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# A Comparative Study of Monopolar and Bipolar HVDC Transmission Systems

**G D Kamalapur and Keerti Arakeri**

*Department of Electrical and Electronics Engineering*
*Sri Dharmasthala Manjuntheshwar College of Engineering and Technology*
*Dharwad, Karnataka-580002*
*gdkpur9@gmail.com*

**ABSTRACT**

*In recent years, there is a rapid growth in the demand for electricity and this demand is geographically uneven. Power is generated at remote locations and the wheeling of this power through AC lines is restricted by stability limitations. With the increasing size and complexity of transmission network its performance decreases. Hence there is a need for upgrading the existing system. This can be done by incorporating FACTS devices or by using HVDC transmission. FACTS devices are effective only for a limited distance and for long transmission HVDC is more advantageous. An attempt is made in this paper for a comparative study of three different long transmission technologies; High voltage AC (HVAC), monopolar High voltage DC (HVDC) and bipolar High voltage DC (HVDC). These are compared in terms of voltage regulation, THD and power loss for different transmission line lengths. The breakeven distance for monopolar and bipolar HVDC systems, power up gradation has been calculated by comparing the receiving end power in HVDC system with conventional HVAC system.*

**Key words:** HVAC, HVDC, monopolar, bipolar

## INTRODUCTION

The development of transmission systems closely follows the growing demand on electrical energy. With the increasing size and complexity of transmission networks, the performance of power systems decreases due to problems related to load flow, power oscillations, and voltage quality. Flexible ac transmission systems (FACTS) and high-voltage direct current (HVDC) technologies offer some effective schemes to meet these demands.

With the increased utilisation of high-voltage direct current (HVDC) links in power systems, it is necessary to upgrade the traditional ac grid focused transmission network expansion planning (TNEP) problem to accommodate multiple HVDC links and even HVDC grids. The study proposes a non-linear formulation for the TNEP problem of dc grids and derives two relaxations of the problem: the linear approximation, the second-order cone convex relaxation as a branch flow model. The presented formulations allow both monopolar and bipolar configurations and this as point-to-point connections and HVDC grids as expansion candidates [1].

The monopolar grounding fault in bipolar HVDC system with phase-modal transformation method is carried out in this study. Initial jumping voltage and maximum voltage on with different kinds of termination are deduced by establishing the modal circuit under the fault [2].

The symmetrical monopolar configuration is the prevailing scheme configuration for HVDC interconnectors utilizing the modular multilevel converter (MMC) topology. However, the rigid bipolar configuration is gaining significance, as first projects are currently in planning stage [3]

The role of MMCs in the power transmission systems and power quality improvement is dealt in this chapter. HVDC systems are the preferred choice over a HVAC transmission system for the long distance power transmission. The MMCs can be used as a series and shunt compensator to compensate the reactive power and grid unbalance in the case of power quality improvement [4].

Symmetrical bipolar MMCs combined with two monopolar MMCs have many benefits, such as high voltage and power level and flexible operation modes. However, the active power and reactive power of the MMC stations will reduce to half when DC side pole-to-ground (PTG) happens, which will cause large disturbance to the AC grid. By means of the improved active and reactive power control method, the disturbance to the AC grid is minimised [5].
To reduce the cost of the expensive hybrid HVDC breaker, H-bridge type HVDC breaker is proposed and different fault isolation strategies are studied in the combination of positive and negative poles. The key components and fault isolation principle of the hybrid HVDC breaker are used in the H-bridge type HVDC breaker. A model of a three-terminal monopolar HVDC grid is developed in PSCAD/EMTDC to verify the validity of the proposed breaker and its fault isolation strategies [6].
The key factors of HVDC are in conversion, switching, control, availability and maintenance. The scope of application is limited by the following factors: [7].

- Converters are expensive and require much reactive power. They generate harmonic, hence ac and dc filters are required.
- The difficulty of breaking dc currents results in the high cost of dc breakers.
- Multi terminal or network operation is not easy.
- An inability to use transformers to change the voltage levels.
- HVDC circuit breakers are difficult to build.
- Complexity of control.

