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Cable Overvoltage for MMC based VSC HVDC System: Interaction with Converters

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Abstract:

MMC (Modular Multilevel Converter) type Voltage Source Converter (VSC) based High Voltage Direct Current (HVDC) transmission system often uses cables as DC power transmission medium. One potential challenge faced by the cable system is new type of OVs (overvoltages) occurring in the dc cable due to faults in the HVDC system depending on system topology and converter design. The cable generally needs to be designed to withstand the voltage occurring during a fault, which makes it important to find the highest possible OV appearing in the cable of various transmission system designs.

An important case in the ongoing discussion are overvoltages occurring in symmetrical monopolar HVDC systems, which are among the most common installed system topologies. When a dc fault happens in a symmetrical monopolar HVDC system the healthy pole experiences a high OV. Namely, immediately after the fault event the faulty pole, being grounded, pushes up the pole-to-ground voltage of the healthy pole, in order to maintain the whole rated pole-to-pole voltage. The healthy pole is thus driven towards 2.0 p.u. of the nominal DC voltage. The peak voltage actually occurring is however limited by pole surge arresters. Rise and decay time of such OV is longer than what is typically required in cable system qualification tests. In order to find the highest possible OV appearing in the cable system in such a configuration this paper focuses on some influences of the MMC VSC on the cable OV.

In the presented case a +/-320 kV monopolar dc system is studied, where two MMC VSC stations are connected via 225 km long sea cable. It is found, that when there is a pole to ground fault in the middle of the cable, then the other (healthy) pole cable experiences the highest OV in the midpoint. When the impedance of the dc circuit suddenly reduces (due to the fault), and at the same time the pole to ground voltage of the healthy pole is pushed up, all the inductances and capacitances of the system form an L-C oscillatory system and start to oscillate. While the surge arresters protect the cable close to the station terminals, the midpoint of the cable remains furthest away and is hence least protected.

Moreover, the magnitude of the OV varies with the amount of transmitted power. Namely, the observed OV is higher with lower power transmitted through the system. For explanation, the impact of converter blocking on the OV is analyzed as well. In MMC HVDC the cell capacitor stores some amount of energy. Blocking of a converter prevents the cell capacitors from discharging which in effect impacts cable charging currents in the early phase of the fault and hence the OV of the cable system.

INTRODUCTION

DC cable systems installations are continuously growing in the world. This development is strongly driven, but not only limited, to the growth in the number of wind farms and their off-shore DC connection. The requirement of a well-organized electricity network structure that serves the different flows of energy also drives more and more installations of direct current based interconnectors between countries. Especially the development in Europe, pushed by the European climate and energy 20/20/20 targets, defined by the European Commission [1] serves as valuable cases to study the impact and performance of this technology direction.

In the early years of DC current based power transmission Line Commutated Converters (LCC) together with paper insulated cables have been the choice of transmission system. However, nowadays most of the installed systems are extruded cable systems with MMC (Modular Multilevel Converter) type Voltage Source Converter (VSC) connections towards the AC network.

Today the most widely used recommendation for qualification cable section is TB496 [2], which dates back to TB219. The latter has been written in 2003, a time when extruded cable systems connected to VSC converters had entered the market at the low end of the HV side. Especially overvoltage testing has not been altered since then, respectively no need was seen to do so. However nowadays, several authors pointed out a potential challenge faced by the cable system in terms of a new type of TOVs (transient overvoltages),e.g. [3], [4]. Such TOV's occur in the DC cable due to faults in the HVDC system, depending on system topology and converter design. Since generally the cable needs to be designed to withstand the voltage occurring during a fault, it is important to find the highest possible OV appearing in the cable, depending on various transmission system designs.

In this paper we do not claim an investigation of the highest of all possible overvoltages, instead we focus on an important case in the ongoing discussion, which is an overvoltage type occurring in a symmetrical monopolar HVDC system. Symmetrical monopolar HVDC systems are today among the most common installed system topologies. In the presented case a +/-320 kV dc system is studied, where two MMC VSC stations are connected via 225 km long sea cable. Parameter variations, such as fault location, location of occurring overvoltage and cable length, are investigated on a specific basis, and tendency of their impact is presented.

