Dynamic Stability Improvement of Power System with VSC-HVDC Transmission

A Thesis submitted in partial fulfilment

of the Requirements for the Award of the degree of

Master of Technology

In

Industrial Electronics

By

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CERTIFICATE

This is to certify that the thesis entitled, **"Dynamic Stability Improvement of Power System with VSC-HVDC Transmission"** submitted by **Mr. Mohapatra Bikash Kumar Sahoo** (Roll No. 212EE5266) in partial fulfilment of the requirements for the award of **Master of Technology Degree in Electrical Engineering** with specialization in **"Industrial Electronics"** during 2012-2014 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any degree or diploma. In my opinion, the thesis is of standard required for the award of a Master of Technology degree in Electrical Engineering.

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ABSTRACT

Presently power system operates under a high stress level which was neglected at the moment they were designed. The operating conditions of power system is being threatened form the reliability, controllability and security point of view. HVDC transmission brings a solution to have secure and improve the stability margins of power system. The characteristic like independent control of real and reactive power improves the power system stability and ensures an efficient power transfer.

This thesis presents the control strategy used for VSC-HVDC transmission to improve the transient and voltage stability of power system. Transient instability caused by a system faults overcome due to the fast power run back capability of the VSC-HVDC transmission. VSC-HVDC prevents the system from transient instability by its instant power reversal ability. The voltage support capability of VSC system helps to protect the system from voltage collapse, hence losing of synchronism can be avoided.

A grid connected back to back VSC-HVDC modeled in MATLAB/ Simulink environment and a current mode control strategy was implemented. The simulation was done to have an observation of a faster and independent control of real and reactive power.

Index terms: VSC-HVDC, stability, pulse width modulation (PWM)

List of Abbreviations:

HVDC	High voltage DC
VSC	voltage source converter
CSC	current source converter
GTO	gate turn off thyristor
IGBT	Insulated gate bipolar transistor
PWM	pulse width modulation
LCC	Line commutated converter
PU	per unit
PLL	phase locked loop
PCC	point of common coupling
SPWM	Sinusoidal pulse width modulation
NPC	Neutral point clamped
DC	Direct current

List of symbols:

U_{dc}	DC link voltage
$U_c(t)$	Converter bus voltage
m_a	Modulation index
δ	Power angle
X	reactance of phase reactor
$\overline{U_s}$	AC side Source voltage phasor
P_{ac}	AC power
Q_{ac}	Reactive power
$T_{\alpha\beta 0}$	Transformation matrix for transforming $abc - to\ \alpha\beta$ −frame
U_d	Direct axis voltage
U_q	Quadrature axis voltage
L	Inductance of phase reactor
R	Resistance of phase reactor
r_{on}	ON resistance of switch
θ	Phase angle
ω	Angular frequency
U_{cd}, U_{cq}	Converter side dq axis voltage

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CHAPTER 1

INTRODUCTION

1. Introduction:

Increasing trend of energy demand and its mitigation by use of several conventional and non-conventional energy sources and transportation of energy from generating station to remote areas is a great challenge. To serve the above purpose it is needed to have a bulk power transmission over a long distance through overhead transmission line and undersea cable, this becomes hectic in case of AC transmission due to high charging current and losses caused by capacitance. Problem related to interconnect the unsynchronized grids to the existing grid, where the voltage level and frequency is the main constraint which restricts the interconnection through an AC link. For the eradication of above problem, it is having a solution by using DC transmission, where a controlled DC transmission provides the flexibility for a bulk power transmission over a long distance through a DC link [2], [5].

Converter stations are being used at the generating end for AC/DC conversion in a controlled manner which enables a controlled power flow. A rapid development and research on power electronics switches provides a better, efficient technique for control mechanism, hence control over power flow.

HVDC transmission resides a two basic type of converter technology. Those are classical line commutated current source converter (CSCs) and self-commutated voltage sourced converters (VSCs) [3]. Classical HVDC technology employs line commutated current source converters with thyristor valve used as a base technology for DC transmission in 1950s. Where thyristors are not fully controlled switches, hence it put limitation to control mechanism used for controlled power flow. Voltage source converter based transmission technology introduces flexibility in power transmission, as it uses fully controllable switches like IGBT which provides one of the efficient control mechanism for control of power flow. Both classical and VSC-HVDC are used for the applications like long distance transmission, underground and undersea cable transmission and interconnection of asynchronous networks. But from control point of view VSC-HVDC having more flexibility and efficient power flow mechanism, as it is capable of controlling both active power and reactive power independently of each other, to keep stable voltage and frequency. Particularly self-commutation, dynamic voltage control and black start capability allows

VSC transmission technology to serve isolated loads on islands over long distance submarine cables [6].

Thyristor based classical HVDC mostly used for point to point large power transmission long distance over land or undersea cables. It has certain disadvantage like commutation failure as thyristors can't be off immediately, and it requires 40 ~ 60 % reactive power supply of the total active power transmission. To have a solution IGBTs are used that can be switched off and on immediately, no commutation problem, active and reactive power control independently, no reactive power compensation required, filter requirement is less as to filter out high frequency signals from PWM, no requirement of telecommunication between two stations of VSC-HVDC system [7]-[9].

VSC -HVDC link consist of a back to back voltage sourced converters (VSCs), a common DC link, which includes a large DC capacitors and DC cables. The control strategy is being designed to coordinate the active power control between two station which is realized by controlling the DC side voltage of one converter where other converter control the active power. Automatic control of power flow between stations is the result of a constant DC voltage source gives "slack bus". AC voltage control and reactive power control will switched as per the requirement.

2. Motivation:

Power system operates closer to their stability limits, which may affect the damping of electromechanical oscillation and risks the system with a decreased system stability margin. As a solution to the above problem, to increase the power transfer capability and to have a good stability margins the only left option is VSC-HVDC transmission.

VSC- HVDC provides the flexibility in power transmission, and an efficient utilization of power networks. An efficient control strategy for VSCs yields a faster and independent control of active and reactive power. VSC-HVDC provides a resistant to disturbance and an efficient faster system recovery after post disturbance.

Using VSC based HVDC can improve transient stability, increase the damping to low frequency oscillations, improve voltage stability and provides a bidirectional power flow. Attracting feature of VSC is that, it can have black start capability and interconnection of asynchronous grids with existing power grids.

3. Literature review:

Literature review from different sources reveals the following things about VSC-HVDC technology. An efficient, rapid and independent control over both active and reactive power improves the transient stability. VSC- HVDC compared with new AC transmission line improves the stability. Basically it greatly enhances the voltage stability and kept the system from collapsing due to lack of reactive power [1]. Hybrid AC/DC transmission system together wide area measurement system could manage the overall power grid operation, security and efficiency. Hybrid AC/DC grid structure enables efficient congestion management, reliable integration of large scale renewable energy sources and improve system dynamic response against disturbances [2]. It can prevent voltage collapse by using gradual P&Q modulation including reducing the active power to increase reactive power capability is needed. A minimized voltage variation and dynamic voltage stabilization can be enhanced by operating the converter as STACOM and SVC [2]. A power system restoration using HVDC which includes two phases, phase I is the DC line connecting to weak grid in the receiving end and phase II is load picking up with HVDC power supporting [3]. HVDC technology can have a control strategy to control the switching instances of IGBTs to have a desired response. Its control strategy does not depend upon the converter type whether it is two level or three level and remain same for both. DC side of NPCs connected in parallel with a split voltage source (represented by two capacitors). Voltages are measured with reference to the DC side mid-point i.e node 0 [4]. The three level converter provides bidirectional flow of power both from DC side to AC and vice versa. To control the power exchange between VSC and AC grid is dependent on the switching pattern. To have a balanced sinusoidal AC side terminal voltage, it is desirable to generate a balanced 3phase reference signal which is a function of time with required amplitude, phase angle and frequency resulting from control strategy [4].

4. Problem formulation:

An efficient and reliable transport of bulk energy over a long distance is a great challenge. Charging current put a limitation to the power transmission through underground cable and undersea cable over a long distance. Problems in interconnection of asynchronous grids with the existing power grids due to frequency and voltage levels not suitable for grid connection. An efficient and stable operation of AC system during and post disturbance conditions is a great challenge for an AC transmission system. For the above problem it is needed to have a HVDC transmission. Which provides a greater flexibility and control of power flow through a DC transmission line and hence stability.

HVDC transmission can be achieved by using a back to back configuration of converter stations. Control of those stations brings a reliability of power flow and efficient operation. Converter station are classified into two categories for high power applications. Classification based on commutation process one is line commutated and forced commutated or self -commutation. Classification based on the terminal voltage and current wave form called as current source converter (where DC side polarity remain same, power flow decided by DC side voltage polarity) and voltage sourced converter (where DC side voltage polarity will remain same, power flow direction decided by DC side current polarity).

Problems related to the current source converter (CSC) is that it require a bipolar switches for its operation, although commercial version of bipolar switches available like GTO, IGCT but it operates at low frequency. In this case VSCs using IGBTs a fully controlled switch provides a greater flexibility in controlling the real and reactive power independently and hence the solution to stability and power exchange related issue.

Now a day's power system based on AC transmission works at high risk as it operates at bottleneck of stability margins. Even a small disturbance can challenge transient stability and voltage stability limits. If the system can't restore itself within a certain time it leads to collapse of complete power system. Hence as a solution to the above problem VSC-HVDC with an efficient control strategy which is capable of controlling the active power and reactive power independently. VSC-HVDC can capable of changing its working point instantly within its capability curve, hence the dynamic stability.

5. Objectives:

Objective of current thesis is to design a VSC- HVDC back to back converter and its control strategy to enhance the dynamic stability of power system. So that a bulk power system can withstand to a wide variety of disturbances. It is desirable to design and operate so that most adverse possible contingencies do not result in an uncontrolled and cascaded power interruptions. In this VSC- HVDC back to back converter is used along with the parallel AC transmission line and its various control strategies to ensure a faster active and reactive power flow control, hence stability. The above is modeled and simulated in the MATLAB/ SIMULINK environment hence the observation. Main focus of the thesis is to

- To have a good understanding in VSC- HVDC transmission system concept.
- Modeling of VSC in MATLAB/SIMULINK environment.
- Focuses on different control strategy and its implementation for VSC controlling purpose.
- Analysis of the system behavior for disturbance condition.

6. Thesis outline:

The thesis studies the control of VSC-HVDC and its application to the power system to enhance the system stability and efficient power exchange between two grids. This report is organized in six chapters.

First chapter deals with the studied subject, containing introduction, literature review, problem formulation, objectives of the current thesis.

Second chapter deals an overview of voltage source based HVDC transmission system, comparing HVAC and HVDC. Application and configuration of HVDC transmission system. Then comparison between CSC based HVDC and VSC based HVDC are discussed.

Third chapter represents the study related to stability issues of power system and enhancement using VSC-HVDC. Study of capability curve of VSC transmission.

Fourth chapter represents the design of control strategies for VSC-HVDC transmission system. PLL technique used to synchronize with the grid voltage. This chapter contains the design of current controller, DC voltage controller, real and reactive power controller and an AC voltage controller.

Fifth chapter deals with the observation related to the result from the simulation of VSC-HVDC transmission system model. The results are discussed in this chapter.

Conclusion of thesis and scope for future work are finally discussed in sixth chapter.

Summary:

This chapter provides the information about introduction to the topic HVDC, literature review and problem formulation. An overall objective to mitigate the problem. Thesis out line is discussed at the end of this chapter.

CHAPTER 2

HVDC TRANSMISSION

Introduction of VSC-HVDC transmission

Comparison between HVDC and HVAC

Application of HVDC

Configuration of HVDC

Classification of HVDC transmission

VSC- HVDC transmission

CHAPTER 2
HVDC TRANSMISSION

HVDC transmission:

In 1970s DC transmission had a revolutionary change with the introduction of thyristor based converter. Once again in the project of interconnecting Swedish mainland and island of Gotland this newly introduced technology was used. Hence the thyristor based converter was the only technology used for DC transmission and is known as current source converter or line commutated converter HVDC (i.e CSC/LCC- HVDC) or commonly referred to as a classical HVDC [10], [11].

1. Introduction of HVDC transmission system:

HVDC transmission is a power electronics based technology used for transmitting bulk power over a long distance. Cables (submarine and underground) and overhead transmission line are used as a transmission path. HVDC transmission used first time in 1954 in the undersea cable interconnection between the island of Gotland (Sweden) and Sweden. Thyristor rating 50kv and 100A were used.

In the year 1970 mercury valves were useful for HVDC transmission. In next 20 years due to the rapid research on power electronics and converter lead to introduce line commutated converter as based component for HVDC transmission system. Further development of high power switching devices availability at low price, self-commutated converter replaces LCCs and now voltage source converters are used as a dominant technology for HVDC transmission [11].

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 requires a simpler tower, insulators and conductor cost will be reduced in comparison with the HVAC transmission [5].
- Conductor losses are reduced about two-third, when DC is used instead of AC one.

- Use of HVDC transmission, skin effect problem is not noticed and also corona losses and dielectric losses are kept at low level hence efficiency of transmission can be improved.
- Disadvantage of DC over AC transmission when cost comes from the use of the converter and filters.
- HVDC transmission is helpful for transmitting bulk power through undersea cables over a long distance where charging current put 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.

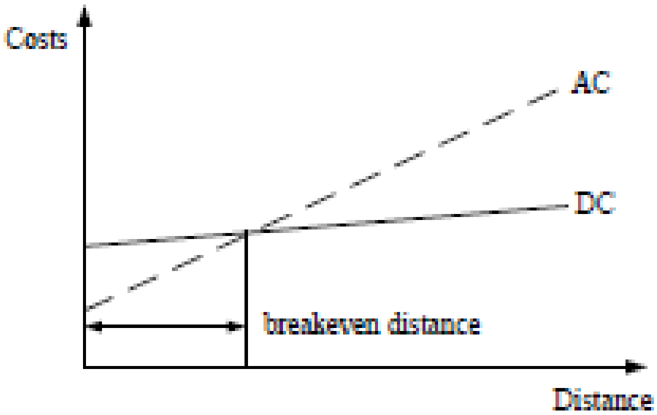

Figure 2.1 Cost VS distance curve

- 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 associated 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 related to line charging issues with AC transmission, while for DC transmission such compensation is not required. This issue put a limitation to HVAC transmission breakeven distance to 50 km [10].
- HVDC transmission was limited due to the factors like high cost converters, complexity of control, generation of harmonics and unable to alter voltage level [11].
- HVDC can be used for interconnection of asynchronous grids which is not being achieved 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 era of power transmission.

