Control and Analysis of VSC based High Voltage DC Transmission

Tripti Shahi[1] K.P.Singh[2]
[1]M.Tech Student [2]Associate Professor
[1,2]Department of Electrical Engineering
[1,2]MMMUT, Gorakhpur, India

Abstract— High Voltage Direct Current system based on Voltage Source Converters (VSC-HVDC) is becoming a more effective, solution for long distance power transmission especially for off-shore wind plants and supplying power to remote regions Confronting with an increasing demand of power, there is a need to explore the most efficient and reliable bulk power transmission system. Rapid development in the field of power electronics devices especially Insulated Gate Bipolar Transistors (IGBTs) has led to the High Voltage Direct Current (HVDC) transmission based on Voltage Source Converters (VSCs).Since VSCs do not require commutating voltage from the connected ac grid, they are effective in supplying power to isolated and remote loads. Due to its advantages, it is possible that VSC-HVDC will be one of the most important components of power systems in the future. The VSC based HVDC transmission system mainly consists of two converter stations connected by a DC cable. This paper presents the performance analysis of VCS based HVDC transmission system. In this paper a 75kM long VSC HVDC system is simulated for various faults on the ACSide of the receiving station using MATLAB/SIMULINK. The data has been analyzed and a method is proposed to classify the faults by using back propagation algorithm. The simulated results presented in this paper are in good agreement with the published work.

Key words: Voltage source converter, Control Strategy, HVDC cables

I. INTRODUCTION

Conventional HVDC transmission employs line-commutated, current-source converters with thyristor valves. These converters require a relatively strong synchronous voltage source in order to commutate. The conversion process demands reactive power from filters, shunt banks, or series capacitors, which are an integral part of the converter station. Any surplus or deficit in reactive power must be accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the system or the further away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance. HVDC transmission using voltage-source converters (VSC) with pulse-width modulation (PWM) was introduced as HVDC Light in the late 1990s by ABB. These VSC-based systems are force-commutated with insulated-gate bipolar transistor (IGBT) valves and solid-dielectric, extruded HVDC cables HVDC transmission and reactive power compensation with VSC technology has certain attributes which can be beneficial to overall system performance. VSC converter technology can rapidly control both active and reactive power independently of one another. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. This control capability gives total flexibility to place converters anywhere in the ac network since there is no restriction on minimum network short-circuits capacity. Forced commutation with VSC even permits black start, that is, the converter can be used to synthesize a balanced set of 3-phase voltages like a virtual synchronous generator. The dynamic support of the ac voltage at each converter terminal improves the voltage stability and increases the transfer capability of the sending and receiving end ac systems. In the present work, possibility of using VSC based HVDC transmission for evacuating power is explored.

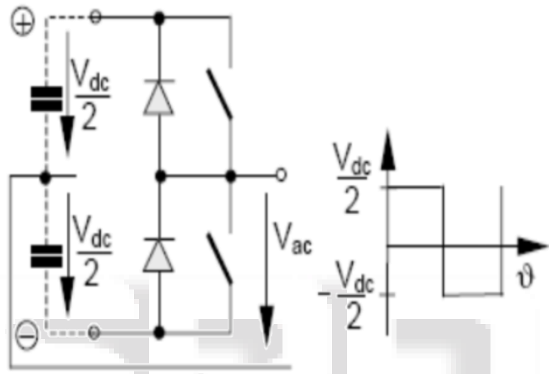


Fig. 1: Operational principle of VSC

The VSC based HVDC transmission system mainly consists of two converter stations connected by a dc cable. Usually the magnitude of AC output voltage of converter is controlled by Pulse Width Modulation (PWM) without changing the magnitude of DC voltage. Due to switching frequency, that is considerably higher than the AC system power frequency the wave shape of the converter AC will be controlled to vary sinusoidal. This is achieved by special Pulse Width Modulation (PWM). A three level VSC provides significant better performance regarding the Total Harmonic Distortion (THD).

A. Components of VSC-HVDC System and its operation

VSC-HVDC is a new dc transmission system technology. It is based on the voltage source converter, where the valves are built by 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 made 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. In this chapter, the topology of the investigated VSC-HVDC is discussed. Design considerations and modelling aspects of the VSC-HVDC are given. The topology selection for the VSC-HVDC is based on the desired capabilities.

1) Physical Structure

The main function of the VSC-HVDC is to transmit constant DC power from the rectifier to the inverter. As shown in Figure1, it consists of dc-link capacitors C_{dc}, two converters, passive high-pass filters, phase reactors, transformers and dc cable.

2) 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.

