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High Voltage Direct Current (HVDC) Transmission and Protection System

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***Abstract*—** Traditionally bulk electricity is transmitted across vast distances through an alternating current (AC) transmission technology. However, transmission through an AC network has a number of disadvantages, including line losses and a poor power factor. To reduce transmission losses and compensate for power factor in the AC network, a frequent system upgrade is required, which comes at a considerable cost. High voltage direct current (HVDC) network for the transfer of bulk power across great distances could be an alternative. HVDC power transmission not only lowers overall costs but also improves system security during outages. The goal of this study is to simulate the hybrid bipolar HVDC transmission network, as well as its protection system, and examine the system under various fault scenarios. The protective mechanism developed in this study could operate the system in an unsecured way by isolating the problematic network part during operation. This research makes use of the MATLAB/SIMULINK as a simulation framework. First of all, the bipolar HVDC system was replicated. The rating voltage is in 500 kilo volts (KV) ranges. The use of bipolar HVDC transmission was that it works even if one line is not working properly. The short circuit fault on one and both of the lines in the system was analyzed. The system demonstrates fast response toward protection from fault by cutting transmission on that line**.**

***Keywords*—** DC circuit breaker, HVDC, Hybrid transmission system, Line commutated converters (LCC) HVDC system,Voltage source converters (VSC) HVDC system.

I. Introduction

The electrical power system is employed to generate, transfer, and distribute cost-effective, stable and dependable electrical energy to consumers. Large-scale power plants generate electricity, which is subsequently transmitted over transmission lines and distributed to dispersed networks. In today's fast moving world, humans rely on a reliable and continuous supply of electricity to maintain a comfortable lifestyle and a higher standard of living. Electricity's utilization demonstrates its significance in society's progress. Electricity has become the most important asset in human society, with applications ranging from home to industrial and commercial. Because of its importance, we require a power system that is dependable, consistent, and cost-effective. To be more effective, the power system must be a viable power system that efficiently and cost-effectively transmits electrical energy from generating stations to load centers.

Initially, electricity was created using direct current (DC), but with the advent of transformers and induction motors around the turn of the century, alternating current (AC) gained the upper hand and became a more popular source of electrical energy transmission and distribution. Another important issue was that in the case of AC, the magnitude of the voltage could be increased or decreased with the use of transformers. As the population grows, so does the demand for electrical energy. Keeping demand and cost in mind, power stations are generally situated near energy sources such as natural gas, water, and coal etc. these stations are very distant from the consumers. As the distance grows, so does the transmission cost. High voltage alternating current (HVAC) and high voltage direct current (HVDC) are the two systems employed to carry high voltage from powerhouses to end-users. Both systems have high voltage ranges, and the distance and expense of the transmission infrastructure decides which system is employed for transmission. Figure 1 depicts the many options for electrical power transmission systems.

