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Performance Analysis of a High Voltage DC (HVDC) Transmission System under Steady State and Faulted Conditions

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Abstract

The modern High Voltage Direct Current (HVDC) transmission technology depends on the development of power electronics based on the semiconductor devices. This paper represents a simple model of HVDC transmission system in which the converter and filter have been designed to increase stability of power transmission. The HVDC transmission system has been proposed on the basis of simulation studies using MATLAB software package (Simulink Model). Using this model, current - voltage (C-V) characteristics have been simulated for steady state condition. 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.

Keywords: *high voltage dc transmission (HVDC) system, converter, rectifier, AC and DC Filter, MATLAB simulink*

1. Introduction

High voltage direct current(HVDC)convert AC voltage to DC voltage in a rectifier and transmits DC power through the transmission line, and then inverts DC into AC power in inverter and supplies the power. With the fast development of converters (rectifiers and inverters) at higher voltages and larger currents, DC transmission has become a major factor in the planning of the power transmission.

The HVDC technology finds application in the transmission of power over long distances or by means of under-water cables, which are a critical component of a voltage-source converter–high-voltage direct current transmission system in any offshore electrical power scheme [1] and in the interconnection of differently managed power systems which may be operated synchronously or asynchronously [2]. Alternating current (AC) is the main driving force in the industries and residential areas; however for the long transmission line AC transmission is more expensive than that of DC transmission. In addition, AC transmission line control is more complicated because of the frequency. DC transmission does not have these limitations, which has led to transfer bulk power over long distances [3]. In the beginning all HVDC schemes used mercury arc valves for high power and voltage proved to be a vital break through for High Voltage Direct Current (HVDC) transmission. Then the development of power electronic technology and the relatively high switching frequency of Pulse Width Modulation (PWM), HVDC transmission system based on Voltage Source Converters (VSCs) has taken on some excellent advantages [4-7]. The high-voltage high power fully controlled semiconductor technology continues to have a significant impact on the development of advanced power electronic apparatus used to support optimized operations and efficient management of electrical grids [8] and develop both HVDC transmission and flexible AC transmission (FACT) technologies. There are different types of Simulation software/tools to analyzing the stability of power system; the HVDC system is simulated using PSCAD/EMTDC software [9] to analyze the performance of HVDC system. MATLAB uses a specialized Toolbox Simulink for simulating control systems and has a powerful graphic user interface with a large library of blocks [10]. The HVDC transmission system based on a new inductive filtering current source converter CSC-

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HVDC system improved steady- and transient-state operating characteristics [11]. Furthermore, the study is to investigate the steady state and the dynamic performance of a 12 pulse HVDC (High Voltage Direct Current) using a system in Matlab/Simulink under different fault conditions [12-13]. In addition, a hybrid multilevel voltage source converter (VSC) with ac-side cascaded H-bridge cells offers the operational flexibility of VSC based HVDC system in terms of active and reactive power control and improved ac fault ride-through capability with current limiting capability during dc fault [14].

In this paper a simple model of HVDC transmission system has designed in order to analyze the performances at steady and dynamic state operation under different fault conditions. The HVDC system has been simulated with respect to nominal voltage, frequency and the physical value of different devices and component parameters. By using MATLAB/Simulink to observe the characteristic of voltage and current both in rectifier and inverter side and compare the simulation result at steady state operation under with and without fault conditions. For suitable arrangement, the rest of the paper is organized as: Section 2 represents the HVDC transmission model and discusses the parameters of HVDC Simulink model. In section 2, the simulation results of the HVDC transmission model are explained and confirm that the control strategy has fast response and strong stability. Finally, Section 4 concludes the paper.

2. HVDC Transmission Model

2.1. Feature of HVDC Transmission model

The thyrister based HVDC transmission technology has the following features:

(a) The capabilities of power transmission of an ac link and a dc link are different, for the same insulation and same conductor size: $V_{dc} = \sqrt{2}V_{ac}$; if skin effect is not considered, $I_{dc} = I_{ac}$. Then the amount of power transmission in both link as follows:

$$P_{dc}=V_{dc}\times I_{dc} \text{ and } P_{ac}=V_{ac}\times I_{ac}\cos\Phi. \quad (1)$$

The ratio of powers: $P_{dc}/P_{ac} = (V_{dc.}\times I_{dc})/(V_{ac}\times I_{ac}\cos\varphi) = \sqrt{2}\ /\ \cos\varphi$. (2)

Hence we get $P_{dc}=1.414\times P_{ac}$ at Unity power factor and $P_{dc}=1.768\times P_{ac}$ at 0.8 power factor.

