

# Performance Analysis of Power Converters for High Voltage Direct Current Transmission (HVDC) Network

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**ABSTRACT:** This work involves design, modelling, simulation and analysis of High voltage Direct Current (HVDC) transmission scheme of twelve (12)-pulse converters using MATLAB/Simulink using relevant mathematical equations. Control system was modelled and disturbances are set in to ascertain the performance of the system. A 500 kV, 2 kA, 50Hz DC system is used for power transmission to a 330 kV, 50 Hz system. The converters are 12-pulse and are interconnected through 450-km line and 0.50H smoothing reactors placed at fixed position controlled by an amplification factor. The harmonic filters act as a source of filter for AC and reactive power compensator for DC. The 12 pulse converter system generates harmonics of the order 11th, 13th, 23rd, 25th and so on in the AC side with the configuration:  $n=kp \pm 1$  and  $n=kp$ . Several tests were carried out and the result was used to check the waveform and variations of voltage and current obtained from variations of generator source voltage. From the analysis, it is observed that HVDC system when connected to AC system can recover from faults very fast. Results presented demonstrated that controller performance in recovery of HVDC links from various disturbances is possible.

**KEYWORDS:** HVDC, MATLAB, 330kV, Harmonics

## I. INTRODUCTION

Electric Power is in the form of Alternating Current (AC). After generation, power is transmitted and distributed as AC except for some machines. In some cases, however, it is important and advantageous to bring Direct Current (DC) scheme to the supply of electrical power. This is true because in some situations, it may be the most efficient method of transmitting power. The modern High Voltage Direct Current (HVDC) transmission technology depends on the development of power electronics based on the semiconductor devices as investigated by M. Zakir Hossain [1]. AC systems have some limitations especially when the system cannot be in synchronism due to difference in frequencies or for long distances which is only economical to use DC transmission. In high voltage direct current (HVDC), power is generated mainly as AC, transmitted as DC and then converted back to AC at the other end. The world has been developing at a rapid rate over the past few decades. It has also been studied for different fault conditions. With the proposed strategy the HVDC system can provide useful and economical way to transmit electric power over the long distance, thereby improving the bulk transmission of electric power and power system stability. In order to sustain their development, there is need for power systems expansion. This has led to interconnection of all kinds of power system network worldwide [2]. The increasing rate of industrialization has led to utilization of electrical energy. This growing demand for power has led to search for efficient means of power transmission at increasing power levels. High Voltage Alternating Current (HVAC) which is used in Nigeria pose a lot of challenges when transmitted over long distances and it is not environmentally friendly, thus HVDC is been suggested. Its application falls into two basic categories:

- ✓ No distance between transmission otherwise known as back to back
- ✓ Distance transmission which can operate in different forms.

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

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Vol. 8, Issue 8, August 2019

Some of the challenges faced by Nigeria power transmission system as the years go by range from urbanization to environmental issues and it is becoming increasingly difficult to acquire rights of way for new lines. Power demand has increased due to population growth and industrialization thereby making it necessary for expansion. It can also be seen that transmission grid upgrade cannot keep pace with power demand. More so, for HVAC, adverse weather condition is a challenge. This paper thus tend to give a way forward with the aim to carry out analysis on HVDC especially Power Converters for HVDC transmission. Derivation of Converter equations, modelling and simulation of HVDC scheme using Matlab/Simulink software and comparison of theoretical values with simulated results will be carried out.

