Performance Analysis of Various Topologies in HVDC Networks

GOVIND KANT MISHRA [1], YADUVIR SINGH [2]

[1] Electrical Engineering Department, A.P.J. Abdul Kalam Technical University, Lucknow, INDIA

[2] Electrical Engineering Department, Harcourt Butler Technical University, Kanpur, INDIA

govindkantmishras@gmail.com

Abstract: The evolution of methods for renewable resources utilization and need of connectivity among far distant resources with electrical grids have pushed the emergence of HVDC networks with various design topologies. This paper attempts to represent overall picture of HVDC network topology and analyse performance of different topologies containing unique combinations of polarities, return paths and multipoint connections. A detailed test system is modelled for the study of their time domain fault response for both pole to pole and pole to ground fault, and their transmission efficiency. Modelling and simulation of various components including transmission line, MMC converter is done in PSCAD-EMTDC program. Results of the simulation have been presented and concluded with recognition of the best topology for HVDC networks.

1. Introduction

The growing demand for electricity has urged the utilization of Renewable Energy Resources (RER). A common problem with RER is the distance between the places where the energy is generated and where it meant to be consumed. These long distances between various sources and load points demand long electrical transmission network [1]. In order to transmit electrical energy over long distances high with a good degree of efficiency, high voltage transmission is required. Transmission system could be traditional AC networks or modern DC networks. HVDC transmission systems have theoretically low conduction losses and economic viability for long distance transmission lines, where long distance means larger than 500 km [2, 3] for overhead lines and for underground cables larger than 40km [4, 5].

Voltage Source Converter (VSC) technology based Multi-Terminal HVDC networks are centre of attraction for researchers as it promises a low-cost MTDC network for weak or even passive AC grid system and best option for integrating offshore wind farms [6]. Development of Modular Multilevel Converters (MMC) have added scalability and smoother operations for HVDC networks [40, 41]. One of the major problems with the HVDC system is their vulnerability towards faults at DC side of the grid. VSC consist of antiparallel diode attached to each IGBT switch, this structure enables VSC to work as Self Commutated Converter, but at the same time exposes itself to DC faults [7]. Antiparallel diodes provide an open path to fault current occurring at DC side of the grid. In DC fault condition capacitor tank discharges rapidly, and due to low rating of DC smoothers, fault current increases exponentially reaching to its peak value within very short time [8]. This short time could be as short as 1 ms [9], thus rapid fault detection, and prompt action DC breaker is required for isolation of faulted branch of the network. Fault current parameters calculation is critical for selection of DC breaker and other protective apparatus and suppressors like Superconducting Fault Current Limiters [10-13]. The topology of HVDC network plays a crucial role in the calculation of fault current parameters. In certain conditions design of HVDC network serves as last wall of protection. Topology of HVDC network also affects transmission efficiency, optimal distribution feasibility and stability.

In recent years significant work has been done for development of the topologies of HVDC network. However, most of the papers focus on particular designs of components of HVDC system and thereby missing the whole scenario. A comparison of topologies based on their fault response in HVDC network has been done considering radial topology only [14]. Moreover, using distributed Pi configuration for modelling of transmission lines shows less accurate results in comparison with Phase Shifted Frequency Model (PSFM) of the transmission line, especially if electricity is to be transmitted over large distances. In [15] another work has been done on HVDC network topologies with the PSFM model of the transmission line but doesn't include topologies based on different polarities and return paths. Different return paths have been discussed in paper [21] but focus has been given only star topology.

This paper explores a complete scenario of interaction among multiple topologies having differences in connection among multiple terminals, polarities and returned per path between two terminals. Test circuits for every popular network design topology with different combinations of connectivity, polarities and return paths have been modelled. In order to make this study more realistic, most of the network components such as Voltage Source Modular Multilevel Converter (VSMMC), transmission lines have been modelled in the view of the popular or state of the art specimens.

This paper reviews performance of VSMMC MTDC network topologies in following sections: Section 2 describes different topologies depending upon the design sections. Section 3 includes mathematical models of components being used in topology and finally overall system model for each of the mention topology. Section 4 observes the results obtained by comparison of different design sections of similar topologies. Finally, Section 5 discusses final result and concludes the best topology.

2. MT-HVDC Topologies

A topology is all about selection of different elements their parameters and arrangement of those elements. Different topologies can exist depending upon the choice of components, parameters and their arrangement. Similarly, Multi Terminal High Voltage Direct Current (MT-HVDC) networks have different topologies depending upon the selection of polarity of the transmission line, ground connection/return path type and arrangement of transmission line connections. In-depth exploration of these design sections is as following-

2.1.Polarity of the transmission line

According to the polarity of charge carrying conductor line, two categories of MT-HVDC network Design exist-

2.1.1 Monopolar Design:

Under monopolar design one conductor or group of conductor lines either positively or negatively charged in order to transmit electricity. This design offers the lowest cost to the network as just one conductor line is required for power transportation. At the same time, it possesses susceptibility towards DC faults. Having just a single conductor line, it's more prone towards transmission power loss during fault condition till fault clears out and Direct Current Circuit Breaker (DCCB) get reconnected. Moreover, in this design, transmission line can't be used for power transmission during repair works.

