# Implications of faults on insulation coordination of dedicated metallic return on bipolar HVDC overhead transmission lines

D. Hart[1], R. Courtellemont[2], A.Xemard[2], A.Bertinato[1]

***Abstract*—This paper focuses on a specific issue of bipolar HVDC lines with a dedicated metallic return (DMR). DMR is insulated to a lower level than the pole and its insulators are shorter. One event, for example, pole-to-ground-fault will cause a fault on both the pole insulation and the DMR insulation simultaneously because the DMR insulation fault will be supported by the DC current and will turn into a DC arc. To ensure independent pole operation, these types of events should be avoided or, if the DMR does flashover, to extinguish the fault as soon as possible. This is studied through the paper and different solutions are tested to protect the DMR.**

***Keywords*: HVDC; Bipolar; Dedicated metallic return; Insulation coordination; Overhead lines**

## I. Introduction

With the more and more widespread presence of renewable energy sources, electricity grids will need significant adaptations in the near future: renewable energy sources are often located far from consumption centres, and they are intermittent. As a consequence, grids will need better control and they will be required to transmit a huge amount of energy from remote places of generation to consumption centres. HVDC is the key technology which enables long-distance transmission with advanced controls and the possibility to provide additional services to the grid [1].

So far, most of the HVDC links have utilized grounding electrodes as a return path for the current while saving costs on towers, conductors and insulators compared to links equipped with a dedicated metallic return (DMR) conductor. Now, in addition, due to environmental concerns, new regulations and N-1 benefits of DC links, all new lines in Europe are supposed to have a DMR conductor [1].

In a bipolar system, the metallic return is shared between the two poles and is electromagnetically coupled. It is usually solidly grounded at one converter station and connected to a surge arrester (SA), and additional grounding apparatus at the other converter station (see Figure 1). Bipolar system stability and security depend on the reliability of the dedicated metallic return during and after fault events. Faults on the DMR insulation will affect pole independence unless they are efficiently detected and cleared. Because the DMR is shared by the two poles, simultaneous faults on the pole insulation and the DMR insulation jeopardize pole independence. Faults on the DMR insulation do not cause power transfer interruption; however, they must be cleared to avoid an outage of the other pole [2] when a pole is subjected to a fault.

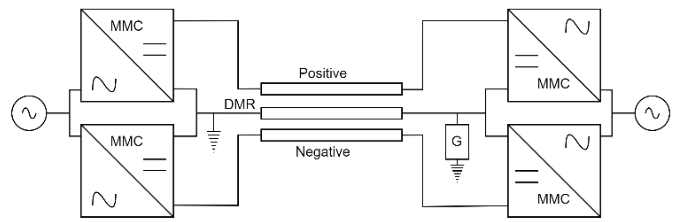


Figure 1 - HVDC bipolar system with DMR

This paper presents a study of a specific problem related to the DMR conductor on HVDC overhead lines (OHL) – the behaviour and extinction of an arc on insulators of a DMR conductor and practical solutions to eliminate the risk of permanent faults.

The outline of this paper is the following: section 2 clarifies the background knowledge of arc extinction mechanism and faults causing the arc. Section 3 describes the line configuration that was selected for the studies and the electromagnetic transient simulation model. Section 4 is devoted to a study of practical solutions to eliminate the risk of permanent faults on the DMR. Conclusions are summarized in section 5.

## II. DMR Faults and Arc Extinction Mechanism

There are two most common situations where one event will cause a fault on both the pole insulation and the DMR insulation simultaneously because the DMR insulation fault will be supported by the DC current and will turn into a DC arc [2].

- During a pole-to-ground fault due for instance to pollution, slow-front overvoltages of several hundred kilovolts are induced on the DMR. Therefore, a pole-to-ground line insulation flashover due to pollution results in high switching-type overvoltages on the DMR conductor might lead to a flashover also on the DMR insulators.
- A lightning strike that causes pole-to-ground insulation flashover also causes a DMR-to-ground fault as the tower structure is shared and the insulation level of the DMR is low.

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If a flashover occurs only on the DMR insulation (e.g., a lightning strike) and the HVDC system was in a bipolar mode of operation before the fault, the differential DC current in the DMR conductor will generally be too low to support a permanent dc arc and the fault will clear spontaneously [2].