## II. RELATED WORK

Gupta in 2005 expressed that the use of D.C for day to day application is much older than that of AC. The first central station was installed by Edison in New York in 1882, which operated at 110V dc. It is of interest to know as to why then A.C. almost replaced all DC lines and why DC again is being used for some HV transmission lines. Sadaat in 1999 opined that one of the reasons is that D.C cannot be easily transmitted at low voltage [3]. The use of transformer for transmitting power over longer distances and at higher voltages justified the use of A.C especially where the electric energy has to be harnessed from power sources which usually are far from load centers. Asplund et al in 1997 justified the use of transformers for safe voltage transformation at both the receiving and sending end as well as, the growth of specialized induction motor and synchronous generators, thus making it possible for AC to almost replace DC [4]. Wadhwa in 2010 opined that the polyphase induction motors which serve the majority of industrial and residential purpose are simpler and rugged in construction and cheaper as compared to D.C motors of the same rating [5]. The commutators of D.C machines impose limitation on voltage, speed and size due to commutation problems. For operating a machine at high voltage, a relatively large diameter commutator is required which restricts the speed of the machine due to centrifugal force and a low speed machine is heavier and costlier than a high speed machine of equal ratings. Cory (1965) in his opinion also stated that the use of steam turbines which have a higher efficiency at high speed made the use of A.C generators superior as compared to D.C generators. For all such reasons, Power was generated, transmitted, distributed and consumed as AC. If, however, some applications needed the use of D.C, AC was converted to DC locally by motor generator sets, rotary converters or by mercury arc valves. Kundur studied the history of Thury System named after a French engineer René Thury who designed the system required for DC transmission [6], with a large number of series wound generators driven by prime movers, to be connected in series for high voltage at the sending end of the line and at the receiving end a compatible number of series wound D.C motors that can be again connected in series to drive low voltage D.C or A.C generators. Adamson et al posited that the system operated at constant current thus making switching and instrumentation simple [7]. Ammeter and voltmeter were the only instruments required. Thury System worked well for transfer of small powers. For bulk power, the limitation of D.C machines came in the way and therefore better converters than motor generator sets were required. Ruderval *et al* stated that mainly electronic devices can be used for HVDC transmission [8]. This is because the devices can rectify AC- a process known as rectification and as well change it back to AC- a process called inversion. Further investigation revealed that the first HVDC scheme was put in place in 1954 in Sweden. It has the capability of transmitting power of about 20MW through a single line cable of 100km. This was a major contribution that opened the way for HVDC scheme of even a higher rating [9]. The success of this HVDC transmission scheme paved the way for many others of even higher ratings. Today, there are many HVDC transmission systems all over the world, although some are still under construction. Extensive research has been carried out especially in Sweden for development of high voltage (HV) converters. Thyristors of ratings 50kV and 100 amperes have been developed and now there are many countries in the world where transmission of power over longer distances and HV is being done by DC requiring converters at each end. At the sending end AC is converted to DC and at the receiving end it is converted back to AC for use. HVDC has been applied to transmit bulk power over long distance for the past 40 years. Several HVDC systems have been constructed for this purpose and have operated successfully. In the last several years, HVDC systems in India and China have been constructed at D.C voltage of 500kV and DC power up to 3000MW. However, in the last 10 years, there is need to generate power at very remote locations far away from its source just like Nigeria and transmit this power to load centers in narrow transmission corridor.

**III. DESIGN OF HVAC/HVDC POWER CONVERTERS USING MATLAB/SIMULINK.**

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Simulink is an interactive environment for modelling, simulating, and analysing dynamic, multi-domain systems. It is used to build block diagrams, simulate system's behaviour, evaluate its performance, and refine the design. Simulink integrates seamlessly with MATLAB, providing immediate access to an extensive range of analysis and design tools. These benefits make Simulink the tool of choice for control system design, DSP design, communications system design, and other simulation applications. Appendix A shows the data used for the model.

**3.1 Description of HVDC Transmission Model**

The schematic diagram of HVDC (twelve-pulse) system is shown in figure 1.0 where  $X_{cr}$  and  $X_{ci}$  are short circuit transformers reactances,  $V_{pr}$ ,  $V_{pi}$ ,  $V_{sr}$  and  $V_{si}$  are transformer voltages on primary and secondary sides respectively.

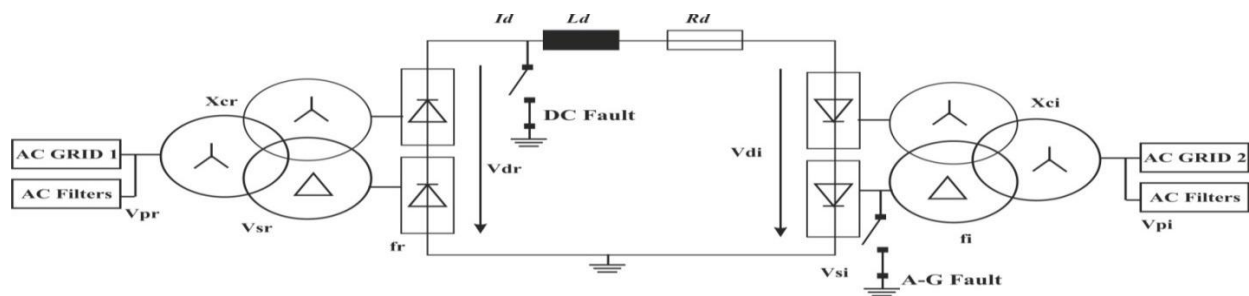


Fig.1.0 Diagram of twelve-pulse HVDC scheme

Equation 1.0 and 2.0 are obtained from Fig 1.0

$$V_{dr} = B \frac{3\sqrt{2}}{\pi} V_{sr} \cos \alpha_r - B \frac{3}{\pi} X_{cr} I_d \quad (1.0)$$

$$V_{di} = B \frac{3\sqrt{2}}{\pi} V_{si} \cos \gamma_{ir} - B \frac{3}{\pi} X_{ci} I_d \quad (2.0)$$