2.1.2 Bipolar Design:

This type of design has two conductors or group of conductor lines with one of them positively charged and second one negatively charged. Both lines have approximately the same amplitude of voltage but opposite polarity. This design offers more flexibility regarding continuity in power transmission [16]. Even if one conductor line is faulty or under maintenance, the other line will continue to operate independently. In certain situations, working conductor line can be loaded with double of its rating if another conductor is defective [17].

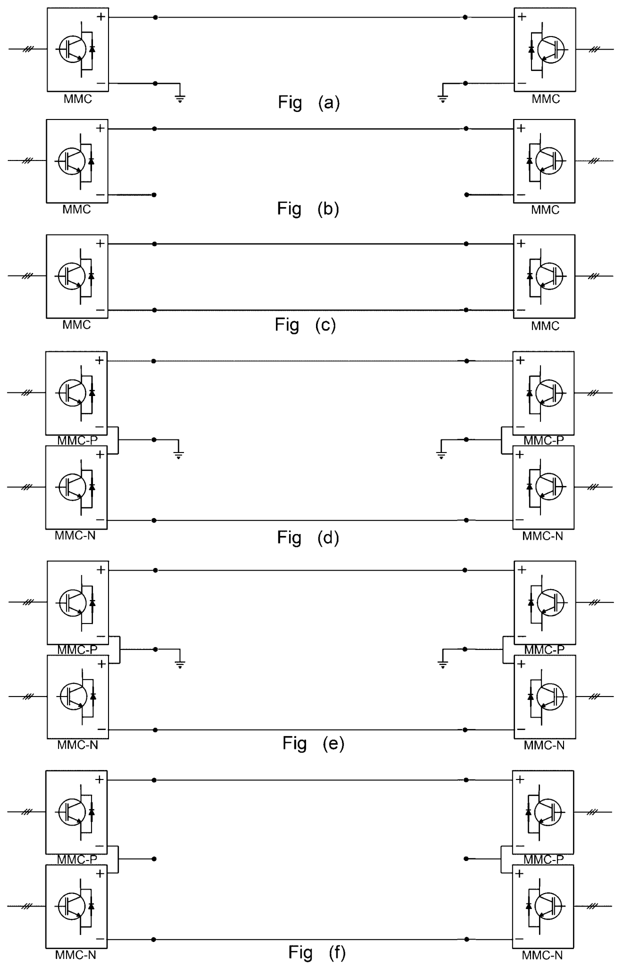


Fig. 1. *Polarity and Return Path*
(a) Monopolar Ground Return design, **(b)** Monopolar Neutral Line Return design, **(c)** Monopolar Symmetric Return design, **(d)** Bipolar Ground Return design, **(e)** Bipolar Neutral Line Return design, **(f)** Bipolar Symmetric Return design

2.2.Return Path

Depending upon the return path of the current between two terminals of HVDC network, Design could be ground return or line return-

2.2.1 Neutral Line return:

A separate conduSctor line with the current rating similar to other conductor line is used in this Design in order to complete the DC circuit [18]. The conductor line may not need high insulation covering as the voltage stress on this line is usually very low in Bipolar Design, less than 10% of rated DC line voltage [19]. This type of design may add up the price of the network but it exhibits better fault response due to the line impedance which is more than ground impedance at respective terminals. Sometimes in underground or Submarine Cable type transmission line, Sheath is used as neutral conductor to avoid the need of additional conductor line.

2.2.2 Ground return:

In this Design, the ground [20] connection at terminal is used as a return path. Ground connection can be solid (very low impedance) or high impedance (capacitor in DC network, inductor in AC network) type [21]. This paper discusses only Solid Ground type connection, and impedance of this type of ground connection must be less than 5 Ω. This type of ground connection may arise certain environmental concerns as the distributed charge may affect the surrounding land.

2.2.3 Symmetric Return:

This type of design creates a silver lining between monopolar and bipolar Design. By definition, it is understandable that a return path will be similar to forward path, i.e. conductor having identical MVA rating is used as return path [22]. Uniqueness in symmetric return model is the neutral junction of VSMMC which connected to ground through high impedance and no other neutral point of entire HVDC network is grounded. Due to this symmetric design DC grid observes almost zero steady-state fault current.

2.3.Connection among multiple terminals

As per the conductor lines connected among multiple terminals, there are following basic topologies exist –

2.3.1 *Star Design:*

In this Design, at least one terminal exist which is directly connected to more than two terminals. At the one terminal with multiple connections (central terminal) a bus bar is installed and no other terminal is needed due to just single connection at the end. This type of Design has the least number of cable connection which makes it way cheaper then ring or mesh design. Start time Design shows vulnerability at DC faults. If the Central Terminal gets faulty the whole grid will be in blackout condition [23].

2.3.2 *Ring Design*:

This type of Design offers two connections of the transmission line set per terminal, hence forming a ring or a series circuit combining all the terminals. This design is one of the simplest to implement on the ground and have longest series of Transmission lines. Due to this series structure of transmission lines impedance gets accumulated, thus ring design suffers from higher conductive power loss in comparison with other topologies. However, in the fault conditions, this structure gets the lowest surge of current.

