From pole-to-ground fault current return paths in a meshed HVDC network to a grounding modelling simplification for protection studies

Myriam Ratajczyk, Bertrand Raison, Alberto Bertinato

Abstract—**Meshed bipolar High Voltage Direct Current grids are considered as one of the preferable solutions for integration of renewable energy sources and increasing the security of power systems on a continental scale. In this context, several fault current studies are proposed in the literature, considering different grounding methods for modular multilevel converter neutral points. But these studies often focus on fault current paths to the fault location, and none of them analyzes the return paths of fault current from the fault location. This article deals with fault currents return paths in case of pole-to-ground fault in a grounding configuration using surge arresters in all stations except one, which is solidly grounded. The influence of this solidly grounded point location on the return paths of fault currents is evaluated. With these results, a modelling simplification is considered for HVDC protection studies. Specifically, the discussion investigates whether all MMC neutral points can be solidly grounded.**

Keywords—**Bipolar configuration, DC grid protection, Fault current analysis, Modular multilevel converter (MMC), Multiterminal HVDC (MTDC) , Surge arrester grounding**

I. Introduction

THE idea of an HVDC Supergrid seems to be a good solution to integrate renewable energy sources and to increase security power systems on a continental scale [1]. The use of Modular Multilevel Converters (MMCs) with a bipolar configuration and a dedicated metallic return (MR) seems to be among the preferred options according to [2] and [3]. But several technical points are still under discussion to find the most adapted configuration, including the MMC neutral point grounding method. The chosen method will influence the grid behaviour in case of fault.

The behaviour of HVDC pole-to-ground fault currents in a bipolar grid from their sources to the fault location has been widely explained in the literature [4] [5] [6] [7]. In case of pole-to-ground fault in a bipolar grid with MMC, the fault current is mainly fed by two kinds of contributions: cables discharge and the MMCs contribution (submodules discharge and AC transmitted contribution) [8]. When the fault happens, the voltage drop caused by the short-circuit spreads into the network, discharging cables capacitances into the fault. Until the first discharging wave reaches a conversion station (in a few milliseconds), the cable discharge is the only current source of the fault [7]. Then, the voltage drop leads to the discharge of MMC submodules capacitances until the station blocks to protect its components. Half-bridge MMC behaviours are then similar to diode rectifiers that transmits AC contributions to the fault [9].

As explained in [3], the impedance, number and location of grounding points are important elements to take into account when considering DC system grounding. Several grounding configuration are discussed in the literature depending on grid topologies [10]. In bipolar configuration, there must be at least one MMC neutral point solidly grounded on the DC side as voltage reference [10]. After a permanent pole-to-ground fault or converter fault, the remaining healthy pole is expected to operate as an asymmetric monopole, using the dedicated metallic return as return path. In this situation or in case of unbalanced operation, if more than one MMC neutral point is solidly grounded in the DC system, current may flow through the ground instead of through the dedicated metallic return [3]. Steady state earth currents are to be avoided for safety and environmental reasons, therefore only one point is chosen to be solidly grounded. To limit both earth currents and over-voltages on MMC neutral points, a possibility is to ground all other MMC neutral points through high-impedances such as surge arresters (SAs) as mentioned in [3].

As stated in [2], the grounding method may have an impact on main and back-up sequences of the protective relays for fault detection and identification. Indeed, [2] explains that depending on the solidly grounded point location, current paths impedances change, influencing voltage and current overall behaviour. [2] considers a grounding configuration where, except for one solidly grounding point, all MMCs are not grounded at all. MMC current contributions are then forced to flow from the fault to the solidly grounded point and use metallic returns to go back to their stations. But with a grounding configuration based on surge arresters as discussed above, other current return paths are allowed, which may influence the overall fault current return paths.

As explained in [11], the design of an HVDC ground electrode is a very complex matter, that first requires selecting the best site based on geographical, geological, and geophysical studies. Therefore, the location of the solidly grounded station is likely to be chosen based on the local ground conditions. For this reason and to ensure reliability, the location of the solidly grounded MMC must be flexible from the protection system point of view. As a result, the

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protection system needs to be designed to accommodate all potential grounding configurations, which can come with a high computing cost. However, if a modelling simplification is employed where all MMCs are solidly grounded, and if it does not unacceptably reduce results accuracy, it could significantly reduce the computing time required for protection studies.