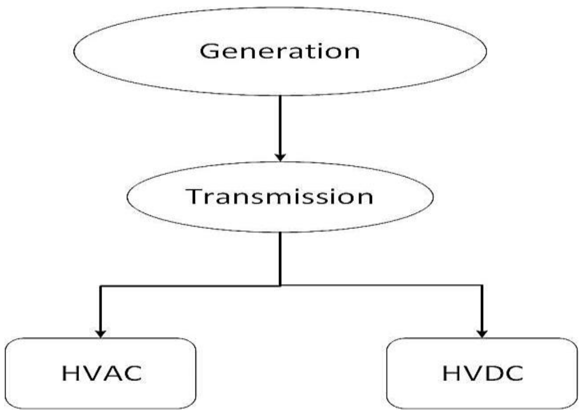

Figure 1. possible choices for electrical power transmission

HVAC and HVDC, both systems have advantages and disadvantages, as most of the appliances on consumer side are AC that is why alternating current (AC) is preferred. Moreover the magnitude can be increased or decreased with the help of transformers with respect to the consumer demand. The drawback of HVAC is the losses it causes, such as corona losses, induction losses, skin effect, and radiation losses. As a result, more power is wasted in the HVAC transmission system, which dissipates as heat, causing line temperatures to rise and, in turn, heating the lines, prohibiting from using the AC lines to their thermal limits and reducing the amount of voltage required to be transferred. As a result of these losses, the AC infrastructure becomes bulky and costly. This bulky model increases the capacitance and inductance in transmission line and thus accounts for reactive power compensation. On the other hand, if the transmission is done through HVDC there is no skin effect and the conductor capacity is fully utilized. Corona losses are reduced because of absence of frequency and due to the uniform magnetic field in the DC there is no radiation, and induction losses, and the current remains uniform in the line, reducing the number of conductors required to carry the same amount of current as compared to HVAC, and as the number of conductors decreases, so does the size of the required transmission tower, in turn reducing the land and overall cost of the HVDC transmission system.HVDC is also utilized to connect offshore wind power installations to existing AC networks and to transport power between asynchronous networks. Since of the foregoing advantages of HVDC over HVAC, it is a good choice for transmission because it allows for greater control over power flow due to the presence of semiconductor devices.

There is a great work available on the side of protection detection and avoidance in HVAC, but toward HVDC there is only one research paper available. In the research [1], the author uses monopole HVDC system and only works toward detection of fault.This research looks at different types of HVDC transmission line configurations as well as HVDC converter control systems. In the research the propose solution was for hybrid bipolar HVDC transmission and protection system. SIMULINK/MATLAB was used to replicate the system for simulation, with various short circuit faults (with single and dual DC transmission lines). The purpose was to create a protective method. To fulfil the purpose the system was tested for 5000MVA for 500KV line voltage.

The paper follows a standard research article format where the need of the research and there need was introduced in section I. Section II, consist of the brief about different systems, protection in those systems, and unexplored HVDC protection system. Section III, is all about the modeling of hybrid bipolar HVDC transmission system which has HVAC generators on both ends. While the results in different cases i.e., normal, and fault are studied in section IV. The paper is concluded in section V.

II. LITERATURE REVIEW

The importance of electricity in human life is demonstrated by its utilization. The HVAC system transmits the majority of the electricity, but it has several drawbacks, including line losses due to long-distance transmission and lagging power factor. Various procedures and equipment are necessary to compensate for these line losses and low power factor difficulties, increasing the overall cost of the HVAC transmission system. When transmission is done with HVDC, however, line losses are much reduced, and there is no concept of power factor in HVDC so in this section different types of HVDC links, DC circuit breaker design, converter types, and control methods are addressed in this section. Monopolar, bipolar, and back-to-back transmission topologies are the three types of HVDC transmission topologies. Details on their construction and application could be found in [2-4]. The converters are the most important components of the HVDC system. The invention and modification of various converters, such as diode multilevel converters, are discussed. This converter is made up of many diodes grouped in a three-level converter, capacitors, and a single DC source, and its construction and operation are described in [5]. In capacitor converters, a different topology is employed to clamp capacitors between switches for voltage sharing. As the number of converter layers increases, the weight, cost, and complexity of the converter. The converter is described and illustrated in [6]. Cascaded H-Bridge converter consists of cells to control an array of converters connected in series, which require a unique DC source for each one, which complicates things the details are given in [7]. Two more advanced topologies for HVDC transmission are voltage source converters and line commutated converters. Detailed information could be found in [8-10]. The technique used for control of LCC is based on controllers, these controller used for protecting valves during AC grid faults are employed through the voltage-dependent current limit (VDCOL) and several other controllers on inverter side are discussed in [11]. Q-Compensation and inductive filters are the other two control mechanisms for LCC topologies listed in [12-14]. Point-to-point LCC-based HVDC systems are studied in [15-17] in terms of current control margin technique and coordinated current control margin, which includes droop characteristics for the control mechanism. Extended current margin control and multistage current margin control are given for parallel linked LCC-based LCCs. Please see [18] for more information. As a result of its simplicity and ability to control both active and reactive power, voltage controllers are commonly employed to regulate voltage source converters. According to [19, 20], the advanced vector current controller, which is built on the d-q method and uses a vector current controller, has a stronger capacity to interact with weak AC grids. As mentioned in [21-24], the voltage droop control approach includes two control loops: an inner and an outer control loop that both regulate DC voltage, as well as choose droop factors using Steady State analysis. Power synchronization using phase-locked loop criteria and an ABC frame controller method is discussed in [25-28]. The use of PI compensators in different control loops to strengthen dynamic behavior and system performance for voltage source converters are given in [29-31].In grid terminals and wind farms, the adaptive back-stepping controller has been used to increase the performance of the existing DC voltage and reduce the overshoot impact the detail is given in [32-34].In VSC converter topology, a stable voltage could be achieved by using the flexible power control approach while also being able to independently adjust the power supply, as described in detail in [35, 36]. A hybrid DCCB has been modeled which consists of an IGBT, residual mechanical switch, and fast mechanical disconnector for grid protection. It is tested in a variety of ways, including opening the circuit breaker during fault current, shutting it down with an insufficiently powerful circuit breaker, and closing it again with current-limiting control explained in [37,38].Another hybrid DCCB using fast thyristors has been designed. The main benefit of this circuit breaker is that its running time is lowered to 2.3ms, and when the load current is interrupted (no fault), the circuit breaker's opening time is extended, as shown in [39]. A new interlink hybrid DC circuit breaker that can be used for unidirectional and bidirectional interruption has been developed. The main circuit breaker is connected in a star network for bidirectional interruption and two low less branches for unidirectional interruption for both lines and DC bus fault current interruption, and the same results are obtained from interlink hybrid circuit breaker as obtained from hybrid circuit breaker but with reduced size and lower cost explanation given in [40]. The zero crossing is generated through the main circuit breaker of two hybrid DC circuit breakers based on couple inductor using LC resonance circuit the main benefits achieved from this topology is that there is no need of surge arrestors and de-magnetization of surge arrestors.

