# MODELLING OF VSC-HVDC LINK

DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
POWER SYSTEMS

Submitted by:

Dheeraj Kumar Saini
(2K14/PSY/06)

Under the supervision of

Dr. Suman Bhowmick

**DEPARTMENT OF ELECTRICAL ENGINEERING**
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

2016

# DEPARTMENT OF ELECTRICAL ENGINEERING

## DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

## CERTIFICATE

I, Dheeraj Kumar Saini, Roll No. 2K14/PSY/06 student of M. Tech. (Power System), hereby declare that the dissertation titled "MODELLING OF VSC-HVDC LINK" under the supervision of Dr. S. Bhowmick, Associate Professor, Department of Electrical Engineering, Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology, has not been submitted elsewhere for the award of any Degree.

Place: Delhi **DHEERAJ KUMAR SAINI**

Date: 25.07.2016

**Dr. S. BHOWMICK**

**SUPERVISOR**

Associate Professor

Electrical Engineering Department

Delhi Technological University

Bawana Road, Delhi-110042

# ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Dr. S. Bhowmick for his guidance and assistance in the thesis. The technical discussions with him were always been very insightful, and I will always be indebted to him for all the knowledge he shared with me. His prompt responses and availability despite his constantly busy schedule were truly appreciated. He always helped me in all the technical and non-technical issues during the production of this thesis. Without his consistent support, encouragement and valuable inputs, this project would not have become possible.

I would like to express my deep gratitude to Prof. Madhusudan Singh, Head, Department of Electrical Engineering for providing his support during my project.

I would also like to thank my batch-mates and friends who encouraged and helped me in completing the thesis work.

Finally, I express my deep sincere thanks to my Parents my brother and sister who motivated and encouraged me for higher studies, without which it wouldn't have been possible.



**DHEERAJ KUMAR SAINI**

(2K14/PSY/06)

M.Tech. (Power System)

Delhi Technological University, Delhi

# ABSTRACT


With the recent developments in semiconductors and control equipments, Voltage Source Converter (VSC) based High Voltage Direct Current (VSC-HVDC) has become feasible. Due to the use of Pulse Width Modulation (PWM) technique in VSC technology, it has a number of potential advantages such as short circuit current reduction, independent control of the active and reactive power etc. With such very favorable advantages, VSC-HVDC will likely be part of future transmission and distribution systems which supply industrial systems with a high load density, high reliability, quality requirements, and high cost associated with production stoppages.

In this thesis, the performance of Voltage Source Converter (VSC) based High Voltage DC (HVDC) transmission system is studied. A 200 MVA, ±100 kV link is modelled between two identical asynchronous AC systems. In addition, a three terminal VSC HVDC system was also studied. The system studies are based on three level neutral point clamped (NPC) converters. Current controlled scheme is used for active, reactive power and dc voltage control. One converter is operated in DC voltage control mode and reactive power control mode, while the other(s) operate in Active and Reactive power (PQ) control mode. The results are carried out in MATLAB-SIMULINK platform. The results validate the work.

# CONTENTS

# LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| HVDC | High Voltage Direct Current |
| NPC | Neutral Point Clamped |
| VSC | Voltage Source Converter |
| CSC | Current Source Converter |
| DC | Direct Current |
| MTDC | Multi Terminal Direct Current |
| AC | Alternative Current |
| GTO | Gate turn off thyristor |
| IGBT | Insulated Gate Bipolar Transistor |
| PWM | Pulse Width Modulation |
| LCC | Line Commutated Converter |
| FCC | Force Commutated Converter |
| PU | Per Unit |
| PLL | Phase Locked Loop |
| PCC | Point of Common Coupling |
| SPWM | Sinusoidal Pulse Width Modulation |

# LIST OF SYMBOLS

| | |
|---|---|
| $U_{dc}$ | DC link voltage |
| $C_{dc}$ | DC link capacitor |
| $S_N$ | Nominal apparent power of the converter |
| T | Time constant of DC link capacitor |
| $f_c$ | Carrier frequency |
| $f_1$ | Fundamental frequency |
| $m_f$ | Frequency modulation ratio |
| $V_{2i}$ | AC voltage at inverter side |
| $i_{vi}$ | AC current at inverter side |
| $V_{1i}$ | AC voltage at transformer secondary side |
| $i_{Ti}$ | AC current at transformer secondary side |
| M | modulation index |
| $\omega$ | Fundamental angular frequency |
| $\phi$ | Phase angle shift |
| X | Phase reactance |
| R | Phase resistance |
| P | Active power |
| Q | Reactive power |
| $P_{sref}$ | Reference active power |
| $Q_{sref}$ | Reference active power |
| $\Delta V$ | Voltage drop |

| | |
|---|---|
| $V_d$ | Direct axis component of voltage |
| $V_q$ | Quadrature axis component of voltage |
| $i_d$ | Direct axis component of current |
| $i_q$ | Quadrature axis component of current |
| $i_{dref}$ | Reference value of direct axis component of current |
| $i_{qref}$ | Reference value of quadrature axis component of current |
| $k_p$ | proportional constant |
| $k_i$ | integral constant |
| $\hat{v}_s$ | Peak value of line to neutral voltage at PCC |

# CHAPTER-1

# INTRODUCTION AND LITERATURE REVIEW

## 1.1 INTRODUCTION

Due to reduced right of way (ROW) requirements, stability considerations in AC transmission and increased requirement of integration with sources of renewable energy, HVDC transmissions have gained more attention. For HVDC transmission, two types of technologies namely, Line Commutated Converter-based HVDC (LCC-HVDC) and Voltage-Sourced Converter-based (VSC-HVDC) are available. The LCC-HVDC is based on thyristor technology and is known as classical HVDC. VSC HVDC systems are realized with Insulated Gate Bipolar Transistors (IGBTs). Pulse Width Modulation (PWM) control of VSCs shift harmonics to high frequencies, reducing the sizes of filters.

The VSC-HVDC technology has many advantages over LCC-HVDC transmission. In VSC-HVDC transmission, without the reversal of polarity of DC voltage, the direction of power flow can be changed. In VSC-HVDC technology, active and reactive power control can be achieved independently. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. Due to PWM control, fast response can be achieved without the risk of commutation failure. In addition, multilevel VSC technique like NPC converters permit higher power handling capability with minimized harmonic distortion. NPC is known as second generation converter with high power transmission capability than two-level VSC.

VSC HVDC can be used for interconnection of weak AC systems. Also, it is more suitable for interconnecting multiple offshore wind farms in a Multi-terminal DC (MTDC) configuration. The VSC-HVDC transmission is costlier than the LCC-HVDC because of IGBTs. In spite of high cost, VSC-HVDC transmission is preferable due to multiple advantages over the LCC-HVDC transmission

## 1.2 Literature Review

[1] reports the availability of high-power, high-frequency semiconductor switches with gate-turn-off ability has made high-power Voltage-Sourced Converters (VSCs) possible for utility applications, including HVDC systems.

[2]-[6] present two types of technologies - Line Commutated Converter based HVDC (LCC-HVDC) and VSC-HVDC. The LCC-HVDC is based on thyristor technology and known as classical HVDC. The VSC HVDC technology employs Insulated Gate Bipolar Transistors (IGBTs) that can be turned on and off and operating on Pulse Width Modulation (PWM) control technology.

[7]-[15] describe the advantages associated with VSC based HVDC transmission compared to conventional HVDC such as independent control of active and reactive power, dynamic voltage support at the converter bus for enhancing stability, possibility to feed weak AC systems or even passive loads, reversal of power without changing the polarity of dc voltage (advantageous in multi-terminal dc systems) and no requirement of fast communication between the two converter stations.

[16-17] present the dynamic model for a back-to-back HVDC system based on the three-level neutral point diode Clamped (NPC) topology.

[18] presents a small signal dynamic model of VSC-HVDC.

[19] presents an equivalent continuous time state-space model of VSC-HVDC in the synchronous dq reference frame.

[20-21] describe an inner current control loop which was designed for a digital control implementation when the converter is connected to a very strong AC network.

[22] presents an outer PI controller combination of an inner deadbeat current controller is used for power converters in to reach good performance for VSC-HVDC system.

[23] Presents some important projects involving HVDC multi-terminal transmission are currently under study.

## 1.3 Outline of the thesis

In this thesis, the performance of VSC based HVDC transmission systems installed between two synchronous as well as asynchronous ac systems, is investigated. The system studies are based on the three level neutral point clamped (NPC) converters. Current controlled scheme is used for active and reactive power control. One converter is operated in DC voltage control mode, while the other is operated in active and reactive power (PQ) control mode. Several case studies are carried out in MATLAB software for validation.

The outline of the remaining chapters are given below.

Chapter-2 represents the overview of conventional and VSC-HVDC systems. In this chapter, the advantages and application of classic as well as VSC-HVDC system are described first. Subsequently, the configuration of a typical HVDC system is presented.

Chapter-3 presents the design and operation of a VSC-HVDC system.

Chapter-4 represents the control system of VSC-HVDC system. A mathematical model of the control system is also described.

Chapter-5 discusses case studies and results of NPC based VSC-HVDC links which are interconnected between asynchronous AC systems.

# CHAPTER-2

# HIGH VOLTAGE DIRECT CUREENT (HVDC) TRANSMISSION

## 2.1 Introduction

The HVDC transmission is advantageous for power delivery over long distances and between asynchronous interconnections by using overhead lines or underground cables. One of the most important aspects of HVDC systems is its fast controllability. It is a well-established technology and since its first commercial introduction in 1954 in Sweden, more than 50 projects have been realized**.**

Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and reliability of each grid, by allowing exchange of power between incompatible networks.

HVDC technology is a power electronics based technology used in electric power systems. It is an efficient and flexible method to transmit large amounts of electrical power over long distances by overhead transmission lines or underground/submarine cables. Until recently, HVDC based on thyristors, which is called traditional HVDC or classical HVDC, was used for conversion from ac to dc and vice versa. Recently a new type of HVDC has become available. It makes use of more advanced semiconductor technology instead of thyristors for power conversion between ac and dc. The semiconductors used are IGBTs (Insulated Gate Bipolar Transistors), the converters are VSCs (Voltage Source Converters) and they operate with high switching frequency (1-2 kHz) utilizing PWM (Pulse Width Modulation).

VSC-HVDC is also used to reverse the power flow direction without changing the polarity of dc voltage (in multi-terminal dc systems) and there are no requirements of fast communication between the two converter stations.

## 2.2 Comparison between HVDC and HVAC:

Comparison between DC and AC transmission basically divided based on the technical and economical point of view.

- Considering insulating requirement for Peak voltage levels, a DC line will carry same power with two conductors as the AC line with three conductors. Thus HVDC transmission system needs a simpler tower, insulators and conductor cost will be reduced in comparison with the HVAC transmission.
- Conductor losses are reduced about two-third, when DC is used instead of AC one.
- Use of HVDC transmission, skin effect problem is not present and also corona losses and dielectric losses are very low hence, efficiency of transmission can be improved.
- Disadvantage of DC over AC transmission arises due to cost of the converter and filters.
- HVDC transmission is helpful for transmitting bulk power through undersea cables over a long distance where charging current puts a limitation for AC transmission.
- Concluding from the above it can be said that HVAC transmission are economical than HVDC transmission when used for small distances. But after a break even distance HVDC transmission will be more economical that can be observed from figure 2.1

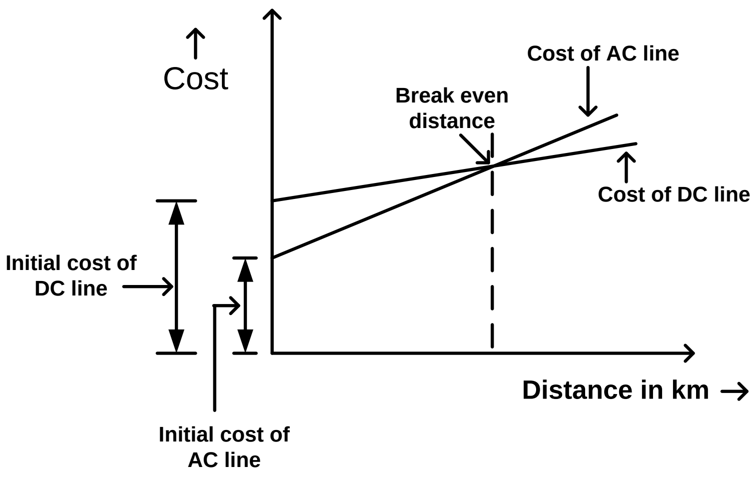



Figure 2.1: Cost vs Distance Curve

- For overhead line break even distance is about 400 to 700 km and for cable transmission it is about 25 to 50 km.
- From the technical point of view, HVDC transmission eliminates the problems related with AC transmission. Stability limits are enhanced as the power carrying ability of the DC transmission is not affected by transmission distance.
- In case of AC transmission power transmission depends on phase angle which increases with increase in distance hence it limits the power transfer.
- Line compensation like STATCOM, SVC etc is used to solve problems associated to line charging issues with AC transmission, while for DC transmission such compensation is not needed. This issue puts a limitation of HVAC transmission breakeven distance to 500 km.
- HVDC transmission is limited due to the factors like high cost converters, complexity of control, generation of harmonics and incapable of altering voltage level.
- HVDC can be used for interconnection of asynchronous grids which cannot be realized by AC transmission.
- The above comparison concludes that advantages like long distance bulk power transmission, long submarine power crossing and interconnection of asynchronous grids leads to use HVDC technology in the area of power transmission.

## 2.3 Configuration of HVDC link

There are four main HVDC configurations used. These configurations can be achieved through both Voltage Source Converter (VSC) and Current Source Converter (CSC) topology.

### 2.3.1 Monopolar HVDC system

In Monopolar links, two converters are used which are separated by a single pole line. Either positive or a negative polarity line is used. By using negative polarity line corona loss can be minimized.

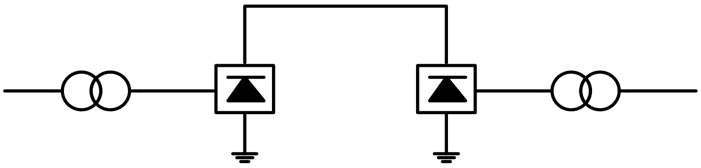


Figure 2.2: Mono polar link

There is only one insulated transmission conductor installed and the ground is used for the return current. Instead of using the ground as a return path, a metallic return conductor may be used.

The main properties of monopolar HVDC system are:

- Single high-voltage conductor.
- Current return through the ground.
- Relatively low costs.

Many existing subsea cable transmissions use monopolar system.

### 2.3.2 Bipolar HVDC system

This is the most commonly used configuration of HVDC power transmission systems. This uses two mono-polar links both positive and negative. Two sets of converter are grounded at middle at single or both ends.

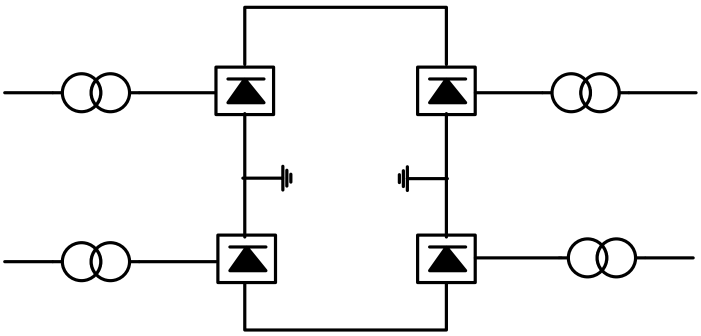


Figure 2.3: Bipolar link

The two poles can be used independently if both neutrals are grounded. It increases power transfer capacity. Under normal operation, the currents flowing in each pole are equal, and there is no ground current. In case of failure of one pole power transmission can continue on the other pole, so its reliability is high. Most overhead line HVDC transmission systems are bipolar.

### 2.3.3 Back-to-back HVDC system.

In this case the two converter stations are located at the same site and no transmission line or cable is required between the converter bridges. The connection may be monopolar or bipolar. A block diagram of a back-to-back system is shown in Figure 2.4.

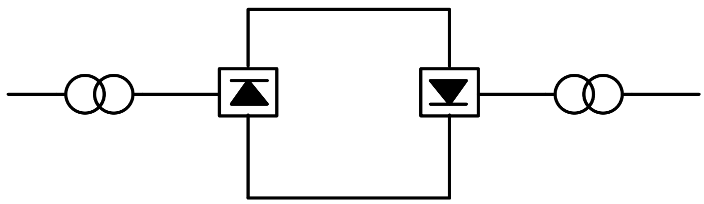


Figure 2.4: Back to Back link

The two ac systems interconnected may have the same or different nominal frequency, i.e. 50Hz and 60Hz (The back-to-back link can be used to transmit power between two neighboring asynchronous systems). The dc voltage in this case is quite low (i.e. 50kV - 150kV) and the converter does not have to be optimized with respect to the dc bus voltage and the associated distance to reduce costs, etc.

### 2.3.4 Transmission between two substations

When it is economical to transfer electric power through dc transmission from one geographical location to another, a two-terminal or point-to-point HVDC transmission shown in Figure 2.5 is used.

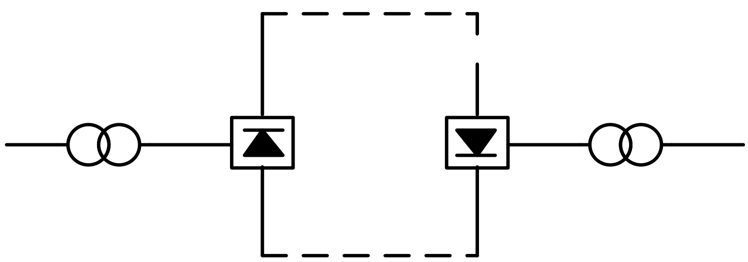


Figure 2.5: Point to Point HVDC system

In other words, dc power from a dc rectifier terminal is transported to the other terminal operating as an inverter. This is typical of most HVDC transmission systems. The link may connect two asynchronous systems or connect two substations within one interconnected system.

### 2.3.5. Multi-terminal HVDC transmission system.

When three or more HVDC substations are geographically separated with interconnecting transmission lines or cables, the HVDC transmission system is multi-terminal. If all substations are connected to the same voltage then the system is parallel multi-terminal dc shown in Figure 2.6. If one or more converter bridges are added in series in one or both poles, then the system is series multi-terminal dc shown in Figure 2.7.

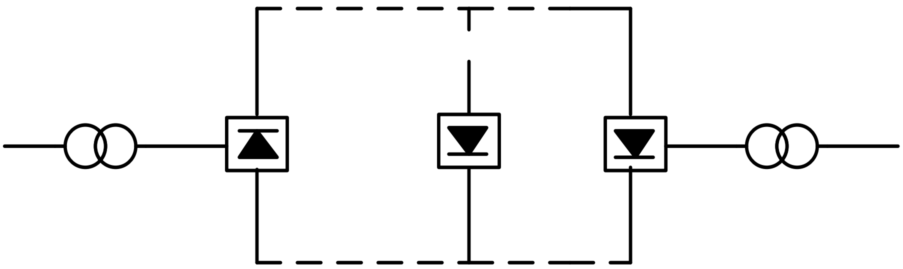


Figure 2.6: Multi terminal link with parallel connection

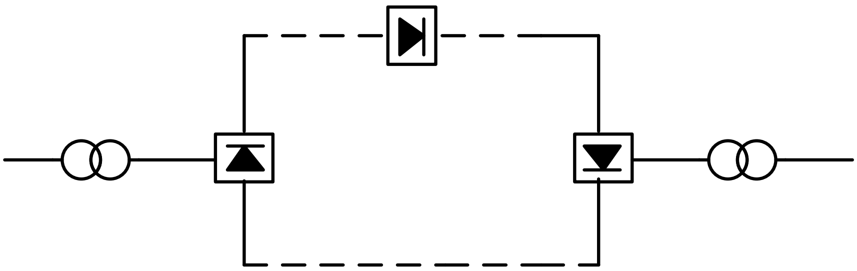


Figure 2.7: Multi terminal link with series connection

A combination of parallel and series connections of converter bridges is a hybrid multi-terminal system. Multi-terminal dc systems are more difficult to justify economically because of the cost of the additional substations.

## 2.4. Classification of HVDC transmission

To achieve the above objective it is needed to design a back to back converter stations along with a desired control strategy. Converter stations classified into two categories with relevant to high power application.

### 2.4.1 Classification based on commutation process:

- **Line Commutated Converter (LCC):** By reversing the AC polarity, commutation processes can be initiated. It is called as naturally commutated converters. Six pulse thyristor converters is an example of line commutated converters.
- **Forced Commutated Converters (FCC):** In this transfer of current from one switch to another is a controlled process for which it is required to have fully controllable switches. A forced commutated converter having a gate turn of capability is called as self-commutated converters. Where self-commutated converters draws a great attention for HVDC application with an efficient control strategy.

### 2.4.2 Classification based on terminal voltage current wave form:

- Current source converter is a converter in which DC side current polarity will remain same and hence the power flow through the converter is determined by the DC side voltage polarity. To have a DC side current continuity a relatively large inductor is connected which represents a current source.

- In a voltage source converter DC side voltage polarity will remain same and the direction of power flow is being controlled by the DC side current polarity. A relatively large capacitor is connected across the DC side which resembles a voltage source.