3. Applications of HVDC transmission:

Several application of HVDC transmission demand its potential use. Those are

- Transmission through underground and undersea cables where charging current put a limitation to AC transmission.
- HVDC transmission is an alternative for AC transmission, when bulk power transmitted over a long distance and is economical comparative to HVAC transmission after the breakeven point. A fewer number of conductors are used with HVDC technology [5], [7].
- It provides an economical way for interconnection of asynchronous grid, and can be achieved by back to back connection of converters without transmission line.
- It is having an efficient control over power flow through DC link, this feature dominates over AC transmission. It mitigates issues like uncontrolled power flow through AC ties which may lead to over load and stability problems [5].

4. Configuration of HVDC transmission:

There are four main configurations used in power system. These configurations can be achieved through both VSCs and CSC converter topology.

Mono-polar system:

In this configuration single pole line is used to interconnect two converters. Either positive or negative polarity lines are used. By using negative polarity line corona loss can be minimized. This configuration uses ground and metallic link as return path as shown in Figure. 2.2 (a), (b).

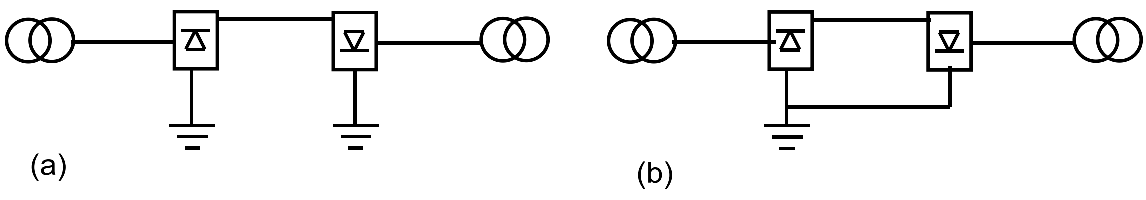

Figure 2.2 (a), (b) Mono-polar links

Bipolar system:

This uses two mono-polar links both positive and negative. Two sets of converter are grounded at middle at single or both ends. Poles can be used independently if the neutral point is grounded. One pole can transmit power if other one is out of service. This is a common configuration as shown in Figure. 2.3.

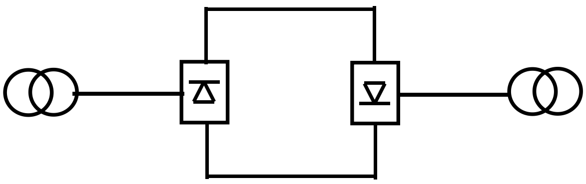

Figure 2.3 Bipolar Link

Back to back system:

Back to back HVDC can be used to interconnect asynchronous grids. It usually placed at same site and no transmission line is there for power transmission over a long distance. As shown in Figure 2.4.

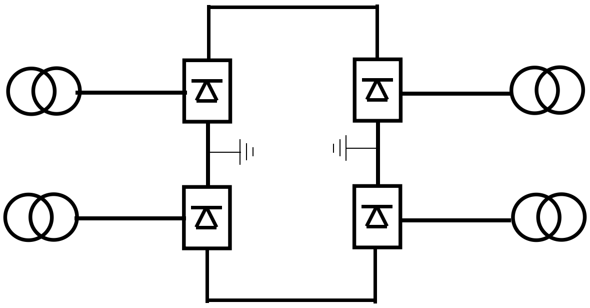

Figure 2.4 Back to back link

Multi terminal system:

Multi terminal HVDC configuration provides a way for connecting three or more converter stations. Some of them are working as rectifiers and some as inverters. This can be divided in to two basic configurations, series and parallel arrangements as shown in

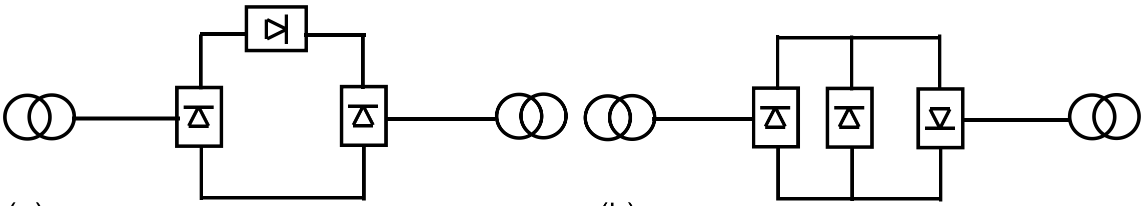

Figure 2.5 (a) Multi terminal link series connection, (b) multi terminal link with parallel connection

5. 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 [4].

Classification based on commutation process:

a. Line commutated converter: By reversing the AC polarity commutation processes can be initiated. It is called as naturally commutated converters. Six pulse thyristor converter is an example of line commutated converters.

b. Forced commutated converters: In this transfer of current from one switch to another is a controlled process for which it is required to have a 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 [4], [5].

Classification based on terminal voltage current wave form:

c. Current sourced 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 [4].

d. In a voltage sourced 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 DC side which resembles a voltage source [4].

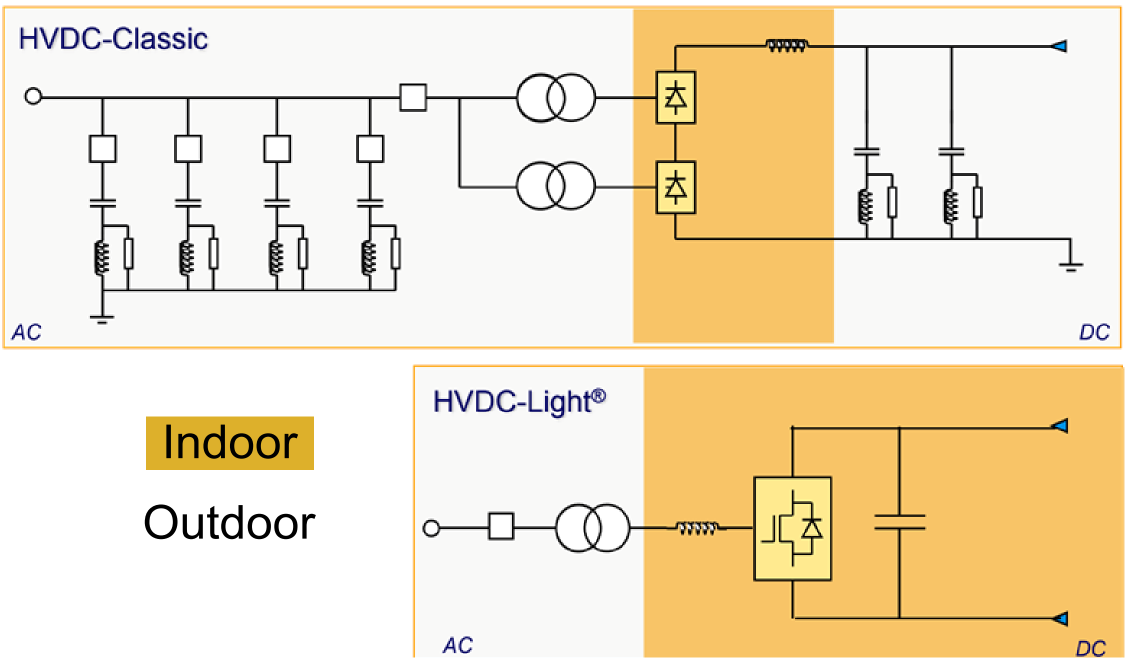

Figure 2.6 HVDC classical and VSC –HVDC

Voltage sourced converters are advantageous then 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 put a limitation to the application for high power electronic converters. In Figure 2.6 shows all the equipment's except transformer are in a compact building in case of IGBT based voltage sourced converter but in case of thyristor based classical HVDC only valves are in side building [3].

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

6. VSC-HVDC transmission:

Current source converter are thyristor based line commuted converters. These converters are called as classical HVDC. Development of high frequency fully controlled switches like IGBT and DSPs for generation of appropriate switching pattern provides a platform for efficient control of power flow through VSC [1]-[4].

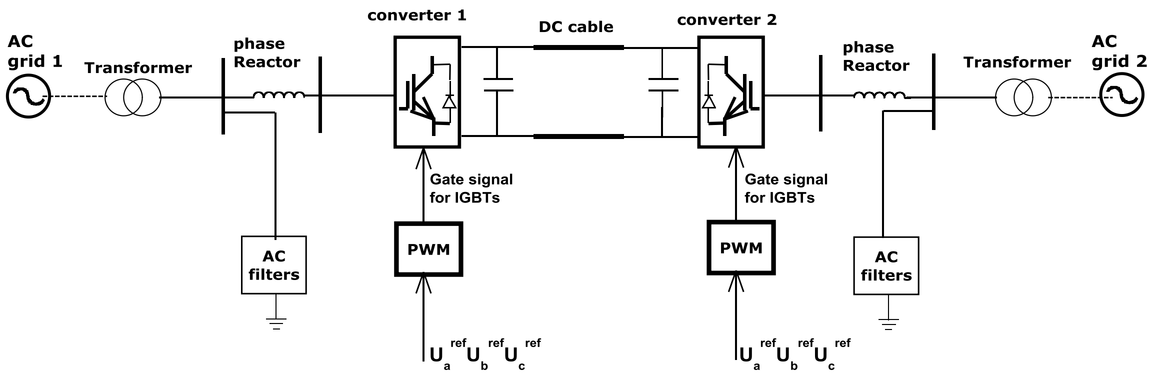

Figure 2.7 A Back to Back VSC- HVDC transmission

From control point of view VSC HVDC provides greater flexibility in high power application then classical HVDC. Advantages of VSC over CSCs are

- It provides an independent control of real and reactive power exchange between VSC with AC grid. No extra reactive power compensation is required.
- No risk of commutation failure occurs due to disturbances in power system.

- It can generate a balanced 3-ph voltage as synchronous generators, hence is useful for black start.
- It won't have any reactive power demand like line commutated converters. It can control reactive power at converter stations to have desired AC voltage waveform.

The above advantages demands VSC for certain applications.

- Dynamic voltage control and black start capability of VSC enables for supply from remote location without any local generation [2], [13].
- Control of reactive power and AC voltage provides an improvement in a reliable power transfer and grid stability [1].

VSC-HVDC based HVDC transmission consists of an AC filter, transformer, phase reactor, DC link capacitor and voltage source converter as shown in Figure 2.7.

6.1 AC side filters:

Filters are required to filter out undesirable harmonics. Harmonics in AC system causes overheating, losses, interference in communication line, malfunctioning of operation, over voltage due to resonance and instability in control system. Filters involved in VSC is 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 [11].

6.2 Phase reactors:

It has advantage like preventing high frequency harmonics in AC line current as it act as like a low pass filter. Restricts 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. It is usually between .1 to .3 pu [11].

6.3 Transformer:

It is helpful for keeping the secondary voltage level as per converter requirement. Reactance of transformer decrease the short circuit current level. It act as like a barrier between AC and DC side. A two winding transformer can be used for VSC converter. It is not needed to block the DC component.

6.4 Converter configuration:

Voltage source converters are connected in back to back fashion where one act as like a rectifier and other one act as like an inverter. Converter that is used may be a 2 level, 3 level or multilevel converters. For 2 level VSC it is needed 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 $-\frac{1}{2}U_{dc}$ [4].

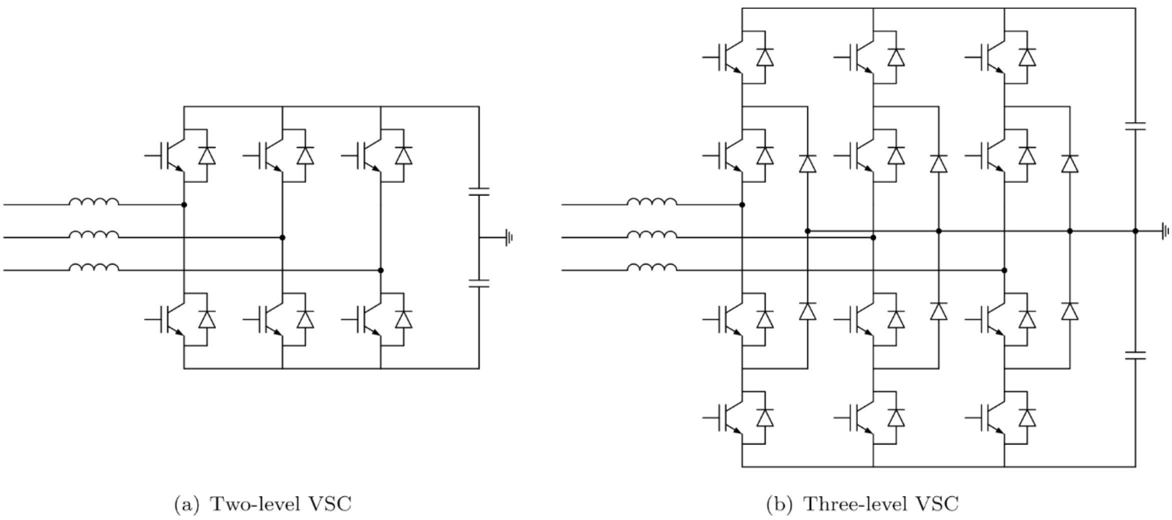

Figure 2.8 (a) Two level VSC (b) Three level VSC

For three level converter there are 12 switches and twelve pulse generator is required for triggering IGBTs. Three are three level of voltages at AC side of converter i.e $\frac{1}{2}U_{dc}$, 0 and $-\frac{1}{2}U_{dc}$. And a comparatively low harmonic contents is realized in three level converters [4].

6.4.1 Three level VSC with capacitive DC side voltage divider:

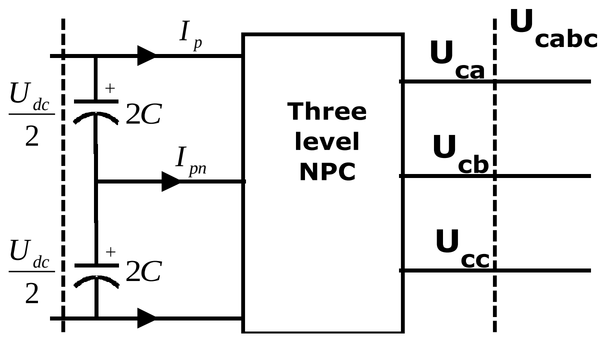

Figure 2.9 Three-level VSC with capacitive voltage divider.