2.3.3 Mesh Design:

This type of Design is most complex one having the largest number of Transmission line connections of all topologies. Having multiple connections among terminals gives an edge in optimal power distribution, moreover in the case of fault on one transmission line this Design offers a chance to divert power supply via other transmission lines from one terminal to another terminal [24]. Combining all these design types produces following distinct network topologies-

As per the Table 1, total 18 different topologies can exist and naming arrangement could be like **first letter** representing **M**onopolar or **B**ipolar design, the **middle letter** representing **M**esh, **S**tar or **R**ing design and **last letter** exhibiting return path of the topology. Hence word '**MSG**' represents **M**onopolar **S**tar **G**round return topology.

3. System Modelling

In order to study the DC fault response of various topology a four terminal DC network system has been taken into consideration. The system under the study has been modelled for each of the topology mentioned above using high-fidelity detailed models of the following components of the DC network-

3.1.Transmission Line

This paper utilizes Frequency dependent phase model [25] of the transmission line rather than traditional Bergeron [26] or Pi model because of the following reasons -

a) Transient response of current includes various current waves of different frequencies; hence the transmission model must be putting high impedance for higher order

Table 1. Different Topologies

	Ground return	**N**eutral line return	**Sy**mmetrical return
Monopolar **S**tar	MSG	MSN	MSSy
Monopolar **R**ing	MRG	MRN	MRSy
Monopolar **M**esh	MMG	MMN	MMSy
Bipolar **S**tar	BSG	BSN	BSSy
Bipolar **R**ing	BRG	BRN	BRSy
Bipolar **M**esh	BMG	BMN	BMSy

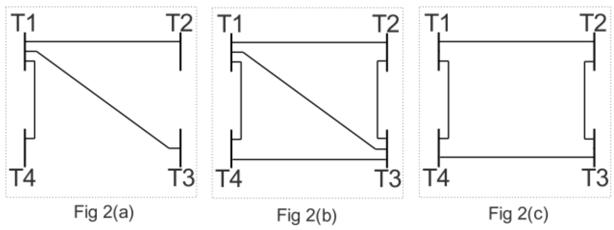


Fig. 2 *Connection among multiple terminals*
(a) Star Design, **(b)** Mesh Design, **(c)** Ring Design

Table 2. Cable Specifications

Layer	Material	Outer radius	ρ (ohm-m)	ε_r	μ_r
Core	Copper	20 mm	1.72×10^{-8}	1	1
Insulation	XLPE	46 mm	--	2.3	1
Sheath	Lead	49 mm	2.2×10^{-7}	1	1
Insulation	XLPE	53 mm	--	2.3	1
Armour	Steel	60 mm	1.8×10^{-7}	1	10
Insulation	PP	63 mm	--	1	1

current waves and vice versa. FDPM best fit in this criterion as it is a distributed Transmission model in which each distributed component (R, L, C) is a function of frequency.

b) This model gives accurate result for both lower and higher frequency current waveforms unlike traditional distributed RLC Pi model tends to have quasi resonance for higher order current waves Or Bergeron model which offers approximately same impedance for all frequency

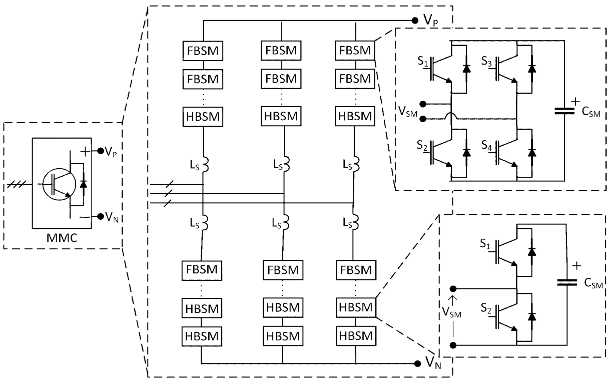


Fig. 3 *Hybrid VSMMC in test circuit*
(a) Internal structure,
(b) Full bridge Sub Module, **(c)** Half bridge sub module

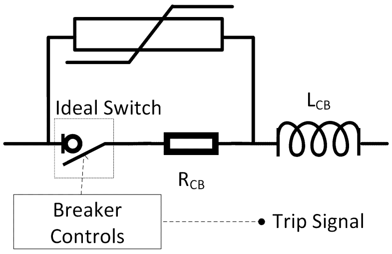


Fig. 4. *DC Circuit Breaker*

components of current.

This paper exploits Electromagnetic Transient Program also said as EMTDC-PSCAD for modelling and analysis of DC network which includes modelling of the transmission line [27].

The transmission line has been model in the view of an actual underwater 320 KV XLPE Cable [28]. Specifications of the model XLPE Cable are given in Table 2.

