SIMULATION AND FAULT ANALYSIS OF HIGH VOLTAGE DIRECT CURRENT TRANSMISSION LINE USING MATLAB

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Abstract— In this paper, first we have discussed the basic structure and principle of High Voltage Direct Current Power Transmission System and types of faults occur on it. We used MATLAB Simulink to simulate the transient processes of this system when the short circuit line to ground (LG) fault occur on HVDC Transmission line. We observed effect of using Solid and Resistive Grounding on fault current. It will be proven by simulation result that the model and the simulating method is valid, visual and time saving.

IndexTerms—HVDC Transmission System, MATLAB Simulation

1. INTRODUCTION

1.1 INTRODUCTION TO HVDC TRANSMISSION SYSTEM

HVDC stands for High Voltage Direct Current. HVDC transmission line is a well proven technology used to transmit electricity over long distances by overhead transmission lines or submarine cables. It is also used to interconnect separate power systems, where traditional or conventional alternating current (AC) connections cannot be used.

With an HVDC system, the power flow can be controlled rapidly and accurately in terms of both power level and direction. This possibility is regularly used to improve the performance and efficiency of the connected AC networks. Applications of electricity started with the use of direct current. The first Central Electric Station was installed by Edison in New York in 1882 supplying power at 110V DC. The invention of transformer and induction motor and the concept of three-phase AC around 1890 initiated or started the use of AC. The advantages of three-phase AC almost eliminated the use of DC system except for some special applications in electrolytic processes and adjustable speed motor drives.

Today DC transmission has staged a comeback in the form of HVDC transmission to supplement or increase the HVDC transmission system. HVDC transmission systems are economically more attractive than HVAC transmission systems tend to be unstable as the distance increase due to presence of line reactance. HVDC systems do not have line reactance problems due to absence of frequency.

The first commercially used HVDC transmission link (power rating was 20MW and transmission voltage 100kV) in world was built in 1954 between the Mainland of Sweden and the island of Gotland. This was a monopolar, 100KV, 20MW cable system making use of sea return. Since then the technique of power transmission by HVDC has been continuously developing. DC transmission is an effective or use full a means to improve system performance. It is mainly used to balance or compliment AC systems rather than to displace these.

In India, the first HVDC 810km long distance overhead (OH) LINE IS Rihand-Delhi (±500 kV, 1500 MW) for bulk/large power transmission from Rihand /Simgrauli to Delhi .The highest transmission voltage reached is ±600 KV. At present the world has over 60 HVDC schemes in operation for a total capacity of more than 66,000 MW and the growth of Dc transmission capacity has reached an average of 2,500 MW/year. HVDC is also used to interconnected system of different frequency (e.g. between north and south island in Japan, which have 50Hz and 60 Hz, respectively)

1.2 INTRODUCTION TO MATLAB SIMULATION:

- MATLAB is the easiest and most productive software environment for engineers and scientists.
- MATLAB Simulation plays an important role in power system studies, planning, design, and operations.
- Typical uses include: Data analysis, exploration, and visualization.

2. PRINCIPLE OF OPERATION

2.1 PRINCIPLE OF OPERATION OF HVDC SYSTEM:

HVDC system basically consists of two converter stations one at each end, connected by a dc transmission line. One converter is operated in rectifier mode so as to convert Ac into DC, known as inverter. At both ends of systems ac supply is available. The main equipments in a converter station are transformers and thyristors valves. Chokes and filters are provided at each end to ensure smooth direct current dc into ac which is utilized at the receiving end.

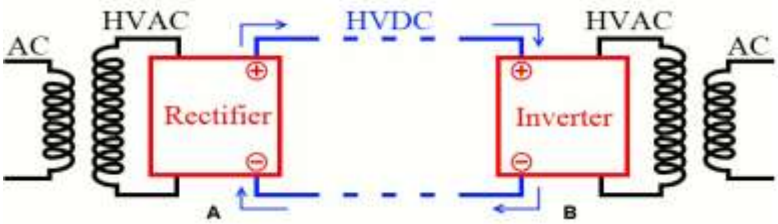


Fig.2.1 Basic Structure of HVDC Transmission System

Figure 2.1 shows single line diagram of a HVDC transmission system where A and B are the two converter stations. Converter station B is supplied from the converter station at sending end A. The voltage is stepped up to suitable value by the thyristors values. Thus at the start transmission line, we have high voltage direct current. This rectified current flows along the transmission line to receiving current-end converting station B, where it is converted into three phase ac current by thyristor valve and then stepped down by the step-down transformer to low voltage for further distribution.