Based on prospective fault current analysis through EMT simulations, this article contains:
- An empirical study of the return paths of pole-to-ground fault currents within a meshed HVDC bipolar grid considering an MMC neutral grounding configuration with SAs and one solid grounding;
- A empirical analysis of the influence of the solidly grounded point location on fault current return paths;
- A discussion about the accuracy of a modelling simplification where all MMCs are solidly grounded for HVDC protection studies in the considered case.

After a presentation of the considered cases in section II, section III analyses the possible fault current return paths. In section IV, the accuracy and potential generalisation of the proposed simplification is discussed. A conclusion sums up the results in section V.

II. Description of the considered cases

The benchmark grid is a bipolar grid with dedicated metallic return (MR), which global structure is based on the PROMOTioN network [12]. The structure is presented in Fig. 1, where only positive poles are represented. The grounding method is defined in Fig. 2 below. Parameter values are taken from NSWPH project [13] and are presented in Table I. The following hypothesis are used:
- MMCs are modelled with average arm models as presented in [14].
- AC networks are modelled as ideal AC voltage sources with impedance.
- 1 GW per pole flows from stations 1 and 2 to 3 and 4.
- This study focuses on cables. Their screens are solidly grounded at both cable ends. Modelling details are given in appendix.
- To study persistent current, MMC blocking and DC reactors (DCR) are considered, but no breaker. MMCs block when the pole-to-neutral point voltage is lower then 325 kV (0.6 pu) or when their arm current is higher than 4 kA (2 pu).
- DC reactors value is fixed at 100 mH as in [2].
- The considered fault is a pole-to-ground fault on the positive pole at the end of cable 13, close to station 1, modelled with a resistance of 10 mΩ in series with an ideal switch closing at 200 ms.

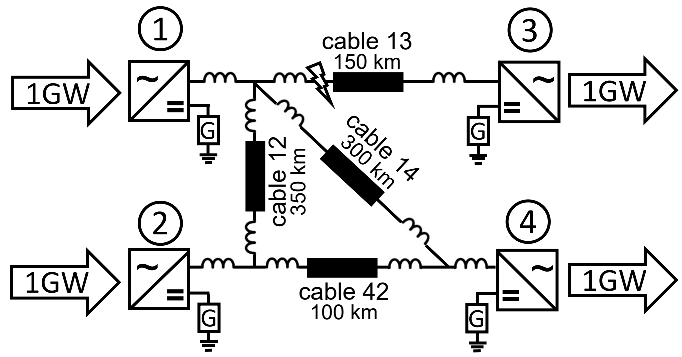


Fig. 1: Benchmark grid (positive pole)

The grid configuration follows the parameters of Table I.

TABLE I: Benchmark grid parameters

Rated DC voltage	525 kV
Rated pole DC current	2 kA
Configuration	Bipolar with metallic return
MMC power	1 GW per pole
Rated primary AC voltage	380 kVRMSLL
Stations 1 and 2 apparent short-circuit power	3600 MVA per pole
Stations 3 and 4 apparent short-circuit power	10000 MVA per pole
DC reactor value	100 mH

EMT simulations were performed using EMTP-RV version 4.2.1, with a simulation time step of 5μs. Except for the solidly grounded point (SGP), MMC neutral points are grounded through SAs as presented in Fig. 2 below.