3) Transformers

Normally, the converters are connected to the ac system via transformers. The most important function of the transformers is to transform the voltage of the ac system to a value suitable to the converter. It can use simple connection (two-winding instead of three to eight-winding transformers used for other schemes). The leakage inductance of the transformers is usually in the range 0.1-0.2p.u.[7].

4) Phase Reactors

The phase reactors are used for controlling both the active and the reactive power flow by regulating currents through them. The reactors also function as ac filters to reduce the high frequency harmonic contents of the ac currents which are caused by the switching operation of the VSCs. The reactors are essential for both active and reactive power flow, since these properties are determined by the power frequency voltage across the reactors. The reactors are usually about 0.15p.u. Impedance.

5) AC Flters

The ac voltage output contains harmonic components, derived from the switching of the IGBTs. These harmonics have to be taken care of preventing them from being emitted into the ac system and causing malfunctioning of ac system equipment or radio and telecommunication disturbances. High-pass filter branches are installed to take care of these high order harmonics. With VSC converters 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 amount of low-order harmonics in the current is small. Therefore the amount of filters in this type of converters is reduced dramatically compared with natural commutated converters.

6) Dc Capacitors

On the dc side there are two capacitor stacks of the same size. The size of these capacitors depends on the required dc voltage. The objective for the dc capacitor is primarily to provide a low inductive path for the turned-off current and energy storage to be able to control the power flow. The capacitor also reduces the voltage ripple on the dc side.

7) 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 preferred choice for HVDC, mainly because of their mechanical strength, flexibility, and low weight.

8) IGBT Valves

The insulated gate bipolar transistor (IGBT) valves used in VSC converters are comprised of series-connected IGBT positions. The IGBT is a hybrid device exhibiting the low forward drop of a bipolar transistor as a conducting device. Instead of the regular current controlled base, the IGBT has a voltage-controlled capacitive gate, as in the MOSFET device.

9) AC Grid

Usually a grid model can be developed by using the Thevenin equivalent circuit. However, for simplicity, the grid was modelled as an ideal symmetrical three-phase voltage source.

II. Converter Topology

The converters so far employed in actual transmission applications are composed of a number of elementary converters, that is, of three-phase, two-level, six-pulse bridges, as shown in Figure.2, or three phase , three-level, 12-pulse bridges, as shown in Figure 3.

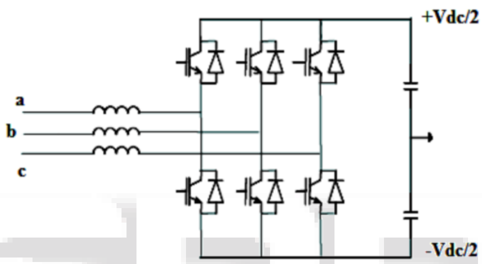


Fig. 2: Two Levels VSC

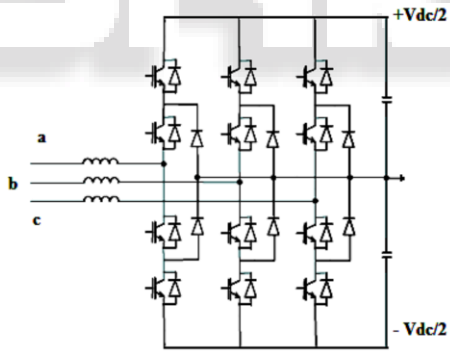


Fig. 3: Three Levels VSC

The two-level bridge is the most simple circuit configuration that can be used for building up a three-phase forced commutated VSC bridge. It has been widely used in many applications at a wide range of power levels. As shown in Figure 2, the two-level converter is capable of generating the two-voltage levels $-0.5 \cdot V_{dcN}$ and $+0.5 \cdot V_{dcN}$. The two-level bridge consists of six valves and each valve consists of an IGBT and an anti-parallel diode. In order to use the two-level bridge in high power applications series connection of devices may be necessary and then each valve will be built up of a number of series connected turn-off devices and anti-parallel diodes. The number of devices required is determined by the rated power of the bridge and the power handling capability of the switching devices. With a present technology of IGBTs a voltage rating of 2.5kV has recently become available in the market and soon higher voltages are expected. The IGBTs can be switched on and off with a constant frequency of about 2 kHz. The IGBT valves can block up to 150kV. A VSC equipped with these valves can carry up to 800A (rms) ac line current. This results in a power rating of approximately 140MVA of one VSC and a±150kV bipolar transmission system for power ratings up to 200MW.

