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Protection of radial MVDC electric network based on DC circuit breaker and DC fuses

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Abstract

The medium voltage direct current (MVDC) electric networks are emerging in power distribution and collection. The MVDC is an attractive solution in the applications involving DC loads or sources where high energy efficiency and high power flow controllability are required. The emergence of MVDC networks strongly relies on the availability of the appropriate protection strategies and equipment. This article proposes a protection strategy for a multi-terminal radial MVDC network based on the principle commonly used in the existing AC distribution networks. The protection strategy involves a single DC circuit breaker (DCCB) and multiple DC fuses. The proposed strategy limits the quantity of sophisticated and costly DCCB used. The cost-effective DC fuses are proposed to protect the parts of the network where the expected short-circuit occurrence is limited and where the automatic reclosing is not mandatory. The article concludes that low grounding resistance is beneficial allowing to easily isolate the faulty circuit. The simulation models are developed allowing to confirm the theoretical analysis.

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Keywords: AC-DC power converters; Circuit breakers; DC-DC power converters; Fuses; Power distribution; Power system protection.

1. Introduction

The medium voltage direct current (MVDC) electric networks are emerging in power distribution and collection, following the expansion of the high voltage direct current (HVDC) in power transmission. The MVDC is an attractive solution in the applications involving DC loads or sources where high energy efficiency and high power flow controllability are required [1]–[5]. There are a few MVDC pilot projects, mainly including point-to-point links [6]–[8] but there are also a few multi-terminal networks [9], [10].

The authors expect that the MVDC networks will develop according to AC distribution networks where the ring and radial architectures are the most common. However, the emergence of MVDC networks strongly relies on the availability of the appropriate protection strategies and equipment. The development of protection strategies and equipment for MVDC networks may benefit from:

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- the experience of AC distribution networks;
- the experience of existing DC systems: HVDC point-to-point links (P2P), DC railway electrification, ships with electric propulsion and photovoltaic systems;
- the research trends for future DC systems: HVDC grids and low voltage DC (LVDC) networks.

The protection of AC distribution network is usually based on overcurrent protection relays, circuit breakers and fuses [11]. The selectivity is achieved thanks to the proper tuning of time-overcurrent characteristics. The technologies for AC current breaking are well established making the benefit of current zero crossing and power transformers that limit the amplitude of the short-circuit current.

The protection strategy of HVDC P2P symmetric monopole (for example ± 320 kV) involves the voltage and current monitoring for pole-ground and pole-pole fault detection [12]. The protection device is the AC circuit breaker (ACCB) localized in the AC-DC converter stations. The AC-DC converters are designed to withstand the fault current until the fault is cleared by the ACCB [13].

The DC railway electrification can be seen as a multi-terminal radial asymmetric monopole network at up to 3 kV dc. The AC-DC substation and each train include DC circuit breakers (DCCB) [14]. The selectivity between the substation DCCB and the train DCCB may be challenging [15]. The railway DCCB uses the arc chutes that draw the arc in and fragment it to extinguish the fault current without relying on current zero crossing.

Ships with electric propulsion may involve DC distribution up to 35 kV [16]. The protection is ensured by ACCB but AC-DC converters may involve additional protection devices like a thyristor crowbar or a diode [17]. A supervisory controller for MVDC ship distribution was proposed in [18]. It coordinates the action of the AC-DC power converter and of the mechanical contactors to eliminate the faulty zone and reconfigure the network.

The protection strategy of photovoltaic installations up to 1.5 kV with IT earthing system involves the insulation monitoring and switchgear for pole-ground fault detection and clearing and DC fuses for pole-pole faults [19].

In recent years there were several researches on multi-terminal HVDC grids and HVDC DCCB [20], [21]. Three fault clearing strategies have been presented in [22], [23]: the fully-selective, the non-selective and the partially selective fault clearing. A demonstration of HVDC circuit breaker performances was carried out within the frame of PROMOTioN project [24]. Three types of DCCB were successfully tested: the voltage source converter assisted resonant current (VARC) injection breaker tested at 80 kV, 16 kA [25], the active current injection breaker tested at 200 kV, 16 kA, and the hybrid breaker tested at 320 kV, 20 kA [26]. A real time simulation model of the VARC DCCB was presented in [27].

A review of LVDC network protection was presented in [28]. In [29] the use of fuses as short-circuit protection in LVDC microgrids was evaluated considering their simplicity, cost, standardization and low steady-state losses.

The state of the art on MVDC network protection is rather limited. A cost-effective protection of MVDC distribution system based on hybrid modular multilevel converter (MMC) and a DC disconnecter was proposed in [30]. However, if the converter blocks or limits the short circuit current (to 1.5 p.u. as example), this could make it difficult to selectively identify and clear only the faulty component of the network. The use of MMC, especially involving full-bridge submodules may not be cost-effective. A similar concept was proposed in [31]. In [32], the radial MVDC system was protected by means of current limiting device and DC switches placed at each new line start and radial section. A novel algorithm was also proposed based on local voltage, current, and di/dt measurements. It is capable to clear the fault without use of communication among protective devices. In [33], a pole to ground fault detection method was proposed. It is based on the identification of the capacitance to ground of the feeder.

In MVDC systems, after a DC short circuit fault occurs, all distributed generators, capacitors and converter interfaced loads contribute to the fault current which will rise rapidly [34]. The short circuit current must be cleared fast to avoid damaging of the power electronics converters. In [35], a hybrid MVDC circuit breaker (CB) was tested showing the mechanical switch to open within 1.5 ms and to clear the fault current within 5 ms. A review of technologies for MVDC circuit breakers was presented in [5], [36]. In [5] a classification was proposed including: mechanical CB, solid state CB and hybrid CB.

In this article a protection strategy of a multi-terminal radial MVDC electric network is proposed. The protection strategy involves a single DCCB and multiple DC fuses. The novelty consists in the demonstration that the protection strategy used in AC distribution networks is applicable in MVDC networks. The proposed strategy limits the quantity of DCCBs. The DCCB is a sophisticated equipment, much more than an ACCB and may not be cost-effective in MVDC networks. On the other hand, the cost-effective and reliable DC fuses are proposed to protect the parts of the

network where the expected short-circuit occurrence is limited and where the automatic reclosing is not mandatory. The article proposes an economically viable protection strategy of MVDC networks, and the presented simulation results prove that no sophisticated strategy is required. The simplicity of the proposed protection strategy may facilitate the emergence of MVDC networks. Moreover, this work provides the elements of requirement specification for the protection and conversion equipment in the future radial MVDC networks.

The analyzed case study is presented in section 2. The proposed protection strategy is detailed in section 3. The simulation model is presented in section 4 and the simulation results are presented in section 5. Section 6 concludes the article and provides with some perspectives.

2. MVDC network architecture and power converter topologies

The existing AC distribution networks in highly populated areas are commonly realized as a ring where the individual loads are supplied from a ring main unit (RMU). A normally open point (NOP) separates the system into two radial networks. The same architecture can be considered for the MVDC networks as presented in Fig. 1. The ratings of the analyzed MVDC network are summarized in Table 1.