Where B is a parameter taken as one for six pulse converters and two for twelve pulses. The transmission line behaviour is given as

$$I_d R_d + L_d \frac{dI_d}{dt} = V_{dr} - V_{di} \quad (3.0)$$

Replacing the extinction angle with firing angle equation 1.0 becomes

$$V_{di} = -B \frac{3\sqrt{2}}{\pi} V_{si} \cos \alpha_i + B \frac{3}{\pi} X_{ci} I_d \quad (4.0)$$

Notice the change in sign. Inserting equations (1.0) and (2.0) into (3.0) gives:

$$I_d R_d + L_d \frac{dI_d}{dt} = B \frac{3\sqrt{2}}{\pi} (V_{sr} \cos \alpha_i + V_{si} \cos \alpha_i) - B \frac{3}{\pi} I_d (X_{cr} + X_{ci}) \quad (5.0)$$

During commutation cycle, overlap angle is given as

$$U_{r/i} = \arccos \left( \cos \left( \alpha_{r/i} - \frac{2\omega I_d L_{cr/i}}{\sqrt{2} V_{sr/i}} \right) \right) - \alpha_{r/i} \quad (6.0)$$

While reactive power consumption is given as

$$Q_r = P_r \tan \left[ (\arccos) \frac{\cos \alpha_r + \cos (\alpha_r + V_r)}{2} \right] \quad (7.0)$$

$$Q_i = P_r \tan \left[ (\arccos) \frac{\cos \gamma_i + \cos (\gamma_i + V_i)}{2} \right] \quad (8.0)$$