Voltage source converters are advantageous than current sourced converters because CSC requires bipolar electronic switches. Although fully controlled version of bipolar electronic switches like GTO and IGCT are available commercially but its switching speed puts a limitation to the application for high power electronic converters. All the equipments except transformers are in a compact building in case of IGBT based voltage source converter but in case of thyristor based classical HVDC only valves are inside the building.

VSC provides continuous reactive power control, dynamic voltage regulation and black start capability. The above features of VSCs over CSCs provide the incentive for potential use in high power applications.

## 2.5 Classical HVDC Systems

The first commercial HVDC transmission link was commissioned in 1954. It utilized line-commutated current-source converters (LCC) with mercury-arc valves. They were followed during the late 1960's by similar converters using semiconductor thyristor valves. Thyristor valves have now become standard equipment for DC converter stations. The turn-on of the thyristors in an LCC is controlled by a gate signal while the turnoff occurs at the zero crossing of the AC current which is determined by the AC network voltage. During forward conduction of the thyristor devices, charges are internally stored, and at turn off these charges must be removed before the valve can reestablish a forward voltage blocking capability. Therefore, the HVDC inverters require a certain minimum time, the recovery time, with negative voltage before forward blocking voltage is applied.

In order to achieve this condition the inverter is operated with a certain commutation margin angle. When sufficient recovery time is not provided the converter may suffer a commutation failure. Most often commutation failures originate from voltage disturbances due to AC system faults.

A commutation failure can, however, also be caused if the connected system has limited short circuit capability and cannot provide the required voltage for the commutation process. As the current is always lagging the voltage, this type of converter, either in rectifier or inverter operation, continuously absorbs reactive power as a part of the conversion process. Therefore, shunt compensation is required to compensate for some or the entire converter VAR requirement.

The amount of reactive power absorbed is determined by the DC control strategy, and typically is in the order of 50% of the active power flow through the converter.

The HVDC converters are HVDC system's most important part. They implement the conversion from ac to dc at rectifier side and from dc to ac at inverter side. CSCs are used in classic HVDC transmission. On the ac side of the converter CSC acts as a constant voltage source. It requires a capacitor as energy storage device, large ac filters for harmonic elimination and a reactive power supply for power factor correction. On the dc side of the converter CSC acts as a constant current source. In this case, CSC requires an inductor as its energy storage device and dc filters that provide appropriate fault current limiting features. The main benefit of CSC is relatively low switching losses.

### 2.5.1 Control of Line-Commutated HVDC Systems

The power transmitted over the HVDC link is controlled through the control system where one of the converters controls the dc voltage and the other converter controls the current through the dc circuit. The control system acts through firing angle adjustments of the valves and through tap changer adjustments on the converter transformers to obtain the desired combination of voltage and current. The control systems of the two stations of a bipolar HVDC system usually communicate with each other through a telecommunication link.

### 2.5.2 Advantages of Classic HVDC Systems

It is important to remark that an HVDC system not only transmits electrical power, but it also has a lot of value added which cannot be achieved by other means in conventional ac transmission. Some of these aspects are:

- No limits in transmitted distance. This is valid for both overhead lines and sea or underground cables.
- Very fast and accurate control of power flow, which implies stability improvements, not only for the HVDC link but also for the surrounding ac system.
- Magnitude and direction of power flow can be changed very quickly (bi-directionality).
- An HVDC link does not increase the short-circuit power in the connecting point. This means that it will not be necessary to change the circuit breakers in the existing network.
- HVDC can carry more power for a given size of conductor.

- The need for right-of-way is much smaller for HVDC than for an ac connection, for the same transmitted power. The environmental impact is therefore smaller with HVDC, and it is easier to obtain permission to build.
- Power can be transmitted between two ac-systems operating at different nominal frequencies or at the same frequency but without being synchronized.

### 2.5.3 Applications of Classical HVDC systems

The first application for classical HVDC systems was to provide point to point electrical power interconnections between asynchronous ac power networks. There are other applications which can be met by HVDC converter transmission which include:

- Interconnections between asynchronous systems. Some continental electric power systems consisting of asynchronous networks.
- Deliver energy from remote energy sources. Where generation has been developed at remote sites of available energy, HVDC transmission has been an economical means to bring the electricity to load centers. The main application has been the connection of remote hydro-stations to load centers.
- Import electric energy into congested load areas. In areas where new generation is impossible to bring into service to meet load growth or replace inefficient or decommissioned plant, underground dc cable transmission is a viable means to import electricity.
- Increasing the capacity of existing ac transmission by conversion to dc transmission. New transmission rights-of-way may be impossible to obtain. Existing overhead ac transmission lines upgraded to or overbuilt with dc transmission can substantially increase the power transfer capability on the existing right-of-way.
- Power flow control. AC networks do not easily accommodate desired power flow control. Power market and system operators may require the power flow control capability provided by HVDC transmission.
- Stabilization of electric power networks. Some wide spread ac power system networks operate at stability limits well below the thermal capacity of their transmission conductors. HVDC transmission is an option to consider for

increasing the utilization of network conductors along with the various power electronic controllers which can be applied on ac transmission.

- An HVDC transmission line has lower losses than ac lines for the same power capacity. The losses in the converter stations have of course to be added, but above a certain break-even distance, the total HVDC transmission losses become lower than the ac losses. HVDC cables also have lower losses than ac cables.

## 2.6 VSC-HVDC SYSTEMS

Development of high frequency fully controlled switches like IGBT for generation of appropriate switching pattern provides a platform for efficient control of power flow through VSC.

The configuration of a VSC-HVDC system shown in Figure 2.8 consists of ac filters, transformers, converters, phase reactors, dc capacitors and dc cables.

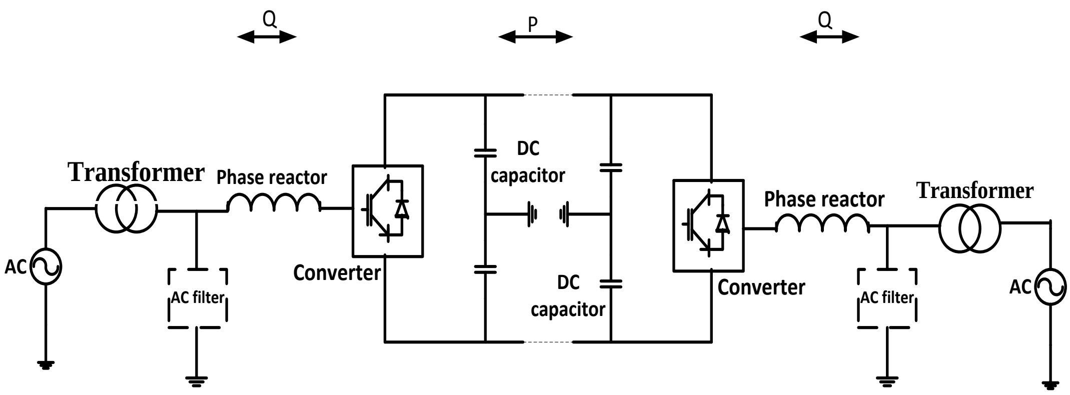



Figure 2.8 Configuration of VSC-HVDC system.

| Function | Classical HVDC | VSC-HVDC |
|---|---|---|
| Converter valves | Thyristor | IGBT |
| Connection valve - ac grid | Converter transformer | Series reactor (+ transformer) |
| Filtering and reactive Compensation | 50% in filters and shunt Capacitors | Only small filter |
| DC current smoothing | Smoothing reactor + dc filter | DC capacitor |
| Telecom between converter station controls | Needed | Not needed |

Table 2.1 Comparison of classic and VSC-HVDC systems

### 2.6.1 Advantages and Applications of VSC-HVDC

- Independent control of active and reactive power without any needs for extra compensating equipment:-
    - With PWM, VSC-HVDC offers the possibility to control both active and reactive power independently. While the transmitted active power is kept constant the reactive power controller can automatically control the voltage in the ac-network. Reactive power generation and consumption of a VSC-HVDC converter can be used for compensating the needs of the connected network within the rating of a converter.
- Mitigation of power quality disturbances:-
    - The reactive power capabilities of VSC-HVDC can be used to control the ac network voltages, and thereby contribute to an enhanced power quality. Further-more, the faster response due to increased switching frequency (PWM) offers new levels of performance regarding power quality control such as flicker and mitigation of voltage dips, harmonics etc. Power quality problems are issues of priority for owners of industrial plants, grid operators as well as for the general public.

- No contribution to short circuit currents:-
    - The converter works independently of any ac source, which makes it less sensitive for disturbances in the ac network and ac faults do not drastically affect the dc side. If ac systems have ground faults or short circuits, whereupon the ac voltage drops, the dc power transmitted is automatically reduced to a predetermined value.
- Reduced risk of commutation failures:-
    - Disturbances in the ac system may lead to commutation failures in classical HVDC system. As VSC-HVDC uses self-commutating semiconductor devices, the presence of a sufficiently-high ac voltage is no longer needed. This significantly reduces the risk of commutation failures, and extends the use of the HVDC system in stability control.
- Communication not needed:-
    - The control systems on rectifier and inverter side operate independently of each other. They do not depend on a telecommunication connection. This improves the speed and the reliability of the controller.
- Feeding islands and passive ac networks:-
    - The VSC converter is able to create its own ac voltage at any predetermined frequency, without the need for rotating machines. It may be used to supply industrial installations or large wind farms.
- Multi-terminal dc grid:-
    - VSC converters are very suitable for creating a dc grid with a large number of converters, since very little coordination is needed between the interconnected VSC-HVDC converters.

However, VSC transmission has some disadvantages, which include potentially high switching power losses and high capital costs compared to classic HVDC, though the technology continues to evolve.

# CHAPTER-3

# DESIGN AND OPERATION OF VSC-HVDC

## 3.1 Introduction

VSC-HVDC is based on the voltage source converter, where the valves comprise IGBTs and PWM is used to create the desired voltage waveform. With PWM, it is possible to create any waveform (up to a certain limit set by the switching frequency), any phase angle and magnitude of the fundamental component. Changes in waveform, phase angle and magnitude can be done by changing the PWM pattern, which can be done almost instantaneously. Thus, the voltage source converter can be considered as a controllable voltage source. This high controllability allows for a wide range of applications. From a system point of view VSC-HVDC acts as a synchronous machine without mass that can control active and reactive power almost instantaneously.

## 3.2 System description

The main function of the VSC-HVDC is to transmit constant dc power from the rectifier to the inverter. As shown in Figure 2.8, it consists of dc-link capacitors $C_{dc}$, two converters, passive high-pass filters, phase reactors, transformers and dc cable.

### 3.2.1 Transformers

It is helpful for keeping the secondary voltage level as per converter requirement. Reactance of transformer decreases the short circuit current level. It acts as like a barrier between AC and DC side. A two winding transformer can be used. The leakage inductance of the transformers is normally in the range 0.1-0.2 p.u.

### 3.2.2 Phase reactors

The phase reactors are used for controlling both the active and the reactive power flow by regulating currents through them. It has advantage like preventing high frequency harmonics in AC line current as it act as like a low pass filter and not allow the change in current direction through the IGBT switches. It provides a decoupled control of real and reactive power by controlling the current through it and it limits short circuit current. The reactors are normally about 0.1-0.3 p.u.

### 3.2.3 AC filters

The ac voltage output has harmonic components, derived from the switching of the IGBT's. Harmonics in AC system result in overheating, losses, interference in communication line, malfunctioning of operation, over voltage due to resonance and instability in control system. High-pass filters are installed to take care of these high order harmonics. With VSCs there is no need to compensate any reactive power consumed by the converter itself and the current harmonics on the ac side are related directly to the PWM frequency. The lower order harmonics present in the current is small in amount. Filters used in VSC are cheaper as compared to classical HVDC as PWM technique reduces the harmonic content to a great extent. It acts as a high pass filter, and connected between transformer and converter which restrict the harmonics to enter in to AC system. We are getting fundamental frequency voltage and current at secondary side.

### 3.2.4 DC capacitors

DC link capacitor required in VSC transmission system act as a constant voltage source. It doesn’t allow the change of polarity of DC bus. It is helpful for maintaining DC link voltage near to its desired value. DC link capacitor decides the transient response of the system. Hence deciding the value of the DC link capacitor is a challenging task. Harmonics generated in the current due to PWM switching of IGBTs flowing to capacitor creates a voltage ripple at DC side.

The design of the dc capacitor should not be based only on the steady-state operation. During disturbances in the ac system (faults, switching actions) large power oscillations may present between the ac and the dc side. This in turn will lead to oscillations in the dc voltage and dc over voltages that may stress the switches. It is important to consider the transient voltage variation constraint when the size of the dc capacitors is selected.

Here, a small dc capacitor $C_{dc}$ can be used, which should theoretically result in faster converter response and to provide an energy storage to be capable to control the power flow. The dc capacitor size is characterized as a time constant τ, defined as the time constant to charge the capacitor from zero to its maximum DC voltage level.

$$\tau = \frac{\frac{1}{2} C_{dc} U_{dcN}^2}{S_N} \tag{3.1}$$

where $U_{dcN}$ denotes the nominal dc voltage and $S_N$ stands for the nominal apparent power of the converter. The time constant is equal to the time required to charge the capacitor from zero to rated voltage $U_{dcN}$ if the converter is supplied with a constant active power equal to $S_N$. The time constant τ can be selected less than 5 ms to satisfy small ripple and small transient over voltage on the dc voltage. This relatively small time constant allows quick control of active and reactive power. Controller speed of less than 5 ms is not practical because the connection will not react. This holds for the control of active power, not for the control of reactive power. Reactive power is generated locally and does not need the dc link.

### 3.2.5 DC cables

The cable used in VSC-HVDC applications is a new developed type, where the insulation is made of an extruded polymer that is particularly resistant to dc voltage. Polymeric cables are the popular choice for HVDC, mainly because of their mechanical strength, flexibility, and low weight.

### 3.2.6 Converters

The converters are VSCs employing IGBT power semiconductors, one operating as a rectifier and the other as an inverter. The two converters are connected either back-to-back or through a dc cable, depending on the application.

Converter that is used may be a 2 level, 3 level or multilevel converters. For 2 level VSC it is required to have a six pulse generator for triggering six switches each switch consists of an IGBT and an anti-parallel diode and it generates two voltage level at AC side i.e $+\frac{1}{2}U_{dc}$ and $-\frac{1}{2}U_{dc}$.

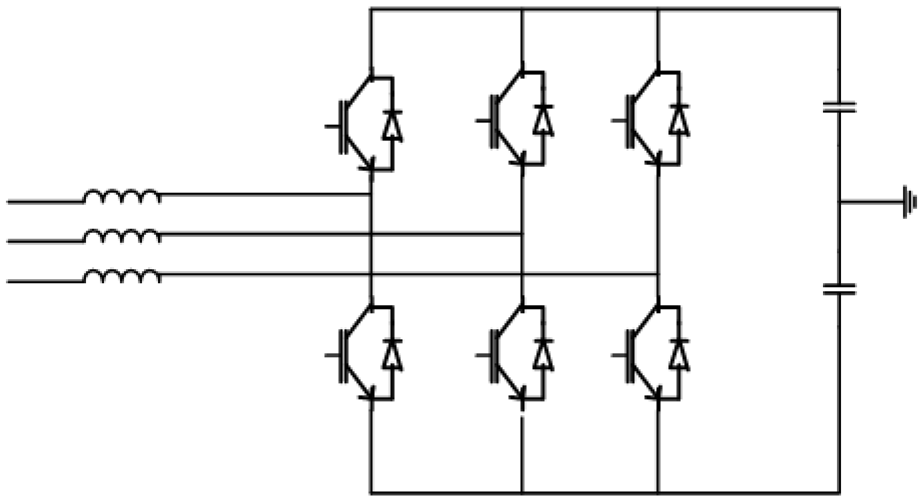


Figure 3.1: Two level VSC converter

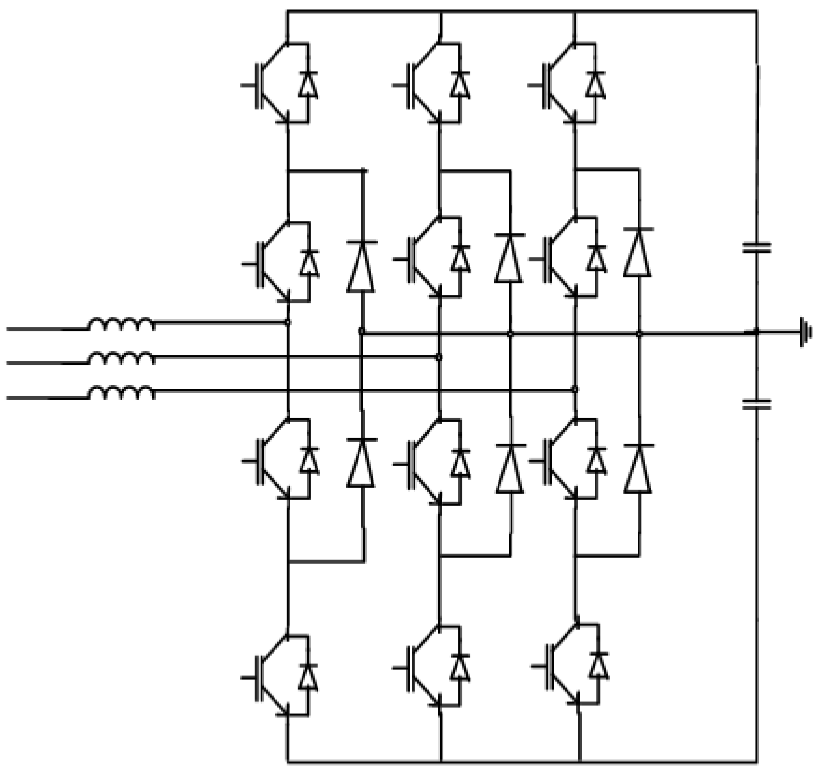


Figure 3.2: Three level VSC converter

The number of devices required is determined by the rated power of the bridge and the power handling capability of the switching devices.

In three level converters, there are 12 switches and 12 pulse generators are required for triggering IGBTs. There are three level of voltages at AC side of converter i.e, $+\frac{1}{2}\mathrm{U_{dc}}$, 0 and $-\frac{1}{2}\mathrm{U_{dc}}$. And a comparatively low harmonic content is achieved in three level converters.

In three level NPC with capacitive voltage divider at its DC side, the total voltage across the DC terminal divides into two equal half by using identical capacitors. This configuration permits a bidirectional power exchange between two AC systems when connected in back to back fashion. But in case of three level NPC supplied from a 12 pulse diode bridge rectifier on DC side does not support for bidirectional power flow.

Even after net DC voltage is maintained at constant level, voltage drift occurs in both steady state and transient state condition due to tolerances of converter and asymmetries in gating pulse commands for switches. Large third harmonic components exist in the mid-point current which results in a lower order voltage harmonics at AC side of the converter.

With the present technology, IGBTs with a voltage rating of 2.5kV have recently become available in the market. The IGBTs can be switched on and off with a constant frequency of about 2 kHz. The IGBT valves can block up to 150 kV. A VSC equipped with these valves can carry up to 800A (rms) ac line current. This results in a power rating of approximately 140 MVA of one VSC and a ±150kV bipolar transmission system for power ratings up to 200MW.

### 3.2.7 Harmonic filtering

Due to the commutation valve switching process, the currents and the voltages at the inverter and rectifier are not sinusoidal. These non-sinusoidal current and voltage waveforms consist of the fundamental frequency ac component along with higher-order harmonics. Passive high-pass ac filters are necessary components of the VSC-HVDC topology to filter the high harmonic components. Hence, sinusoidal line currents and voltages can be obtained from the transformer secondary sides. Therefore, the reactive power compensation may be accomplished by high-pass filters.

A PWM output waveform contains harmonics ($M \times fc \pm N \times f_1$), where $f_c$ is the carrier frequency, $f_1$ is the fundamental grid frequency. M and N are integers, and the sum M+N is an odd integer. Next to the fundamental frequency component, the

spectrum of the output voltages contains components around the carrier frequency of the PWM and multiples of the carrier frequency.
Frequency modulation is the ratio of carrier frequency to fundamental frequency.

$$m_f = \frac{f_c}{f_1} \tag{3.2}$$

The selection of $m_f$ depends on the balance between switching losses and harmonic losses. A higher value of $m_f$ (i.e. a higher number of commutations per second) increases the switching losses but reduces the harmonic losses.

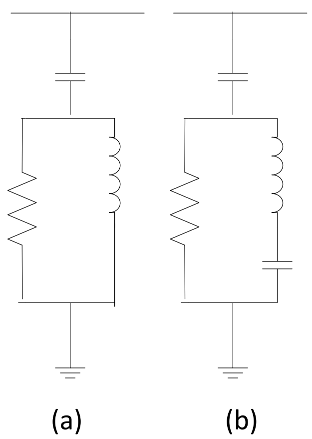



Figure 3.3- Passive high-pass filter (a) Second-order filter (b) Third-order filter

The higher $m_f$ , the higher the frequency of the lowest order harmonics produced. With the use of PWM, passive high-pass damped filters are selected to filter the high order harmonics. Normally second and third-order passive high-pass filters shown in Figure 3.3 are used in HVDC schemes. These are designed to reduce the injection of harmonics above the 17th order into the ac network.

When designing the high damping filters the quality factor Q is chosen to obtain the best characteristic over the required frequency band. There is no optimal Q with tuned filters. The typical value of the quality factor Q is between 0.5 and 5.

