Comparison of Fault Currents in Multiterminal HVDC Grids with Different Grounding Schemes

Matthias K. Bucher, Student Member, IEEE, and Christian M. Franck, Senior Member, IEEE

Abstract—The requirements of dc circuit breakers used to protect multiterminal HVDC networks are specified by the prospective fault current. The fault current, however, strongly depends on the grounding scheme of the network. Low-ohmic and high-impedance earthing practices with different grounding points are presented and compared with each other in terms of fault currents and overvoltages during a pole-to-ground fault. To do so, monopolar and bipolar configurations of a multiterminal HVDC cable network are implemented in PSCAD and simulations are performed.

Index Terms—HVDC transmission, Power system faults, Power system simulation, PSCAD.

I. INTRODUCTION

MULTITERMINAL high voltage dc (HVDC) networks are widely recognized as a key technology for the future bulk power transmission. Several initiatives from academia, industry consortia, and environmental NGOs [1]–[4] propose the building of such a network to overcome the technical and economical shortcomings of a HVAC based network with long transmission lines. An unresolved issue of multiterminal HVDC (MTDC) networks is their protection. HVDC circuit breakers (CBs) are needed to reliably clear faults and isolate the affected lines in a MTDC network. The fault clearing concept as used in point-to-point HVDC links, where ac CBs interrupt the current on the ac side of each converter, cannot be adapted to MTDC networks due to the required de-energization of the entire network [5], [6]. Several HVDC concepts have been proposed [7], [8], which still have drawbacks in either speed or on-state losses and additional fault clearing support is required [9]. The specification of the HVDC CB requirements demands a good knowledge of the transient currents and voltages in the CB during a fault. To get a deeper understanding of such transients, the fault current is broken down into the individual contributions from the different network components as proposed in [10] and a comparison of cable and overhead line networks is presented in [11]. The influence of the network layout on the fault current through the CB is analyzed in [12] and [13]. All of the aforementioned studies assume a low-ohmic grounding of the MTDC network.

The paper at hand presents additional MTDC grounding strategies for monopolar and bipolar MTDC cable configurations and compares them in terms of transient CB current and overvoltage at the healthy pole during single pole-to-ground faults based on simulations in PSCAD. Moreover, advantages and disadvantages of each grounding scheme regarding operation and costs are explained. The emphasis in this paper is on pole-to-ground faults, since they are regarded as significantly more frequent compared to pole-to-pole faults [14], although the latter would lead to more severe conditions.

The paper is structured as follows: Section II introduces the possible HVDC configurations and Section III the grounding practices. Section IV presents the fundamental transient behavior of a pole-to-ground fault and shows its implications and in Section V, the modeling in PSCAD is explained. The simulation results are presented and compared in Section VI and conclusions are drawn in Section VII.

II. HVDC CONFIGURATIONS

In general, monopolar and bipolar system configurations are distinguished. Monopolar systems are intended for moderate power transfers and are the least expensive systems [15]. Only one converter is used for each terminal. The asymmetric monopole as depicted in Fig. 1 with earth return is the simplest configuration. It requires only one fully insulated high-voltage conductor, but at the expense of a constant dc current through the ground that can cause corrosion of buried metallic structures such as pipes and earthing equipment of substations, transfer of high potentials, and saturation of transformers [16]. The use of a dedicated low-voltage neutral conductor (cf. Fig. 1, dashed line) mitigates the aforementioned problem, but requires the installation of two cables/lines and reveals higher transmission losses and costs compared to systems with earth return [17]. The symmetric monopole shown in Fig. 2 is the most popular configuration for point-to-point HVDC links. There are no ground currents during normal operation, but two fully insulated pole conductors have to be installed. The bipolar configuration in Fig. 3 has a higher transmission capacity than the other systems and provides more flexibility and redundancy due to two independently controlled poles. After a ground fault or the loss of one converter, the bipole can still be operated as a monopole at reduced capacity. A metallic return (cf. Fig. 3, dashed line) is used again for the monopolar operation, if dc ground currents are not permissible. This solution results in higher costs compared to the earth return scheme because of the additional neutral cable.

