 else it is 0.The carrier signal is triangular or saw tooth signal having frequency higher than that of sinusoidal signal. The ratio of carrier signal frequency and the sine wave frequency is usually odd integer. The output PWM pulses are fed to the gate of the switches in a VSC converter. It is the most widely used PWM technique. Because of its low replacing loss, simple design circuits and implementation and other advantages when compared with other methods. The frequency of VSC converter voltages and current is same as that of sine signal whereas its magnitude and phase is controlled by the carrier wave. In Fig.2.6, the three phase AC voltages are compared with triangular signal of high frequency and gate pulses for 2 level VSC converters is generated. Also, the output AC phase voltages are shown. This technique is used further in the control scheme.

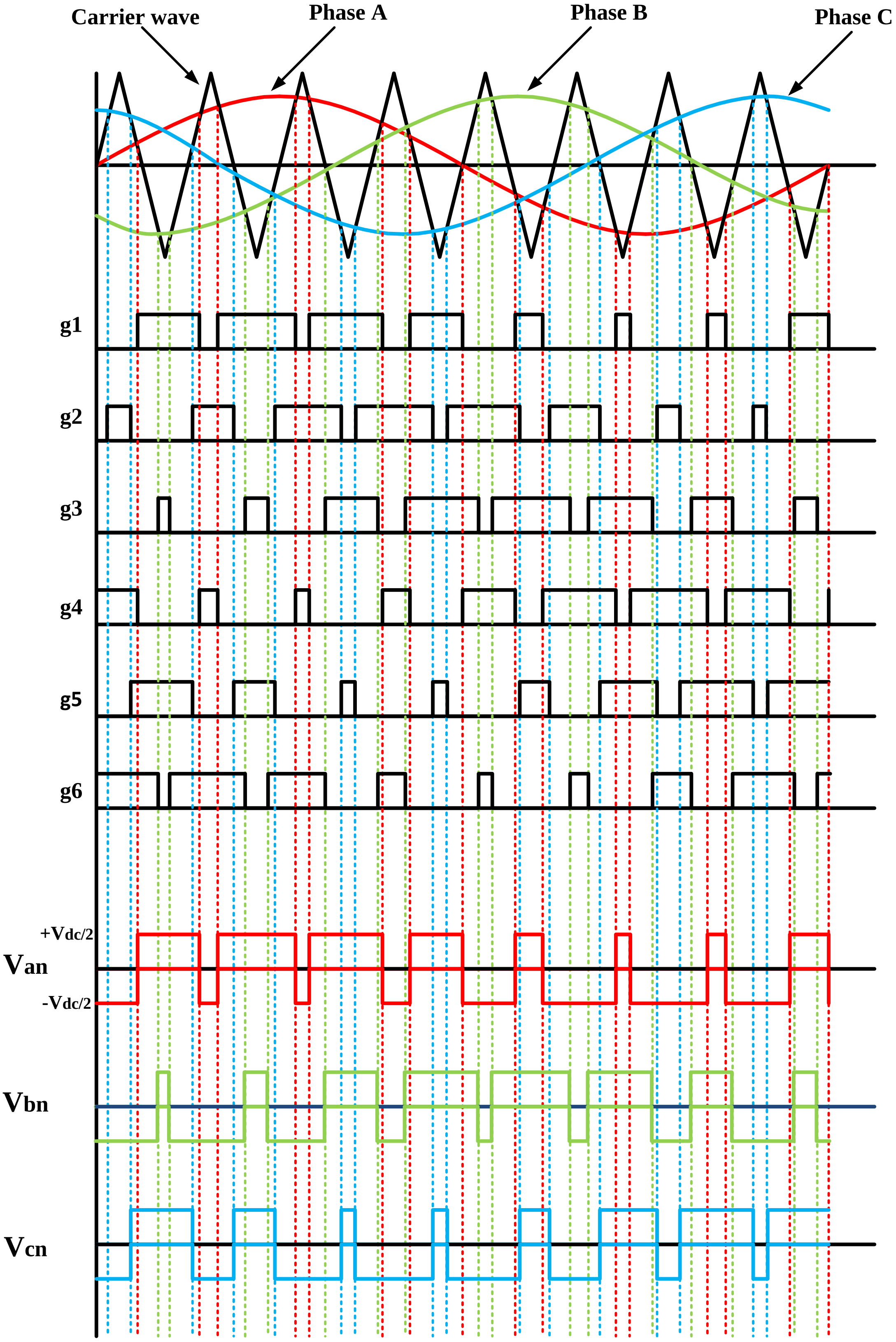


Fig. 2.6: Sinusoidal Pulse Width Modulation showing phase voltages of a two level system

2.4 CONTROL ALGORITHM

VSC based HVDC systems offers several advantages over the conventional HVDC due to its better control abilities such as the independent control of both active and reactive power by using self commutating switches and PWM technology. There are several methods used in the control system for a VSC based HVDC system. The overall control structure for a VSC based HVDC system is shown in Fig.2.7.

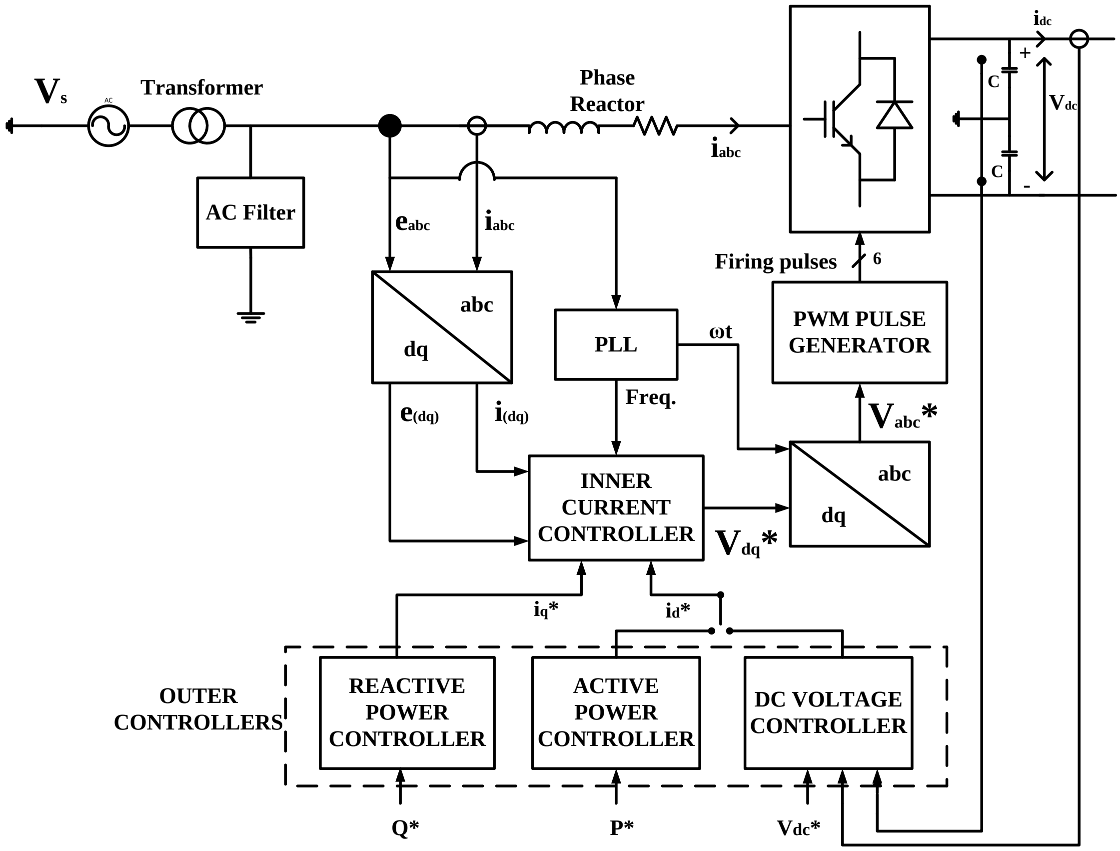
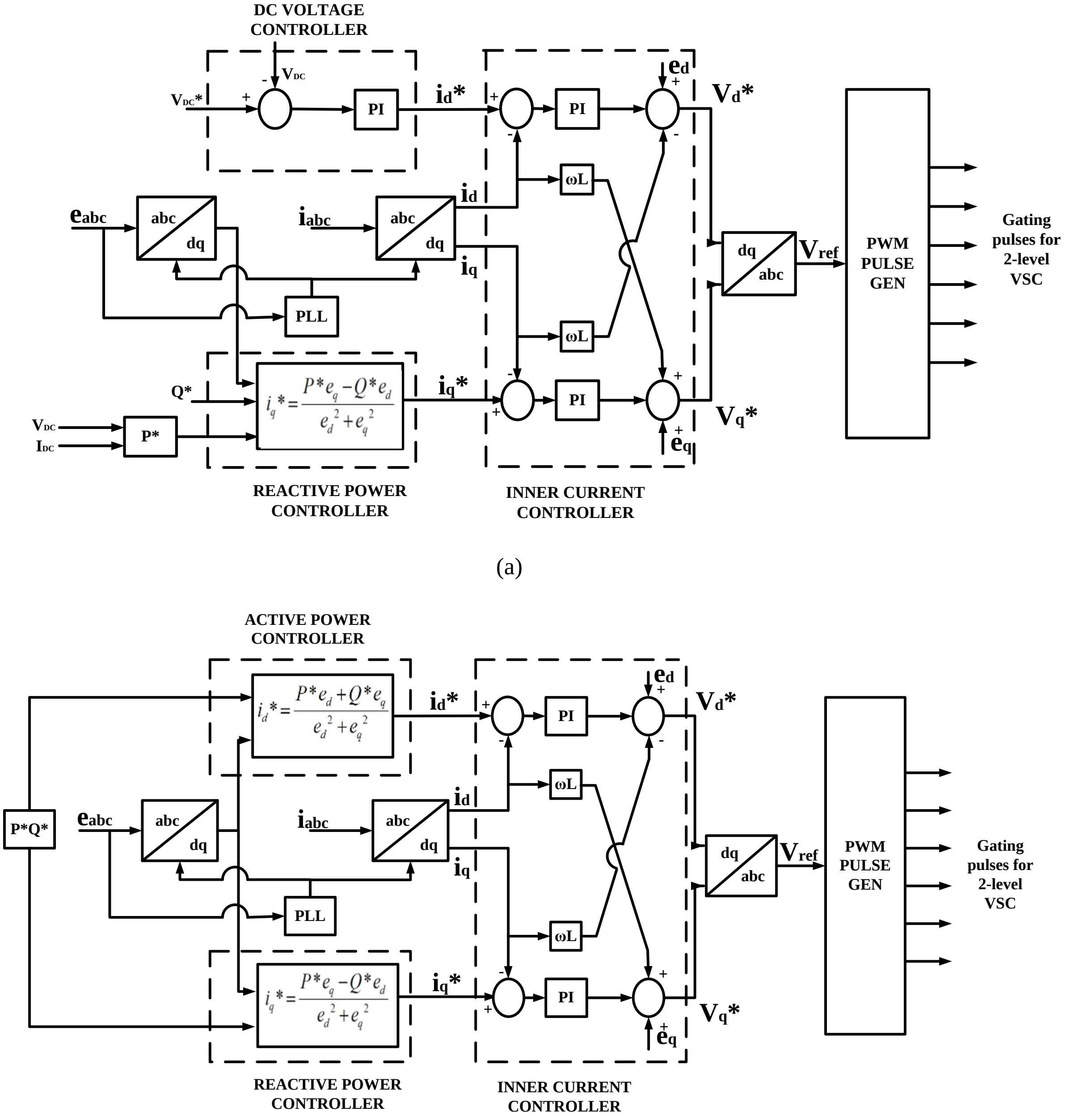


Fig. 2.7: Overall control structure of a VSC based HVDC system

The system can be controlled by changing the VSC AC voltage phase angle which will have direct effect on active power flow, while the change in its magnitude will have effect on reactive power. The synchronous reference dq theory is used for design of control algorithm. The voltages and currents converted from abc frame of reference to th dq frame as shown in Fig. 2.7. These dq components are provided to the outer controllers which are active power controller, reactive power controller and the dc link voltage controller. These outer controllers provide current references and which are fed to fast inner current controller to give three phase reference voltages. These generated reference voltages are then compared to a triangle wave of carrier frequency (1650 hz) to provide gate pulses for VSC converter.



(a)

(b)

Fig. 2.8: Control strategy (a) Strategy 1 & (b) Strategy 2

The ‘d’ component is used by outer loop to control DC link voltage, while ‘q’ component is used to control reactive power. By using the combination of outer controllers and inner current controller 2 strategies are designed and simulated with the help of MATLAB/SIMULINK. The 2 strategies are shown in Fig.2.8 (a) and Fig 2.8. (b).

Strategy 1 combines a DC link voltage controller and a Reactive power controller and at the same time Strategy 2 employs Active and Reactive power controllers.

The active current reference can be obtained either by active power controller or by DC voltage controller. On the other hand the reactive current reference can be obtained through reactive power controller. The inner controller is a fast current controller. Since the reactive power is controlled separately at both VSC's hence the need of reactive power controllers arises in the control algorithm of both the converter. At a particular time instant only one of the two strategies can be used for a VSC converter station. The details of the controllers are described below:

A. Outer Controllers

- **Active Power controller**: The control for AC active power transfer is governed by the phase angle δ. The active power controller can be realised using the proportional controller (PI). The active power controller provides the active current component (i_d*) which is obtained through the equation of instantaneous active and reactive power stated below:

$$P = e_d i_d + e_q i_q \tag{2.18}$$

$$Q = e_q i_d - e_d i_q \tag{2.19}$$

By using above equation, the active current reference is obtained as:

$$i_d * = \frac{P * e_d + Q * e_q}{{e_d}^2 + {e_q}^2} \tag{2.20}$$

where P* and Q* are the reference values for active and reactive power and id* and iq* are reference currents.

- **Reactive Power controller**: The magnitude of the AC voltage on the VSC converter governs the amount of reactive power flow from that VSC converter station. The reactive power controller can also be realised using a second proportional controller (PI) in a manner similar to as the active power controller. The reactive power controller provides the reactive current component (i_q*) which is obtained through the equation of instantaneous active and reactive power stated in equation (2.18) and (2.19) respectively.

The reactive current reference is obtained as:

$$i_q^* = \frac{P^* e_q - Q^* e_d}{{e_d}^2 + {e_q}^2} \tag{2.21}$$

- **DC Voltage controller**: The main aim of the DC voltage controller is to maintain DC link voltage. This controller is used at only one of the converter station. It can be realised using a separate PI controller

B. Inner Current Controller

The inner current controller is realized by using additional PI controller. However, the PI controllers need to be designed properly for satisfactory performance of coupled systems. The inner current controller must be faster than the outer controllers as to ensure the stability of the system. The inner current control is designed in synchronously rotating reference frame. The controller is presented in the Fig. 2.9.

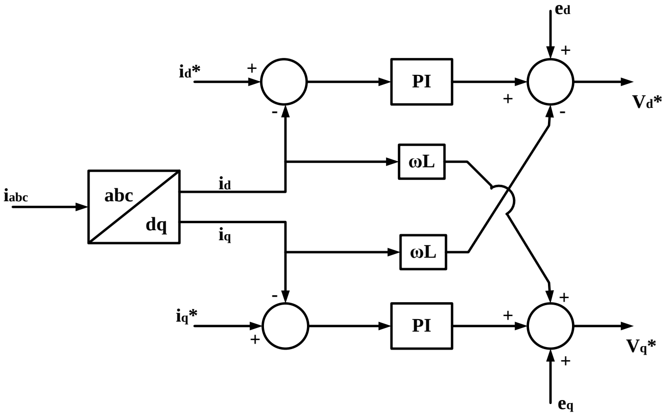


Fig. 2.9: Inner Current Controller

2.5 SYSTEM CONSIDERED

A VSC based HVDC system having two area connected to a transmission line of 300 km of in length is considered and is taken from [48]. The VSC based HVDC has Bipolar configuration. Both the VSC converters have two equal capacitors on the dc side connected between the poles and a neutral. The system considered is combination of a three phase generator or grid, converter transformer, phase reactor and AC filters and all the parameters are discussed in appendix A. During simulation of VSC based HVDC system three phase generator or grid is represented by three phase ideal source, converter transformer, phase reactor represented by a three phase series inductor and AC filter by a combination of tuned filters. The combination of filters were tuned for carrier frequency and integer multiple of carrier frequency.

2.6 SIMULATION AND RESULTS

The simulation of the VSC based HVDC system described above was performed in MATLAB/SIMULINK with the following conditions.

- At time t=0 sec, the system is initialized and the reference value of the DC link voltage reference is set to 1 pu, Active power reference is set to 1 pu i.e. 1 pu active power is flowing from VSC1 to VSC2, Reactive power reference for VSC1 is set to 0 pu and reactive power reference for VSC2 is set to -0.2 pu. It takes approximately1 sec for VSC based HVDC system to reach steady state conditions.
- At time t=1 sec, the reference value of the active power is changed to 0.5 pu.
- At time t=1.5 sec, the reference value of reactive power for VSC1 is changed to 0.2 pu.
- At time t=2.0 sec, the reference value of DC link voltage is decreased by 0.1 pu and new reference is 0.9 pu.
- At time t=2.5 sec, the reference value of reactive power for VSC2 is changed to 0.1 pu.

The VSC based HVDC system was simulated for 2 cases.

2.6.1 CASE-I

In this case strategy 1 is applied on VSC2 and strategy 2 is applied on VSC1 i.e. VSC1 is having active and reactive power controllers and VSC2 has DC link voltage and reactive power controller.

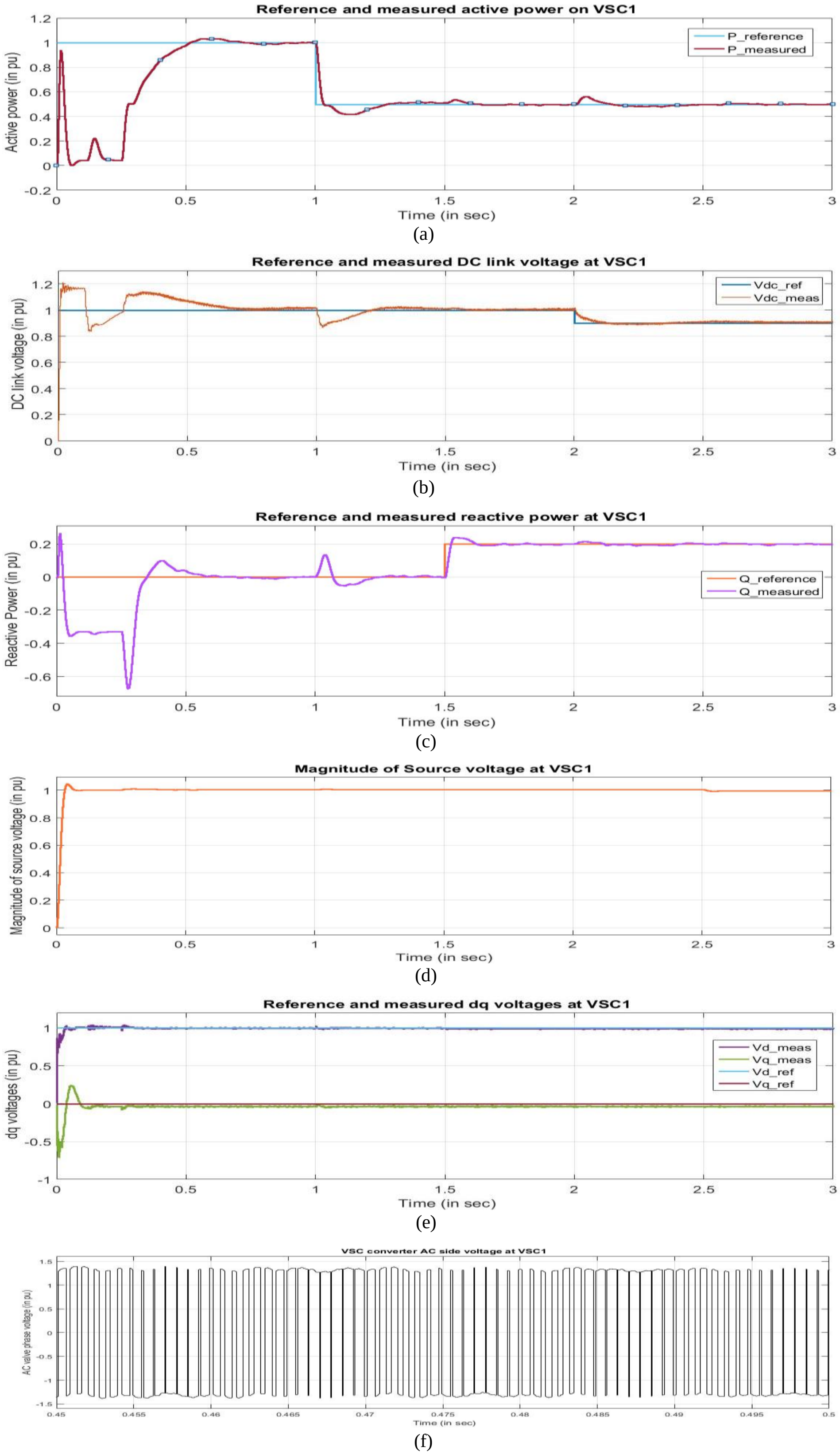
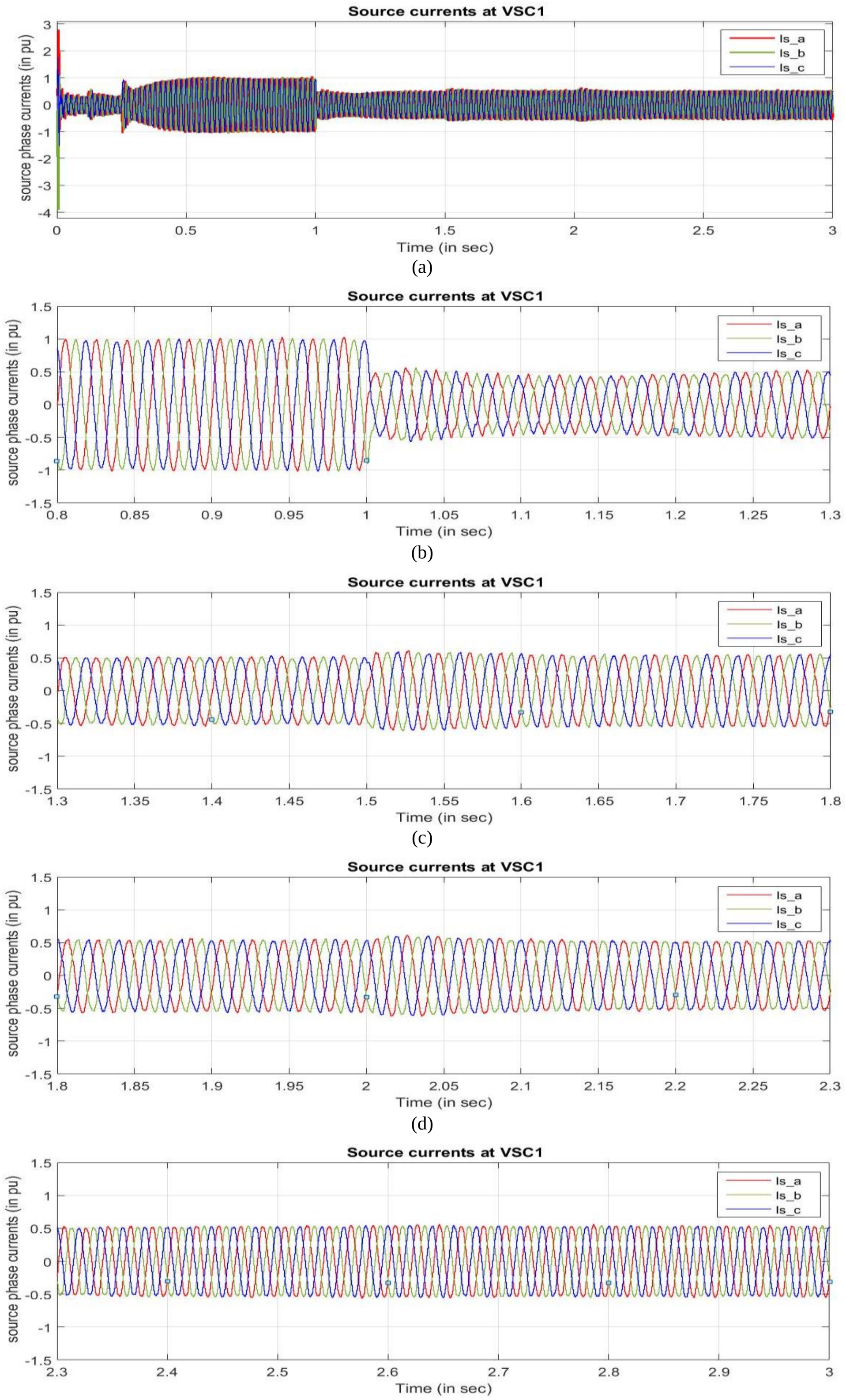