## 3.3 Operation of power-angle control

The fundamental operation of VSC-HVDC may be explained by considering each terminal as a voltage source connected to the ac transmission network via series reactors. The two terminals are interconnected by a dc link, as schematically shown in Figure 3.4

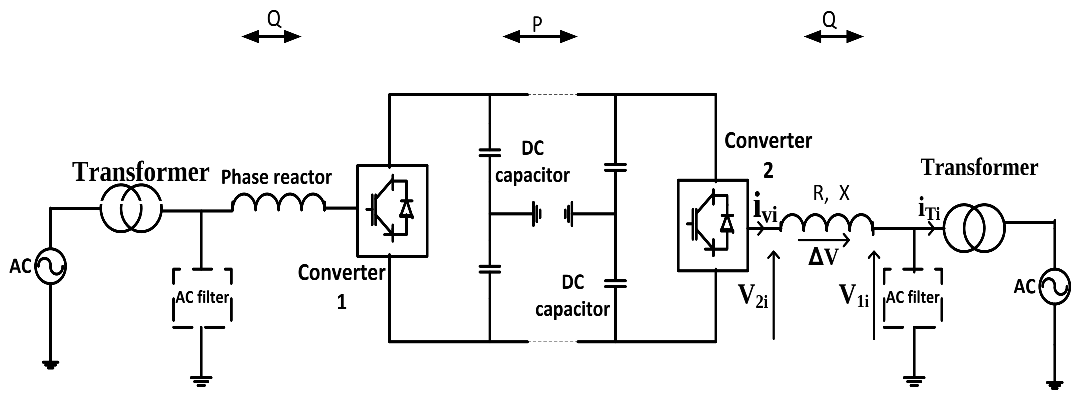



Figure 3.4: Topology of a VSC-HVDC connection.

As mentioned above the converter can be represented as a variable ac voltage source where the amplitude, the phase and the frequency can be controlled independently of each other. It means that the VSC bridge can be seen as a very fast controllable synchronous machine with the instantaneous phase voltage as express by the following equation.

$$V_{2i} = \frac{1}{2} U_{dc} M \sin(\omega t + \phi) + \text{harmonics terms} \tag{3.3}$$

where M is the modulation index which is defined as the ratio of the peak value of the modulating wave and the peak value of the carrier wave, ω is the fundamental frequency, ϕ is the phase shift of the output voltage, depending on the position of the modulation wave.

Variables M and ϕ can be adjusted independently by the VSC controller to give any combination of voltage magnitude and phase shift in relation to the fundamental-frequency voltage in the ac system. As a result, the voltage drop (ΔV shown in Figure 3.5) across the reactor (X shown in Figure 3.4) can be varied to control the active and reactive power flows.

Figure 3.5 shows the fundamental frequency phasor representation for a VSC operating as an inverter and supplying reactive power to the ac system. In this case the

VSC output voltage has larger amplitude and is phase advanced with respect to the ac system.

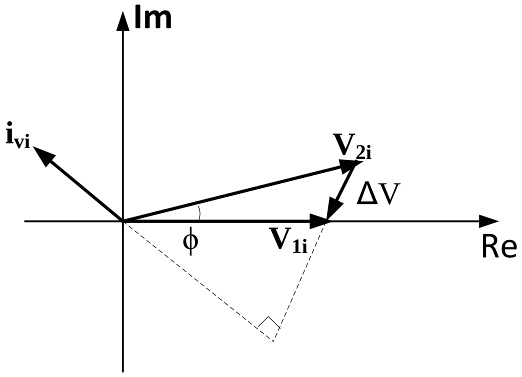



Figure 3.5: Phasor Diagram

The active power flow between the converter and the network can be controlled by changing the phase angle (ϕ) between the fundamental frequency voltage generated by the converter ($V_{2i}$) and the voltage ($V_{1i}$) on the bus. The power is calculated according to Equation (3.4) assuming a lossless reactor (X).

$$P = \frac{V_{2i}\, V_{1i}\, \sin\phi}{X} \tag{3.4}$$

The reactive power flow is determined by the amplitude of $V_{2i}$ which is controlled by the width of the pulses from the converter bridge. The reactive power is calculated according to Equation (3.5). The maximum fundamental voltage out from the converter depends on the dc voltage.

$$Q = \frac{V_{2i}\,(V_{2i} - V_{1i}\cos\phi\,)}{X} \tag{3.5}$$

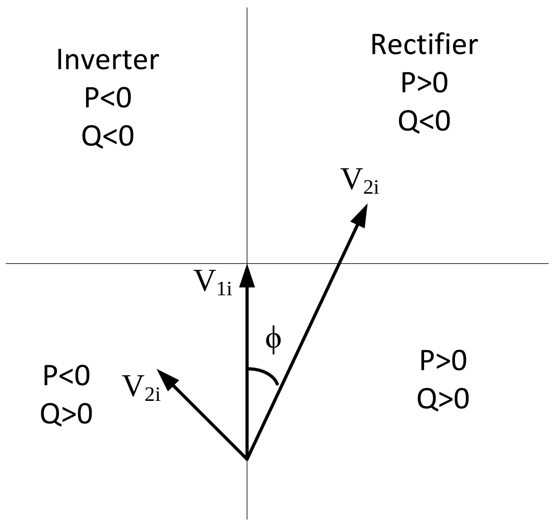



Figure 3.6: Phasor diagram (fundamental) and direction of power flows. The location of the $V_{2i}$ phasor determines the operation mode (rectifier or inverter).

The phasor diagram in Figure 3.6 indicates how the signs of the active and reactive powers depend on the phase and the amplitude of the converter bridge voltage if the line voltage phasor is assumed constant. For example, if the line voltage $V_{1i}$ is leading the bridge voltage $V_{2i}$, the active power flows from the ac network to the converter.

In VSC-HVDC connections, the active power flow to the ac side is equal to the active power transmitted from the dc side in steady state (losses neglected). This can be fulfilled if one of the two converters controls the active power transmitted at the same time as the other converter controls the dc voltage. The reactive power generation and consumption can be used for compensating the needs of the connected network.

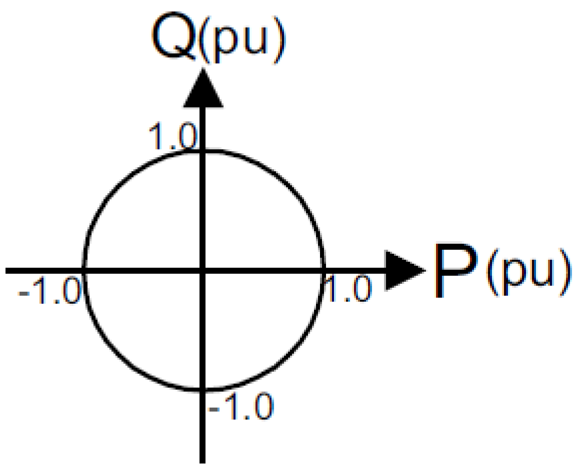



Fig3.7: P-Q characteristics of VSC-HVDC

The active /reactive power capabilities can easily be seen in a P-Q diagram shown in Figure 3.7. For the sake of simplicity, the P-Q characteristics are drawn by using per unit values with the assumption that the ac systems at both sides are operated at 1.0 p.u. voltage.

The VSC-HVDC is able to operate at any point within the circle. The radius of which represents the converter MVA rating. The reactive power capabilities can be used to control the ac voltages of the networks connected to the converter. The controllable active power can be transferred in both directions with equal maximum value which is only limited by the power rating.

# CHAPTER-4

# CONTROL STRATEGY OF VSC-HVDC

## 4.1 Introduction

In the case of VSC-based HVDC transmission systems the transfer of power is controlled in the same way as in the case of a classic HVDC transmission. The inverter side controls the active power, while the rectifier side controls the dc voltage. With classical HVDC system the reactive power cannot be controlled independently of the active power. VSC-HVDC makes it possible to control the reactive power and the active power independently. The reactive power flow can be controlled separately in each converter by the ac voltage that is requested or set manually without changing the dc voltage. The active power flow can be controlled by the dc voltage on the dc side or the variation of frequency of ac side, or set manually. Thus, the active power flow, the reactive power flow, the ac voltage, the dc voltage and the frequency can be controlled when using VSC-HVDC.

## 4.2. Operation of VSC-HVDC

The VSC-HVDC system is based on self-commutated PWM technique. PWM generates pulse-width modulated signal by comparing the instantaneous magnitude of a triangular waveform with sinusoidal input reference.

Thus, the VSC can produce its own voltage waveform independent of the ac system. PWM controls the average output voltage during a very short period, which is called switching period. PWM technique uses a sinusoidal reference signal and produces the desired output voltage. Active and reactive power can be independently controlled by means of PWM technique that can be changed almost instantly. Changing the fundamental frequency voltage phase angle across the series reactor controls the active power, whereas changing the fundamental frequency voltage magnitude across the series reactor controls the reactive power.

Different control strategies of VSC-HVDC are present. One way to control VSC-based HVDC converters is power-angle control which is already explained in section 3.3, which is also called voltage-angle control. It is perhaps the most straightforward controller for grid-connected VSCs**,** second widely used method of VSC-HVDC control is vector control.

## 4.3 dq-frame representation and control of three phase systems

The control in αβ-frame has the feature of reducing the number of required control loops from three to two. Therefore, the reference, feedback, and feed-forward signals are in general sinusoidal functions of time. Therefore, to achieve a good performance and small steady-state errors, the compensators may require being of high orders, and the closed-loop bandwidths must be appropriately larger than the frequency of the reference commands. Therefore, the compensator design is not a easy task, especially if the operating frequency is variable.

The dq-frame-based control offers a solution to this problem. In dq-frame, the signals assume DC waveforms under steady-state conditions. This, in turn, allows the utilization of compensators with simpler structures and lower dynamic orders. Furthermore, zero steady-state tracking error can be gained by including integral terms in the compensators. A dq-frame representation of a 3-ϕ system is also more suitable for analysis and control design tasks. For example, the abc-frame representation of a salient-pole synchronous machine consist of time-varying self- and mutual inductances. However, if the machine equations are transformed to a proper dq-frame, the time-varying inductances manifest themselves as constant parameters.

### 4.3.1 Phase-locked loop

A very important and compulsory feature of grid side converter control is the grid synchronization. The synchronization algorithm is capable to detect the phase angle of grid voltage in order to synchronize the delivered power. The motive of this method is to synchronize the inverter output current with the grid voltage, in order to gain a unity power factor. The inputs of the PLL model are the 3-ϕ voltages measured on the grid side and the output is the tracked phase angle. The PLL model is implemented in synchronous dq reference frame, where a Park transformation is used. The phase-locking of the system is achieved by varying the q-axis voltage to zero. A PI controller is used for this purpose. By integrating the sum between the PI output and the reference frequency the phase angle is obtained.

#### 4.3.2 dq-Frame Representation of a Space Phasor

For the space phasor

$\vec{f} = f_\alpha + jf_\beta$, the αβ- to dq-frame transformation is defined by

$$f_d + j\,f_q = \left(f_\alpha + \,jf_\beta\right)\,e^{-j\varepsilon(t)} \qquad (4.1)$$

which is similar to a phase shift in f (t) by the angle −ε(t). The dq- to αβ-frame transformation can be achieved by multiplying both sides of (4.1) by $e^{j\varepsilon(t)}$ Thus

$$f_\alpha + j\,f_\beta = \left(f_d + \,jf_q\right)\,e^{j\varepsilon(t)} \qquad (4.2)$$

To highlight the usefulness of the transformation given by (4.1), assume that f has the following general form:

$$\vec{f}(t) = f_\alpha + j\,f_\beta = \hat{f}(t)e^{j[\theta_0 + \int \omega(\tau)d\tau]} \qquad (4.3)$$

where ω(t) is the (time-varying) frequency and $\theta_0$ is the initial phase angle of the three-phase signal corresponding to $\vec{f}(t)$ . If $\varepsilon(t)$ is selected as

$$\varepsilon(t) = \varepsilon_0 + \int \omega(\tau)d\tau \qquad (4.4)$$

Then based on equation 4.1, the dq-frame representation of $\vec{f}(t)$ becomes

$$f_d + j\,f_q = \hat{f}(t)e^{j(\theta_0 - \,\varepsilon_0)} \qquad (4.5)$$

which is stationary and, therefore, the constituents of its corresponding 3-ϕ signal are DC quantities. Note that θ(t) and ε(t) are not necessarily equal, but dθ(t)/dt = dε(t)/dt must be ensured.

To better describe the dq-frame transformation, let us rewrite (4.2) as

$$\vec{f}(t) = \,f_d(1 + 0.\,j)e^{j\varepsilon(t)} + \,f_d(0 + 1.\,j)e^{j\varepsilon(t)} \qquad (4.6)$$

An interpretation of (4.6) is that the vector $\vec{f}(t)$ is represented by its components, that is, $f_d$ and $f_q$, in an orthogonal coordinate system whose axes are along the unit vectors $(1 + 0 \cdot j)\, e^{j\varepsilon(t)}$ and $(0 + 1 \cdot j)\, e^{j\varepsilon(t)}$. In turn, $(1 + 0 \cdot j)$ and $(0 + 1 \cdot j)$ are the unit vectors along the α-axis and the β-axis of the αβ-frame, respectively. Therefore, as illustrated in Figure 4.1 one can consider $\vec{f}(t)$ as a vector represented by the components $f_d$ and $f_q$ in a coordinate system that is rotated by ε(t) with respect to the αβ-frame. We refer to this rotated coordinate system as α dq-frame. For the reason given above, the dq-frame is also known as rotating reference frame, in the technical literature. Usually, the rotational speed of the dq-frame is selected to be equal to that of $\vec{f}(t)$

Based on the Euler's identity $e^{j(.)} = \cos(.) + j\sin(.)$, equation 4.1 can be written as

$$\begin{bmatrix} f_d(t) \\ f_q(t) \end{bmatrix} = R[\varepsilon(t)] \begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} \tag{4.7}$$

Where

$$R[\varepsilon(t)] = \begin{bmatrix} \cos\varepsilon(t) & \sin\varepsilon(t) \\ -\sin\varepsilon(t) & \cos\varepsilon(t) \end{bmatrix} \tag{4.8}$$

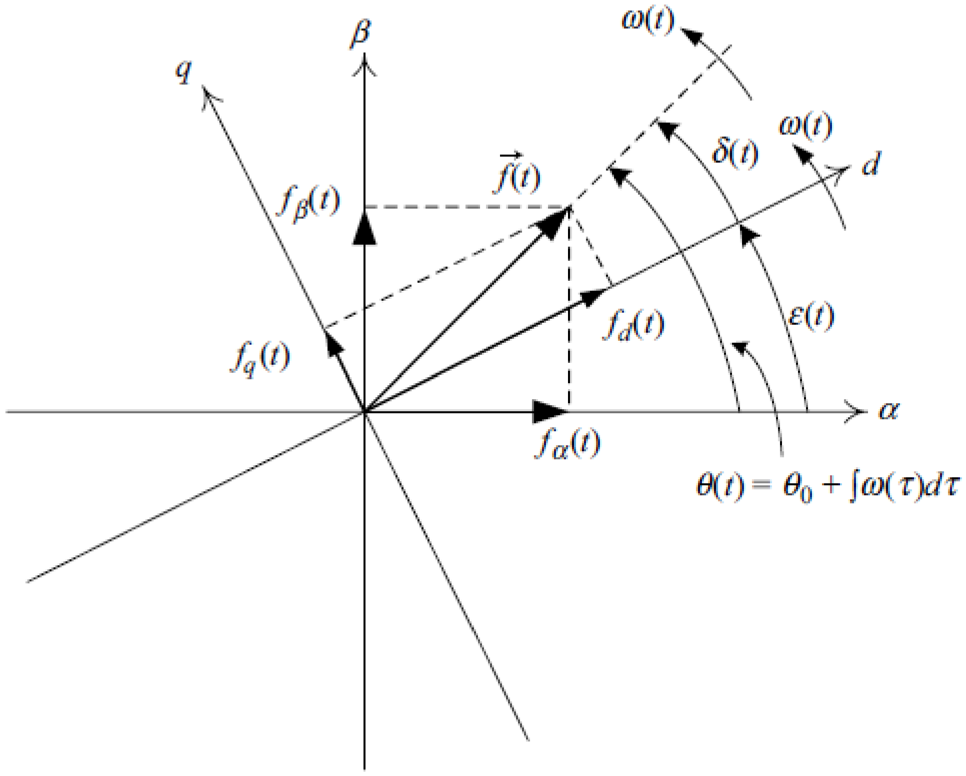



Fig.4.1: αβ and dq frame coordinate systems.

Similarly, the dq to αβ-frame transformation can be written as from equation 4.2

$$\begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} = R^{-1}[\varepsilon(t)] \begin{bmatrix} f_d(t) \\ f_q(t) \end{bmatrix}$$

$$\begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} = R[-\varepsilon(t)] \begin{bmatrix} f_d(t) \\ f_q(t) \end{bmatrix} \tag{4.9}$$

Where

$$R^{-1}[\varepsilon(t)] = R[-\varepsilon(t)] = \begin{bmatrix} \cos\varepsilon(t) & -\sin\varepsilon(t) \\ \sin\varepsilon(t) & \cos\varepsilon(t) \end{bmatrix} \tag{4.10}$$

It can also be verified that

$$R^{-1}[\varepsilon(t)] = R^T[\varepsilon(t)] \tag{4.11}$$

As we know that

$$\begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} = \frac{2}{3} C \begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} \tag{4.12}$$

Where

$$C = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{4.13}$$

A direct transformation from the abc-frame to the dq-frame can be obtained by substitution of $[f_\alpha \;\; f_\beta]^T$ from equation (4.12) in (4.7),as

$$\begin{bmatrix} f_d(t) \\ f_q(t) \end{bmatrix} = \frac{2}{3} T[\varepsilon(t)] \begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} \tag{4.14}$$

Where

$$T[\varepsilon(t)] = R[\varepsilon(t)]C = \begin{bmatrix} \cos[\varepsilon(t)] & \cos\left[\varepsilon(t) - \frac{2\pi}{3}\right] & \cos\left[\varepsilon(t) - \frac{4\pi}{3}\right] \\ \sin[\varepsilon(t)] & \sin\left[\varepsilon(t) - \frac{2\pi}{3}\right] & \sin\left[\varepsilon(t) - \frac{4\pi}{3}\right] \end{bmatrix} \tag{4.15}$$

As we know that

$$\begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} = C^T \begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} \tag{4.16}$$

Similarly, a direct transformation from the dq-frame to the abc-frame can be obtained by substituting for $\left[f_\alpha \;\; f_\beta\right]^T$ from equation (4.9) in (4.16) as

$$\begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} = T[\varepsilon(t)]^T \begin{bmatrix} f_d(t) \\ f_q(t) \end{bmatrix} \tag{4.17}$$

Where

$$T[\varepsilon(t)]^T = C^T R[-\varepsilon(t)] = \begin{bmatrix} \cos[\varepsilon(t)] & \sin[\varepsilon(t)] \\ \cos\left[\varepsilon(t) - \frac{2\pi}{3}\right] & \sin\left[\varepsilon(t) - \frac{2\pi}{3}\right] \\ \cos\left[\varepsilon(t) - \frac{4\pi}{3}\right] & \sin\left[\varepsilon(t) - \frac{4\pi}{3}\right] \end{bmatrix} \tag{4.18}$$

Based on the Figure 4.1, one deduces

$$\hat{f}(t) = \sqrt{f_d^2(t) + f_q^2(t)} \tag{4.19}$$

$$\cos[\delta(t)] = \frac{f_d(t)}{\hat{f}_d(t)} = \frac{f_d(t)}{\sqrt{f_d^2(t) + f_q^2(t)}} \tag{4.20}$$

$$\sin[\delta(t)] = \frac{f_q(t)}{\hat{f}_q(t)} = \frac{f_q(t)}{\sqrt{f_d^2(t) + f_q^2(t)}} \tag{4.21}$$

$$\theta(t) = \varepsilon(t) + \delta(t) \tag{4.22}$$

It can be verified that

$$\frac{2}{3} TT^T \begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} f_d \\ f_q \end{bmatrix} \tag{4.23}$$

Equation (4.23) can be used in conjunction with (4.17) to formulate dq-frame equations for a three-phase system, based on abc-frame equations. It can also be shown that

$$\frac{2}{3} T^T T \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \tag{4.24}$$

Equations (4.23) and (4.17) can be used to transform a set of dq-frame equations to an equivalent set of equations in abc-frame.

### 4.3.3 Formulation of Power in dq-Frame

As we know that power in three-wire three-phase systems is given by as

$$P(t) = \mathrm{Re}\left\{\frac{3}{2} \hat{v}(t) \vec{i}^{*}(t)\right\} \tag{4.25}$$

$$Q(t) = \mathrm{Im}\left\{\frac{3}{2} \hat{v}(t) \vec{i}^{*}(t)\right\} \tag{4.26}$$

Where

P(t) and Q(t) are instantaneous active and reactive power Complex power is as

$$S(t) = P(t) + jQ(t) = \frac{3}{2}\hat{v}(t)\vec{i}^{*}(t) \qquad (4.27)$$

We derive active and reactive power in term of dq-frame variables. Based on equation (4.2), we substitute for $\hat{v}(t) = (v_d + jv_q)e^{j\varepsilon(t)}$ and $\vec{i}^{*}(t) = (i_d - ji_q)e^{-j\varepsilon(t)}$ in equation (4.25) and (4.27)

$$P(t) = \frac{3}{2}\left[V_d(t)i_d(t) + V_q(t)i_q(t)\right] \qquad (4.28)$$

$$Q(t) = \frac{3}{2}\left[-V_d(t)i_q(t) + V_q(t)i_d(t)\right] \qquad (4.29)$$

Equations (4.28) and (4.29) suggest that if $v_q$=0, the real and reactive power components are proportional to $i_d$ and $i_q$, respectively. This property is widely used in the control of grid-connected three phase VSC systems.