III. GROUNDING PRACTICES

Analogous to ac networks, HVDC systems are grounded either through a low-ohmic connection or via a high impedance. The low-ohmic grounding has the advantage of reduced overvoltages at the healthy pole during a pole-to-ground fault, but suffers high overcurrents. In contrast, high-impedance
A. Asymmetric Monopole

The MTDC network based on asymmetric monopoles can be grounded either low-ohmic at all terminals (Fig. 1 option A) or via a high-impedance reactor together with a dedicated metallic return (MR) conductor as illustrated in Fig. 1 (option B). Using the latter option, the MTDC network can either be grounded at all terminals or at one terminal only, which serves then as voltage reference. Metal oxide surge arresters (MOA) are usually connected in parallel to the grounding reactors to avoid overvoltages [19]. In metallic return operation, the non-grounded terminals are protected by MOAs and metallic return circuit breakers (MRTB) to clear faults on the neutral conductor [16], [20]. The grounding MOAs and MRTBs are not shown in Figures 1-3.

B. Symmetric Monopole

For the symmetric monopole network in Fig. 2, the dc capacitor midpoint can be earthed solidly (option A) or via a reactor (option B), the dc busbars can be connected to earth through a high-ohmic resistance (option C) or the converter side of the transformer can be grounded via a star point reactor (option D) as proposed in [21], [22]. For all options, the network can be grounded at all terminals or at only one. MOAs are used again to avoid excessive voltages across the grounding reactors and at non-grounded capacitor midpoints.

C. Bipole

The proposed bipole options are: solid grounding of the capacitor midpoint (option A in Fig. 3), grounding through a reactor (option B), and high resistance dc busbar earthing (option C). If the bipole has to be capable of monopolar operation after a fault at one pole or the loss of one converter, the system has to be either solidly grounded at all terminals or in case of high-impedance grounding, a metallic return is required with grounding at one terminal. The dc capacitor midpoints at the other terminals are protected again by MOAs and MRTBs.

IV. Pole-to-Ground Faults

Pole-to-ground faults may occur due to aging of the cable main insulation or external damages due to digging or anchoring in case of sea cables [23] and subsequent breakdown of the cable insulation. After the ground fault occurs, the voltage at the fault location decreases rapidly and negative voltage surges start to travel from the fault location into both directions...
towards the terminals. Along its way, the distributed cable capacitance is discharged gradually into the ground fault. Upon the arrival at the terminals, the negative voltage surge is partly reflected back as a positive surge due to the dc capacitors [24] and partly transmitted into the adjacent feeder cables at the same busbar [10]. DC capacitors include the VSC capacitors and possible tuned filter capacitors, which are usually installed on the dc side of a VSC in order to reduce the voltage ripple injected by the converter. The converter technology determines the size of the dc capacitor as explained in [10]. The dc capacitors and the neighboring cable capacitance are discharged given a ground loop between the fault and the earthing points of the system and depending, therefore, on the grounding scheme described in the previous section. The capacitor discharge current is superposed on the reflected, backward traveling surge. As the positive surge arrives again at the fault location, it is reflected with opposite polarity and sent back towards the terminal. The forward and backward traveling waves result in multiple peaks in the fault current wave form. In addition, the ac side feeds the ground fault through the freewheeling diodes of the blocked half-bridge based converter after the voltage at the dc bus has dropped below the converter’s ac side voltage, but only in bipolar and asymmetric monopolar configuration. In contrast, symmetric monopole configurations and full-bridge converter topologies are able to block the ac infeed completely.

V. Modeling

A description of the PSCAD models of the network and cables for the simulation study are presented in this section.