Fig. 2.10: Simulation results at VSC1 (a) Active power, (b) DC link voltage, (c) Reactive power, (d) magnitude of source voltages (e) dq voltages (f) AC valves voltage



(a)

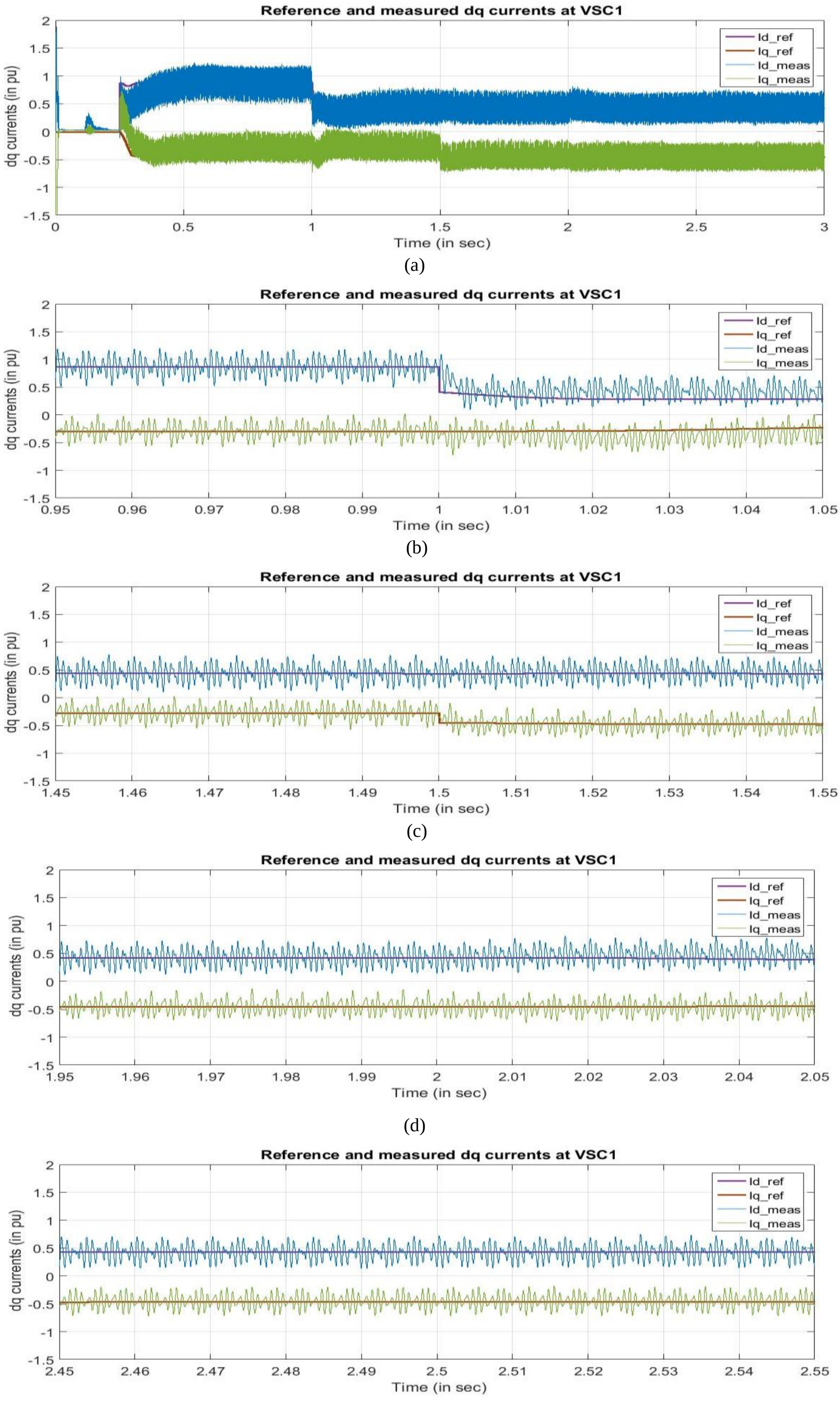
(b)

(c)

(d)

(e)

Fig. 2.11: Source currents at VSC1 for different time intervals- (a) 0 to3 sec, (b) 0.8 to 1.3 sec, (c) 1.3 to 1.8 sec, (d) 1.8 to 2.3 sec (e) 2.3 to 3 sec



(a)

(b)

(c)

(d)

(e)

Fig. 2.12: dq component currents at VSC1 for different time intervals- (a) 0 to3 sec, (b) 0.95 to 1.05 sec, (c) 1.45 to 1.55 sec, (d) 1.95 to 2.05 sec (e) 2.45 to 2.55 sec

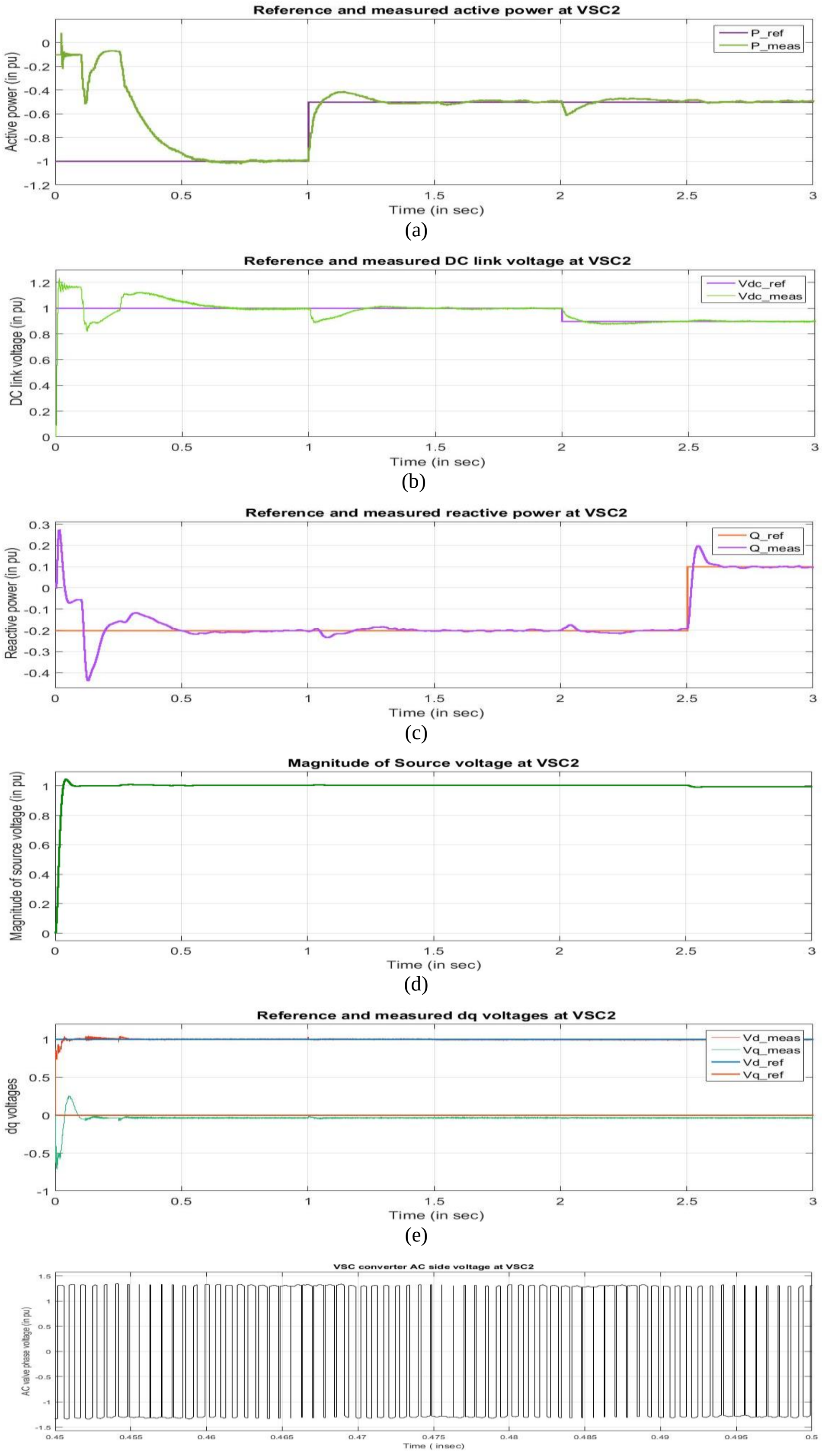
The change in various parameters such as active power, reactive power and DC link voltage can be observed from the Fig.2.10 to Fig.2.15 for strategy 1. The Simulation results for VSC1 are shown in Fig.2.10, Fig.2.11 and Fig.2.12.

From Fig.2.10 following observations have been made for VSC1:

- It is observed that the active power changes from 1 pu to 0.5pu as the reference of active power changes at time t=1 sec.
- At time t=1.5 sec, the reactive power reference changes from 0 to +0.2 pu and the measured reactive power follows the reference and settles to +0.2 pu after a few cycles.
- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles as shown Fig. 2.10(b).
- Fig.2.10 (d) & (e) shows that there is no such change in either the source voltages or the dq components obtained from these voltages with the changes in active power, reactive power and DC link voltage.
- Fig. 2.10 (f) shows that the converter side AC voltage has two levels.

From Fig.2.11 & 2.12 following observations have been made for VSC1:

- Fig. 2.11 shows, the change in source current following a change in active power from 1 to 0.5 pu at t=1 sec, change in reactive power from 0 to +0.2 at t=1.5 sec.
- It is also seen from Fig. 2.12 that the ‘d’ component current varies with active power and ‘q’ component current varies with reactive power.
- It is observed that the change in references of active and reactive power references at VSC1 forces the source currents and dq component currents at VSC1 to change.



(a)

(b)

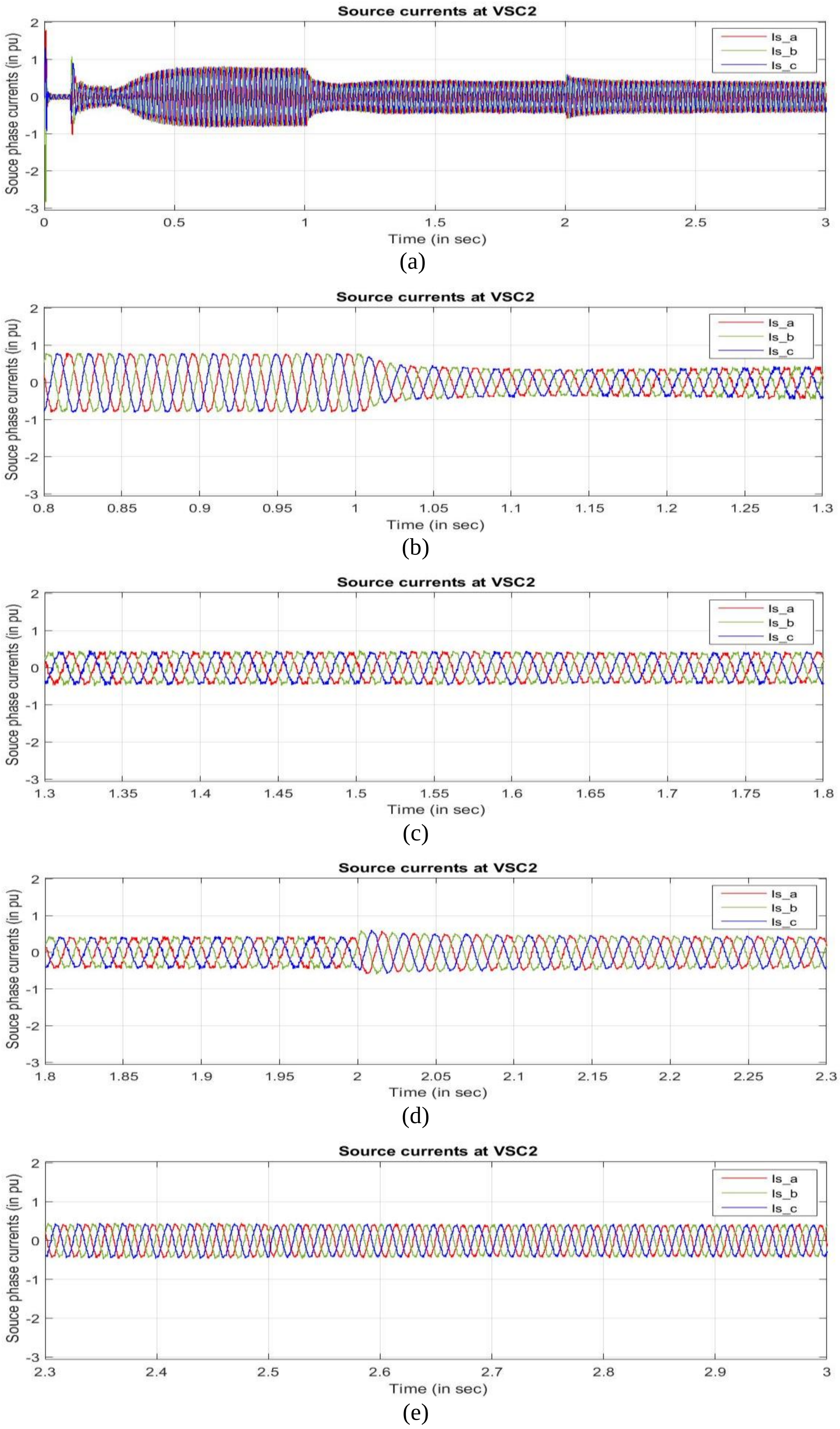
(c)

(d)

(e)

(f)

Fig. 2.13: Simulation results at VSC2 (a) Active power, (b) DC link voltage, (c) Reactive power, (d) source voltages (e) dq voltages (f) AC valves voltage



(a)

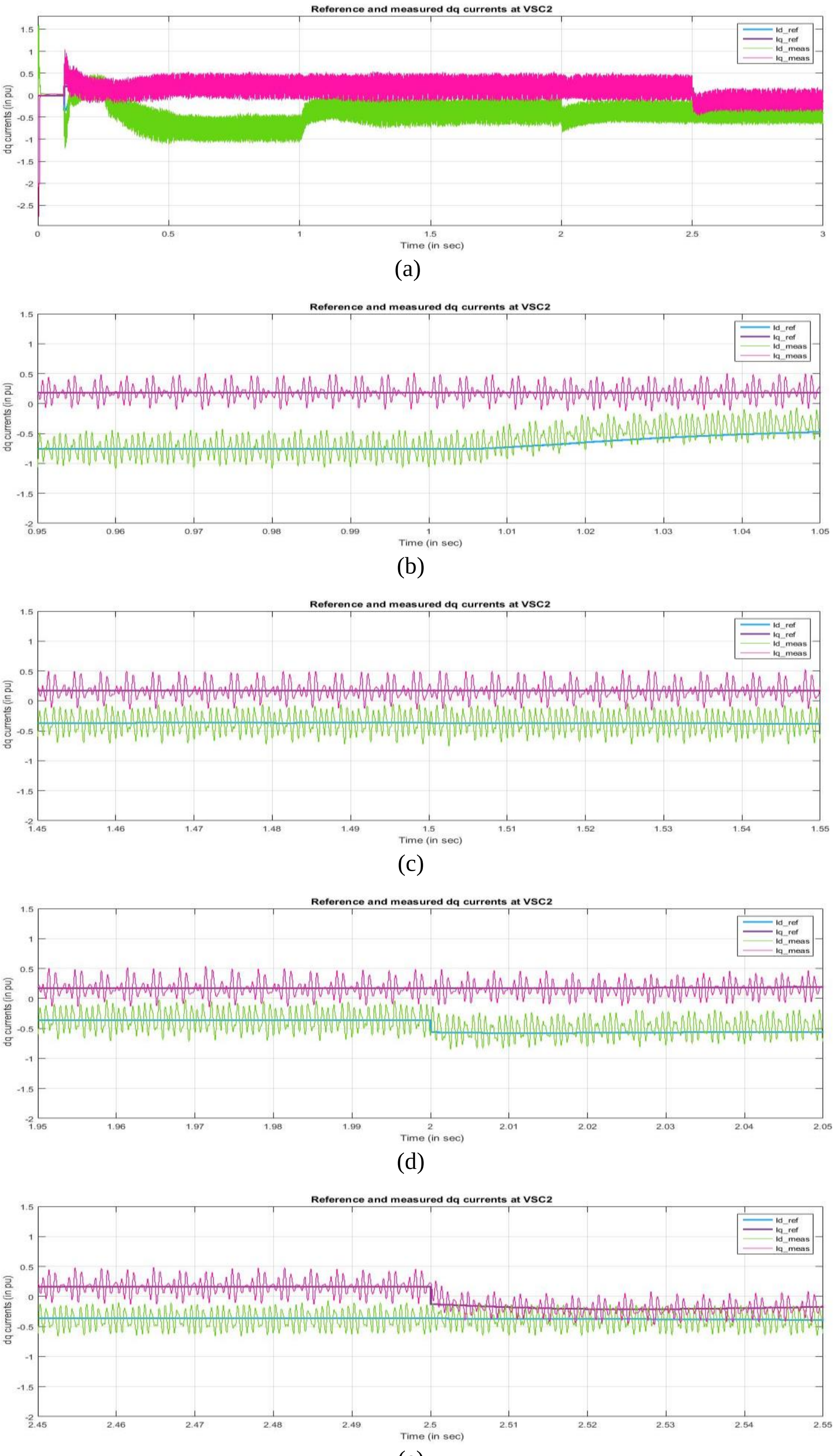
(b)

(c)

(d)

(e)

Fig. 2.14: Source currents at VSC2 for different time intervals- (a) 0 to3 sec, (b) 0.8 to 1.3 sec, (c)1.3 to 1.8 sec, (d) 1.8 to 2.3 sec (e) 2.3 to 3 sec



(a)

(b)

(c)

(d)

(e)

Fig. 2.15: dq component currents at VSC2 for different time intervals- (a) 0 to3 sec, (b) 0.95 to 1.05 sec, (c) 1.45 to 1.55 sec, (d) 1.95 to 2.05 sec (e) 2.45 to 2.55 sec

The change in various parameters such as active power, reactive power and DC link voltage can be observed from the Fig.2.10 to Fig.2.15 for strategy 1. Also, The Simulation results for VSC2 are shown in Fig.2.13, Fig.2.14 and Fig.2.15.

From Fig.2.13 following observations have been made for VSC2:

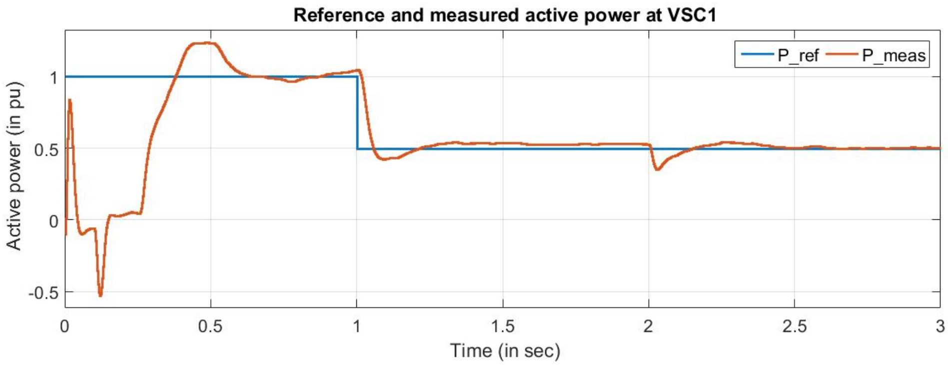
- It is observed that the active power changes from -1 pu to -0.5pu as the reference of active power changes at time t=1 sec and negative power shows that VSC is working as an inverter.
- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles.
- At time t=2.5 sec, the reactive power reference changes from -0.2 to +0.1 pu and the measured reactive power follows the references and settles to +0.1 pu after a short period.
- Fig.2.13 (d) & (e) shows that there is no such change in either the source voltages or the dq components dawn from these voltages with the changes in active power, reactive power and DC link voltage.

From Fig.2.14 & 2.15 following observations have been made for VSC2:

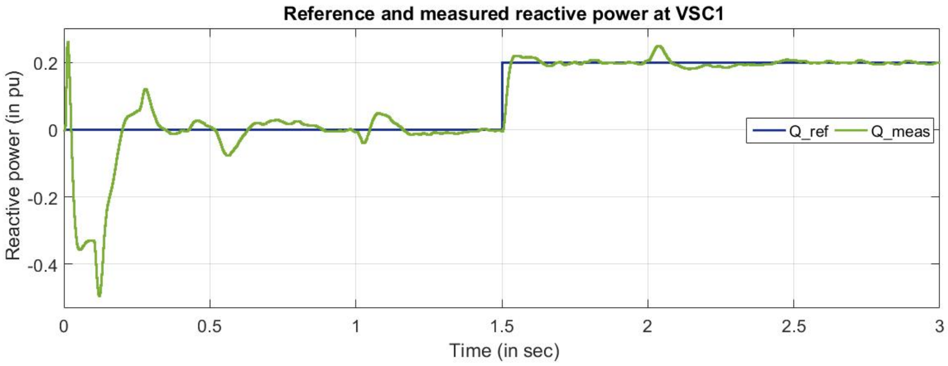
- It is observed that as the power is reduced at t=1 sec the source current gets correspondingly reduced.
- It is also seen that the ‘d’ component current varies with DC link voltage and ‘q’ component current varies with reactive power.
- Also, the change in references at both the VSC the source currents and their dq component currents not only varies with the change in reference of the controllers used in control of VSC2 but also varies with active power i.e. the change in references of DC link voltage and reactive power references at VSC2 and the also the change in active power at VSC2 forces the source currents and dq component currents at VSC2 to change.

2.6.2 CASE-II

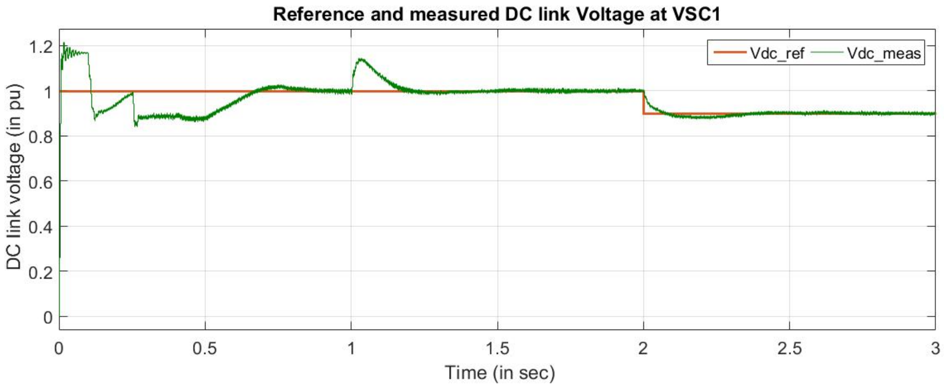
In this case strategy 1 is applied on VSC1 and strategy 2 is applied on VSC1 i.e. VSC2 is having active and reactive power controllers and VSC2 has DC link voltage and reactive power controller.