(b) For transmitting a specific quantity of power at a specific insulation level required less conductor cross-section. Let the same transmitted power P, same losses P_L and same peak voltage V_m and R_{dc} and R_{ac} are the corresponding values of conductor resistance for dc and ac respectively, neglecting skin resistance.

Therefore, for dc power: $I_{dc}=P/V_m$, and,

power loss: $P_L=(P/V_m)^2 R_{dc} = (P/V_m)^2 \times(\rho l/A_{dc})$. (3)

For ac power: $I_{ac}= P/(Vm/\sqrt{2}) \cos\varphi = \sqrt{2} P/ V_m \cos\varphi$, and (4)

power loss: $P_L=[\sqrt{2}P/(V_m \cos\varphi)]^2 R_{ac}=2 (P/V_m)^2\times(\rho l/A_{ac}\cos^2\varphi)$. (5)

Since power losses are same, therefore:

$$(P/V_m)^2 \times(\rho l/A_{dc})= 2 (P/V_m)^2\times(\rho l/A_{ac}\cos^2\varphi). \quad (6)$$

This gives the result for the ratio of cross-section area as:

$$A_{dc}/A_{ac} = \cos^2\varphi /2. \quad (7)$$

Hence we get $A_{dc}= 0.5\times A_{ac}$ for unity power factor and $A_{dc}=0.32\times A_{ac}$ for 0.8 power factor. The result has been calculated at unity power factor and at 0.8 legging to illustrate the effect of power factor on the ratio.

(c) The HVDC links can be used to interconnect asynchronous AC systems that can be operated with different nominal frequencies (50 and 60Hz) respectively and the short-circuit current level for each AC system interconnected will not increase.

(d) When an ac transmission system is extended, the fault level of the whole system goes up, sometimes necessitating the expensive replacement of circuit breakers with those of higher fault levels. This problem can overcome with HVDC as it does not contribute current to the ac short circuit beyond its rated current.

The HVDC system has modeled using the Simulink package is based on a point-to-point DC transmission system. The DC system is a bipolar, 12 pulse converter using two universal thyristor bridge connected in series. DC interconnection has used to transmit power from a 275kV, *50Hz* network to *250kV*, *50Hz* network. Distance between the receiving end and the sending end of AC systems are considered *110km* DC transmission line in this system.

2.2. Simulation Model of HVDC Transmission System

The most relevant components that comprise a HVDC system are the AC System, the converter station, converter transformer, smoothing reactor, AC and DC filter and control system.

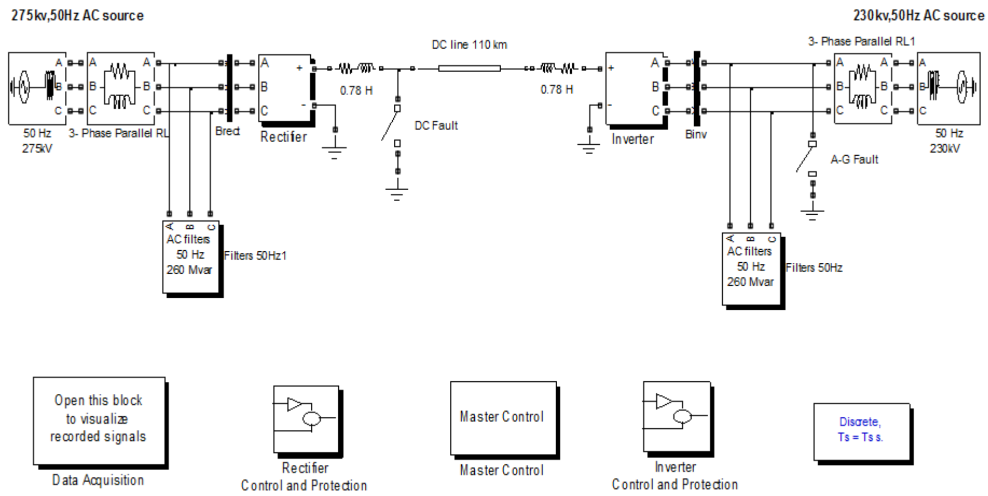


Figure 1. Simulink Diagram of HVDC Circuit

2.2.1. AC System

The AC networks, both at the rectifier and inverter end are represented as infinite sources separated from their respective commutating buses by system impedance. The impedances are represented as simple parallel R-L branch. The components value of AC system is at rectifier side *275kV*, *50Hz* at inverter side *250kV*, *50Hz* and $R = 0\Omega$, $L = 98mH$.