The converter at the sending end acts as a rectifier while the converter at the receiving end acts as an inverter. By varying the firing angle of the thyristor valves in the converter the dc output voltage magnitude is controlled.

In rectifier the firing angle is between 0°<α<90° and in inverter the firing angle between 90°<α<180°. AS The dc output voltage is a function cosine of firing angle in converter. Hence, the converter voltage becomes negative when the firing angle α<90°. This makes the converter to operate as an inverter [5].

Practically, HVDC converter station is a three-phase bridge converters employed at the both end (sending as well as receiving end). Reversible operation of converters as well as bidirectional power flow HVDC link is possible simply by the control of firing angle. By varying α operates in rectifier and inversion mode.

2.2 Components of HVDC Transmission System:

A. Converter

The HVDC system we have simulated is based on Six pulse Converter:

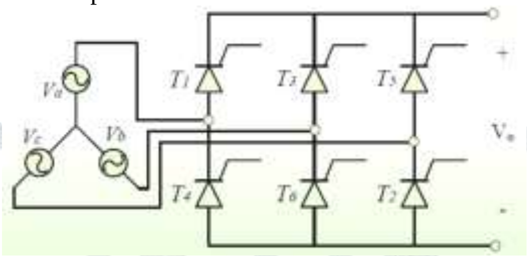


Fig. 2.2 Internal structure of Six pulse HVDC converter

The operating principle of the circuit is that, the pair of SCR connected between the lines having highest amount of line-to-line voltage will conduct provided that the gate signal is applied to SCRs at that instant.

Between 0≤ t ≤ π/3 the highest line-to-line voltage is Vcb, with T4 & T5 initially conducting. By firing T6 at delay angle of α, results Vcb at load. The converters are called Line Commutated converters or current source converter.

At every 60º one Thyristor from +ve limb and one Thyristor from –ve limb is triggered

B. Smoothing reactors

- They are high reactors with inductance as high as 1 H in series with each pole. They decrease harmonics in voltages and currents in DC lines
- They prevent commutation failures in inverters
- Prevent current from being discontinuous for light loads

C. Harmonic filters

- Converters generate harmonics in voltages and currents. These harmonics may cause overheating of capacitors and nearby generators and interference with telecommunication systems.
- Harmonic filters are used to mitigate these harmonics.

D. Reactive power supplies

- Under steady state condition, the reactive power consumed by the converter is about 50% of the active power transferred.
- Under transient conditions it could be much higher.
- Reactive power is, therefore, provided near the converter.
- For a strong AC power system, this reactive power is provided by a shunt Capacitor.

E. Electrodes

- Electrodes are conductors that provide connection to the earth for neutral. They have large surface to minimize current densities and surface voltage gradients.

F. DC lines

- They may be overhead lines or cables.
- DC lines are very similar to AC lines.

G. AC circuit breakers

- They used to clear faults in the transformer and for taking the DC link out of service.
- They are not used for clearing DC faults.
- DC faults are cleared by converter control more rapidly.

2.3 HVDC LINE FAULTs

Faults on DC transmission line are generally caused by external mechanical stress, lightning strikes and pollution. In HVDC transmission system, Line to Ground fault and Line to Line fault are common types of faults. These faults are permanent and for which a lengthy repair is needed. After detecting the cable faults in DC transmission line, the converter should be stopped immediately. These faults are likely to be temporary which required fault restoration after the fault clearance. There are number of faults occurred on HVDC transmission system, but in this paper we have only discussed Line to Ground (LG) fault which is mainly occurred in six pulse HVDC system [2]

DC Line to Ground Fault

The DC Line to Ground fault is caused by insulation failure between DC conductor and ground. In overhead HVDC transmission system, the DC Line to Ground fault is temporary which is caused by lightning strikes and pollution. For underground HVDC transmission system, the DC line to ground fault is the most frequent fault. The equivalent circuit of DC Line to ground fault as shown in figure 6. This fault will produce ground point besides the mid-point of DC-link capacitor and the neutral-ground link of transformer [4].