## 4.4 VSC-HVDC system control

Vector current control is the most popular control method used for VSC-based HVDCs. The basic principle of the vector current controlled VSC is to control instantaneous active and reactive grid currents independent of each other. By utilizing synchronously rotating dq reference frame independent active and reactive power control is possible. Initially, system currents and voltages are described as vectors in a stationary αβ reference frame, and then they are transformed to the rotating dq coordinate system.

The control system of the VSC-HVDC is based on a fast inner current control loop controlling the ac current. The ac current references are supplied by the outer controllers. The reference value of the active current can be derived from the dc voltage controller, In all these controllers, integrators can be used to eliminate the steady state errors. Either side of the link can choose between ac voltage control and reactive power control. Each of these controllers generates a reference value for the inner current controller.

Compared to the abc-frame control, the αβ-frame control of a VSC-HVDC system reduces the number of plants to be controlled from three to two. Furthermore, instantaneous decoupled control of the real and reactive power, exchanged between the VSC system and the AC system, is possible in αβ-frame. Therefore, the control variables, that is, feedback signals, feed-forward signals, and control signals are sinusoidal functions of time. The dq-frame control of a VSC system features all advantages of the αβ-frame control, in addition to the advantage that the control variables are DC quantities in the steady state. This feature it facilitates the compensator design, especially in variable-frequency scenarios.

To achieve zero steady-state error in the αβ-frame control, the bandwidth of the closed-loop system must be approximately larger than the AC system frequency; alternatively, the compensators can include complex-conjugate pairs of poles at the AC system frequency and other frequencies of interest, to increase the loop gain. In the dq-frame control, however, zero steady-state error is easily achieved by including integral terms in the compensators since the control variables are DC quantities.

Compared to the αβ-frame control, the dq-frame control requires a synchronization mechanism that is usually achieved through the phase-locked loop (PLL). This requirement can be regarded a demerit of the dq-frame control.

## 4.5 Real and Reactive power controller

To control the real and reactive power exchange with the ac system two control mode are available. First one is voltage mode control and second one is current mode control. In this thesis, current mode control is used to control the active and reactive power.

### 4.5.1 Voltage mode control

The first method that is known as voltage-mode control and illustrated in Figure 4.2 has been utilized in high-voltage/-power applications such as in FACTS controllers.

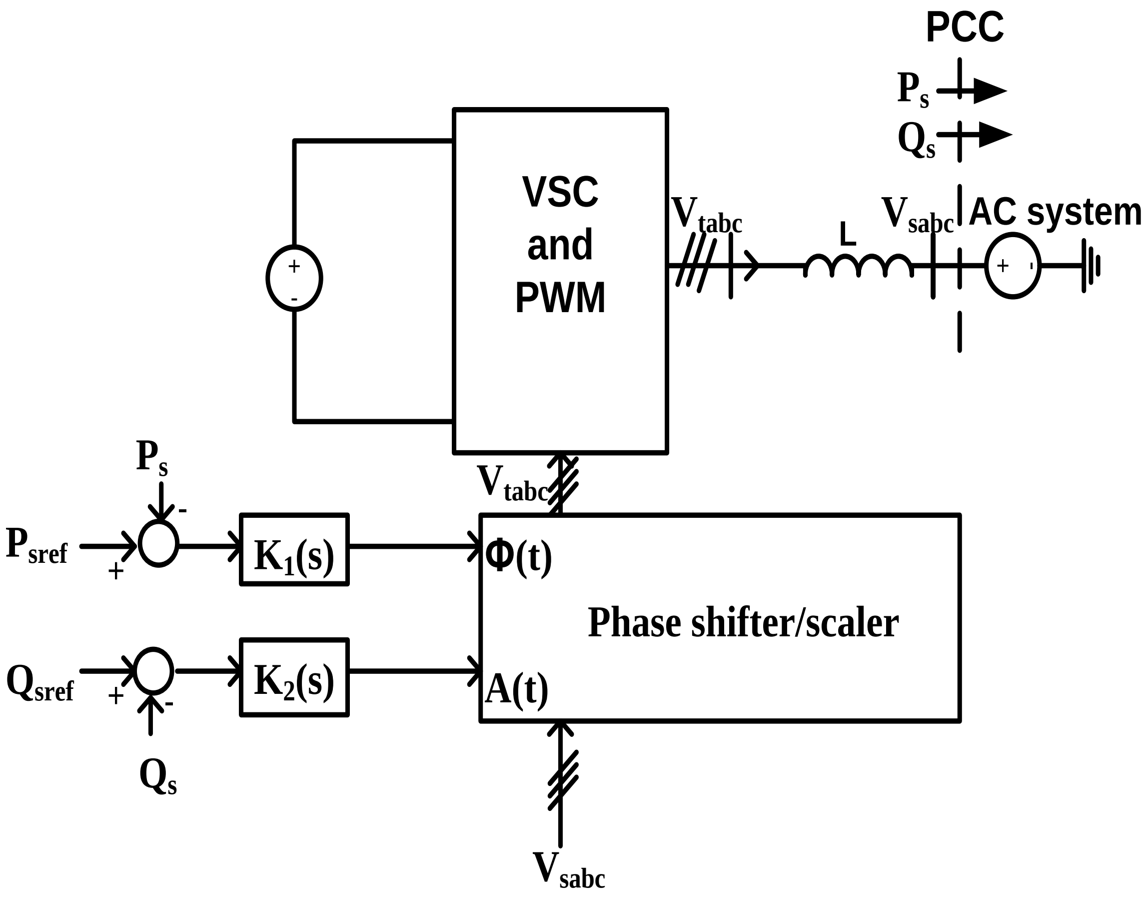



Fig.4.2: Schematic diagram of a voltage-controlled real-/reactive-power controller.

In a voltage-controlled VSC system, the real and reactive powers are controlled, respectively, by the phase angle and the amplitude of the VSC AC-side terminal voltage with respect to the PCC voltage. If the amplitude and phase angle of $V_{tabc}$ are close to those of $V_{sabc}$, the real and reactive power are almost decoupled and two independent compensators can be used for their control. The voltage-mode control is simple and has a low number of control loops. Therefore, the main shortcoming of the voltage-mode control is that there is no control loop closed on the VSC line current. Therefore, the VSC is not secured against over currents, and the current may undergo large excursions if the power commands are rapidly changed or faults take place in the AC system.

### 4.5.2 Current mode control

The second method to the control of the real and reactive power in the VSC system of Figure 4.3 is referred to as the current-mode control. In this method, the VSC line current is regulated by a current-control scheme, through the VSC AC-side terminal voltage. Then, the real and reactive power are controlled by the phase angle and the amplitude of the VSC line current with respect to the PCC voltage. Thus, due to the current regulation scheme, the VSC is secured against over current conditions. Other advantages of the current-mode control include robustness against variations in parameters of the VSC system and the AC system, superior dynamic performance, and higher control precision.

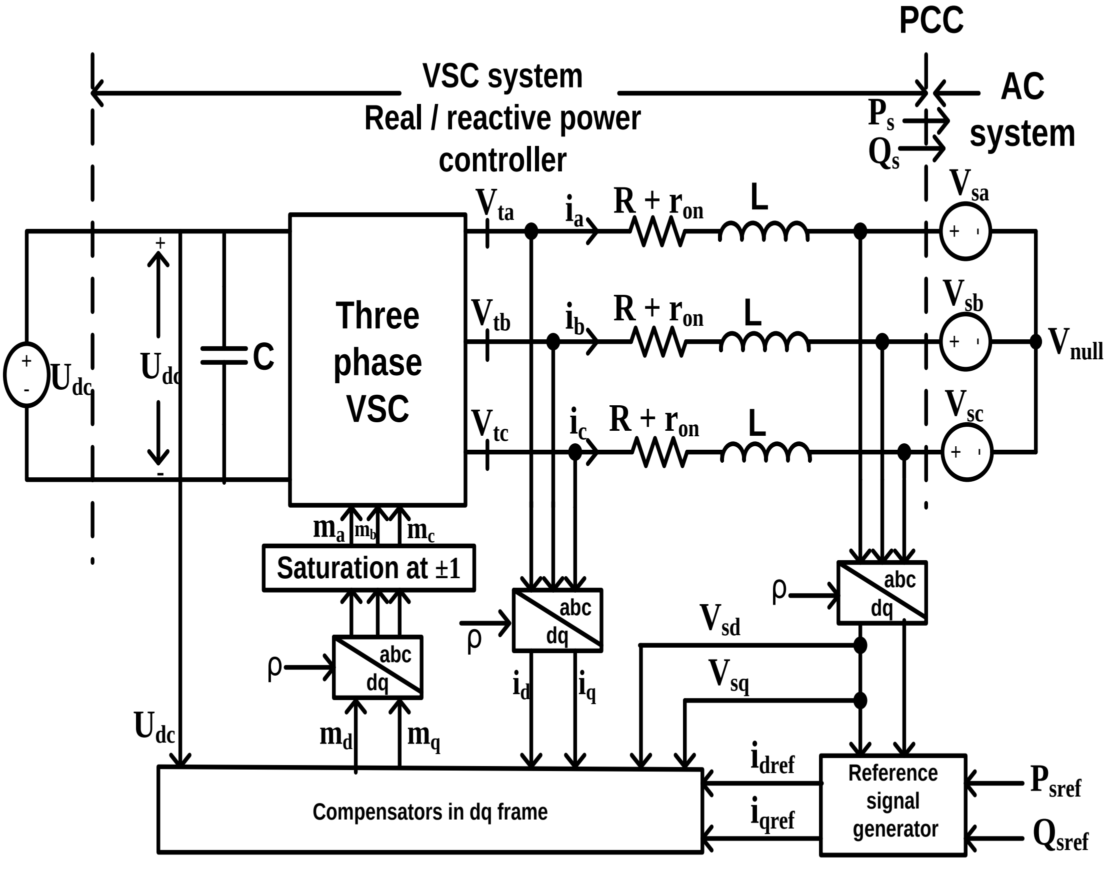



Fig.: 4.3 Schematic diagram of a current-controlled real-/reactive-power controller in dq-frame.

Figure 4.3 shows a schematic diagram of a current-controlled real-/reactive-power controller, illustrating that the control is performed in dq-frame. Thus, $P_s$ and $Q_s$ are controlled by the line current components $i_d$ and $i_q$. The feedback and feed-forward signals are first transformed to the dq-frame and then processed by compensators to produce the control signals in dq-frame. Finally, the control signals are transformed to the abc-frame and fed to the VSC (Fig. 4.3). To protect the VSC, the reference commands $i_{dref}$ and $i_{qref}$ are limited by the corresponding saturation blocks (not shown in the figure).

#### 4.5.2.1 dq-Frame current-controlled scheme (Inner Control Loop)

In this thesis, both VSC systems, that is, the real-/reactive power controller and the controlled DC-voltage power port, are controlled based on the current-mode control strategy. The current mode control strategy is employed for controlling the real and reactive power that each VSC system exchanges with the corresponding AC system.

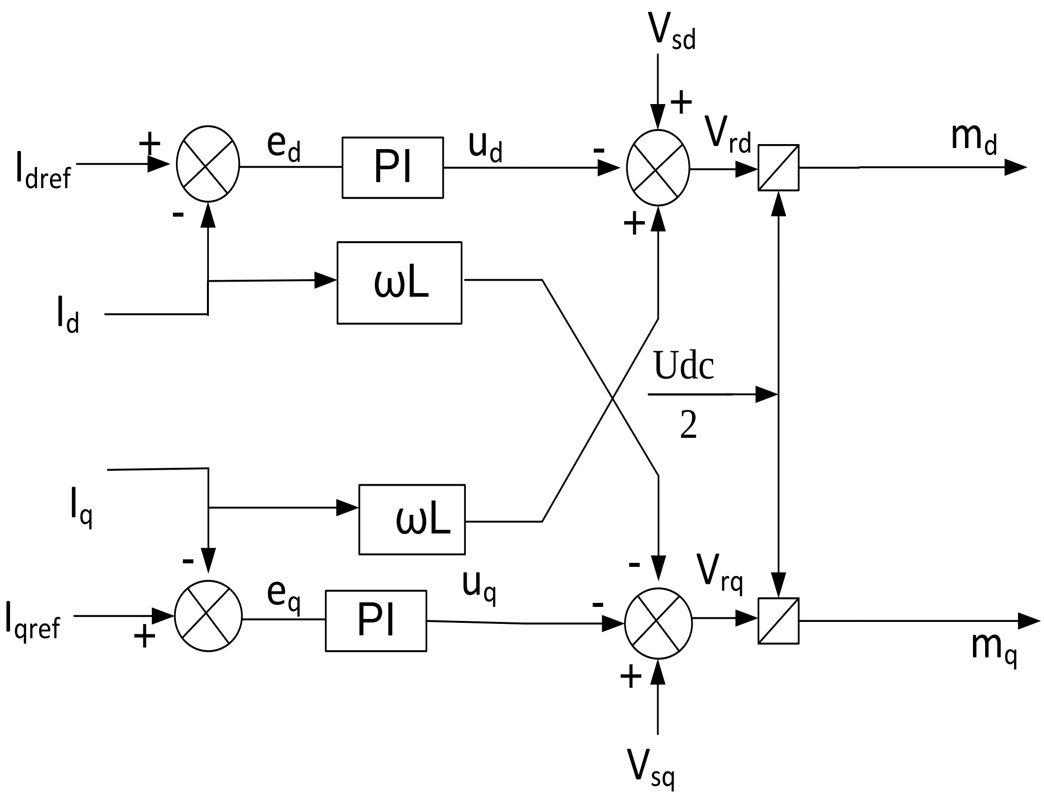



Fig. 4.4: Block diagram of the dq-frame current-control scheme for the real-/reactive power controller and the controlled DC-voltage power port.

Figure 4.4 illustrates a block diagram of the dq-frame current-control scheme, As Figure 4.4 shows, the d- and q-axis compensators, $k_d(s)$ and $k_q(s)$, process the error signals $e_d = i_{dref} - i_d$ and $e_q = i_{qref} - i_q$ and deliver the outputs $u_d$ and $u_q$, respectively. Then, $u_d$ and $u_q$ are augmented by feed-forward signals $V_{sd} - L\omega i_q$ and $V_{sq} + L\omega i_d$, and the signals $V_{tdref}$

and $V_{tqref}$ are generated. $V_{tdref}$ and $V_{tqref}$ are equivalent to d- and q-axis components of the VSC averaged AC-side terminal voltage. By the subscript ref we distinguish them from their counterparts in the actual AC-side terminal voltage, that is, $V_{td}$ and $V_{tq}$.

The feed-forward compensation is used to

- To decouple dynamics of $i_d$ and $i_q$.
- To enhance the disturbance rejection capability of the closed-loop system.
- To ensure a bump less system start-up.
- To decouple dynamics of $i_d$ and $i_q$ from those of the AC system.

For the feed-forward compensation, ω, that is, the rotational speed of the dq-frame, is obtained from the PLL. If the PLL dynamics are ignored, ω can be replaced by the (constant) value $\omega_0$.

Figure 4.4 also shows that to generate $m_d$ and $m_q$, $V_{tdref}$ and $V_{tqref}$ are divided by $V_{DC}(t)/2$. This operation can be considered as a feed-forward compensation, and has to compensate for the VSC conversion gain $V_{DC}(t)/2$ and to ensure that $V_{td}$ and $V_{tq}$ (in the actual converter AC-side terminal voltage) are an accurate reproduction of, respectively, $V_{tdref}$ and $V_{tqref}$ in spite of DC-bus voltage fluctuations. In Figure 4.4, $V_{DC}(t)$ can be replaced by its steady-state value, that is, $V_{DCref}$ , if the DC-bus voltage is relatively constant. Otherwise, its dynamically measured value should be used.

$K_d(s)$ is a proportional-integral (PI) compensator,

$$k_d(s) = \frac{k_p s + k_i}{s} \tag{4.30}$$

where $k_p$ and $k_i$ are the proportional and integral gains, respectively. Selecting

$$k_p = \frac{L}{\tau_I} \tag{4.31}$$

$$k_i = \frac{R + r_{on}}{\tau_i} \tag{4.32}$$

We have

$$\frac{I_d(s)}{I_{dref}(s)} = G_i(s) = \frac{1}{\tau_i(s) + 1} \tag{4.33}$$

where the time constant $\tau_i$ is a design choice. Equation (4.33) indicates that if $k_p$ and $k_i$ are selected based on (4.31) and (4.32), the step response of $i_d(t)$ to $i_{dref}$ (t) is a first-order exponential function with time constant $\tau_i$. This is desirable since the first-order exponential response is smooth and exhibits no steady-state error or overshoot. $\tau_i$ specifies the speed of response and is usually selected in the range of 0.5–5 ms, depending on the VSC switching frequency, the desired speed of response, the DC-bus voltage level, and the types of transients. The same compensator as $k_d(s)$ can also be adopted for the q-axis compensator, that is, $k_q(s)$. Thus,

$$\frac{I_q(s)}{I_{qref}(s)} = G_i(s) = \frac{1}{\tau_i(s) + 1} \tag{4.34}$$

Based on (4.28) and (4.29), the real and reactive power that the VSC system exchanges with the corresponding PCC are respectively

$$P_s(t) = \frac{3}{2}\left[V_{sd}(t)i_d(t) + V_{sq}(t)i_q(t)\right]$$

And

$$Q_s(t) = \frac{3}{2}\left[-V_{sd}(t)i_q(t) + V_{sq}(t)i_d(t)\right]$$

If the PCC voltage is balanced, then in steady state $V_{sq}$ = 0, and $V_{sd}$ becomes equal to the amplitude of the PCC line-to-neutral voltage. Therefore, $P_s$ and $Q_s$ become proportional to $i_d$ and $i_q$, respectively. Thus,

$$P_s = \frac{3}{2}\hat{V}_s i_d \tag{4.35}$$

$$Q_s = -\frac{3}{2}\hat{V}_s i_q \tag{4.36}$$

Where $\hat{V}_s$ is the peak value of the line-to-neutral voltage of the PCC and assumed to be a constant parameter. Figure 4.4 illustrates that $i_{dref}$ and $i_{qref}$ are the reference inputs to the VSC current-control scheme. Thus, in view of (4.35) and (4.36), $i_{dref}$ and $i_{qref}$ are calculated based on the desired real and reactive power, that is, $P_{sref}$ and $Q_{sref}$ , as illustrated in the block diagram of Figure 4.5. Then, $i_d$ and $i_q$ track $i_{dref}$ and $i_{qref}$ , based on the closed-loop transfer functions of (4.33) and (4.34). Substituting for $i_d(t) = G_i(p)i_{dref}(t)$ and $i_q(t) = G_i(p)i_{qref}(t)$ in (4.35) and (4.36), we obtain

$$P_s(t) = G_i(p)P_{sref}(t) \tag{4.37}$$

$$Q_s(t) = G_i(p)Q_{sref}(t) \tag{4.38}$$

#### 4.5.2.2 The outer controller

Common objectives for the outer loop controller is to provide the reference value of $i_d$ and $i_q$ to the inner control loop. Active current ($i_d$) is used to control active power flow or dc voltage level. Similarly, reactive current ($i_q$) is used to control reactive power flow into stiff grid connection. Reference value of $i_d$ and $i_q$ is obtained by outer control loop which is given to inner control loop.

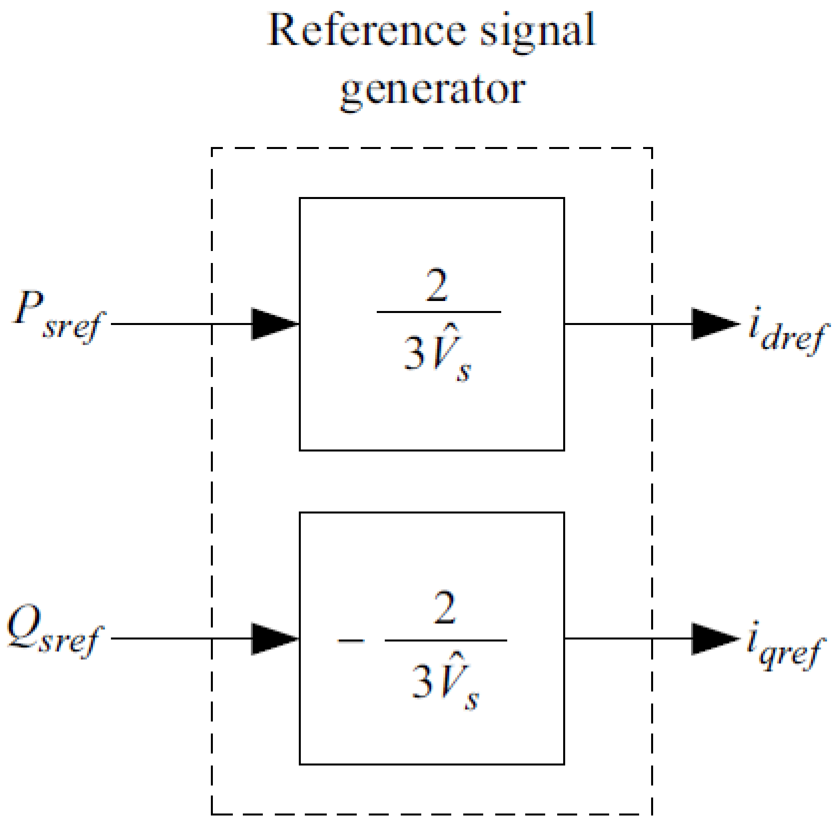



Figure 4.5: Control block diagram of the current reference signal generator.