The configuration as shown in the Figure 2.9 is a three level NPC with capacitive voltage divider at its DC side. The total voltage across the DC terminal divides in to two equal half by using identical capacitors. The configuration shown in Figure 2.9 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, but 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 in mid-point current which results in a lower order voltage harmonics at AC side of the converter [4].

6.5 DC link capacitor:

DC link capacitor used in VSC transmission system act as a constant voltage source. It won't allow the change of polarity of DC bus. It is helpful for maintaining DC link voltage close to its desired level. DC link capacitor decides the transient response of the system. Hence deciding the value of the DC link capacitor is a challenging task. As the current with harmonics generated from PWM switching of IGBTs, flowing to capacitor creates a voltage ripple at DC side. Size of capacitor can't be determined from steady state operation as it lead to DC over voltage. It is important to consider the transient over voltage constraint when choosing the DC capacitor value [11].

Time constant τ determines the time required to charge the Dc capacitor from zero to its DC voltage level at nominal apparent power of the converter is

$$\tau = \frac{1}{2} C \frac{{U_{dc}}^2}{S_n} \qquad (2.1)$$

Where U_{dc} is the DC link voltage and S_n is the nominal apparent power. τ is the time constant to charge the capacitor from zero to its maximum DC voltage level [4], [11], [12].

6.6 DC cable:

Extruded polymeric insulations are used particularly to provide resistant to the DC voltage, hence it is used in VSC-HVDC application. Whereas AC XLPE cables are not directly used for HVDC application due to a phenomenon called space charges. Electric field created by the DC voltage cause the space charge to move and concentrate at a certain spot of the insulation, resulting in degradation. Special XLPE cables are developed to avoid problem caused due to space charge. A rapid change in polarity change causes a high stress in insulation. As in VSC-HVDC polarity reversal is not required, XLPE cables can be used. Cables with $\pm$ 320 kv DC are presently available [11].

Summary:

This chapter summaries the VSC-HVDC transmission, comparison between HVDC and HVDC. The application, configuration and classification of HVDC is discussed. Finally a VSC-HVDC model is described.

CHAPTER 3

STABILITY WITH VSC-HVDC TRANSMISSION

VSC AC side equivalent model

Capability chart of VSC transmission

Different grid configurations and stability issues

Series connection of the VSC converter and AC system

Parallel connection of VSC and AC transmission

Asynchronous infeed from VSC converter

3. Stability with VSC-HVDC transmission:

It is needed to have a stable and reliable control of real and reactive power as power system is highly dependent on it. Losing its control leads to collapse of the system. Voltage source converter transmission system has the capability to change its working point almost within its capability curve. VSC provide a best support to the grid with active and reactive power, during stressed condition. In comparison with the other cases, mix active and reactive power is the best solution then to active or reactive power only. VSC-HVDC plays a key role at the time of grid restoration considerable as it can control voltage and stabilize frequency when active power is available at remote end. VSC transmission can also capable of influencing the asynchronous grid conditions, power quality and harmonic problems. N-1 criterions or similar can be used to establish the maximum load that can be a critical grid can transfer. VSC transmission can change its operating mode and strengthen the grid until other action restore the grid [1], [4], [6].

1. VSC AC side equivalent model:

AC side of the VSC can be considered as a controllable voltage source as the VSC using PWM technique to control independently frequency, the phase and amplitude of AC voltage. VSC side AC voltage can be represented as

$$U_c(t) = \sqrt{2}\, U_c\ \sin(\omega t + \delta) + harmonics \qquad (3.1)$$

With $U_c = m_a \frac{Udc}{2}$ (3.2)

Where m_a stands for the modulation index, ω is the angular frequency of fundamental and δ is the phase difference between the converter fundamental and grid side voltage [9], [11].

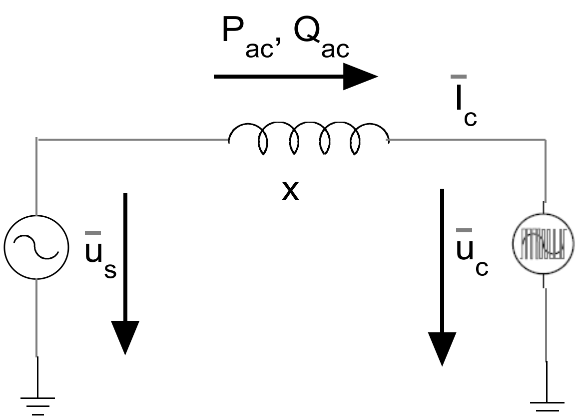

Figure 3.1 VSC-AC side equivalent model

Due to the presence of phase reactor, AC filters and transformers, switching harmonics can be disregarded.

Equivalent diagram of an AC side VSC is shown in the Figure-2.1. An AC voltage system is connected to a controllable voltage source via a phase reactor ‘x’. AC voltages are represented as $\overline{U_s} = U_s e^{j0}$ and $\overline{U_c} = U_c e^{j\delta}$. The resistance of the transformer and phase reactor are neglected (i.e lossless) [9], [11].

Power flow between AC grid and the VSC can be represented as

$$P_{ac} = \frac{U_s U_c}{X} \sin \delta \tag{3.3}$$

From the above equation active power flow can be controlled by varying the phase angle δ and maintaining all other variables unchanged. This can be achieved by controlling the switching instances of IGBTs using PWM technique.

Where δ can be varied to have an inversion and rectification mode of operation.

$$\begin{cases} \delta < 0,\ \overline{U_c}\ lagging\ \overline{U_s}, P_{ac} < 0\ (Invertion) \\ \delta > 0, \overline{U_c}\ leading\ \overline{U}_s, P_{ac} > 0, (Rectification\ ) \end{cases} \tag{3.4}$$

When $\delta = 0$, there will be no transfer of active power hence the VSC will act as a reactive power compensator, this is the case where VSC act as a STATCOM. In this mode of operation it absorbs or provides reactive power as per the requirement.

Reactive power flow between the AC grid and the VSC can be represented by the equation

$$Q_{ac} = \frac{U_s}{X}(U_s - U_c \cos \delta) \tag{3.5}$$

From the above equation 2.5 it can be observed that if the real component of the VSC side AC voltage $U_c \cos \delta$ is smaller than the AC grid voltage, system will consume reactive power from AC network. If the real component of VSC side AC voltage $U_c \cos \delta$ is greater than AC grid voltage than the system will provide reactive power.

$$\begin{cases} U_c \cos \delta > U_s,\ Q_{ac} < 0\ \ (delivering) \\ U_c \cos \delta < U_s,\ Q_{ac} > 0\ \ (absorption) \end{cases} \tag{3.6}$$

Active power is influenced by varying phase angle δ but its effect on reactive power is negligible since δ is small ($\delta \approx 0$). Whereas the magnitude of converter voltage compared to the AC grid voltage has a great effect on the reactive power. And a negligible effects on the active power. Hence the control of active and reactive power can be achieved independent of each other [9], [19], [21].

2. Capability chart of VSC transmission:

As the real and reactive power are independent of each other, VSC can theoretically operate at any point on P, Q plane. This P, Q characteristic is represented by a circle due to the operating possibility in any of the four quadrants. Factors affecting the operating range of converters are the maximum current through the converter switches and maximum DC voltage value. Maximum current limitation is needed to protect converter switches. Hence the VSC will operate within rated current corresponds to a circle of radius 1 pu [27].

Voltage magnitude of VSC determines the reactive power capability of the converter. Over voltage limitation can be decided by the DC voltage level.

Rearranging the above equation 3.3 and 3.5 we will get a circle of radius $\left(\frac{U_s U_c}{X}\right)$ pu with a center at $\left(0, -\frac{{U_s}^2}{X}\right)$ is obtained from

$$\left(\frac{U_s U_c}{X}\right)^2 = \left\{ {P_{ac}}^2 + \left({Q_{ac}}^2 + \frac{{U_s}^2}{X} \right)^2 \right\} \tag{3.7}$$

Active power transfer capability, which requires a minimum voltage magnitude to be transmitted. Steady state and dynamic operation differs due to the parameters that constrain the (P, Q) diagram change during the operation [14], [18], [25].

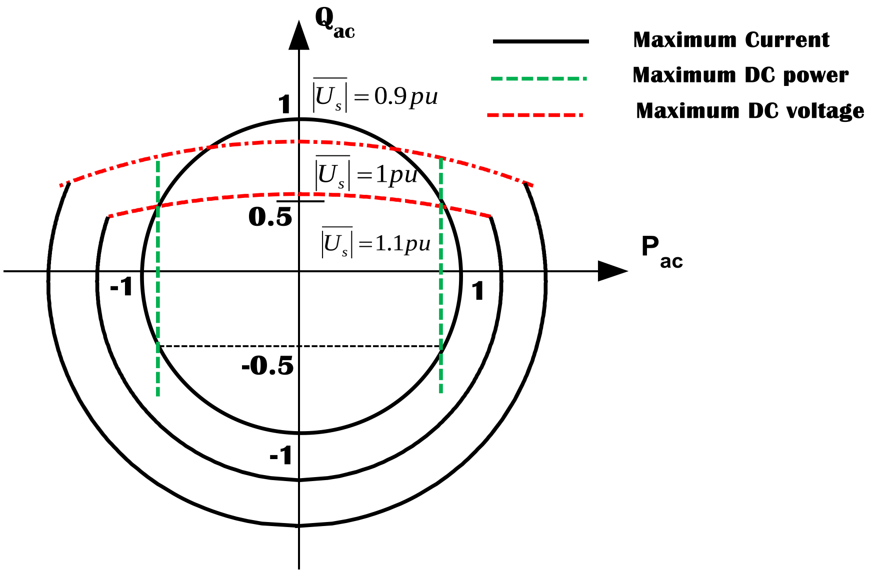

Figure 3.3 Capability chart of VSC

Analogy between synchronous generator and VSCs capability curve. The maximum current that can flow through the converter switches is the armature current. Converter voltage limit corresponds to maximum field current and lastly the maximum power through DC cable is the maximum turbine output.

From the Figure 3.3 it is discussed about the limiting factors. First one is the maximum current through IGBTs gives the maximum MVA circle. MVA capability directly proportional to AC voltage. Second limiting factor is Maximum Direct voltage which regulates the AC voltage through converter. Reactive power exchange directly depends on the difference between AC voltage generated by VSC and AC grid voltage. Third limiting factor is maximum current through DC cables. For low AC voltage the MVA limit is dominating but in case of high AC voltages the DC limit is quit restrictive [14].

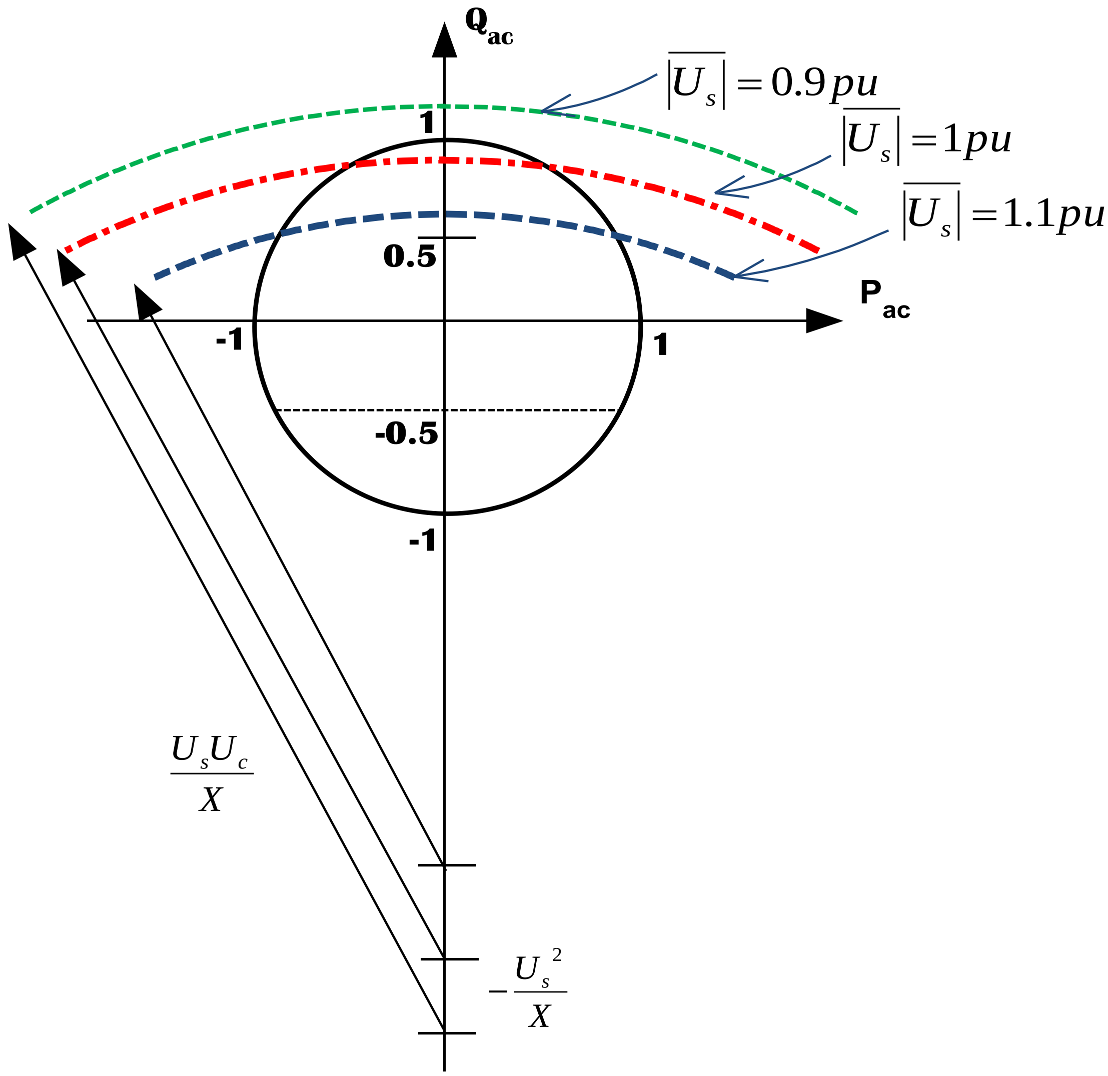

Figure 3.4 P &Q chart of VSC –HVDC station.

3. Different grid configurations and stability issues:

There are two different aspect to consider. Firstly the type of the system stability issue the VSC transmission system exposed to. There are two phenomena, voltage stability and rotor angle stability. Secondly VSC configuration in which VSC configured with AC system. There are three basic types

- Series connection of VSC converter and AC system
- Parallel connection of VSC transmission and AC system
- Asynchronous infeed from the VSC converter into the AC system.