MODEL

The HVDC system layout of the symmetrical monopole investigated in this paper is depicted in Figure 1. As an electromagnetic transient modelling tool we have used PSCAD. Two 3-phase, 50 Hz ac networks are exchanging power through a HVDC system. S1 and S2 represent ac-dc and dc-ac converters respectively, and the ac side of the converters connects to the ac network via YΔ transformers, with Δ side towards the converter. Tap changers are placed in the Y (line side) of the transformer. On the dc side, the stations are connected by cables. Note that for simplification the stations are directly connected to the sea cable, which in reality will be via small land cable section. Also surge arresters are placed in various locations of the stations on both ends. The nominal dc voltage and other station parameter settings of the system are taken representing a 320 kV system. The power rating of the system is slightly above 1 GW.

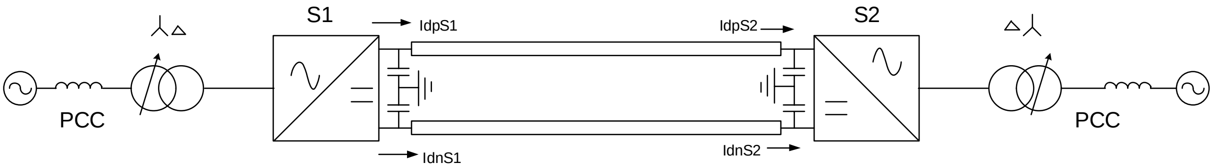

Figure 1: Symmetrical monopole HVDC system

When modeling the cable, we are using PSCAD Frequency Dependent Phase model cf. [5]. Within this option we model an extruded sea cable including metallic sheath and armoring layers as well as filling tape sheath layers. In Figure 2 a schematic comparison between the PSCAD geometry and an extruded cable design is shown. Note that in PSCAD the conducting polymeric layers (semicon, tapes) between the cable main insulation, e.g. XLPE insulation, and the metallic sheath have to be incorporated into the model insulation layer. This is usually done by adapting the permittivity, such that the capacitance of the modelled cable reflects the capacitance of the actual cable.

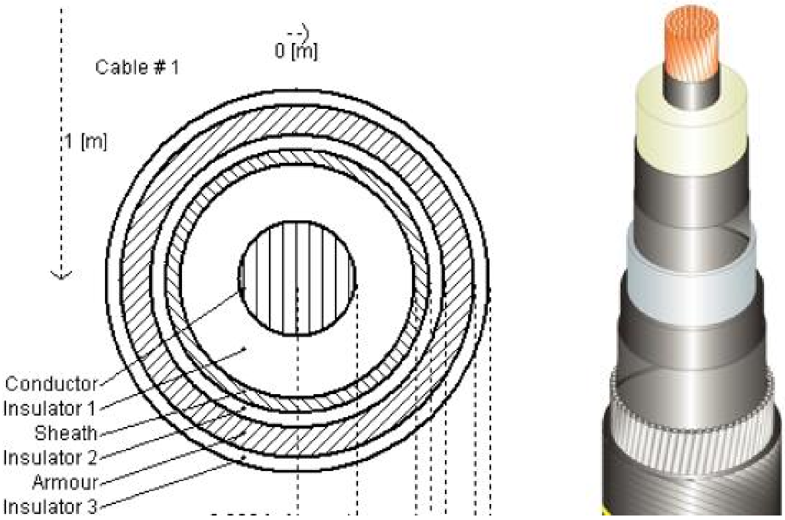

Figure 2 : Modelling sea cable in PSCAD vs a realistic sea cable design

The ac-dc/ dc-ac converter is basiaclly half bridge MMC (Modular Multilevel Converter) based VSC (Voltage Source Converter) and the transformer connection considered is Delta-Star. As shown in Figure 3there are 6 arms connected between the dc link of +/-320 kV, with each arm being cascade connection of half bridge cells. The arms are connected via air core reactors to the ac terminals (e.g. Phase A). The half bridge cells are made of capacitor (C) and power electronic switches, IGBTs (S), and anti-parallel diodes (D). Internal overcurrent and overvoltage protection protects the IGBTs from damage due to excessive current and/or, voltage mostly occuring due to faults.