The interface with the AC grid is ensured by an AC-DC station with a voltage source converter (VSC) and a transformer. A neutral point clamped (NPC), IGBT-based VSC is selected considering the industrially available technologies [37]. A cascaded NPC converter, as presented in Fig. 2a, with a multi-winding transformer allows to avoid or to minimize the number of series connected IGBTs. A modular multilevel converter (MMC) could be also considered but it may not be cost-effective minding the voltage and power ratings [38], [39]. The transformer provides the galvanic separation and it adjusts the voltage between AC and MVDC networks. It also has a significant role in AC-DC converter harmonics filtering and fault current limitation. The AC-DC station could provide several MVDC feeders according to Fig. 1 but in this article only one feeder is considered.

The power of LV DC load/source is assumed significantly lower than the MVDC feeder rating (100 times lower) what is typically observed in AC distribution systems. A DC-DC converter is considered to interface with LV DC load/source. The galvanic separation between MV and LV circuits is mandatory. The isolated DC-DC converters provide inherent fault current limitation and they can be either bidirectional [40] or unidirectional [41]. The isolated unidirectional DC-DC converter based on the phase shifted full bridge (PSFB) topology (Fig. 2b) was selected for further analysis. The converter is composed of a LV inverter (SiC MOSFET-based), medium frequency transformer (MFT), MV rectifier (series connected SiC diode-based) and output filter (LC). This converter was detailed in [42] where it was shown that the output filter has the major influence on the fault response.

The MVDC network is realized with underground cables. There are a MVDC cable rated at AC-DC converter station power and a tee-off/tee-in cable rated at DC load/source power. The use of standard AC single-core cables is considered.

The RMUs are evenly spaced along the MVDC line. They include disconnectors and protection equipment.

Designing an MVDC network, the choice of line topology is between asymmetric monopole, symmetric monopole, bipole or hybrid [2]. In this article the symmetric monopole line topology is selected. It is expected to be the most cost-effective while offering good availability. The grounding scheme may involve high impedance or low impedance, either on AC or DC side of the AC-DC converter as presented in Fig. 3. The AC grounding may be realized thanks to the transformer star-point (if available) or an additional star-point reactor [43]. The DC grounding is selected in this article and the influence of the grounding resistance on the protection of the MVDC network is discussed in the following section.

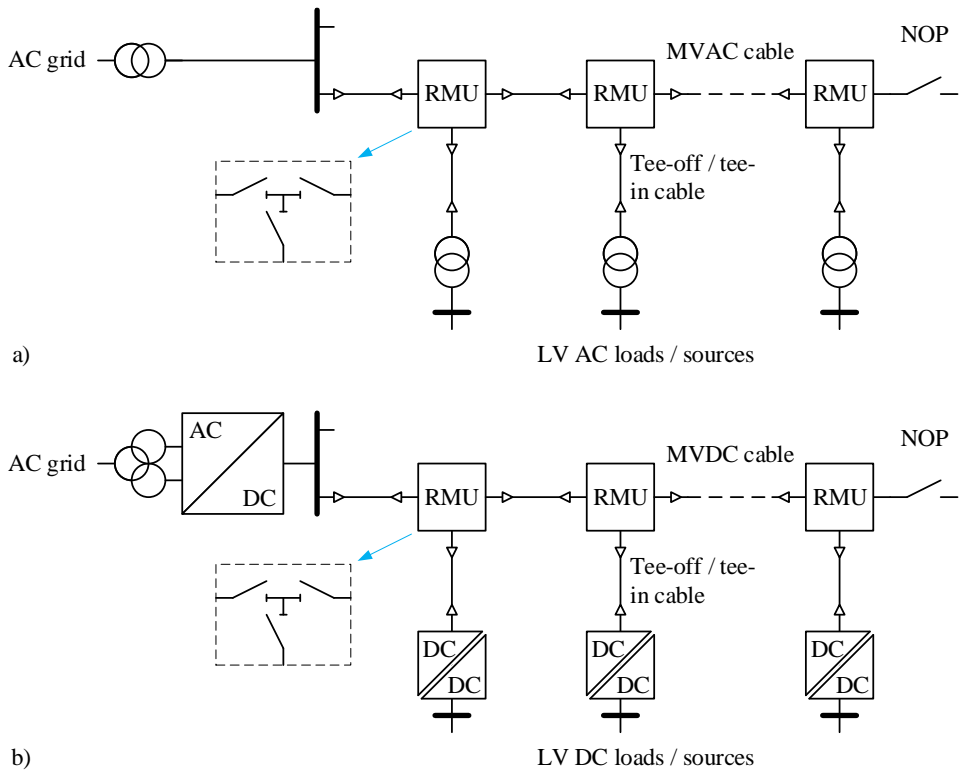


Fig. 1. Single line diagram, excluding protections, of: the typical MVAC distribution network (a) and the proposed MVDC network (b).

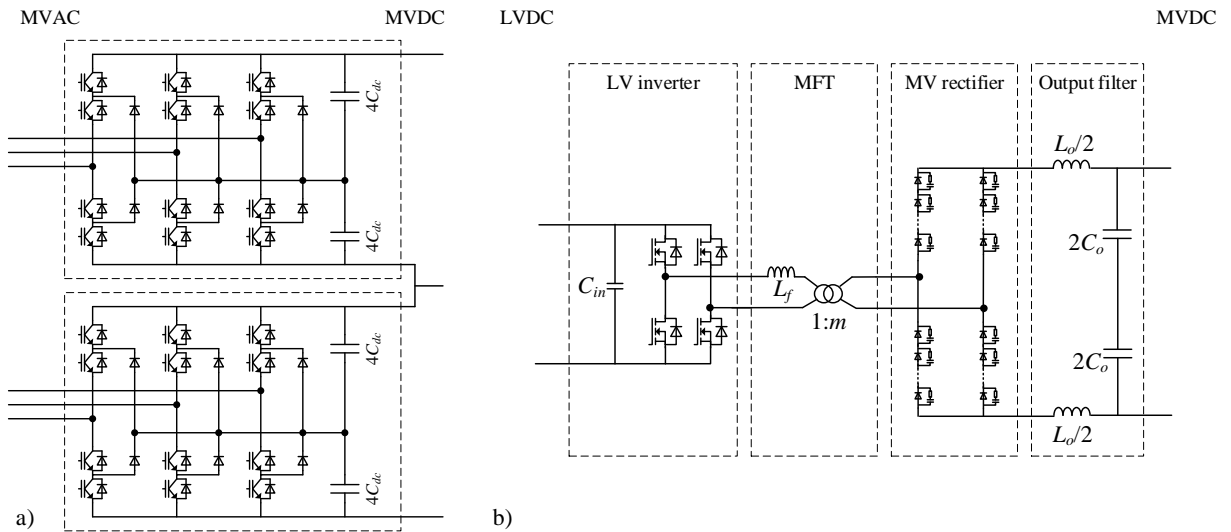


Fig. 2. Selected power converter topologies for the MVDC network: AC-DC cascaded neutral point clamped – NPC (a) and DC-DC phase shifted full bridge – PSFB (b)