3.1 Series connection of the VSC converter and AC system:

A situation revels that the power flow equation for the receiving end power circle diagram combined with capability curve of the VSC transmission shown in fig. 3.3 will immediately reveal the maximum transferable active power. The crossing between the capability curve of VSC transmission and the receiving end power circle will indicate the stable solution for that particular voltage level. If the sending end voltage drops it is possible to reestablish a new stable operating point solution in the power circle plane [25],[27].

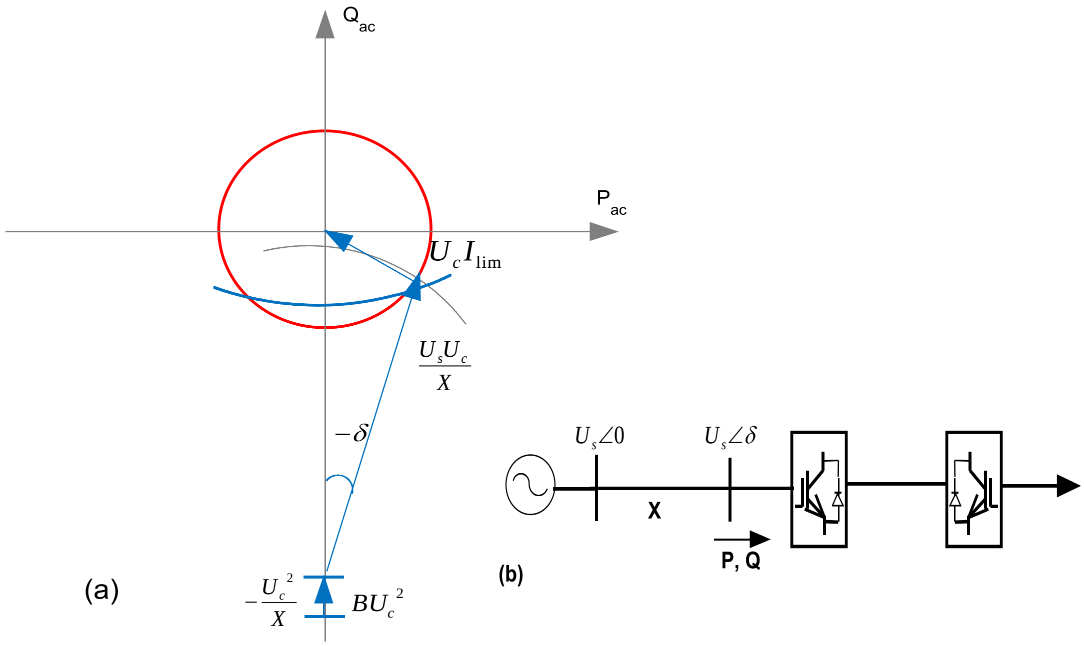

Figure 3.5 Series connection of VSC and AC system

3.2 Parallel connection of VSC and AC transmission:

Connecting a VSC transmission in parallel with the AC transmission and controlling the VSC transmission will have impact on the AC power flow. To have a better utilixzation of AC system it is needed to vary the power factor of DC transmission system. In the stressed system condition it is needed to operate the VSC transmission with a best power factor.

Figure. 3.6 shows parallel case associated with power circle plane. Studying the receiving end power circle it can be seen that the power flow on the AC line following the arc angle δ to which power flow through the VSC line is added (the vector within the small circle) [6].

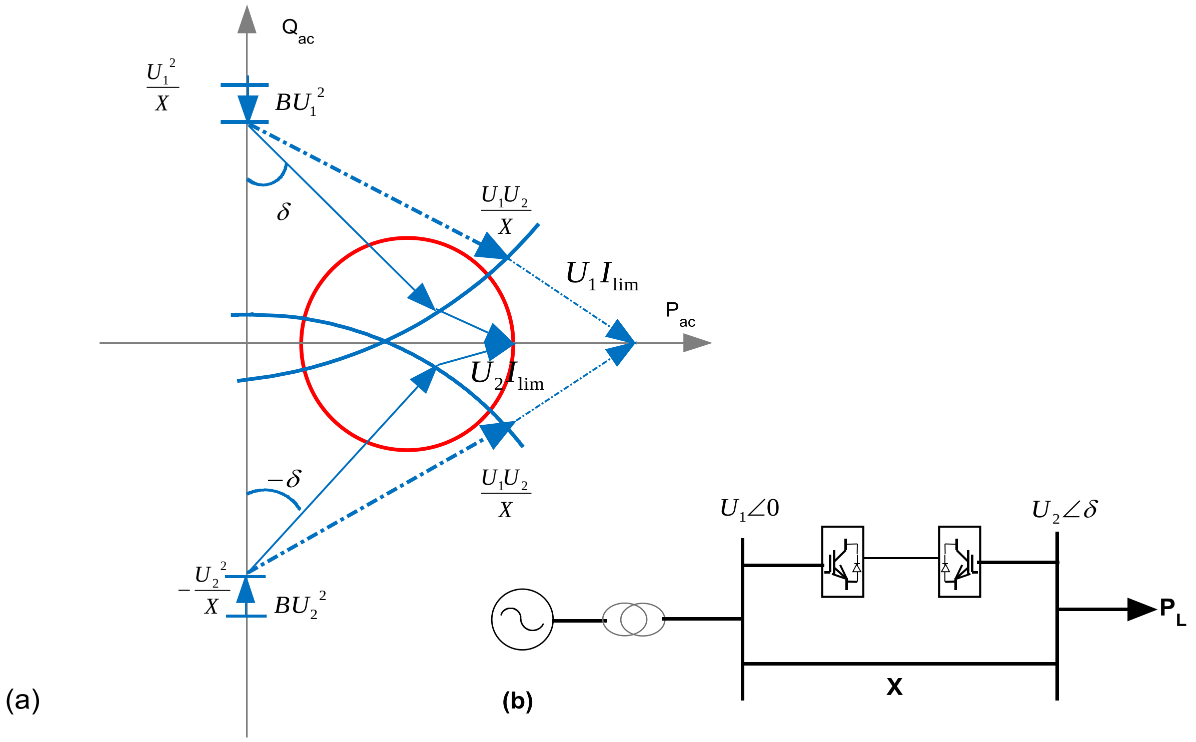

Figure 3.6 Parallel connection of VSC and AC transmission

The AC line requires a small amount of reactive power which is fed from the VSC system. The MVA circle is valid for the VSC transmission it is observed that the MVA capacity is at its maximum point for the DC system i.e we cannot transfer more power over the combination. An increase in the DC flow or AC flow (requiring more reactive power to keep AC voltage) would violate the capability curve. If we decrease the DC active power transfer and are able to inject more reactive, it is possible to transfer more active power over the combination. A best choice is made according to

$P_{dc} = I_{lim}.U_2 \sin(\delta_1 - \delta_2)$ and $Q_{dc} = I_{lim}.U_2 \cos(\delta_1 - \delta_2)$.

3.3 Asynchronous infeed from VSC converter:

A VSC converter fed active power in to AC grid from an interconnected asynchronous grid operating at different frequency to have a improved transmission performance. Thevenin equivalent of infeed shown in figure 2.5 (b). Aligning the vectors by changing power factor, maximum loadability can be achieved [27].

VSC-HVDC transmission can provide best support for grid configuration and stability problems a mixture of active and reactive power control. Stability can be achieved with a suitable power factor supported by VSC transmission system.

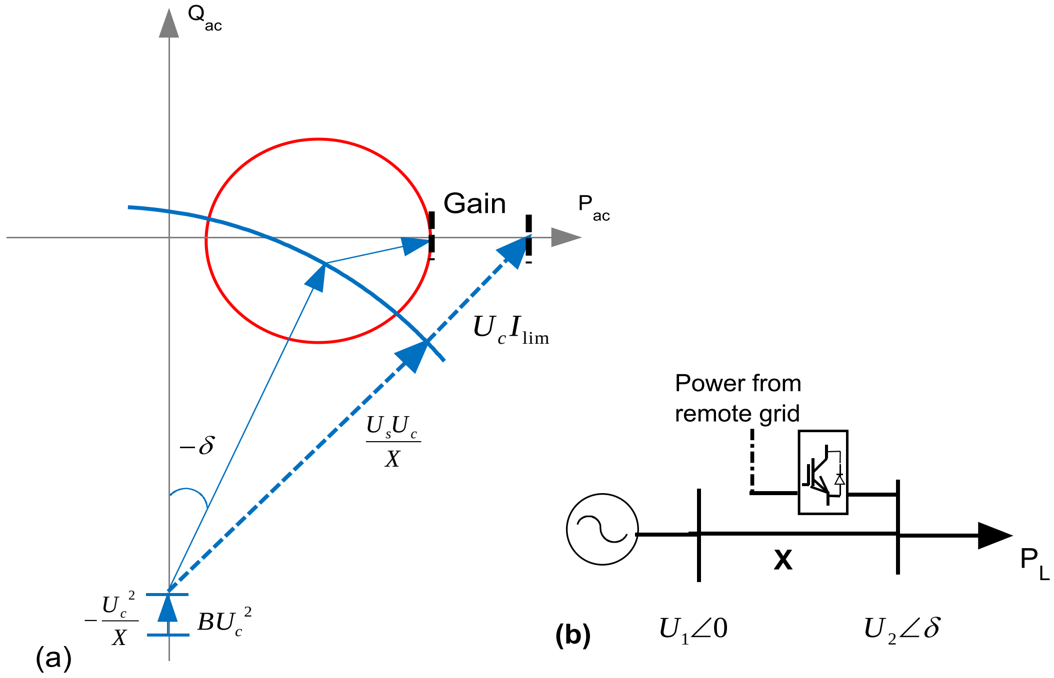

Figure 3.7 Asynchronous INFEED from VSC converter

Summary:

In this chapter VSC ac side model is described and capability chart of VSC transmission is discussed. Different grid configuration of VSC along with the capability chart and stability issues are discussed.

CHAPTER 4

CONTROL AND DESIGN OF VSC

abc to dq- transformation

Phase locked loop (PLL)

Dynamic model of ac side VSC

Control structure of VSC

Inner current controller

Outer control layer

Active and reactive power controller

DC side voltage controller

AC voltage controller

Current limiter

CHAPTER 4

CONTROL AND DESIGN OF VSC

4. Control and design of VSC:

Design of control strategy in 3-ph (abc)-frame is much more difficult as well as a more complex compared to $\alpha\beta$ −frame. As it reduces the control vector from three to two. It provides a decoupled control for active and reactive power. The decoupled control of power exchange between VSC and AC system can be realized by $\alpha\beta$ −frame. But it has certain demerits as its control variables, feedback and feed forward signal are sinusoidal, which demands more complex control strategy. dq- frame is having all merits of $\alpha\beta$ −frame along with merits to have a control variables as DC quantities at steady state. It provides a simpler control strategy for controlling independently active and reactive power as control variables are DC signals [1]- [4].

Parameters like modulation index ‘m’, phase angle δ and frequency ω_0 can be controlled using an appropriate control strategy. Control over reactive power can be achieved by controlling the AC voltage which is the result of controlling modulation index. System AC voltage is being compared with reference and provided to reactive power controller.AC voltage at converter terminal is resulting from PWM modulation index. Hence lower the AC voltage magnitude at converter bus, converter absorbs reactive power and higher the AC voltage at converter bus, delivers the reactive power to grid [22], [24].

Frequency control can be achieved by controlling the frequency of firing sequence. Active power can be controlled by controlling the phase angle δ, and DC link voltage.

To have a control over active power and reactive power independently there are two methods, voltage mode control and current mode control. Current mode control provides over current protection to VSC but the same is the drawback of voltage mode control. In this the line current is tightly controlled by a dedicated control scheme. Then a real and reactive power is controlled by controlling the phase angle and amplitude of the VSC line current with respect to AC side voltage [4].

Current control mode is used in VSC-HVDC control strategy for operation. Inner current control loop resided in the VSC control strategy. It receives signal from outer control loop (AC voltage controller, reactive power controller, DC voltage controller and active power controller) compared to its reference value to generate a reference voltage vectors.and hence the control action.

The control can be achieved by transforming voltage and current vectors from abc-to dq-frame.

4.1 abc to dq- transformation:

To achieve the above transformation we need to transform abc –frame to $\alpha\beta$ −farme and then to *dq-frame*. In $\alpha\beta$ −farme the feed-forward, feed-back, and control signals are sinusoidal function of time. To process the DC signal rather than AC signals for control purpose it is need to transformation $\alpha\beta$ −farme to *dq-frame.*

Clarke transformation converts the three phase balanced quantities to 2 phase balanced orthogonal quantities.

abc- to $\alpha\beta$ −frame

Transformation matrix is given below

$$[f_{\alpha\beta 0}] = [T_{\alpha\beta 0}][f_{abc}] \qquad (4.1)$$

Where $T_{\alpha\beta 0}$ is the transformation matrix.

$$[T_{\alpha\beta 0}] = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (4.2)$$

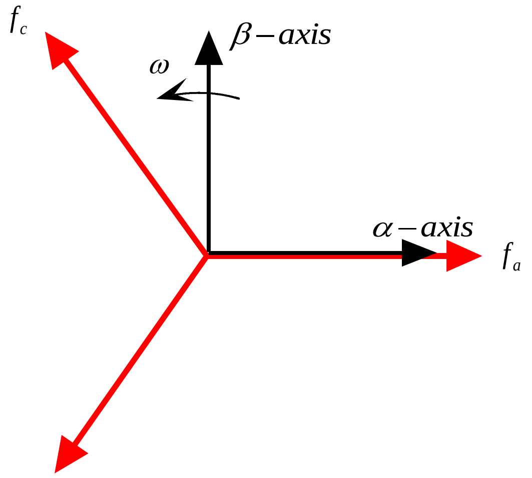

Figure 4.1 abc- to $\alpha\beta$ −frame

Where f represents the voltage, current, flux linkage and electric charge.

$\alpha\beta$ –Frame to dq – Frame transformation:

Parks transformation is split into Clarke transformation and one rotation.