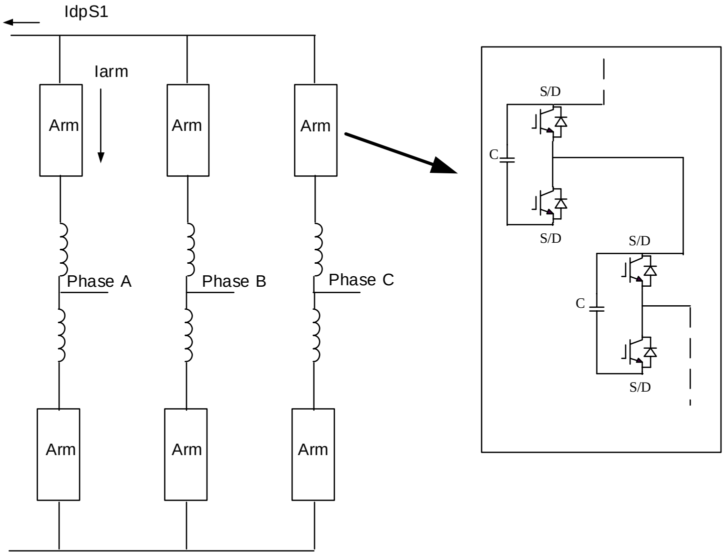

Figure 3: Sketch of an MMC based VSC

Faults are modelled by connecting the cable conductor to ground via a very low impedance. During a fault all the external protections are disabled so the converters blocks / trips only due to their internal overcurrent/ overvoltage protection.

RESULTS AND DISCUSSION

Target of the study is the overvoltage appearance along the healthy cable, i.e. the voltages at different locations along the cable length are studied. For one cable length, faults are applied at different load conditions and at different locations. A typical result is plotted in Figure 4, where a negative pole to ground fault in the middle of a 225 km long cable under a high load condition is simulated. It shows the positive and negative pole dc currents in the station dc terminals S1 and S2, i.e. IdpS1, IdpS2, IdnS1, IdnS2 (Figure 4a and 4b), as well as the positive and negative pole voltages in the station dc terminals, V0P, V0N for station S1 (Figure 4c and 4d), and V100P, V100N for station S2 (Figure 4e and 4f).