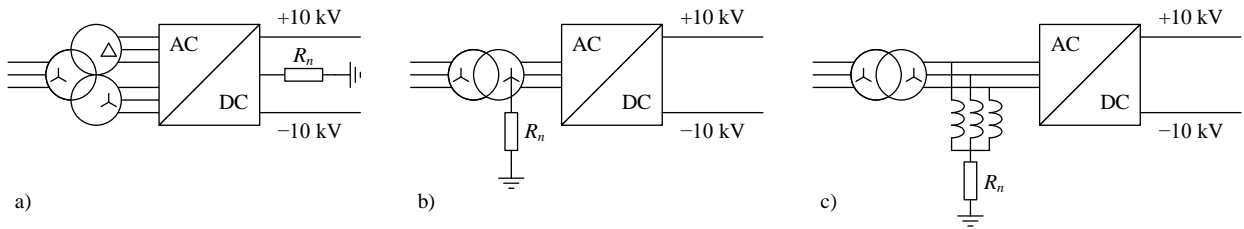


Fig. 3. Grounding schemes of the MVDC network: DC grounding (a), AC grounding through transformer star-point (b), AC grounding with star-point reactor (c). The value of the grounding resistance R_n influences the performance of the system in steady state and transients.

Table 1. Ratings of the case study MVDC network and AC grid

Parameter	Value
MVDC voltage	± 10 kV (20 kV)
AC-DC converter power	20 MW
MVDC line current	1 kA
MVDC line length	20 km
LV load / source power	200 kW
Tee-off / tee-in line current	10 A
AC grid short-circuit power	∞
Transformer short-circuit voltage	20%

3. MVDC network protection

The protection strategy in ring or radial AC distribution networks usually involve an AC circuit breaker (ACCB) in the primary substation and an ACCB or an AC fuse in the secondary substation [11]. The fuse is usually preferred in the secondary substation because it offers lower cost and higher reliability when compared to ACCB. The selectivity is achieved thanks to the proper tuning of time-overcurrent characteristics. The automatic or manual fault location is possible [11].

The protection strategy of the multi-terminal radial MVDC electric network must take into account high short-circuit current in the entire MVDC network [34]. The high short-circuit current is due to the converter and cable capacitor discharge and AC grid short circuit contribution. The entire MVDC network exhibits similar fault current due to low resistance of DC lines and due to capacitor discharge. Moreover, low short-circuit current withstand of IGBT-based VSC is a major constraint for the protection system which has to be fast [34]. The i^2t value of a typical high voltage 1500 A IGBT is in the range between $0.3 \text{ MA}^2\text{s}$ and $1 \text{ MA}^2\text{s}$. Depending on the fault current derivative, the maximum converter withstand would be a few milliseconds only. This means that the fault clearance in the MVDC network must be faster than in the AC systems which are usually designed to withstand the short circuit current during 200 ms [44] or even more. However, it is important to highlight that once the fault is cleared, then the restoration of the MVDC system could be rather slow. This is a significant difference when compared to HVDC system restoration which must be fast in order to ensure the power system stability. The power transmission system restoration is expected in a few milliseconds while the power distribution system restoration is accepted in a few seconds, even minutes or hours.

The contribution of DC loads/sources to fault current is neglected in this article. This is valid considering the isolated DC-DC converter with fault current limiting capability. The isolated DC-DC converters typically provide fault blocking capability [40], [42], [45]. However, if a DC-AC converter interfacing with a low voltage AC network was considered, then the load/source fault current contribution should not be neglected. The authors highlight the benefit

of using DC-DC converters, allowing to avoid the fault detection and isolation issues in the distribution networks involving distributed power generators [46].

The synthesis of possible protection options is summarized in Table 2. The full DCCB protection offers the highest availability of the network, but it requires a large number of costly DCCB. It should be noted that the sizing of the DCCB is mainly related to the fault current level. Even if the nominal DC load/source current is low, the DCCB in the RMU and in the AC-DC station would require a similar design given the similar value of short circuit current. The DCCB feeder protection combined with RMU DC fuse offers good availability and cost. The DC fuse feeder protection reduces the availability because automatic reclosing is not possible. The full DC fuse protection might be considered if the lowest cost was required.

Table 2. Protection options of the MVDC network

Feeder	RMU	Network availability	Protection cost
DCCB	DCCB	++	--
DCCB	Fuse	+	+
Fuse *	DCCB	-	--
Fuse *	Fuse	--	++

* a pyro-fuse [47] might be considered minding that high current fuses are not common

In this article the option with the DCCB feeder protection and RMU DC fuse is selected and it is presented in Fig. 4. A DC inductor L_{DC} is connected in series with the DCCB in order to limit the fault current rise. The inductance value should be as low as possible in order to avoid MVDC network stability issues [34]. The RMU DC fuse protects the equipment up to and including the DC-DC converter. The fuse also serves as a backup protection of the fault blocking DC-DC converter. The DCCB is the back up protection for the DC fuse. The protection of the transformer in the AC-DC converter station is assumed with an ACCB. The ACCB also serves as a backup protection of the MVDC feeder but the opening time of the ACCB may not be fast enough to efficiently protect the NPC converter.

In order to achieve full protection selectivity in the analyzed MVDC network, the time-overcurrent characteristics of DCCB and DC fuse must be properly tuned, avoiding any overlaps. This can be achieved because the rated DC load/source current is significantly lower than the rated MVDC line current (100 times). Considering a typical fuse characteristic, the breaking time is faster if the fault current is higher. A standard mechanical circuit breaker would never reach such a fast current breaking time, even if the fault current was high. For the studied MVDC network a standard AC fuse was selected with the pre-arc i^2t of 1.7 kA²s and minimum breaking current of 200 A. The protection relay of the DCCB was set to trip either at current threshold of 1.5 kA or i^2t threshold of 0.5 MA²s. The i^2t threshold was selected according to the typical AC-DC converter withstand. The minimum operating time of the DCCB was assumed 5 ms which is feasible for a solid state DCCB and challenging but feasible for a mechanical and hybrid DCCB. All parameters are summarized in Table 3 and the time-overcurrent characteristics are visualized in Fig. 5.

The selectivity between DCCB and DC fuse, combined with the rapid fault clearing requirement is only possible if the pole-pole fault and pole-ground fault currents are high. The pole-pole fault current is always high (considering low resistance short circuit) but the high value pole-ground fault current can be achieved only with the low value of grounding resistance R_n . In case of a fault in the DC load/source, the fuse should break the current before the trip of the DCCB. Once the fuse has brought the current to zero then the RMU disconnecter isolates the DC load/source while the MVDC network remains connected to the AC grid. The fuse striker triggers the disconnecter that isolates the faulty part of the network.