**HVDC Scenario in India**

In recent years, HVDC transmission has been considered a feasible planning alternative in India to increase power grid delivery and capability and remove identified network bottlenecks. India is one of the few countries that have a large number of HVDC schemes in operation, under commissioning, construction, and planning. Quite a few HVDC transmission projects have been constructed (Table 1) or planned. There are a couple of HVDC links under active consideration for implementation within three to six- years, along with interlinking with the national grids of neighbouring countries, namely Sri Lanka, Bangladesh, Bhutan and Nepal. (Table 2I)

**Table -1 Existing HVDC systems**

| Line | Transmission capacity (MW) |
|---|---|
| a) Bipole line +/- 500KV<br>Chandrapur-Padghe (1999)<br>Rihand-Dadri (1990)<br>Talcher-Kolar (2002)<br>Balia-Bhiwadi (2009)<br>Biswanath-Agra (2014) | <br>1,500<br>1,500<br>2,500<br>2,500<br>4,000 |
| b) Bipole line +/-500 kV Circuit kilometers<br>Chandrapur-Padghe<br>Rihand-Dadri<br>Talcher-Kolar<br>Balia-Bhiwadi<br>Biswanath-Agra | 1,504<br>1,634<br>2,738<br>1,800<br>3600 |
| c) Back to Back Transmission capacity (MW)<br>Vindhachal (1989)<br>Chandrapur (1999)<br>Gazuwake (2009)<br>Sasaram (2002)<br>Vizag (1990) | 500<br>500<br>1,000<br>500<br>1,000 |
| d) Monopole line Barsur-Lower Sileru (2000) | 162 circuit kilometers-200MW |

**Table -2 Upcoming HVDC projects**

| | |
|---|---|
| India-Bangladesh multi terminal system | +/- 800KV<br>6000MW<br>1728 km |
| India- Srilanka Interconnection | +/- 400KV<br>4×250 MW<br>Overhead line-334km<br>Submarine cable-90km |
| Champa-Kurukshetra | +/- 800KV<br>3000 |

**Advantages of HVDC over HVAC**

- Beyond the breakeven distance, HVDC has the ability to transmit large amounts of power with lower capital costs and lower losses than ac.
- HVDC can carry more power per conductor. The power delivered in an a.c system is defined by the root mean square (RMS) of an ac voltage, but RMS is only 70.7% of the peak voltage. The peak voltage of ac determines the actual insulation thickness and conductor spacing. HVDC operates at a constant maximum voltage, with equally sized conductors and insulation to carry more power into an area.
- For ac used cable transmission, additional current must flow in the cable to charge the cable capacitance, which generates additional losses in the conductors of the cable. There is also a dielectric loss component

contributing to power loss. For dc, the cable capacitance is charged only when the cable is first energized or when the voltage is changed; there is no steady-state additional current required.

- HVDC does not suffer from the skin effect; hence it needs fewer, thinner conductors.
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.
- Connecting a remote generating plant to the distribution grid and power transmission and stabilization between unsynchronised ac distribution systems.
- Stabilizing a predominantly ac power-grid, without increasing prospective short circuit current.
- Both ac and dc transmission lines can generate coronas, the former case in the form of oscillating particles, in the latter, a constant wind. Due to the space charge formed around the conductors, an HVDC system may have about half the loss per unit length of a HVAC system carrying the same amount of power.
- Tie-line power is easily controlled. Less radio interference, especially in foul weather, for a certain conductor diameter and rms voltage.
- Reduction of transients and disturbances increases the system stability. This prevents cascading failures from propagating from one part of a wider power transmission grid to another.
- Synchronous operation is not required in HVDC. The magnitude and direction of power flow through a dc link can be directly commanded and changed as needed to support the ac networks at either end of the dc link.
- Cables can be worked at a higher voltage gradient, and the line power factor is always unity.
- The frequency and the intermediate reactive components cause stability problems in the ac line. On the other hand, HVDC transmission does not have the stability problem because of the absence of the frequency.
- HVDC needs fewer conductors, as there is no need to support multiple phases. This reduces the line cost. Other advantages include simpler line construction, ground as a return path, and each conductor operated as an independent circuit. Distance is not limited by stability and low short-circuits current [7].