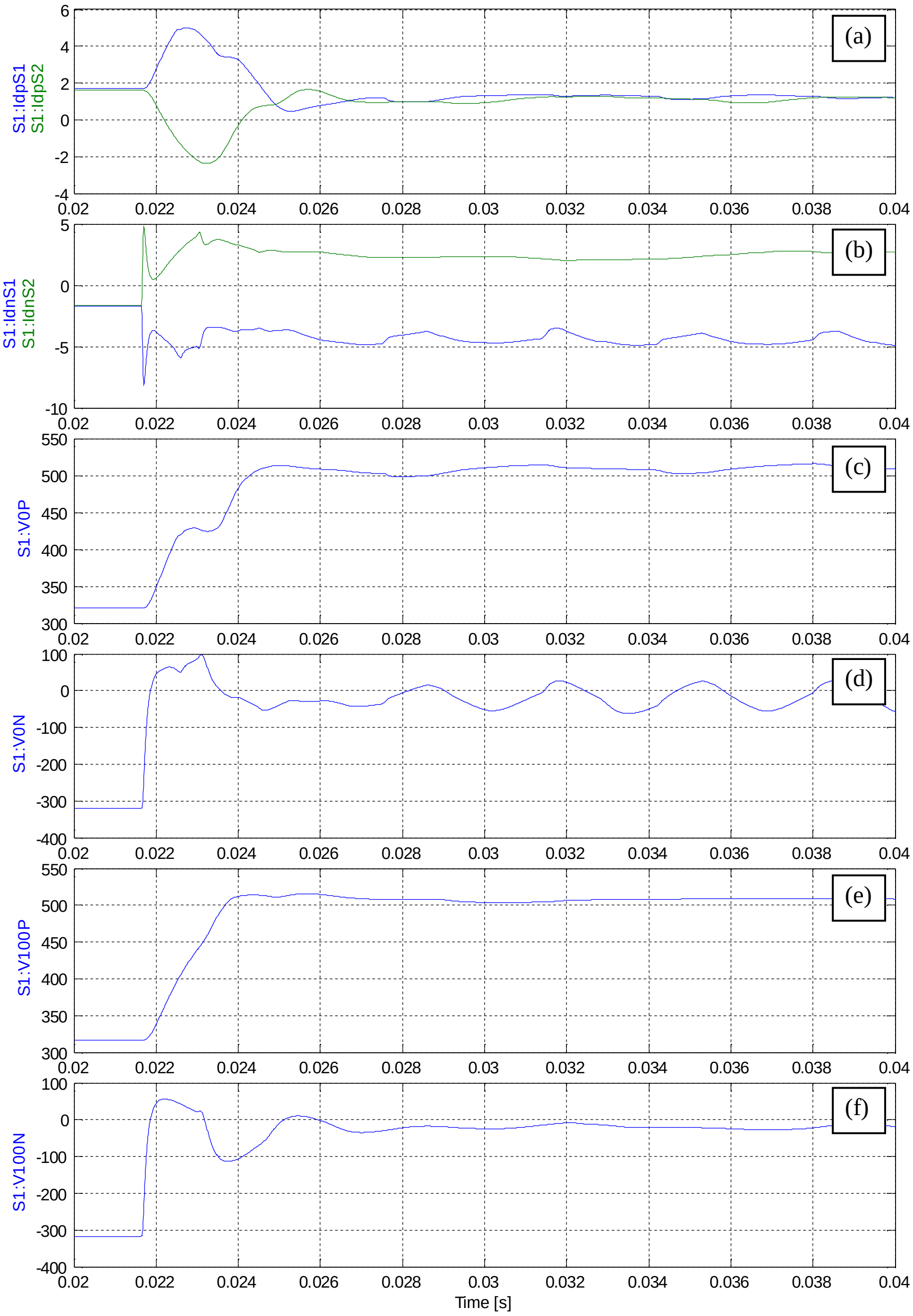

Figure 4: Results of a pole to ground fault on the negative pole for a 225 km long cable under high load. The plots show: rectifier and inverter current on the positive pole (a), on the negative pole (b), positive (c) and negative (d) pole voltage at the rectifier, and positive (e) and negative (b) pole voltage at the inverter.

As a first observation from Figure 4c and 4e, the overvoltage shape on the healthy pole rises on the same polarity from the operating voltage of 320 kV to a peak voltage of 510 kV within 3 to 4 ms. The peak voltage in this case is rather a slow decaying plateau than a peak. The decay of this plateau is determined by the discharging of the cable and can generally be expected being of the order of 15 to 30 minutes if no additional means for controlling this process are undertaken. However, the decay time goes beyond the time resolution of the tools applied in this study and will not be further dealt with in this study. It should also be noted from Figure 4d and 4f, that there is oscillation voltage behavior on the faulty pole, i.e. the polarity on the link is reversed. This is also not of further focus in this study, as the reversed voltage peak seems to be limited in magnitude.

In detail, the observation points along the cable line have been chosen in % distance from the converter station terminal S1 as 0%, 25%, 50%, 75%, and 100% of the total cable length. Those "overvoltages measurement points" are sketched also in Figure 5 in the upper, i.e. the positive pole. Also depicted in Figure 5 are the seven fault locations along the line, which have been considered. They are also given in terms of % distance from the converter station terminal S1, but this time as 0%, 10%, 25%, 50%, 75%, 90%, and 100% of the total cable length.