The grounding with the high value resistance R_n is also possible. It results in low pole-ground fault current. Other fault detection methods are required, including for example the ground current measurement. In case of pole-ground fault, there is a current flowing through the R_n which can be measured and compared to a threshold and trigger the DCCB. Alternatively, the voltage across the R_n could be measured or the voltage of two poles to ground. Moreover, additional equipment is required to localize the fault since the DC fuse cannot trip at low fault current. The differential current localization method can be used, but it requires high precision current measurement due to low fault current

value. It is important to highlight that the pole-pole fault current does not depend on the value of R_n so anyway all the network equipment, including the AC-DC converter, must be sized for the high value short circuit current.

The fault localization in the MVDC network may be the same as in the AC network [48]. If the fault trips the fuse in one of the DC loads/sources than the fuse striker helps identifying the fault location. If the fault is somewhere in the MVDC cable, then the current measurement at each end of the cable section is required. Fig. 6 presents the measurements needed to localize faults in the line by the differential current approach. By doing the subtraction of the measurements taken on both ends of the line and comparing this result with a threshold, the fault position could be identified. Note that this process requires communication between the DC stations.

The design of the MVDC network protection must take into account different constraints. The VSC short circuit current withstand is probably the most challenging. During a DC pole-pole fault, the NPC-VSC experiences the converter capacitor discharge (limited by L_{DC}) followed by the L_{DC} discharge through the freewheeling diodes and then the AC grid short circuit current [34]. Depending on the sizing of the VSC and the value of L_{DC} , the maximum allowed operating time of the protection device would be approximately a few milliseconds only. Some VSC reinforcement (for example with a bypass thyristor or diode [17]) could extend the maximum operating time to a few tens of milliseconds. On the other hand, the DCCB is designed to a maximum value of fault current derivative di/dt . Simply, if the di/dt is too high, during the DCCB operating time the fault current would exceed the maximum breaking current. The DCCB must also absorb the entire magnetic energy of the circuit, including the energy of L_{DC} . The fuse is designed to operate above the minimum breaking current. The system must be designed in a way so that the fuse never experiences the current higher than the rated and lower than the minimum breaking current. Moreover, the fuse can withstand a maximum total i^2t . The performance of a standard AC fuse in a DC system must be addressed but it exceeds the scope of this article. The VSC control should be designed in a way to ensure the DC fault ride through. Even if the NPC-VSC cannot control the DC current under pole-pole fault, it should be able to restart seamlessly once the fuse has cleared the fault.

Table 3. Parameters of the protection equipment models

Parameter	Value
Fuse pre-arc i^2t	1.7 kA ² s
Fuse total i^2t	12 kA ² s
Fuse minimum breaking current	200 A
Circuit breaker threshold i^2t	0.5 MA ² s
Circuit breaker threshold current	1.5 kA
Circuit breaker minimum operation time	5 ms

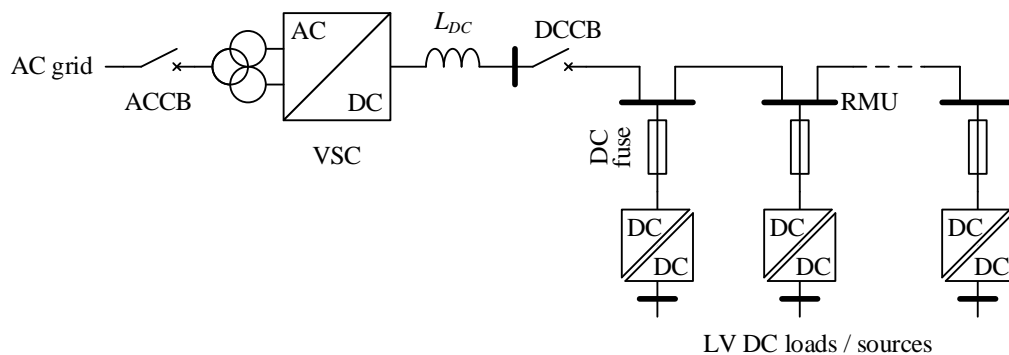


Fig. 4. Protection equipment of the MVDC network.

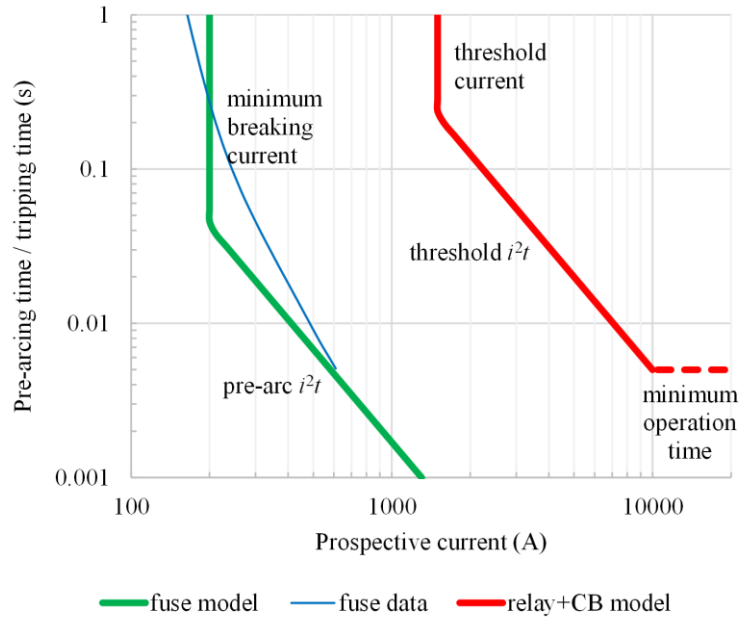


Fig. 5. Time-overcurrent characteristic of: simplified model of a DC fuse and example data of an AC fuse, and simplified model of a DC protection relay and circuit breaker.

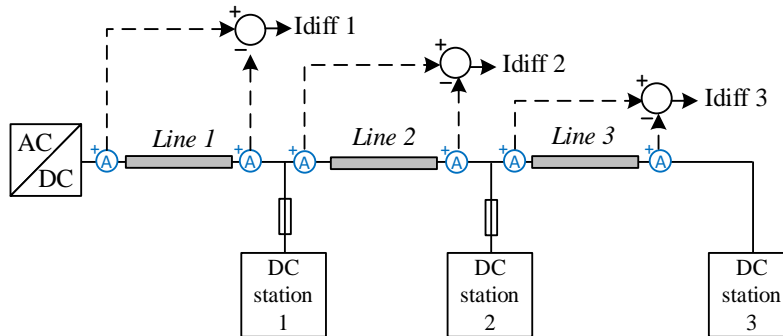


Fig. 6. Differential current measurements for localization of faults in the line.