III. CONTROL (PWM)

A converter is interconnecting two electric networks to transmit electric power from one network to other, each network being coupled to a respective power generator station. The converter, having an AC side and a DC side, includes a bridge of semiconductor switches with gate turn-off capability coupled to a control system to produce a bridge voltage waveform having a fundamental Fourier component at the frequency of the electric network coupled to the AC side of the converter. The control system includes three inputs for receiving reference signals allowing controlling the frequency, the amplitude and the phase angle of the fundamental Fourier component and the alternating voltage of the network coupled to the DC side of the converter [4]. The principle characteristic of VCS-HVDC transmission is its ability to independently control the reactive and real power flow at each of the AC systems to which it is connected, at the Point of Common Coupling (PCC). In constant to line commutated HVDC transmission, the polarity of the DC link voltage remains the same with the DC current being reversed to change the direction of power flow. The choice of different kinds of controllers to calculate the reference values of the converter current will depend on the application and may require some advanced power system study. For example: the active power controller can be used to control the active power to/from the converter; the reactive power controller can be used to control the reactive power; the ac voltage controller which is usually used when the system supplies a passive network can be used to keep the ac voltage.

If the load is a passive system, then VSC-HVDC can control frequency and ac voltage. If the load is an established ac system, then the VSC-HVDC can control ac voltage and power flow. But it should be known that because the active power flow into the dc link must be balanced, the dc voltage controller is necessary to achieve power balance. The other converters can set any active power value within the limits for the system. The dc voltage controller will ensure active power balance in all cases.

IV. SIMULATION AND RESULTS

The 230 kV, 2000 MVA AC system (AC system and AC system 2 subsystems) are modeled by damped L-R equivalents, with an angle of 800 at fundamental frequency (50HZ) and at the third harmonic. The simulation model is as shown in Figure 2. The VSC converters are three-level bridge blocks using close to ideal switching device model of IGBT/diodes. The control capability of IGBTs and its suitability for high frequency switching has made this device the better choice over GTO and thyristor. Like all power electronic converters, VSC generate harmonic voltages and currents in the AC and DC systems connected. In a simplified manner, from the AC system a VSC can be considered a harmonic current source connected in parallel to the storage capacitor. This behavior is just opposite to those of conventional line commutated converters. Harmonics generated depends on the station topology, switching frequency of IGBTs and pulse pattern applied. Using 12 pulse configurations instead of 6 pulse will improve harmonic condition both on AC and DC side. Characteristic AC side harmonics will have the ordinal numbers

$$V_{ac}=12n+1 \text{ ; } n = 1, 2 \ldots\ldots\ldots \quad (1)$$

Characteristic DC harmonic will have the ordinal numbers

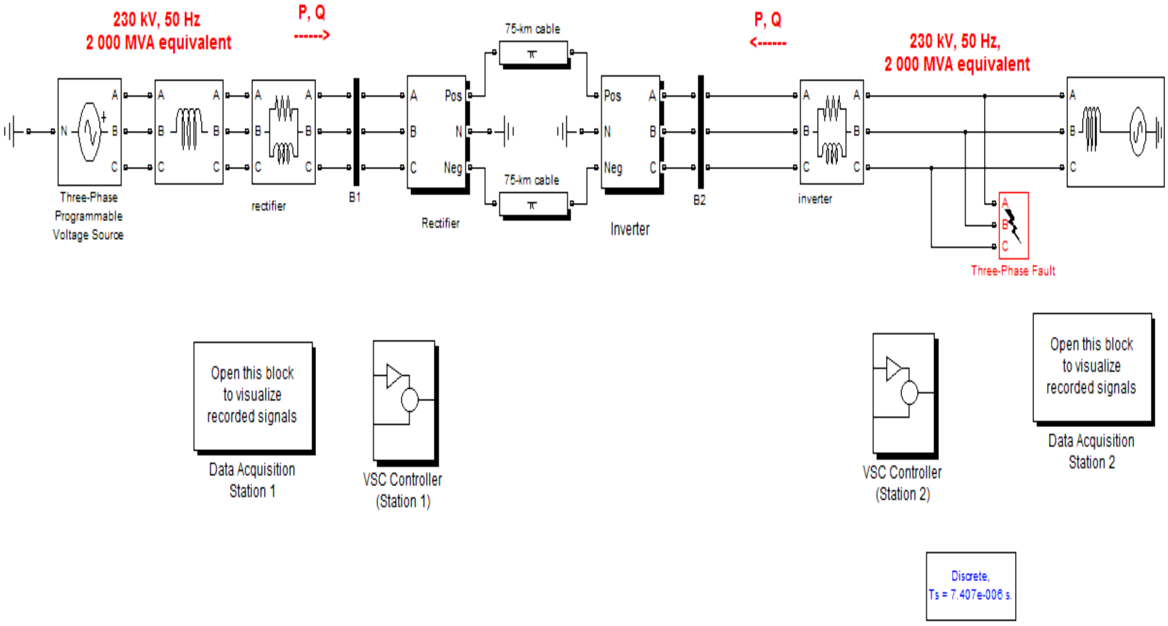
$$V_{dc}=12n; \ n = 1, 2 \ldots\ldots\ldots \quad (2)$$