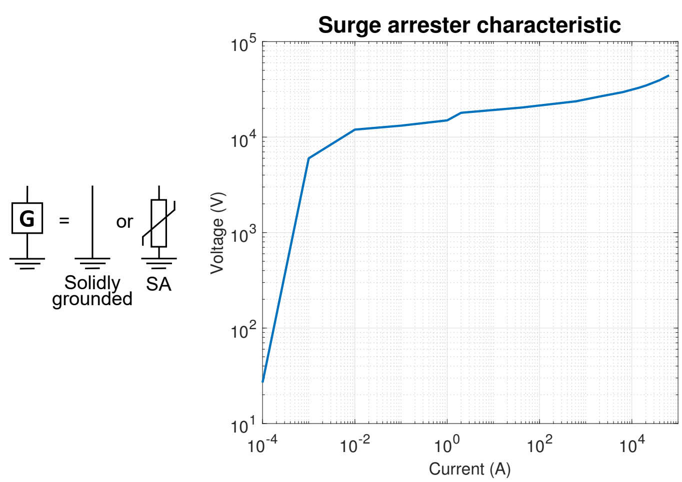


Fig. 2: Considered grounding methods

The following part analyses fault current return paths in the described network.

III. Current return paths analysis

A. Current contributions and mediums to return

As explained in [6], the fault current can be considered as composed of several current contributions. One current contribution can be defined by its source, either MMC or cable. In the case under study, there are 8 contributions to consider (4 positive pole cables and 4 positive pole MMCs).

Each of them flows through one or several loops through the network. The first part of these loops, from sources to fault location, is always through the positive faulted pole core and adjacent ones, whatever the grounding situation. To return from the fault location to their current sources, currents can use 3 mediums as can be seen in Fig.4: the ground, cables screens and/or metallic returns cores.

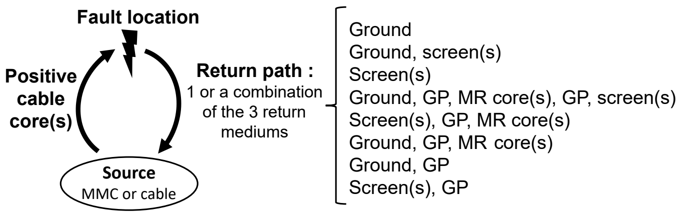


Fig. 3: Possible current contribution loops. GP: Grounding Point; MR: Metallic Return

Each cable contribution uses all possible return paths, but some of them are favored, depending on paths global impedance.

Each medium has a different impedance, that can be evaluated based on [15] work. The following graph, Fig. 4, presents the lineic impedance of different current loops through the 3 mediums for the benchmark cable described in [13] and in appendix. It only takes into account the cable and ground impedances, considering that the cable is long enough to neglect cable terminations.

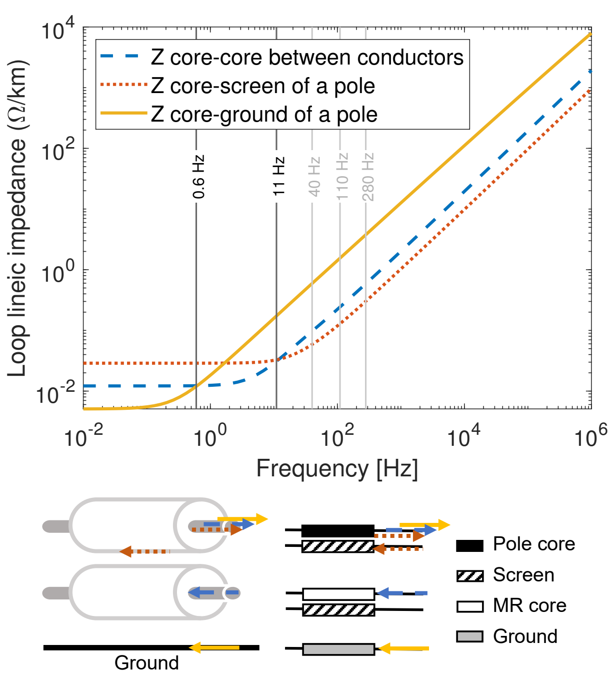


Fig. 4: Current loops lineic impedances

Considering all these paths, an example of the connection of a station is given in Fig. 5 below. It considers a station that is connected to only one cable. MMC neutral point grounding is represented as "G" and the current flowing through G is labelled "GP". It is either solidly grounded or grounded through a surge arrester as represented in Fig. 2. Voltages across grounding connections G are defined from MMC neutral points to the ground.