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} \quad (4.3)$$

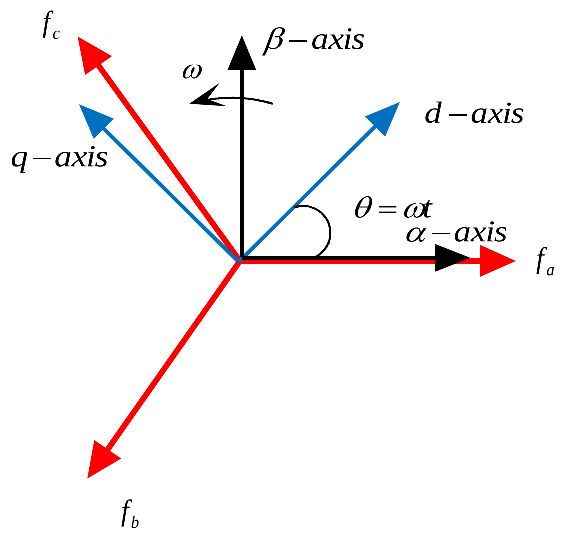

Figure 4.2 ($\alpha\beta$ –frame to dq-frame)

4.2 Phase locked loop (PLL):

It is a common method of finding the AC side voltage phase angle to synchronize the delivered power. There are several methods of detecting phase angle. Those are zero crossing detection, filtering grid side voltage and using PLL technique. PLL is having a phase tracking mechanism where a synchronized output with input phase and frequency. This mechanism is used to synchronize current and AC side voltage to get a unity power factor operation. A 3-phase AC voltage input is given to PLL model. This model is implemented on dq-frame by controlling q axis voltage ie. U_q to zero. PI controllers are used to achieve this purpose [4], [16], [17].

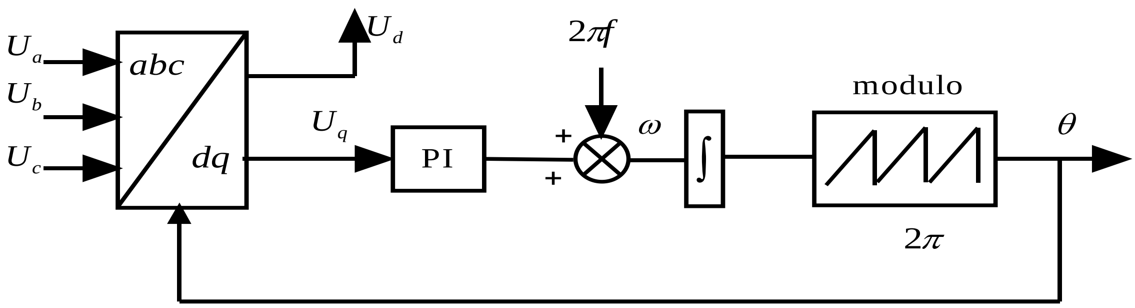

Figure 4.3 Phase locked loop to set the U_q at zero for balanced condition.

4.3 Dynamic model of AC side VSC:

AC side equivalent model of voltage source converter is shown in the Figure 4.4.

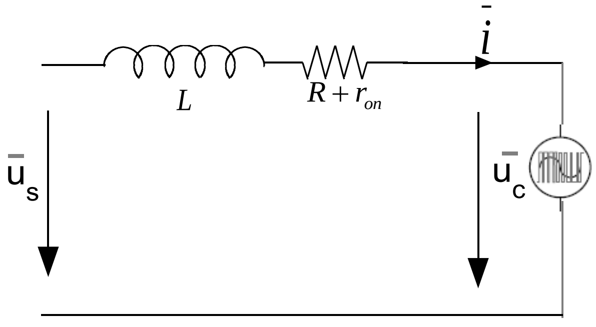

Figure 4.4 VSC -AC side equivalent model

Where $\overline{U_s}$ *and* $\overline{U_c}$ are grid side AC voltage and converter bus AC voltages respectively. L *and* $R + r_{on}$ are inductance and resistance of both inductor and converter switches respectively.

$$\overline{U_{sa}} = \widehat{U_s}\sin(\omega t + \theta), \tag{4.4}$$

$$\overline{U_{sb}} = \widehat{U_s}\sin\left(\omega t + \theta - \frac{2\pi}{3}\right), \tag{4.5}$$

$$\overline{U_{sc}} = \widehat{U_s}\sin\left(\omega t + \theta - \frac{4\pi}{3}\right), \tag{4.6}$$

where $\widehat{U_s}$ is peak value of line to neutral voltage, ω is the angular frequency of the AC system, θ is the initial phase angle of the system.

Dynamics of AC side of the VSC system:

$$\overline{U_s} = L\frac{d\bar{I}}{dt} + (R + r_{on})\bar{I} + \overline{U_c} \tag{4.7}$$

By reversing the current directin as VSC interact with AC system and exchanging power with AC system. The equation 4.7 is modified to ,

$$\overline{U_c} = L\frac{d\bar{I}}{dt} + (R + r_{on})\bar{I} + \overline{U_s} \tag{4.8}$$

$$L\frac{d\bar{I}}{dt} = -(R + r_{on})\bar{I} + \overline{U_c} - \overline{U_s} \tag{4.9}$$

Writing the above equation (4.9), implementing it in dq –frame by substituting $\bar{I} = I_{dq}e^{j\rho}$ and $\overline{U_c} = U_{cdq}e^{j\rho}$ in equation (4.9) we get

$$L\frac{d(I_{dq}e^{j\rho})}{dt} = -(R + r_{on})I_{dq}e^{j\rho} + U_{cdq}e^{j\rho} - \widehat{U_s}e^{j(\omega t+\theta)} \tag{4.10}$$

Where $\overline{U_s} = \widehat{U_s}e^{j(\omega t+\theta)}$ is the space phasor representation of AC grid voltage.

Decomposing the above equation (4.10) into its real and imaginary components we have

$$L\frac{d(I_d)}{dt} = \left(L\frac{d\rho}{dt}\right)I_q - (R + r_{on})I_d + U_{cd} - \widehat{U_s}\cos(\omega t + \theta - \rho) \tag{4.11}$$

$$L\frac{d(I_q)}{dt} = -\left(L\frac{d\rho}{dt}\right)I_d - (R + r_{on})I_q + U_{cq} - \widehat{U_s}\sin(\omega t + \theta - \rho) \tag{4.12}$$

$$\omega_0 = \frac{d\rho}{dt}, \tag{4.13}$$

Equations described in (4.11)-(4.13) are non-linear equations. Control inputs are $\omega_0, U_{cd}\ and\ U_{cq}$. State variables that to be controlled are $I_d, I_q and\ \rho$. Assuming initial condition of ρ is zero. Hence $\omega_0(t) = 0$; the equation (4.11) and (4.12) are described below as a decoupled first order system.

For VSC system dq- frame can be realized by selecting $\omega_0\ and\ \rho$. If $\omega_0 = \omega\ and\ \rho(t) = (\omega t + \theta), then$

Equation (4.11) and (4.12) takes the form of

$$L\frac{d(I_d)}{dt} = (L\omega)I_q - (R + r_{on})I_d + U_{cd} - \widehat{U_s} \tag{4.14}$$

And

$$L\frac{d(I_q)}{dt} = -(L\omega)I_d - (R + r_{on})I_q + U_{cq} \tag{4.15}$$

(4.14) and (4.15) are second order linear equations. It is excited by an input $\widehat{U_s}$. Where $U_{sd}, U_{sq}, I_d\ and\ I_q$ are DC variables in steady state. That can be realized by keeping the $\rho(t) = (\omega t + \theta)$ using phase locked loop mechanism [4], [8], [9], [23].

4.4 Control structure of VSC:

Control of VSC is aiming towards the control of both active and reactive power. Different control strategy are used for control purpose. Direct control and vector control methods are used. Which are basically a voltage controlled VSC and current controlled VSC respectively [9], [11], [22].

Voltage controlled method is to control the real and reactive power by directly controlling the phase angle and converter output voltage. But in case of current control scheme converter act as like a controlled current source. Where the current vector tracks the reference current vector. Advantages of current mode control over voltage mode control are

- Short-circuit protection to converter as it tightly controls the converter line current.
- Power quality improves as it is less affected by grid harmonics and disturbances.
- Decoupled control of real and reactive power.

4.4.1 Direct control:

Power transfer between converter and AC system is

$$p = \frac{U_S U_C}{X} sin\,\delta \text{ and} \tag{4.16}$$

$$Q = \frac{U_S(U_S - U_C\cos\delta)}{X} \tag{4.17}$$

From the equation 4.16 and 4.17 the real and reactive power can be controlled by altering power angle and modulation index for magnitude of the converter voltage. Error in power angle is processed through power angle controller. Actual power is calculated from terminal quantities and compared with desired power angle to get an active power order. Similarly reference reactive power and actual is compared to have a reference modulating signal. PLL circuit is used to synchronise the converter output voltage with the AC grid. Control scheme for direct control mode is shown in Figure. 4.5. Change in the power angle affects both P and Q hence an independent control of real and reactive power can't be realized [4], [19].

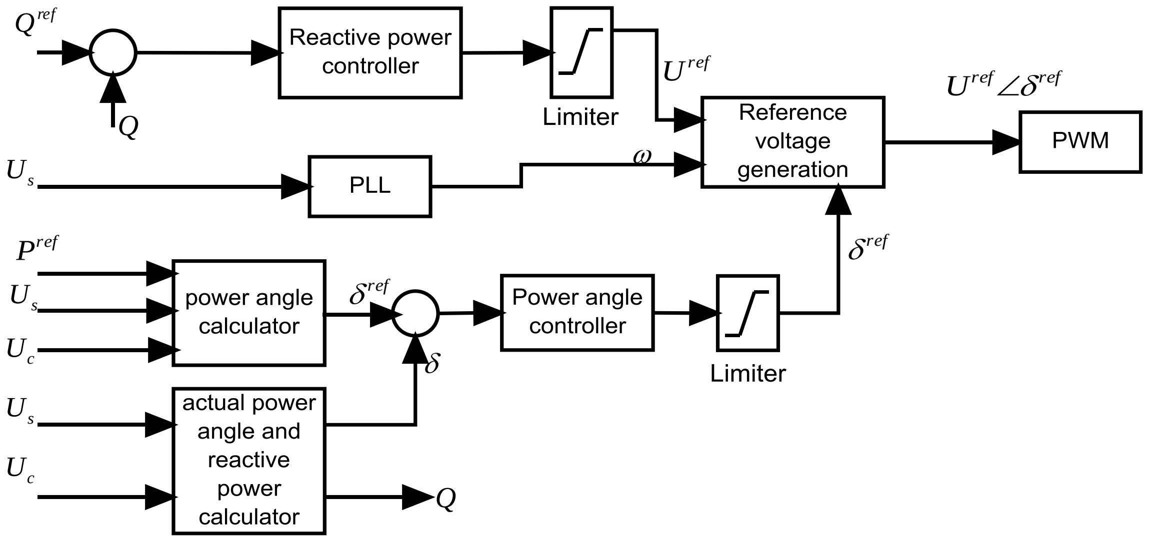

Figure 4.5 Direct voltage control mode

4.4.2 Vector control:

VSC control mechanism that can be achieved by a three layer mechanism. Outer layer control, inner current control loop and PWM signal generation. Control mechanism discussed here is for a 3 level neutral point clamped voltage sourced converter. For a 3 level neutral point clamped converter it is needed to have a 12 pulse generator. Pulses given to the IGBTs are resulting from the control mechanism of outer controller and inner current control loop. Reference voltage signals generated from the inner current controller is compared with triangular carrier wave for generation of triggering pulses [4], [15]. The overall control structure of VSC is shown in the Figure 4.6.

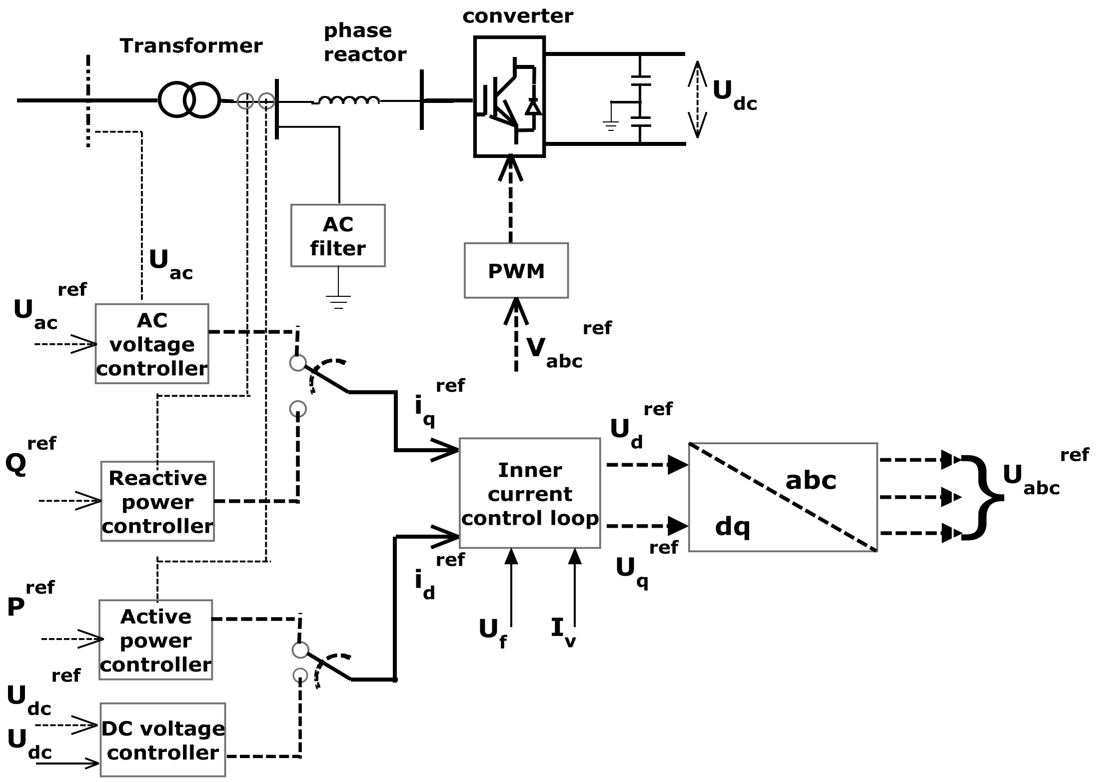

Figure 4.6 control structure for current control mode of VSC

Inner current controller:

Inner current controller produces a required control signals to ensure the maximum limit of converter current. Hence line current through the converter switches can be tightly controlled. The whole control mechanism that is realized by transforming the 3-phase converter current and AC grid voltage into its corresponding dq- rotating frame. Where phase locked loop plays an important role of synchronization with AC grid voltage. The control mechanism is experienced in inner current control loop to generate a voltage reference signal in dq- rotating frame. This can be further transformed back to 3phase abc – frame and given as a reference signal for PWM generation [16].