All harmonics will be cancelled out under ideal conditions. Due to its inherent harmonic elimination capability the harmonic interface of VSC converter is rather small in comparison to the conventional line commutated converters. However harmonics filters might be necessary on the AC and DC sides depending on the harmonics performance requirements both for AC and DC sides [5]. AC system harmonic impedance, DC line/cable impedance and loss evaluation.

V. SIMULATION MODEL

A. *System Description*

A 300 MW (± 150 kV) forced-commutated voltage-sourced converter (VSC) interconnection is used to transmit DC power from a 400 kV, 2000 MVA, 50 Hz system to another identical AC system [17]. The AC systems (1 and 2) are modelled by damped L-R equivalents with an angle of 80 degrees at fundamental frequency and at the third harmonic. The rectifier and the inverter are three-level Neutral Point Clamped (NPC) VSC converters using close IGBT/Diodes. The rectifier and the inverter are interconnected through a 125 km cable (i.e. 2 pi sections) and two 8 mH smoothing reactors. The sinusoidal pulse width modulation (SPWM) switching uses a single-phase triangular carrier wave with a frequency of 27 time's fundamental frequency (1350 Hz). A converter transformer (Wye grounded /Delta) is used to permit the optimal voltage transformation. The present winding arrangement blocks tripplen harmonics produced by the converter. The 0.15 pu phase reactor with the 0.15 pu transformer leakage reactance permits the VSC output voltage to shift in phase and amplitude with respect to the AC system Point of Common Coupling (PCC) and allows control of converter active and reactive power output. The tap position is rather at a fixed position determined by a multiplication factor applied to the primary nominal voltage of the converter transformers. The multiplication factors are chosen to have a modulation index around 0.85 (transformer ratios of 0.915 on the rectifier side and 1.015 on the inverter side). To meet AC system harmonic specifications, AC filters form an essential part of the scheme. They can be connected as shunt elements on the AC system side or the converter side of the converter transformer. Since there are only high frequency harmonics, shunt filtering is therefore relatively small compared to the converter rating. The 78.5 Mvar shunt ACare 27th and 54th high-pass tuned around the two dominating harmonics.



B. Design Procedure

In the present work, the rectifier/inverter are three levels VSC that use the IGBT/diode module available in the MATLAB/Simulink/Simpower system. The case study is done for a VSC based HVDC transmission link rated 315 MVA (300MW, 0.95), ±150kv.

The system on AC side has: step down Y-Δ transformer, AC filters, Converter reactor. The system on DC side has: Capacitors and DC filters. The design of the components on AC and DC side are shown below. DC voltage rating: ±150kV System frequency: 50Hz Source AC voltage: 400kV line voltage Rated DC current=Rated DC power/Rated DC voltage.

C. AC System Modeling

AC system is modelled as a simple three phase AC source with internal resistance and inductance that is calculated from short circuit level MVA calculations. $(MVA)_B$ = 2000MVA $(KV)_B$= 400 kV (Phase to Phase rms).

Transformer Design Y grounded /Δ Transformer is used to permit the optimal voltage transformation. It also blocks the triplen harmonics produced by the converter. The following data for the transformer is considered: Nominal Power =315MVA (total for three phases) Nominal frequency=50Hz. Winding1 specifications: Y connected, nominal voltage = 400kV rms (Line to Line) X 0.915 (to simulate a fixed tap ratio) = 366kV Resistance = 0.0025pu, Leakage reactance = 0.0075pu Winding 2 specifications: Δ connected, nominal voltage = 150kV rms (Line to Line), Resistance = 0.0025pu, Leakage reactance = 0.075pu Magnetizing losses at nominal voltage in % of nominal current: Resistive 5 %(=500pu), Inductive 5 % (500pu).