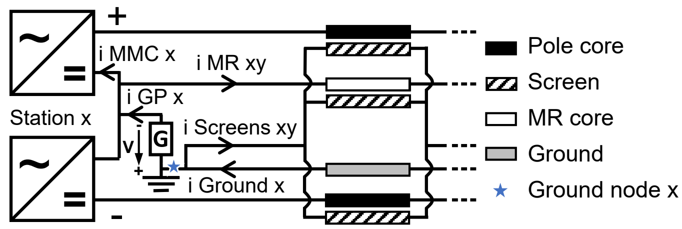


Fig. 5: Example of a station connection to one cable considering all possible kind of path

So, for a fault current contribution, it is possible to explain which return paths are favoured by knowing:
- the source of the fault current contribution
- frequencies of the fault current
- the solidly grounded point location
- surge arresters behaviour and impedance
- the different return medium loop lineic impedances.

Parts III-B and III-C below report on fault current contributions behaviours observed in EMT simulations, and uses the principles presented in part III-A to explain the observed phenomena.

B. Cable discharge

Fig.6 below shows a comparison for all 4 SGP locations of the cable discharge currents that loop through the capacitive coupling between the core and the screen of each positive pole cable. These contributions are measured by the difference between currents flowing in and out of screens.

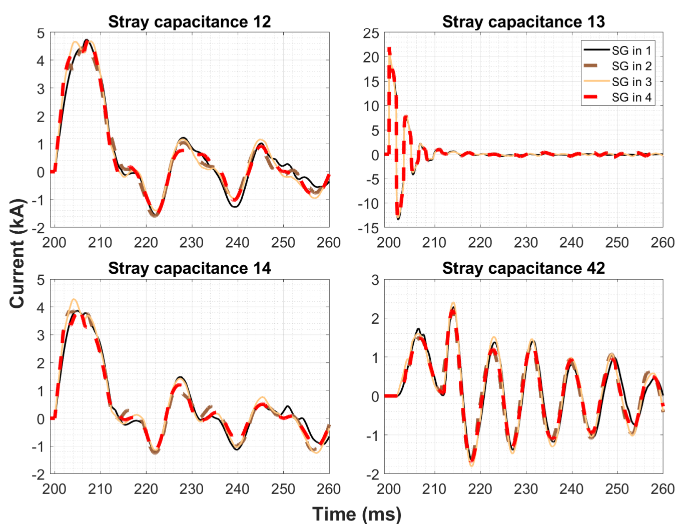


Fig. 6: Currents flowing though core-screen stray capacitances : difference of current flowing in and out of each positive pole screen

As can be seen on Fig.6, all curves overlap, hence cable discharge contributions are not influenced by the SGP location. Thus, it can be assumed that these fault current contributions do not flow through grounding points.

By approximating the curves of Fig.6 with sine waves, one can estimate the lower bound frequencies to be on the order of 40 Hz for screens 12 and 14, 110 Hz for screen 42 and 280 Hz for screen 13. As it can be seen on Fig. 4, for these frequency values, current would favour screens. It is then coherent with the observations that the cable discharge current do not flow through metallic return cores via grounding points. According to Fig. 4 again, and because their frequencies are high, cable discharge currents are also very unlikely to flow through the ground. Thus, cable discharge currents flow through their screens and adjacent screens. The frequencies of cable discharge current depend on cable lengths and inductances values. A higher inductance value could lead to a frequency reduction that would make the current favour another path. This conclusion is then specific to the case under study.

During the very first ms following the fault, the predominant fault current contribution is composed of cable discharge currents. For example, on the Ground node 1 in Fig. 7, the fault current and the screen 13 current overlap during the first ms following the fault. Algorithms based on first waves should indeed not be impacted by MMC grounding method or location, which is consistent with the results presented in [2].

C. MMC contribution

Two representative situations are studied. The solidly grounded point (SGP) is located in 1, close to the fault, or in 4, far from the fault.

1) Solidly grounded point in station 1: Currents of ground nodes, as defined by the star in Fig.5, are presented in Fig.7 below. The SGP is located in station 1.