From the equivalent circuit of AC side of VSC from the figure 4.4 we have

$$\overline{U_s} - \overline{U_c} = L\frac{d\bar{I}}{dt} + (R + r_{on})\bar{I}, \quad (4.18)$$

The above equation can be realized using dq- rotating frame.

$$U_{sd} - U_{cd} = (R + r_{on})I_d + L\frac{dI_d}{dt} - \omega L.I_q \quad (4.19)$$

$$U_{sq} - U_{cq} = (R + r_{on})I_q + L\frac{dI_q}{dt} - \omega L.I_d \quad (4.20)$$

Where U_{sd}, U_{cd}, I_d *and* I_q are the AC grid voltage and current signals in dq-rotating frame. $(R + r_{on})$ and L are total resistance and the inductance between the converter bus and AC grid.

Laplace transforming the above equation (4.19) and (4.20) we have the structure shown in the Figure 4.7.

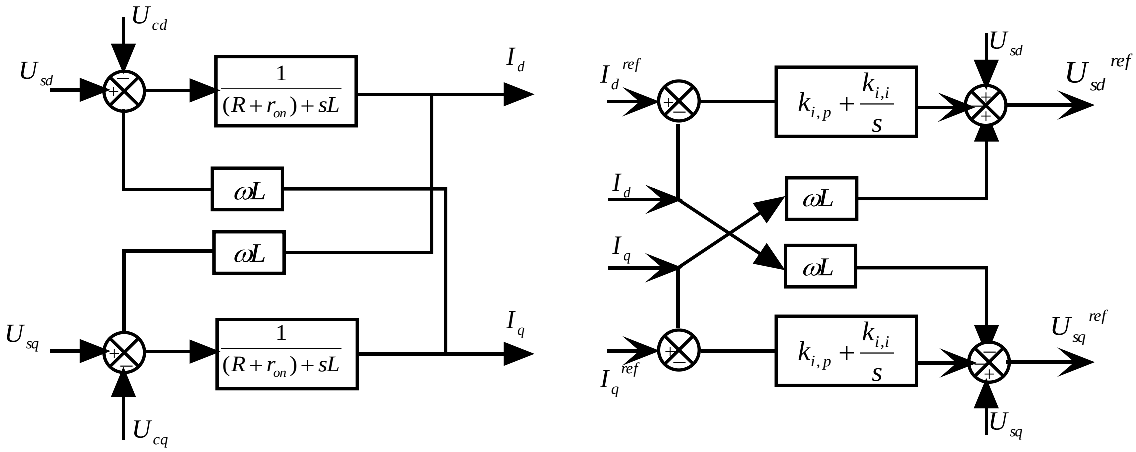

Figure 4.7 Inner current control loop

Outer control layer:

Outer control layer consists of different controllers to generate current reference signals i.e I_d^{ref} *and* I_q^{ref}. Those controllers are active power controller, DC voltage controller responsible for generation of I_d^{ref} and reactive power controller, AC voltage controller responsible for generation of I_q^{ref}. Every controller is equipped with a PI controller to have a reduced steady state error [1]-[4], [11].

Active and reactive power controller:

Control signals used for controlling the active power and reactive power are transformed from 3 phase abc-frame to dq-rotating frame, a DC equivalent of AC signal. The control signals transformed using park's transformation. Signals are transformed from time varying sinusoidal signal to a DC equivalent signal, to have a simple, reliable and efficient control strategy.

Active and reactive power that can be calculate from a balanced three phase system in dq frame is given below

$$P_{ac} = U_{sd}.I_d + U_{sq}.I_q \tag{4.21}$$

$$Q_{ac} = U_{sq}.I_d - U_{sd}.I_q \tag{4.22}$$

When $d - axis$ is aligned with AC voltage phasor using a phase locked loop (PLL) model, the $q - axis$ voltage in balanced condition is zero and $d - axis$ voltage shows the magnitude of AC voltage.

Hence the equation (4.21) and (4.22) can be rewritten as

$$P_{ac} = U_{sd}.I_d \tag{4.23}$$

$$Q_{ac} = -\boldsymbol{U_{sd}.I_q} \tag{4.24}$$

This shows a decoupled controlled of real and reactive power.

$$\boldsymbol{I_d{}^{ref} = (P_{ac}{}^{ref} - P_{ac})(k_{i,p} + \frac{k_{i,i}}{s})} \tag{4.25}$$

$$\boldsymbol{I_q}^{\boldsymbol{ref}} = (\boldsymbol{Q_{ac}}^{\boldsymbol{ref}} - \boldsymbol{Q_{ac}})(\boldsymbol{k_{i,p}} + \frac{\boldsymbol{k_{i,i}}}{\boldsymbol{s}}) \quad (4.26)$$

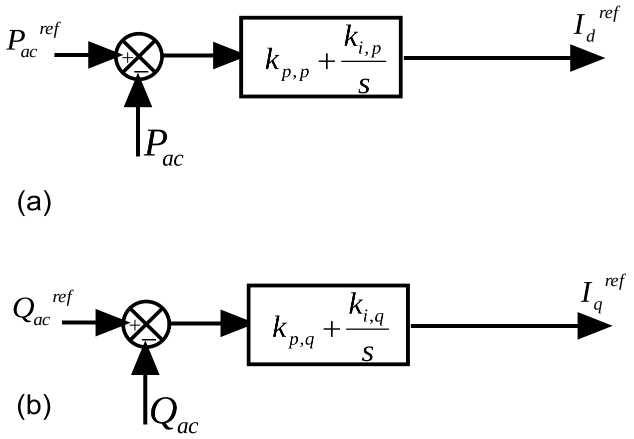

Figure 4.8 Active and Reactive power controller

DC side voltage controller:

DC side voltage control depends on the set reference signal. DC voltage at DC bus remain at its reference value and regulates real power exchange between AC grid and VSC. DC voltage controller generates a current reference signal i.e $\boldsymbol{I_d}^{\boldsymbol{ref}}$. Power corresponds to capacitor is $P_c = U_{dc}.I_c$

$$I_c = sCU_{dc}$$

$$hence\ \ P_c = s\,CU_{dc}^{\ 2} \quad (4.27)$$

Energy stored in capacitor

$$E_c = \frac{1}{2}\,CU_{dc}^{\ 2} \quad (4.28)$$

From the equation 4.27 and 4.28 revels that power across capacitor is proportional to square of DC voltage. To avoid non linearity in DC voltage controller we use difference between square of DC voltage. Then it is passed through PI controller to ha ve a I_d^{ref}.

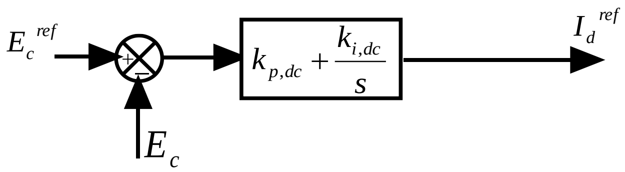

Figure 4.9 DC voltage controller

AC voltage controller:

Reactive power controller is used to have a control over PCC voltage level that can be maintained at desired level. Reactive power exchange between the VSC and AC grid is decided by the converter limits. It can regulate AC voltage by comparing it with reference value. Controller gives I_q^{ref} as its output signal.

$$I_q^{ref} = (U_{ac}^{ref} - U_{ac})(k_{p,ac} + \frac{k_{i,ac}}{s}) \tag{4.29}$$

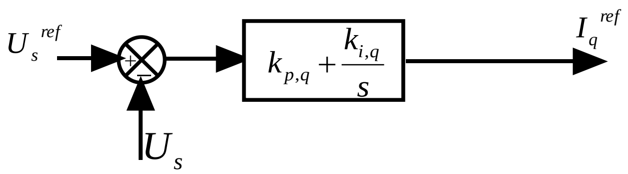

Figure 4.10 AC voltage controller

Current limiter:

VSC have a limitation over the maximum current as per the switch ratting and it is also benefit to control the AC voltage at desired level. As synchronous generator it does not have overload capability. For safe operation of VSC it must operate in safe operating in its capability curve. For proper operation of VSC the maximum limit of current so chosen that modulation index is equal to or less than one for SPWM [4], [24].

Choice of the current limit depends on its applications. $I_d^{\lim}$ *and* $I_q^{\lim}$ achieved when the converter current exceeds the maximum limit. When a VSC connected to a strong grid, to generate more power priority given to the $I_d^{\lim}$ (active reference current) as shown in Figure 4.11(a). And $I_q^{\lim}$ is given maximum priority when VSC connected to the weak grid as shown in Figure 4.11(b). It supports AC side voltage by increasing the reactive power. And last strategy is the one when current exceeds limit equal priority is given to active and reactive current component as shown in Figure 4.11 (c).

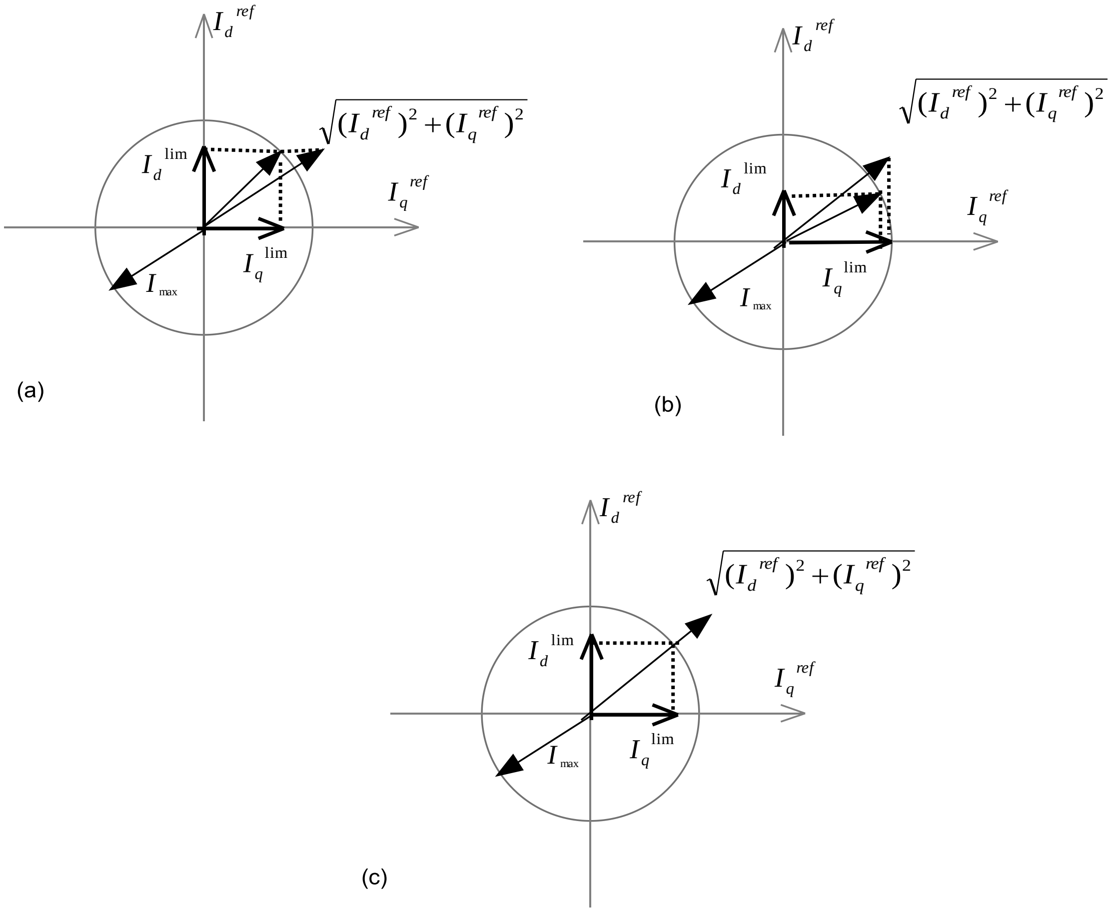

Figure 4.11 Current limiter

Summary:

In this chapter control design of VSC is discussed. A control strategy to control active and reactive power is discussed.

CHAPTER 5

RESULTS AND DISCUSSION

Control of active and reactive power using reference signals

Disturbance at Grid 2 and its effect with and without VSC

RESULTS AND DISCUSSION

Results and Discussion:

Interconnection of two AC grids through voltage source converter based HVDC link was simulated in MATLAB/SIMULINK environment. Where the converter used is a three level neutral point clamped converter. Simulation was done for analysis and observation of bulk power transfer over DC link. To achieve an independent control over active and reactive power. And its response to disturbance in power system, hence stability.

5.1 Control of active and reactive power using reference signals:

All the magnitudes of voltage, current and power are taken in per unit basis.