**Types of HVDC Systems**

1) Monopole and earth return: In monopole, (Fig. 1) one of the terminals of the rectifier is connected to earth ground. The other terminal, at a potential high above or below ground, is connected to a transmission line. If no metallic conductor is installed, current flows in the earth between the earth electrodes at the two stations. One terminal of the converters is connected to earth; the return conductor need not be insulated for the full transmission voltage, which makes it less costly than the HV conductor. Monopole earth return suffers with electrochemical corrosion of long-buried metal objects like pipelines.
2) Bipolar: In bipolar, (Fig. 2) transmission, a pair of conductors is used, each at a high potential with respect to ground, in opposite polarity. Since these conductors must be insulated for the full voltage, transmission line cost is higher than a monopole with a return conductor. However, there are many advantages to bipolar transmission, which can make it an attractive option.
3) Homopolar: In a homopolar, (Fig. 3) type of link, two conductors having the same polarity can be operated with ground or metallic return. A homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages.
4) Back to back: Back-to-back HVDC technology enables the interconnection of two asynchronous ac networks. An HVDC system takes electrical power in an ac system and converts it into high-voltage dc using a converter station. It then transmits the dc to a remote system, where it is converted back again to ac by another HVDC converter station. A back-to-back HVDC arrangement is used when two asynchronous ac systems need to be interconnected for bulk power transmission or for ac system stabilization reasons. Back-to-back improves the voltage regulation, system stability, and contribute for effective load flow analysis.

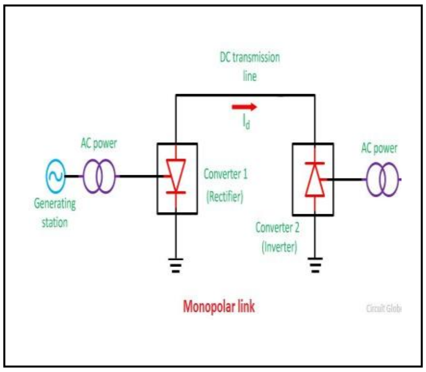



**Fig. 1** Monopolar HVDC system [8]

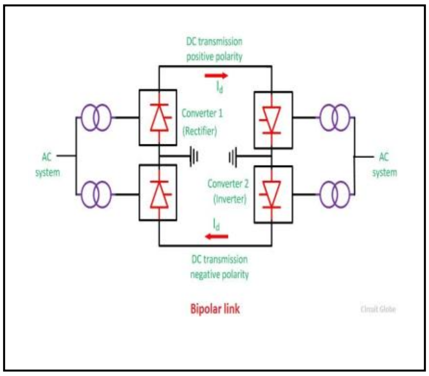



**Fig. 2** Bipolar HVDC system [8]

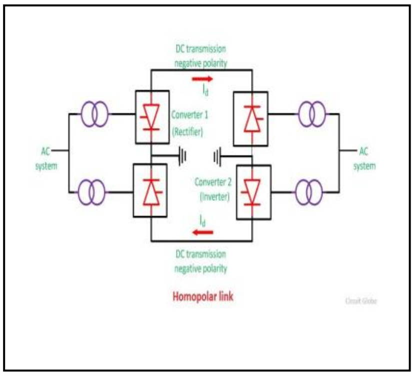



**Fig. 3** Homopolar HVDC system [8]

## SIMULATION

An HVDC transmission system consists of three basic parts: (1) a converter station to convert ac to dc (2) a transmission line, and (3) a second converter station to convert back to ac. HVDC transmission systems can be configured in many ways on the basis of cost, flexibility, and operational requirements. The simplest one is the back-to-back interconnection, and it has two converters on the same site with no transmission line. This type of connection is used as an intertie between two different ac transmission systems. The monopolar link connects two converter stations by a single conductor line and earth or sea is used as a return path. The multi-terminal HVDC transmission systems have more than two converter stations, which could be connected in series or parallel. Among the various components and subsystems existing at an HVDC station, the HVDC transmission line and the converter transformer are the major components that have a significant impact on the total reliability of the HVDC system.