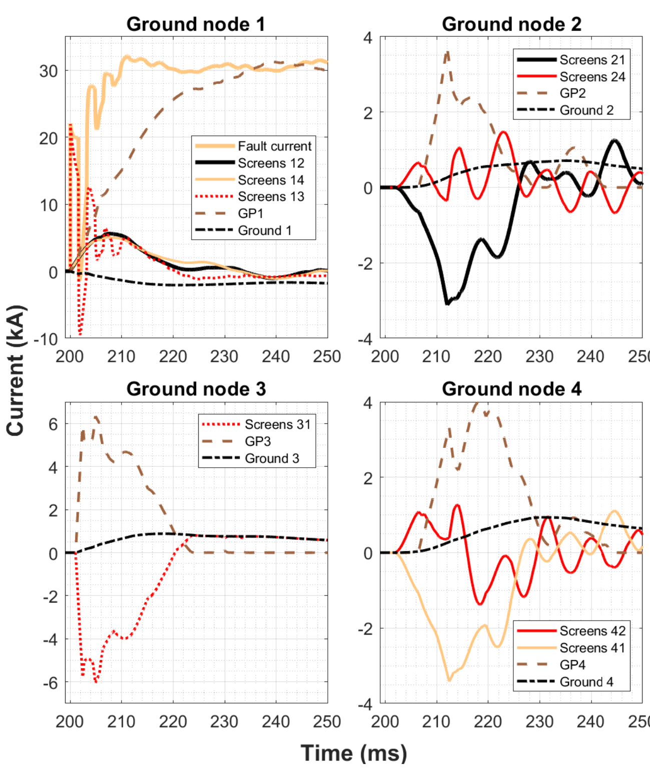


Fig. 7: Ground nodes when the SGP is located in 1

As can be seen on Fig. 7, MMC1 current returns through the grounding point 1. MMC 2, 3 and 4 currents are first conveyed by screens, again because they are the medium of the lowest impedance for current above 11 Hz. Almost no current flows through the ground (see Ground node 1 in Fig. 7).

As current flows through screens and grounding points, SAs voltages in grounding points 2, 3 and 4 rise as it can be seen on Fig. 9. Since the MMC neutral point 1 is solidly grounded, it creates voltage differences between terminals of metallic returns 12, 13 and 14 as represented in Fig. 8. These voltages, and the fact that current frequencies gets lower with time in a damped system, progressively drive return currents to flow through metallic returns instead of screens. After 30 ms, the grounding point one and metallic returns become the major current paths to convey MMC contributions.

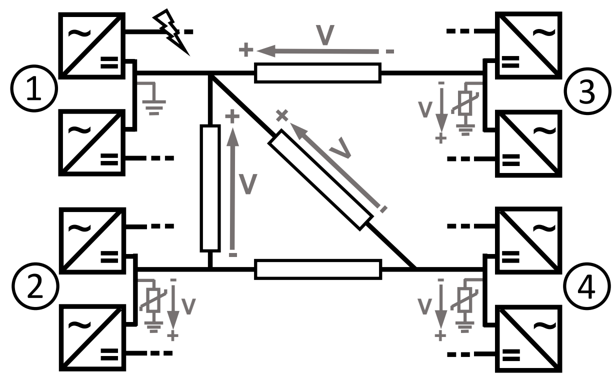


Fig. 8: MR voltage maps when the SGP is located in 1

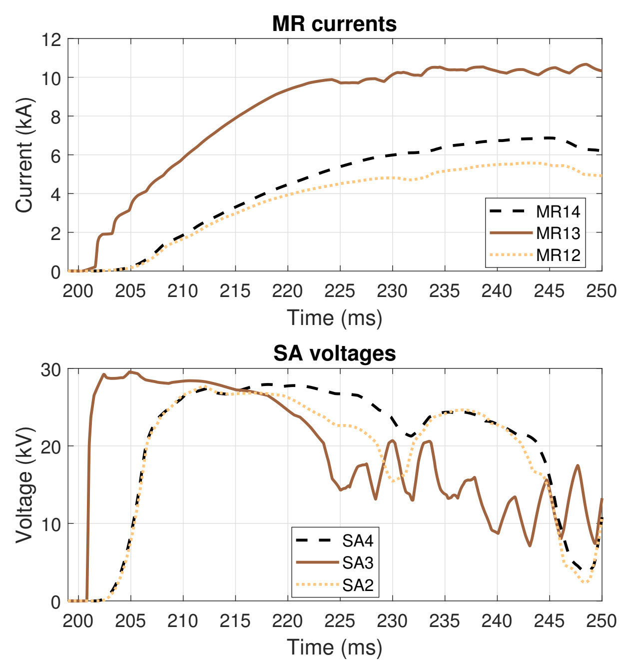


Fig. 9: MR currents and and SA votlages (accordingly to voltage convention presented in Fig. 8) when the SGP is located in 1