2.2.2. Converter Station

A converter station consists of basic converter unit, which primarily contains converter valve, converter transformer, smoothing reactor, AC filter, and DC filter. The thyristor or IGBT valves make the conversion from AC to DC and thus are the main component of any HVDC. Basic converter units can be classified into 6-pulse and 12-pulse converter units. Usually most HVDC schemes employ the 12-pulse converter as the basic converter unit. In order to form a 12-pulse converter unit, two 6-pulse converter units are connected in series on the DC side and in parallel on the AC side.

2.2.3. Converter Transformer

The *1200MVA* converter transformer Y_g, Y/Δ is modeled with three $1\text{-}\Phi$ phase *3*-winding transformer. The parameters adopted (based on AC rated conditions) are considered as typical for transformers found in HVDC installation such as leakage: $X = j0.24$pu.

2.2.4. DC Side of the System

The DC side of the converter system consists of a smoothing reactor of 0.78H for the rectifier and the inverter bridges. The DC line is modeled in distributed parameter line model with lumped losses. Smoothing reactor can prevent step impulse waves caused by DC lines or DC switching yard entering the valve hall, thereby avoiding the damage to the converter valve due to overvoltage stress.

2.2.5. AC Filters and Capacitor Banks

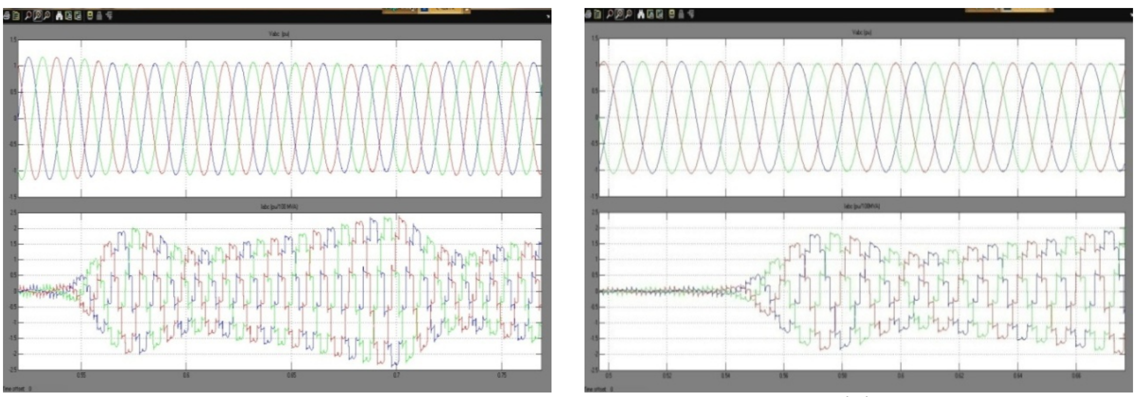
On AC side of 12-pulse HVDC converter, current harmonics of the order of 11, 13, 24 and higher are generated. Filters are installed in order to limit the amount of harmonics to the level required by the network. In the conversation process the converter consumes reactive power to meet this reactive power demands using capacitor banks of *260MVAR*, *275kV*, *50Hz* on each side for reactive power compensation.

2.2.6. Control System

The HVDC transmission systems must transport very large amounts of electric power that can only be accomplished under tightly controlled conditions. DC current and voltage is precisely controlled to affect the desired power transfer. In a two-terminal (point-to-point) HVDC transmission system, the capacity and direction of power flow can be controlled rapidly, so as to satisfy the operational demands for the entire AC/DC hybrid systems. Therefore, it is necessary to continuously and precisely measure system quantities that include at each Converter Bridge, the DC current, DC side voltage and delay angle, and for an inverter, its extinction angle.