Because of the large dimensions of the pole insulators and the effective shielding of the HVDC towers, flashovers due to shielding failures are rare; therefore, the lightning performance of the pole insulation is equivalent to the back-flashover performance [2] which is generally small because of the high insulation level of the poles, contrary to the DMR. As an illustration, the backflashover rate of the poles and of the DMR in the configuration considered in this paper (see Appendix), have been calculated based on the simplified method presented in [3][4] for a ground flash density of 1 lightning stroke per $km^2$ per year. The backflashover rate of the poles was close to zero and one of the DMR is approximately 6 / year / 100 km.

During the HVDC OHL design process, it is not considered a justifiable investment to install the same insulator strings on the DMR as on poles to withstand switching-type overvoltages due to pole-to-ground faults and lightning overvoltages. Due to the size of the insulator strings and their withstand voltage, a significant number of slow-front and fast-front overvoltages will result in a flashover over the DMR insulators. To avoid damage to the insulators and keep the arc away from the surface of the insulators, arcing horns are installed in parallel to them. Arcing horns elongate the arc by a combination of magnetic force and thermal buoyancy force until it becomes unstable, possibly leading to its extinction.

While Li et al. [5][6] discussed the application of arcing horns on the HVDC grounding electrode line, their study and its results are applicable to the case studied in this paper. Authors in [6] find that the difference between the elongation rate of vertical and horizontal gaps is not significant, similar results are presented in [7], where it is indicated that this difference may be due to local short-circuit processes. This is valuable input for line designers to assume that the tension and suspension tower arc horns will behave the same.

To find the maximum protection region of arc horns, in other words, the conditions which can guarantee the extinction of an arc, the static stability criterion Voltage-Current characteristic method, or U-I characteristic method as seen in Figure 2, is used in the literature to calculate the protection efficiency of the arc horns [2][5].

An arc will go to extinction if the U-I characteristic of the fault arc is higher than the U-I characteristic of the external system because in this case, the external system cannot provide sufficient energy to keep the fault arc burning. The area which is lower than the U-I characteristic of a fault arc is called the protected zone. The arcing horns can reliably extinguish dc arcs only if the arc current and supporting voltages are within the capabilities of the arcing horns.

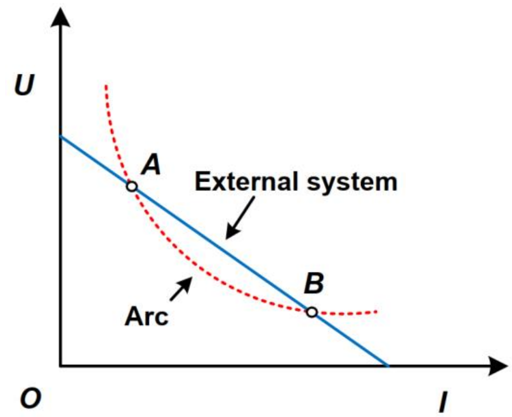

Figure 2 - U-I characteristic of an arc and the external system [5]

To expand on the U-I characteristic method, authors in [6] performed an experimental study of the characteristics of the long free-burning arc (>100mm). Long arcs have quite different properties compared to short arcs ( < 10mm) [7] and the arc in closed space because of their complex behaviour. Based on the observations, the arc development was divided into four phases. According to the experimental results, the arc elongates rapidly at first and then fluctuates around a stable length $L_{st}$ much longer than the discharge gap length $L_{gp}$. Consequently, it is advised by the authors to use the actual arc length instead of the gap length when considering the insulation coordination. In our configuration, the gap length $L_{gp}$ is 0,6 m which has a stable arc length $L_{st}$, according to [6], of 1313 mm and this value is used in the study to calculate the protection region of the line.

Furthermore, authors [6] have theoretically analyzed the factors influencing the protection performance of arcing horns and proposed an approximation solution of the state equation for the (relative) protection region of arcing horns equation for the analysis of influence factors. Based on the equation and the analysis, the effective ways to improve the protection performance of arcing horns are increasing the arc voltage and tower footing resistance and reducing the total resistance of the HDVC electrode line system.