2) Solidly grounded point in station 4: Similarly to the previous case, MMC1 contribution flows through the grounding point 1, and MMC 2, 3 and 4 contributions first return through screens and stations grounding points (see Fig. 10 below).

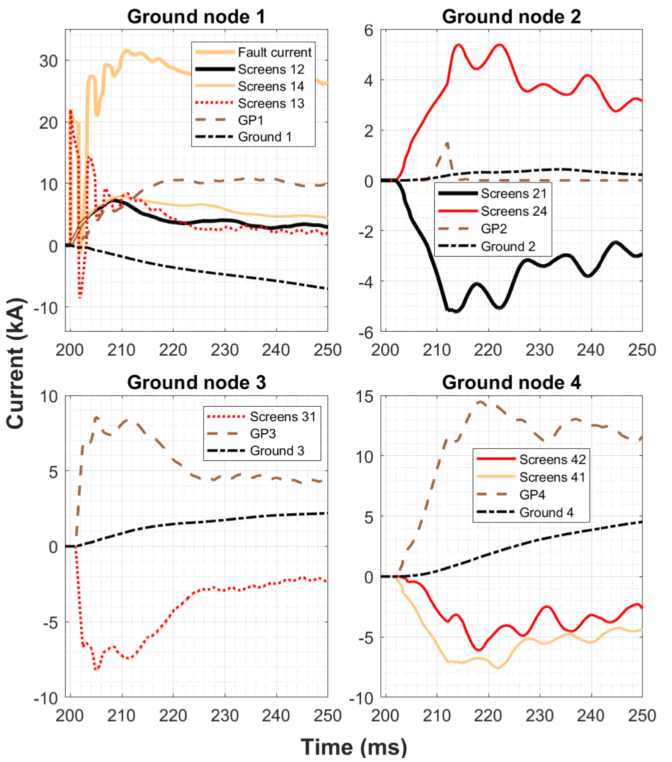


Fig. 10: Ground nodes when the SGP is located in 4

This causes the voltage of surge arresters 1, 2 and 3 to increase. But as the solidly grounded point is now located in 4, voltage differences on metallic returns are set in different directions that can be visualised in Fig. 11 below.

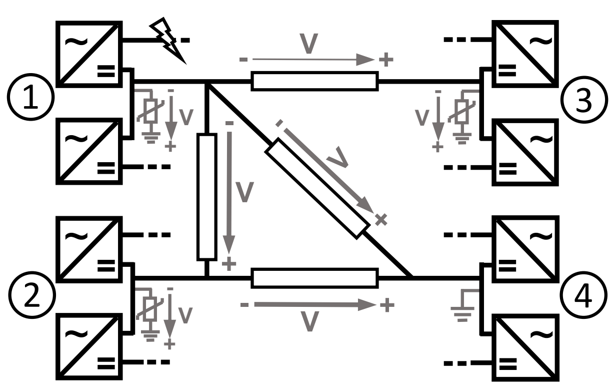


Fig. 11: MR voltage maps when the SGP is located in 4

MR24 current is then favoured from station 4 to 2. But the voltage difference at MR41 terminals does not favour currents in a direction that drives MMC current contributions back to their own MMCs. Thus the MR14 flows almost no current as can be seen on Fig.12. It is the same situation for MR12, and with a much smaller scale for MR13. But for the latter, its voltage is not high enough to stop the current from flowing.