Hereby the extinction angle can be stated as follows

$$\gamma_{r/i} = 180^\circ - \alpha_{r/i} - U_{r/i} \quad (9.0)$$

### 3.2 Controls

The pole control is split in the rectifier and inverter

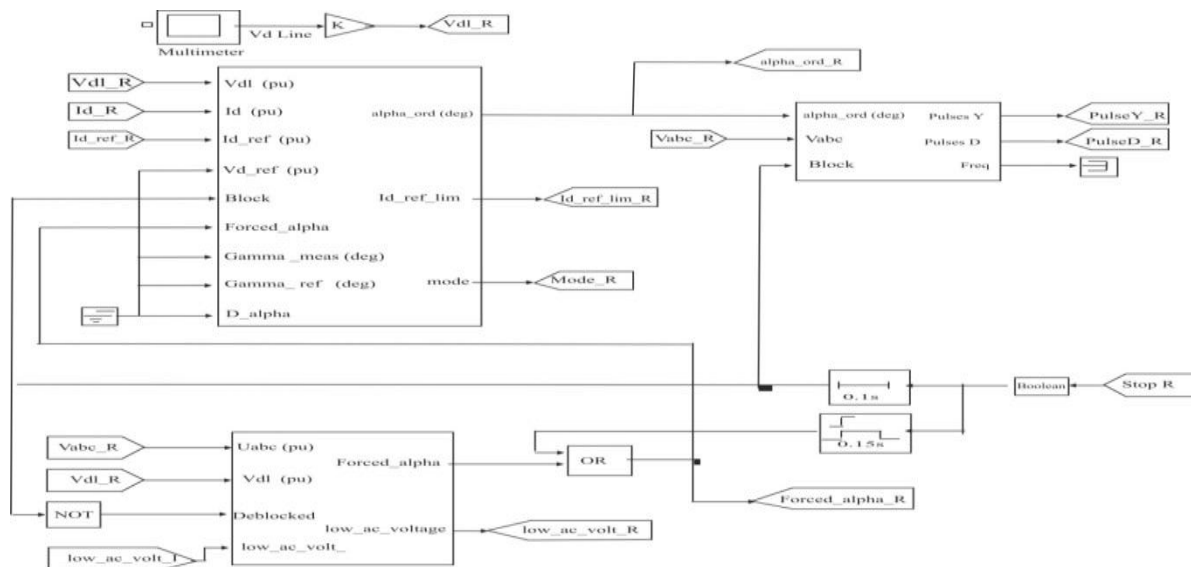


Fig 2.0 Control system used in Simulink mode

Figure 2.0 shows simulation and analysis of HVDC transmission scheme of 12 pulse converters. Disturbances are set in to see the performance of the system. A 500 kV, 2 kA, 50Hz DC system is used for power transmission to a 330 kV, 50 Hz system. The converters are 12-pulse and are interconnected through 450-km line and 0.50H smoothing reactors. It is placed at a fixed position controlled by an amplification factor. The harmonic filters act as a source of filter for AC and a reactive power compensator for DC. The 12 pulse converter system generates harmonics of the order 11th, 13th, 23rd, 25th and so on in the AC side with the configuration:  $n=kp \pm 1$  and  $n=kp$  on the DC side. The filters are put into two

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groups. The first is tuned in to remove lower harmonics, while a different group is tuned to remove the higher harmonics.

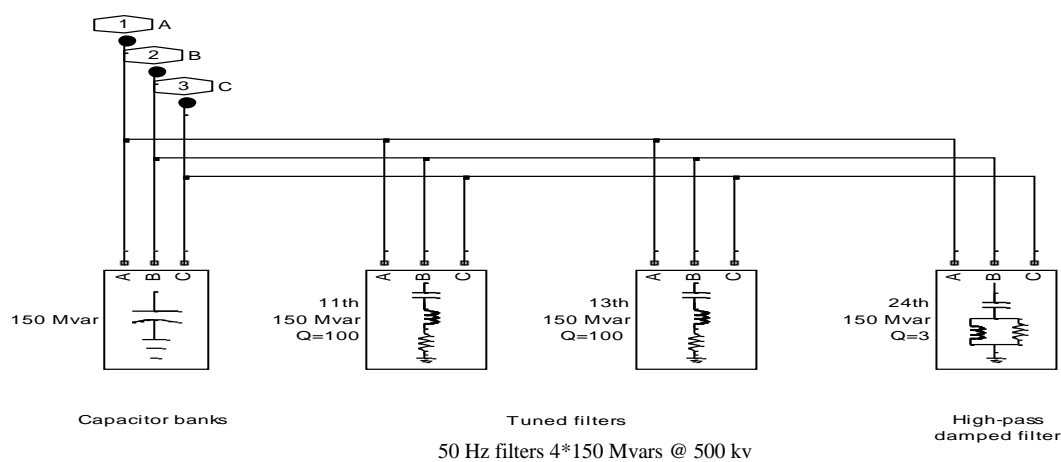


Fig 3.8: Filter used in Simulink model

### 3.3 Simulation

HVDC system is set up to start at a zero (0) impulse until it reaches steady state. Then a pulse signal is programmed initially to the current being referenced and then to the voltage. Observations will then be made to see the response of this system during these perturbations. Finally, the transmission system is brought down and the converters blocked after which stop sequence is initiated to bring the power transmission smoothly down before blocking the converters.

Table 3.1: HVDC parameters for simulation

$V_{pr} = V_{sr}$	500KV	$R_d = 1\Omega$
$V_{pi} = V_{si}$	330KV	$L_d = 0.5H$
$X_{cr} = X_{ci}$	$0.7\Omega$	$I_{dref} = 2KVA$
$F_r = F_i$	50Hz and $t = 0.15$	$K = 0.4$

## IV. EXPERIMENTAL RESULTS AND DISCUSSION

The simulation software was used to carry out several tests and the results was used to check the waveform and variations of voltage and current that will be obtained from variations of generator source voltage. Several tests were carried out. These include steady state and step response.

### 4.2 Steady-State and Step Response

In the Master Control, the converters pulse generators are deblocked and power transmission is started by ramping the reference current at  $t = 20$  ms. The reference reaches the minimum value of 0.1 pu in 0.3s. Observe that the DC current starts to build and the DC line is charged at its nominal voltage. At  $t = 0.4$  s, the reference current is ramped from 0.1 to 1pu (2 kA) in 0.18 s (5 pu/s). The DC current reaches steady state at the end of the starting sequence at approximately 0.58s. The rectifier controls the current and the inverter controls the voltage. Trace 1 of both Rectifier and Inverter scopes shows the DC line voltage (1 pu = 500 kV). At the inverter, the voltage reference is also shown. Trace 2 shows