## III. MODELLING OF THE SYSTEM

### A. *Modeling of the system*

In the base configuration, the converter rating is 1000 MVA, +/- 320 kV, the current is 1920 A for the base case, a 300 km long line. The HVDC system configuration is bipolar with a DMR as seen in Figure 3. The HVDC line's AC systems on each side are represented as Thevenin Equivalent. One of the converters regulates voltage, and the other is regulating active power. EMTP 4.2.1 software is used to model the system and simulations were performed in the time domain [8][9].

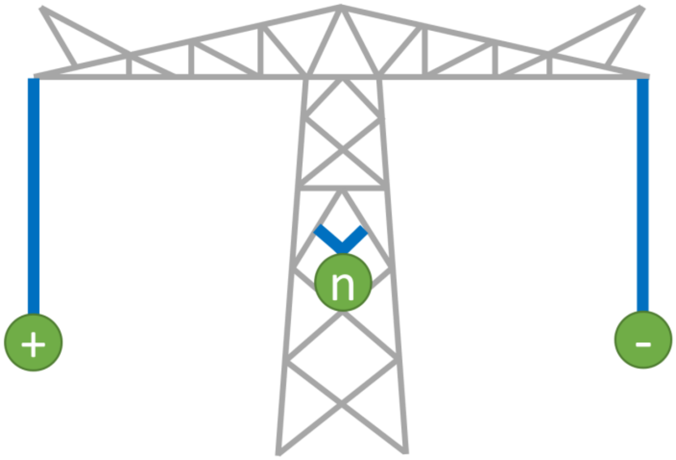

Figure 3 - HVDC overhead line tower and pole configuration

In EMTP, the overhead line is modelled by a Frequency-Dependent (FD) line model. The conductors are not considered bundled, which is conservative regarding protection region [6]. The DMR in the system is solidly grounded at one converter station and connected to a grounding apparatus consisting of at least a SA and different elements discussed later in the paper, at the other converter station. The solidly grounded end is also used for providing the voltage reference point of the HVDC system. The discharge gap length between the two arcing horns for the pole insulators is 4.65 m and 0.6m for the DMR insulators.

When a pole is unavailable, the system works in an asymmetrical monopolar mode with the return of the current by the DMR. The maximum continuous DC operating voltage of the DMR insulators is equal to the voltage drop on the DMR during the maximum power transfer in a monopolar configuration.

The initial model is constructed by representing the whole line length with towers spaced by a span of 500 meters between 2 towers, for example, 200 spans for a 100km line. The equivalent tower impedance is set at 16 µH, and ground resistance at 10 Ω. The spark gaps are modelled with flashover switches. They are other models that physically represent the time of ignition of the air gap, see [10]. For the purpose of the study, it is not necessary to use more complex gap and arc models. Analysis and understanding of the arc behaviour were done in section II. More precise gap representations will not have an influence on the voltage waveform and the flashover of the gap but this influence is not significant enough to interfere with the understanding of DMR behaviour. The withstand voltage of an air gap is a probabilistic function: when an air gap is subjected to an overvoltage, it has an ignition probability. This is generally represented by a Gaussian or Weibull distribution function.

If $U_{50}$ is the medium value ($U_{50}$ is the 50% sparkover voltage), The required withstand voltage $U_{rw}$ is chosen with (1):

$$U_{rw}=U_{50} - n\sigma \quad (1)$$

Where:

*$\sigma$ is the standard deviation*

*n is used to widen the gap with $U_{50}$.*

(1 is based on standard [11]: the required withstand voltage of the air gap, $U_{rw}$ , may be expressed as a function of the 50 % withstand voltage of the air gap $U_{50}$ . The idea is to minimize $U_{rw}$ sufficiently in comparison to $U_{50}$ so that the risk of flashover becomes statistically very limited.

For transient overvoltages (slow front and fast front), n is 1.3. It leads to a probability of ignition of 10% when the surge $U_{rw}$ is applied to the air gap. Reference [12] is used to calculate the $U_{rw}$ value used in the simulations from experimental values of discharge voltage rod and plane ("Rod to Plane"). As a result, the following values are obtained, $U_{rw} \approx 340$ kV for the DMR spark gaps and $U_{rw} \approx 1595$ kV for the pole spark gaps.