(a)



(b)



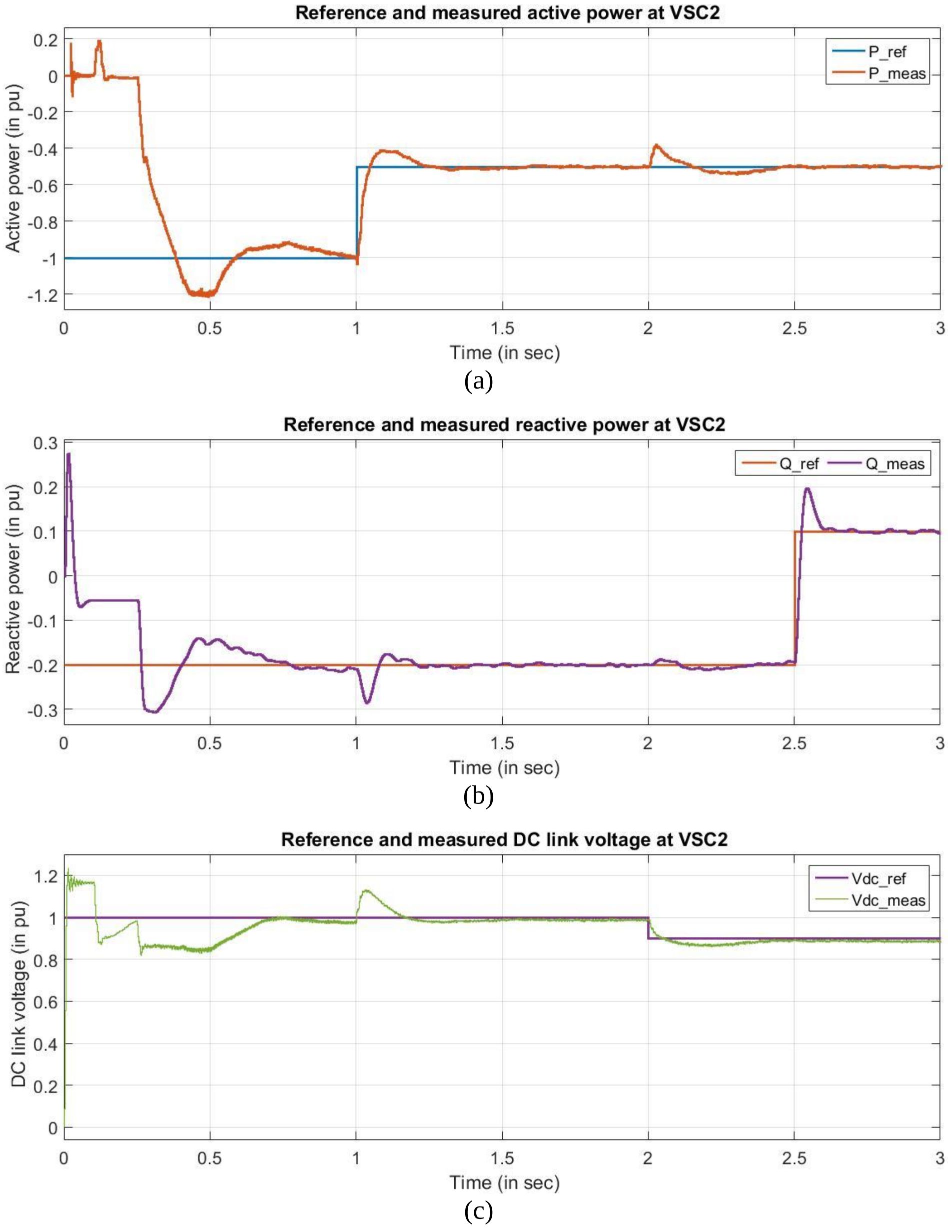
(c)

Fig. 2.16: Simulation results at VSC1 (a) Active power, (b) DC link voltage, (c) Reactive power

From Fig. 2.16 following observations have been made for VSC1:

- It is observed that the active power changes from 1 pu to 0.5pu as the reference of active power changes at time t=1 sec.
- At time t=1.5 sec, the reactive power reference changes from 0 to +0.2 pu and the measured reactive power follows the references and settles to +0.2 pu after a short period.

- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles.



(a)

(b)

(c)

Fig. 2.17: Simulation results at VSC1 (a) Active power, (b), Reactive power (c) DC link voltage

From Fig. 2.17 following observations have been made for VSC2:

- It is observed that the active power changes from 1 pu to 0.5pu as the reference of active power changes at time t=1 sec.
- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles.

- At time t=2.5 sec, the reactive power reference changes from -0.2 to +0.1 pu and the measured reactive power follows the references and settles to +0.1 pu after a short period.

By comparing results in CASE-I and CASE-II following observations were made:

- It is observed that the active power, reactive power and DC link voltage change as desired and follows their reference values for both CASE-I and CASE-II.
- The overshoot of active power for CASE-II is much more than that of in CASE-I.
- The settling time in CASE-II is litter higher and responses are less accurate.

2.7 CONCLUSIONS

The power transfer capabilities of a VSC based HVDC system and some PWM techniques were studied in this chapter. A synchronous reference theory based control system for a two level VSC based HVDC system is designed consisting of outer controllers which includes Active power controller, Reactive power controller and DC voltage controller and fast inner current controllers. Two different control strategies were stated and implemented on a two level VSC based HVDC system. On comparison of the two cases under the same dynamic changes the following conclusions are drawn:

- The two level VSC based system shows satisfactory performance in both the cases for regulating various parameters such as active and reactive power at both the converter station. Also, the DC link voltage was maintained as per the reference value.
- The performance of the VSC based system is slightly better when Strategy 1 is applied on VSC2 and Strategy 2 is applied on VSC1 (case I). In case II, the responses for the controllers were slow and less accurate as compared to case II. i.e. a VSC based HVDC system having active power controller and reactive power controller on VSC converter working as Rectifier and DC link voltage controller and reactive power controller on VSC converter working as a Inverter shows the better results.
- It can also be observed from the simulation results, that the reactive powers of both the VSC converters in both the cases is independent of each other and can be controlled efficiently at each VSC converter station.

CHAPTER-3 : THREE LEVEL VSC BASED HVDC SYSTEM

3.1 INTRODUCTION

In this chapter, the simulation of a three level VSC based system using MATLAB/SIMULINK is performed and the various parameters of the VSC based HVDC system are analyzed by using two cases. These cases are the combination of two different outer controllers in a control system of a VSC converter. Also, the control algorithm for the three level VSC based system is explained and its performance for the system is observed. This chapter also includes comparison of three level VSC and three level VSC system. Also, VSC based HVDC system modelling is done.

3.2 DYNAMIC MODEL OF 3 LEVEL VSC BASED HVDC SYSTEM

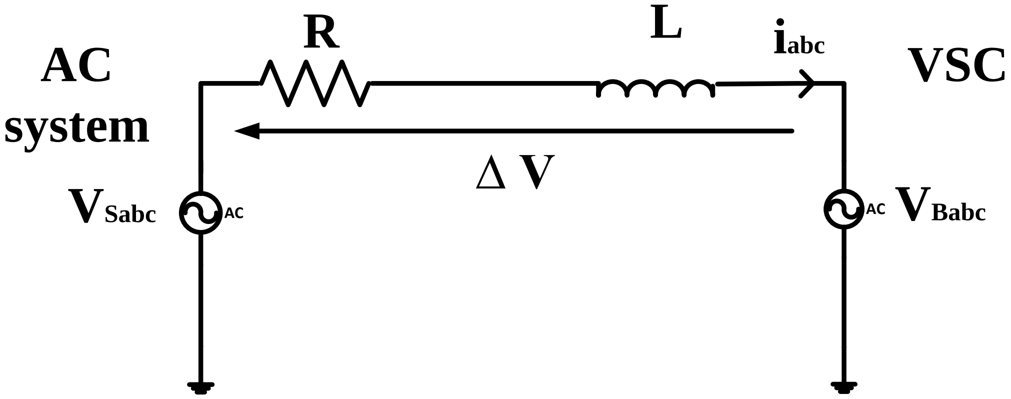


Fig. 3.1: AC side equivalent of VSC

A VSC based HVDC system can be modelled by transforming its abc reference quantities into dq reference frame as follows:

$$V_{Sabc} = I_{abc}R + L\frac{dI_{abc}}{dt} + V_{Babc} \tag{3.1}$$

$$P_{VSC} = V_{Ba}I_a + V_{Bb}I_b + V_{Bc}I_c \tag{3.2}$$

$$Q_{VSC} = \frac{1}{\sqrt{3}}\left\{V_{Ba}\left(I_b - I_c\right) + V_{Bb}\left(I_c - I_a\right) + V_{Bc}\left(I_a - I_b\right)\right\} \tag{3.3}$$

where V_{Sabc} and V_{Babc} represents abc phase voltages at AC grid and VSC converter.

I_{Sabc} represents abc phase currents and R & L are equivalent resistance and inductance.

The equivalent system model of a three-phase AC-DC VSC station is shown in Fig. 3.2.

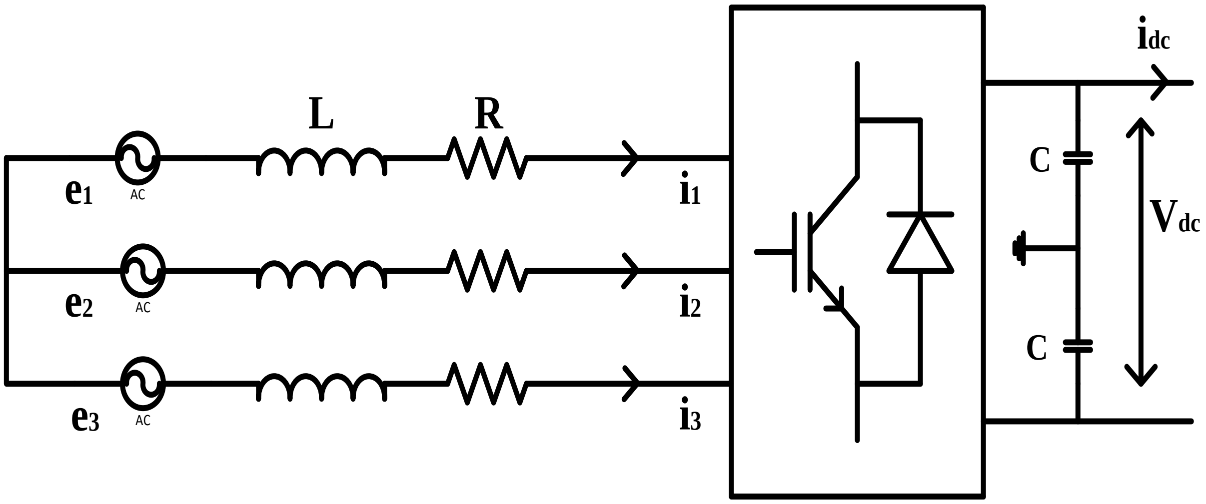


Fig. 3.2: Equivalent circuit model for a 3 phase VSC station

Using Park's transformation the ac quantities of VSC converter are transformed into dq0. These quantities which are in synchronously rotating reference frame (such as (e_1, e_2, e_3) and currents (i_1, i_2, i_3)) are used for mathematical modelling of the VSC system. Hence the system can be modelled by using equation (1), (2) & (3)

$$C\frac{dv_{DC}}{dt} = \frac{3}{2}\left(i_q d_q + i_d d_d\right) \tag{3.4}$$

$$L\frac{di_q}{dt} + \omega L i_d + R i_q = e_q - v_{dc} d_q \tag{3.5}$$

$$L\frac{di_d}{dt} - \omega L i_q + R i_d = e_d - v_{dc} d_d \tag{3.6}$$

where i_d and i_q are the 'd' and 'q' components of current through phase reactors respectively, 'e_d' and 'e_q' are the 'd' and 'q' components of grid voltages, d_d and d_q are the duty cycle and v_{dc} represents the dc link voltage, R and L are the resistance and inductance of the phase reactor and ω is the system frequency.

3.3 CONTROL FOR 3-LEVEL VSC BASED HVDC SYSTEM

There are several methods used in the control system for a VSC based HVDC system. The overall control structure for a VSC based hvdc system is shown in Fig. 3.4.

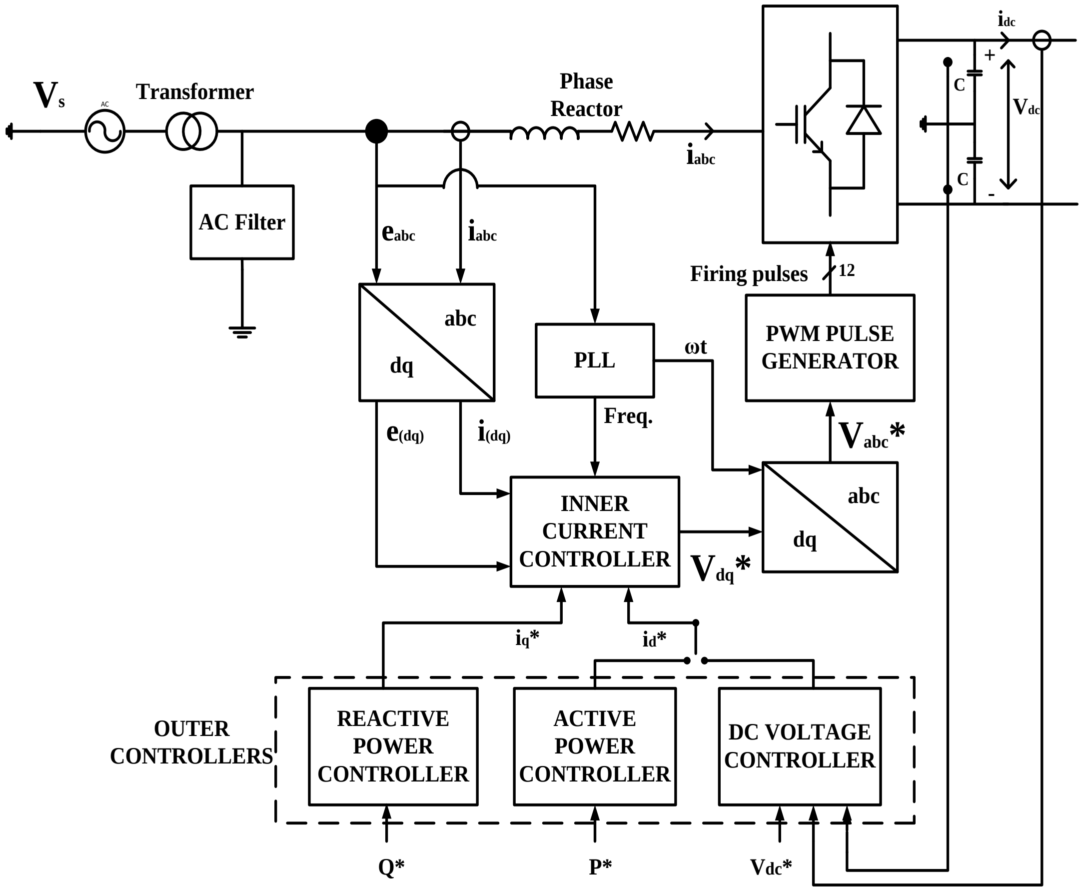
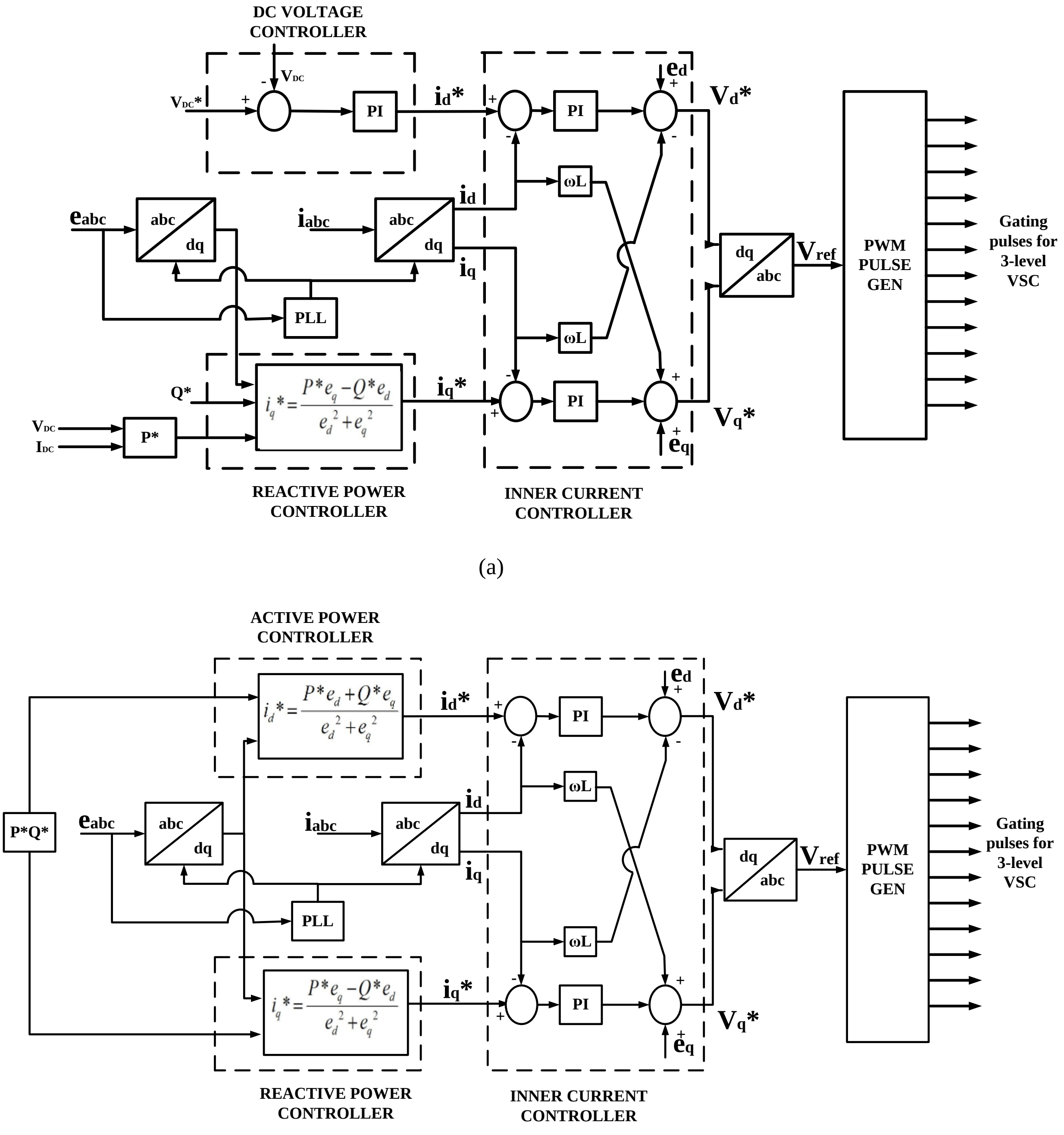


Fig. 3.3: Overall control structure of a VSC based HVDC system

The system can be controlled by changing the VSC AC voltage phase angle which will have direct effect on active power flow, while the change in its magnitude will have effect on reactive power. The dq theory is used for the control, the source voltage V_S, source current I_S, point of common coupling voltage V_F, VSC converter voltage V_B and current I_B are converted to their respective dq components. These dq components are provided to the outer controllers which are active power controller, reactive power controller and the dc link voltage controller. These outer controllers provide current references and those current reference are fed to fast inner current controller to give three phase reference voltages. These voltages are then compared to a triangle wave to provide gate pulses for VSC converter. The d component is used by outer loop to control direct voltage, while q component is used to control reactive power. By using the combination of outer controllers and inner current controller two strategies are designed and simulated with the help of MATLAB/SIMULINK. The two strategies are shown in Fig. 3.4 (a) and Fig. 3.4 (b).



(a)

(b)

Fig. 3.4: Control strategy (a) Strategy 1 & (b) Strategy 2

Strategy 1 combines a DC link voltage controller and a Reactive power controller and at the same time Strategy 2 has Active and Reactive power controllers.

The active current reference can be obtained either by active power controller or by DC voltage controller. On the other hand the reactive current reference can be obtained through reactive power controller. The inner controller is a fast current controller. Since the reactive power is controlled separately at both VSC's the need of reactive power controllers arises in control algorithm of both the converter. At a time instant not all the controllers are used, at one side DC voltage controllers and reactive power controller is used and on the other side active power controller and reactive power controller. All of the controllers discussed above are already described in section 2.4 and can be realised as same for the three-level VSC based HVDC system.

3.4 THREE LEVEL VSC

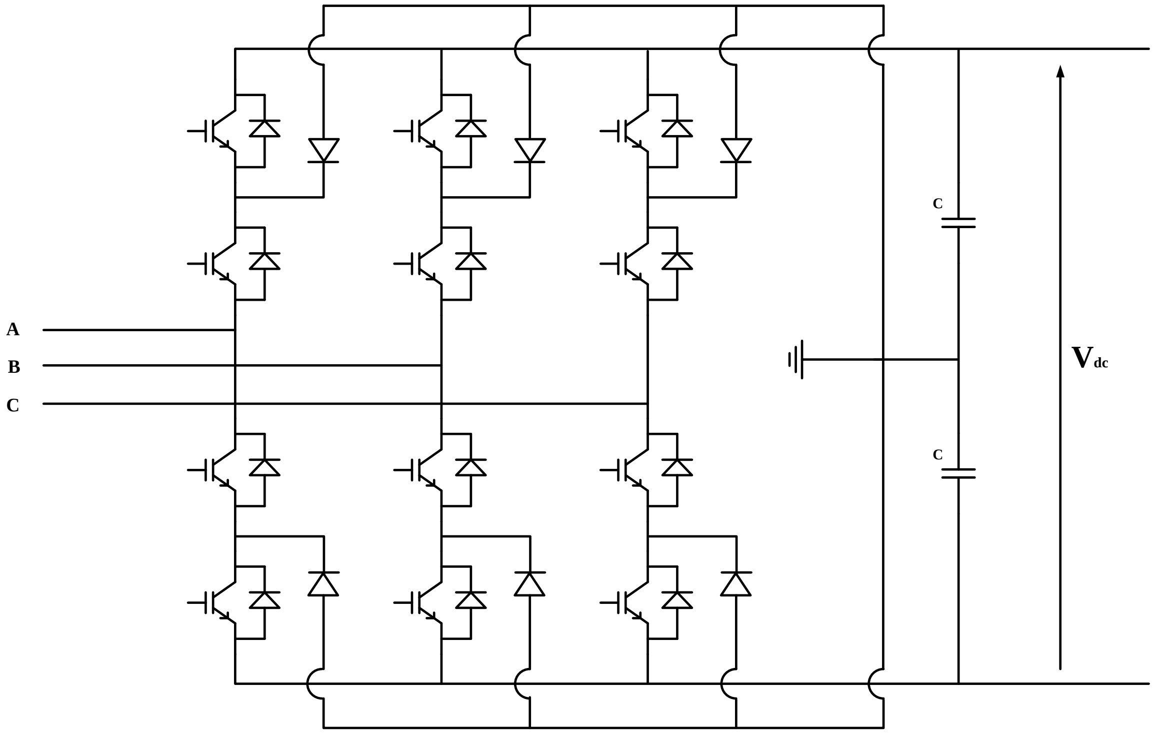


Fig. 3.5: Diode clamped three level NPC voltage source converter

In Fig. 3.5, a three phase three level diode clamped VSC converter is shown. The AC output of such converters has three voltage levels (+V_{dc}, 0 and -V_{dc}) and therefore the output voltage steps are half of the steps in two level VSC converters. These converters have three legs each for one phase. Each leg has for IGBT switches. These converters have two sets of valves in series, with their connection show in Fig. 3.5. Each series set has two valves centre taped via extra diode. The major advantage of such converters is that for the same values used as of two level VSC converter these provide twice the DC link voltage. Fig. 3.6 shows a single leg of the NPC converter. The switching sequence for phase to phase voltages output could be analysed and also the generation of PWM pulses can be observed from Fig. 3.7.