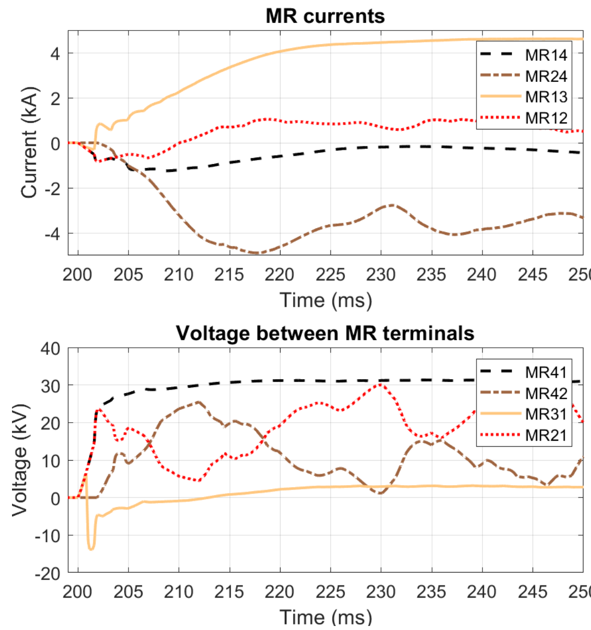


Fig. 12: MR currents and voltages (accordingly to voltage convention presented in Fig. 11) when the SGP is located in 4

As time goes by, MMC current frequencies decrease, and screens are less and less favoured by currents. Since some MRs are unavailable to flow MMC contributions in the right direction, the ground becomes an interesting path for the current. As can be seen on Fig. 10, currents flow through the ground to the station 3 and 4.

MMCs fault current contributions initially favour screens and grounding points to return. Subsequently, surge arresters set a voltage map on MRs cores. Depending on the SGP location, the voltage map either favours MR cores as return paths, or it disadvantages them, leading indirectly to favour the ground. Therefore, the SGP location influences MMC current return paths and impedances, ultimately affecting the fault current magnitude.

Based on previous observations of cable discharge and MMC fault current contributions, the following section discusses the accuracy of a simplified grounding modelling, that assumes all stations solidly grounded. The discussion focuses on the network under study for the time range relevant for HVDC protection studies.

IV. Discussion

Based on the findings presented in section III, it can be concluded that a simplified model built without any surge arresters does not adequately account for the return paths of fault currents. Therefore, this modelling approach is inadequate for conducting studies that specifically investigate any element of these return paths, including the ground, screens, MRs, and grounding points. However, the modelling simplification can be accurate enough for some specific protection studies delailed below.

In the case of a fully-selective protection strategy, as defined in [3], DC circuit breakers (DCCBs) are required to open at both cable ends in case of a pole-to-ground fault. The slowest DC breaker (mechanical breaker) would open in less than 10 ms [13]. But in case of DCCB failure, adjacent DCCBs must open. These breakers would have opened within a maximum of 20 ms after the fault.

As can be seen on Fig.13 below, in the time range relevant for the primary sequence of a fully-selective protection strategy, MMC fault current contribution is not impacted by the location of the SGP. But in the time range of a back-up sequence, the influence of the SGP location can already be significant. Thus, the latter is important to be considered for simulations related to protection design.

Fig.13 suggests that a solidly grounded MMC provides a higher fault current contribution than an MMC grounded with a surge arrester. This difference is even more important when the MMC is close to the fault. Indeed, SAs impose voltages between MMC neutral points and the ground. Unlike when the MMC is solidly grounded, these voltages are also imposed between the terminals of positive-pole MMCs grounded through SAs. The voltage difference between the terminals of the latter MMCs are then maintained above the voltage of their SAs.