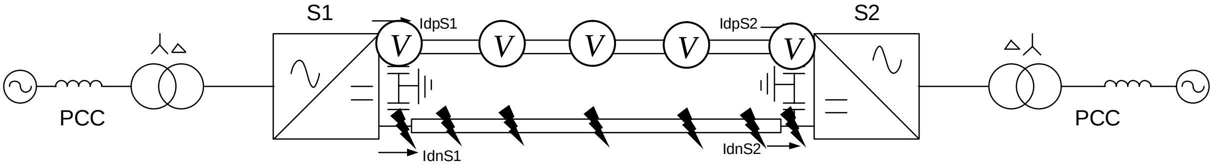

Figure 5: Fault locations and voltage measurement points sketched along the line.

Different load scenarios have been considered, which vary between full and zero load. Finally, different cable length values have been investigated, in a range substantially shorter as well as substantially longer than the 225 km long cable link presented in Figure 4.

For taking maximum overvoltage the multirun feature in PSCAD is used. For this, many fault instances are simulated, whereas the faults instances are syncronized to one cycle of a phase of the line voltage, and distributed over this cycle with a time interval of 1 ms.

Overvoltage dependence on the observation location along the line

Using a fault scenario of a pole to ground fault in the middle of a low loaded negative pole cable, the principal behavior of the overvoltage peak observed at different locations on the healthy pole is shown in Figure 6. The data points are taken according to the observation points in Figure 5. When the impedance of the dc circuit suddenly reduces (due to the fault), and at the same time the pole to ground voltage of the healthy pole is pushed up, cf. Figure 4, all the inductances and capacitances of the system form an L-C oscillatory system and start to oscillate. While at the station terminals the overvoltage peak is expected to be dominated by the surge arrester protection level, the midpoint of the cable remains furthest away and is hence least protected. Interference phenomena of incoming and reflecting waves from both sides, result therefore in higher voltages in the middle of the cable.

Overvoltage dependence on the location of the fault

The highest voltage as shown in Figure 6 is also depending on the fault location, as shown in Figure 7. Higher voltages are observed on the healthy pole if the fault occurs in the middle of the link. Generally, a parameter dependent variation on the overvoltage is expected to be largest in due distance to the surge arresters.

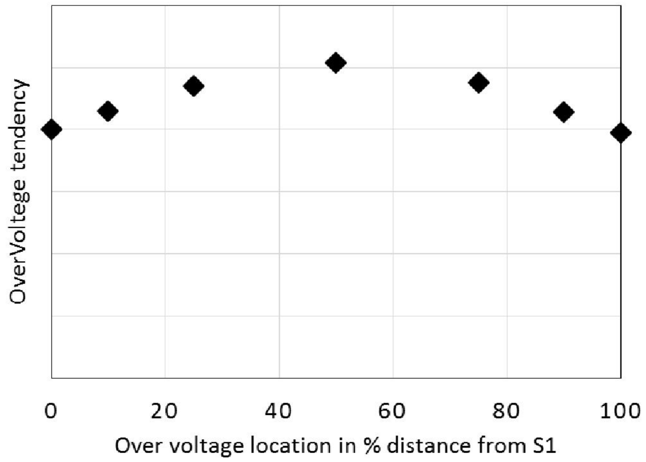

Figure 6: Peak overvoltage tendency at the healthy pole for low load conditions in dependence of different locations along the (healthy) cable.

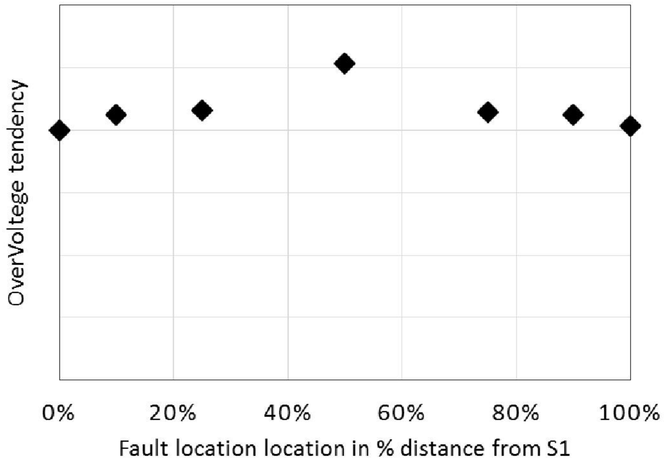

Figure 7: Peak overvoltage tendency at the healthy pole for low load conditions in dependence of the fault location at the faulty cable.