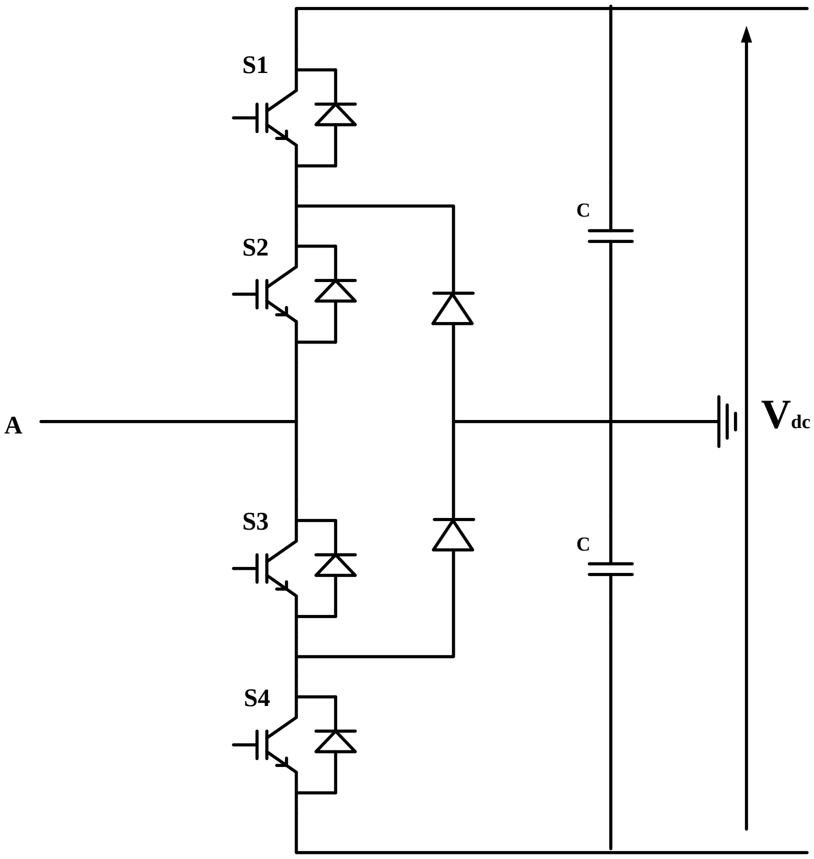


Fig. 3.6: single leg of a diode clamped three level NPC voltage source converter

Switching status				V_{AN}
S1	S2	S3	S4	
ON	ON	OFF	OFF	+Vdc/2
OFF	ON	ON	OFF	0
OFF	OFF	ON	ON	-Vdc/2

Table 3.1: Switching sequence of valves for a single phase leg of a three level VSC

As the Table 3.1 shows, V_{AN} will be positive for Switch S1 and S2 are on and others are off i.e. switching on the upper series set of valves produce positive V_{AN}. Similarly, for negative V_{AN} lower series set could be turned on. For Van to be zero S2 and S3 are on.

Fig. 3.7 shows PWM pulses and phase voltage V_{AN}.

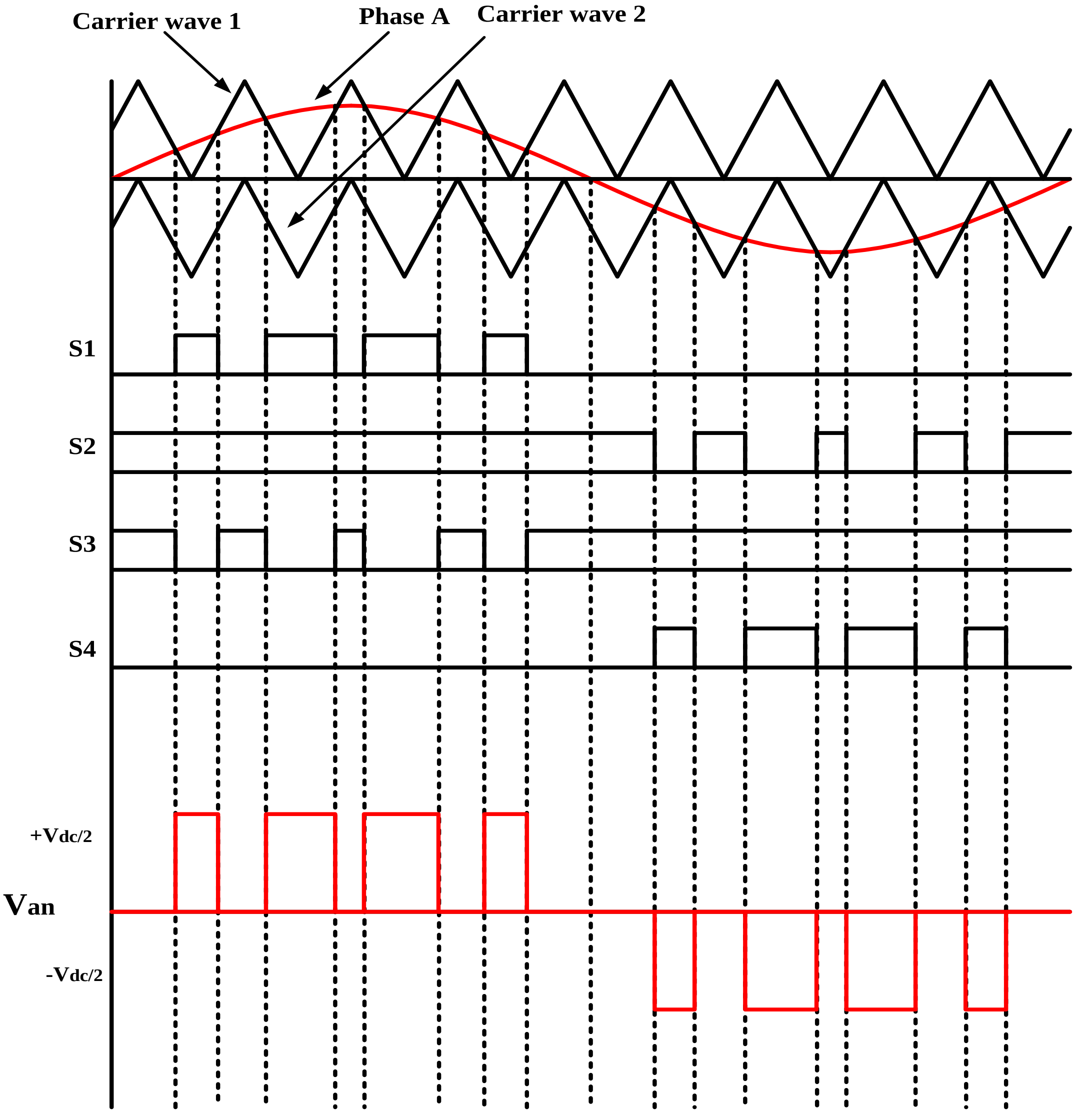


Fig. 3.7: PWM pulse for a single phase leg of a three level VSC

For generating PWM pulses for a three level VSC there are two triangle wave of same frequency are required. PWM pulses are generated according to Table 4.2.

T1 represents carrier triangle wave 1, T2 represents carrier triangle 2 and ref represents sinusoidal reference signal.

Conditions	Output = 1 for switch
Ref > T1	S1
Ref > T2	S2
Ref < T1	S3
Ref < T2	S4

Table 3.2: PWM switching of valves for a single phase leg of a three level VSC

3.5 SIMULATION AND RESULTS

A VSC based HVDC system having two area connected to a transmission line of 300 km of in length is considered and is taken from []. The VSC based HVDC has Bipolar configuration. Both the VSC converters have two equal capacitors on the dc side connected between the poles and a neutral. The system considered is combination of a three phase generator or grid, converter transformer, phase reactor and AC filters and all the parameters are discussed in appendix A. During simulation of VSC based HVDC system three phase generator or grid is represented by three phase ideal source, converter transformer, phase reactor represented by a three phase series inductor and AC filter by a combination of tuned filters. The combination of filters were tuned for carrier frequency and integer multiple of carrier frequency.

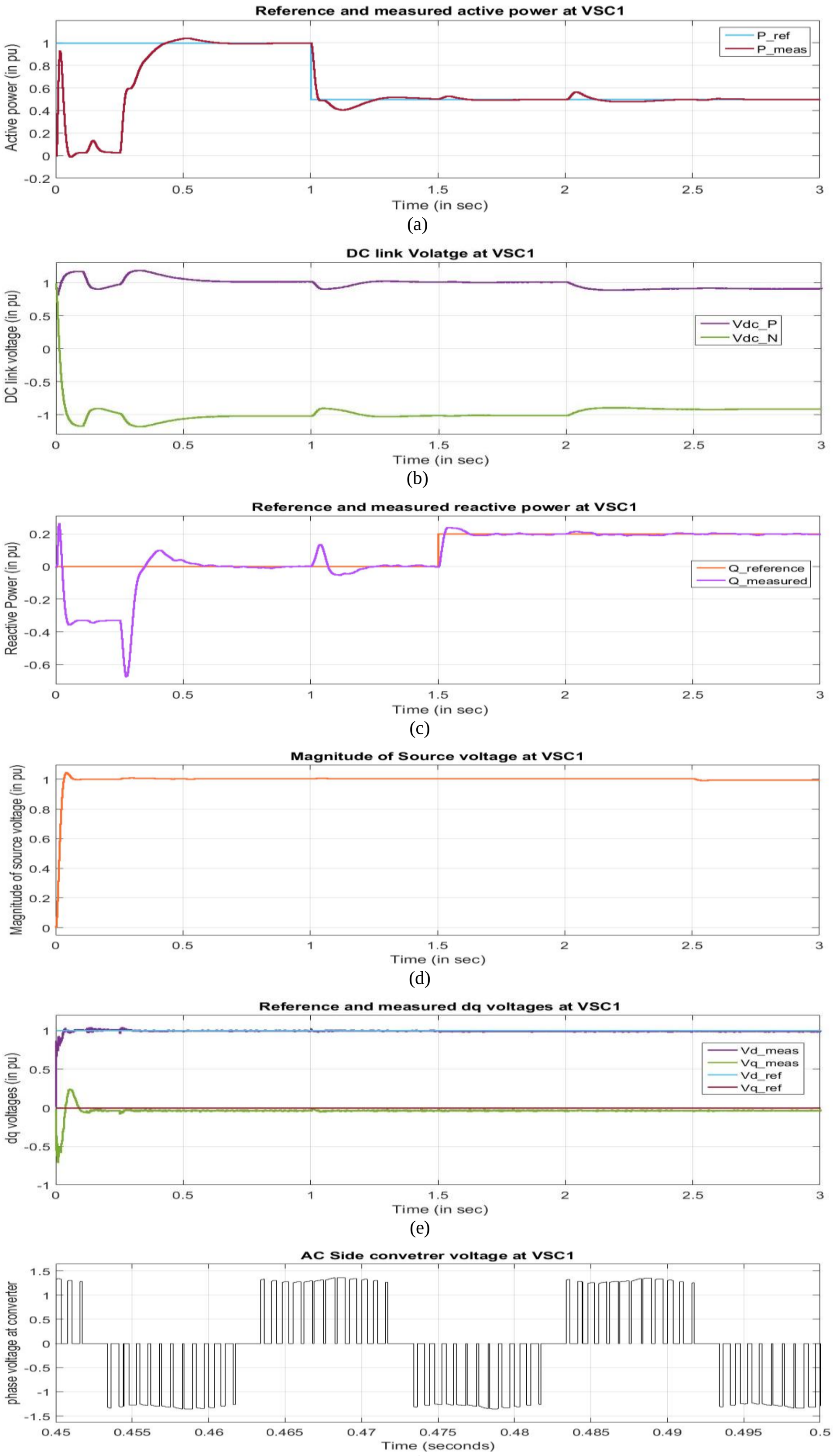
The simulation of the VSC based HVDC system described above was done in MATLAB/SIMULINK with the following conditions.

- At time t=0 sec, the system is initialized and the reference value of the DC link voltage reference is set to 1 pu, Active power reference is set to 1 pu i.e. 1 pu active power is flowing from VSC1 to VSC2, Reactive power reference for VSC1 is set to 0 pu and reactive power reference for VSC2 is set to -0.2 pu. It takes 1 sec for VSC based HVDC system to reach steady state conditions.
- At time t=1 sec, the reference value of the Active Power is changed to 0.5 pu.
- At time t=1.5 sec, the reference value of reactive power for VSC1 is changed to 0.2 pu.
- At time t=2.0 sec, the reference value of DC link voltage is decreased by 0.1 pu and new reference is 0.9 pu.
- At time t=2.5 sec, the reference value of reactive power for VSC2 is changed to 0.1 pu.

The VSC based HVDC system was simulated in two cases.

3.5.1 CASE-I

In this case strategy 1 is applied on VSC2 and strategy 2 is applied on VSC1 i.e. VSC1 is having active and reactive power controllers and VSC2 has DC link voltage and reactive power controller.



(a)

(b)

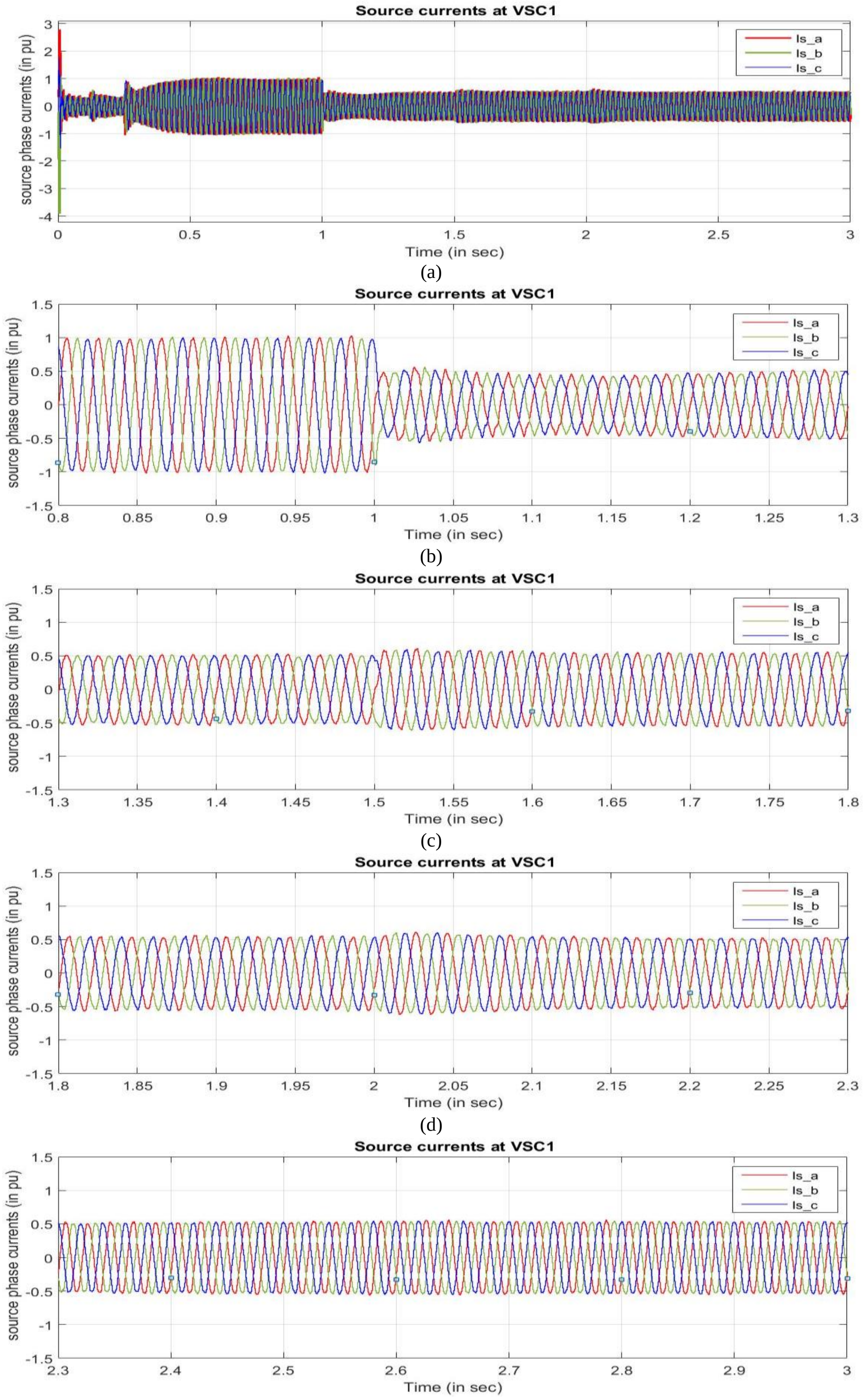
(c)

(d)

(e)

(f)

Fig. 3.8: Simulation results at VSC1 (a) Active power, (b) DC link voltage, (c) Reactive power, (d) Source voltages (e) dq voltages (f) AC valves voltage



(a)

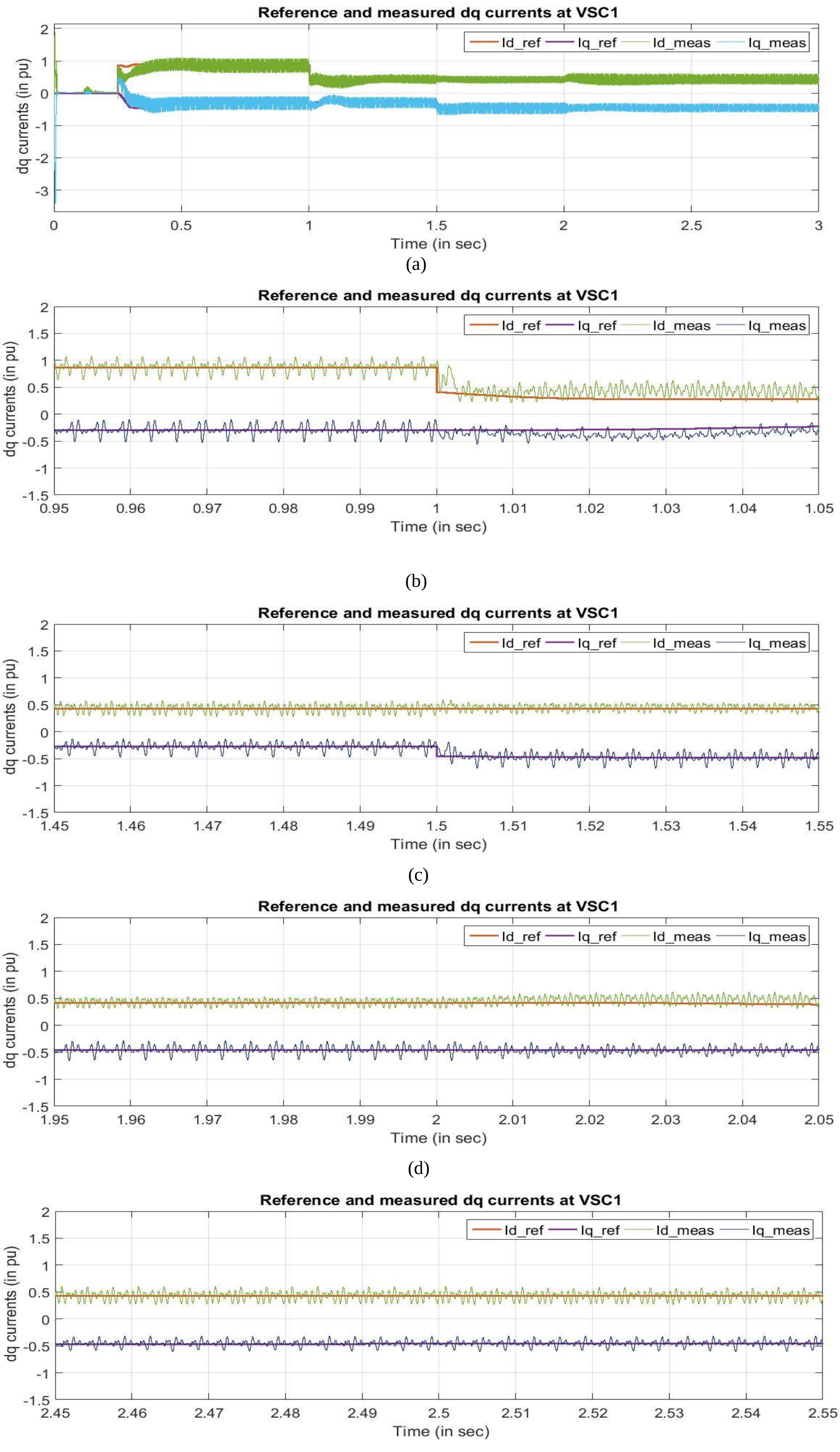
(b)

(c)

(d)

(e)

Fig. 3.9: Source currents at VSC1 for different time intervals- (a) 0 to3 sec, (b) 0.8 to 1.3 sec, (c) 1.3 to 1.8 sec, (d) 1.8 to 2.3 sec (e) 2.3 to 3 sec



(a)

(b)

(c)

(d)

(e)

Fig. 3.10: dq component currents at VSC1 for different time intervals- (a) 0 to3 sec, (b) 0.95 to 1.05 sec, (c) 1.45 to 1.55 sec, (d) 1.95 to 2.05 sec (e) 2.45 to 2.55 sec

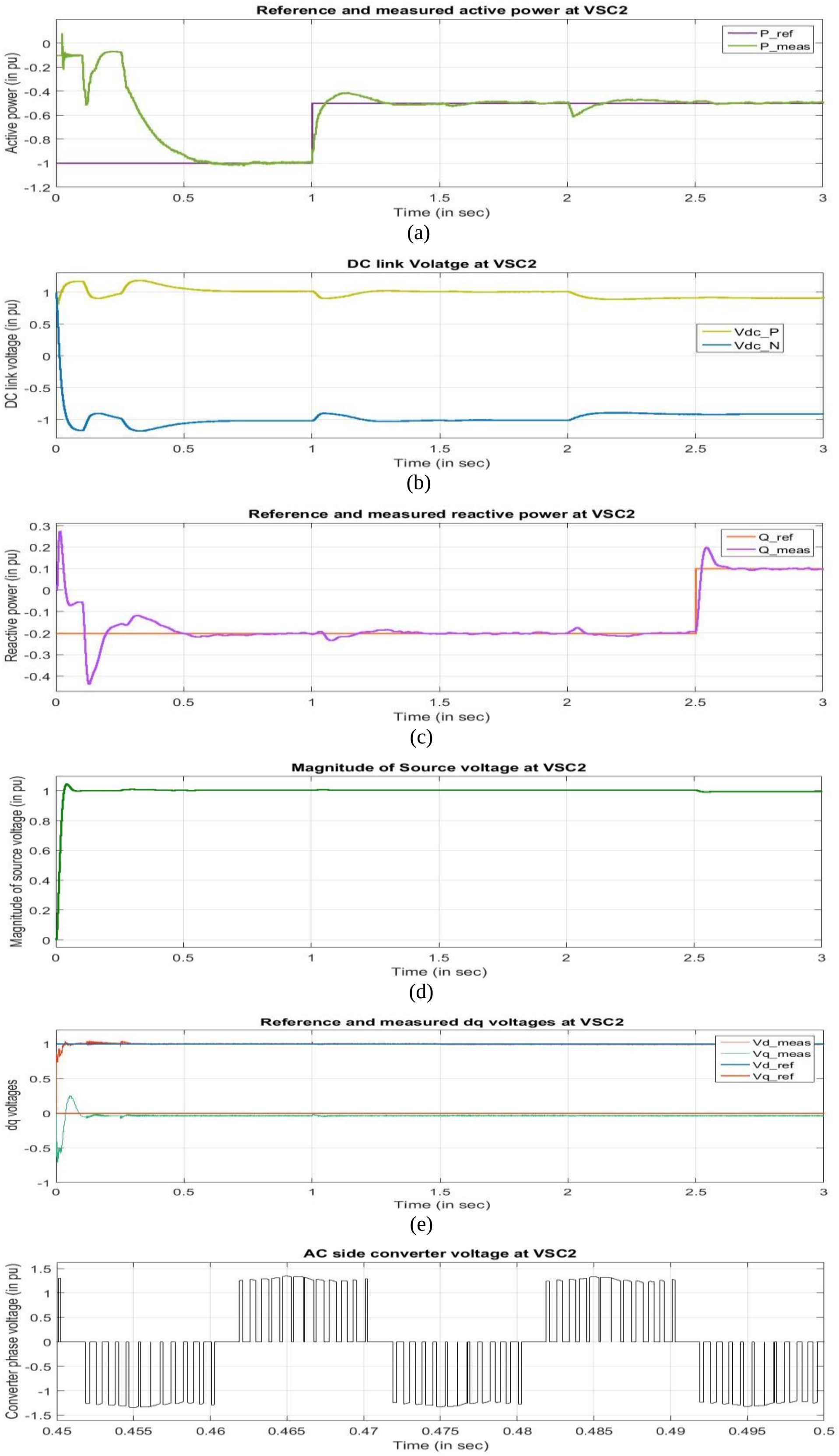
The change in various parameters such as active power, reactive power and DC link voltage can be observed from the Fig. 3.8 to Fig. 3.13 for strategy 1. The Simulation results for VSC1 are shown in Fig. 3.8, Fig. 3.9 and Fig. 3.10.