Detail is given in [41]. Pre-charged capacitors are employed to suppress the fault current when turning off the faulty line in a hybrid HVDC circuit breaker. Instead of IGBTs, the developed device makes use of thyristors to reduce power loss and circuit breaker failure explain in [42].In solid state circuit breakers IGBTS and diodes are used and instead of using capacitors which stores energy MOV are used for energy is dissipation, the main benefit of this circuit breaker is that it can operates in less than 3 µsec when senses the fault the detail is given in [43].A hybrid DC circuit breaker is created for DC grid based on VSC, which is used on both sides of the DC lines, using PEM (power electronic module). The circuit breaker follows a step by step sequential auto reclosing approach outlined in [44]. Zhangbei project developed a prototype DC breaker and 500kv VSC valve for symmetrical bipolar DC transmission system that uses a half-bridge multi-level converter topology to meet the project's demands, and the circuit breaker should be configured on both sides of the DC line to clear the potential for DC faults explained in [45-50].

In the preceding discussion, many studies are conducted on HVDC links, converter topologies, and control characteristics, and DC circuit breakers are constructed in various ways for protection, as well as work on monopolar transmission systems and fault detection, as described in [1]. However, in this paper, the proposed solution is to model a hybrid bipolar HVDC transmission system, and in the same paper, short circuit faults are generated on single and both DC lines, and then an instantaneous over current relay is designed for these faults to isolate the faulty part of the system from the rest of the system. The main advantage of a bipolar transmission system is that if one of the lines fails, power is continuously supplied to the other.

III. METHODOLOGY

A. *STRUCTURE AND BASIC PRINCIPLE OF NEW HYBRID HVDC TRANSMISSION MODE.*

Figure 2 depicts the hybrid HVDC transmission system basic model. There are AC sources on both the transmitting and receiving ends, and the transmission is solely DC, therefore in the suggested model, there is a combination of both AC and DC, this is why it is called a hybrid system, along with this other components which the proposed model include are converter transformers, AC filters, and two three-phase bridge converters are employed. The two bridges are connected in series to give a total of twelve pulse converters. These twelve pulses are thyristors based and are known as line-commutated converters (LCC). The three-phase source power is supplied to the converter transformer, which connects the AC and DC sides. The transformer is followed by a rectifier station that converts the AC supply to DC, and then a 300-kilometer DC transmission line for DC transmission. Due to the hybrid nature of the system, an inverter station follows the DC transmission line, converting the DC supply to AC, a converter transformer and another three-phase generating source. AC filters are used on both ends of the transmission system to filter out harmonics. Firstly the system is operated to check the continuity of the system and after a normal operation fault is generated on one of the DC lines and both lines at different times for which a relay is designed and activated when the fault occurs. The algorithm flow chart is shown in figure 2a.