Converter transformers are located on either ends of the HVDC transmission line. The transformers used in HVDC have different requirements due to superimposed dc voltage and current. Converter transformers designed for 12 pulse rectifiers have three windings. They are single phase three winding transformers. A bank of three transformers will be used for a 12-pulse converter. Out of the three windings of a converter transformer, one of the windings is connected to the ac network, and the other two are connected to a converter bridge, i.e., one connected in delta and the other in star. As an important component of an HVDC system, the converter transformer is responsible for the stable and reliable power transmission.

The HVDC system modelled, using the Simulink, is based on a point-to-point dc transmission system. Fig. 4 shows the Simulink diagram of Monopolar HVDC system. Fig. 5 shows the Simulink diagram of a Bipolar HVDC system. The dc system is a 12-pulse converter using two universal bridges connected in series, rated 1,000 MW, 2 kA, 500 kV, at the inverter. DC interconnection is used to transmit power from a 500 kV, 5,000 MVA, and 50 Hz network to a 345 kV, 3,000 MVA, and 50 Hz network. The converters are interconnected through a 300-km transmission line and a 0.5-H smoothing reactor. The converter transformer is modelled with a three-phase, three-winding transformer. The ac networks, both at the rectifier and inverter end, are modelled as infinite sources separated from their respective commutating buses by system impedances.

Back-to-back technology allows for the two-way flow of electricity, while acting as firewall to isolate disturbances. HVDC transmission does not have the stability problem due to the absence of the frequency. The cost per unit length of an HVDC line is lower than that of HVAC line of the same power capability and comparable reliability, but the cost of the terminal equipment of an HVDC line is much higher than that of HVAC line.

The monopolar and bipolar are simulated using Simulink (Fig. 4 and Fig.5)