From Fig. 3.8 following observations have been made for VSC1:

- It is observed that the active power changes from 1 pu to 0.5pu as the reference of active power changes at time t=1 sec.
- At time t=1.5 sec, the reactive power reference changes from 0 to +0.2 pu and the measured reactive power follows the reference and settles to +0.2 pu after a few cycles.
- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles as shown Fig. 3.8 (b).
- Fig. 3.8 (d) & (e) shows that there is no such change in either the source voltages or the dq components obtained from these voltages with the changes in active power, reactive power and DC link voltage.
- Fig. 3.8 (f) shows that the converter side AC voltage has three levels.

From Fig. 3.9 & 3.10 following observations have been made for VSC1:

- Fig. 3.9 shows, the change in source current following a change in active power from 1 to 0.5 pu at t=1 sec, change in reactive power from 0 to +0.2 at t=1.5 sec.
- It is also seen from Fig. 3.10 that the ‘d’ component current varies with active power and ‘q’ component current varies with reactive power.
- It is observed that the change in references of active and reactive power references at VSC1 forces the source currents and dq component currents at VSC1 to change.



(a)

(b)

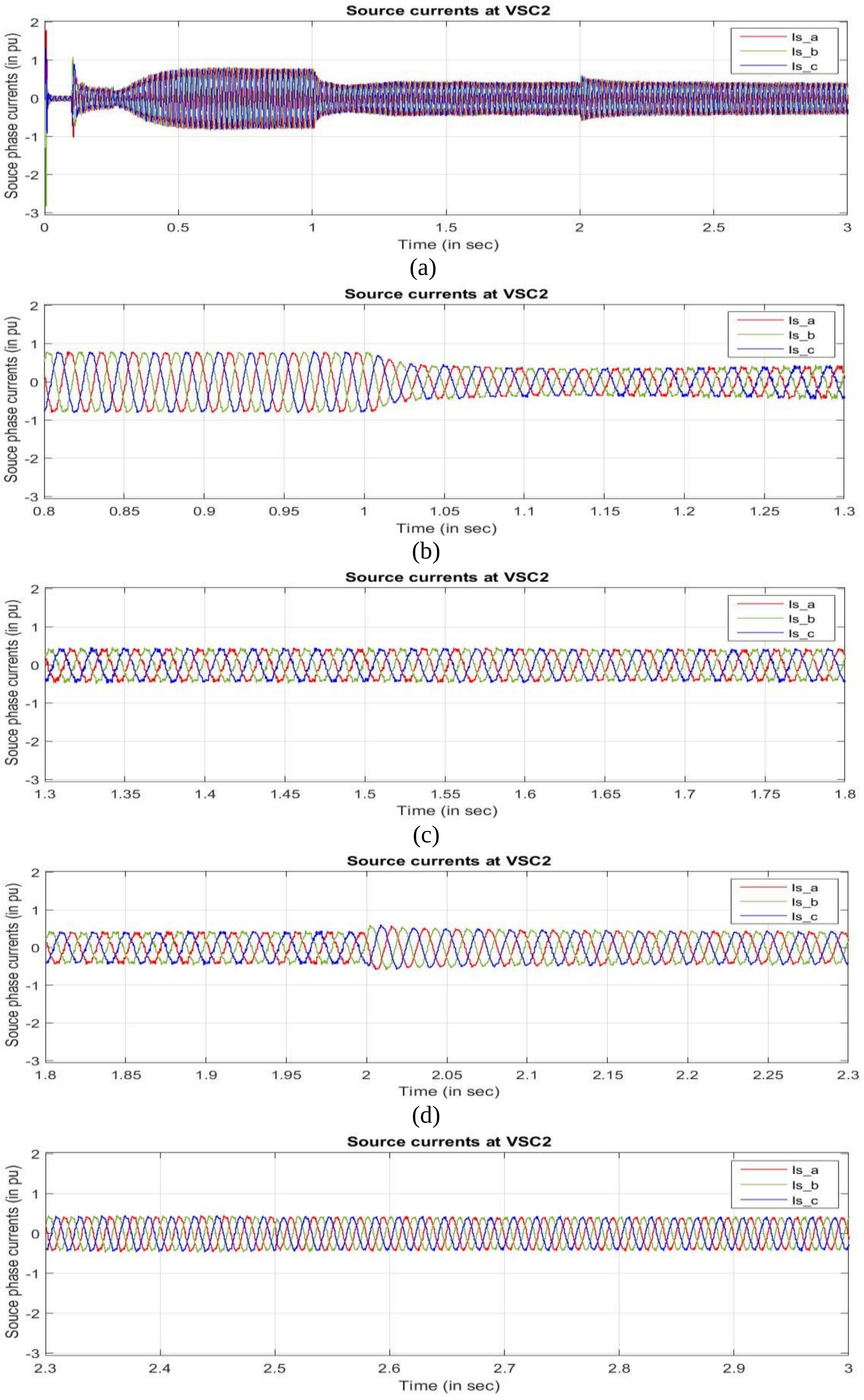
(c)

(d)

(e)

(f)

Fig. 3.11: Simulation results at VSC2 (a) Active power, (b) DC link voltage, (c) Reactive power, (d) source voltages (e) dq voltages (f) AC valves voltage



(a)

(b)

(c)

(d)

(e)

Fig. 3.12: Source currents at VSC2 for different time intervals- (a) 0 to3 sec, (b) 0.8 to 1.3 sec, (c)1.3 to 1.8 sec, (d) 1.8 to 2.3 sec (e) 2.3 to 3 sec

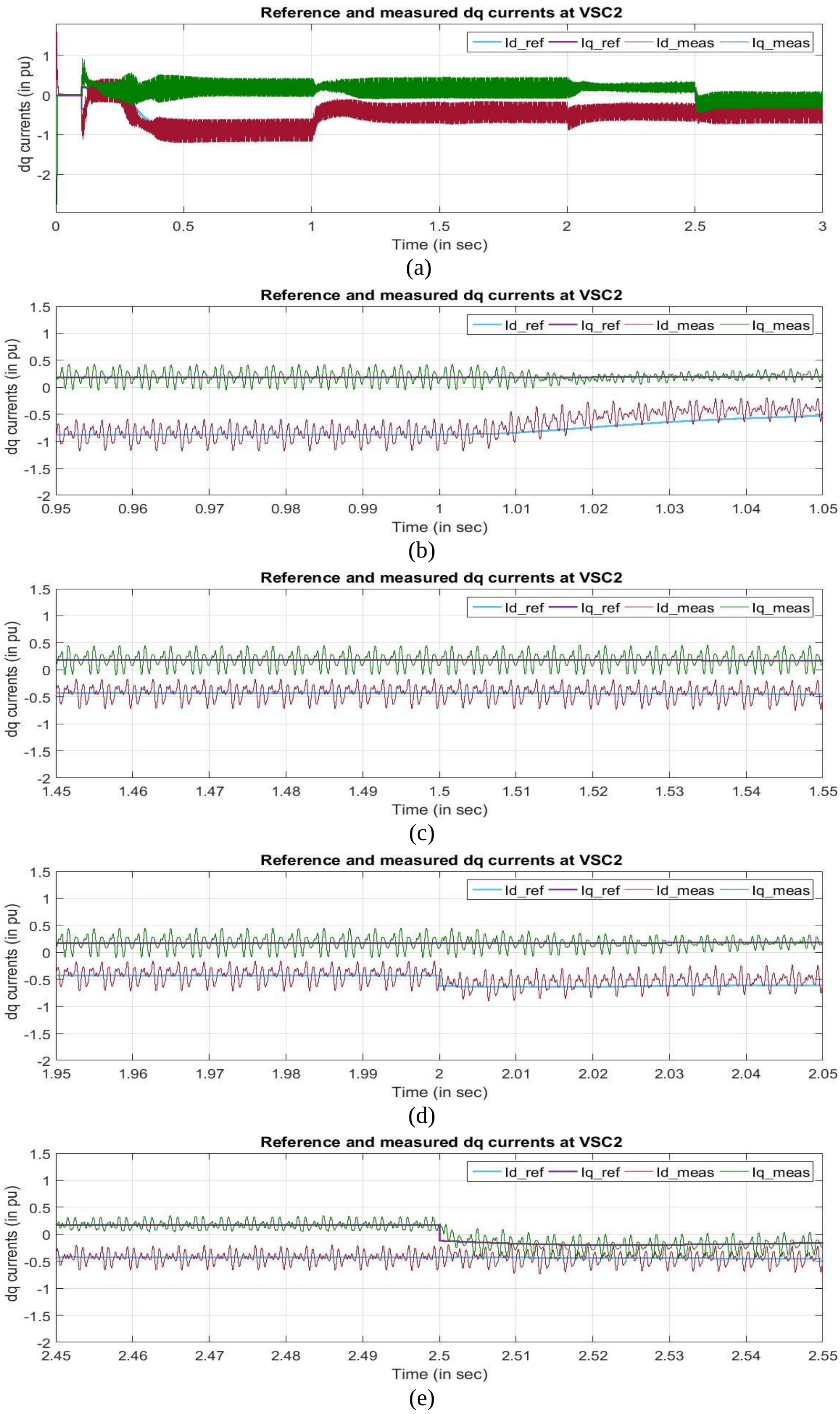


Fig. 3.13: dq component currents at VSC2 for different time intervals- (a) 0 to3 sec, (b) 0.95 to 1.05 sec, (c) 1.45 to 1.55 sec, (d) 1.95 to 2.05 sec (e) 2.45 to 2.55 sec

The change in various parameters such as active power, reactive power and DC link voltage for VSC2 can be observed from the Fig. 3.11 to Fig. 3.13for strategy 1

From Fig. 3.11 following observations have been made for VSC2:

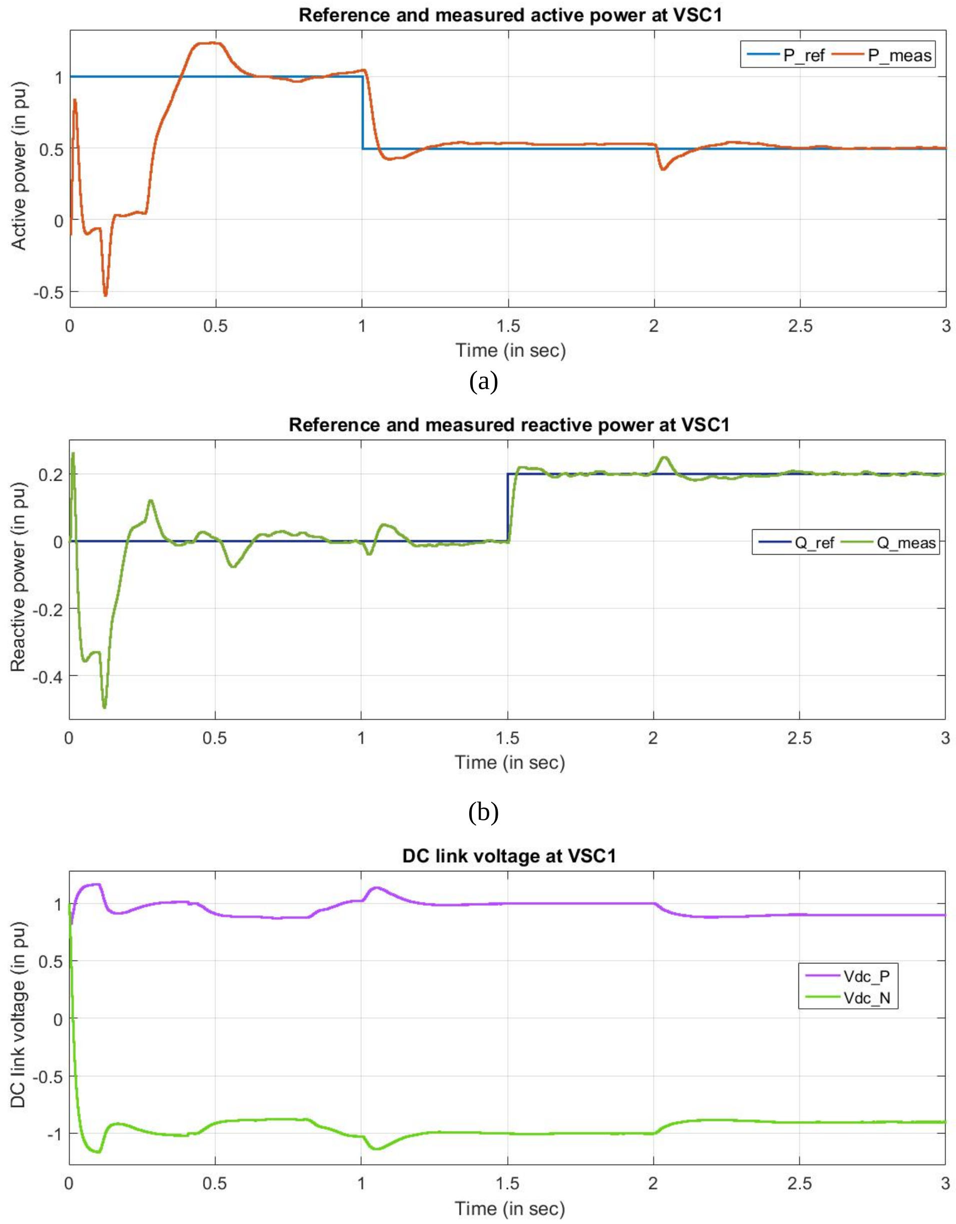
- It is observed that the active power changes from -1 pu to -0.5pu as the reference of active power changes at time t=1 sec and negative power shows that VSC is working as an inverter.
- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles.
- At time t=2.5 sec, the reactive power reference changes from -0.2 to +0.1 pu and the measured reactive power follows the references and settles to +0.1 pu after a short period.
- Fig. 3.11 (d) & (e) shows that there is no such change in either the source voltages or the dq components dawn from these voltages with the changes in active power, reactive power and DC link voltage.

From Fig. 3.12 & 3.13 following observations have been made for VSC2:

- It is observed that as the power is reduced at t=1 sec the source current gets correspondingly reduced.
- It is also seen that the ‘d’ component current varies with DC link voltage and ‘q’ component current varies with reactive power.
- Also, the change in references at both the VSC the source currents and their dq component currents not only varies with the change in reference of the controllers used in control of VSC2 but also varies with active power i.e. the change in references of DC link voltage and reactive power references at VSC2 and the also the change in active power at VSC2 forces the source currents and dq component currents at VSC2 to change.

3.5.2 CASE-II

In this case strategy 1 is applied on VSC1 and strategy 2 is applied on VSC1 i.e. VSC2 is having active and reactive power controllers and VSC2 has DC link voltage and reactive power controller.



(a)

(b)

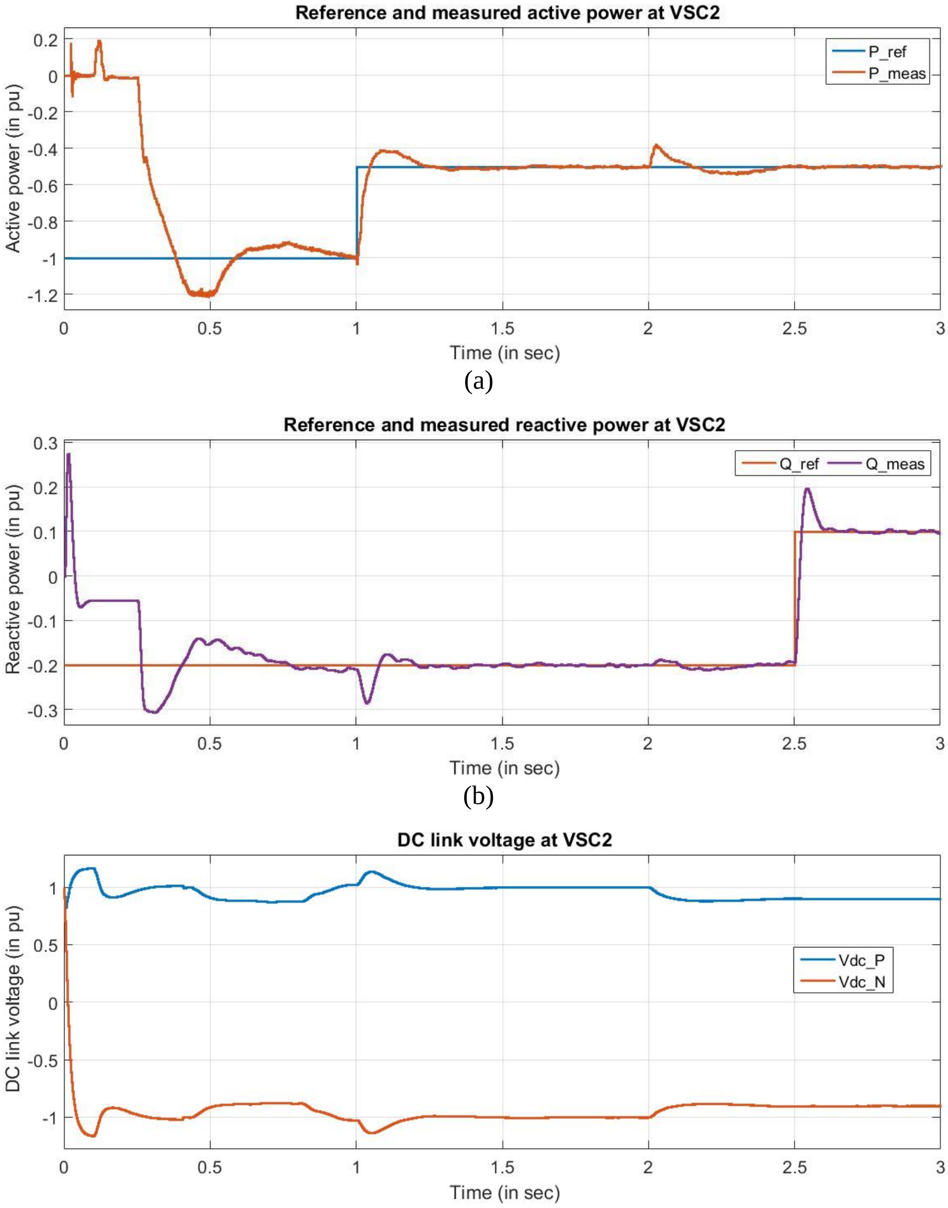
(c)

Fig. 3.14: Simulation results at VSC1 (a) Active power, (b) DC link voltage, (c) Reactive power

From Fig. 3.14 following observations have been made for VSC1:

- It is observed that the active power changes from 1 pu to 0.5pu as the reference of active power changes at time t=1 sec.
- At time t=1.5 sec, the reactive power reference changes from 0 to +0.2 pu and the measured reactive power follows the references and settles to +0.2 pu after a short period.

- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles.



(a)

(b)

(c)

Fig. 3.15: Simulation results at VSC1 (a) Active power, (b) DC link voltage, (c) Reactive power

From Fig. 3.15 following observations have been made for VSC2:

- It is observed that the active power changes from 1 pu to 0.5pu as the reference of active power changes at time t=1 sec.

- At time t=2 sec, the DC link voltage reference is reduced by 0.1 pu to a new value of 0.9 pu. The DC link voltages slowly starts dipping and reaches to 0.9 pu and settles.
- At time t=2.5 sec, the reactive power reference changes from -0.2 to +0.1 pu and the measured reactive power follows the references and settles to +0.1 pu after a short period.

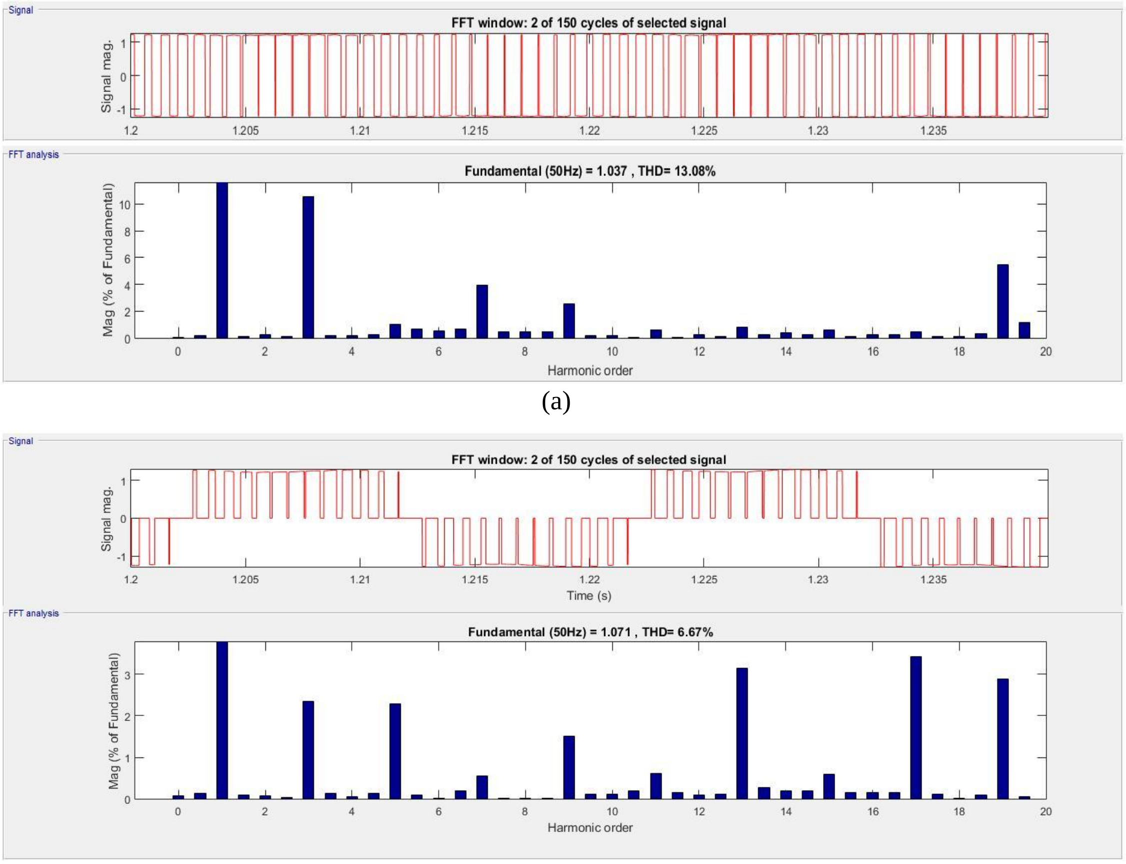
By comparing results in CASE-I and CASE-II following observations were made:

- It is observed that the active power, reactive power and DC link voltage changes as their reference values varies similar to that of CASE-1.
- The overshoot of active power for CASE-2 is much more than that of in CASE-1.
- Although, the response time in CASE-2 is litter shorter but responses are less accurate.

3.6 COMPARISON BETWEEN 2 LEVEL AND 3 LEVEL VSC BASED HVDC SYSTEM

The major difference between the 2 configurations of VSC based HVDC system is their VSC converters. As the names suggest a 2 level VSC system has 2 levels ($+V_{dc}$ & $-V_{dc}$) and a 3 level VSC system has 3 levels ($+V_{dc,}$ 0 & $-V_{dc}$) in the AC side voltage of the converter. The AC side voltage consists of these voltage levels changes at high carrier frequency according to PWM technique.

FFT analysis shows the THD in these voltages for both configurations. Fig.3. shows FFT analysis for 2 level configuration and Fig.3. shows FFT analysis for 3 level configuration. From these figures it was observed that 3 level VSC based systems has lower THD (6.67%) than the THD (13.8%) of a 2 level VSC based HVDC system. Lower THD means less need of AC filters which is economically beneficial.