3.2.Converter

Multiple configurations of MMC converter have been proposed in recent years and discussing all of them in one

Table 3. *Converter Specifications*

Parameter	Rating
Rated DC Voltage	±320 KV
Rated Converter Power	500 MW
Capacitor in submodule	2100 μF
Number of submodules N_S	250
Equivalent Resistance in submodules	0.001 Ω
Smoothing Reactance in each arm	2.5 mH
DCCB Inductance L_{CB}	9 mH
DCCB Resistance R_{CB}	0.01 Ω

Table 4. *System Specifications*

Parameter	Rating
AC Source Voltage (L-L)	220 KV
AC Source Frequency	50 Hz
Rated Current	2.3 KA
SCR Value	3.0
X/R Value	5
Transformer Rating	500 MVA
Leakage Reactance	0.1 p.u.
Turns Ratio	220/330
Commutation Reactance per phase	5mH

paper is not feasible. Hence only one type of configuration, which is a hybrid Voltage Source Modular Multilevel Converter (VSMMC) has been considered for modelling in test system. This hybrid configuration includes $2N_S/3$ Full Bridge Sub-Module (FBSM) and $N_S/3$ Half Bridge Sub-Module (HBSM) as shown in Fig. 8 where N_S is the number of total submodules used in VSMMC converter. Specifications of converter have been given in Table 3. For the study of fault current, VSMMC converter can be simplified as an uncontrolled bridge rectifier because at the event of occurrence of fault IGBT module get blocked by converter protection system [29,30]. This action pushes fault current to flow from the freewheeling diodes and hence making the whole converter an uncontrolled bridge rectifier.

3.3.Breaker

In this paper, the focus has been given to time domain fault current response of the network and hence circuit breaker is so model that within delay time no protection arrangement within the breaker work, resulting no attenuation from circuit breaker till operating time. However, during conduction time, the breaker has some conduction loss which is model by joining limiting impedance Z_{CB} in series with the ideal switch [31]. Following diagram gives the idea about the model circuit breaker. Delay time of the circuit breaker has been chosen in the view of hybrid circuit breaker. [32, 33]

3.4.AC Network

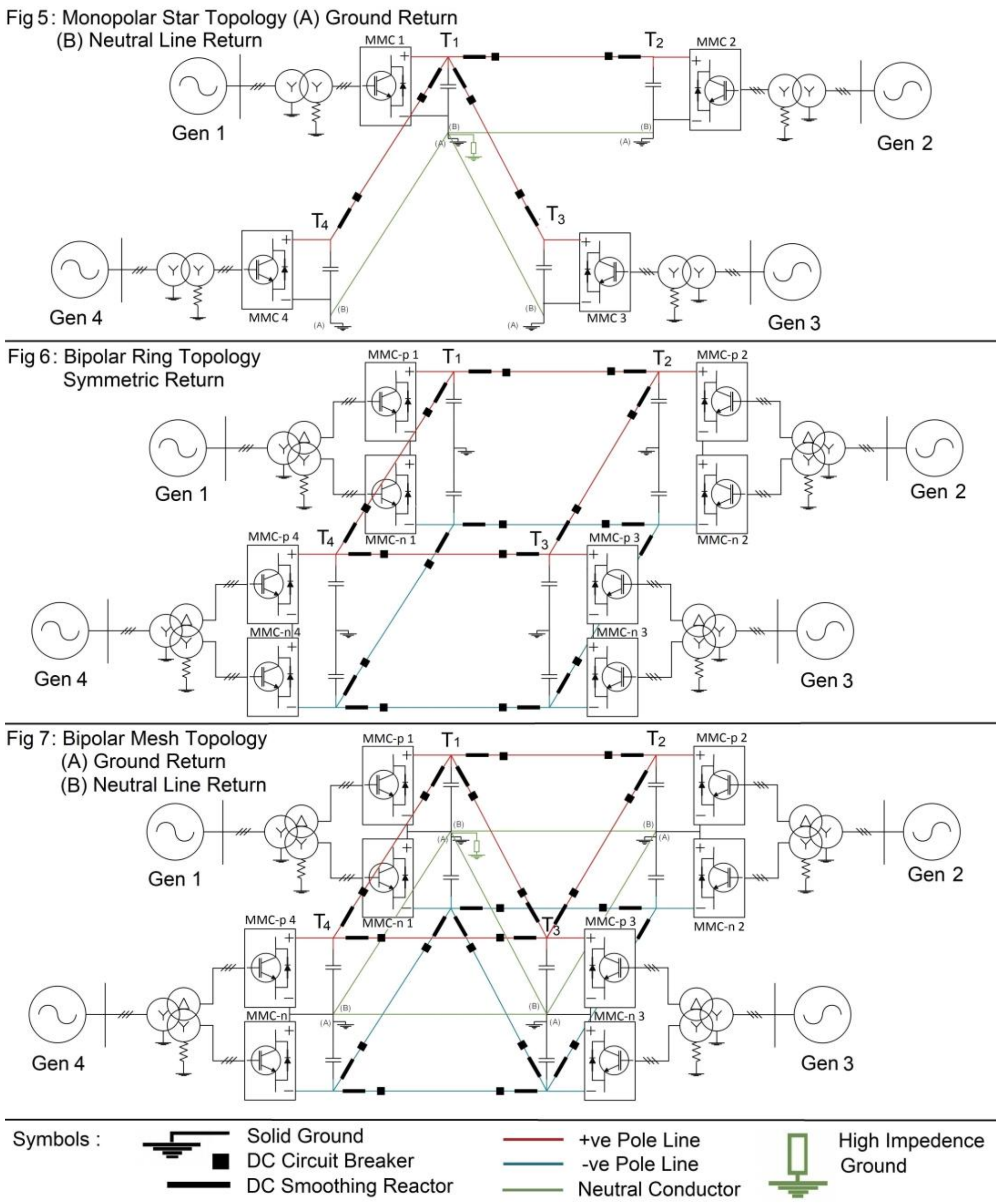
A practical AC network can produce a limited amount of current on short circuit which is known as short circuit current limit (SCL). SCR is another factor used to define capability of AC network defined as the ratio of SCL to rated delivered power at terminals. If value of SCR for a network is 3 or below, that network is regarded as weak network. Most of the Practical AC networks in all over the world are generally weak networks [34-36]. Moreover, the networks connecting windfarms only have even lower short circuit current limit at a given time. VSC based converters can be applied to these networks as their STATCOM base structure is advantages in harnessing the incoming power and have reactive power generating capability. In this paper the test model exploits weak AC network having SCR value between 2 to 3. AC network has been modelled as an ideal voltage source with Thevenin's equivalent impedance connected to it in series [37]. SCR value of network has been calculated at the common coupling point or junction. Specifications are given in Table 3.