A. Converter and Network Model

The 3 terminal radial HVDC networks shown in Figures 1-3 are modeled in PSCAD. In all configurations, the cable connecting terminal 1 and 2 is 270 km long and the cable between terminal 1 and 3 has a length of 350 km. A pole-to-ground fault occurs 100 km away from terminal 1 assuming the worst case with zero fault resistance. In the following, the current through the CB at terminal 1, which is the closest to the fault, will be analyzed. The converters are modeled as a 320 kV two-level VSC topology with concentrated dc capacitors of 10 µF and 10 mH pole reactors \( L_p \). For a better comparison of the results, the monopolar configurations are assumed to have the same rating of 900 MW as the bipole. The converter control protects the Insulated Gate Bipolar Transistor (IGBT) modules from overcurrents through blocking of the valves making the half-bridge based VSC an uncontrolled diode rectifier [25]. Therefore, the converter model to be implemented for the transient study can be simplified.

The ac network adjacent to the converter terminal is modeled by its equivalent short-circuit impedance consisting of \( R_{AC} \) and \( L_{AC} \), and a voltage source \( V_{AC} \). The ac network impedance is calculated assuming a short-circuit ratio (SCR) of the ac grid of 20. The windings of the converter transformer have star configuration with grounded neutral on the high voltage side and delta configuration on the converter side. A phase reactor \( L_n \) is installed between converter bridge and transformer for harmonic filtering of the ac currents. The system parameters are summarized in Table I.

In all configurations as illustrated in Figures 1-3, the dc busbars are protected against overvoltages by MOAs. The V-I characteristics of the MOA for dc applications are taken from [26]. The voltage is scaled up and the dc reference voltage of the MOA at 1 mA is set to the nominal dc system voltage of 320 kV. The resulting V-I curve is depicted in Fig. 4 with a logarithmic scale for the arrester current and the arrester voltage normalized to the nominal dc system voltage.

The dc busbar earthing (option C in Fig. 2) is provided by a 1 MΩ resistor in order to maintain the dc currents at a reasonable low level during normal operation. For the dc side high-impedance grounding scheme (option B in Figures 1-3), a 100 mH reactor is used. The ac side earthing (option D in Fig. 2) uses a star point reactor with 5000 H, which is grounded through a 5 kΩ resistor as proposed in [22].

![Fig. 4. V-I characteristics of the MOA](image)

B. Cable Model

The system is modeled in PSCAD and makes use of a detailed frequency-dependent, distributed-parameter cable model. The general design of the cable cross-section is derived from a real 150 kV XLPE VSC-HVDC submarine cable [27], [23]. The cross-section was scaled up to a 320 kV cable respecting the diameter of the copper conductor [28], while keeping the electric field stress (cold condition) similar. The material properties and cable cross-section dimensions are
given in [10]. The shunt conductance of the XLPE insulation is set to $10^{-12}$ S/km and the sheath is assumed to have ground potential over the whole cable length.

VI. RESULTS AND DISCUSSION

In this section, the results of the CB fault current simulations with the different earthing schemes are compared and discussed. The results are presented for the symmetric monopole and the bipole configuration. During pole-to-ground faults without capacitive coupling of the poles, asymmetric monopoles show the identical behavior as bipole systems and are not presented here.

A. Symmetric Monopole Configuration

Figure 5 illustrates the fault current through the CB in the symmetric monopole system during the first 30 ms after fault occurrence for the different grounding options. The symmetric monopole inhibits the contribution from the ac side through the converter’s freewheeling diodes and has, therefore, zero steady-state fault current. There are, however, the capacitive contributions from the dc capacitors and the adjacent feeder capacitance [10] that lead to a steeply increasing CB current. Even in grounding configurations without dc capacitor midpoint earthing (HRB and HLAC in Fig. 5), the capacitors are discharged. If no capacitor midpoint ground is provided, the ground loop is closed through the earthed sheath of the healthy pole cables. The cable capacitances and the dc capacitors form a series circuit and are discharged into the ground fault. As expected, the LRGND scheme leads to the highest CB current and the HRB and HLAC options to the lowest fault current levels. The HRB (cyan curve) and the HLAC (black curve) schemes are identical. Both options have a very high ohmic path for the ground current. For the chosen dc capacitor size of 10 µF, the earthing scheme has only a marginal influence on the CB current peak (blue, green, cyan, and black curve), since the cable discharge contribution from the negative, healthy poles is dominant. Large dc capacitors of 100 µF, however, yield much higher discharge peaks in LRGND configuration (red curve) and the advantage of lower fault currents in the non-solidly earthed HRB scheme (magenta curve) becomes more accentuated. Whether the symmetric monopole network is grounded at all terminals or only at one does not affect the capacitive discharge dominated period due to the delay of the contributions from the remote terminal 3 [10].