4. Simulation model

The case study presented in Fig. 1 was modelled in Matlab/Simulink – Simscape Electrical as shown in Fig. 7. The model is composed of a 20 MW AC-DC converter station (including two cascaded NPC converters, 10 MW each), and three DC stations (two of them rated at 200 kW and the third one at 19.6 MW). The grounding is realized on the DC side, at the connection of two NPC converters. The value of the grounding resistance R_n is modified to investigate the influence on the protection strategy. Considering the control of the network, the AC-DC station controls the DC voltage and the reactive power at the AC grid terminal, while the DC stations are in power control mode.

The AC-DC converters are modelled using a detailed model. The cables are modelled using a π -section model. For the DC stations, two different models are used.

The two DC stations of 200 kW closer to the AC-DC converter are modelled using an average model [49]. In this model, a controlled voltage source controls the current being exchanged with the MVDC network. A combination of

an ideal switch and a freewheeling diode allows to model the converter behavior during blocked state. When the DC station detects a fault, it opens the switch and the current flows through the freewheeling diodes.

The third DC station represents the rest of the loads/sources in the network, it is rated at 19.6 MW. This station is modelled using a current source with a capacitor in parallel (Fig. 7).

For the DCCB, a simplified model of a mechanical DCCB is used [50]. It is composed of a main branch implemented with an ideal switch, and two parallel branches with a capacitor and a surge arrester. The parallel branches absorb the energy during the DCCB opening. The surge arrester is selected to limit the overvoltage to 1.5 p.u. When the trip order arrives to the DCCB, a delay of 5 ms is considered to open the switch of the main branch. After the switch opening, the fault current commutates to the parallel branches. It will be effectively cut when all the line inductive energy has been absorbed by the surge arrester and capacitor.

The fuse model is made of a main branch implemented with an ideal switch and a secondary branch in parallel made by a set of a capacitor, an ideal switch, and a resistance [51]. The parallel branch models the arc during the fuse opening. When the energy threshold of the fuse is exceeded, the switch in the main branch opens, and the arc branch is switched on. The fault current flows through the capacitor and resistance in the arc branch. It is eliminated when the capacitor and the resistance absorb the inductive energy of the line. When the current reaches zero, the arc branch switch is opened.

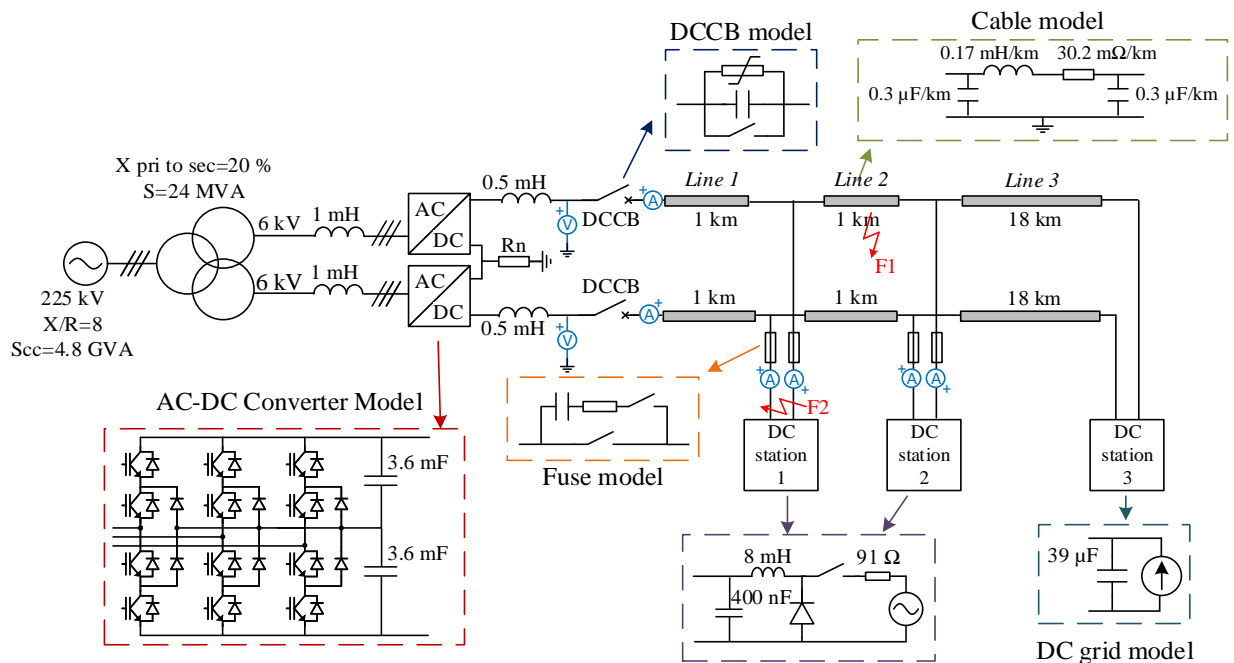


Fig. 7. Simulation model of the MVDC network including: AC grid, AC-DC converter, DC-DC converters, DC circuit breaker, DC fuse, DC cable and fault locations.

5. Simulation results

The case study MVDC network was simulated under DC fault conditions considering two different fault locations: in the cable and in DC station 1 (respectively F1 and F2 in Fig. 7). Two types of faults were considered: pole-pole and pole-ground faults. For the case of pole-ground faults, the fault was done at the positive pole, and two different values of neutral resistance R_n were considered: high resistance value of 1 k Ω and a solid grounded (0 Ω). The ground inductance and cable-cable inductance were neglected.

Fig. 8 shows the simulation results for a fault in the cable. The fault occurs at $t=2$ s. Before the fault, the system is in steady state at nominal operation point, i.e. the voltage is ± 10 kV, and the current in the DC line (at the AC-DC converter terminals) is 1 kA. It is considered that all DC stations behave as sources, injecting their nominal power.

The voltages in the DC lines are shown (see Fig. 7 for the position of the measurements), as well as the current in the MVDC lines at the AC-DC station and the currents in DC stations 1 and 2.

For the case of a pole-pole fault, the voltage of the two poles collapses to zero and a high current is seen in the MVDC lines (around 15 kA on both poles for this example). The DC stations do not contribute to the fault current (no overcurrent is observed), since they are blocked and they prevent any contribution to the fault coming from the LV side. As consequence, only the DCCBs in the main line are tripped, but not the fuses in DC stations. It is observed that around 5 ms (the considered delay time to model the mechanical switch) after the DCCBs trip order, the fault current starts to decrease in both poles. With the DCCB opening, the DC voltage increases to the nominal value. An overvoltage is observed but it is limited according to the DCCB surge arrester characteristic. After the fault, there are some high frequency oscillations which are due to the stored energy in passive components. The damping of these oscillations could be modelled more precisely if a wide band cable model was used [52].

In the case of a cable pole-ground fault, two different behaviors are observed depending on the value of the neutral resistance R_n .

In the case of high value resistance R_n , there is a voltage shift in the system: while the faulty pole voltage collapses to zero, the voltage in the healthy pole goes up to 2 p.u. in steady state (during transients some overvoltage is observed). For this case, given the high R_n value, the fault current is low. In consequence there is neither trip of the DCCBs nor the fuses. Thus, the fault is not eliminated. To eliminate the fault, the switchgear in the RMUs next to the faulty cable should be operated. This requires determining first where the fault is.