Overvoltage dependence on the converter loading

Figure 8 shows the fault scenarios of a pole to ground fault in the middle of the negative pole, but for two different loading conditions of the cable. For both cases, S1 is a rectifier and S2 is an inverter. The midpoint voltage of a 225 km long sea cable after fault is plotted in Figure 8c and 8d. From Figure 8c it is observed that the overvoltage is significantly higher in the low load case compared with the high load. Specifically, the low loaded line experiences approximately an additional 10% of voltage stress in the transient overvoltage as compared to a high loaded line considered in this example. This behavior can be understood observing in Figure 8a that the rectifier positive pole current (IdpS1) for the high loading case rises faster to a high value after fault compared with the low loading case. This post fault increase in the dc currents are a consequence of the increase in the arm currents. It was found that the higher DC overvoltage is directly related to higher DC postfault current increase, whereas the higher DC current increase is related to duration between the occurrence of the DC fault and the blocking of the converter. The faster blocking of the converter, the lower the DC current increase, thus the lower the DC overvoltage.

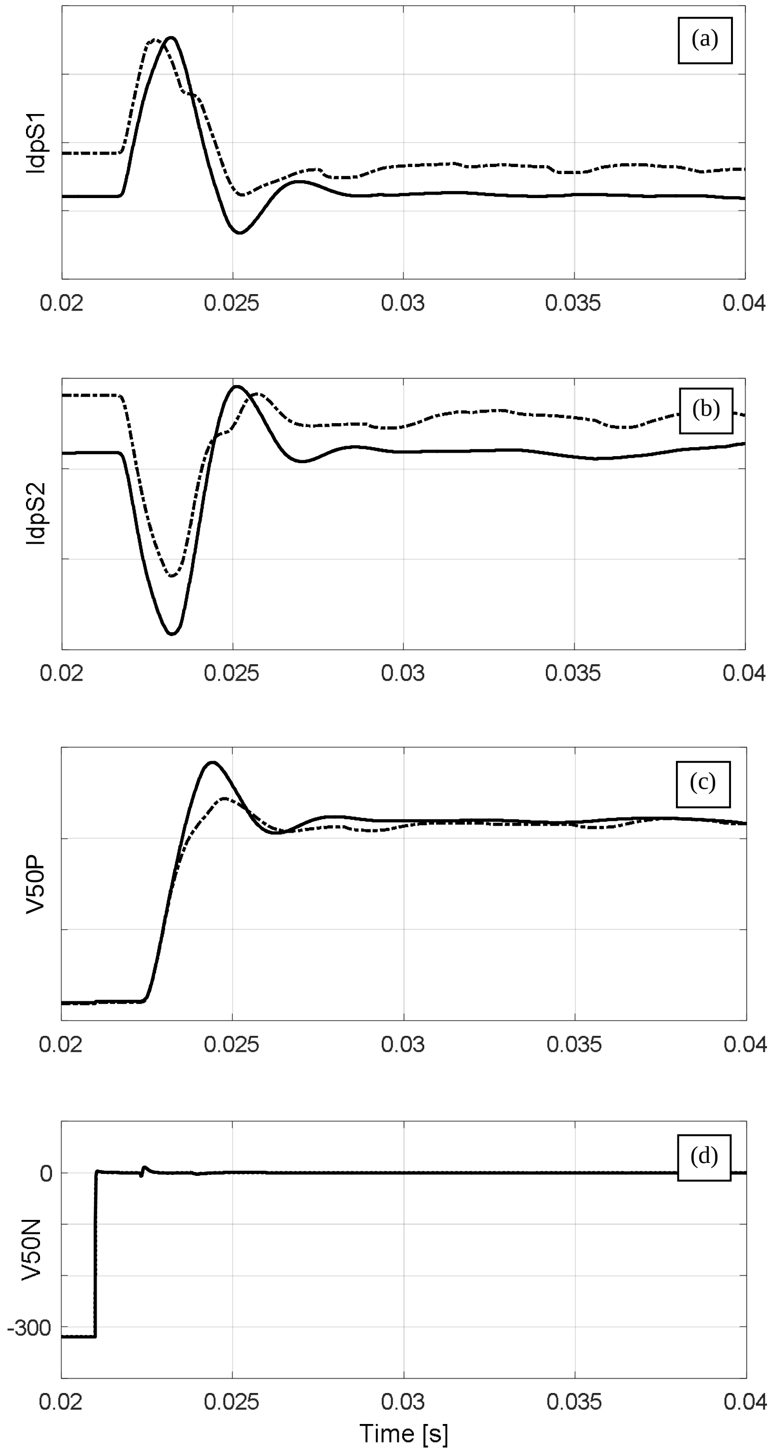

Figure 8: Overvoltage and current comparison of a pole to ground fault located in the middle of the negative pole for a low load and a high load scenario. Observation point is the middle of the cable.

Overvoltage dependence on the cable length

In this section the behavior of the transient overvoltage on the healthy pole in dependence of the cable length is investigated. Considering the worst fault location and the worst peak voltage, it is found that the magnitude of the voltage varies with the length of the cable. Figure 9 shows the voltage monitored at the middle point of a cable