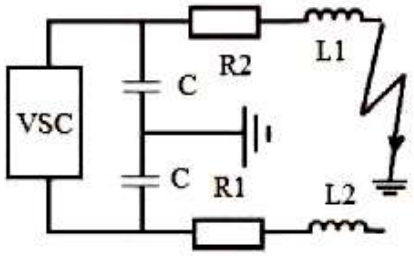


Fig.2.3 An equivalent circuit of DC Line to Ground Fault

This fault can be divided to three stages are as follows:

a) DC Side Capacitor Discharge Stage

When a DC Line to Ground faults occurs, a discharge circuit is formed among the fault pole capacitor and fault impedance through the fault line. After the fault occurs, the system experiences the DC side capacitor discharge stage [3].

b) Grid-Side Current Feeding Stage

When DC Line to Ground faults occurs; the DC side capacitor discharging due to this the DC voltage drops constantly. When the DC voltage drops to below any grid phase voltage, then the system will experience the grid side current feeding stage [3].

c) Voltage Recovery Stage

The fault pole capacitor voltage drops and non-fault pole capacitor voltage rising with the capacitor discharging. The DC voltage gradually restores, so the system enters the voltage recovery stage [3].

3. METHODOLOGY

.1 Simulation Diagram

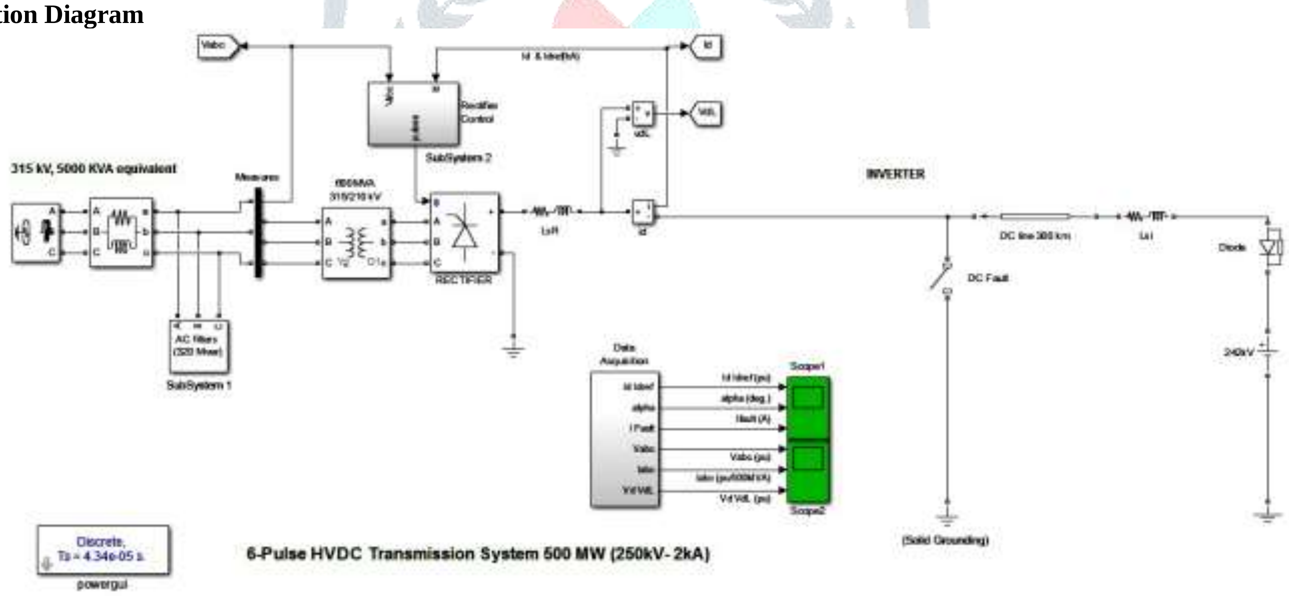


Fig. 3.1 Simulation diagram

3.2 DESCRIPTION OF EACH BLOCK IN SIMULATION DIAGRAM:

1. The Three-Phase Source block

The Three-Phase Source block implements a balanced three-phase voltage source with an internal R-L impedance. The three voltage sources are connected in Y with a neutral connection that can be internally grounded or made accessible. You can specify the source internal resistance and inductance either directly by entering R and L values or indirectly by specifying the source inductive short-circuit level and X/R ratio.