A ground fault in a symmetric monopole leads only to moderate overvoltages at the healthy pole for all earthing schemes. The maximum steady-state overvoltage of about 19% occurs in the HRB earthing scheme.

B. Bipole Configuration

During the first 5 ms after fault occurrence, the results of the bipole system depicted in Fig. 6 are identical to those in the symmetric monopole as shown in Fig. 5. Afterwards, the bipole reveals much higher fault current levels due to the additional infeed from the ac side. The lowest steady-state fault current through the CB is seen in the HRB option (magenta curve), because of the largest impedance in the ground current path compared to the other grounding practices. The dc capacitor midpoint earthing options LRGND (blue curve) and HLGND (green curve) exhibit an almost equal steady-state fault current, but it increases slower in the HLGND due to the grounding reactor. Slightly lower steady-state CB currents can be observed with metallic return (red and cyan curve) than with earth return (blue and green curve) due to the single grounding point and the additional neutral cable impedance in the ground current path, which reduces the ac side contributions from terminal 3 and decreases the $\frac{di}{dt}$ of the resulting CB current.

Figure 7 shows the voltage at the healthy pole in the bipole configuration for the different earthing schemes. No overvoltages are observed with LRGND at all terminals using the earth return (blue curve) and the highest permanent overvoltages in HRB configuration (magenta curve) due to the high-ohmic grounding point in the dc grid. The LRGND option (blue and red curve) has better transient performance than the system with HLGND (green and cyan curve) due to the temporary voltage shift of the capacitor midpoints and resulting higher voltages at the healthy pole. Moreover, it suffers higher permanent overvoltages in case of a metallic return with single grounding point at terminal 1 (red and cyan curve) due to the permanent midpoint voltage shift at the non-grounded terminals, which affects also the voltage at the healthy pole of the grounded terminal 1.

VII. CONCLUSIONS

The results have demonstrated the expected effect of high fault currents and low overvoltages in systems with solid earthing on the dc side and the opposite effect in high-impedance grounding schemes. The earth reference option through high resistors at the dc busbars exhibits the lowest fault currents, but the highest overvoltage stresses at the healthy pole. In general, only a marginal influence of the earthing practice can be observed during the first 5 ms, when the capacitive discharge dominates and the dc capacitor size is much more
In terms of overvoltages, the grounding at a single terminal symmetric monopole suffers less overvoltages than in a bipole. Moreover, the healthy pole in a monopole configuration. Additionally, the healthy pole in a bipole configuration does not experience any overvoltage during this period. Afterwards, the CB current increases gradually in a bipole due to the increasing ac infeed.

**Fig. 6.** CB current in bipole configuration - LRGND: Low R midpoint grounding, HLGND: High L midpoint grounding, HRB: High R busbar grounding, ER: Earth return, MR: Metallic return

**Fig. 7.** Voltage at healthy pole in bipole configuration - LRGND: Low R midpoint grounding, HLGND: High L midpoint grounding, HRB: High R busbar grounding, ER: Earth return, MR: Metallic return

decisive. Bipole and symmetric monopole configurations yield the same results during this period. Afterwards, the CB current increases gradually in a bipole due to the increasing ac infeed and it decreases to zero in the ac infeed blocking symmetric monopole configuration. Moreover, the healthy pole in a symmetric monopole suffers less overvoltages than in a bipole. In terms of overvoltages, the grounding at a single terminal performs worse than grounding at all terminals due to the dc capacitor midpoint shift at non-grounded terminals.

**REFERENCES**