Where

$$P_{sref} = \frac{3}{2}\hat{V}_s i_{dref} \tag{4.39}$$

$$Q_{sref} = -\frac{3}{2}\hat{V}_s i_{qref} \tag{4.40}$$

Equation (4.37) and (4.38) can be expressed in the Laplace domain as

$$\frac{P_s(s)}{P_{sref}(s)} = \frac{Q_s(s)}{Q_{sref}(s)} = G_i(s) \tag{4.41}$$

that is, $P_s$ and $Q_s$ track their respective reference commands based on the transfer function $G_i(s)$, which is a first-order transfer function with a time constant of $\tau_i$, (4.33) and (4.34).

## 4.6 DC side voltage controller:

DC side voltage control depends on the set reference signal. DC voltage remains at its reference value and regulates real power exchange between AC grid and VSC. DC voltage controller generates a current reference signal i.e $I_{dref}$.

Power corresponds to capacitor is $P_c = U_{dc}.I_c$

$$I_c = sCU_{dc} \tag{4.42}$$

Hence,

$$P_c = sCU_{dc}^2 \tag{4.43}$$

Energy stored in the capacitor is

$$E_c = \frac{1}{2}CU_{dc}^2 \tag{4.44}$$

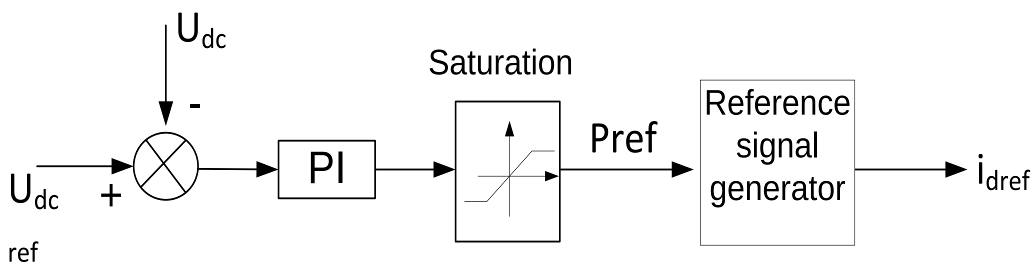



Figure 4.6 DC voltage controller

From equations 4.43 and 4.44 it is observed that the power across the capacitor is proportional to the square of the DC voltage. To avoid non linearity in DC voltage controller we use the difference between the square of DC voltage. Then it is passed through PI controller to have a $P_{sref}$.

# CHAPTER-5

# CASE STUDIES AND RESULTS

Two asynchronous AC 230 kV, 2000 MVA, systems are interconnected through a 200 MVA ± 100 kV VSC-HVDC link of 85 Km length. The rectifier and the inverter are connected through a 85 km cable and two 8 mH smoothing reactors. Both the converters are using IGBT based three level NPC technology. The carrier frequency is taken to a value of 27 time of fundamental frequency to generate PWM. Each station consists step down star (grounded)-delta transformer, the AC and DC filters, the converter reactor and the capacitors.

In this link, resistance p.u length, inductance p.u length and capacitance p.u length are taken to a value of 0.0139 (ohm/km), 0.000159 (H/km) and 0.000000231(F/km), respectively.

## 5.1 Two terminal VSC-HVDC system

Simulink model of two terminals VSC-HVDC system is shown below.

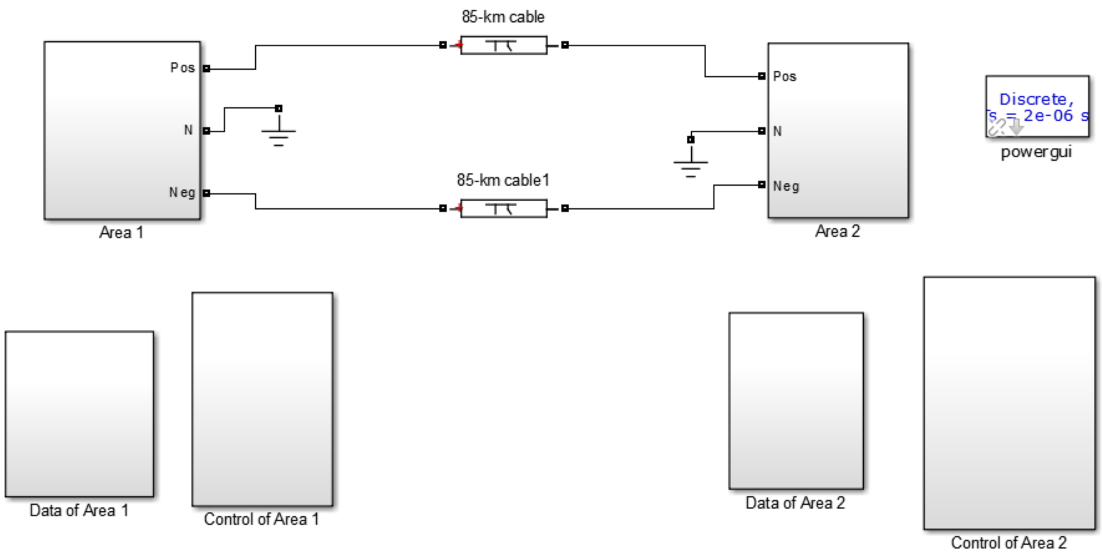



Figure 5.1: Simulink model of two terminal VSC-HVDC system

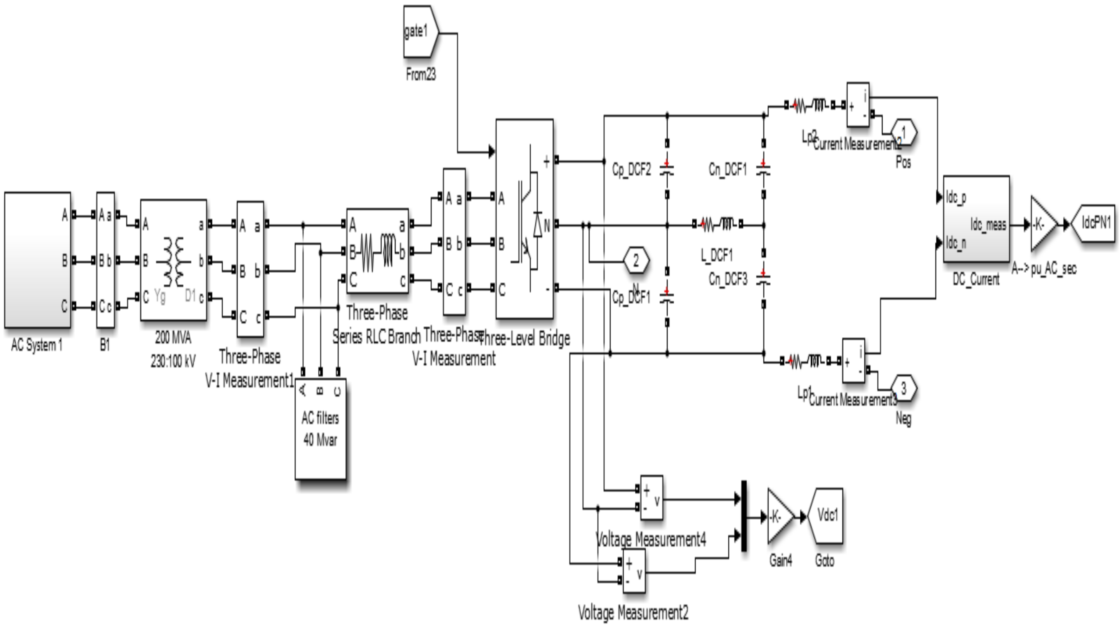



Figure 5.2: Simulink model of area-1 (rectifier or inverter)

Simulink model of area-1 and area-2 are similar and current controlling scheme is used in both the converters. All the magnitudes of voltage, current and power are taken in per unit basis.

**Case study I:**

In two terminals VSC-HVDC system, first converter maintains active and reactive power while the other maintains reactive power and DC voltage. For first converter, the reference active power is change from 0.5 to -0.5 p.u after 2 sec and reactive power is change from -0.2 to 0.2 p.u after 2 sec. For second converter, the reference reactive power is change from 0.2 to -0.2 p.u after 2 sec and DC voltage are specified to 1 p.u.

Figure 5.3 shows, the active power exchange between the AC system and VSC. Where the reference value is set at 0.9 p.u and triggering is applied at zero second. Hence PI controller tracks the reference signal. But it shows a transient behavior because at starting condition capacitor is not in charged. We need to charge the capacitor to avoid that transient behavior. For that triggering is applied after 0.2 second. So we will have a better transient response as shown in Figure 5.4

In this respect, the results for converter station-1 and converter station -2 are shown in Fig. 5.4 and Fig. 5.5, respectively.

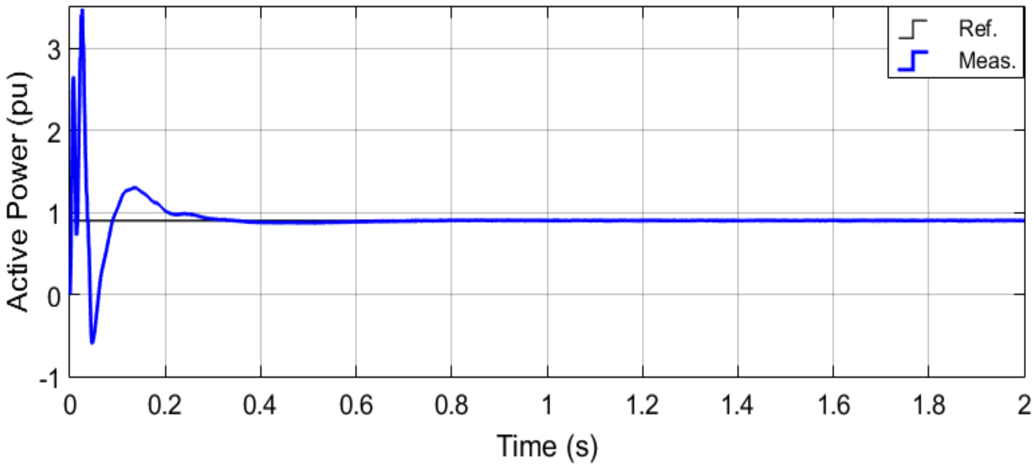
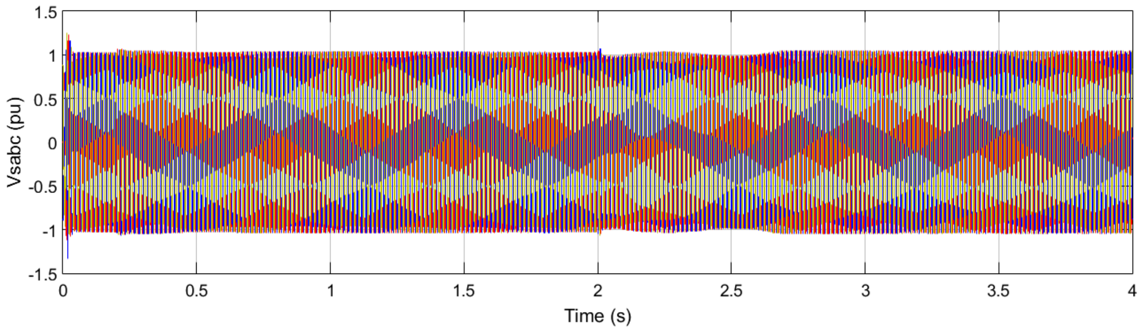
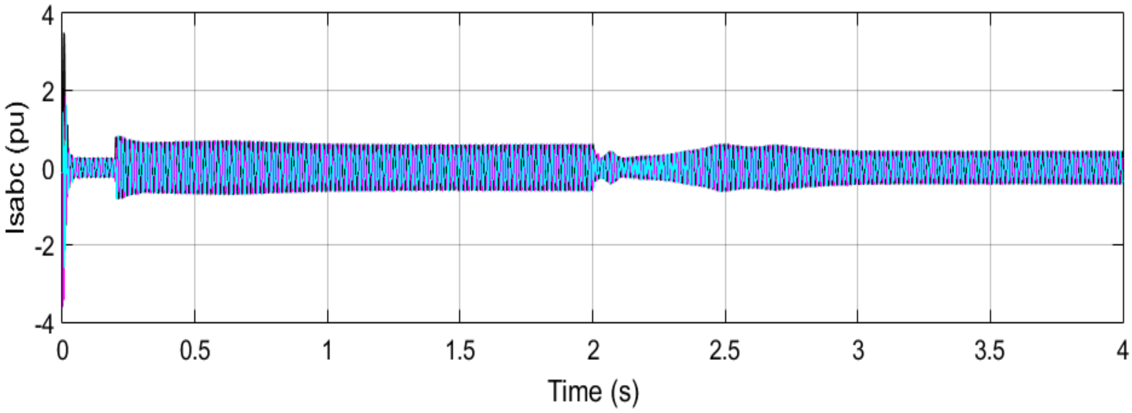


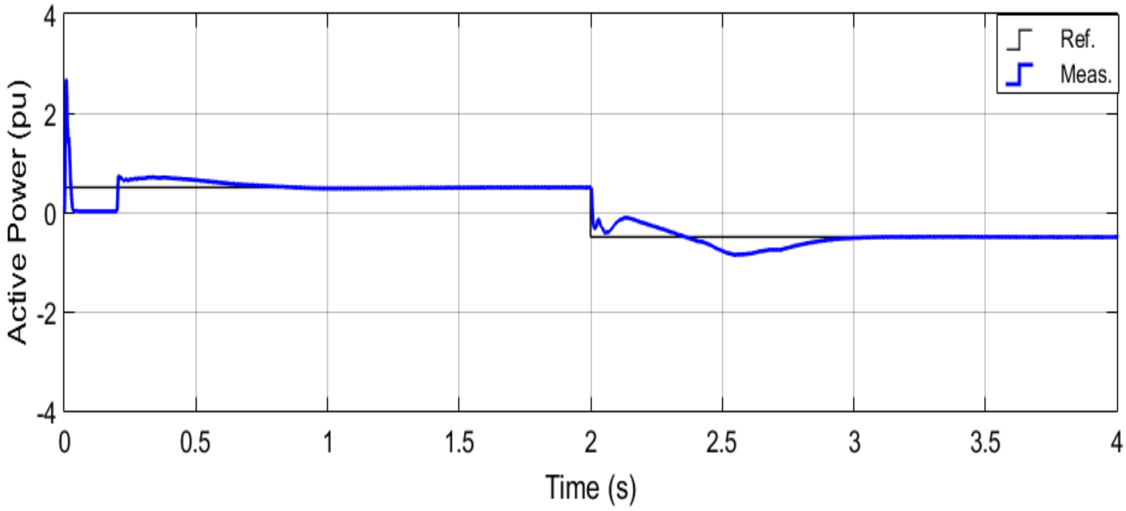

Figure 5.3 Active Power exchange between ac source and converter-I when triggering is applied at zero second.




(a)

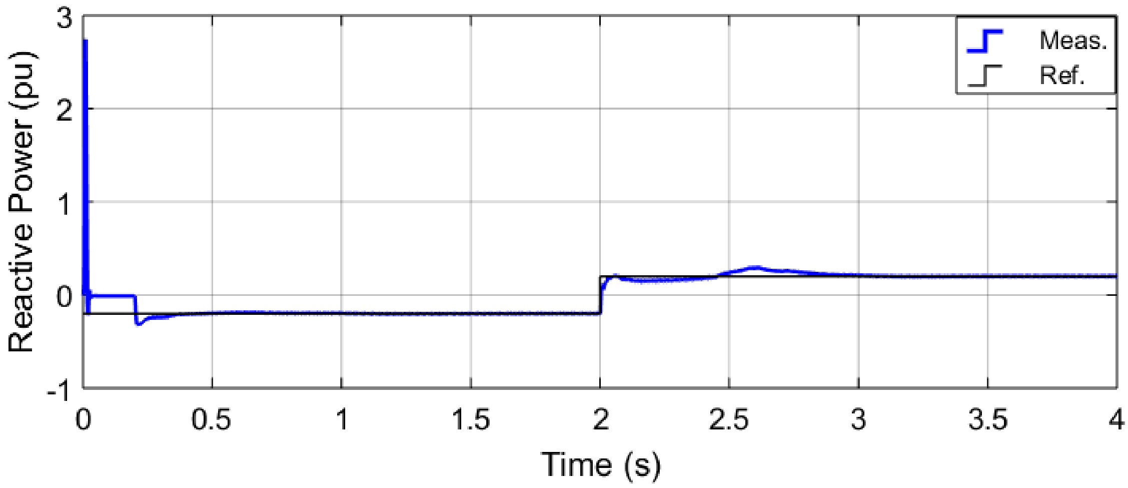



(b)



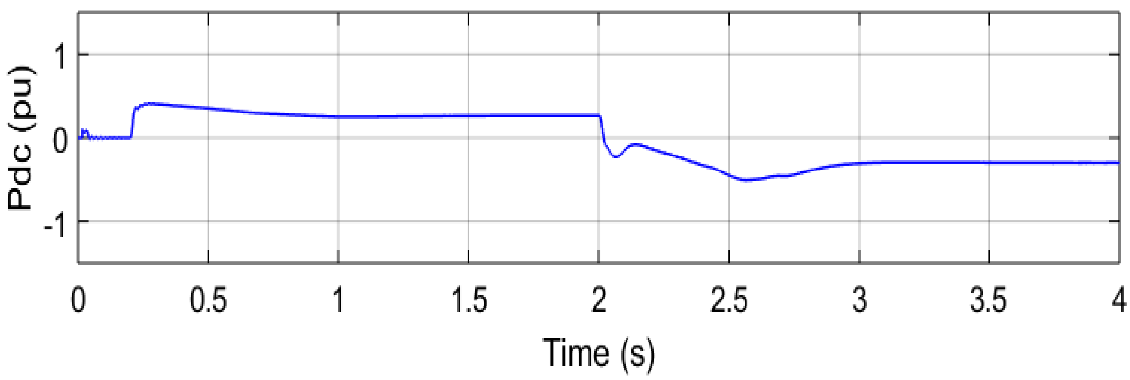
Ref.
Meas.
Active Power (pu)
4
2
0
-2
-4
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)


(c)



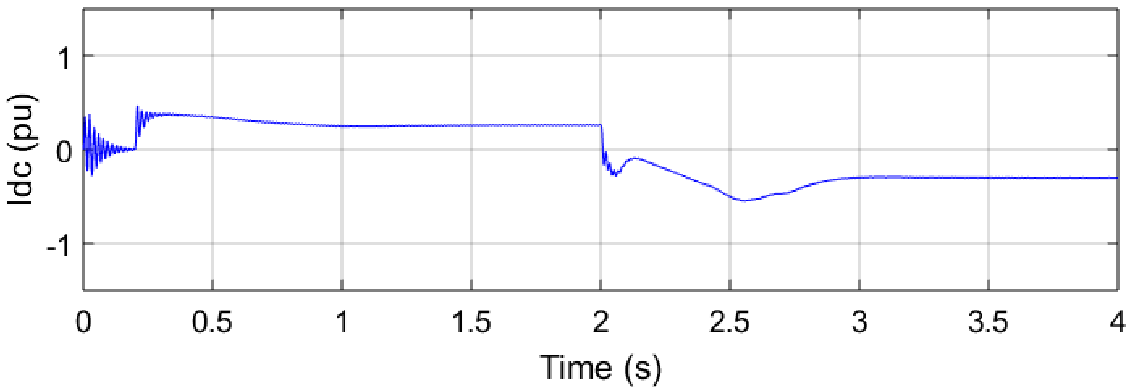
Meas.
Ref.
Reactive Power (pu)
3
2
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)


(d)



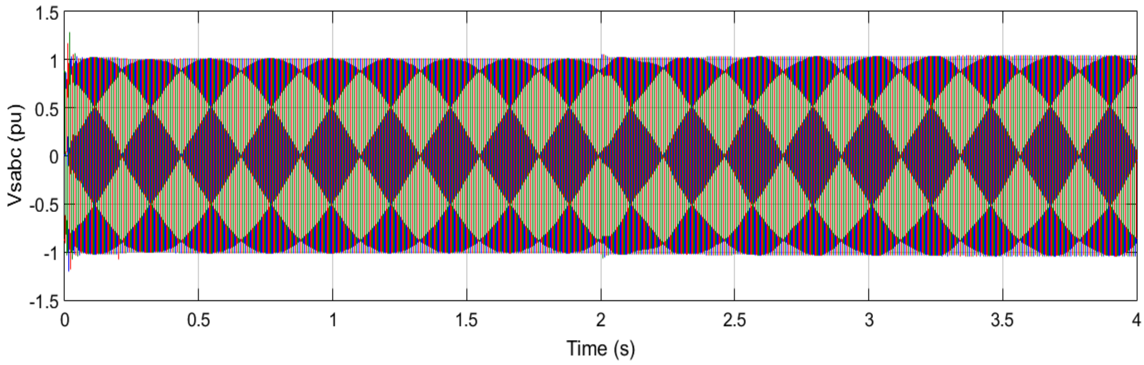
Pdc (pu)
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)