2. Three-Phase Parallel RLC Branch block

The Three-Phase Parallel RLC Branch block implements three balanced branches consisting each of a resistor, an inductor, a capacitor, or a parallel combination of these.

3. Subsystem-1 AC Filters

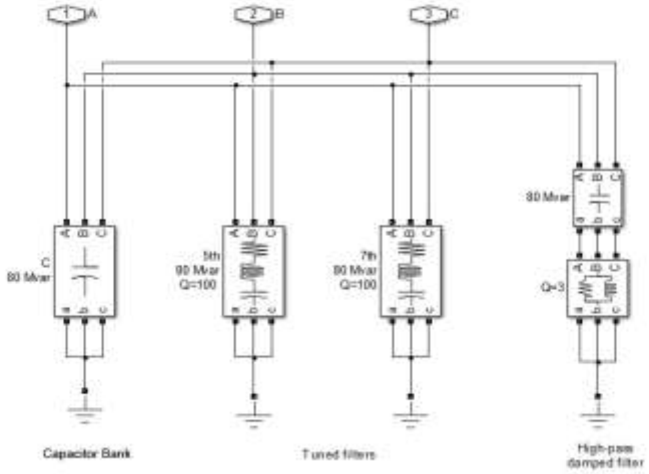


Fig. 3.2.1 AC Filters internal Structure

The AC filter consists of Capacitor Bank, Tuned filter and High Pass Filter each performing their own function as explained bellow:

Capacitor Bank

A Capacitor Bank is a group of several capacitors of the same rating that are connected in series or parallel with each other to store electrical energy. The resulting bank is then used to counteract or correct a power factor lag or phase shift in an alternating current (AC) power supply

Tuned Filter

The ac/dc filters are always needed in HVDC converter stations to suppress harmonic currents/voltages. HVDC converter stations usually require ac/dc filters, the main purpose of which is to mitigate current/voltage distortion in the connected networks. In addition, the ac side filters significantly compensate the network demanded reactive power.

High Pass filter

A high - pass filter (HPF) is an electronic filter that passes signals with a frequency higher than a certain cutoff frequency and attenuates signals with frequencies lower than the cutoff frequency. The amount of attenuation for each frequency depends on the filter design. Resulting bank is then used to counteract or correct a power factor lag or phase shift in an alternating current (AC) power supply

4. Measurement mask link

The block can output the voltages and currents in per unit values or in volts and amperes.

5. Three Phase Transformer Two windings

This block implements a three-phase transformer by using three single-phase transformers.

The two windings of the transformer can be connected in any way as follows:

Y, Y with accessible neutral, Grounded Y, Delta (D1), delta lagging Y by 30 degree, Delta (D11) or delta leading Y by 30 degrees.

6. Rectifier block (Universal Bridge)

The Universal Bridge block implements a universal three-phase power converter that consists of up to six power switches connected in a bridge configuration. (Working Principle of 6 pulse thyristor is explained in HVDC components details)

7. Series RLC Branch block (Smoothening Reactor)

The Series RLC Branch block implements a single resistor, inductor, or capacitor, or a series combination of these.

8. Current Measurement block

The Current Measurement block is used to measure the instantaneous current flowing in any electrical block or connection line. The Simulink output provides a Simulink signal that can be used by other Simulink blocks.

9. Voltage Measurement block

The Voltage Measurement block measures the instantaneous voltage between two electric nodes. The output provides a Simulink signal that can be used by other Simulink blocks.