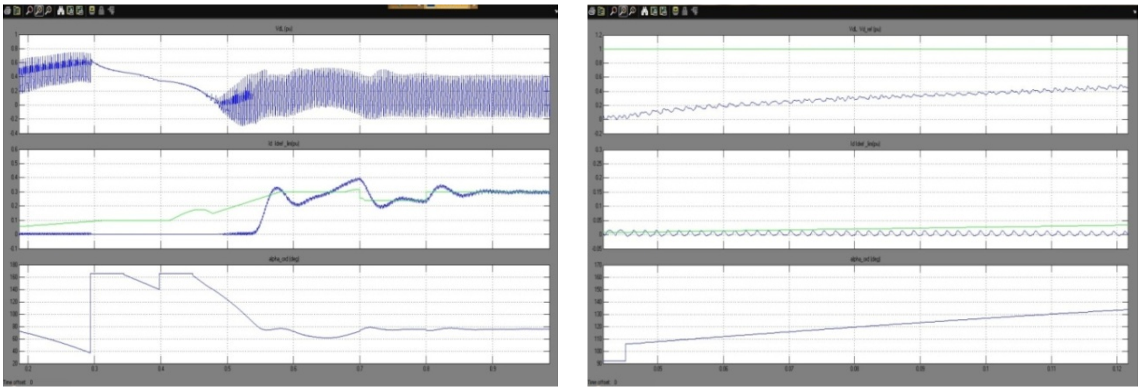
3. Simulation Result and Analysis

The Figure 2 represents the simulation results of voltage and current under without fault at rectifier and inverter sides. It is seen that at the rectifier side, at time $t = 0.55$ sec, the peak value of the current is lower ($I_{abc}= 0.5$pu) and increasing trend, whereas the three phase voltage V_{abc} is around *1.17*pu, under without fault condition. After elapse time, the value of I_{abc} gradually increases with slight fluctuation. The results at the inverter side are almost similar to the rectifier with a little delay at output current. At steady state operation, under without DC fault, it can be noted that at the rectifier (Figure 3(a)), firing angle α is maximum at time, $t = 0.29$ sec, the current I_d remains constant and voltage $V_{dc}= 0.6$pu (approx.). However, from $t = 0.45$sec, firing angle start to decrease, whereas current I_d is slowly growing up. On the other hand, at the inverter side (Figure 3(b)), current and voltage characteristics are more steady than the rectifier side.



(a) (b)

Figure 2. Voltage (V_{abc}) and Current (I_{abc}) Characteristics under without Fault Condition at (a) rectifier side and (b) inverter side.

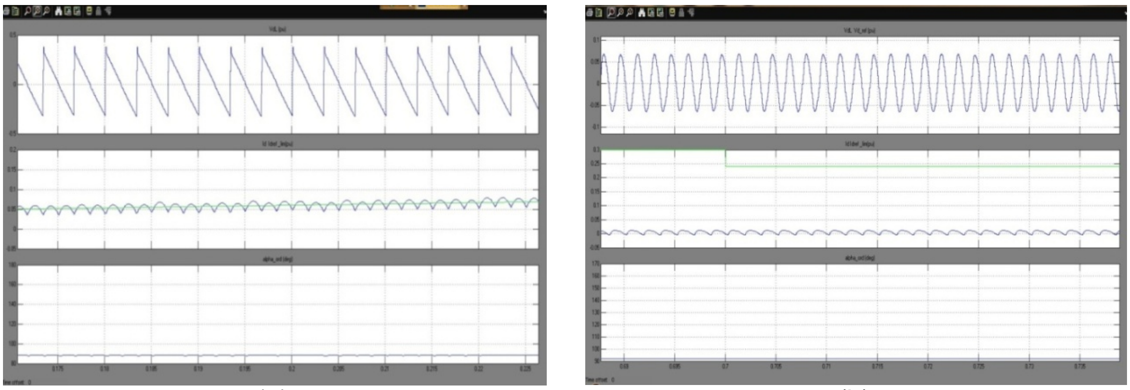


(a) (b)

Figure 3. Voltage (V_{abc}) and Current (I_{abc}) Characteristics at Steady State Operation under without Fault at (a) rectifier side and (b) inverter side.