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the reference current and the measured Id current (1 pu = 2 kA). During the ramp, the inverter is actually controlling the current (Trace 4: Mode = 1) to the value of Id\_ref\_lim less the Current Margin (0.1 pu) and the rectifier tries to control the current at Id\_ref\_lim. At the inverter, the control mode changes from current control to gamma control (Mode = 6) before stabilizing to voltage control (Mode = 2) at t = 0.3 s. The rectifier becomes thereafter in control of the current. However, a control mode change will occur and alpha is limited to the minimum value of 5 degrees (Mode = 3) during an increase of the DC voltage initiated by a voltage reference increase at the inverter. At steady state (measured at t between 1.3 and 1.4 s),  $\alpha$  firing angles are around 16.5 degrees and 143 degrees respectively on the rectifier and inverter side. The inverter control measures the extinction angle  $\gamma$  for each thyristor of the two six-pulse bridges (i.e., the bridge connected to the Wye and Delta windings) by determining the elapsed time expressed in electrical degrees from the end of current conduction to the zero crossing of the commutating voltage. The mean value of the measured gamma for the last 12 extinctions (6 of the Delta converter and 6 of the Wye converter) is shown in traces 5 along with Gamma reference. In steady state, the mean  $\gamma$  is around 22.5 degrees. At t = 0.7s, a -0.2 pu step is applied during 0.1s to the reference current so that the dynamic response of the regulators can be observed. Later on, at t = 1.0s, a 0.1 pu step is applied during 0.2s at the inverter reference voltage. Observe that at the inverter the extinction angle reaches the reference value (e.g., the minimum acceptable value) and that the Gamma regulator takes control at t around 1.1s. At t around 1.3s the voltage regulator retakes control of the voltage. At t = 1.4s, the Stop sequence is initiated by ramping down the current to 0.1pu. At t = 1.6s a Forced-alpha (to 166 deg) at the rectifier extinguishes the current and at the inverter the Forced-alpha (to 92 deg with a limited rate) brings down DC voltage due to the trapped charge in the line capacitance. At t = 1.7s the pulses are blocked in both converters.