3.5.Overall System Rating

For each of the topology, a distinctive test system has been designed with identical models of the transmission line voltage source converter and breaker as mentioned above. These distinctive systems differ from each other on the basis of connections among terminals and return path type as per the respective topology. All other topologies have been implemented in a similar manner in order to study the fault response. The load distribution in the test system has been kept at fixed value for all of the above topologies. Following Fig. 8 shows the load distribution on terminal in the pre-fault scenario.

Although for simplicity ratings of converters are same, current flow from one terminal to another depends upon the power demand and due to fix demand from power stations for both converters the current in bipolar topology is half of the monopolar topology. In the similar manner symmetric return monopolar gets only half of the voltage at both transmission lines with respect to ground.

For the study of fault response of the topology, when fault F1 is triggered at 9 sec, DC breakers get opened at both ends of the faulty transmission line and the fault current get discharged via fault. However, converters get switched on soon after breakers operation and still convert reactive power for the AC networks. In case of star topology and ring topology total blackout condition for one terminal can be seen from the fault, but in mesh topology terminal get power supply from the alternate transmission line at the cost of conduction loss due to additional path which is longer than



Complete model of topology

Fig. 5. *Monopolar Star topology* **(a)** Ground Return, **(b)** Neutral Line Return
Fig. 6. *Bipolar Ring topology Symmetric Return*
Fig. 7. *Monopolar Star topology* **(a)** Ground Return, **(b)** Neutral Line Return

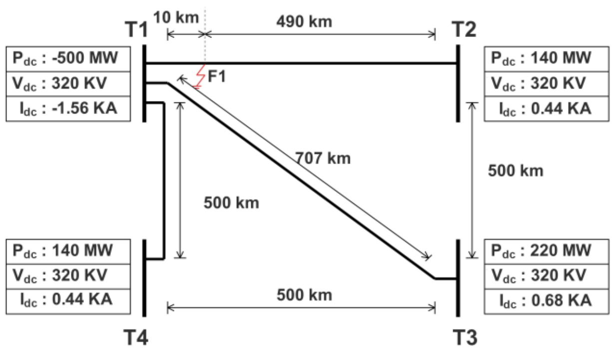


Fig. 8. *Rated load flow at all terminals*

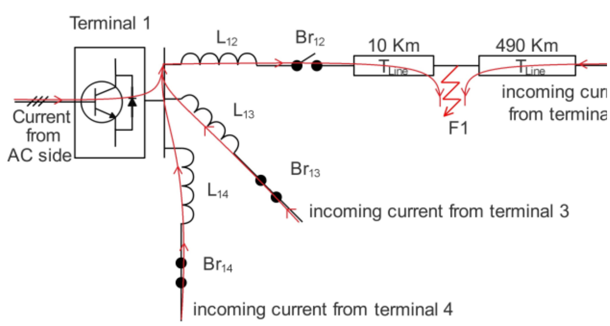


Fig. 9. *Fault current flow*

faulty path. Fault F1 is located about 10 km from the Terminal T1. Fault resistance has been taken as 5 ohms.

Fig. 10 shows the comparison of simulated fault current with MVDC fault current standard IEC 61660-1 [38] for fault F1 in Monopolar Star Ground return topology. Difference between simulated result and calculated fault current from IEC standard is observable and it should be due to following reasons-

a) IEC standard for fault current is itself not a standard for HVDC networks but medium level DC network, hence more prone to be inaccurate in high voltage scenarios.

b) In IEC standard it is assumed that the length of transmission lines is low and hence capacitance of the line can be neglected. While in the simulation capacitive effect of the transmission line has been included and length of transmission line is quite large enough to have dominating RLC characteristics over fault current.

c) IEC standard uses concentrated by network model for the calculation of fault current but in the simulation transmission model is distributed Frequency dependent phase model which is clearly can represent more accurate results in time domain for the fault current [39].