with length of 225 km and with length above 1000 km. It can be observed that both the rate of voltage rising and the peak value is affected by the length of the cable. This is mainly due to different lengths of the cable which gives different total capacitance as well as different wave travelling time.

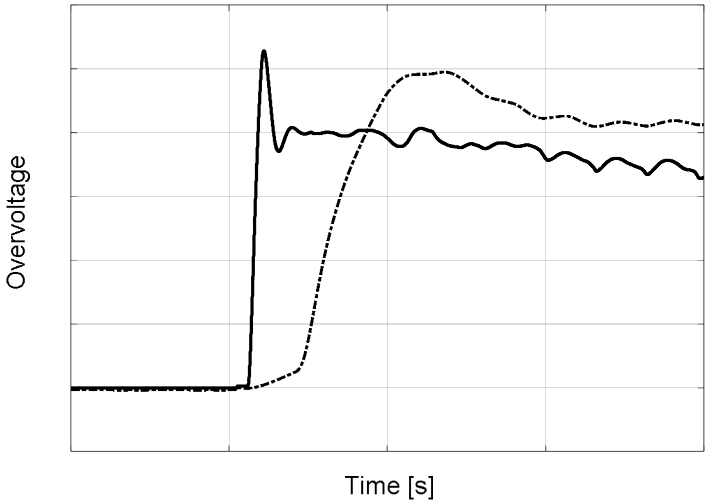

Figure 9: Healthy pole mid-point overvoltage for a pole to ground fault in the middle of the link. Shown is the low load case for a 225 km (solid line) link compared to a link above 1000 km (dot-dashed line).

CONCLUSION

For VSC based HVDC symmetric monopole transmission system with extruded cables pole to ground faults on the link have been investigated. Based on the above findings the general conclusion is that the cable midpoint is expected to see highest overvoltage due to longest distance from the station arresters. Moreover, the overvoltage magnitude is expected to increase with decreasing load. This is explained with a relation of the DC overvoltage, DC current and the converter blocking, where the DC current is related to the loading of the cable. This also leads to the conclusion that the speed of protection can affect the overvoltage. As the DC current dynamics after fault at the terminal is also affected by the fault location on the line, a consequence is, that a DC fault appearing in the middle of the cable, furthest away from the terminals, gives the highest overvoltage on the healthy pole. The overvoltage magnitude is also depending on the length of the line, however the variation may not be in a linear fashion such as increasing the length, decreasing the overvoltage linearly. It is therefore concluded that for studying the transient overvoltage due to a pole to ground fault in a symmetric monopolar HVDC systems it is sufficient to study the mid point voltage of a fault in the middle of the line with low loading.

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