(e)

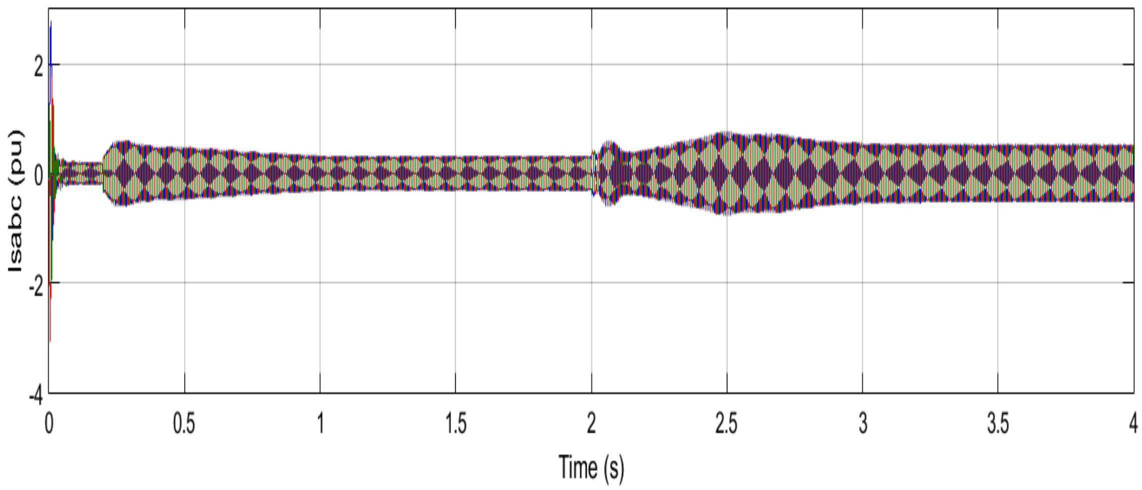



(f)

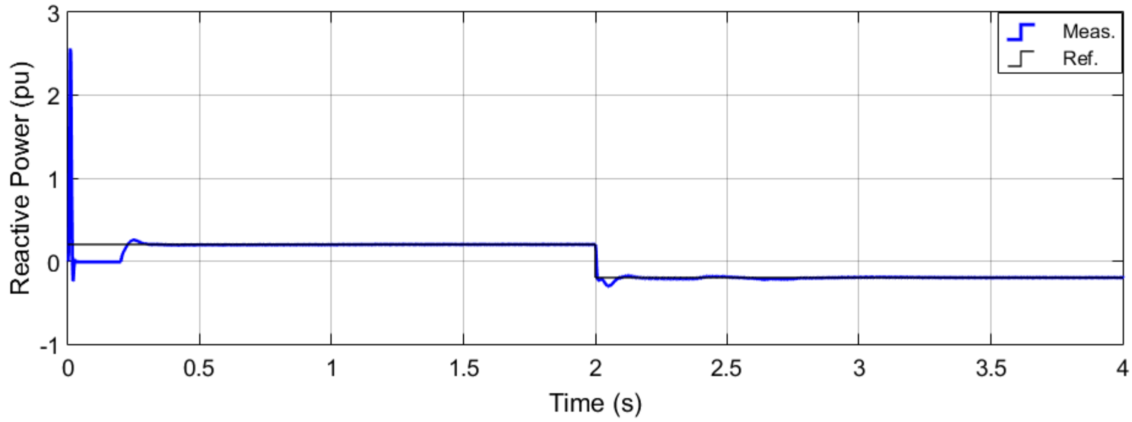
Figure 5.4: System performance at rectifier end (converter-I). (a) AC source voltage (b) AC source current (c) Active power exchange between converter-I and ac source (d) Reactive power exchange between converter-I and ac source (e) DC power (f) DC current.



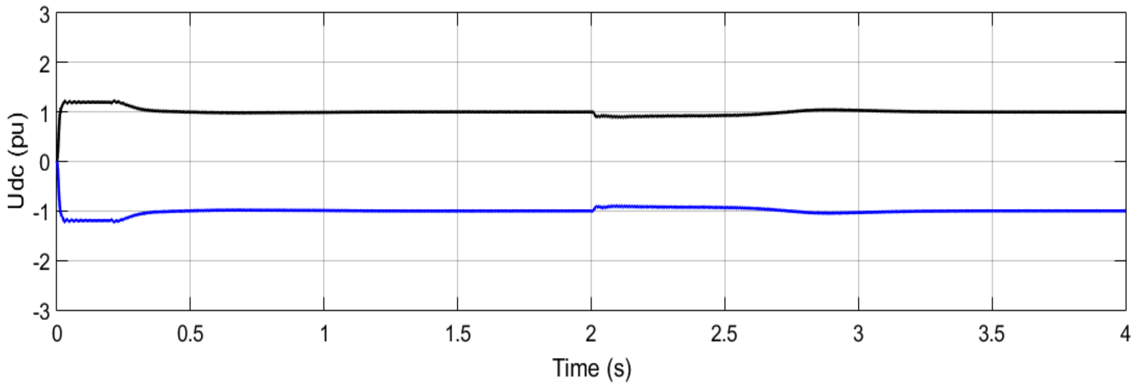

(a)



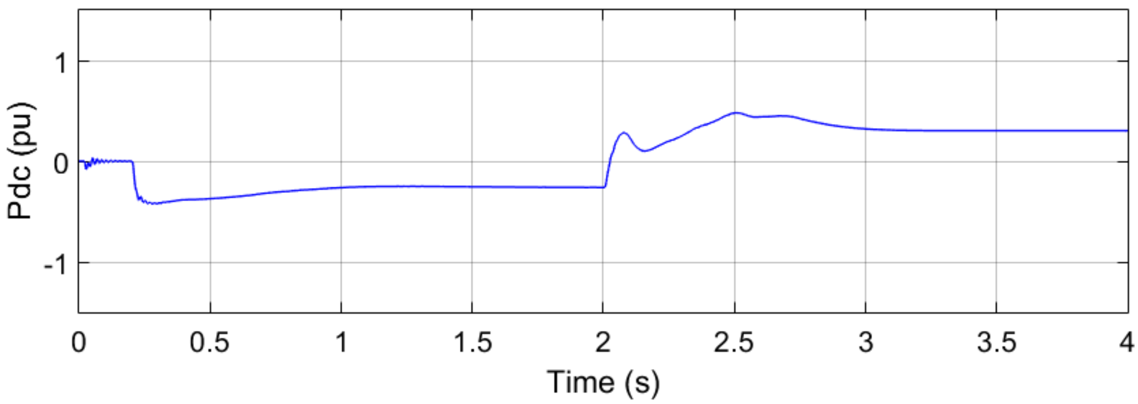

(b)




(c)




(d)

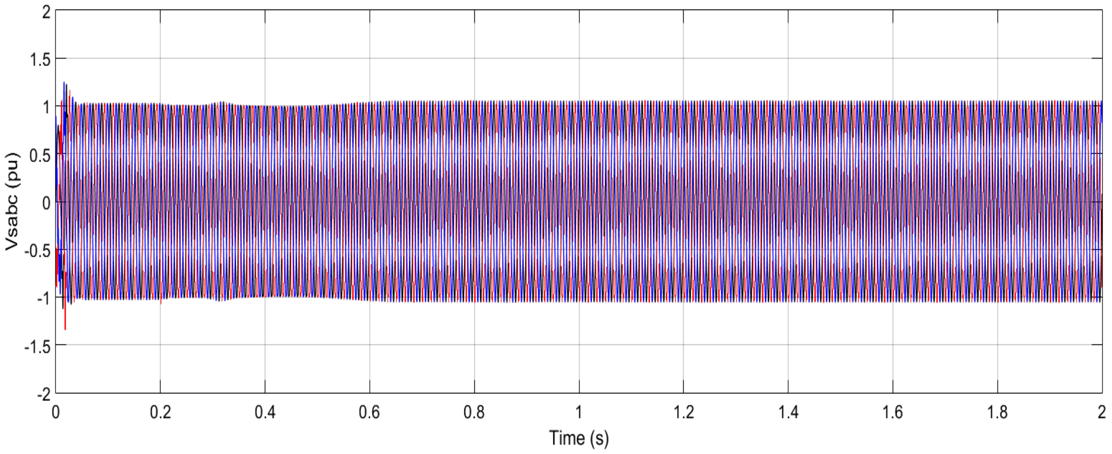



(e)

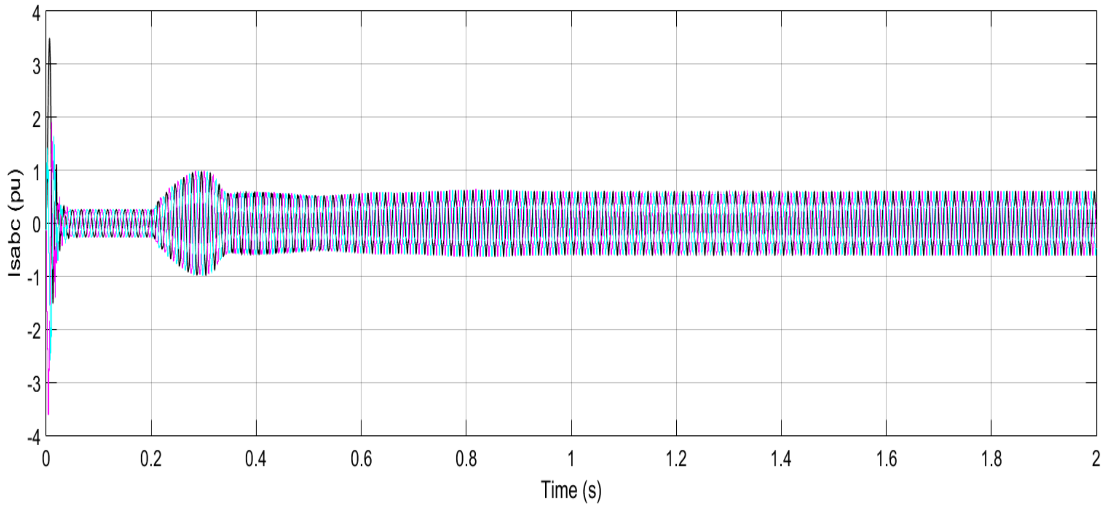
Figure 5.5: System performance at inverter end (converter-II) (a) AC source voltage (b) AC source current (c) Reactive power exchange between converter-II and ac system (d) DC side voltage (e) DC side power

**Case study II**:

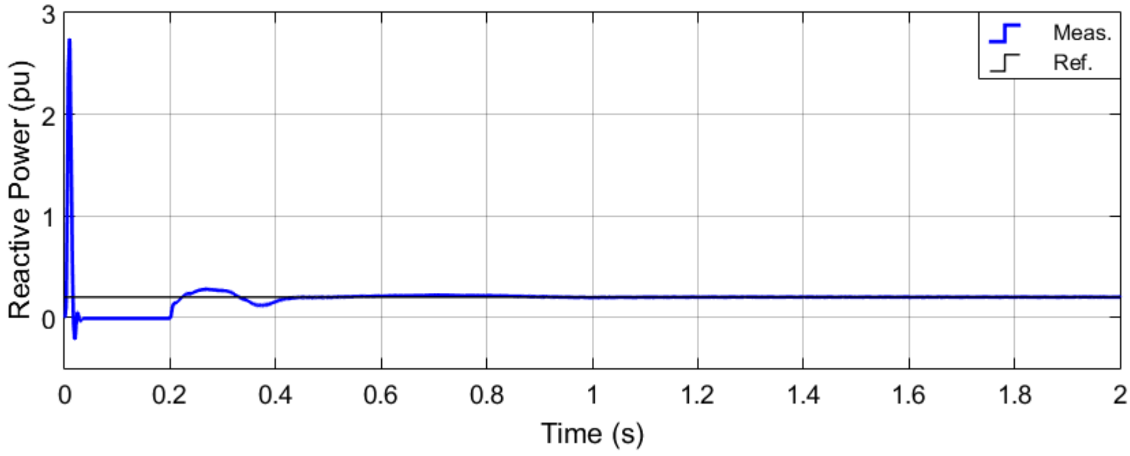
This case study is vice versa of case study-1. In this case study, the reactive power and DC voltage are specified for converter-1. The reactive power and DC voltage are specified to a value of 0.2 and 1 p.u respectively. The converter-2 operates in PQ control mode. The active and reactive power are set to 0.9 p.u and 0.3 p.u respectively. In this respect, the results for converter station-1 and converter station -2 are shown in Fig. 5.6 and Fig. 5.7, respectively.



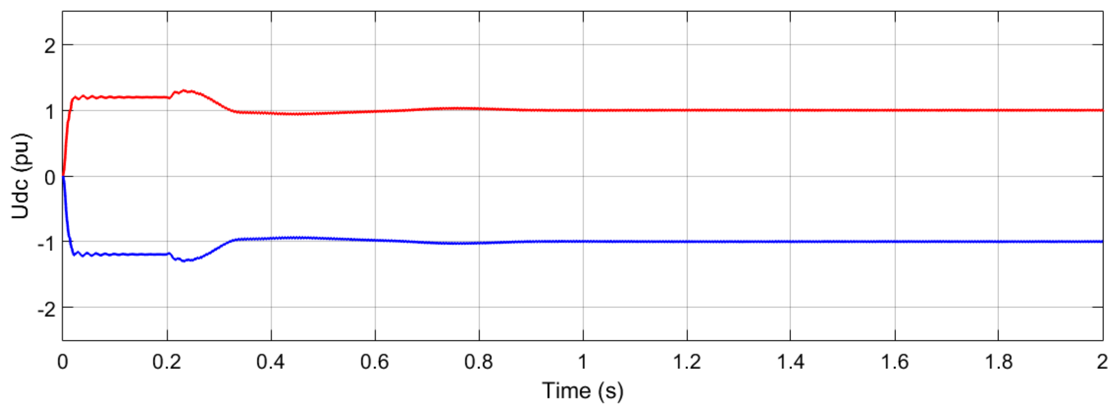

(a)



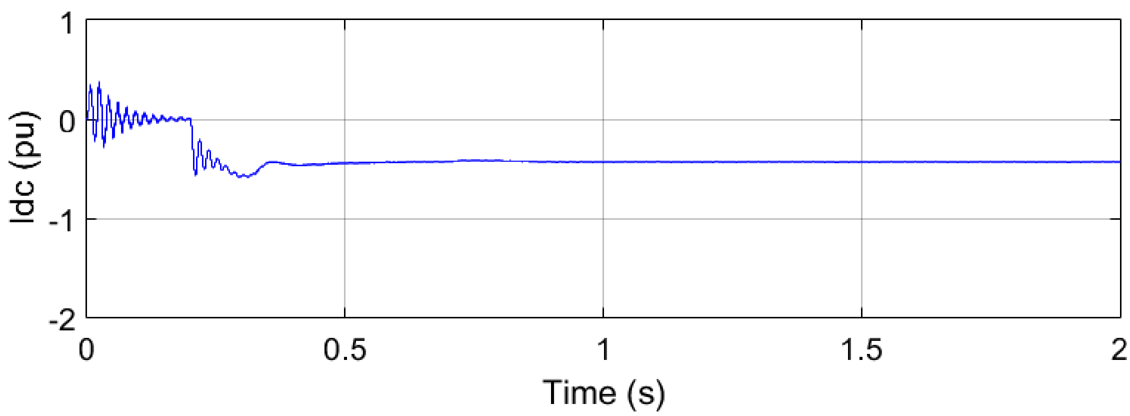

(b)



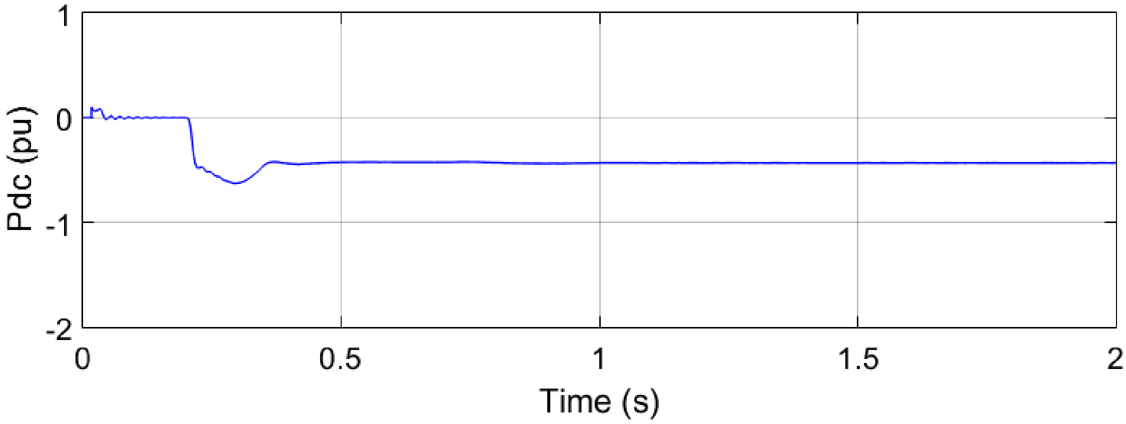

(c)




(d)

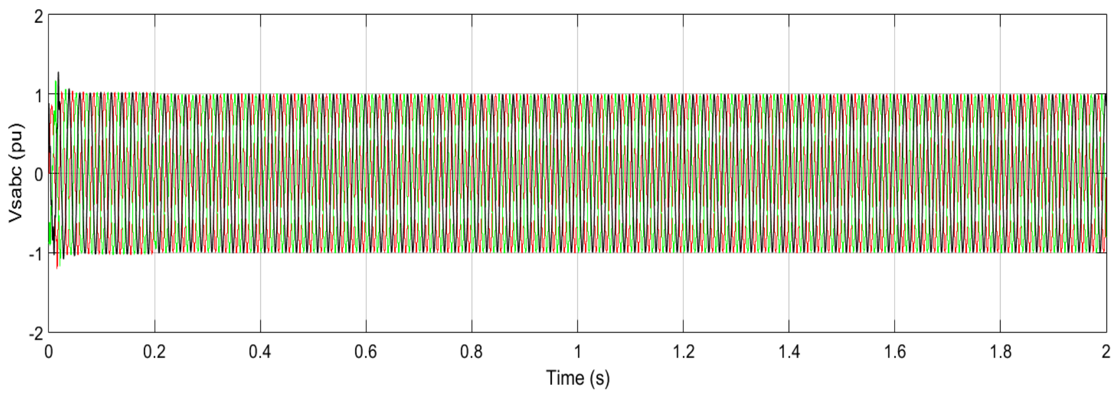



(e)

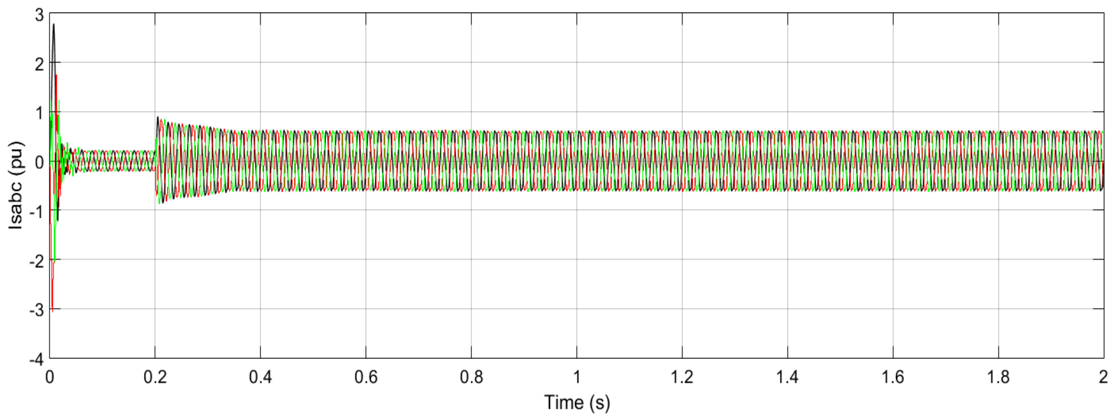



(f)