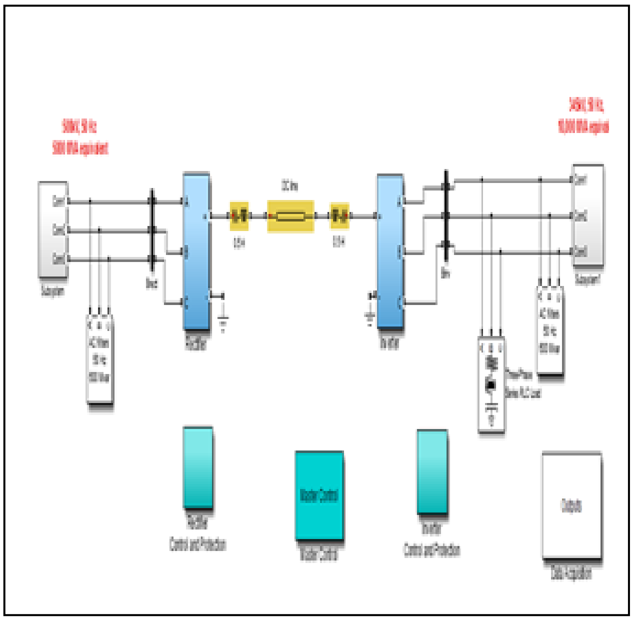


**Fig. 4** Simulink diagram of Monopolar HVDC system

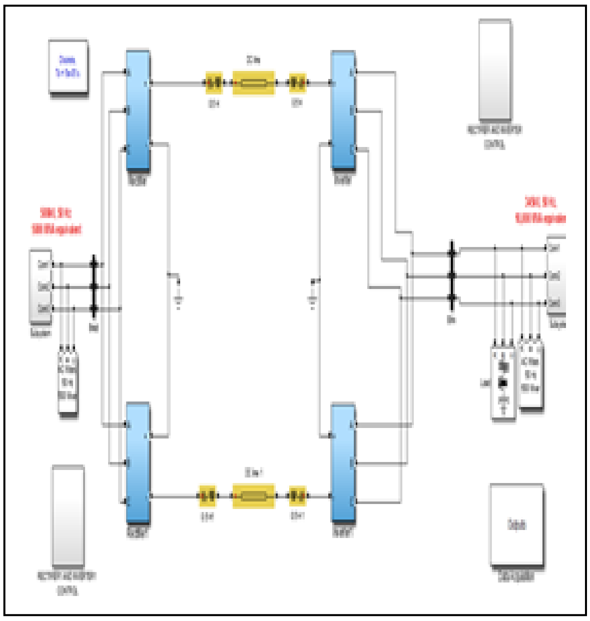


**Fig. 5** Simulink diagram of Bipolar HVDC system

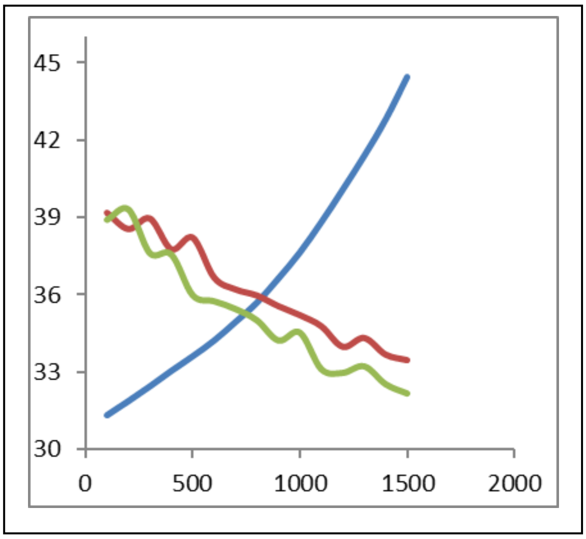
## RESULTS AND DISCUSSION

The variation of Voltage Regulation with distance, for HVAC, monopolar HVDC and bipolar HVDC is shown in Fig 6. From the graph, the breakeven distance of overhead lines of monopolar HVDC system is found to be 815 km and for bipolar HVDC system is found to be 745km, compared with HVAC. The voltage regulation for different line lengths is shown in Table 3. The power losses for all the three systems, for different line lengths are shown in Table 3 and Fig 7. The power upgradation for monopolar and bipolar systems compared to HVAC are shown in Table 4 and Fig. 8.

THD for HVAC 4.71%, monopolar 1.99% and bipolar 0.11% system.

**Table -3 Percentage Voltage regulation versus Transmission distance (km) and Power loss (kW) in Monopolar and Bipolar systems**

| Line length (km) | %VR for HVAC | %VR for monopolar | %VR for Bipolar | Line Length(km) | Power loss for monopolar (kW) | Power loss for bipolar(kW) |
|---|---|---|---|---|---|---|
| 100 | 31.33 | 39.2 | 38.9 | 100 | 381 | 303 |
| 200 | 31.88 | 38.569 | 39.3 | 200 | 363 | 289 |
| 300 | 32.45 | 38.98 | 37.61 | 300 | 347 | 281 |
| 400 | 33.05 | 37.78 | 37.56 | 400 | 329 | 267 |
| 500 | 33.62 | 38.23 | 35.98 | 500 | 311 | 253 |
| 600 | 34.23 | 36.675 | 35.75 | 600 | 296 | 241 |
| 700 | 34.95 | 36.214 | 35.45 | 700 | 281 | 230 |
| 800 | 35.7 | 35.979 | 35.01 | 800 | 270 | 220 |
| 900 | 36.64 | 35.562 | 34.23 | 900 | 259 | 211 |
| 1000 | 37.64 | 35.213 | 34.54 | 1000 | 243 | 202 |
| 1100 | 38.82 | 34.78 | 33.12 | 1100 | 226 | 195 |
| 1200 | 40.08 | 33.981 | 32.98 | 1200 | 204 | 178 |
| 1300 | 41.39 | 34.324 | 33.234 | 1300 | 198 | 162 |
| 1400 | 42.8 | 33.676 | 32.541 | 1400 | 183 | 158 |
| 1500 | 44.44 | 33.459 | 32.184 | 1500 | 179 | 147 |