(a)

(b)

Fig. 3.16: THD in AC Voltage at VSC in (a) 2-level VSC, (b) 3-level VSC,

3.7 CONCLUSIONS

A dq theory based control system for a 3 level VSC based HVDC system is designed consisting of outer controllers which includes Active power controller, Reactive power controller and DC voltage controller and fast inner current controllers. With correct combination of outer controllers 2 strategies were stated and implemented on a 3 level VSC based HVDC system. After applying both the strategies with different combinations as described in case I and case II following conclusions are drawn:

- The 3-level VSC based system shows satisfactory performance in both the cases for regulating various parameters such as active and reactive power at both the converter station. Also, The DC link voltage was maintained as per the reference value.
- The performance of the VSC based system is better when Strategy 1 is applied on VSC2 and Strategy 2 is applied on VSC1 (case I). In case II, the responses

for the controllers were slow and less accurate as compared to case I. i.e. a VSC based HVDC system having active power controller and reactive power controller on VSC converter working as Rectifier and DC link voltage controller and reactive power controller on VSC converter working as a Inverter shows the best results.

- It can also be observed in this chapter, That the reactive powers of both the VSC converters in both the cases is independent of each other and can be controlled efficiently at each VSC converter station.
- Also, the performance of 3-level VSC based systems is superior to 2-level VSC based HVDC system as the THD is less for 3-level VSC systems.

CHAPTER-4 : FAULT ANALYSIS OF A VSC BASED HVDC SYSTEM

4.1 INTRODUCTION

Every power system ever designed is sensitive to power quality problems such as disturbances and surges in ac systems. Normally the AC system operates under balanced conditions, but sometimes unbalance conditions such as a single line fault, three phase to ground fault or double line to ground fault may also occur in the system. It is essential to ensure stability of VSC based HVDC from DC link voltage dip or rise and change in active and reactive power during disturbances from ac systems and sensitive loads, it is necessary to study the response of VSC-HVDC with control algorithm during asymmetrical conditions

In this chapter, the simulation of a 3 level VSC based HVDC system for different types of faults using MATLAB/SIMULINK is performed and the various parameters of the VSC based HVDC system are analyzed in such cases. Single line to ground fault and three phase faults are applied on both VSC as two different cases and system performance is analyzed.

4.2 PQ CHARACTERISTICS

The maximum power transfer through a VSC based HVDC maintaining the stability is limited by the following factors:

- Maximum current carrying capability of IGBT’s. As the AC voltage reduces power through IGBT also reduces. Hence, this limits the power transfer capability to a circle.
- Maximum DC link voltage: The VSC converter AC voltage is directly proportional to the DC link voltage. The reactive power depends upon the VSC converter AC voltage and source voltage. If the source voltage is high it can match with the VSC converter AC voltage for maximum DC link voltage and the reactive power capability is quite moderate and increases with decreasing AC voltage.

- Maximum DC link current.

Fig. 4.1 shows the active and reactive power converter capabilities for a VSC converter.

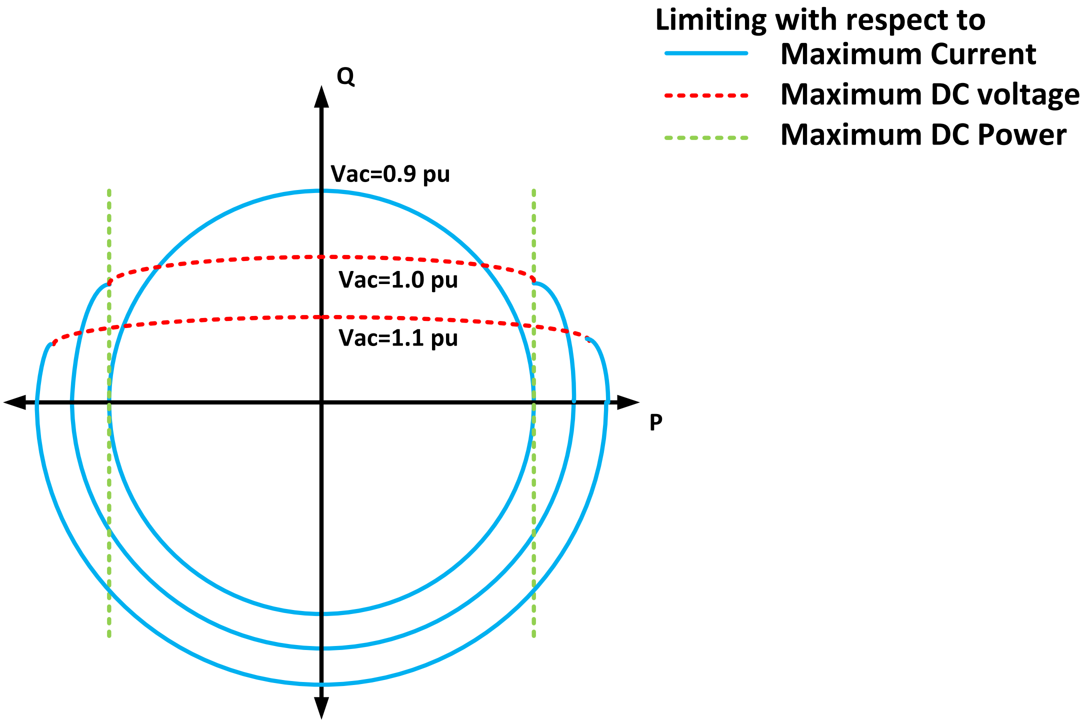


Fig. 4.1: Active and reactive power converter capabilities [4]

In previous chapters, the following observations are drawn for VSC based HVDC system in which VSC1 works as rectifier and VSC2 works as inverter:

- For VSC1, Active power controller provides the d component of the reference current.
- For both VSC, Reactive power controller provides q component of the reference current.
- For VSC2, DC link voltage controllers provides d component of the reference current.

To ensure the stability of VSC based HVDC system under disturbance the system parameters should satisfy following conditions:

- The DC link voltage or current should not rise or fall below a certain value for a fault which occurs at a location other than the DC line. Because it reduces the reliability of the system.

- The VSC based system should reach study state as the disturbance removes from the AC system. i.e. the DC link voltage, active power and reactive power may suffer dip or rise during disturbance but as the disturbance clears the VSC based system must come to a steady state where its parameters settles on their reference values.

4.3 SIMULATION AND RESULTS

In this section, the 3-level VSC based HVDC system and its control algorithm used chapter 3will be analyzed for single line to ground fault and three phase to ground fault at both inverter and rectifier.

The simulation of the VSC based HVDC system described above was done in MATLAB/SIMULINK with the following conditions.

- At time t=0 sec, the system is initialized and the reference value of the DC link voltage reference is set to 1 pu, Active power reference is set to 1 pu i.e. 1 pu active power is flowing from VSC1 to VSC2, Reactive power reference for VSC1 is set to 0 pu and reactive power reference for VSC2 is set to -0.2 pu. It takes around 1 sec for VSC based HVDC system to reach steady state conditions.
- At time t=1.1 sec, A 5-cycle fault is applied either on rectifier or on inverter.
- At time t=1.2 sec, the fault is cleared.

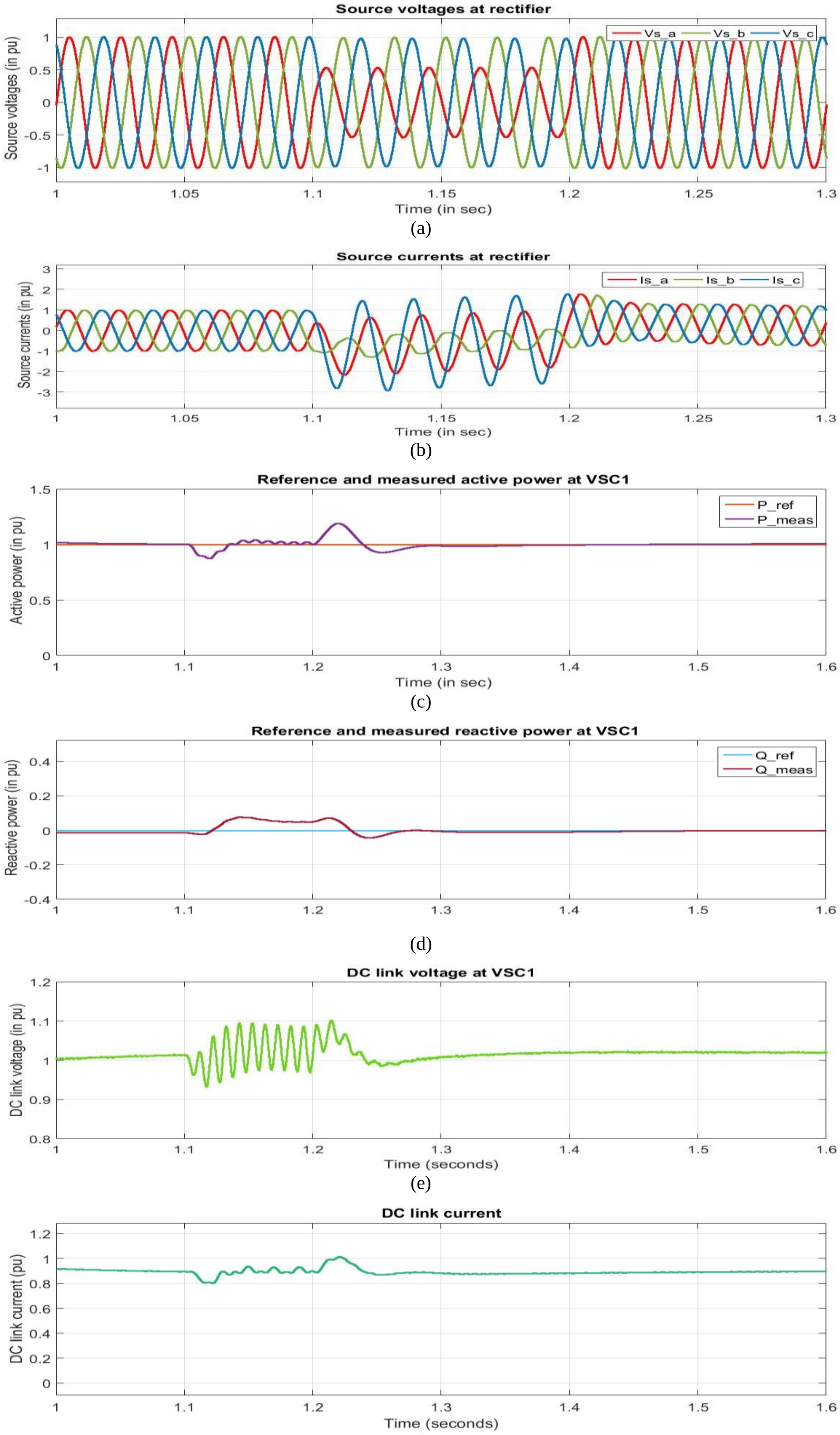
The VSC based HVDC system was simulated for single line to ground fault and three phase to ground fault.

4.3.1 SINGLE LINE TO GROUND FAULT

A 50 % single line to ground fault will be applied on rectifier or inverter phase A.

4.3.1.1 FAULT ON RECTIFIER SIDE

In this section the faults will be applied on the rectifier side and the parameters of both the VSC will be observed.



(a)

(b)

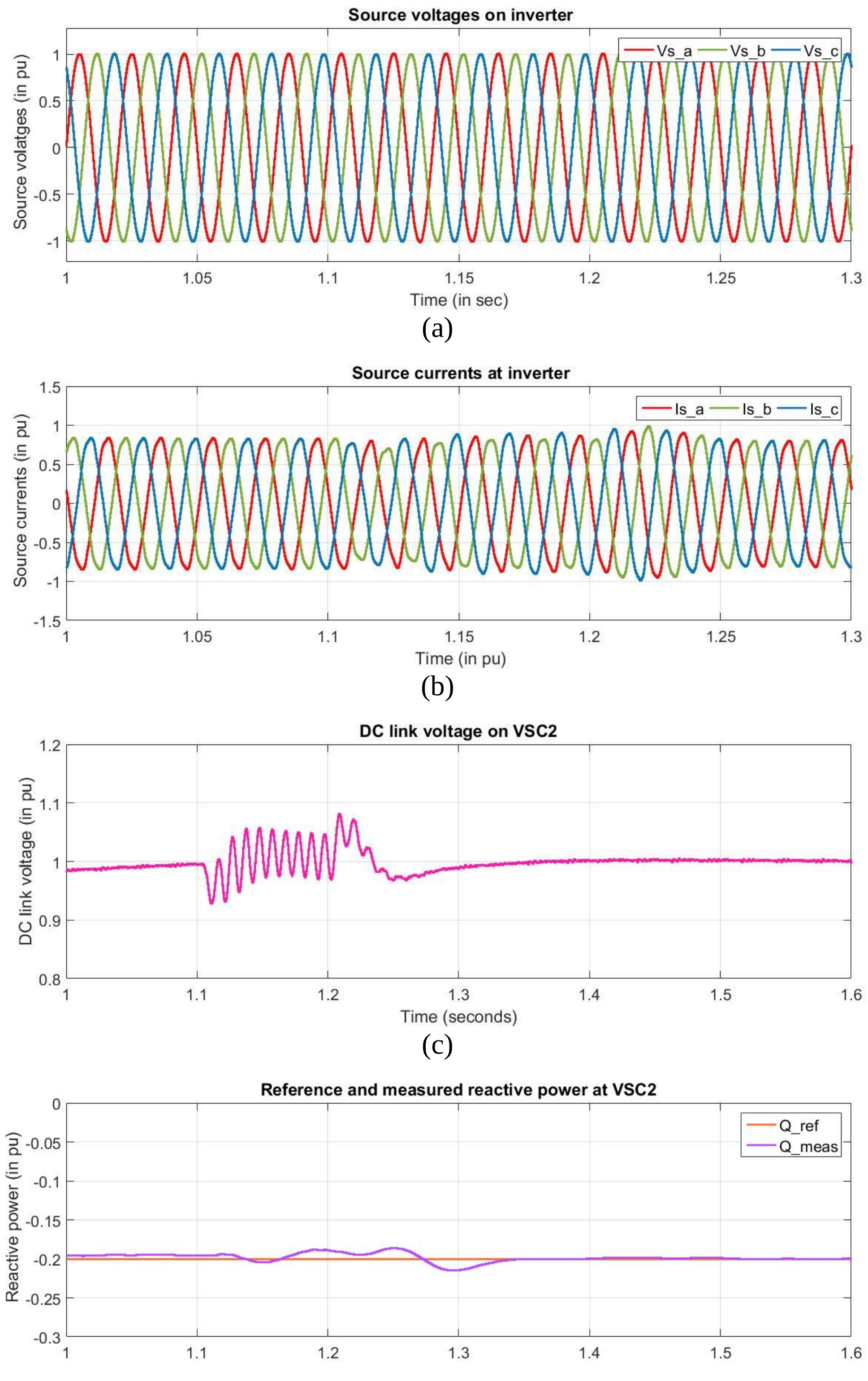
(c)

(d)

(e)

(f)

Fig. 4.2: Simulation results for VSC1 due to single line to ground fault at rectifier (a) Source voltages, (b) Source currents (c) Active power (d) Reactive power (e) DC link voltage (f) DC link current



(a)

(b)

(c)

(d)

Fig. 4.3: Simulation results for VSC2 for single line to ground fault at rectifier (a) Source voltages, (b) Source currents (c) DC link voltage (d) Reactive power

The change in various parameters such as active power, reactive power, DC link voltage, DC link current, source voltages and currents can be observed from the Fig. 4.2 for a single line to ground fault on rectifier terminal. The Simulation results for Single line to ground fault on rectifier are shown in Fig. 4.2 and Fig. 4.3.

From Fig. 4.2 following observations have been made for rectifier:

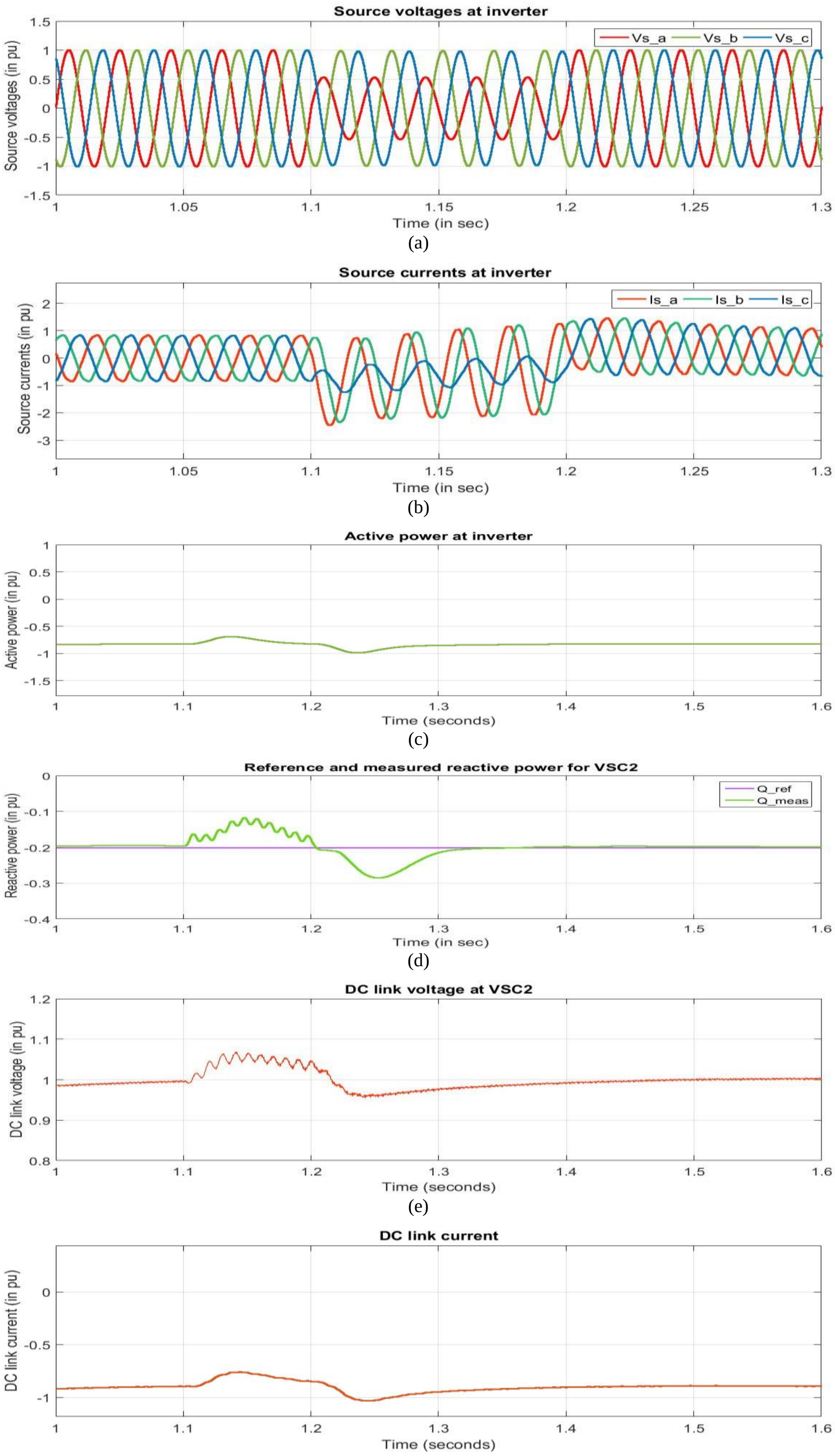
- From Fig. 4.2 (a) it is observed that the source voltages are unbalanced during faults and the voltage of the phase having fault is around 0.5 pu.
- Fig. 4.2 (b) shows that during fault source currents are unbalanced and high.
- Fig. 4.2 (c) presents that the active power as a small dip and again rises to its reference value and has very small oscillation.
- In Fig. 4.2 (d), the reactive power increases to about 0.1 pu as the fault occurs and settles backs to its reference.
- The DC link voltage fluctuates between 0.9 to 1.1 pu as the fault occurs and regains to its reference after the fault is cleared shows fig. 4.2 (e)
- In Fig. 4.2 (f), The DC link currents have a small dip as the fault occurs and later have very small fluctuations.

From Fig. 4.3 following observations have been made for inverter:

- From Fig. 4.3 (a) it is observed that the source voltages are balanced for inverter end and have no effect of fault
- Fig. 4.3 (b) shows that during fault source currents are unbalanced but not that high for inverter end.
- Fig 4.3 (c) shows that the impact of fault also occurs on the DC link voltage at inverter end as it fluctuates between 0.9 to 1.1 pu as the fault occurs and regains to its reference after the fault is cleared.
- In Fig. 4.3 (d), the reactive power has a small fluctuation as the fault occurs and settles backs to its reference.

4.3.1.2 FAULT ON INVERTER SIDE

In this section a 50 % single line to ground fault will be applied on the inverter side and the parameters of both the VSC will be observed.



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 4.4: Simulation results for VSC2 due to single line to ground fault at inverter (a) Source voltages, (b) Source currents (c) Active power (d) Reactive power (e) DC link voltage (f) DC link current

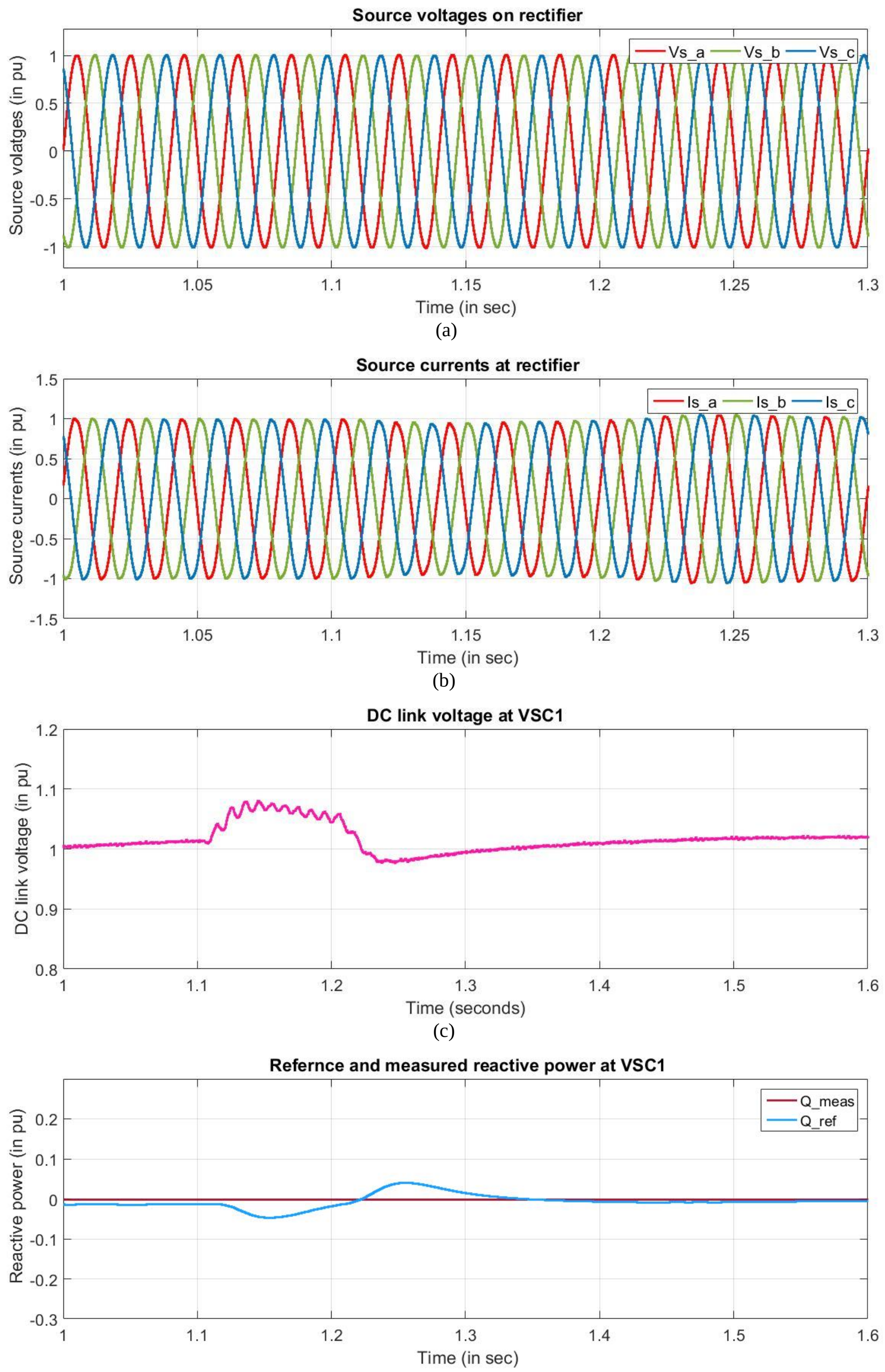


Fig. 4.3: Simulation results for VSC1 for single line to ground fault at inverter (a) Source voltages, (b) Source currents (c) DC link voltage (d) Reactive power

The change in various parameters such as active power, reactive power, DC link voltage, DC link current, source voltages and currents can be observed from the Fig. 4.4 for a single line to ground fault on inverter terminal. The Simulation results for Single line to ground fault on inverter are shown in Fig. 4.4 and Fig 4.5.