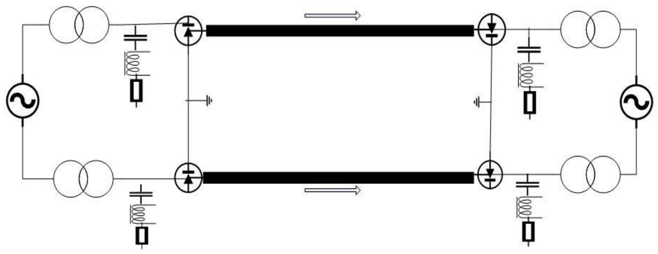

Figure 2. Basic model of hybrid bipolar HVDC system

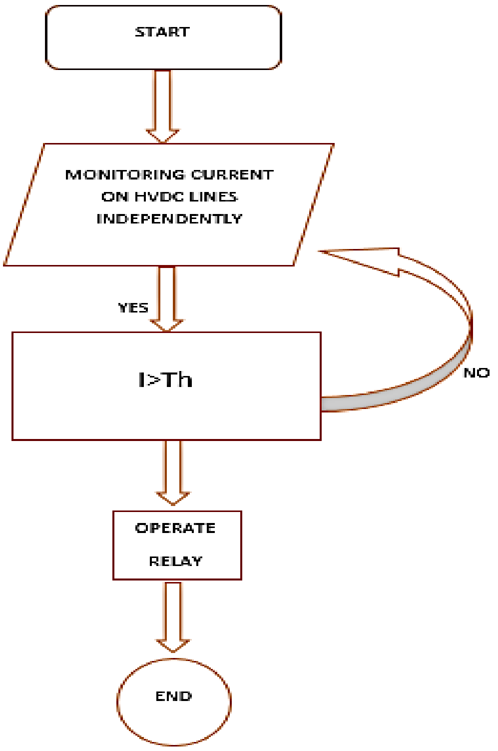

Figure.2a. Algorithm flow chart for relay operation

The three-phase source delivers 500x103V at 50Hz. Source inductance and resistance are also part of the source. The source inductance and resistance are calculated using the short circuit capacity formula in equation 1.

$$Z_{SSC} = \frac{V^2}{S_{SC}} \quad (1)$$

Source inductance would be obtained from

$$0.998xZ \quad (2)$$

Source resistance would be obtained from

$$R = \sqrt{Z^2 + X^2} \quad (3)$$

Because the hybrid system uses thyristors based twelve pulse converters, 300 phase shift is necessary to run these converters, which is provided by the converter transformer and is given by equation 4.

$$\text{Phase shift} = \frac{2\pi}{\text{pulse number}} \quad (4)$$

B. PROPOSED SCHEME FOR REQUIRED SYSTEM

In this part, the HVDC system's proposed scheme is discussed. For simulation and theoretical research, the hybrid bipolar HVDC model is chosen and then built in MATLAB/ Simulink. After the model has been created, it is tested to examine how it operates in the presence of faults, and for this purpose, all possible faults are generated in the model. The designed model for MATLAB simulations is shown in Figure 3. Despite the fact that there are various HVDC transmission systems, only the bipolar model is examined in depth in this research.