10. SubSystem-2 Model of Control Strategy

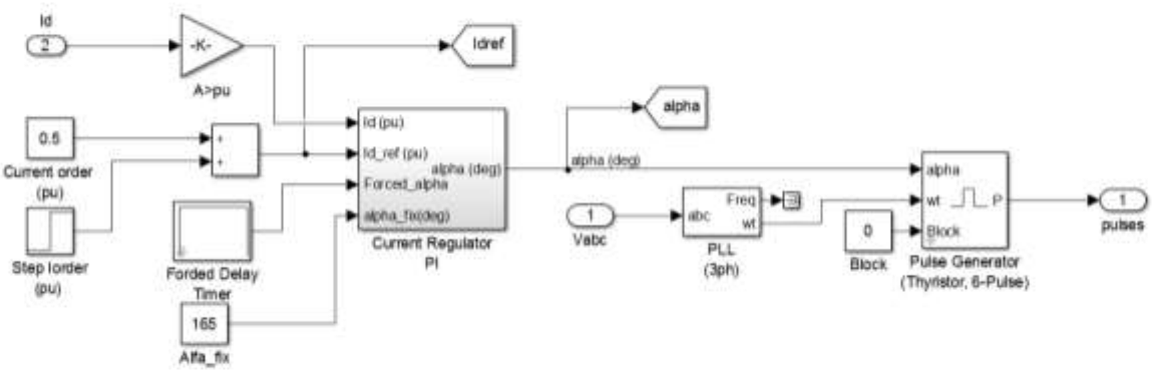


Fig.3.2.2 Model of Converter Station Control Strategy

We use the constant DC Current control mode, which is to control α, trigger pulse from the pulse generator. With the Model of Control Strategy We simulate the transient Process when DC Circuit of the rectifier side is grounded [1].

11. DC LINE 300 KM

The Distributed Parameter Line block implements an N-phase distributed parameter line model with lumped losses. The model is based on the Bergeron's traveling wave method used by the Electromagnetic Transient Program (EMTP) [1]. In this model, the lossless distributed LC line is characterized by two values (for a single-phase line): the surge impedance *Zc*=G*l*/*c* and the wave propagation speed *v*=1/G*lc*. *l* and *c* are the per-unit length inductance and capacitance.

12. Data Acquisition Block

This block is used to link various input signals to the Scope to see graphical outputs.

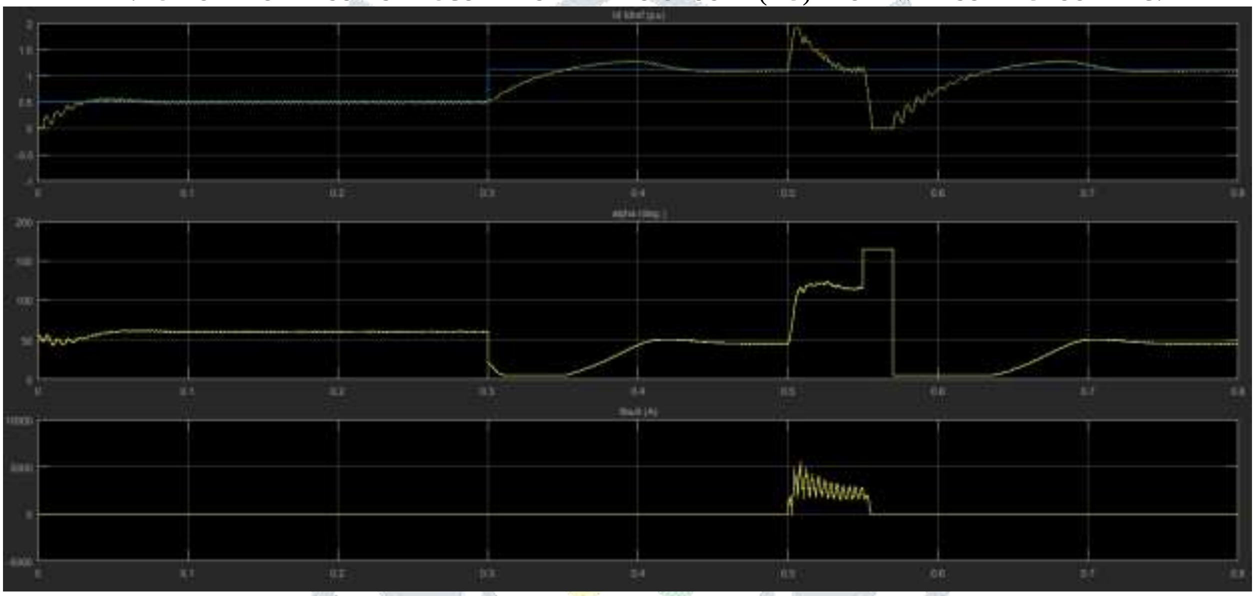
3.3 Simulation

The system is discretized (sample time 1/360/64 = 43.4 us). Setting, the sample time in to zero, will change to continuous integration for the power system. The system is programmed to start and reach a steady state. Then, a step is applied on the reference current to observe the dynamic response of the regulator. Finally a DC fault is applied on the line.