In the case of a pole-ground fault with a low value of R_n , the fault current in the faulty pole is high. It is observed that the DC stations do not contribute to the fault (no overcurrent is seen), and that only one pole in the MVDC line carries the fault current. In consequence, only the DCCB in the faulty line is tripped and not the DCCB on the healthy line neither the fuses in the DC stations. Considering the voltages, the healthy pole voltage does not shift. The faulty pole goes to zero at the fault moment and comes back to the nominal value with the DCCB opening. An overvoltage is observed but limited by the DCCB surge arrester.

Fig. 9 presents the simulation results for a fault in the DC station 1. In the case of a pole-pole fault, the fault current is high at both poles in DC station 1 and in the AC-DC station. DC station 2 does not contribute to the fault. The trip of the fuses in DC station 1 breaks the fault current faster than in the case of a fault in the cable where the DCCBs took around 15 ms in total (see Fig. 8). The selectivity of protection is achieved, in this case the fuses trip but not the DCCBs, thanks to the proper selection of the time-overcurrent characteristics of the devices (see Fig. 5). Fig. 10a shows in more details the current in the positive pole measured in the DCCB and in the fuse, as well as the value of i^2t . In the figure, the threshold for opening the fuse is also presented. The DCCB i^2t threshold is not shown given that it is several times higher and does not fit the figure.

In case of a pole-ground fault in the DC station 1 with a high neutral resistance, the current transient caused by the discharge of the cable and converter capacitors is high enough to trip the fuse. The voltage in the healthy pole shifts to 2 p.u. but comes back to the nominal value as soon as the fuse opens. Fig. 10b shows in more detail the currents and the value of i^2t of the fuse. It is seen that the threshold value of the fuse is reached by the transient of the current. Thus, even if a low current is expected in steady state given the value of R_n , the fault transient is enough to cause the fuse trip, eliminating the fault.

In case of low value of R_n and a pole-ground fault, the fault current is high in the positive pole at the AC-DC converter and the DC station 1. As in the case of pole-pole fault, the fault is eliminated by the DC station fuse, and the selectivity of DCCB and fuse is assured by the device characteristics.

The proposed protection strategy ensures the protection of the power electronics converters. The pole-pole fault is the worst case for the AC-DC converter. The short-circuit current withstand of the AC-DC converter was assumed 0.5 MA²s. The simulation results for the fault in the MVDC cable (F1) and in the DC station 1 (F2) are presented in Fig. 11. The current of the converter diode which experiences the highest magnitude as well as the diode i^2t are displayed. In case of fault F1 the diode i^2t is just below the limit 0.5 MA²s but in case of fault F2, the fuse breaks the current so fast that the diode current increases only a little.

Table 4 summarizes the main conclusions of the presented simulation results.

Table 4. Synthesis of simulation results

Parameter	Pole-pole fault		Pole-ground fault $R_n=1\text{ k}\Omega$		Pole-ground fault $R_n=0\text{ }\Omega$	
	Cable (F1)	DC station 1 (F2)	Cable (F1)	DC station 1 (F2)	Cable (F1)	DC Station 1 (F2)
Fault Current in AC-DC station	High	High	Low	Low	High	High
Fault Current in DC station 1	Low*	High	Low	High in transient, low in steady state	Low*	High
Fault Current in DC station 2	Low*	Low*	Low	Low	Low*	Low*
Protection device	DCCBs	Fuses	None (should be done by switchgear)	Fuse (trip caused by current transient)	DCCB on faulty pole	Fuse on faulty pole
DC line voltage	Overtoltage during DCCB opening	Overtoltage during fuse arcing	Voltage shifting	Voltage shifting	Overtoltage on faulty pole during DCCB opening	Overtoltage during transient

*Assumes that DC stations can block the propagation of faults from/to the LVDC side

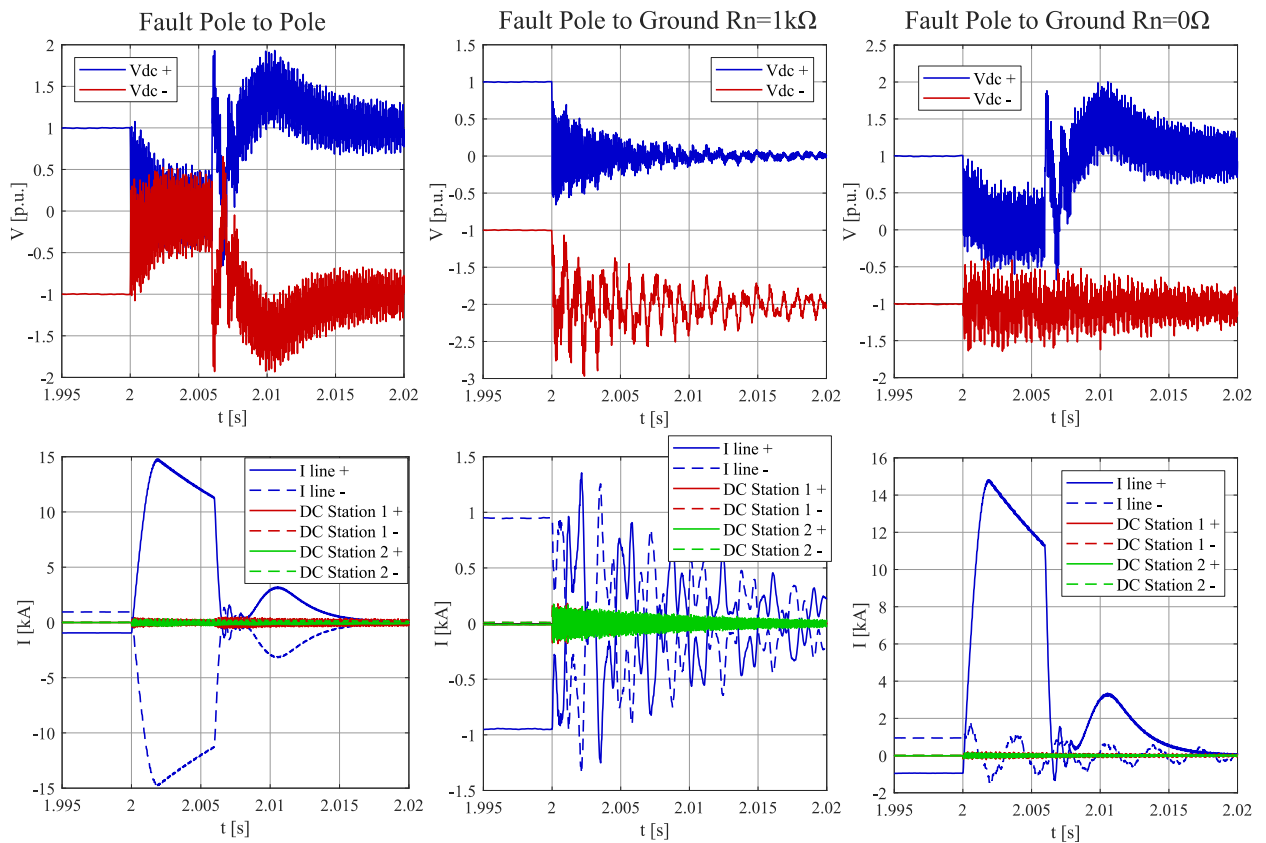


Fig. 8. Simulation results for a fault in the MVDC cable (F1).