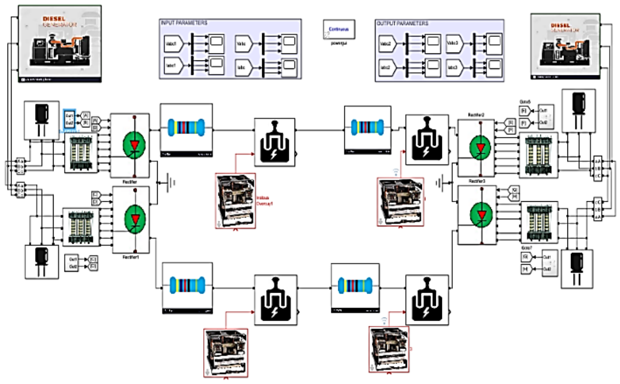

Figure.3. MATLAB model for HVDC system

IV. RESULTS & DISCUSSION

Figure 2 depicts the proposed plan for the bipolar HVDC system, which was created in MATLAB/Simulink. Figure 3 depicts the blocks that were employed in the modelling of this scheme. At the sending point, an AC power generation unit generates AC power, which is subsequently converted to DC power for long-distance of 300 km transmission. For domestic users, DC electricity is inverted into AC power at the receiving end. Table 1 lists the parameters for the bipolar HVDC model that was chosen.

TABLE I
PARAMETERS DESCRIPTION FOR THE PROPOSED SYSTEM

Sr. No	Parameters	Sending End	Receiving End
1	Power Capacity	5000 MVA	10000 MVA
2	Line Voltage	500kV	500kV
3	Frequency	50 Hz	50 Hz

At the sending and receiving ends, AC systems are installed, but the transmission between them is entirely DC. In this system, there are also rectifiers and inverters installed for this reason. The suggested system's usual operation is depicted in Figure 3. Figure 4 and figure 5 shows that all AC voltage and current signals are running smoothly and without errors. Figure 6 depicts the voltages of both DC lines.

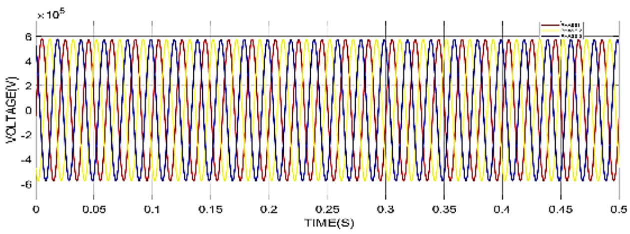

Figure 4. AC Voltage

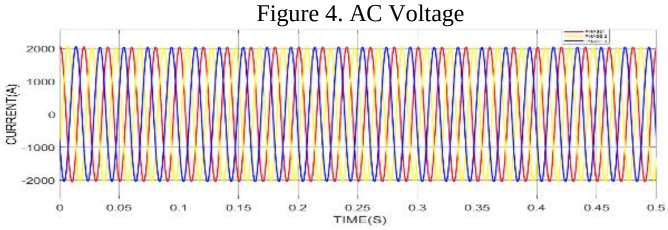

Figure.5. Figure 5. AC currents

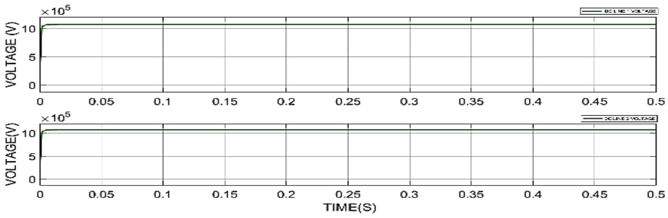

Figure 6. DC voltages

A. *Fault on DC transmission line*

I. *Case study 1*

At t=0.1s after the HVDC system has been operating normally, a short circuit fault on the positive DC line is generated, and the impact on the system is examined using scopes in the Simulink model. Figure 4,7 depicts a DC line fault, with the amount of current flowing during the fault abruptly increasing to 3000A at t=0.1s, as seen in Figure 7.

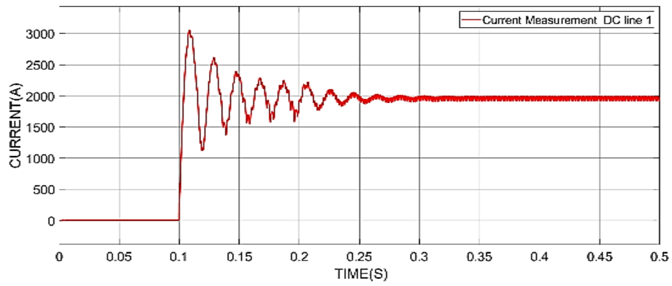

Figure 7. Faulty DC line current

Because a relay is utilized in this hybrid HVDC model and is activated when a fault occurs, figure 8 depicts DC current when the relay is activated and initiation of the relay when the fault occurs, resulting in the system returning to a stable and normal functioning condition at t=0.15s.