To have a reasonable simulation time when it comes to long lines, models were optimized by reducing the number of modelized towers and checked if this simplification is acceptable for the simulations in this paper. The simplification consists in having 4 spans on each side of the fault location. For this purpose, a 40 km line was considered with a pole-to-ground fault in the middle of the line (20km from each station) at 400 ms. This was simulated on 2 EMTP models:

- The first one with all towers and spans represented
- The second one with 4 spans represented on each side of the fault location and a tower just before the converter stations. The rest of the line was represented by FD line models

The difference between the two simulations was presented in Figure 4 and Figure 5. The flashover of spark gaps was disabled to obtain the same system behaviour of these 2 models. At the fault location and at the end of the line, the DMR arcing horn voltage is approximately the same shape. Representing all towers and spans in the model has a smoothing effect on the curve. With simplification, there is more variability and a risk that the voltage peak is overestimated and the results presented in this paper are slightly conservative.

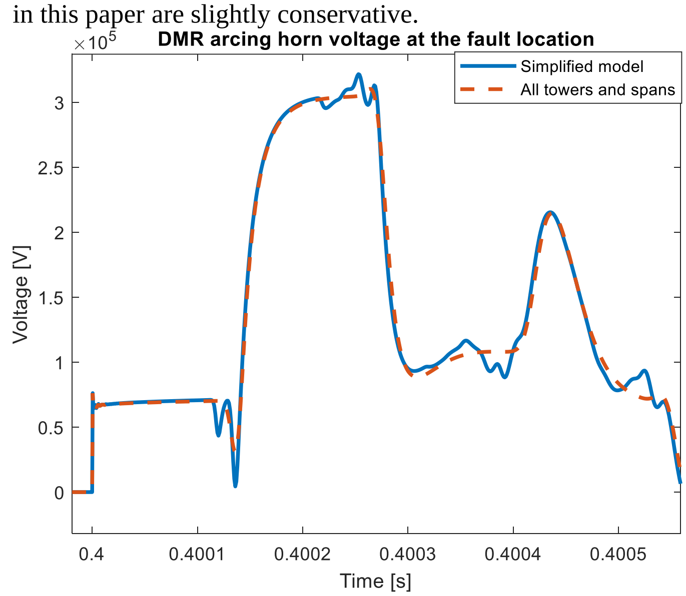

Figure 4 - DMR arcing horn voltage at the faulted tower

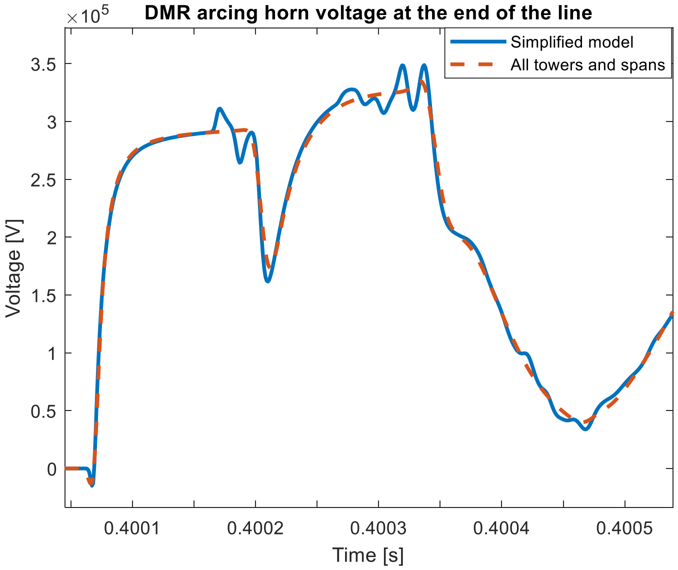


Figure 5 - DMR arcing horn voltage on a tower at the end of the line tower

In the configuration mentioned above, with the simplification, the peak value of the voltage at the fault location is 4.1 % higher and the peak value of the voltage at the end of the simulated line is 3.6 % higher. The error between the model with all towers and spans and the simplified one is considered acceptable regarding the objective of this study.

TABLE 1 – COMPARISON OF SIMULATION TIME

| **40 KM LINE** | | **100 KM LINE** | |
|---|---|---|---|
| **standard** | **optimized** | **standard** | **optimized** |
| 4m34s | 2m36s | 9m02s | 2m39s |

With a time step set to 1 µs and the simulation time of 800 ms, the difference in simulation time is shown in In Table 1. It is shown that EMTP needs approximately the same time to treat different line lengths if they are modelled through one of the built-in line models.