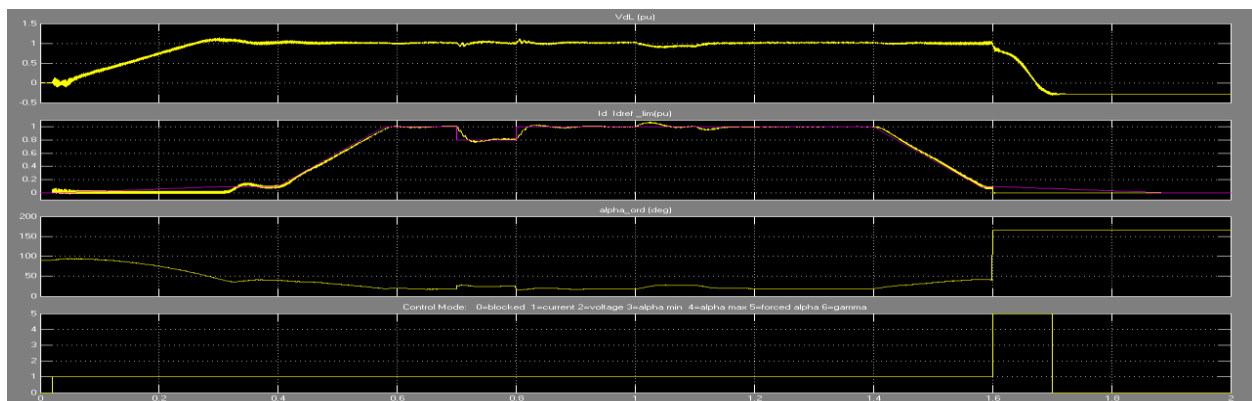


Figure 4.1: Rectifier at Steady State

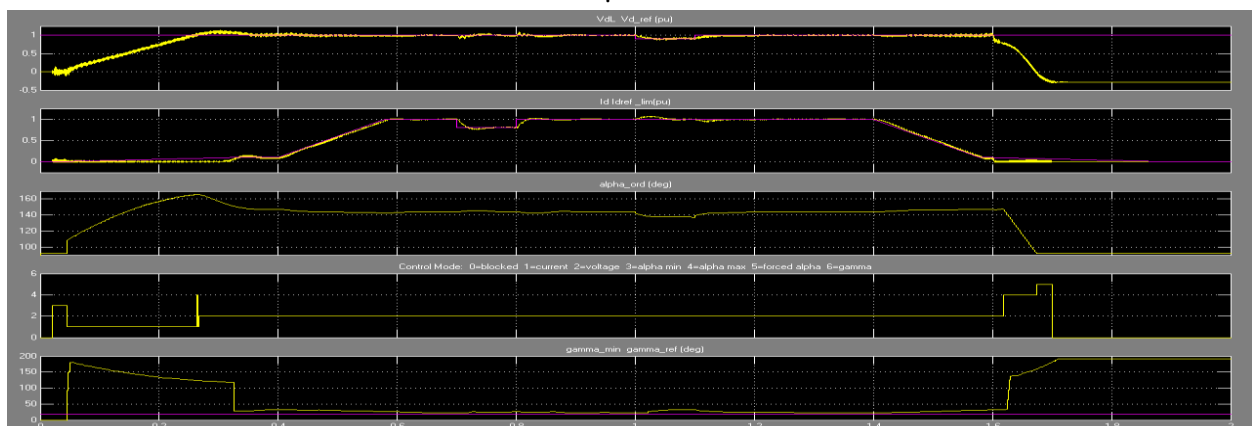


Figure 4.2: Inverter at Steady State.



### 4.3DC Line Faults

Deactivate the steps applied on the current reference and on the voltage reference in the Master Control and in the Inverter Control and Protection respectively by setting the switches in lower position. In the DC Fault block, change the multiplication factor of 100 to 1, so that a fault is now applied at  $t = 0.7s$ . Open the Rectifier scope as well as the Fault scope to observe the fault current and the Protection Rectifier scope to observe the DC Fault protection action. Restart the simulation. The following graphs were obtained.