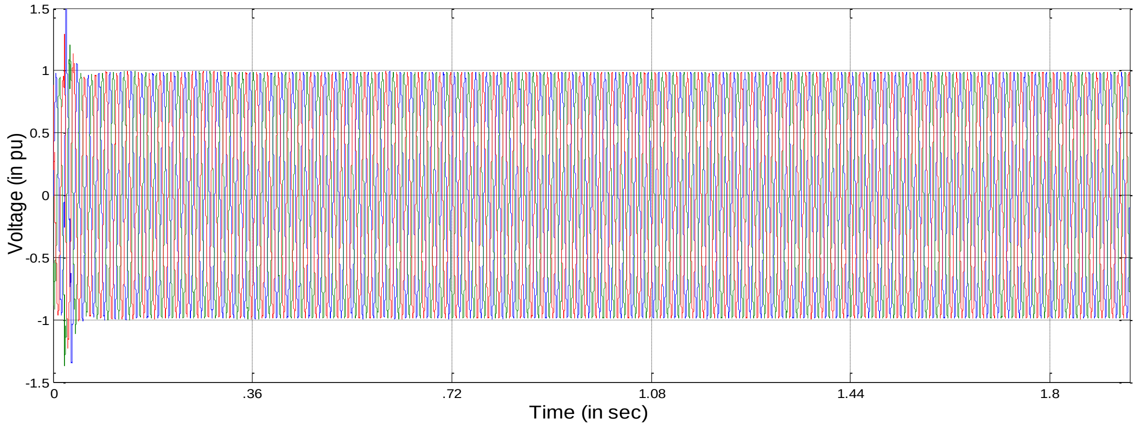

Figure 5.1 Input Voltage wave form of AC grid 1 and grid 2

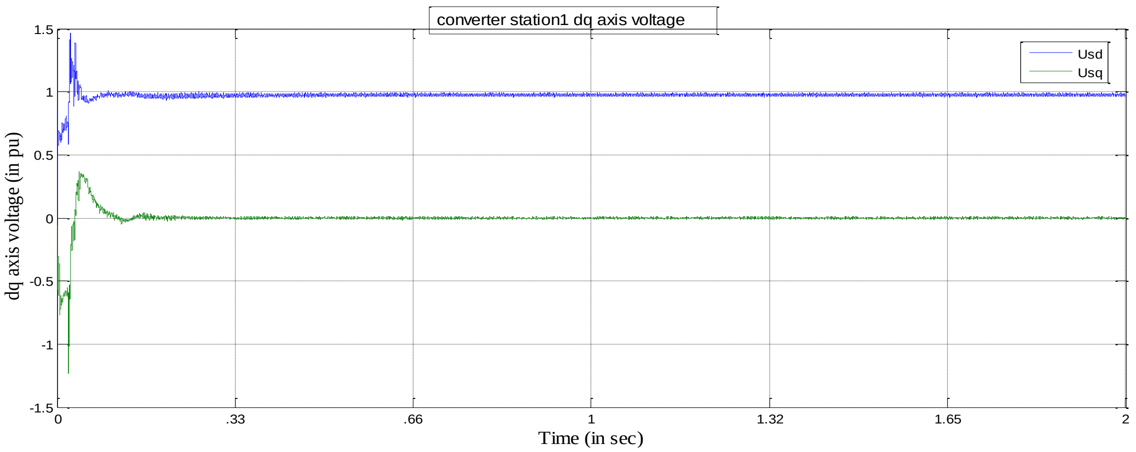

Figure 5.2 dq –transformation of AC voltage

The above transformation of abc to dq-frame was done using a PLL. Where AC voltage is given to PLL model to keep $q - axis$ voltage to zero, so that the total magnitude of the AC

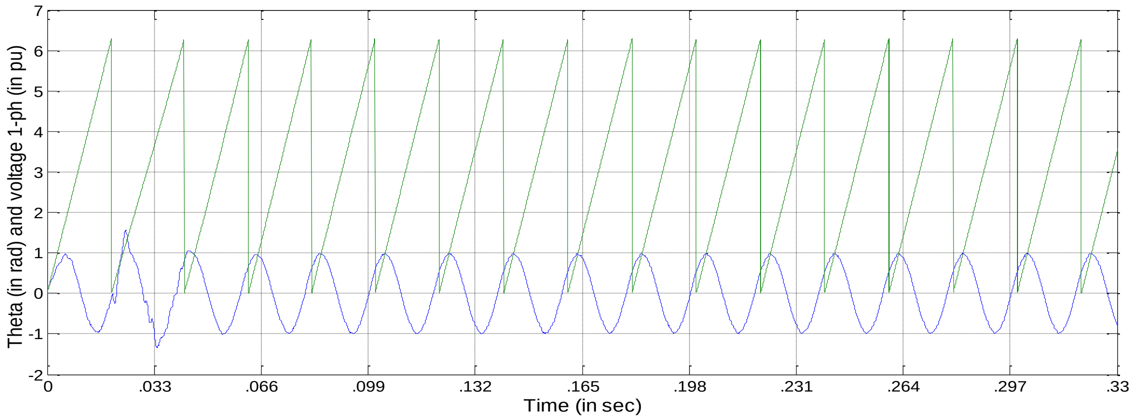

Figure 5.3 θ and phase voltage U_{sa}

voltage can be shown in $d - axis$. By keeping the $q - axis$ voltage to zero current control technique can be used for an independent control of active and reactive power. PLL uses a phase tracking mechanism to provide a synchronized output with input phase and frequency.

5.1.1 Power exchange between grid 1 and VSC 1:

Current control strategy is used for the control of active and reactive power through VSC. The above can be achieved by controlling the $d - axis$ and $q - axis$ currnet.

Figure 5.4 shows, the active power exchange between the AC grid and VSC. Where the reference value is set at 1 pu. 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. Hence at starting condition P_{ref} is set to zero. And then it is increased to set a desired value. So we will have a better transient response as shown in Figure 5.5.

Figure5.6 shows that the reference value of the reactive power is set at 0 pu. Hence the PI controller tracks the reference signal by generating corresponding $I_{d\ ref}$ and $I_{q\ ref}$ signals. From the above active power and reactive power controlled independently by changing the P_{ref} and Q_{ref}. The current reference signals processed through inner current control loop to provide $dq - axis$ voltage reference signal, then the $dq - axis$ voltage inverse transformed to get a 3phase reference signal. That 3ph reference signals compared with carrier signal generates the gating pulses for IGBTs.

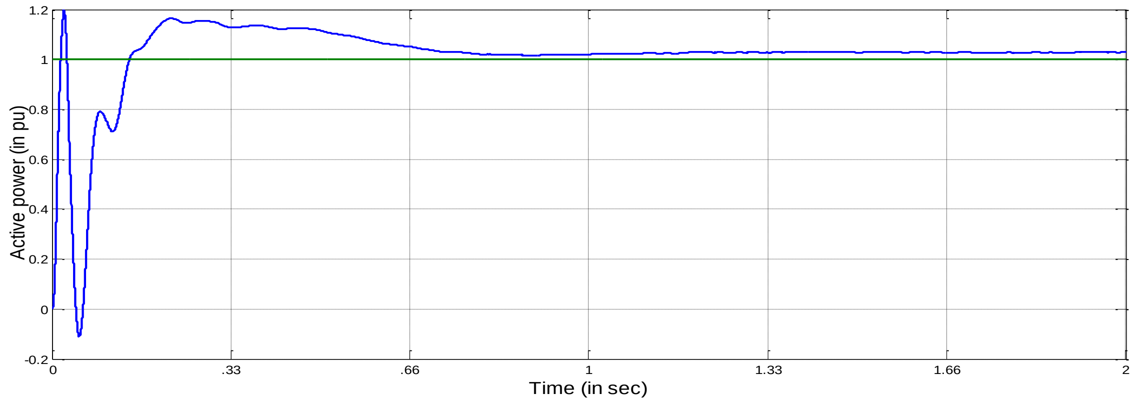

Figure 5.4 Active power Exchange between AC grid 1 and VSC 1

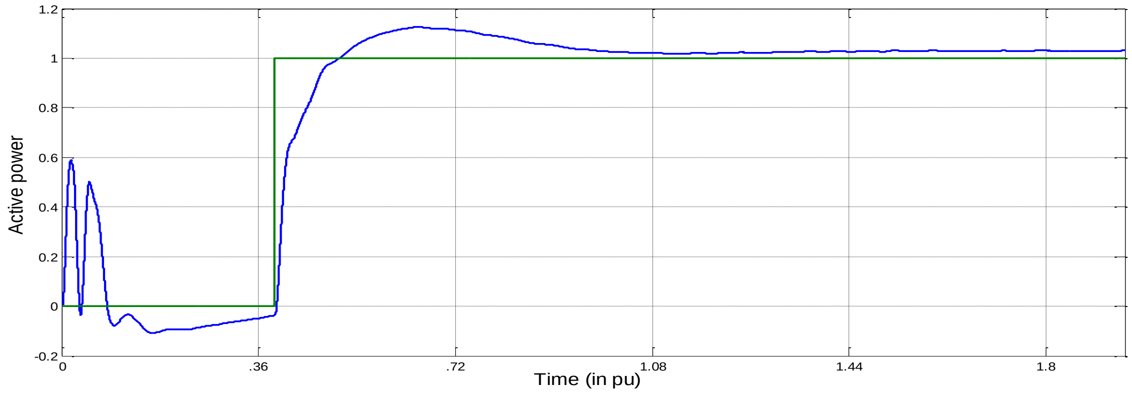

Figure 5.5 Active power Exchange between AC grid 1 and VSC 1 with step as reference signal with starting condition zero.

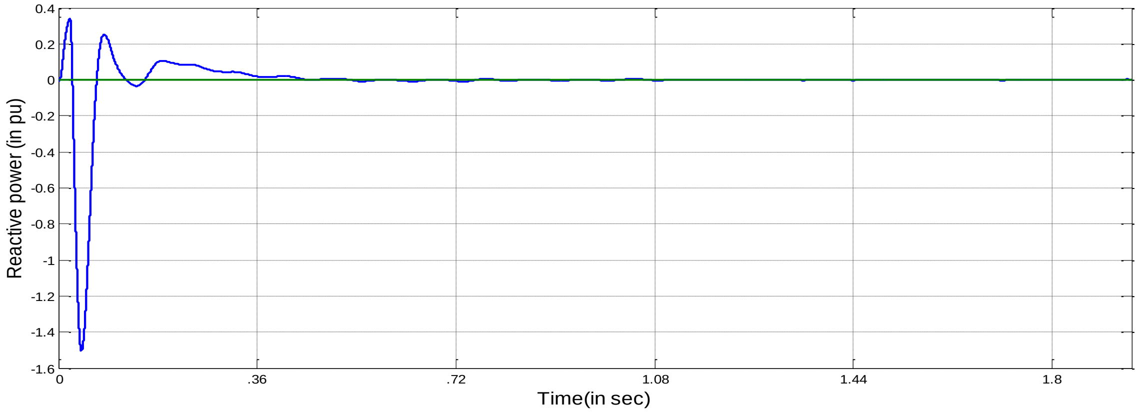

Figure 5.6 Reactive power exchange between AC grid 1 and VSC 1. With reference value 0pu.

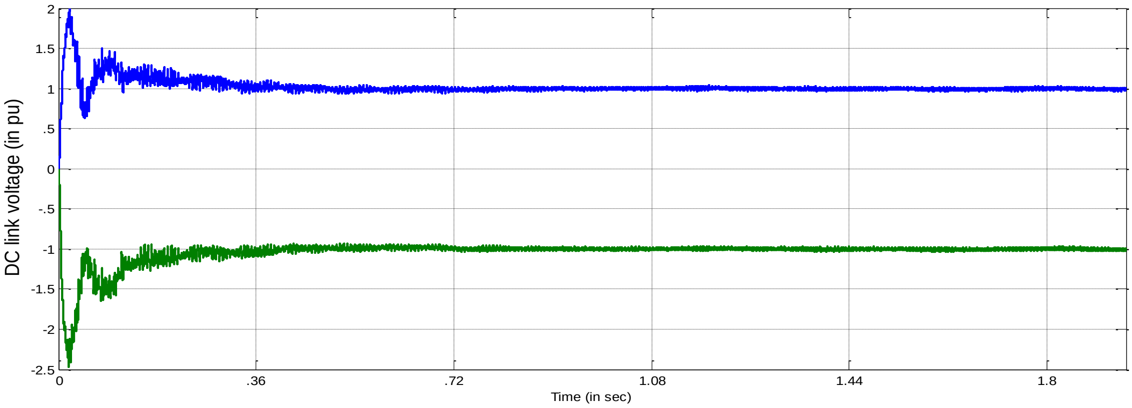

Figure 5.7 Bipolar DC link voltage

5.1.2 Power exchange between AC grid 2 and VSC 2:

Converter at AC grid 2 will act as like an inverter which exchanges power through VSC with AC grid. Power available at DC side is the power exchanged from grid 1. At the inverter side it is needed to have a dc voltage controller and reactive power controller.

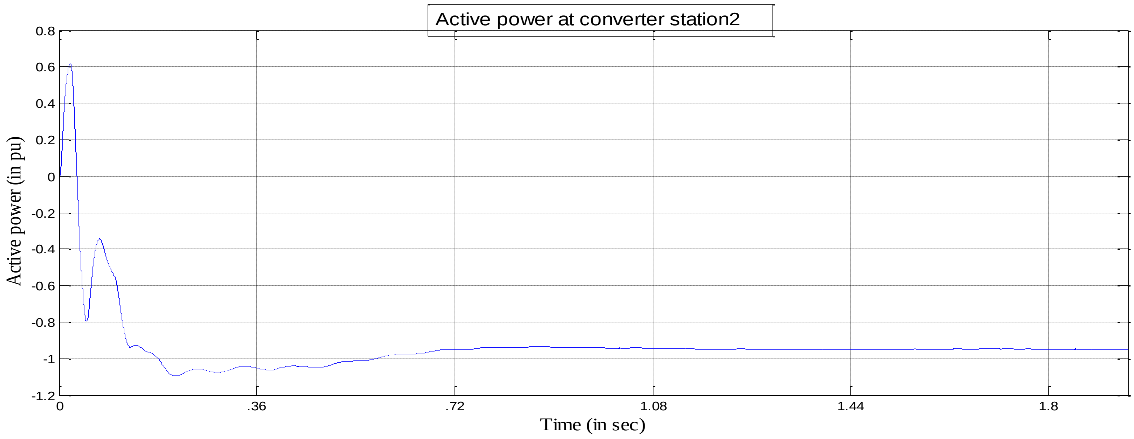

Figure 5.8 Active power exchange between VSC 2 and AC grid 2 with reference value of 1pu set at grid 1.

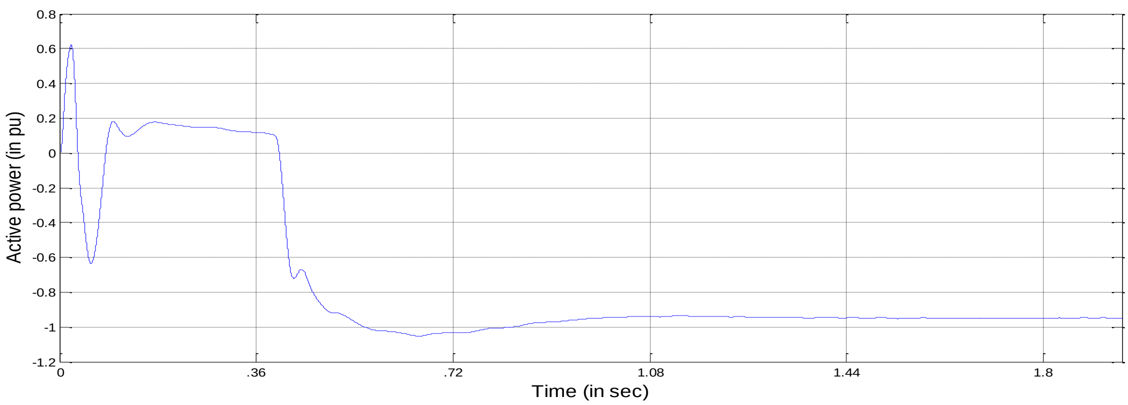

Figure 5.9 Active power exchange between VSC 2 and AC grid 2 with step reference value set at grid 1, zero initial condition.