D. AC Filters

Three-phase harmonic filters are shunt elements that are used in power systems for decreasing voltage distortion and for power factor correction. Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths. Harmonic filters are designed to be capacitive at fundamental frequency, so that they are also used for producing reactive power required by converters and for power factor correction. In order to achieve an acceptable distortion, several banks of filters of different types are usually connected in parallel. The most commonly used filter types are Band-pass filters, which are used to filter lowest order harmonics such as 5th, 7th, 11th, 13th, etc. Band-pass filters can be tuned at a single frequency (single-tuned filter) or at two frequencies (double-tuned filter).High-pass filters, which are used to filter high-order harmonics and cover a wide range of frequencies. A special type of high-pass filter, the C-type high-pass filter, is used to provide reactive power and avoid parallel resonances. It also allows filtering low order harmonics (such as 3rd), while keeping zero losses at fundamental frequency. The The resistance, inductance, and capacitance values are determined from the filter type and from the following parameters: Reactive power at nominal voltage Tuning frequencies Quality factor. The quality factor is a measure of the sharpness of the tuning frequency. It is determined by the resistance value. The filter is made up of passive R,L,C components their values can be computed using specified nominal reactive power, tuning frequency and quality factor.

Nominal voltage: 150kV

Nominal frequency: 50Hz

Nominal reactive power: 25% of real power (300MW) = 78.5Mvar

Tuning frequency= 27*50 and 54*50.

Quality factor= 15.