From Fig. 4.4 following observations have been made for inverter:

- From Fig. 4.4 (a) it is observed that the source voltages are unbalanced during faults and the voltage of the phase having fault is around 0.5 pu.
- Fig. 4.4 (b) shows that during fault source currents are unbalanced and high.
- Fig. 4.4 (c) presents that the active power as a small dip of about 0.1 pu and again rises to its reference value and has very small oscillation.
- In Fig. 4.4 (d), the reactive power increases about 0.1 pu as the fault occurs and settles backs to its reference.
- The DC link voltage starts to rise as the fault occurs and saturates to about 1.05 pu and also with rise some fluctuations of very small magnitude is also seen in it. As the fault clears it regains to its reference shows fig. 4.4 (e)
- In Fig. 4.4 (f), The DC link currents have a small dip as the fault occurs and later adjusts itself as the fault clears.

From Fig. 4.5 following observations have been made for rectifier:

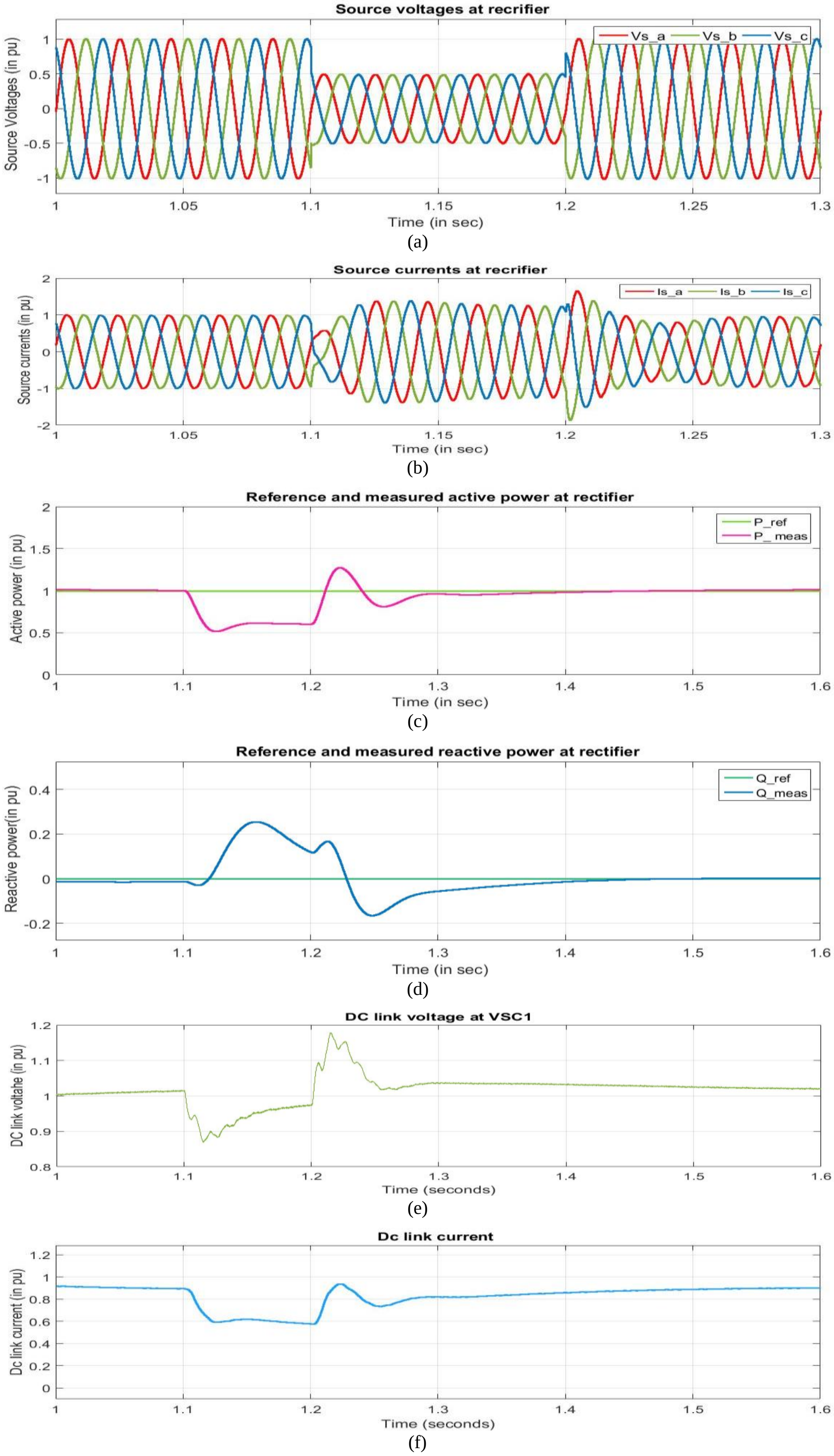
- From Fig. 4.5 (a) it is observed that the source voltages are balanced for rectifier end and have no effect of fault
- Fig. 4.5 (b) shows that during fault source currents suffers a small dip.
- Fig 4.5 (c) shows that the impact of fault also occurs on the DC link voltage at the rectifier end as it rises and saturates to about 1.05 pu and fluctuates on its own position as the fault occurs and settles to its reference as the fault clears.
- In Fig. 4.5 (d), the reactive power has a small fluctuation as the fault occurs and settles backs to its reference.

4.3.2 3 PHASE TO GROUND FAULT

A 50 % three phase to ground fault will be applied on rectifier or inverter phase A.

4.3.2.1 FAULT ON RECTIFIER SIDE

In this section the fault will be applied on the rectifier side and the parameters of both the VSC will be observed.



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 4.6: Simulation results for VSC1 due to three phase to ground fault at rectifier (a) Source voltages, (b) Source currents (c) Active power (d) Reactive power (e) DC link voltage (f) DC link current

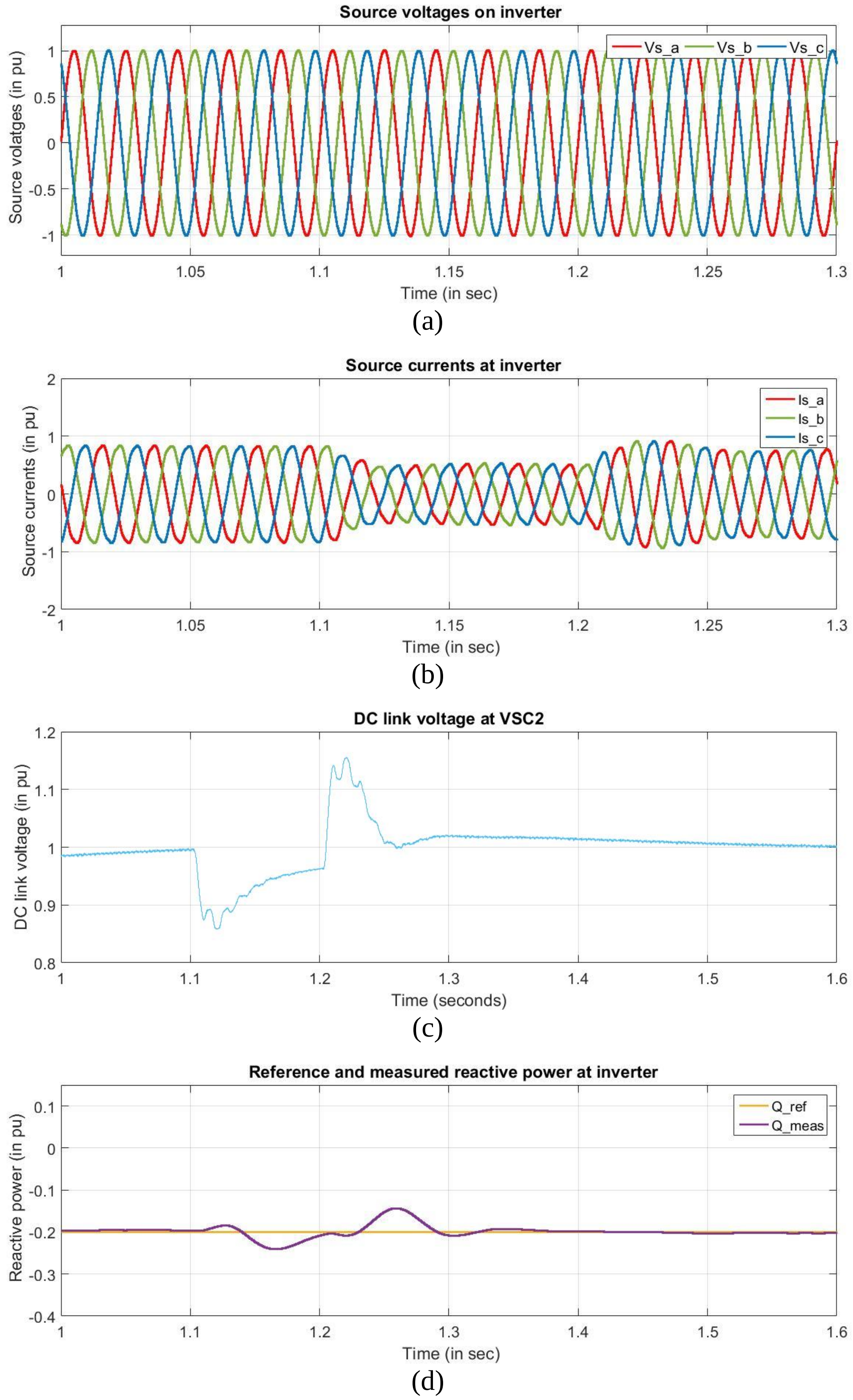


Fig. 4.7: Simulation results for VSC2 for three phase to ground fault at rectifier (a) Source voltages, (b) Source currents (c) DC link voltage (d) Reactive power

The change in various parameters such as active power, reactive power, DC link voltage, DC link current, source voltages and currents can be observed from the Fig. 4.6 for a three phase to ground fault on rectifier terminal. The Simulation results for three phase to ground fault on rectifier are shown in Fig. 4.6 and Fig. 4.7.

From Fig. 4.6 following observations have been made for rectifier:

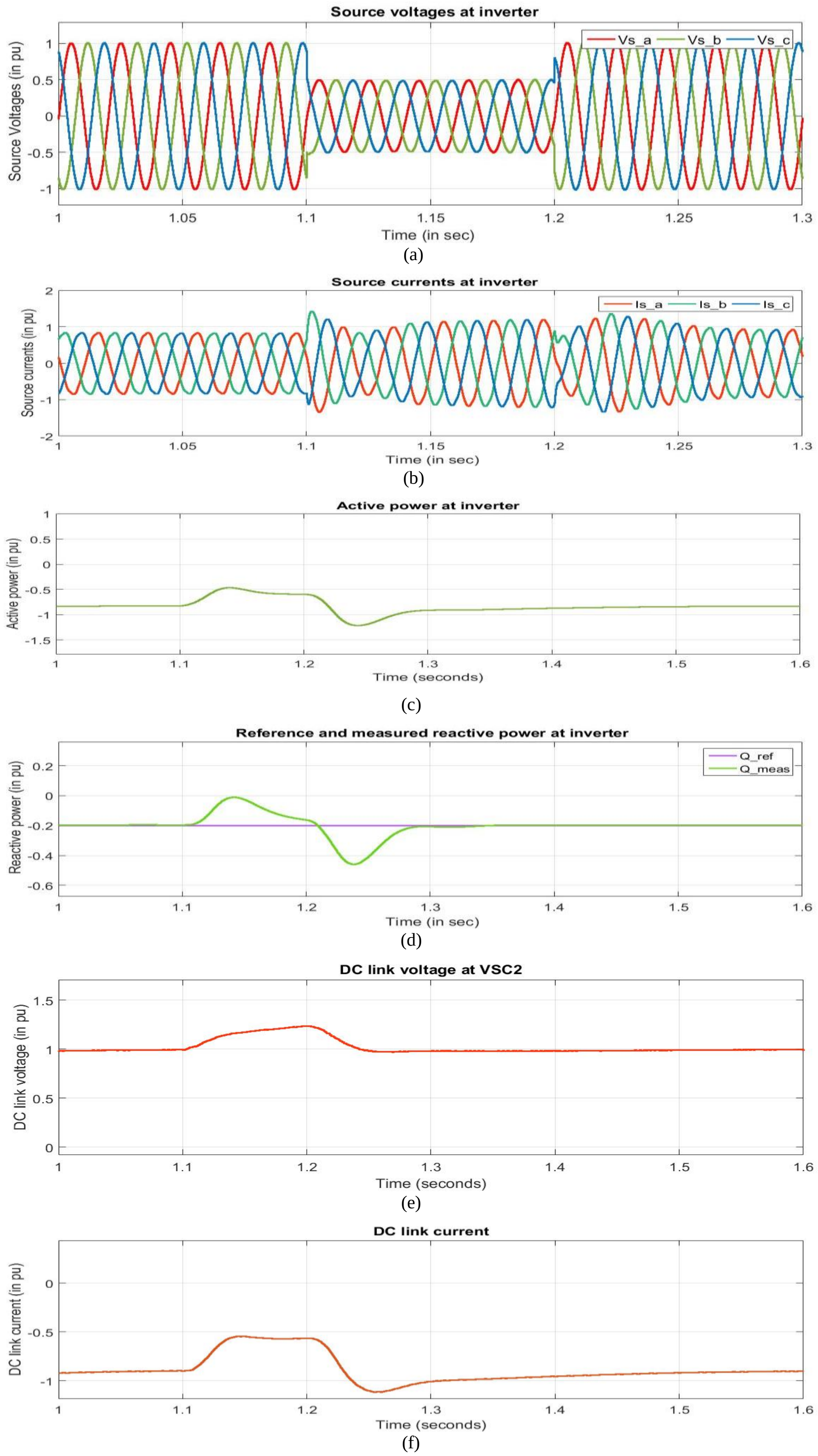
- From Fig. 4.6 (a) it is observed that the source voltages are balanced during faults and the voltage of the phase is around 0.5 pu.
- Fig. 4.6 (b) shows that during fault source currents are higher than 1 pu.
- Fig. 4.6 (c) presents that the active power has a huge dip of about 0.5 pu and again rises to its reference value when fault clears.
- In Fig. 4.6 (d), the reactive power increases to about 0.3 pu as the fault occurs and settles backs to its reference after the fault clears.
- The DC link voltage suddenly drops to 0.9 and tries to reach 1 pu. As the fault clears it reaches1.1 pu suddenly and settels on 1 shows fig. 4.6 (e)
- In Fig. 4.6 (f), The DC link currents have a huge dip of about 0.4 pu as the fault occurs.

From Fig. 4.7 following observations have been made for inverter:

- From Fig. 4.7 (a) it is observed that the source voltages are balanced for inverter end and have no effect of fault
- Fig. 4.7 (b) shows that during fault source currents are unbalanced and also drops to around 0.5 pu at inverter end.
- Fig 4.7 (c) shows that the impact of fault also occurs on the DC link voltage at inverter end as it suddenly dips to 0.9 pu as the fault occurs and increases during fault but could not reach 1 pu and regains to its reference after the fault is cleared.
- In Fig. 4.7 (d), the reactive power has a small fluctuation as the fault occurs and settles backs to its reference.

4.3.2.2 FAULT ON INVERTER SIDE

In this section a 50 % three phase to ground fault will be applied on the inverter side and the parameters of both the VSC will be observed.



(a)

(b)

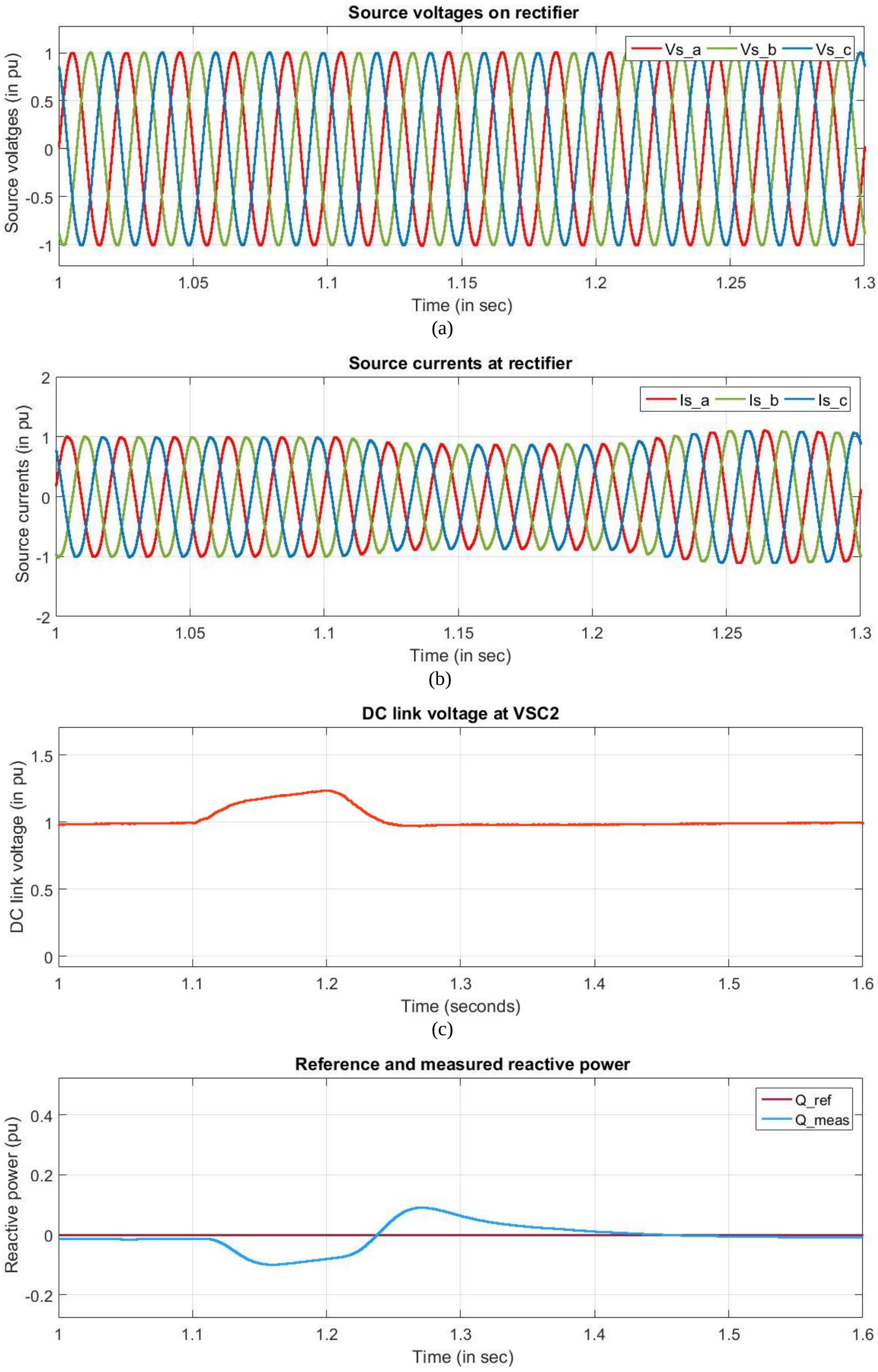
(c)

(d)

(e)

(f)

Fig. 4.8: Simulation results for VSC2 due to three phase to ground fault at inverter (a) Source voltages, (b) Source currents (c) Active power (d) Reactive power (e) DC link voltage (f) DC link current



(a)

(b)

(c)

(d)

Fig. 4.9: Simulation results for VSC1 for three phase to ground fault at inverter (a) Source voltages, (b) Source currents (c) DC link voltage (d) Reactive power

The change in various parameters such as active power, reactive power, DC link voltage, DC link current, source voltages and currents can be observed from the Fig. 4.8 for a three phase to ground fault on inverter terminal. The Simulation results for Single line to ground fault on inverter are shown in Fig. 4.8 and Fig 4.9.

From Fig. 4.8 following observations have been made for inverter:

- From Fig. 4.8 (a) it is observed that the source voltages are balanced during faults and the voltage of the phase is around 0.5 pu.
- Fig. 4.8 (b) shows that during fault source currents are unbalanced and higher than 1 pu.
- Fig. 4.8 (c) presents that the active power has a huge dip of about 0.5 pu and again rises to its reference value when fault clears.
- In Fig. 4.8 (d), the reactive power increases about 02 pu to a new value around 0 as the fault occurs and settles backs to its reference after the fault clears.
- The DC link voltage starts to rise as the fault occurs and reaches around 1.25 pu when the fault is cleared and as the fault clears it regains to its reference shows fig. 4.8 (e)
- In Fig. 4.8 (f), The DC link currents have a huge dip of about 0.5 pu as the fault occurs and later adjusts itself as the fault clears.

From Fig. 4.9 following observations have been made for rectifier:

- From Fig. 4.9 (a) it is observed that the source voltages are balanced for rectifier end and have no effect of fault
- Fig. 4.9 (b) shows that during fault source currents suffers a small dip.
- Fig 4.9 (c) shows that the impact of fault also occurs on the DC link voltage at the rectifier end as it rises and reaches around 1.25 pu when the fault is cleared and as the fault clears it regains to its reference
- In Fig. 4.9 (d), the reactive power has a small fluctuation as the fault occurs and settles backs to its reference.

4.4 CONCLUSIONS

Fault analysis of a three level VSC based HVDC system having a synchronous reference dq theory based control system consisting of outer controllers which includes Active power controller, Reactive power controller and DC voltage controller and fast inner current controllers was performed. With replacing the controllers systems performance is analysed and following conclusions are drawn:

- In fault analysis, it is observed that if the fault is at rectifier end the DC link voltage drops but if fault is on inverter end it starts to rise and it is also observed that for the fault on inverter side the DC link voltage have more fluctuation in comparison with fault on rectifier side. This happens because the DC voltage controller is working on inverter. So, whenever a fault occurs it cannot control the DC link voltage because of interaction of fault with inverter parameters.
- For Single line to ground fault on both rectifier and inverter there is only small fluctuations in active power, DC link voltage, DC link current and the reactive power
- For 3 phase to ground fault on rectifier the VSC based system suffer with huge dip in active power and DC link current, negligible variations in reactive power and when fault occurs at inverter the DC link voltage rises to a extremely high value
- It can also be observed in this chapter that for previous control algorithm the performance of VSC based HVDC system for Single line to ground fault at both rectifier and inverter and also for three phase to ground fault at rectifier and inverter is satisfactory.
- It is also observed that during fault the system still delivers active power i.e. the VSC based HVDC system has fault ride through capacity.

CHAPTER-5 : SOME INVESTIGATIONS ON VSC BASED HVDC SYSTEM

5.1 INTRODUCTION

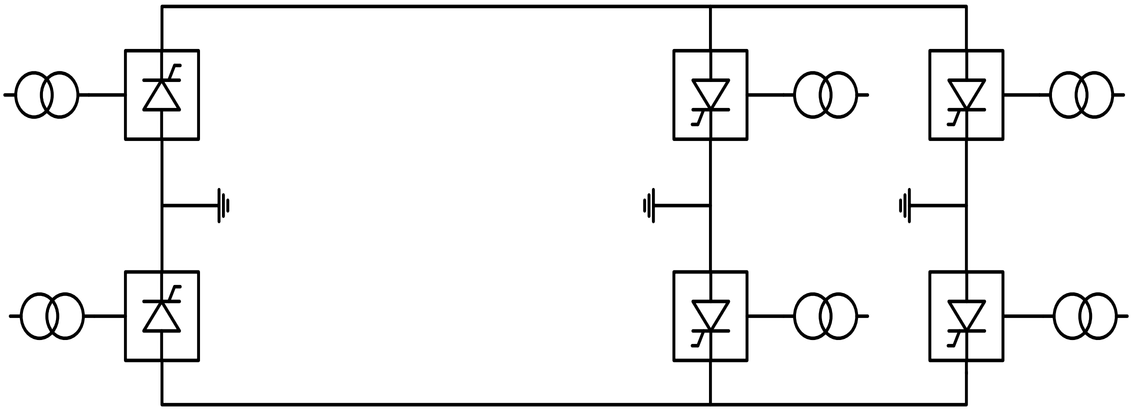
A multi-terminal transmission system has more than two converter station connected to each other through DC lines or cable. Some of these converters operate as rectifier and some would operate as inverters. These converters are connected in parallel. As the HVDC systems does not require phase and frequency synchronization as AC systems the present a better choice for transmission of electricity.