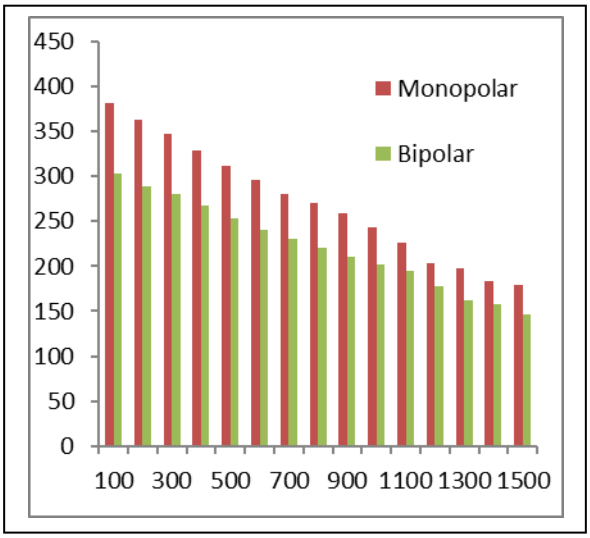




**Fig. 6:** % Voltage reg. v/s Transmission distance (km) **Fig. 7** Power loss (kW) in Monopolar & Bipolar system

**Table -4 Percentage Power Upgradation**

| Line length (km) | Power upgradation for monopolar (%) | Power upgradation for bipolar (%) |
|---|---|---|
| 100 | 6.7 | 8.3 |
| 200 | 7.9 | 10.1 |
| 300 | 9.8 | 11.6 |
| 400 | 11.6 | 12.48 |
| 500 | 14.8 | 15.54 |
| 600 | 16.9 | 18.48 |
| 700 | 19.3 | 21.51 |
| 800 | 20.9 | 23.48 |
| 900 | 21.6 | 27.87 |
| 1000 | 22.7 | 30.98 |
| 1100 | 24.3 | 32.61 |
| 1200 | 26.9 | 34.25 |
| 1300 | 28.3 | 35.71 |
| 1400 | 31.1 | 36.23 |
| 1500 | 33 | 38.1 |

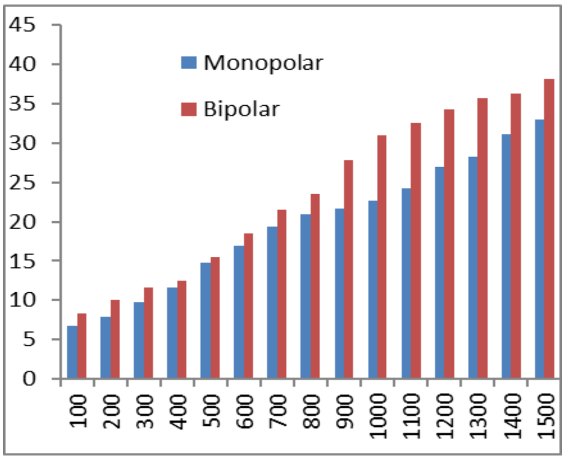



**Fig. 8** Power up gradation for monopolar and bipolar systems w. r.to transmission line length (km)

## CONCLUSION

This paper presents simulations of monopolar and bipolar HVDC systems carried out in MATLAB/Simulink. For transmission distance greater than the breakeven distance, HVDC is found to be more advantageous than HVAC. With increasing line length, the voltage regulation decreases for HVDC systems. THD for bipolar HVDC system is lesser than monopolar HVDC system. The power losses showed a tremendous decrease as the line length increases. Power up gradation is better for bipolar HVDC than monopolar HVDC. Comparing the voltage regulations, Total Harmonic Distortion, power losses and power up gradation, Bipolar HVDC is found to be better than monopolar HVDC and HVAC systems.

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