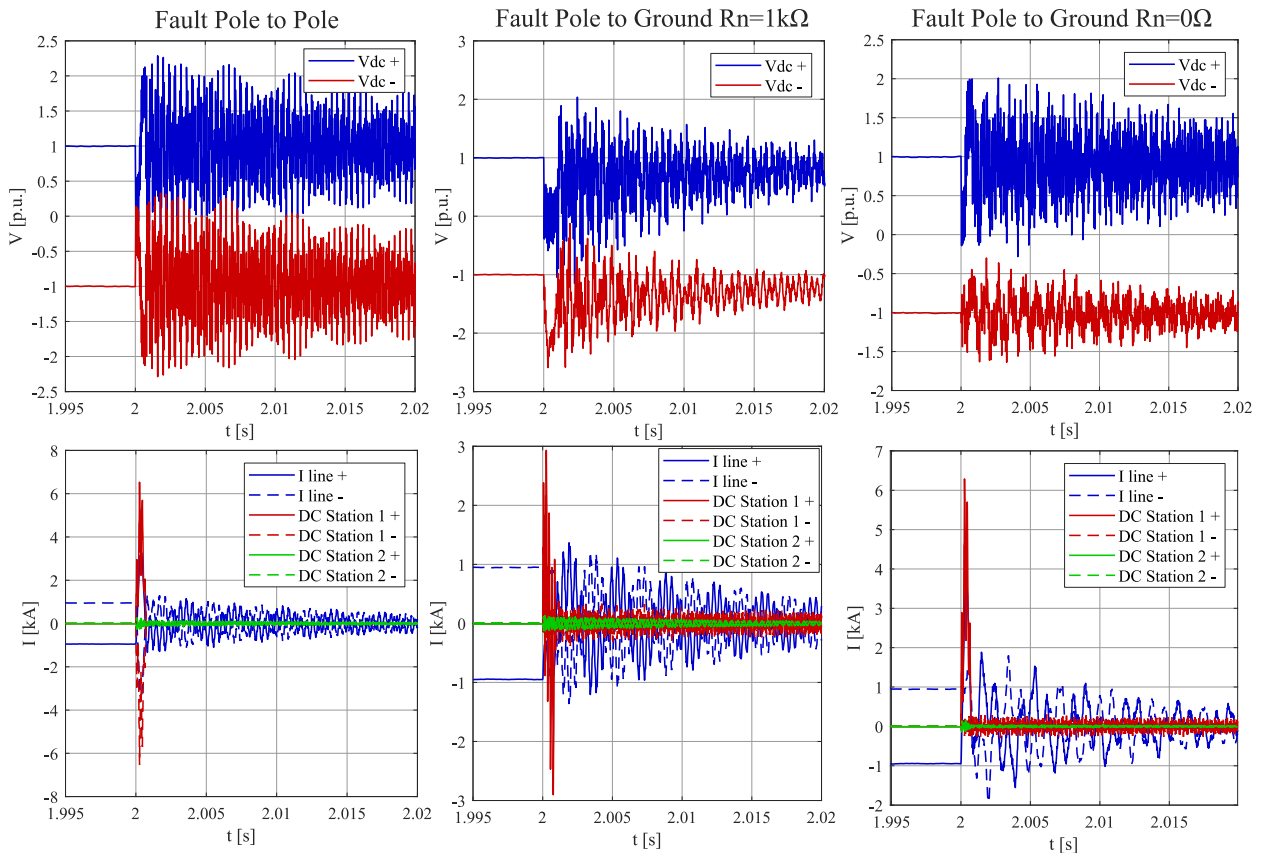


Fig. 9. Simulation results for a fault in the DC station 1 (F2).

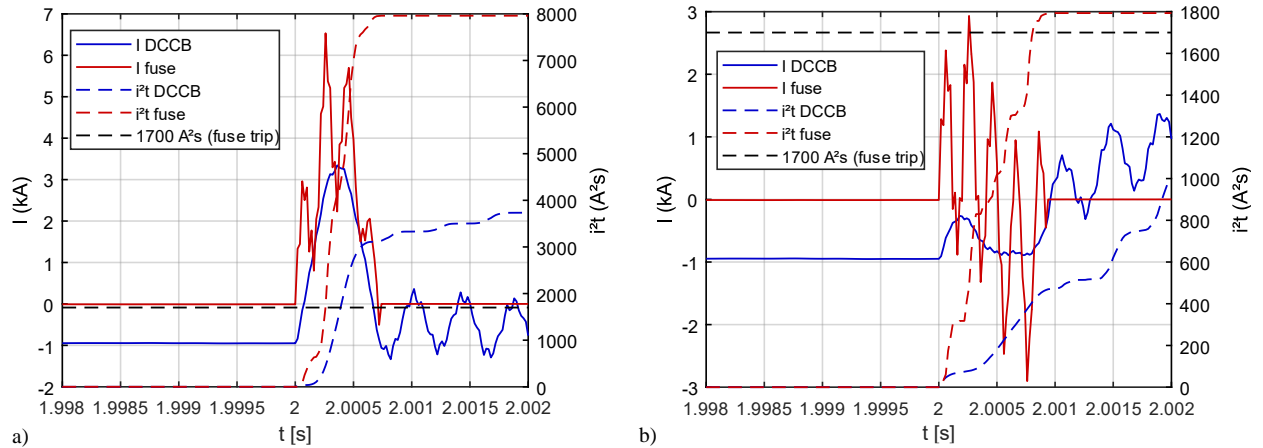


Fig. 10. Current and i^2t of DCCB and fuse for a fault in the DC station 1: pole-pole fault (a) and pole-ground fault with $R_n=1k\Omega$ (b). The threshold value for the DCCB $0.5 MA^2s$ is not shown.