## IV. STUDY OF PRACTICAL SOLUTIONS TO ELIMINATE THE RISK OF PERMANENT FAULTS ON THE DMR OF A 320 KV DC OHL

Based on the modelling of the system presented in the previous section, the influence of different pole-to-ground faults was tested and then, for the same faults, the efficiency of DMR protection and fault prevention of different solutions was evaluated.

### *A. Study of the base case configuration*

In the initial simulations, DMR is solidly grounded at the sending end and ungrounded on the receiving end to take into consideration and present the influence of the SA. To understand the influence of the disturbance on the DMR caused by pole-to-ground fault, the fault location was moved along the pole line from the beginning to the end of the line. If the pole-to-ground fault is in the first half of the line length closer to the sending end which is solidly grounded, the DMR does not flashover. The overvoltage increases as the fault moves closer to the ungrounded receiving end. The most critical point, with the highest overvoltage, along the line is around three-quarters of the line. Based on these findings, in this section, only three fault locations are used to demonstrate the disturbances on the DMR – middle, three-quarters and the end of the line.

In the second step, the SA was dimensioned. The SA was dimensioned at 130kV rated voltage, the line discharge class chosen is 4 and the energy absorption capability of 10 kJ/kV which results in maximum energy absorption of 1.3 MJ. The SA long-duration current impulse rating is 1.6kA, the rated short circuit current of 65kA and the maximum value of the residual voltages is 250 kV at 1 kA discharge current. For the system configuration simulated in this paper, by looking at the power scope of the ZnO SA model in EMTP and integrating the power scope output to obtain the energy, energy absorbed during the worst location of a pole-to-ground fault was below the maximum energy of 1.3 MJ. Furthermore, 130kV is well above the steady-state voltage, 17 kV of the DMR in an asymmetrical monopolar operation meaning that it will only conduct in case of significant disturbances. A more detailed dimensioning process is necessary for later design stages to fine-tune the rated voltage and energy class of the SA. Even though SA has an important impact on the system's performance, compared to other components, the cost of SA is negligible and even if more energy absorption is necessary, two or more SAs can be put in parallel without impacting the overall project cost.

Another useful component that could be added along the line is line arresters on critical towers along the line. But they require complex dimensioning processes in collaboration with manufacturers and, desirably, laboratory tests of the designed configuration and this is out-of-scope of this paper [13].

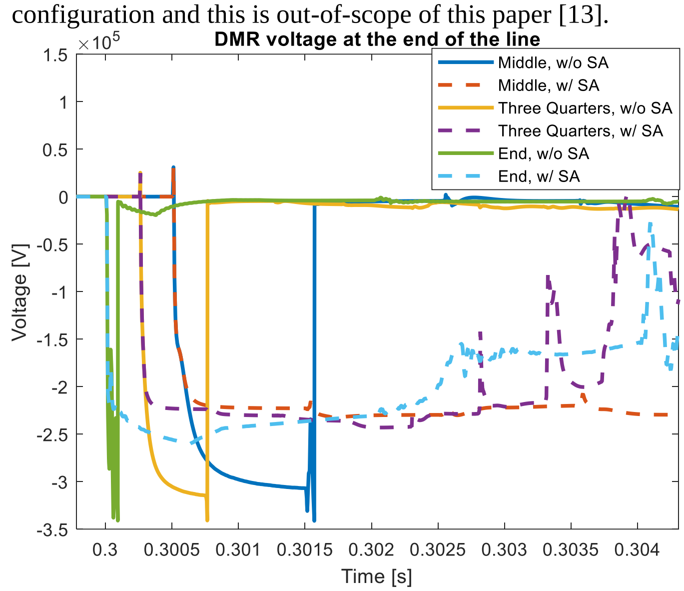


Figure 6 - DMR voltage measured at the end of the line for different fault locations

Both simulation series, with and without SA, at the three fault locations previously mentioned along the pole line are plotted in Figure 6. As can be seen, without SA, DMR flashes over after pole-to-ground fault at all three locations, but, with SA implemented in the grounding system, it efficiently prevents flashover at all three locations simulated. It is important to note the learnings from line simulations with all towers and spans represented – the DMR flashover doesn't happen on towers and spark gaps parallel to the fault location but further down the line towards the end of the line, not necessarily the last tower on the line as presented in this simulation series with the simplified line representation that was explained in section III.