Apparently, there is no standard for calculation of fault current in HVDC networks, although in certain papers fault calculation method is proposed but it's yet to be validated on networks [42, 43]. Hence, simulated fault response is compared with IEC standard fault response in Fig. 10, and it exhibits closeness of fault currents as time moves after the fault. Despite of differences, this closeness does support the approach of modelling the test system.

4. Result and Discussion

This paper shows a wide array of data resulted by simulation of all mentioned topologies. For better understanding the results have been arranged in the following categories-

4.1 Monopolar vs bipolar

In this experiment for simplicity the rating of monopolar VSMMC and bipolar VSMMC are same, rated voltage from Pole to Ground is 320 KV for both cases, hence fault characteristics are expected to be similar. However, it can be observed form Fig. 11 that Bipolar Pole to Ground fault has a bit higher peak current as compared to monopole. This is due to relatively higher voltage drop per unit distance in monopolar topology resulting lower pre-fault voltage of monopolar line. A Single conductor in monopolar topology carries relatively higher amount of current compared to bipolar topology in this test circuit due to similar power rating of converters and load connected to each terminal.

4.2 Ground, Neutral line and Symmetric return

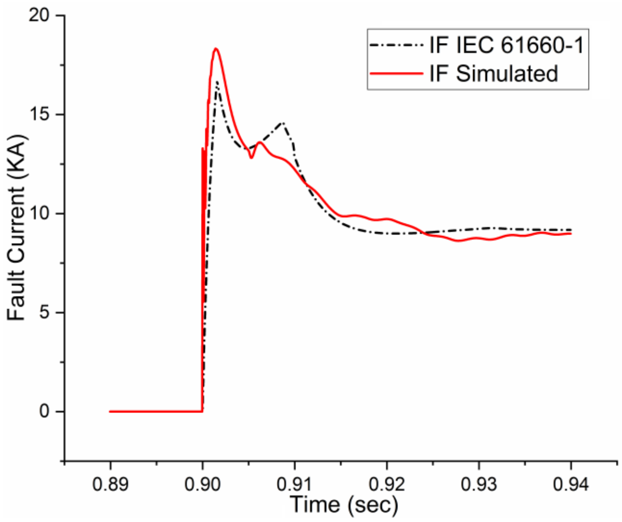


Fig. 10. *Simulated vs IEC 61660-1 P-G fault (dash) in Monopolar Star Ground return topology*

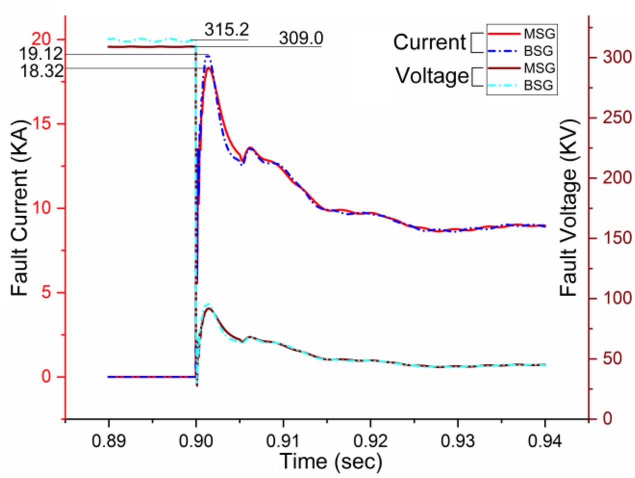


Fig. 11. *Monopolar Vs Bipolar Pole to Ground fault*

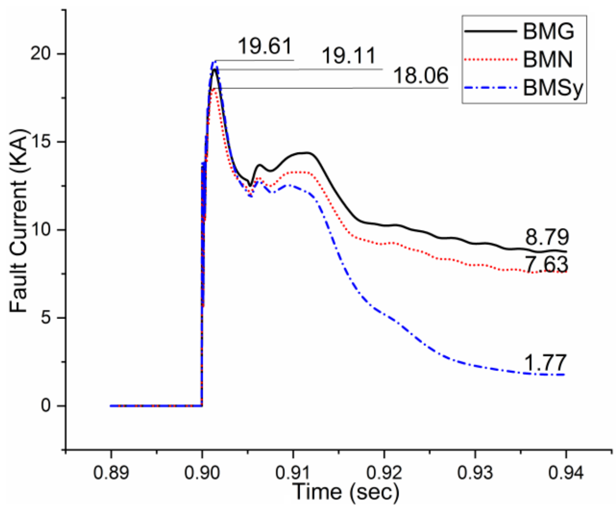


Fig. 12. *Fault Current for Bipolar Mesh design Ground, Neutral and Symmetric return*

It is observable from Fig. 12 that having a metallic return path or neutral return path offers increased impedance as compared to solid ground path resulting lower peak fault current compared to ground return. It's also visible that

Symmetric return has lowest steady-state fault current due to symmetric structure of topology.

4.3 Mesh, Star and Ring

It is quite apparent from Fig. 13 that ring structure has the lowest fault current value and this is due to obvious higher relative impedance with compared to star and mesh topology. It also can be seen that mesh topology has a secondary peak as compared to star topology. This is because of delayed individual peak current from the same path for star topology while mesh topology has an alternative path for fault current.