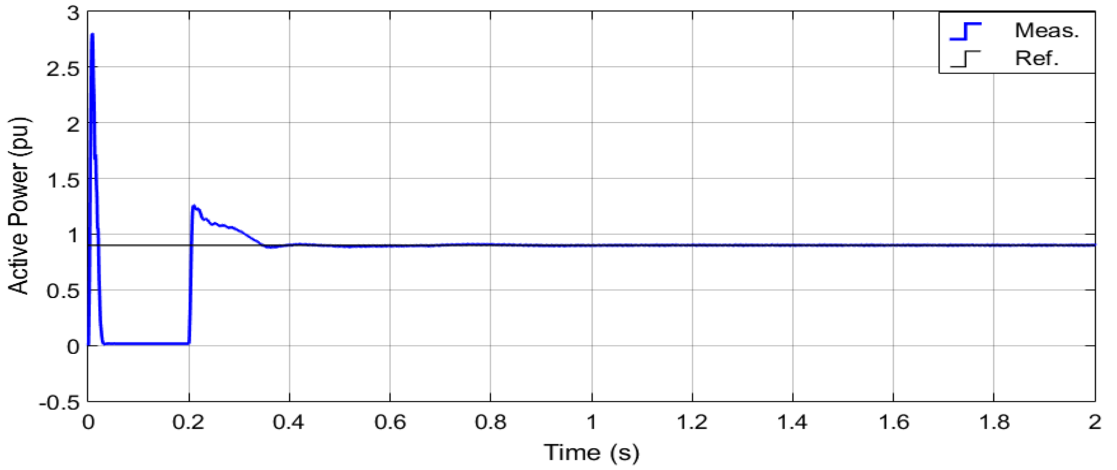
Figure 5.6: System performance at converter-I side (a) AC source voltage (b) AC source current (c) Reactive power exchange between converter-I and ac system (d) DC side voltage (e) DC current (f) DC side power



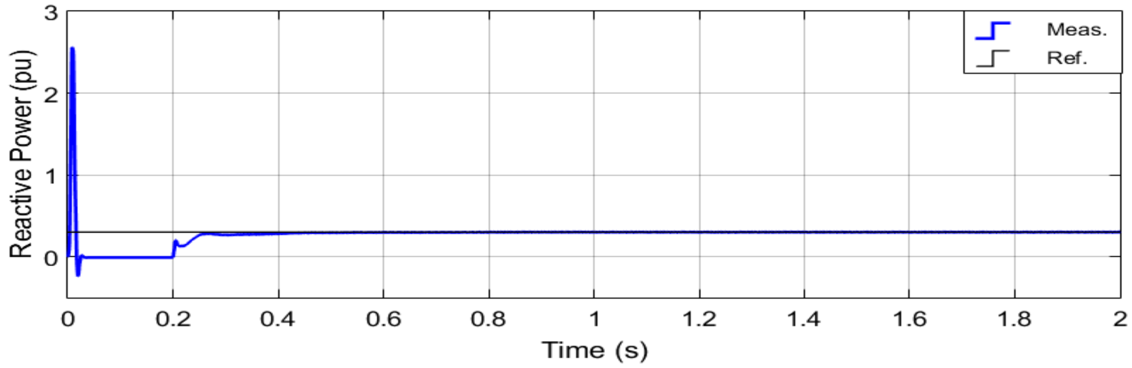

(a)



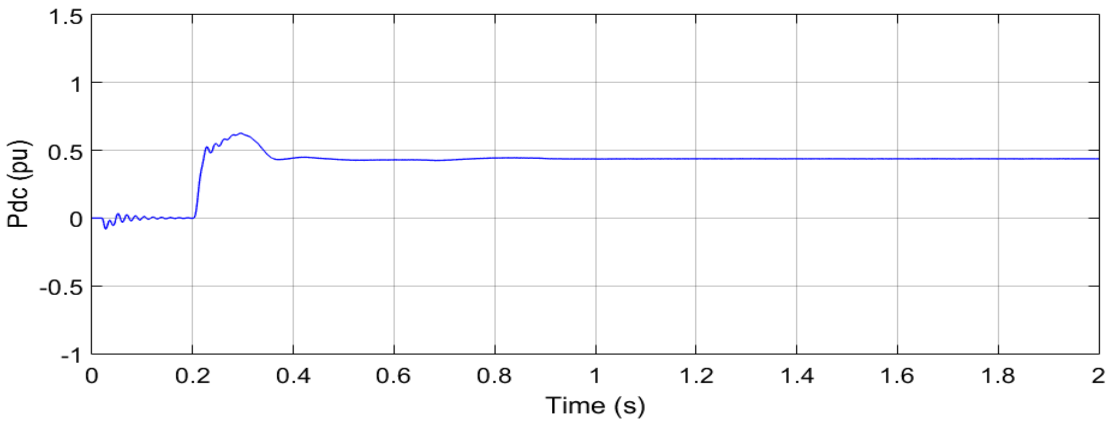
(b)




(c)




(d)




(e)

Figure 5.7: System performance at converter-II side (a) AC source voltage (b) AC source current (c) Active power exchange between converter-II and ac system (d) Reactive power exchange between converter-II and ac system (e) DC side power

## 5.2 Three terminal VSC-HVDC system

Simulink model of three terminal VSC-HVDC system is show below

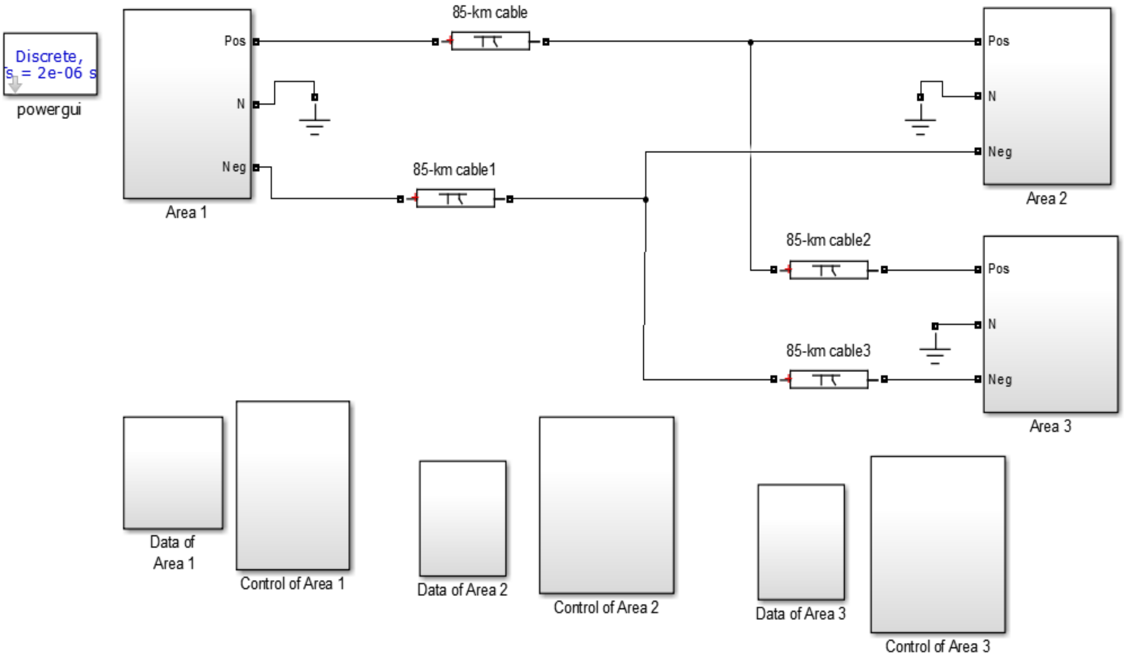
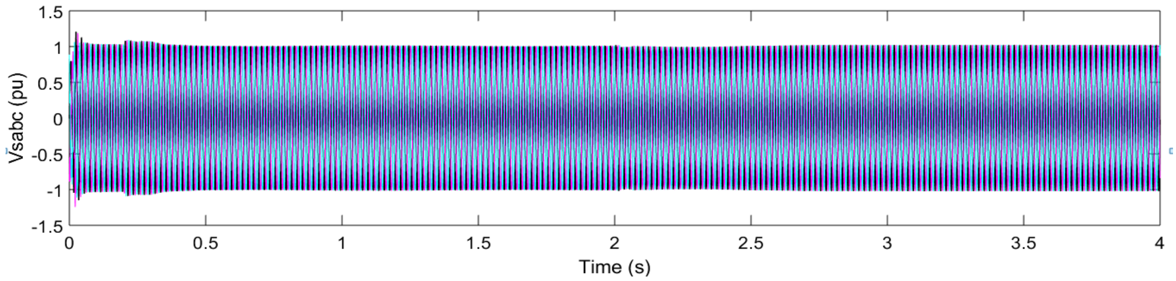


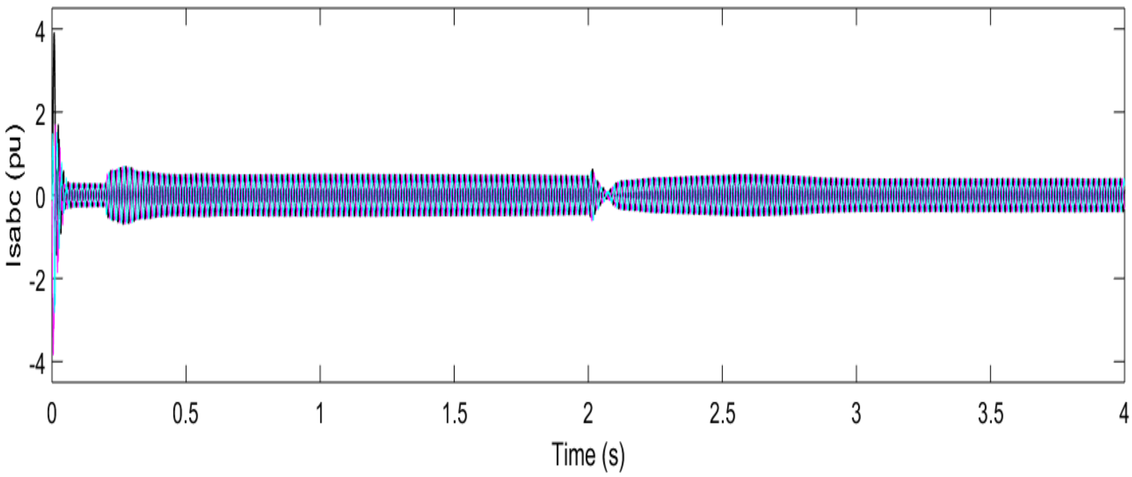

Figure 5.8: Simulink model of three terminal VSC-HVDC system

In three terminals VSC-HVDC system, first converter is maintains reactive power while the other both converters maintain active and reactive power. For first converter, the reference reactive power is change from -0.2 to 0.2 p.u after 2 sec and DC voltage is specified to 1 p.u. For second converter, the reference active power is change from -0.5 to 0.5 p.u and reactive power is changed from 0.2 to -0.2 p.u after 2 sec. For third converter, the reference active power is changed from 0.9 p.u to -0.9 p.u and reactive power is changed from -0.2 to 0.2 p.u after 2 sec.

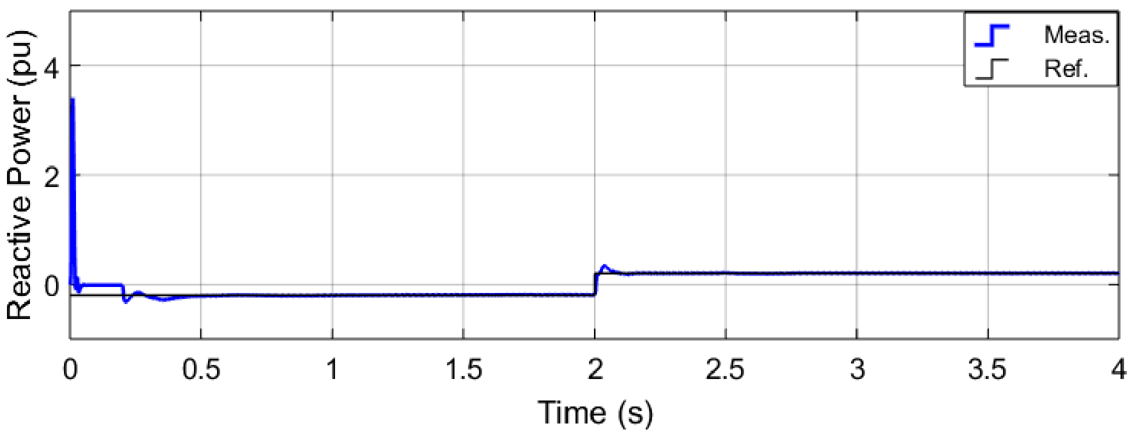
System performance of converters is shown as below



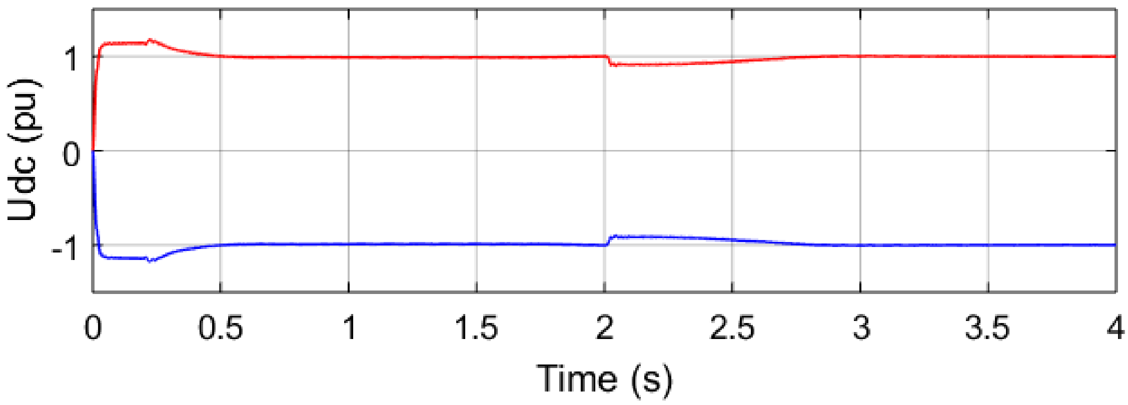

(a)



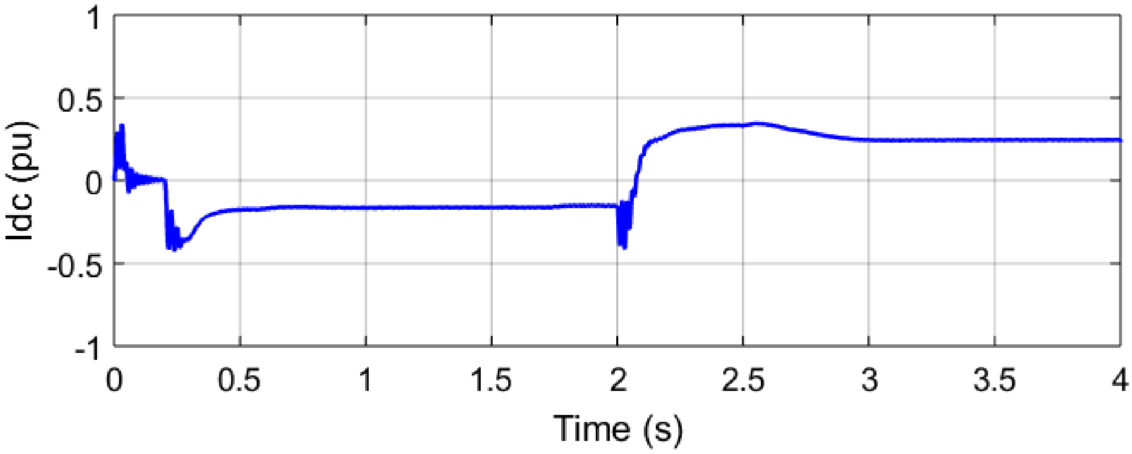

(b)



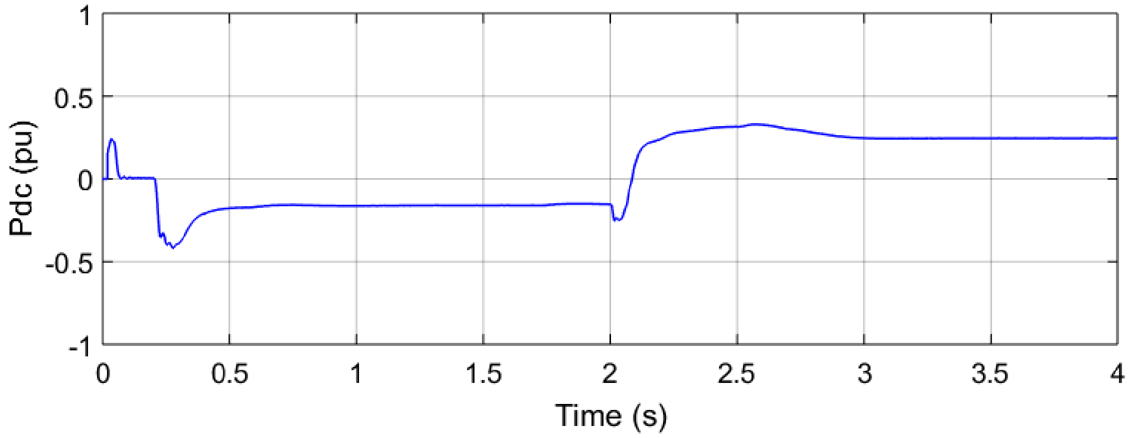

(c)




(d)

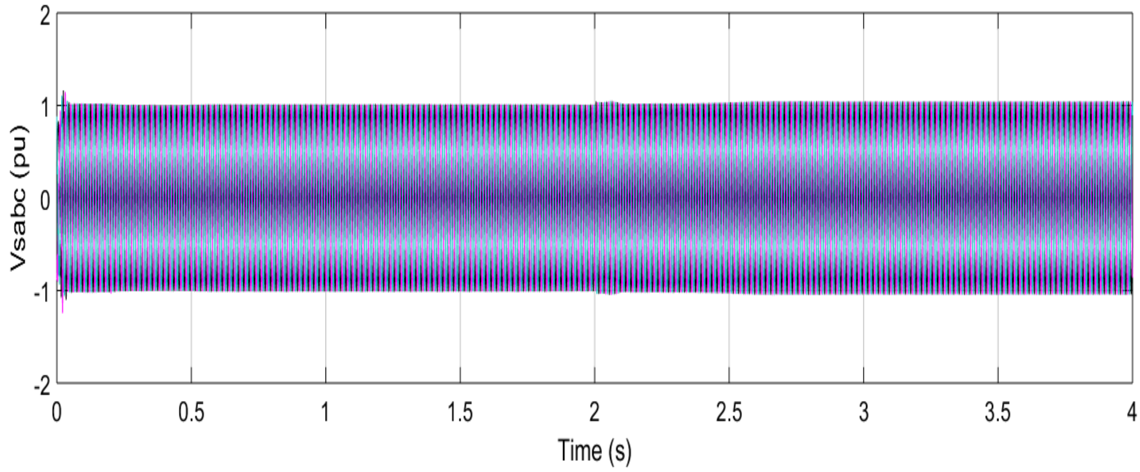



(e)

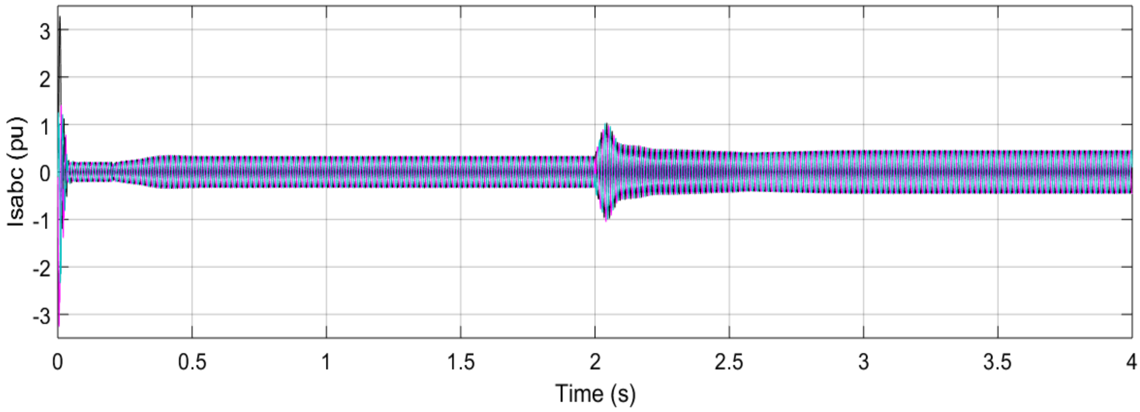



(f)

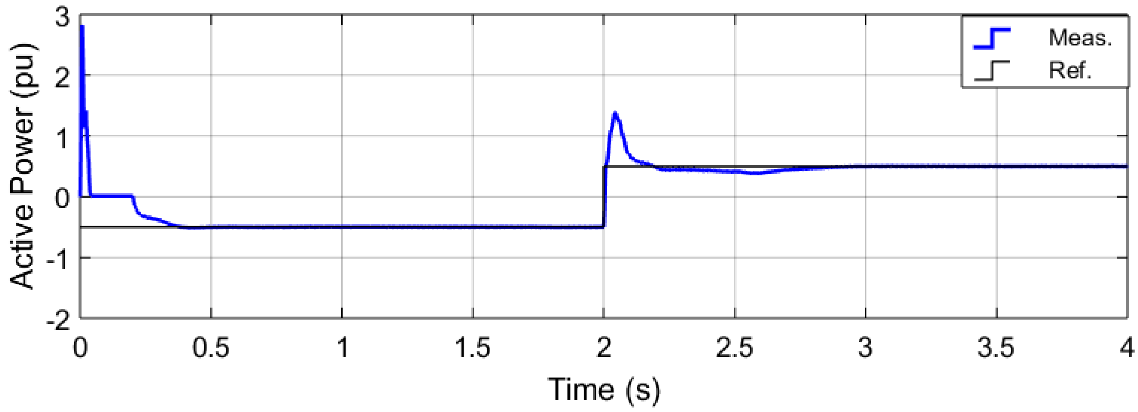
Figure 5.9: System performance at converter-I side (a) AC source voltage (b) AC source current (c) Reactive power exchange between converter-I and ac system (d) DC side voltage (e) DC side current (f) DC side Power