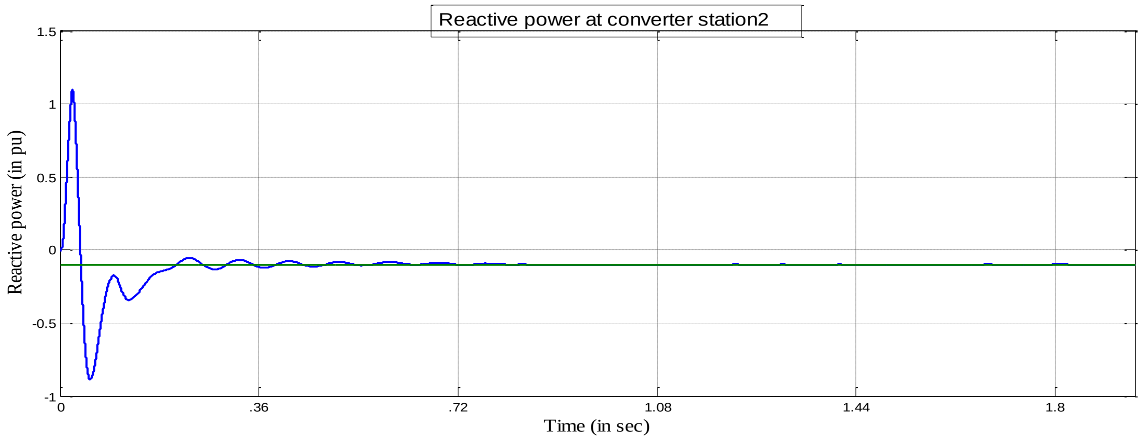

Figure 5.10 Reactive power exchange between grid 2 and VSC 2 with a -0.1 pu set reference value.

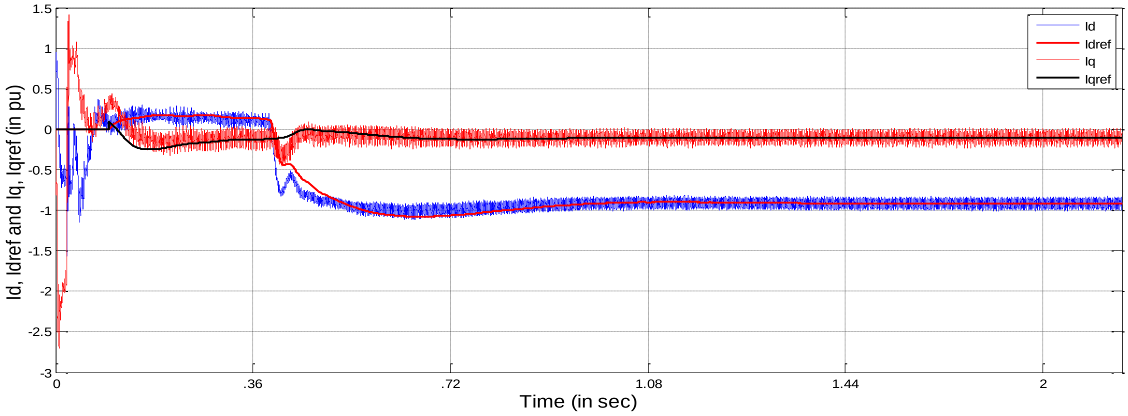

Figure 5.11 I_d , $I_{d\,ref}$ and I_q , $I_{q\,ref}$ of converter station 2

At converter station 2 the reactive power is set at -0.1 pu. Figure 5.10 shows the exchange of reactive power. The dq – axis current and its reference signals are shown in the figure5.11.

5.2 Disturbance at Grid 2 and its effect with and without VSC:

A three phase to ground fault is provided at grid 2 refer to Figure.2.7. Its effect on voltage profile in case of the AC transmission line was observed. And then by connecting the VSC was observed. A 3phase to ground fault takes place between the interval .75s to .85s from the figure 5.12, AC voltage without VSC decreases to fifty percent when there is a 3phase to ground fault take place at grid 2. Which may lead to voltage collapse at grid 1. As shown in Figure 5.13 (a) and (b). This is due to the excessive demand of reactive power at the fault location.

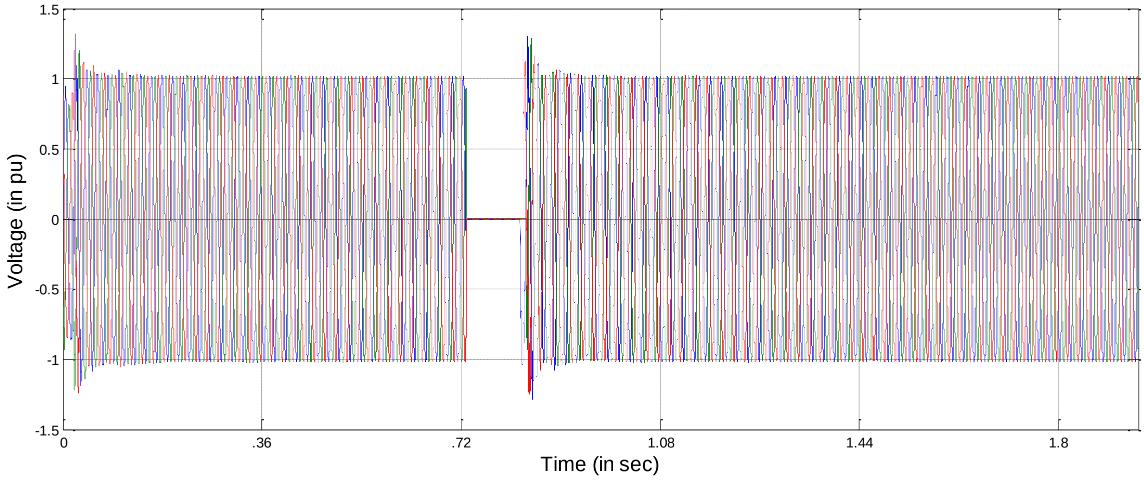

Figure 5.12 AC voltage at grid 2 with 3-ph to ground fault

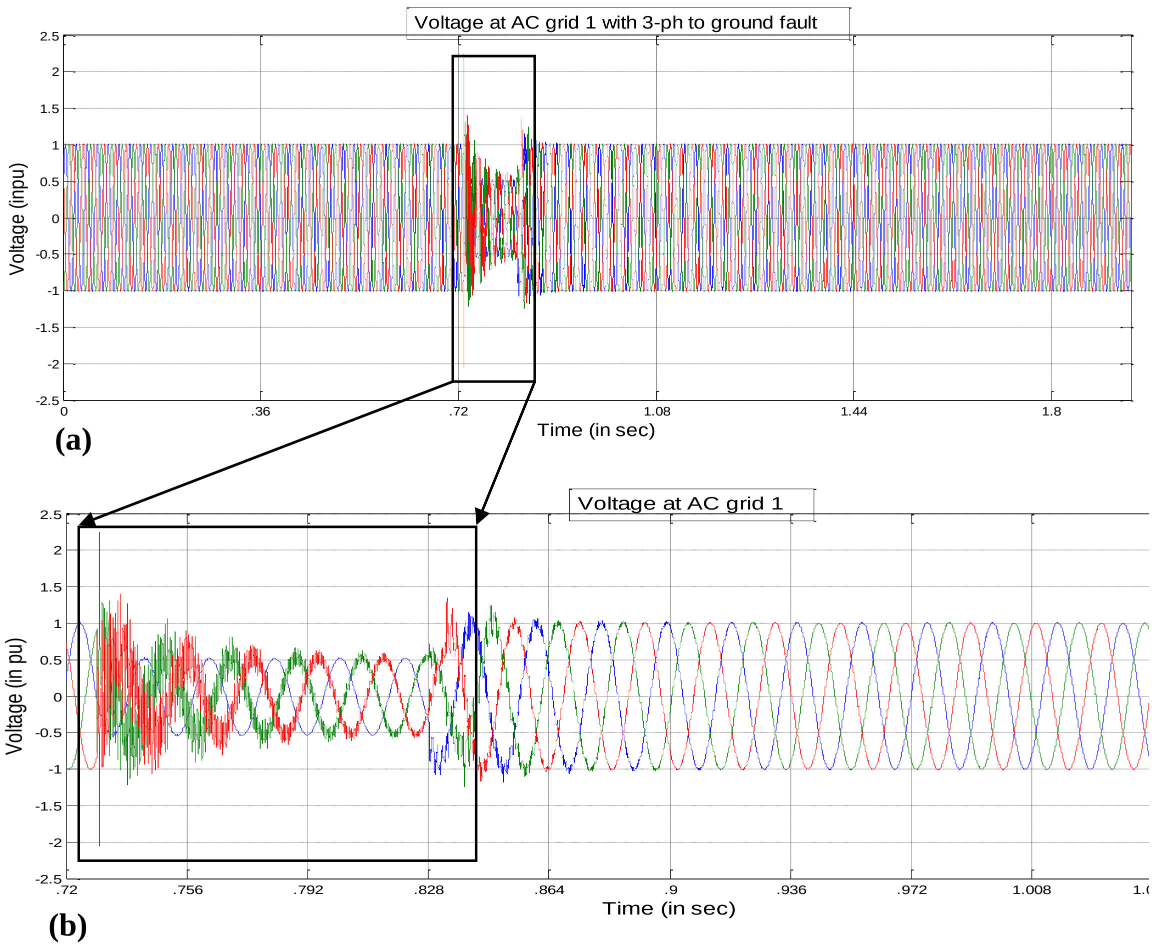

Figure 5.13 (a), (b) AC voltage at grid 1 with 3-ph to ground fault at grid 2

With voltage source converter based HVDC transmission, a reactive power support is provided to the fault location and keep the voltage magnitude at grid 1 at its level. As shown in Figure 5.14(a), (b). which maintains the voltage profile at grid 1.

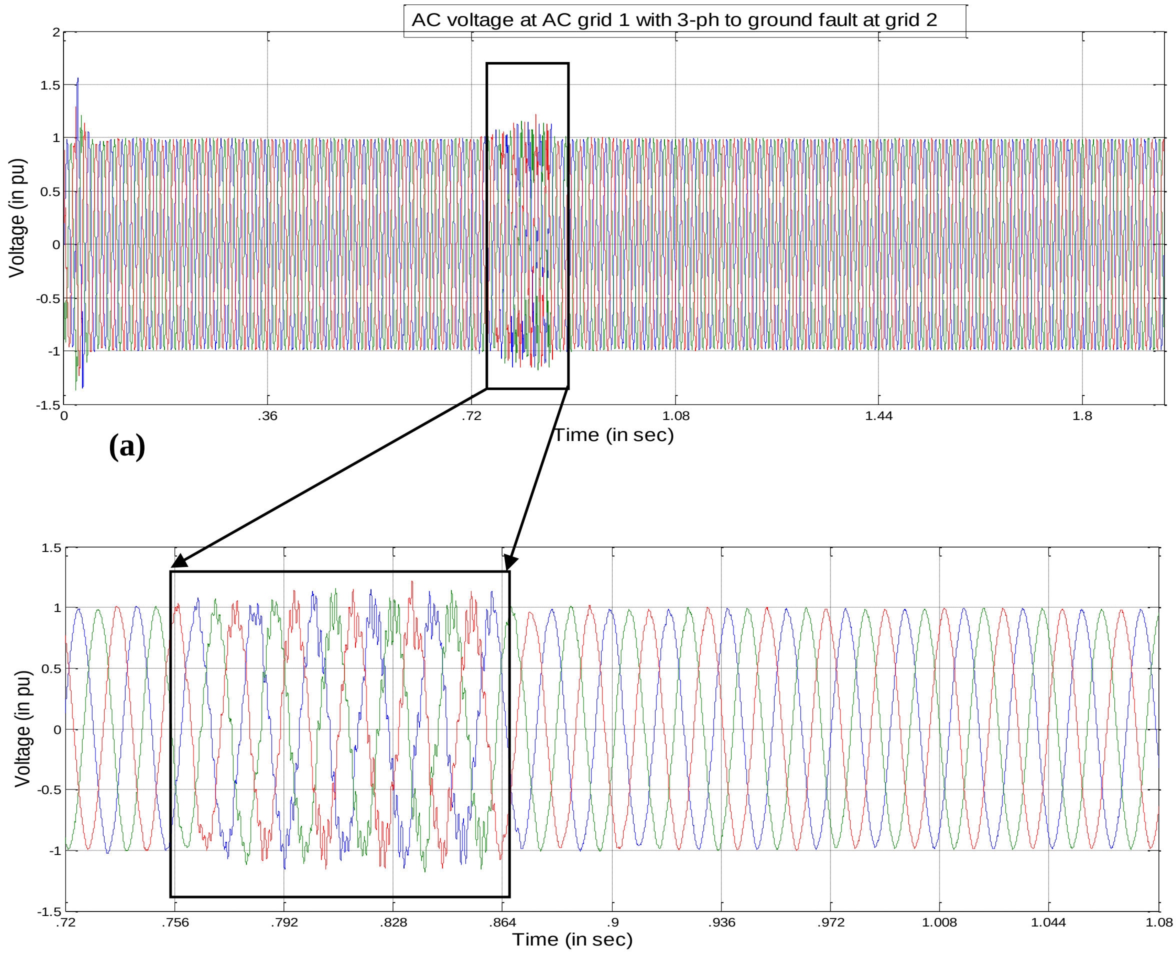

Figure 5.14 (a), (b) voltage at grid 1 with VSC-HVDC transmission at grid 1 with 3-ph to ground fault at grid 2.

Summary:

VSC-HVDC is simulated in MATLAB environment the wave forms were observed. Where VSC HVDC is an efficient technology for bulk power transfer and interconnecting AC grids. It provides a reactive power support to fault location and hence voltage stability. It reduces the chance of voltage collapse at generating ends.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 Conclusion:

This thesis deals with the application of VSC-HVDC transmission for the improvement of power system stability. Simulation result reveals that faster, independent control of real and reactive power can greatly improve the stability of power system. Some application of VSC-HVDC like interconnection of asynchronous grids and benefits like black start capability, frequency support, and voltage regulation can be achieved. Voltage stability was improved and protect the system from voltage collapsing due to lake of reactive power.

6.2 Future scope:

Some aspects with the VSC-HVDC technology that were not taken to consideration and could be subject for future scope.

- Implementation of frequency control system. The frequency control is possible when the VSC is connected to weak network or passive loads, i.e the VSC is the main source of power. The frequency control in this case is obtain by varying the frequency of the valve pulse firing sequence in the PWM technique.
- VSC capability chart was not implemented. However its presence is very important since it prevents the station from working in overloading operation point.

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Pubilication:

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