### *B. The use of a grounding switch*

After presenting the insufficient protection region that arcing horns provide on the DMR, authors in [2] propose a grounding breaker to be considered as a main DMR-to-ground fault-clearing device and authors in [5] advised to consider introducing additional protection tools.

A high-speed switch (HSS) was added to the system, in parallel to the SA. It is assumed that the fault identification algorithm needs 1 ms to identify the fault and an additional 1 ms is needed to close the switch. In the simulations, the switch was modelled as an ideal switch with a closing delay of 2 ms after the fault wave reaches the end of the line. As shown in Figure 7, even with 2 ms of total reaction time, it is not fast enough to prevent the fault from happening. For this example of a pole-to-ground fault at the middle of the line, the fault wave arrives at the end of the line at around 300.5 ms and the switch closes at 302.5 ms, by that point, there is already a flashover on the DMR insulators and it happens somewhere close to the end of the line as explained in the previous section.

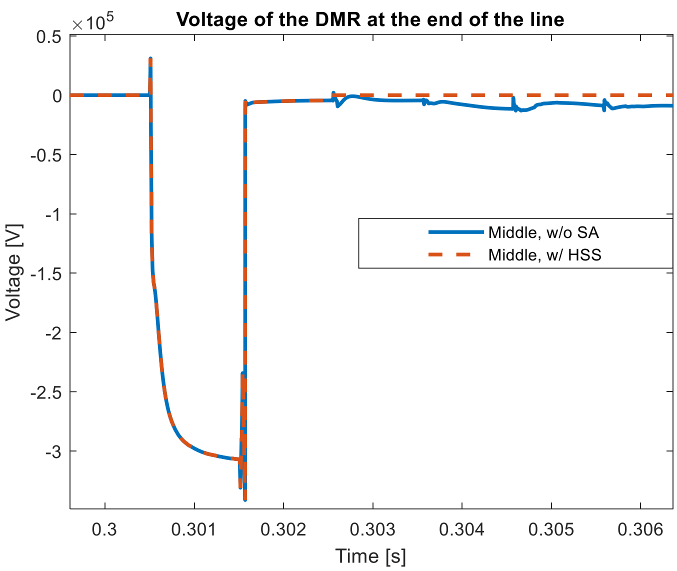


Figure 7 – Voltage of the DMR at the end of the line

The advantage of closing the HSS is to reduce the current in the DMR fault and then to have the possibility to extinguish the fault more easily because the U-I characteristic of the fault is moved below the U-I characteristic of the arcing horn (refer to Figure 2). In this case, the fault along the DMR is supposed to self-extinguish. In Figure 8, the current of the DMR at the end of the line is plotted for the positive pole-to-ground fault location at the middle of a pole line. It can be seen that with an HSS, the peak fault current at the end of the line is lowered by almost a factor of two – from 8.7 kA to 5.4 kA. For the same fault at three-quarters of the line, by implementing an HSS, the peak current goes from 9.8 kA to 5.4 kA. In case of a fault at the end of the line, an HSS is not very efficient as it is a parallel path to the ground, very close to the fault location.

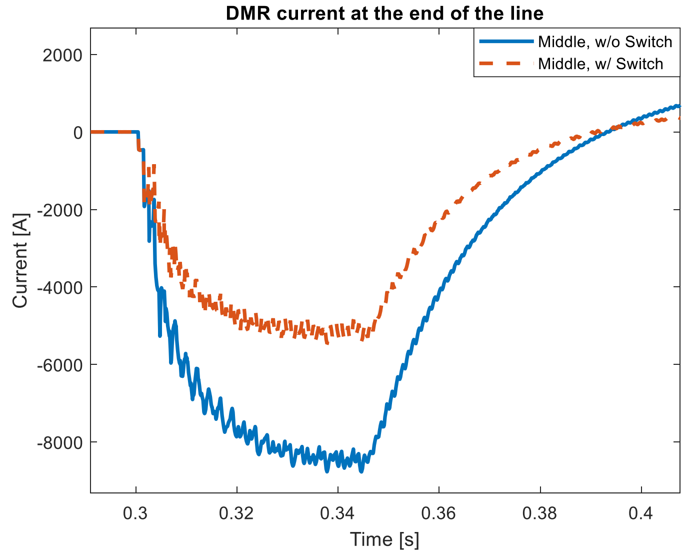


Figure 8 – The current of the DMR at the end of the line

During the fault extinguishing or the process of eliminating a disturbance on the DMR, with the switch closed, there will be a current flowing through the ground. Adequate converter control of the healthy pole in coordination with the switch closing and opening actions and protection sequence is required to ensure the system's stability and fault extinction. The duration of an earth current in a fault state is subjectable to regulation and different transmission system operators in the world will have different regulations so it is important to verify compliance with the local standards and avoid unwanted influence on the surrounding infrastructure and environment.