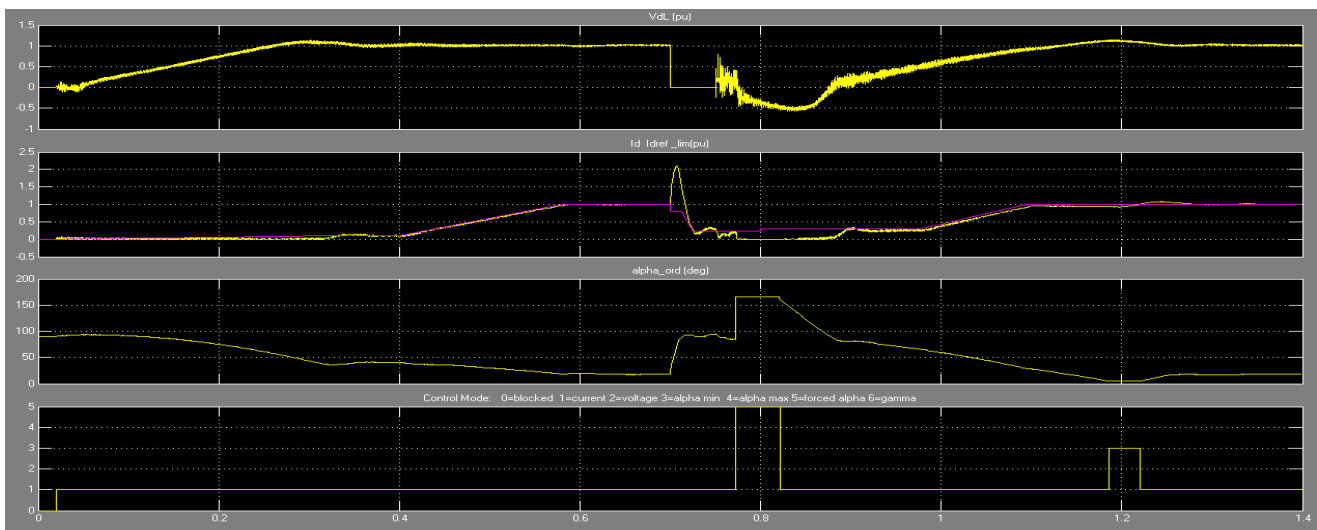


Figure 4.3: Rectifier at DC Line Fault

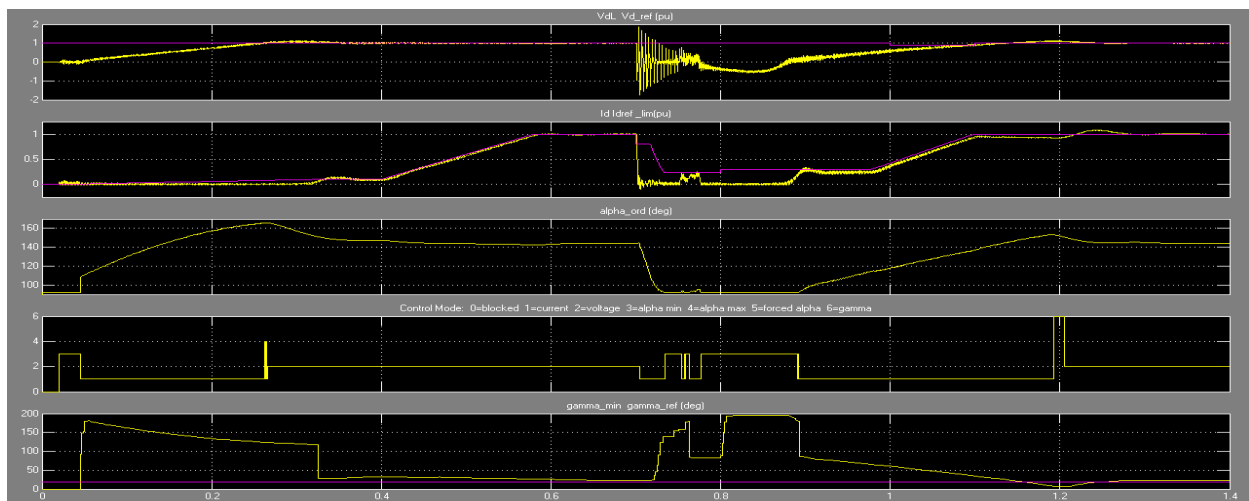


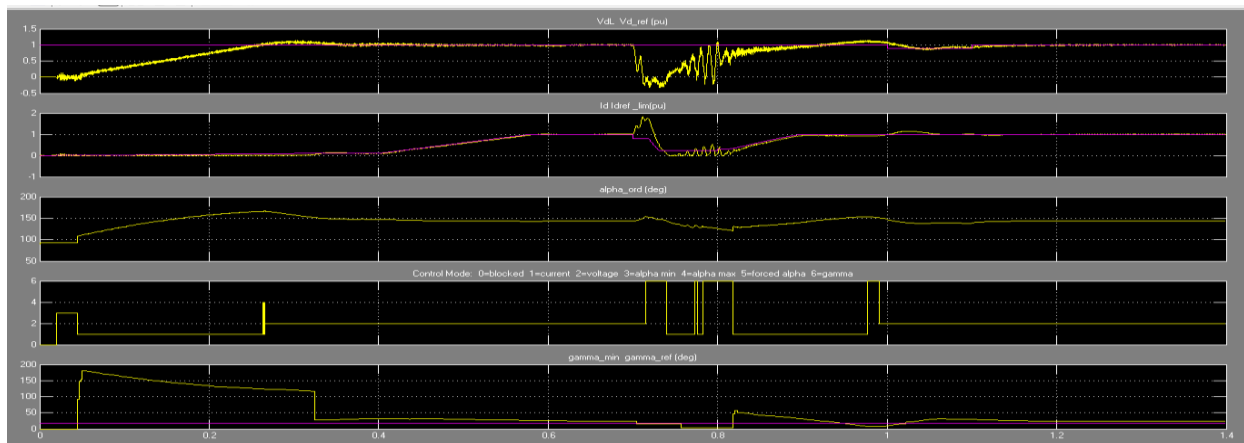
Figure 4.4: Inverter at DC Line Fault.

At fault application ( $t = 0.7 s$ ), the DC current increases to 2.2 pu and the DC voltage falls to zero at the rectifier. This DC voltage drop is seen by the Voltage Dependent Current Order Limiter (VDCOL) and the DC Fault protection. The VDCOL reduces the reference current to 0.3 pu at the rectifier. A DC current still continues to circulate in the fault. Then, at  $t = 0.77 s$ , the rectifier  $\alpha$  firing angle is forced to 166 degrees by the DC Fault protection after detecting a low DC voltage. The rectifier now operates in inverter mode. The DC line voltage becomes negative and the energy stored in the line is returned to the AC system, causing rapid extinction of the fault current at its next zero crossing. Then  $\alpha$  is

released at  $t = 0.82$  s and the normal DC voltage and current recover in approximately 0.5 s. Notice, the temporary mode change in the Rectifier controls between 1.18 s and 1.25 s