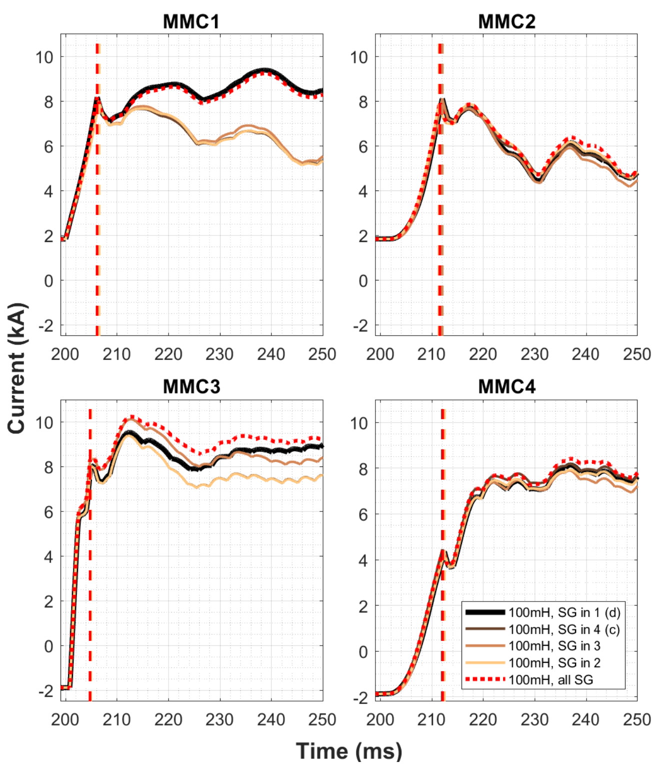


Fig. 13: MMC current comparison for different solidly grounded point locations. Dashed lines are MMC blocking times. MMCs 1 and 2 block due to overcurrents; MMCs 3 and 4 due to undervoltages.

According to Fig.13, when all MMCs are solidly grounded (red dotted curve), and for the time range relevant to protection as discussed above, each MMC provide the same contribution as if they were the only solidly grounded MMC in the network.

The grounding modelling simplification is then accurate enough for studies that considers both
- fault currents on their way from their source to the fault
- scenarios that lead to the highest fault currents.

For instance, this modelling simplification could be applied for inductances or DCCB sizings studies.

V. Conclusion

This paper analysed current return paths from a DC pole-to-ground fault to current sources (MMCs and cables) in a meshed bipolar grid grounded through surge arresters. One MMC neutral point is solidly grounded and the impact of its location on the path of different fault current contributions was studied.

Cable discharge current only flows through cable screens to return from the fault. Thus they are not impacted by the solidly grounded point location.

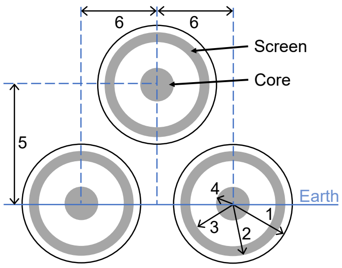
MMC current contributions first return through screens shortly after the fault occurrence to reach MMC grounding points. It increases surge arresters voltages, and sets a voltage map on metallic returns. Depending on the location of the solidly grounded point, these voltages either favour metallic returns as fault current return paths, or in the contrary it disadvantages them, making the ground a more advantageous path. A solidly grounded MMC provides a higher fault current contribution compared to an MMC grounded with a surge arrester. This difference is even more important when the MMC is close to the fault.

In the final section of the paper, the accuracy of a simplification in grounding modelling was discussed. This simplification assumes that all MMCs are solidly grounded. For the time required for a DCCB to open in a fully-selective protection strategy, this simplification is accurate enough for studies that focus on scenarios that lead to the highest fault currents on their way to the fault location. For instance, it is accurate enough for DCCB or inductance sizing studies. However, it is not accurate enough to study any element on current return paths from the fault locations, such as the ground, screens, metallic returns, and grounding points.

Because the impedances of fault current return paths are frequency-dependent, it may be necessary to conduct further studies, such as mathematical analysis, to generalise these conclusions to different inductance values and network topologies.

VI. Appendix: Cable parameters

Cables were modelled with the frequency-dependent wideband model provided by EMTP-RV using the following parameters:



1	63.9 mm
2	58.2 mm
3	56.9 mm
4	32 mm
5	250 mm
6	250 mm

Fig. 14: Cables parameters

The metallic return conductor is located on the top and is modelled with the same cable than poles. Core resistivity is 1.72e-8 Ωm and 2.83e-8 Ωm for screens. All insulator relative permittivity is set to 2.5.

VII. Acknowledgment

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