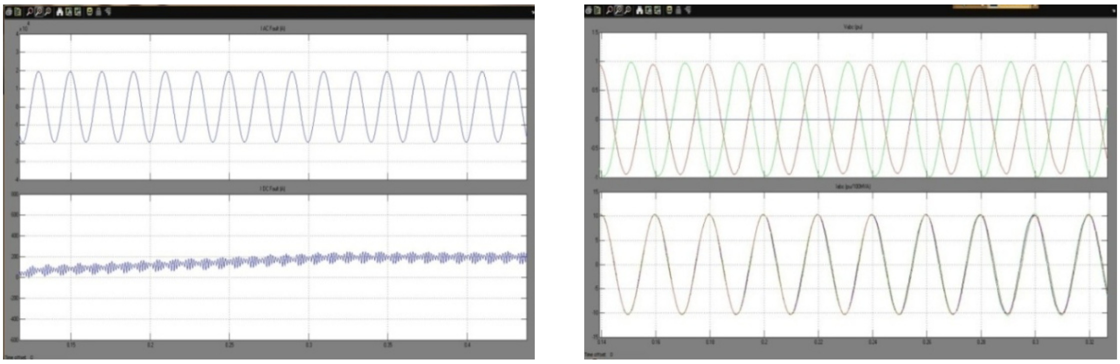
Under fault condition, at steady state operation (Figure 4(a) & 4(b)), voltages are rectangular and sinusoidal shapes at sending end (rectifier side) and receiving end (inverter side) respectively.

However, current at both sides are pulsating, slightly lower value at receiving end. Whereas firing angle is almost constant for the both cases. On the other hand, fault current is very high (around $I_{ac}= 2\times10^4 A$ and $I_{dc} = 200A$ at $t = 0.3 sec$) for dc and ac faults shown in Figure 5(a) with modulated dc current wave. At the inverter side, for single line to ground fault, voltage for phase A has become zero and currents for other two phases are in phase as shown in Figure 5(b). However, fault at phase A has no interference on the voltages and currents of the remaining phases. Furthermore, current and voltage for double line to ground fault (Figure 6(a)) are similar to the expected forms, voltages for fault phases are zero and current is slightly higher than the healthy phase. In contrary, in the case of line to line fault, voltage has become doubled for the two shorted phases and current rises to a certain spike and then recovers gradually.



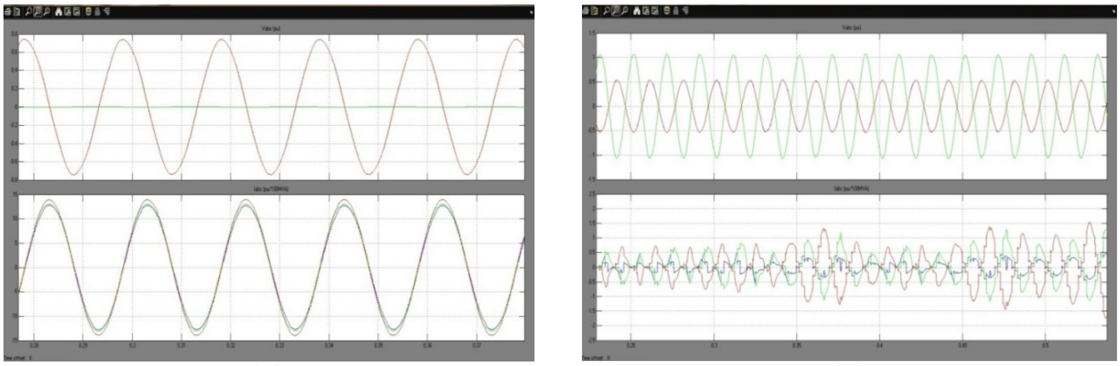
(a) (b)

Figure 4. Voltage (V_{abc}) and Current (I_{abc}) Characteristics at Steady State Operation under DC Fault Conditions at (a) rectifier side and (b) inverter side



(a) (b)

Figure 5 (a) Current (I_{abc}) characteristics: line to ground fault at inverter side (ac) and DC fault at rectifier side, and (b) voltage (V_{abc}) and current (I_{abc}) for single line to ground fault at inverter side



(a) (b)

Figure 6. Voltage (V_{abc}) and Current (I_{abc}) Characteristics at Inverter Side under (a) double line to ground fault and (b) line to line fault

4. Conclusion

This paper shows a simple approach of HVDC model by considering power electronic devices for control the overall system in order to improve power transfer as well as to achieve reliability in the power transfer. Software based studies of transient disturbances have been carried out using the Simulink in MATLAB. Current - voltage (*C-V*) characteristics have also been simulated for steady state condition and also for different fault conditions at both the rectifier and inverter sides. It has found that current and voltage strongly depend on the types of fault. The HVDC system has been used to transmit power from a *275kV*, 50 Hz network to *250kV*, 50 Hz network. The receiving end and sending end AC systems are separated by *110km* DC transmission line. The analytical results obtained in this proposed model can be a useful tool in system design and optimization.

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