#### 4.4 AC Line to Ground Fault at the Inverter

Now modify the fault timings to apply a line-to-ground fault. In the DC Fault block, change the multiplication factor of 1 to 100, so that the DC fault is now eliminated. In the A-G Fault block, change the multiplication factor in the switching times to 1, so that a six-cycle line-to-ground fault is now applied at  $t = 0.7$  s at the inverter. Restart the simulation



Graph 4.5: Inverter at AC Line to Grand Fault

Notice the 120 Hz oscillations in the DC voltage and currents during the fault. An unavoidable commutation failure occurs at the inverter at the very beginning of the fault and the DC current increases to 2 pu. A commutation failure is the result of a failure of the incoming valve to take over the direct current before the commutation voltage reverses its polarity. The symptoms are a zero DC voltage across the affected bridge causing an increase of the DC current at a rate determined mainly by the DC circuit inductance. When the fault is cleared at  $t = 0.8$  s, the VDCOL operates and reduces the reference current to 0.3 pu. The system recovers in approximately 0.35 s after fault clearing.

#### Comparing Results

The main equations for the steady state operation of DC system for 12 pulse converter is given equation 10.0

$$V_d = \frac{3\sqrt{2}}{\pi} V_L \cos \alpha - \frac{3 X_c I_d}{\pi} \quad 10$$

Where  $V_L$  = line to line rms commutating voltage

$X_L$  = commutating reactance

$$V_L = \frac{0.96 \times 20^{\circ}}{0.9} = 213.3KV$$

$$I_d = 2KA$$

$$\alpha = 16.5^{\circ}$$

$$X_C = 0.24pu \text{ base on } 1200MVA = 9.874\Omega$$

Therefore, this theoretical voltage corresponds well with the expected rectifier voltage calculated from the inverter voltage and voltage drop in dc line ( $R = 4.5 \Omega$ ) and in the Rectifier smoothing reactor ( $R = 1\Omega$ ).

$$V_d = V_{dL} + R_{dc \text{ line}} + R_{reactor} ) X I_d$$

$$V_d = 500KV + (4.5 + 1) \times 2 = 511KV$$

By Substituting

$$V_d = \frac{3 \times \sqrt{2}}{\pi} \times 213 \cos(16.5^{\circ}) - \frac{3 \times 9.814 \times 2}{\pi}$$

$$V_d = 515KV$$



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## V. CONCLUSION

It is seen that for so many reasons, dc transmission scheme is more reliable when compared to that of ac scheme. Also many countries in the world today are now operating HVDC transmission. Research has shown that it is possible to operate HVDC in parallel with HVAC. Although extensive research is still going to check the control parameters, improvements have been made to thyristors to achieve a greater reliability. For example, the light triggered thyristors in use today does not need a supply for turning on the device thereby reducing the cost of terminal equipment. Further research is going on extensively on VSC based HVDC system. In this technology, the insulated gate bipolar transistors (IGBTs) are used and can switch off currents, which means that there is no need for an active commutation voltage and reactive power can be controlled independently, there giving no need for reactive power compensation, which will further reduce the cost of implementing the scheme because of the reduction in the size of the filters although most VSC transmission in use today operates with voltages lower than thyristor based HVDC. It is assumed that the short circuit level after the faults is not below the minimum specified for satisfactory converter operation. Both energy availability and transient reliability of existing DC system with thyristor valves is 95% of more. The average failure rate of thyristors in a valve is less than 0.6% per operating year. It is therefore recommendation to provide redundant thyristors in the series string composing a HVDC valve, so that failed thyristors can be replaced during scheduled maintenance (once or twice a year). From the analysis of the simulation results, it is observed that HVDC system when connected to AC system can recover from faults very fast. Results presented demonstrate the controller performance in recovery of HVDC links from various disturbances.

## Acknowledgement

The authors wish to acknowledge and say a big thank you to members of staff of eseogietec engineering company ([www.eseogietec.com](http://www.eseogietec.com)) for all the support academically and financially given towards the completion of this work

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## Appendix A

### Specifications of HVDC system model

AC Terminal equipment:

5000MVA equivalent at Rectifier:

VL = 500 kV

f = 50 Hz

Connection: Y Grounded

Source inductance= 98.03 mH

Parallel RL Branch connected in series with the AC source:

R = 26.07  $\Omega$

L = 48.86 mH

10000MVA equivalent at Inverter:

VL = 330 kV

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$f = 50 \text{ Hz}$

Connection: Y Grounded

Source inductance= 28.0 mH

Parallel RL Branch connected in series with the AC source:

$R = 6.205$

$L = 13.96 \text{ mH}$  .

### BIOGRAPHY



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