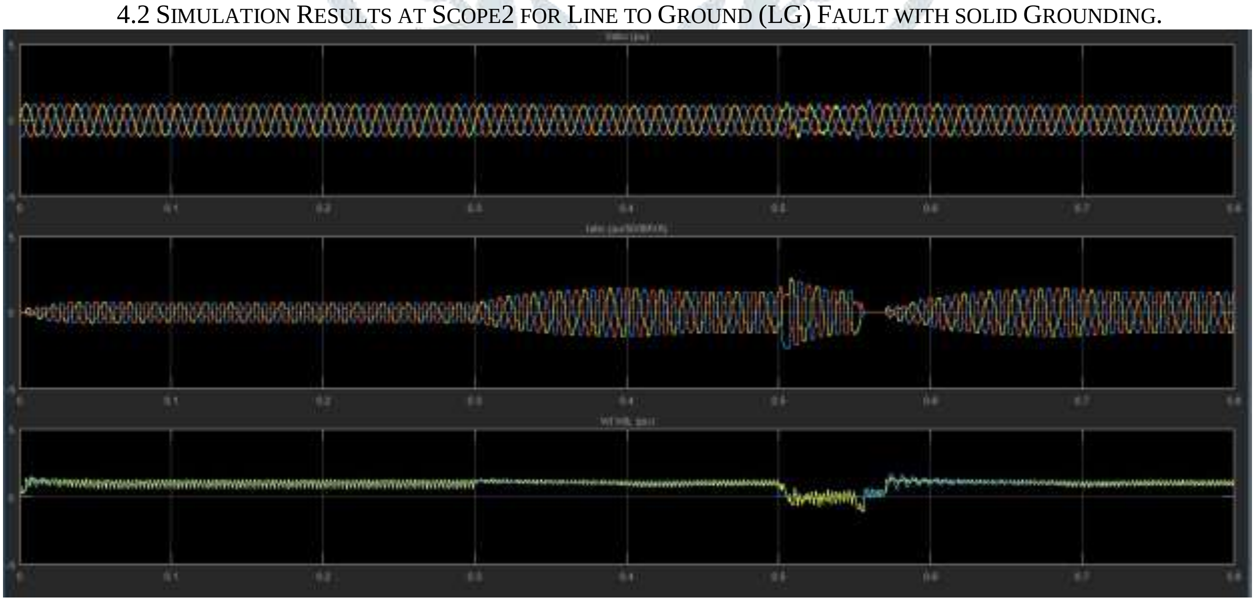
4 SIMULATION RESULTS

- Results are taken for two different grounding conditions that is solid and resistive grounding. And effects of each condition are discussed in Analysis section.
- At Scope1: Trace1 Shows the reference current (magenta) and the measured Id current (yellow), Trace2 Shows the firing angle alpha (in degree) at converter station, Trace3 Shows the Fault current Ifault (in Amperes)
- At Scope2: Trace1 Shows the AC side Voltage Vabc (pu), Trace2 Shows AC Source side current Iabc (pu), Trace3 shows DC line current Vd (pu).