VI. SIMULATION RESULTS

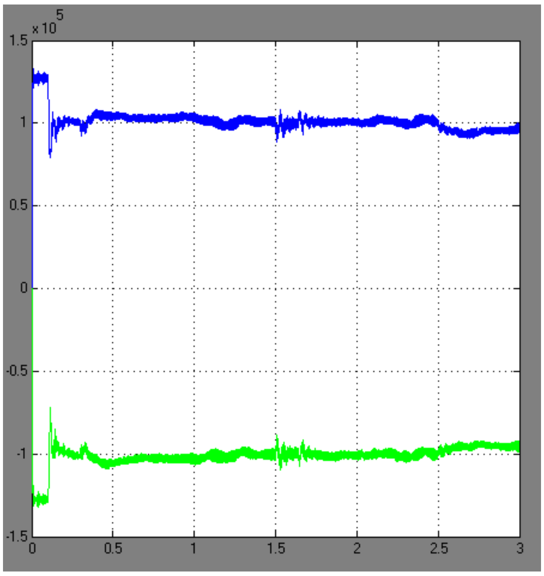


Fig. 5: DC Voltage at sending end

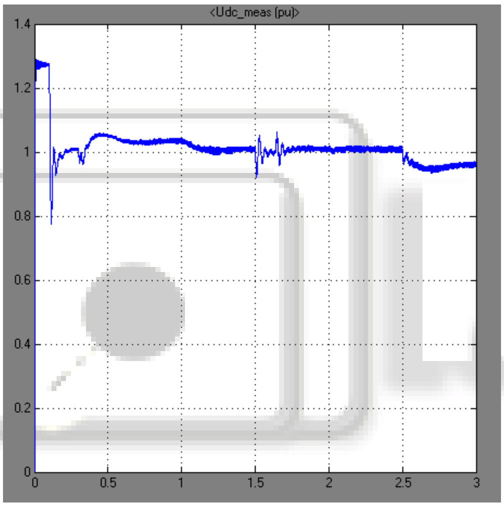


Fig. 6: DC voltage in p.u at sending end

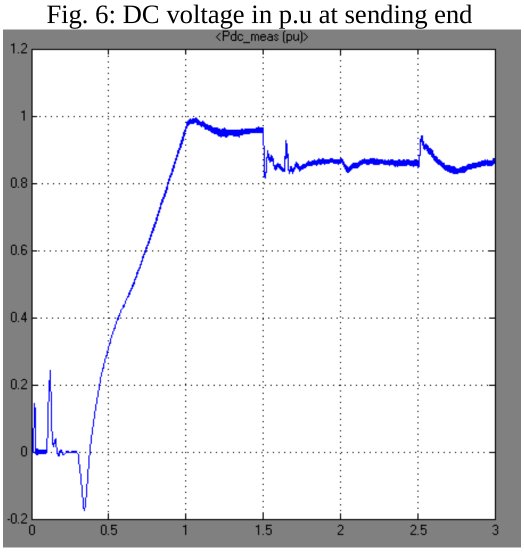


Fig. 7: DC real power in p.u at sending end

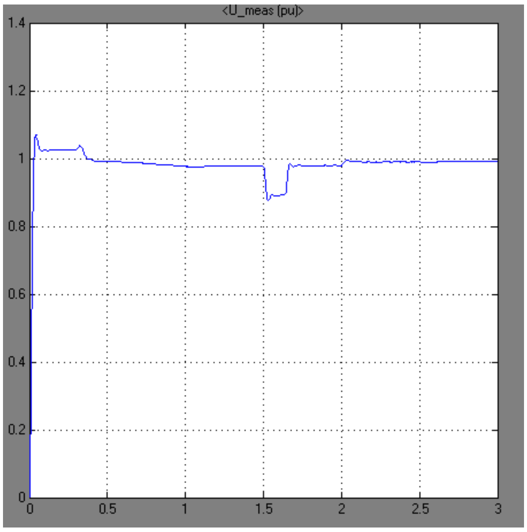


Fig. 8: Sending end AC voltage measured in p.u

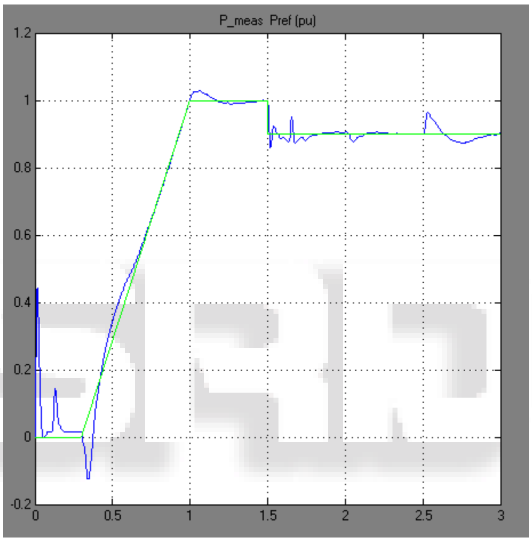


Fig. 9: Active power in p.u at sending end

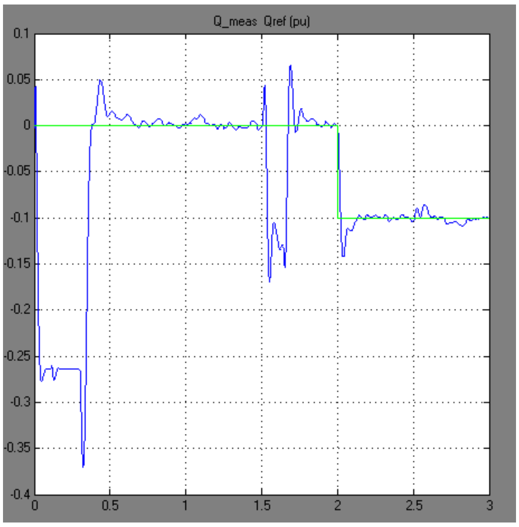


Fig.10: Reactive power in p.u at sending end

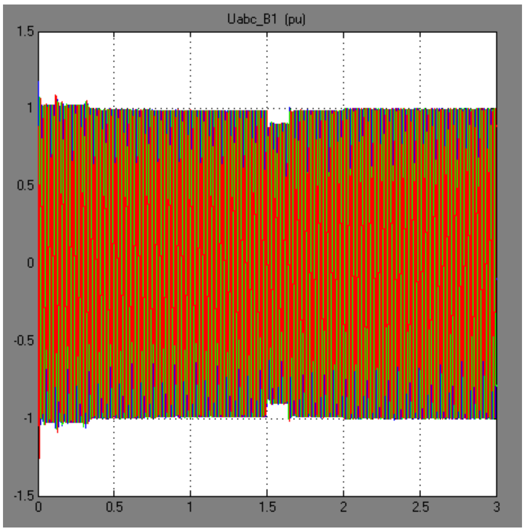
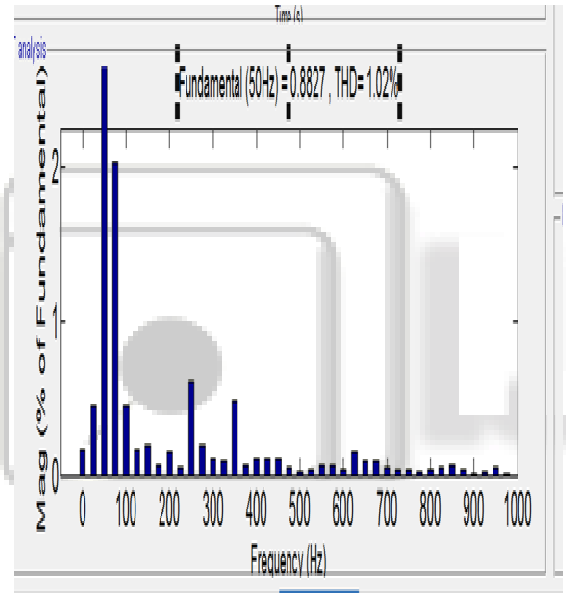