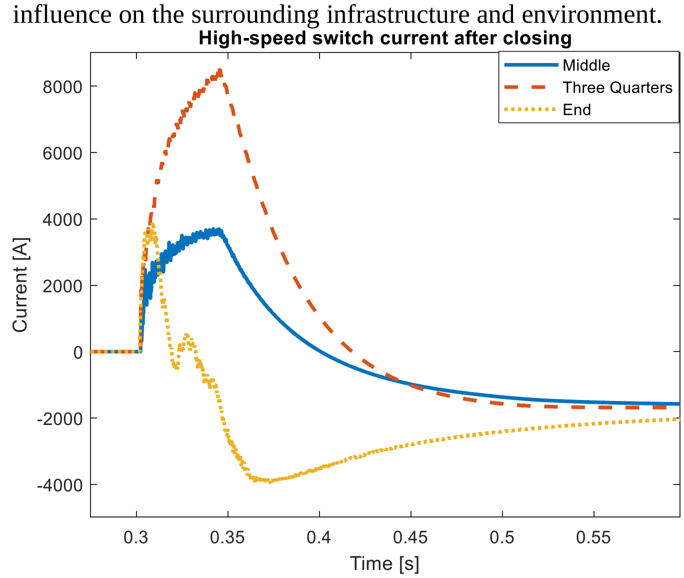


Figure 9 – High-speed switch current after closing

Once the power commutates from the SA to the switch, after the switch closes, voltage decreases and the current through the switch increases reaching the peak value of around 3.6 kA for faults at the end and the middle of the line and around 8.4 kA for a fault at the three-quarters of the line as is shown in Figure 9.

A high-speed switch is an additional component which requires proper activation and automation and its reliability during the design process has to be taken into consideration.

## V. CONCLUSIONS

To ensure the independent and reliable operation of a DMR, great care needs to be paid to the coordination and understanding of a lot of different aspects during the line design, some of which were covered in this paper. The authors paid special attention to the consequences of faults in the system on the DMR. First, a state-of-the-art of DMR faults and arc extinction mechanism was presented and later used for the system modelling. The system was simulated with different faults and fault locations to understand the influence of lightning strokes and pole-to-ground faults on the operation of DMR and, if the DMR has a fault, to understand the fault extinction. It was demonstrated that a surge arrester positioned at the receiving end can greatly limit the slow front overvoltages and effectively prevent DMR flashover. In addition, to facilitate the extinction of the arc in case of a fault along the DMR a high-speed implementation was investigated. For the implementation of an HSS, the time required by the relay to close the switch is not so important but what is important is the fact that it can significantly reduce the current in the faulty arcing horn. Consequently, a combination of a surge arrester as a fault-limiting device and a high-speed switch as a fault-clearing device has to be meticulously designed and coordinated in DMR protection.

## VI. APPENDIX

### A. *Tower configuration*

The tower configuration dimensions used in simulations are presented in Table 2.

TABLE 2 – TOWER CONFIGURATION

| | Height of the conductors at towers (m) | Horizontal distance from the axis of the tower (m) |
|---|---|---|
| Pole 1 | 31.5 | 6.55 |
| Pole 2 | 31.5 | - 6.55 |
| Metallic return | 33.5 | 0 |
| Sky wire 1 | 38.29 | 6.45 |
| Sky wire 2 | 38.29 | - 6.45 |

The characteristics of the conductors are shown in Table 3.

TABLE 3 – CONDUCTOR CHARACTERISTICS

| | Diameter (mm) | Lineic resistance (ohm / km) |
|---|---|---|
| Poles (Aster 1144) | 44 | 0.0292 |
| Metallic return | 44 | 0.0292 |
| Sky wires | 25.2 | 0.162 |

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