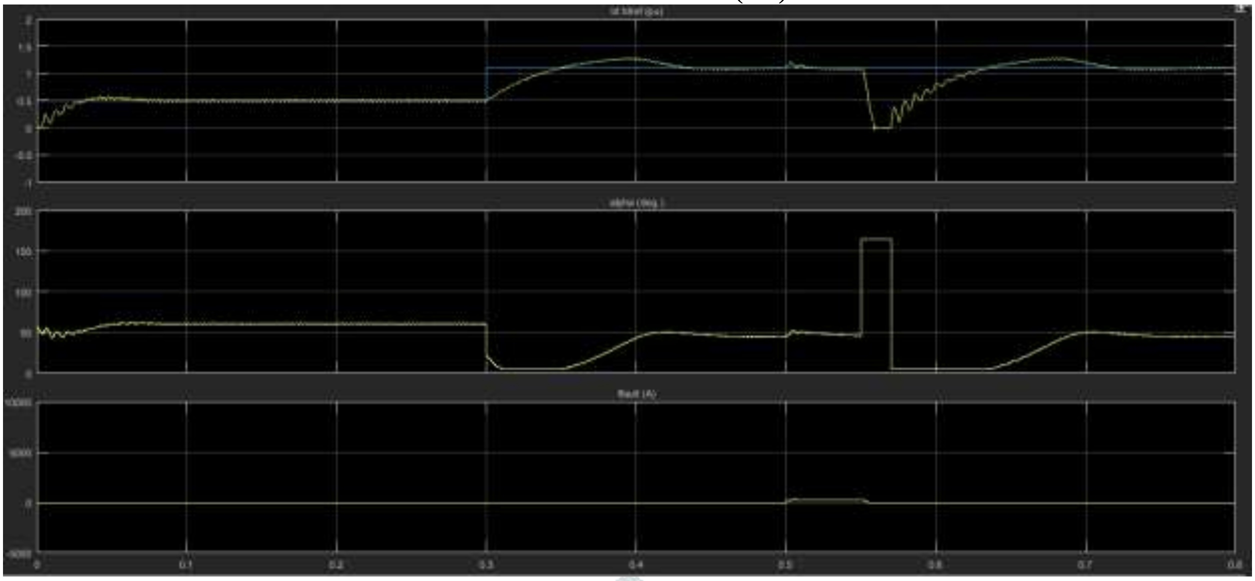
4.1 SIMULATION RESULTS AT SCOPE1 FOR LINE TO GROUND (LG) FAULT WITH SOLID GROUNDING.



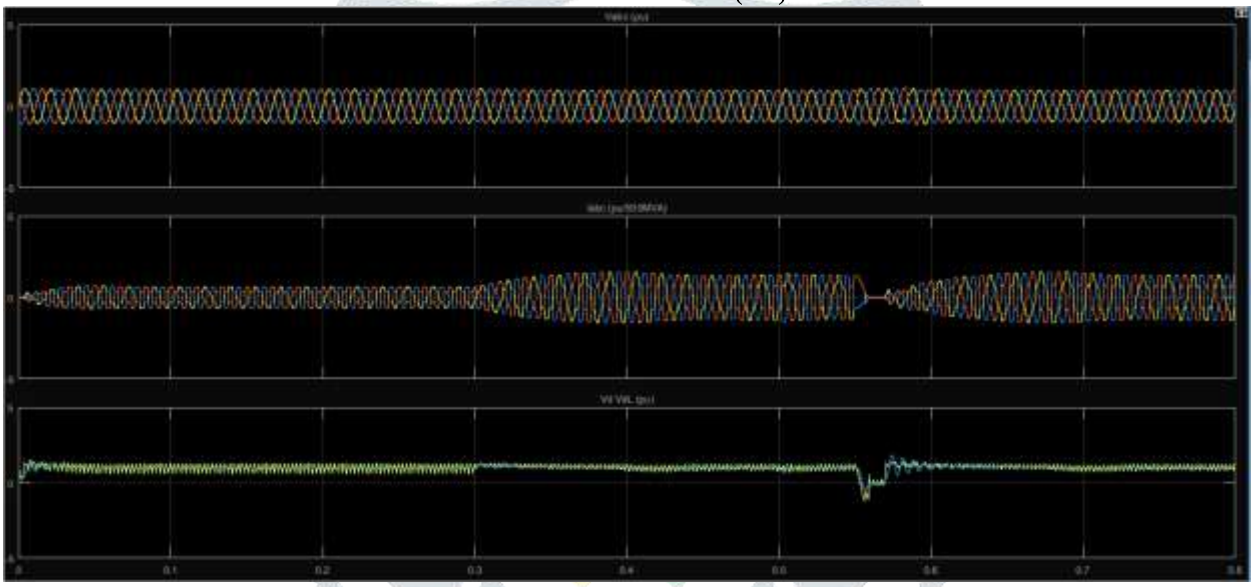
4.2 SIMULATION RESULTS AT SCOPE2 FOR LINE TO GROUND (LG) FAULT WITH SOLID GROUNDING.