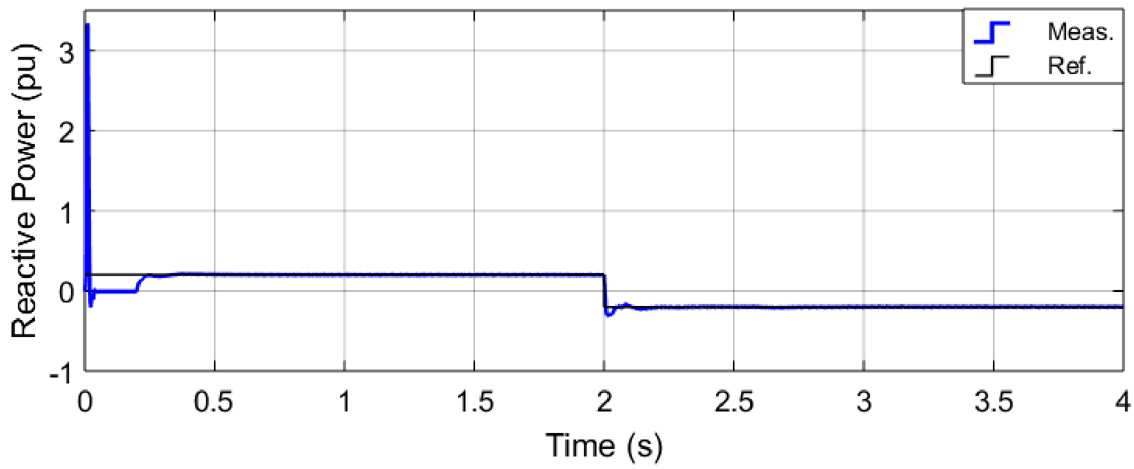

(a)



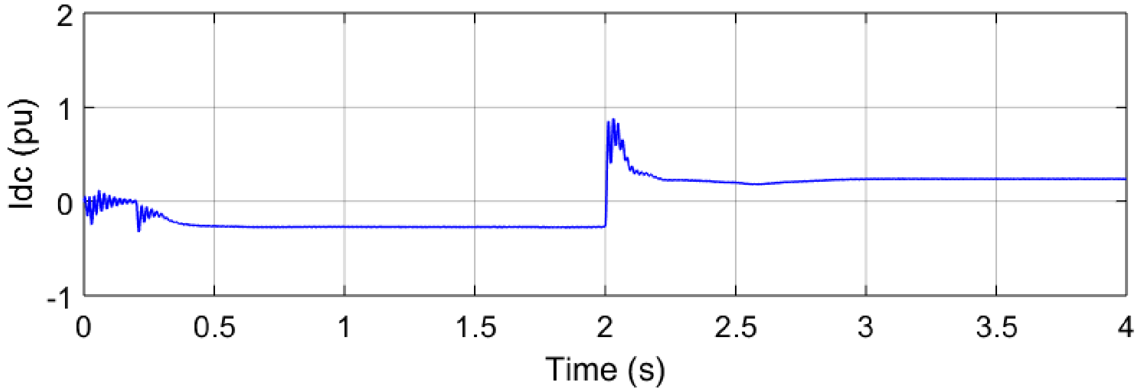

(b)



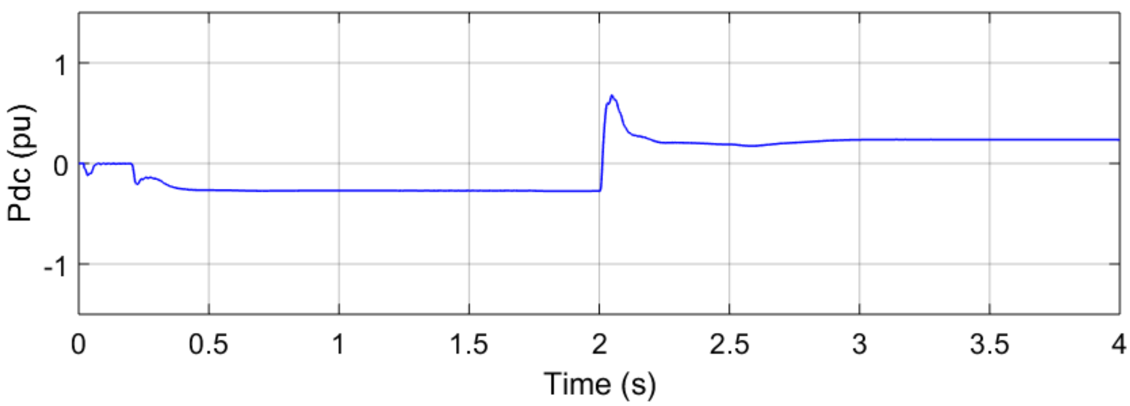

(c)




(d)

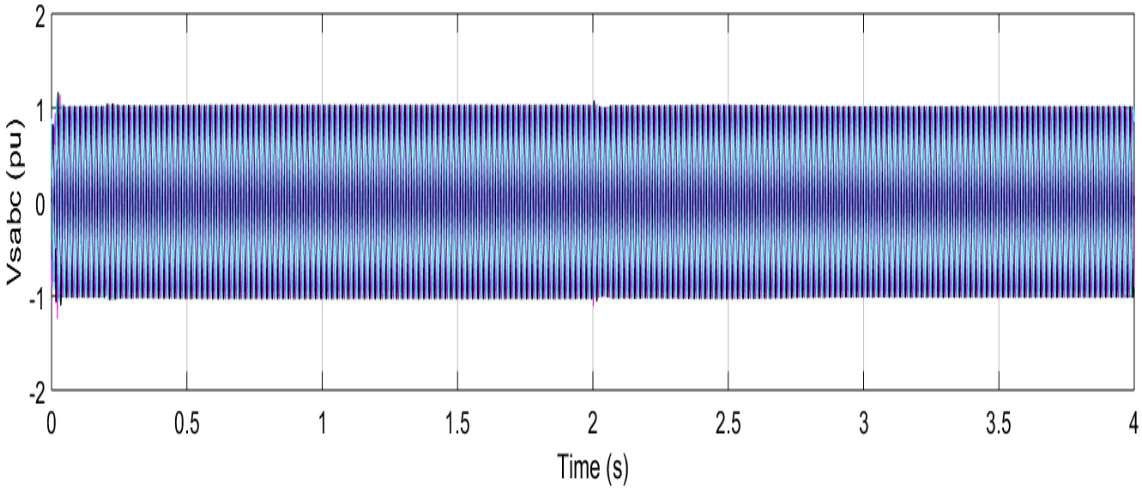



(e)

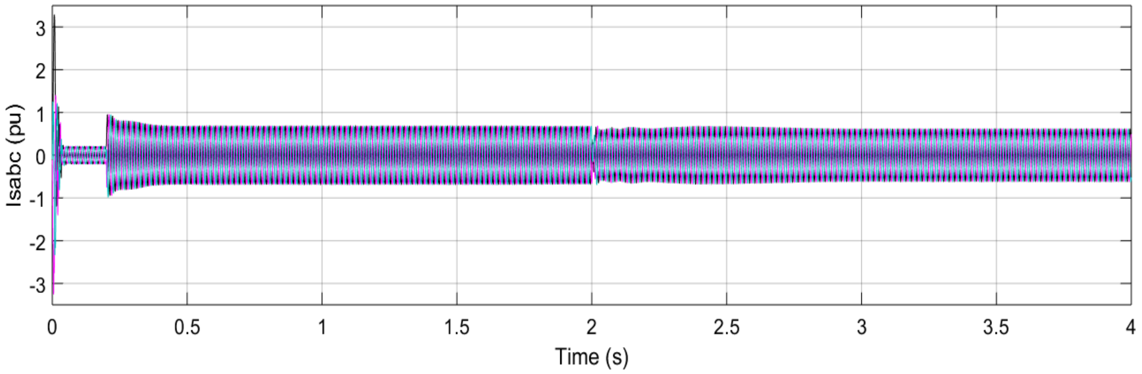



(f)

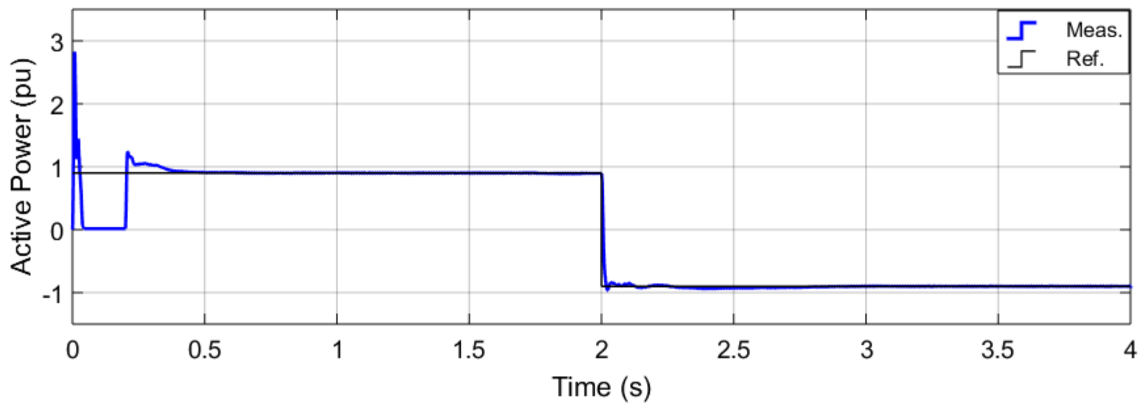
Figure 5.10: System performance at converter-II side (a) AC source voltage (b) AC source current (c) Active power exchange between converter-II and ac system (d) Reactive power exchange between converter-II and ac system (e) DC side current (f) DC side power


2
1
0
-1
-2
Vsabc (pu)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)

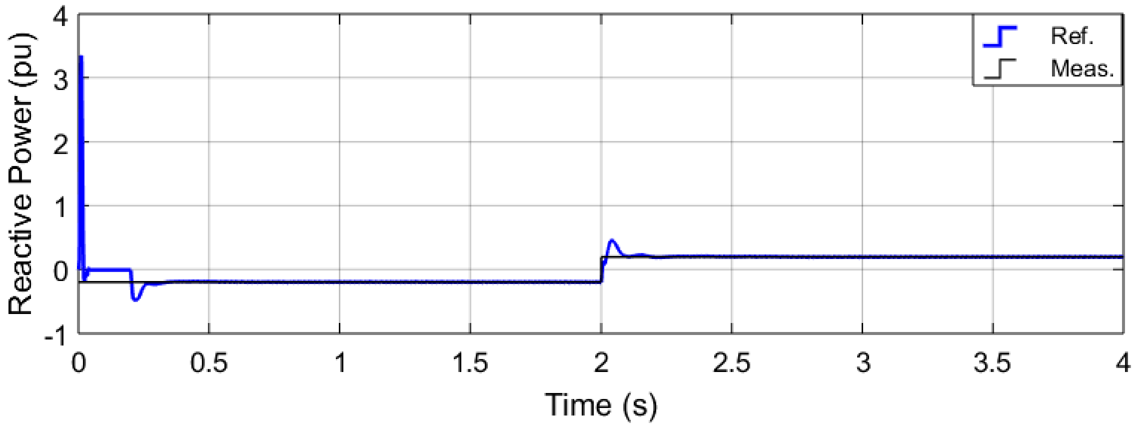
(a)


3
2
1
0
-1
-2
-3
Isabc (pu)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)

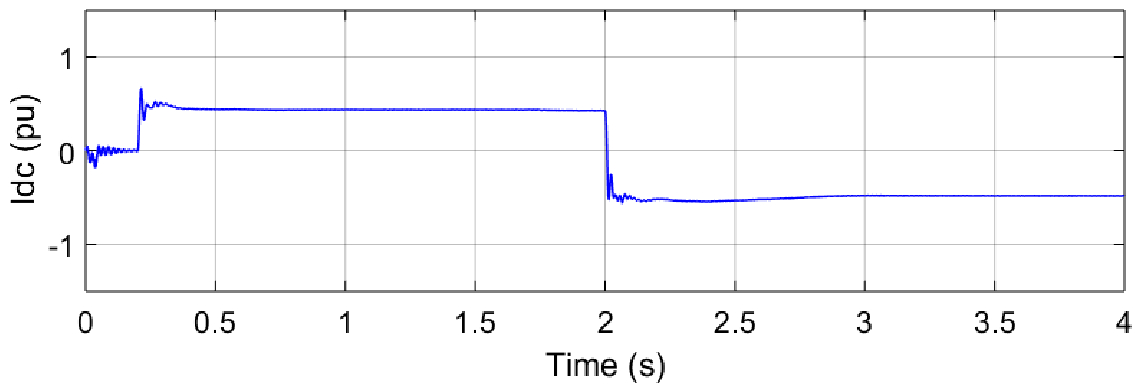
(b)


Meas.
Ref.
3
2
1
0
-1
Active Power (pu)
0
0.5
1
1.5
2
2.5
3
3.5
4
Time (s)

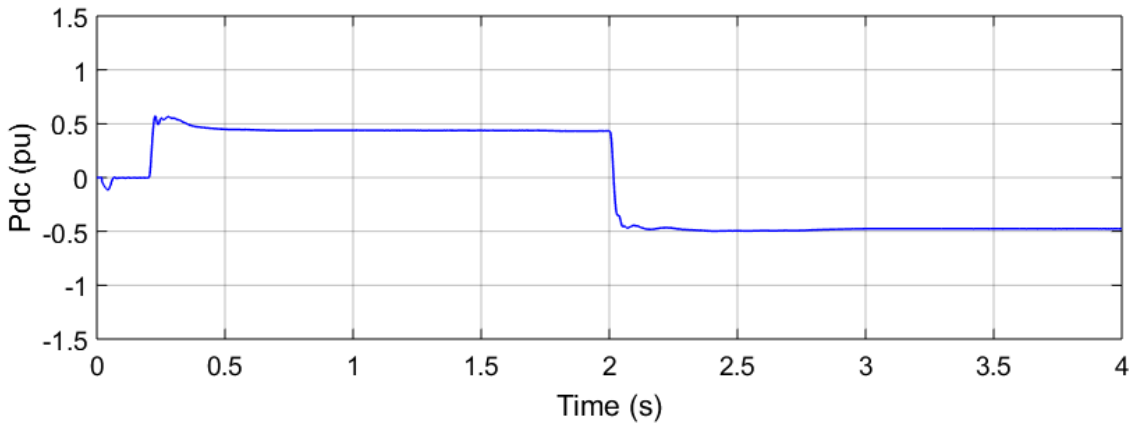
(c)




(d)




(e)




(f)

Figure 5.11: System performance at converter-III side (a) AC source voltage (b) AC source current (c) Active power exchange between converter-III and ac system (d) Reactive power exchange between converter-III and ac system (e) DC side current (f) DC side power

## CONCLUSIONS

This work shows the analysis of a NPC based VSC-HVDC system using MATLB-SIMULINK platform. In this thesis, a two terminal VSC-HVDC link was interconnected between two asynchronous AC systems. The system was operated in master-slave control scheme. One converter was operated in constant DC voltage and reactive power control mode. While the other converter was operated in active and reactive power control mode. The current control scheme is used for active and reactive power control of the converters. In addition, a three terminal VSC HVDC system was also analyzed. It is observed that any converter in multi-terminal VSC HVDC systems can be operated in any control mode like PQ and DC voltage control mode. The smoothness of DC voltage and DC power shows the better performance of NPC based VSC–HVDC over two levels VSC-HVDC.

## FUTURE SCOPE

Some aspects with the VSC-HVDC technology were not taken in this thesis which may be done in future. These are given below

- Implementation of frequency control system is required for interconnection of VSC HVDC system to weak network or passive loads. For this, variation of the frequency for pulse firing sequence in the PWM technique is required.

- Interconnection of renewable energy source through VSC-HVDC system.

- Implementation of VSC-HVDC systems in meshed DC grid.

## REFERENCES


[1]. N. Hingorani and L. Gyugyi, Understanding FACTS. New York: IEEE, 2000.

[2]. J. Arrillaga, Y. H. Liu and N.R. Watson, *Flexible Power Transmission*: The HVDC Options, John Wiley & Sons Ltd, 2007.

[3]. V. K. Sood, HVDC and FACTS Controllers – Applications of Static Converters in Power Systems, Kluwer, 2004.

[4]. K.R Padiyar, *HVDC Power Transmission Systems*, 2nd ed., New Age International Publishers, 2012.

[5]. N.R Chaudhuri, B. Chaudhuri, R. Majumdar and A. Yazdani, *Multi- terminal Direct Current Grids Modelling Analysis and Control*, IEEE Press, Wiley, 2014.

[6]. N. Flourentzou, V.G. Agelidis and G.D. Demetriades, "VSC-based HVDC power transmission systems: an overview", *IEEE Trans. Power Electronics*, vol. 24, no.3, pp. 592-602, March 2009.

[7]. S. Khan and S. Bhowmick, "A novel power flow model of multi-terminal VSC HVDC systems" Electrical Power System Research, vol.,-133, pp. 219-227, April, 2016.

[8]. J. Zhang, S. Li, J. Shang, W. Zhao and C. Li, "Multi-target controller of three Level NPC based VSC-HVDC transmission system and its RTDS simulation," IEEE conf. ICSET, pp. 793-797, 2008.

[9]. I.G. Torress, H. Miranda, V. Cardenas and R.A. Salas, "Gain Scheduling Scheme Assisting the Control Strategy for Three-Level NPC VSC-HVDC Transmission System, "IEEE conf. IECON, pp. 4635-4641, 2014.

[10]. L. Weimer, "HVDC light: a new technology for a better environment," IEEE Power Engineering Review, Vol. 18, No. 8, pp. 19-20, 1998.

[11]. G. Venkataramanan, B. K. Johnson. "A superconducting DC transmission system based on VSC transmission technologies," IEEE Transactions on Applied Superconductivity, Vol. 13, No. 2, pp. 1922- 1925,2003.

[12]. Juan Manuel Mauricio, Antonio Gomez Exposito. "Modeling and control of an HVDC-VSC transmission system," Transmission & Distribution Conference and Exposition: Latin America, pp. 1-6, 2006.

[13]. L. Jian, Y. Jianguo, Di Wu, W. Chuanxin, Y. Shenchun, and L. Ji, "Application research on VSC-HVDC in urban power network," in Power Engineering and Automation Conference (PEAM), 2011 IEEE, Wuhan, 2011, pp. 115-119.

[14]. O. Vestergaard, B. Westman, G. McKay, P. Jones, J. Fitzgerald, and B. Williams, "HVDC - enabling the transition to an energy system based on renewables," in AC and DC Power Transmission, 2010. ACDC. 9th IET International Conference on, London, 2010, pp. 1-6.

[15]. L. Xiaolin, Y. Zhichang, F. Jiao, W. Yizhen, L. Tao, and Z. Zhe, "Nanao multi-terminal VSC-HVDC project for integrating large-scale wind generation," in PES General Meeting Conference & Exposition, 2014 IEEE, National Harbor, MD, 2014, pp. 1-5.

[16]. A. Yazdani, R. Iravani, "Dynamic model and control of the NPC based back-to-back HVDC system," IEEE Trans. Power Delivery., Vol. 21, No. 1, pp. 414-424, Jan. 2006.

[17]. J. H. Zhang, S. Li, J. F. Shang, W. W. Zhao, C. Y. Li, "Multi-target Controller of Three-level NPC Based VSC-HVDC Transmission System and Its RTDS Simulation," IEEE International Conference on Sustainable Energy Technologies, PP: 793-797,2008.

[18]. C. Zheng, X. X. Zhou, "Small signal dynamic modeling and damping controller designing for VSC based HYDC," Proceedings of the CSEE, Vol. 26, No. 2, pp. 7-12,2006.

[19]. M. Yin, G. Y. Li, T. Y. Niu, et ai, "Continuous-time state-space model of VSC-HVDC and its control strategy," Proceedings of the CSEE Vol. 25, No. 18, pp. 34-39,2005.

[20]. A. Lindberg, L. Lindberg, "High voltage source converter control response at large ac voltage phase shifts," Power Electronics and Drive Systems, Proceedings of 1995 International Conference on, pp: 719 -725,1995.

[21]. H. Ouquelle, L.-A. Dessaint, S. Casoria, "An average value model based design of a deadbeat controller for VSC-HVDC transmission link," IEEE Power and Energy Society General Meeting, pp. 1-6,2009.

[22]. X. Fu, L.-A. Dessaint, R. Gagnon, K. Zhou, and M. Cheng. "Modeling and simulation of VSC-HVDC with current deadbeat control," Proceedings of IEEE International Conference on Electrical Machines and System, Beijing, China, pp. 1-6, 20 II.

[23]. Eduardo Prieto-Araujo, Fernando D. Bianchi, Adria Junyent-Ferre, and Oriol Gomis-Bellmunt, "Methodology for droop control dynamic analysis of multiterminal VSC-HVDC grids for offshore wind farms ", IEEE Transactions on Power Delivery, Vo1.26, No.4, pp: 2476-2485, 2011.