In this chapter, the simulation of a multi-terminal three level VSC based system using MATLAB/SIMULINK is performed and the various parameters of the VSC based HVDC system are analyzed in such cases. A control scheme for such systems is proposed in accordance with the active and reactive power capabilities of the VSC converters. Also, the performance of the multi-terminal three-level VSC based system is observed.

5.2 MULTI-TERMINAL VSC BASED HVDC SYSTEM:

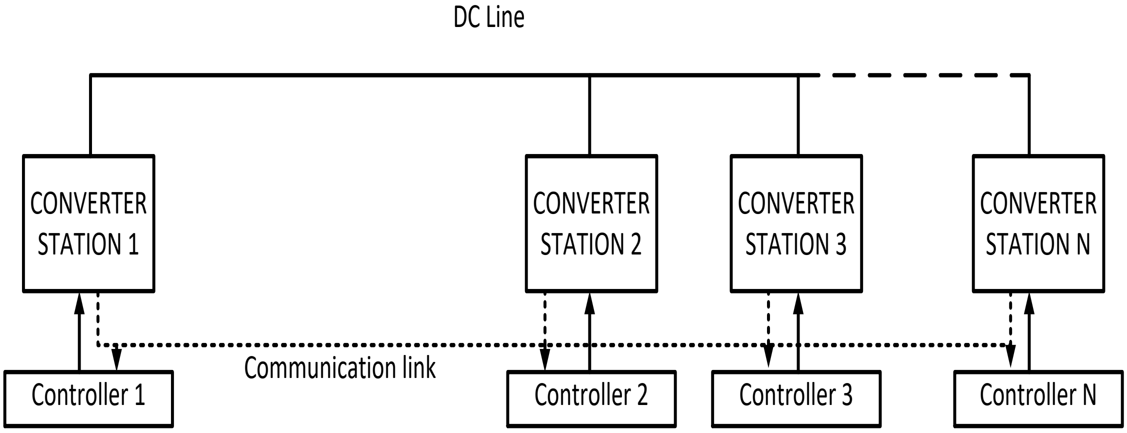
Multi-terminal HVDC systems are based suited for a power system which have a huge generation unit placed offshore and the power generated is now needs to be transferred to many load centres. VSC based HVDC definitely a better option than conventional HVDC system because they have better control over active power transfer and maintaining the DC link voltage. Also, the reactive power at each converter station can be controlled independently. Fig. 5.1 shows a multiterminal HVDC system. There are two possible types of MTDC systems:

- Series
- Parallel



5.3 CONTROL OF MULTI-TERMINAL VSC BASED HVDC SYSTEM:

In the previous chapters, the designing of controllers for two level and three VSC based HVDC system is already done. For the control of Multi terminal VSC based HVDC systems we follow the same approach of synchronous reference theory and design a control system for MTDC. Fig .5.2 shows that there are N numbers of VSC converter station in a MTDC system and every controller has its own controller. That means there are also N numbers of controllers. Out of these N controllers one is used to maintain the DC link voltage and the rest maintains the active power and reactive power. Since the active power is controlled for each converter station the algebraic sum of active power of the converters except converter station having DC voltage controller will be equal to the power delivered by the converter having DC voltage controller.



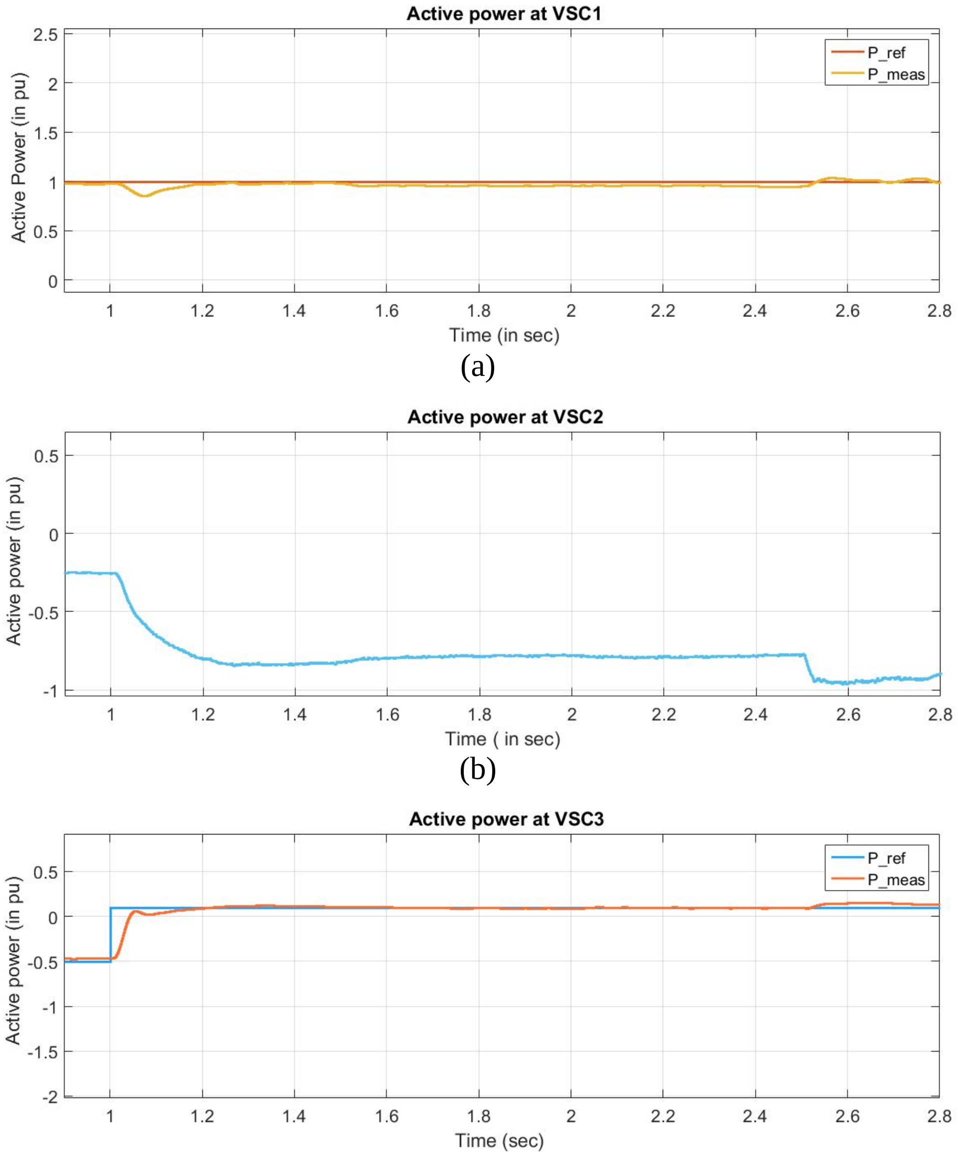
5.4 SIMULATION AND RESULTS

A three terminal three level system is considered for simulation.

- VSC1 works as a rectifier and has active and reactive power controller.
- VSC2 works as inverter and has DC voltage controller and reactive power controller.
- VSC3 works as both rectifier and inverter and has active and reactive power controller.

The simulation of the multi-terminal VSC based HVDC system described above was done in MATLAB/SIMULINK with the following conditions.

- At time t=0 sec, the system is initialized and the reference value of the DC link voltage reference is set to 1 pu, Active power reference is set to 1 pu for VSC1 and -0.5 for VSC3 i.e. 1 pu active power is flowing from VSC1 to VSC2 and VSC3, Reactive power reference for VSC1 is set to 0 pu, reactive power reference for VSC2 is set to -0.2 pu and reactive power reference for VSC3 is set to -0.1 pu. It takes around 1 sec for VSC based HVDC system to reach steady state conditions.
- At time t=1.0 sec, active power reference for VSC3 is changed to +0.1 from -0.5.
- At time t=1.5 sec, the reactive power reference for VSC 1 is changed to -0.1.
- At time t=2.0 sec, the reactive power reference for VSC 3 is changed to 0.
- At time t=2.5 sec, the DC link voltage reference is changed to 0.9.



(a)

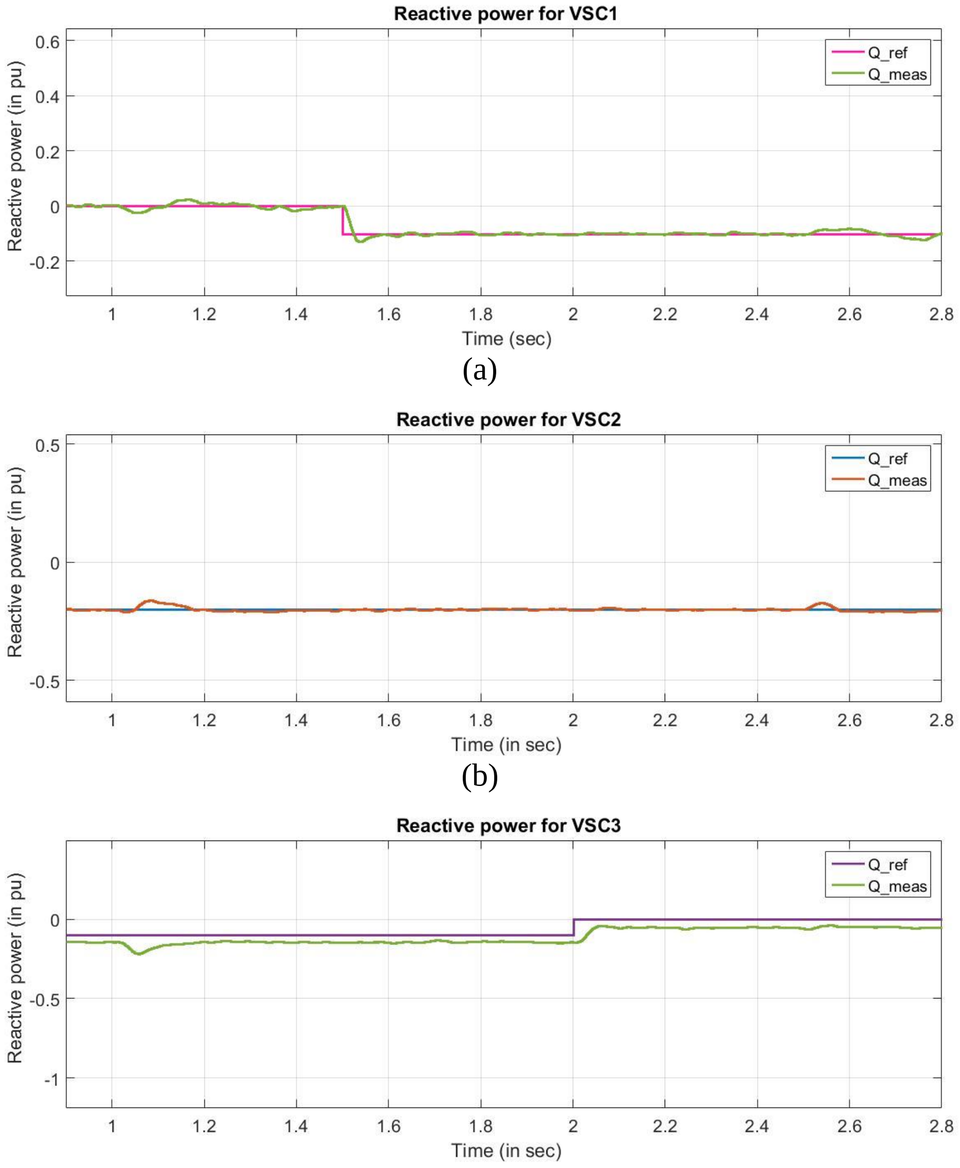
(b)

(c)

Fig. 5.3: Simulation results of Active power for (a) VSC1, (b)VSC2 (c) VSC3

From the Fig. 5.3 following observation are made for Multi-terminal HVDC system:

- At time t= 1, the reference active power of VSC3 changes from -0.5 to +0.1 and active power measured at VSC3 follow the reference value.
- The active power through VSC1 does not varies because it has its own active power controller which does not let it vary its active power.
- The active power through VSC2 varies because it has a voltage controller and there is no controller for active power at VSC2.
- Also, the change in VSC3 is equal to change in VSC2.



(a)

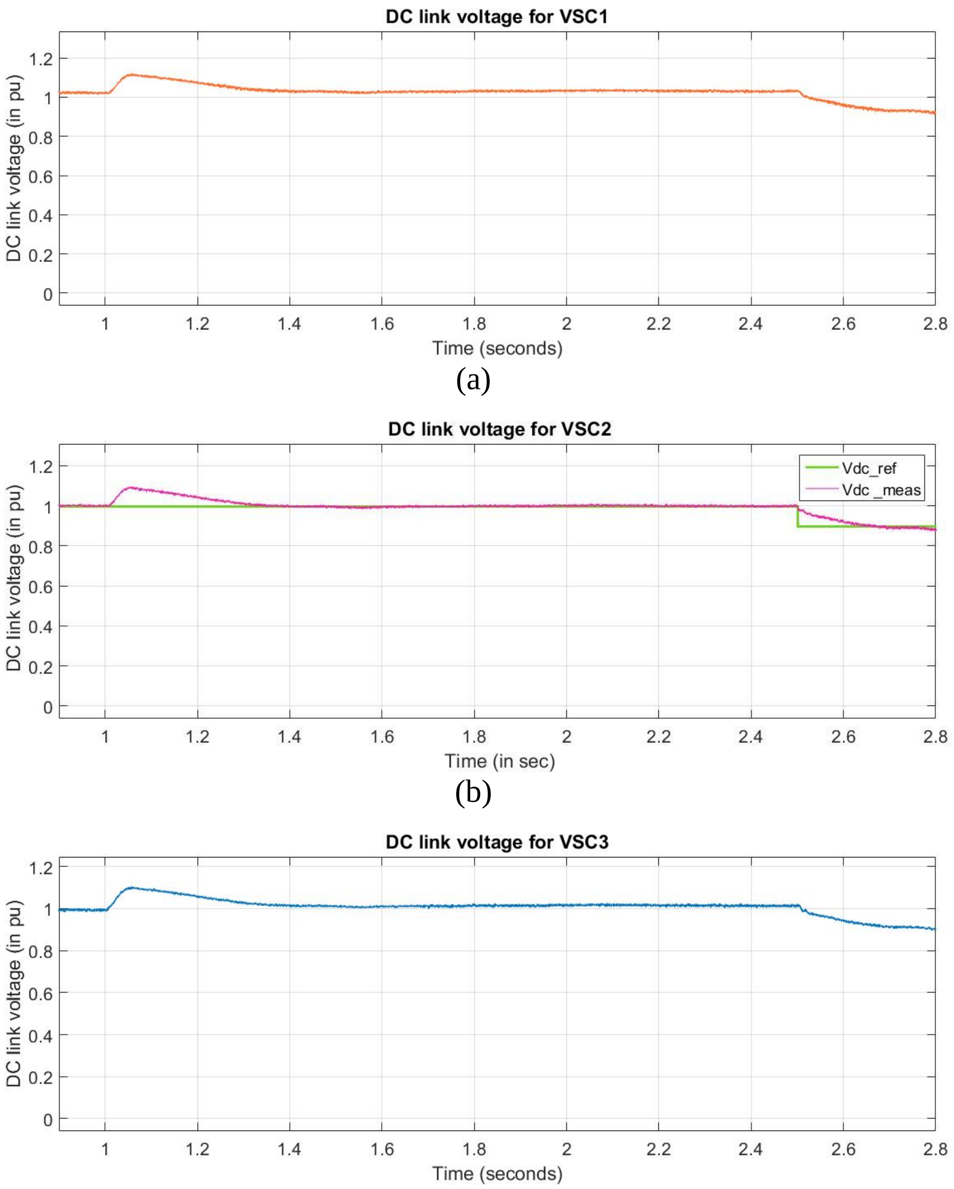
(b)

(c)

Fig. 5.4: Simulation results of Reactive power for (a) VSC1, (b)VSC2 (c) VSC3

From the Fig. 5.4 following observation are made for Multi-terminal HVDC system:

- At time t= 1.5, the reference reactive power of VSC1 changes from 0 to -0.1 and reactive power measured at VSC1 follow the reference value.
- At time t= 2, the reference reactive power of VSC3 changes from -0.1 to 0 and reactive power measured at VSC3 follow the reference value.
- At time t=1.5 the reactive power through VSC1 or VSC 2 does not varies and also at time t=2 the reactive power through VSC1 or VSC 2 does not varies because all VSC have their own reactive power controller which does not let them vary their reactive power for change in reference of other. This means that reactive power for each VSC converter can be controlled independently.



(a)

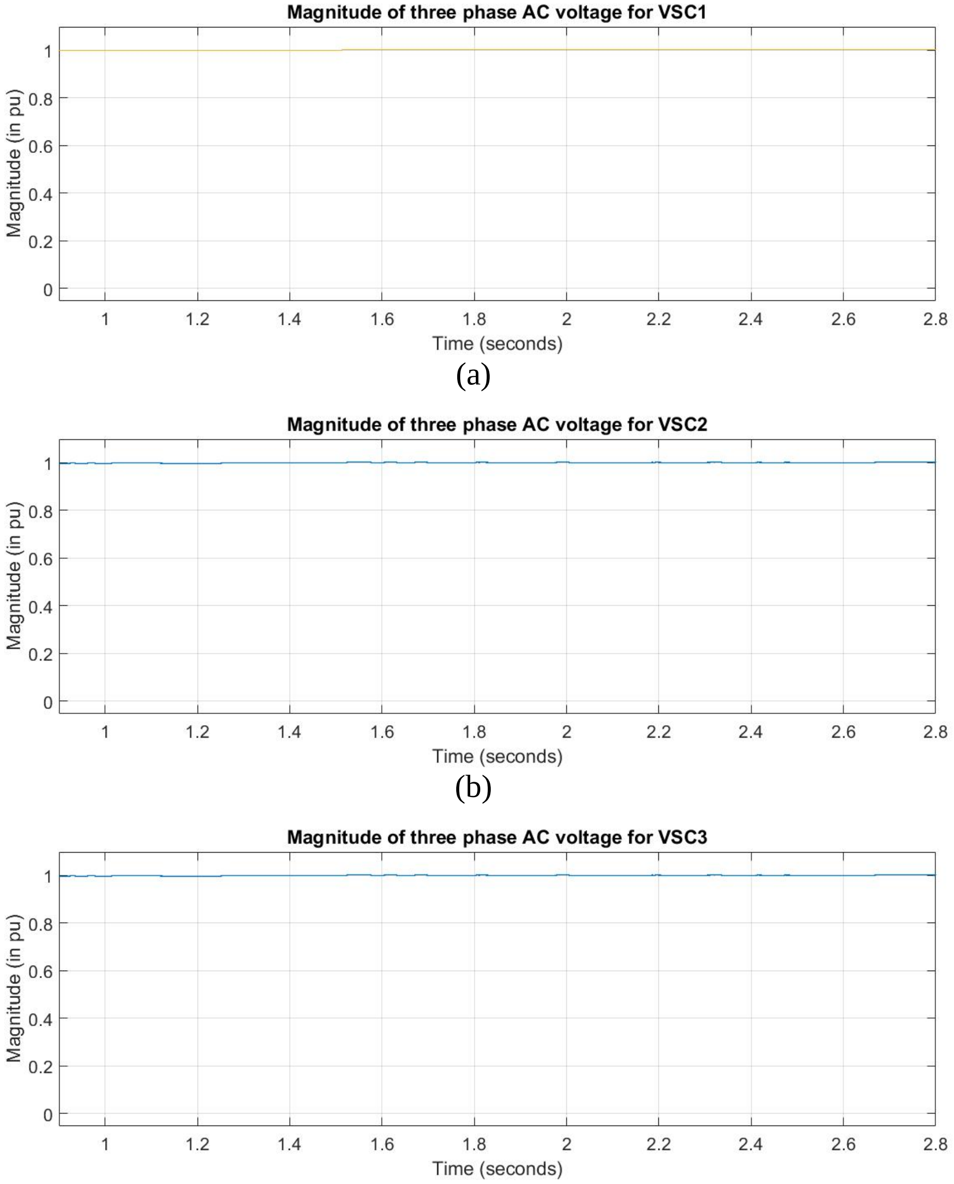
(b)

(c)

Fig. 5.5: Simulation results of DC link voltage for (a) VSC1, (b)VSC2 (c) VSC3

From the Fig. 5.5 following observation are made for Multi-terminal HVDC system:

- At time t= 2.5, the reference for DC link voltage is changed to 0.9 pu for VSC2 and the DC link voltage measured at VSC2 follow the reference value.
- The DC link voltage across VSC1 and VSC3 also changes as for this three level three terminal HVDC system VSC2 controller controls the DC voltage



(a)

(b)

(c)

Fig. 5.6: Simulation results of magnitude of AC voltages for (a) VSC1, (b)VSC2 (c) VSC3

From the Fig. 5.3 following observation are made for Multi-terminal HVDC system:

- Fig. 5.6 shows that there is no change in magnitude of the AC voltage for any change in reference value for any VSC converter.

5.5 CONCLUSIONS

The power transfer capabilities of a three terminal three level VSC based HVDC system and control for the same is studied in this chapter. A synchronous reference theory based control system for a three terminal three level VSC based HVDC system is designed consisting of outer controllers which includes Active power controller, Reactive power controller and DC voltage controller and fast inner current controllers. Through simulation results for dynamic changes following conclusions are drawn:

- The three terminal three level VSC based system shows satisfactory performance for regulating various parameters such as active and reactive power at both the converter station. Also, the DC link voltage was maintained as per the reference value.

- It can also be observed from the simulation results, that the DC link voltage of all three terminal VSC based HVDC system is regulated by controller of VSC2 and its performance is excellent.

- It can also be observed from the simulation results, that the reactive powers of all three VSC converters is independent of each other and can be controlled efficiently at each VSC converter station.

CHAPTER-6 : FUTURE SCOPE FOR WORK

1. Various other control algorithms such as fuzzy logic, genetic algorithm can be implemented for VSC based HVDC system.

2. Design the control algorithm and implementation of multilevel converters in HVDC applications.

3. Implementation of control techniques for wind power plant for onshore or offshore VSC based HVDC transmission system.

APPENDIX

Different system parameters and control gains are shown below:

1. CHAPTER-2

VSC rated power	1000 MW
Rated direct voltage (pole-to-pole)	320 kV
Rated voltage at transformer’s ac-grid side	400 kV
Rated voltage at transformer’s converter side	320 kV
Ac-side rated power	1000 MVA
Phase reactor inductance	0.10pu
Phase reactor resistance	0.0010pu
Dc-side converter capacitor	0.01mF
VSC switching frequency	1650 Hz
AC filter 1 (Single tuned filter)	Q=15, tuning freq.=1650 Hz
AC filter 2 (High pass filter)	Q=15, tuning freq.=3300 Hz

2. CHAPTER-3

VSC rated power	1000 MW
Rated direct voltage (pole-to-pole)	640 kV
Rated voltage at transformer’s ac-grid side	400 kV
Rated voltage at transformer’s converter side	320 kV
Ac-side rated power	1000 MVA
Phase reactor inductance	0.10pu
Phase reactor resistance	0.0010pu
Dc-side converter capacitor	0.01mF
VSC switching frequency	1650 Hz
AC filter 1 (Single tuned filter)	Q=15, tuning freq.=1650 Hz
AC filter 2 (High pass filter)	Q=15, tuning freq.=3300 Hz

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