4.4 Effect of distance

From the Fig.14 one can easily observe that as the fault position moves away from the terminal peak fault current decreases. Fault F1 is positioned at distance of 10 km from terminal T1, F2 is positioned at 25 km from T1 and so on for F3, F4, and F5. At in steady-state value of fault current may not be observable due to very less change in impedance during the length of the transmission line.

4.5 Pole to pole faults

Pole to Pole (PP) type faults are most severe in the bipolar and monopolar symmetric return topology. For simplicity the fault resistance from pole to pole is taken as 5 Ω. In Fig. 15 it can be seen that natural response of fault is higher than pole to ground (PG) fault. It also can be observed that peak PP fault current value of MSSy is approximately half due to half of the terminal voltage (320 KV) compared to bipolar design (640 KV). However, steady-state value of the PP fault current of MSSy topology is higher than its bipolar counterpart, obviously due to double converters associated in bipolar design. In this paper steady-state value has been taken by averaging last 10 ms values of fault current.

4.6 Transient and Forced Response

Symmetric design is observed as being least affected by forced fault current contributed by adjacent feeders and associated AC network from another side of the VSMMC Converter. In Fig. 18 fault response of Bipolar Symmetric Return with Mesh, Star and ring designs is displayed with current measured at individual terminals. It's clearly observable that Bipolar Ring Symmetric return topology has better fault response at each terminal compared to mesh and star designs.

4.7 Power Dissipation

Overall power loss in the transmission of electricity during normal operation is an important criterion to evaluate different network topologies. From Fig. 17 it is observable that overall bipolar topology considering all the combinations of design sections lower power loss compared to monopolar topology. Following could be the reason for higher power loss in monopolar design –

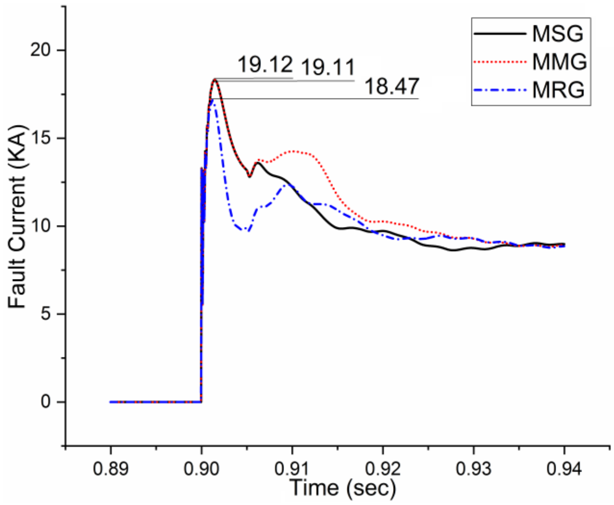


Fig. 13. *Mesh, Star and Ring Sections fault response in Bipolar Ground return*

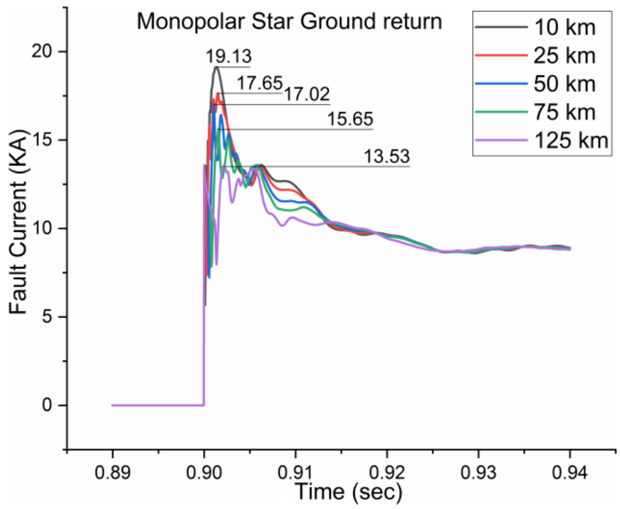


Fig. 14. *Effect of distance over P-G fault in Monopolar Star Ground return*

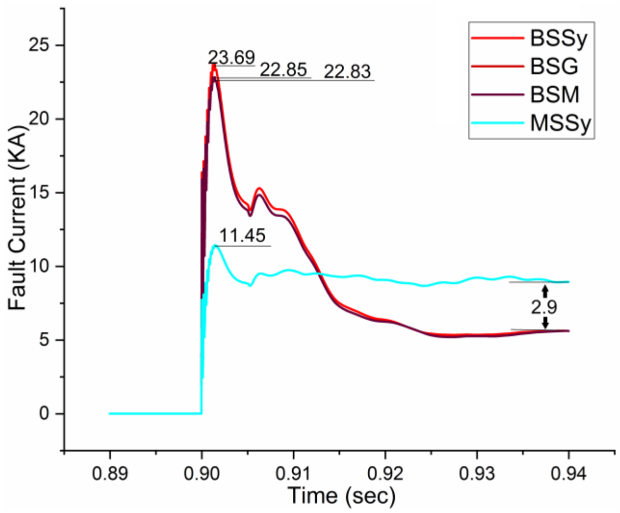


Fig. 15. *Pole to pole fault response in monopolar star symmetric topology and bipolar star design for different returns*

a) Rated voltage difference in bipolar design is 640KV pole to pole, while in monopolar design 320KV pole to pole. Power rating of converter and connected load is same in all topologies. This leads to lower current in the transmission line for bipolar design compared to monopolar design.

b) Neutral return conductor is no extra conductor line but 'sheath' of cable in this test system as specified in Table 2, puts higher resistance and power loss in neutral return design.