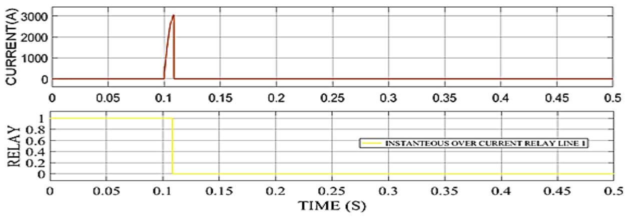

Figure 8. DC current when relay operated and relay initiation when fault occurs

II. *Case study 2*

As there is possibility of fault to be occur on both lines at different times, so the fault is now generated at t=0.1s on the positive line and t=0.3s on the negative line, to monitored the impact on the system with these type of short circuit faults

with the impact on the system being monitored. Figure 9 depicts the fault on both the positive and negative lines, with the current jumping to 3000A in both the positive and negative directions in 0.1s and 0.3s, respectively. Figure 10 depicts the relay operation and the behaviors of both DC lines when the relay is turned on. Figure 11 depicts the behavior of both DC lines when the relay is turned on.

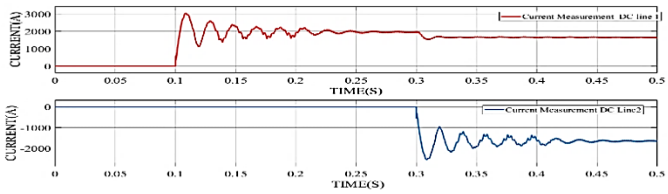

Figure 9. Fault on both DC lines

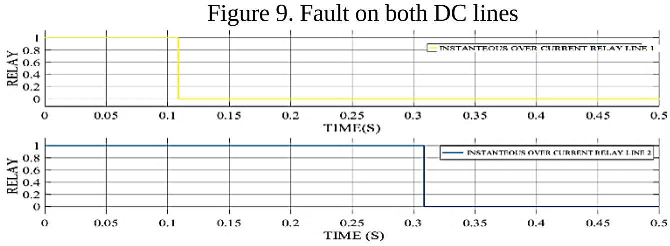

Figure 10. Relay operation for fault clearance

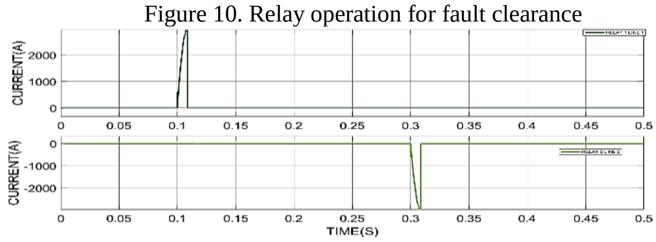

Figure 11. DC current behavior after the operation of relay

CONCULSION

A High Voltage Direct Current (HVDC) network is one of the available ways to carry high power over great distances. When compared to the HVAC system, HVDC operation improves the power system's stability and ensures that electricity is delivered even during grid outages. As a result, the HVDC network is preferred over the HVAC network for transmission of high power across long distances for secure and stable power system operation. Furthermore, when two places must be connected with the same or different frequencies, as well as when high power must be carried from faraway areas, such as offshore wind farms, utilizing underground cables, the HVDC network is preferred. When compared to an AC system, however, the HVDC network requires more attention in terms of protection.

This research involved the development of a bipolar high-voltage direct current transmission, as well as the modelling of the protective system in MATLAB/Simulink. The simulation model is a two-terminal system that includes a rectifier and inverter, a converter transformer, alternating current filters, and relays. Both in normal system operation and when faults were introduced on a single DC line and both lines, the model was put to the test and found to be accurate. The instantaneous overcurrent relay modelled in this work has the potential to isolate the malfunctioning component of the system while leaving the rest of the system intact, hence ensuring the safe operation of the power grid.

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