4.3 SIMULATION RESULTS AT SCOPE1 FOR LINE TO GROUND (LG) FAULT WITH RESISTIVE GROUNDING.



4.4 SIMULATION RESULTS AT SCOPE2 FOR LINE TO GROUND (LG) FAULT WITH RESISTIVE GROUNDING.



5 ANALYSIS

Sr. No.	Time Point	Observation (For Solid Grounding Condition)
1	0 < t < 0.3 s	Trace 1 shows the reference current (magenta) and the measured Id current (yellow). The reference current is set to 0.5 pu (1 kA). The DC current starts from zero and reaches a steady-state in 0.1 s. Trace 2 shows the alpha firing angle required to obtain 0.5 pu of current (30 degrees).
2	0.3 < t < 0.5 s	At t = 0.3 s, the reference current is increased from 0.5 pu (1 kA) to the nominal current 1pu (2 kA). The current regulator responds in approximately 0.1 s (6 cycles). The alpha angle decreases from 30 degrees to 15 degrees.
3	0.5 < t < 0.55 s	At t = 0.5 s, a DC fault is applied on the line. The fault current (trace 3) increases to 5 kA and the Id current increases to 2 pu (4 kA) in 10 ms. Then, the fast regulator action lowers the current back to its reference value of 1 pu.
4	0.55 < t <0.57 s	At t = 0.55 s, the alpha angle is forced by the protection system (not simulated) to reach 165 degrees when the Forced alpha input of the current regulator goes high (1). The rectifier thus passes in inverter mode and sends the energy stored in the line back to the 345 kV network. As a result, the arc current producing the fault rapidly decreases. The fault is cleared at t = 0.555 s when the fault current zero crossing is reached.
5	0.57 < t < 0.8 s	At t = 0.57 s, the regulator is released and it starts to regulate the DC current again. The steady-state 1 pu current is reached at t = 0.75 s.

Sr. No.	Time Point	Observation (For Resistive Grounding Condition)
1	0 < t < 0.3 s	Trace 1 shows the reference current (magenta) and the measured Id current (yellow). The reference current is set to 0.5 pu (1 kA). The DC current starts from zero and reaches a steady-state in 0.1 s. Trace 2 shows the alpha firing angle required to obtain 0.5 pu of current (30 degrees).
2	0.3 < t < 0.5 s	At t = 0.3 s, the reference current is increased from 0.5 pu (1 kA) to the nominal current 1pu (2 kA). The current regulator responds in approximately 0.1 s (6 cycles). The alpha angle decreases from 30 degrees to 15 degrees.
3	0.5 < t < 0.55 s	At t = 0.5 s, a DC fault is applied on the line. The fault current (trace 3) increases to 5 kA and the Id current increases to 2 pu (4 kA) in 10 ms. Then, the fast regulator action lowers the current back to its reference value of 1 pu.
4	0.55 < t <0.57 s	Here we used Resistive Type of Grounding (Grounding Resistance = 1KΩ) to limit the fault current So we can see that fault current does not rising. At t = 0.55 s, protection system 165 degrees when the Forced alpha input of the current regulator goes high (1). The rectifier thus passes in inverter mode and sends the energy stored in the line back to the 345 kV network. As a result, the arc current producing the fault rapidly decreases. The fault is cleared at t = 0.555 s when the fault current zero crossing is reached.
5	0.57 < t < 0.8 s	At t = 0.57 s, the regulator is released and it starts to regulate the DC current again. The steady-state 1 pu current is reached at t = 0.75 s.

6 ADVANTAGES

MATLAB Simulation has following advantages against classical physical model:

1. Simulink results are Valid, Visual and Time saving.
2. Greater flexibility, parameters can be changed anytime to desired value.
3. MATLAB performs all mathematical operations at higher speed, so it makes a design to be produced at very short time.
4. High accurate and reliable results are obtained because it also helps to reduce the probability of error.
5. Easy documentation.

7 LIMITATIONS

1. Operations are performed by considering ideal values of parameters, but in case of practical situation or physical modeling, results may vary.
2. Cost of MATLAB Software is high.

8 CONCLUSION

Nowadays HVDC Transmission grid has becoming an important part of Power Transmission Network. So the temporary steady-state simulation of HVDC System for power System Studies, Planning and operation plays an important role. In this paper 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 LG fault condition for Solid and Resistive Grounding Condition. It has been observed that Resistive Grounding can be effective to limit the fault current. The analytical results obtained in this proposed model can be useful tool in system design and optimization

9 FUTURE SCOPE

In future works, the system will be tested with DC faults at the multi terminal network, and various possible fault criteria would be analyzed. This would lead the way to determine the quantitative requirements for the protection logic in the HVDC system.

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