During normal operation, bipolar design holds almost negligible current flowing through neutral return conductor while monopolar design has only one path for current to return which is neutral return conductor path.

5. Conclusion

In this paper, various topologies have been defined, modelled and compared on the basis of their time domain fault response. Results of this paper contain higher accuracy, fidelity than other papers as the transmission lines variables taken in this paper dominates over converter variables. Following conclusions can be drawn from above analysis-

1. Monopolar and bipolar structures produce same results for optimal load. Time domain fault response for P-G type fault and power consumption will be same for optimal load.
2. Neutral return design produces relatively higher conduction loss for monopolar structure compared to bipolar structure because later has additional return path for current.
3. Ring design causes more than double conduction loss for monopolar symmetrical design compared to bipolar symmetrical design as former suffers from circulating current in the ring structure of transmission line.
4. For Pole to Pole faults, natural fault response favours monopolar design and bipolar in forced fault response.

For each of the modelled system representing unique topology as mentioned in Table 1, performance index can be calculated by using following equation-

$$\boldsymbol{Performance\ Index} = \frac{\{(I_{PGmax} + \epsilon I_{PGsteady}) * (I_{PPmax} + \epsilon I_{PPsteady})\}}{\epsilon^2 P_{Loss}} \quad (1)$$

For this equation-

I_{PGmax} = Peak current under Pole to Ground fault

$I_{PGsteady}$ = Steady Current* under P-G fault

I_{PPmax} = Peak current under Pole to Pole fault

$I_{PPsteady}$ = Steady Current* under P-G fault

ϵ = Performance Constant ('2' for Eq. (1))

P_{Loss} = Total Power loss in transmission under normal operation of the system

*= average value of fault current of last 10 ms

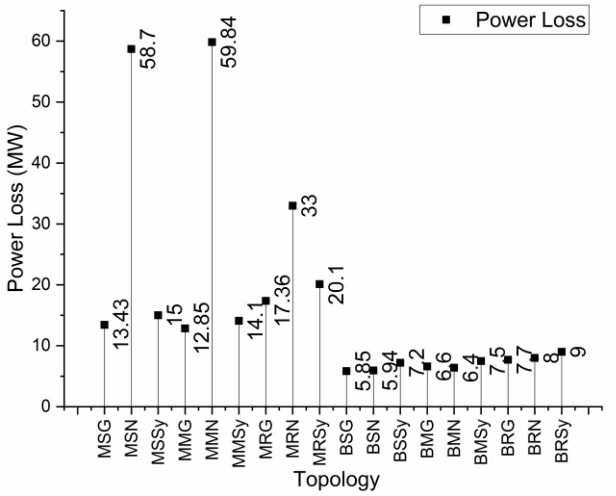


Fig. 16. *Overall power loss in Transmission of each topology*

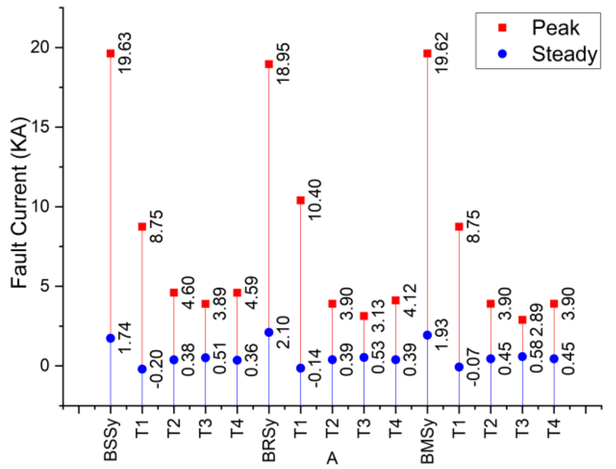


Fig. 17. *Transient and Forced Response in Bipolar Symmetric return topologies with current observed at terminals*

If one type of topology has to be chosen from all topologies mentioned in Table 1 on the basis of fault current response only, it will be Monopolar Ring Symmetric return (MRSy) topology as it exhibits best fault response in the time domain in all design sections. However, it may not be economical in terms of energy transmission as it has higher conduction loss. Combining factors of transmission efficiency and fault response, as per performance index is given in Table 5, Bipolar Star Symmetric Return topology (BSSy) is the best topology to be applied for power transmission in HVDC networks.

6. Acknowledgements

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Table 5. Performance Index (P.I.)

Topology	P.I.
MSG	1.4
MSN	0.5
MSSy	4.2
MMG	1.5
MMN	0.5
MMSy	4.1
MRG	1.2
MRN	0.9
MRSy	3.6
BSG	3.4
BSN	3.7
BSSy	4.3
BMG	3.0
BMN	3.4
BMSy	4.1
BRG	2.7
BRN	2.8
BRSy	3.5

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