Fig. 11: Three phase Voltage in p.u at sending end

A. FFT Analysis of Output Voltage At Sending End:



B. Receiving End Waveforms:

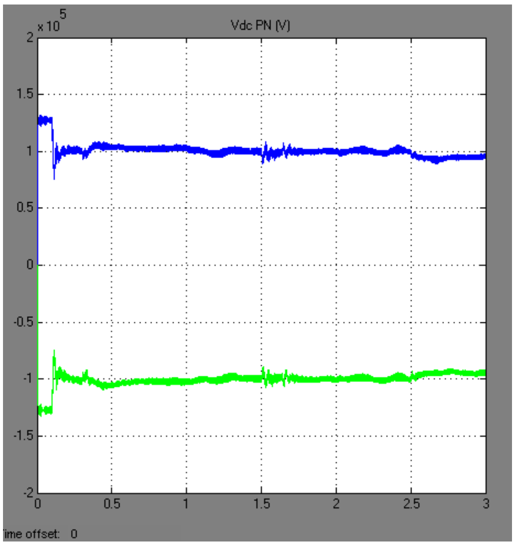


Fig. 12: DC Voltage at receiving end

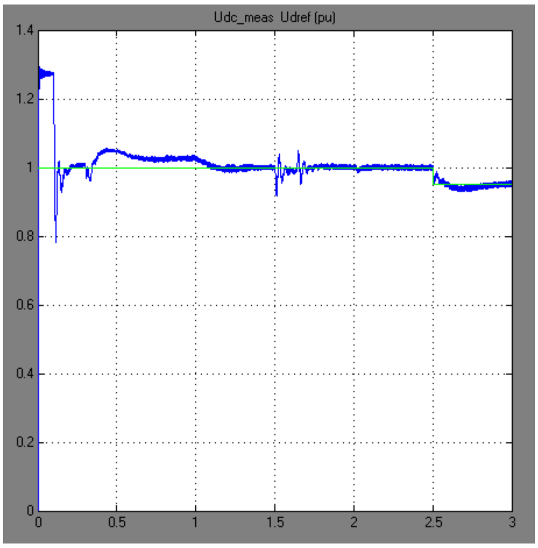


Fig. 13: DC Voltage in p.u at receiving end

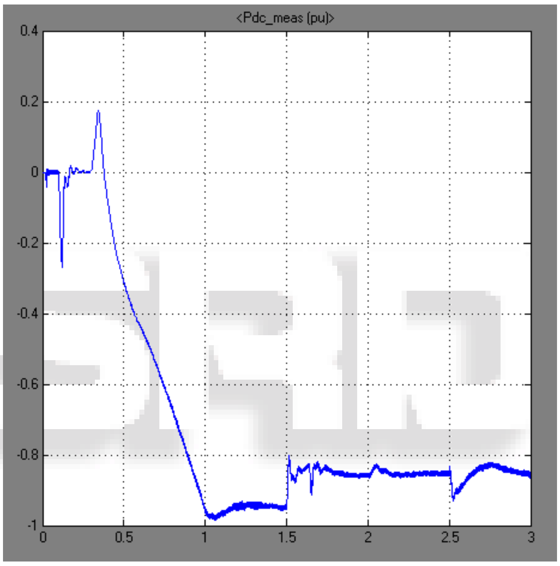


Fig. 14: DC real power in p.u at receiving end (Y

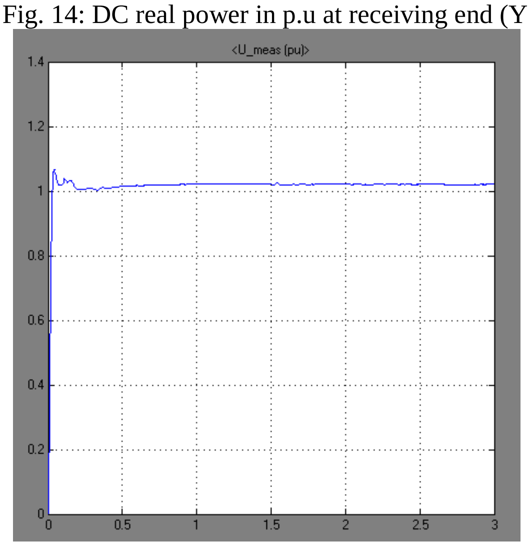


Fig. 15: Receiving end AC voltage measured in p.u

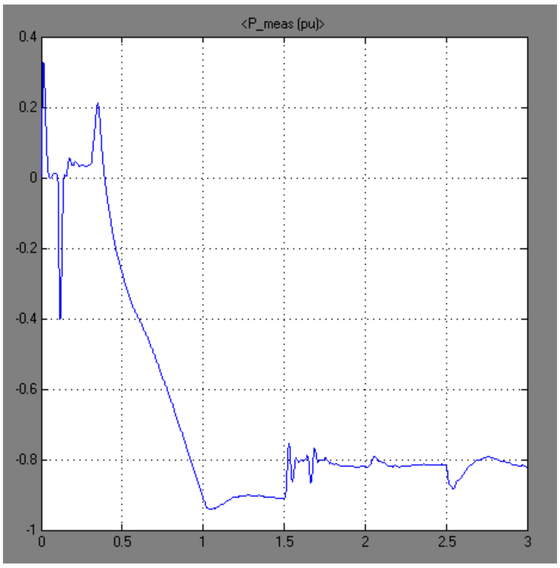


Fig. 16: active power in p.u at receiving end

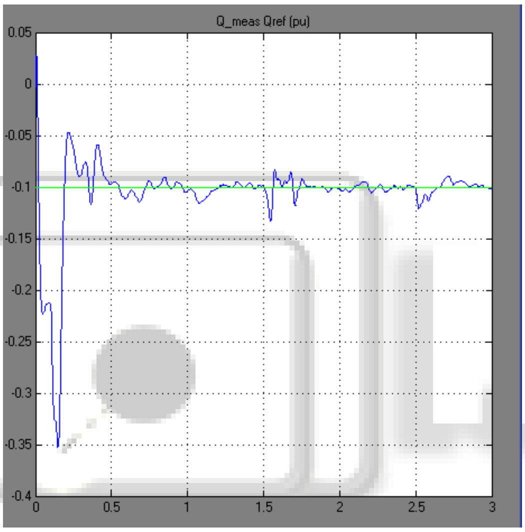


Fig. 17: Reactive power in p.u at receiving end

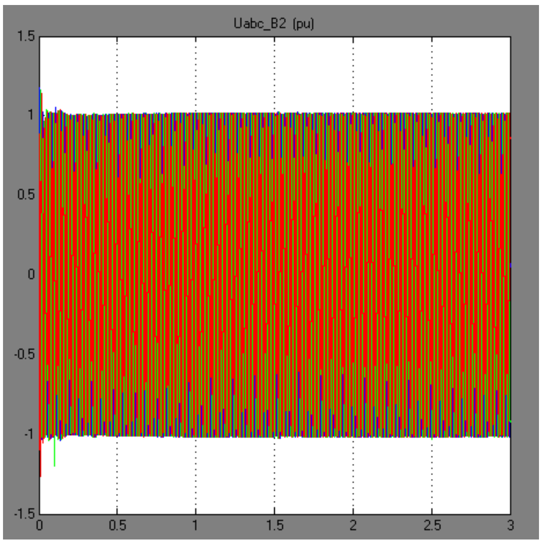
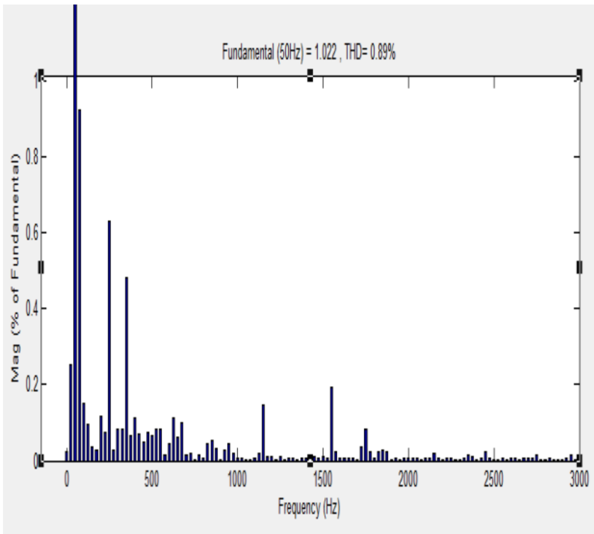


Fig. 18:Three phase Voltage at receiving end

C. *FFT Analysis of Output Voltage At Receiving End:*



VII. Conclusion

This Paper presents the steady-state performance of AC Transmission System and VSC based HVDC transmission system. The modeling details of HVDC system with three levels **VSC** are discussed. From the simulation results, it is concluded that the system response is fast; high quality ac voltages and ac currents can be obtained; and that the active power and the reactive power can be controlled independently and are bi-directional. The proposed scheme also ensures that, the receiving end voltage is maintained at 1 pu without any compensation.

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