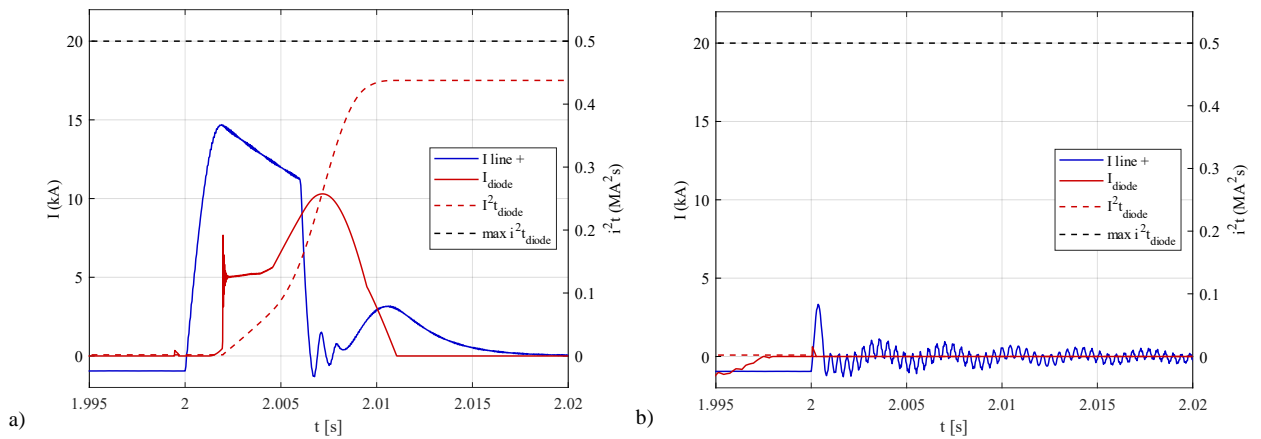


Fig. 11. AC-DC converter withstand under pole-pole faults: in the MVDC cable - F1 (a) and in the DC station 1 – F2 (b). The maximum AC-DC converter diode i^2t equal to $0.5 \text{ MA}^2\text{s}$ is never exceeded.

From the presented results, it is concluded that the fault can be eliminated by the proposed protection equipment in case of pole-pole faults or in case of pole-ground faults with low neutral resistance. However, the elimination of the fault current by the protection equipment does not necessarily isolate the faulty part of the network. This should be done to continue the service with the healthy part of the system. To isolate the faulty lines, the RMU disconnectors should be used, which requires to localize the fault first and then to operate the concerned RMU only.

Concerning the pole-ground faults in the cable and high neutral resistance, there is no protection device that isolates the fault. This should be done by the RMU disconnectors what requires to localize the fault first. Concerning the fault in the DC station, the fuse eliminates the fault thanks to the high current transient.

According to the simulation results (see Table 4), the pole-pole faults and pole-ground faults at the DC stations can be localized easily by the fuse strikers. For all other fault cases an analysis of the differential current in the lines should be done (see Fig. 6). Since it is considered that there is not a major problem to localize faults when the fuse has been tripped, from the 6 analyzed cases of Table 4 only 3 are considered for the localization analysis.

Fig. 12 shows the results of the differential current in each line for the cases of pole-pole fault and pole-ground fault with high neutral resistance. The case of pole-ground with low neutral resistance is not shown since the analysis should be the same as for a pole-pole fault (see current waveforms in Fig. 8). In case of a pole-pole fault in the cable, the localization of the fault is easy because the differential current in the faulty line can be easily discriminated against the other lines. However, in case of pole-ground fault with high neutral resistance, the measured current value is not high enough to discriminate the fault. Indeed, two lines show similar behavior. In case of pole-ground fault in the cable, it is not clear if the fault is in the cable or in the DC station 1. From this analysis, it is observed that for the proposed protection strategy based on fuses in the DC load/sources, a low neutral resistance is beneficial to eliminate the fault and to localize it in all cases. Alternatively, highly sensitive differential current measurements are required.

The proposed protection strategy remains valid for different grounding schemes, including AC grounding and DC grounding (see Fig. 3). The protection against pole-pole faults is the same regardless the choice of the grounding scheme. However, the detection and localization of pole-ground faults may differ because the fault current depends on the short circuit impedance. In case of AC grounding, the DC fault current circulates through the transformer windings (or start point reactor) which represent a high value inductance, in the range of 1 H (considering 2% magnetizing current). This high value inductance impacts the dynamics of the fault current and high value pole-ground fault currents cannot be reached. The fault detection should rely on the ground current measurement through R_n and the fault localization requires highly sensitive differential current measurements. Some simulation results are presented in Appendix A. The design of different grounding systems exceeds the scope of this article.

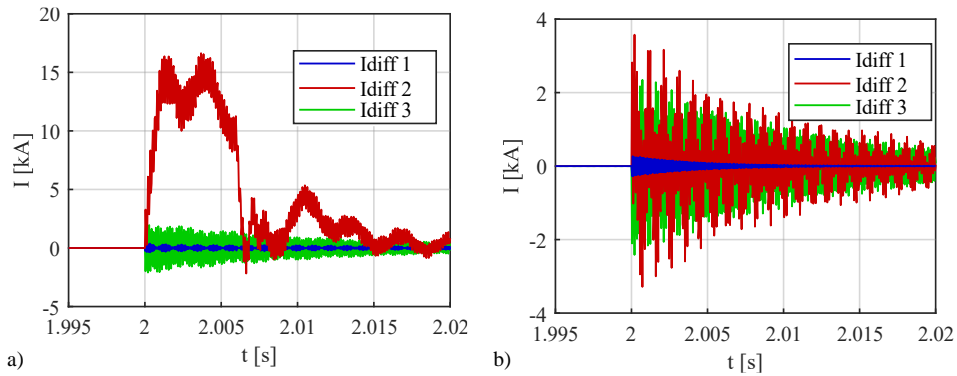


Fig. 12. Differential current for fault localization: pole-pole (a) and pole-ground $R_n=1\text{k}\Omega$ (b). The presented cases are for a fault in the Line 2.

6. Conclusion

The protection strategy of a multi-terminal radial MVDC electric network was presented. The protection strategy involves a single DCCB and multiple DC fuses. The simulation models were developed allowing to confirm the theoretical analysis. The article demonstrates that the protection principle used in AC distribution networks is applicable in MVDC networks. The proposed strategy limits the quantity of sophisticated and costly DCCB used. The cost-effective DC fuses are proposed to protect the parts of the network where the expected short-circuit occurrence is limited and where the automatic reclosing is not mandatory. It was observed that for the proposed protection strategy, it is beneficial to have a low neutral resistance which allows to isolate the fault and to localize it. However, in case of high neutral resistance and the pole-ground fault in DC station, the energy stored in the capacitors is high enough to trip the fuse. Based on the results of this article, the requirements for the DCCB and DC fuse can be established for the future MVDC networks. Moreover, fault current withstand of the AC-DC converter station can be defined.

Several perspectives were identified. The design of the grounding scheme for different converter topologies (NPC and MMC in particular) should be addressed and the intermediate values of grounding resistance should be considered ($0 < R_n < 1 \text{ k}\Omega$). The operation and performance of DCCB and DC fuses must be further investigated mainly under network transients. The performance of a standard AC fuse in the DC system must be assessed. The wide band cable model should be considered, representing more precisely the high frequency transients. The protection strategy in a radial network with several feeders supplied from the AC-DC station should be evaluated. The contribution of LV loads/sources should be considered.

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Appendix A. Influence of the grounding scheme on pole-ground faults

The influence of the grounding scheme of the MVDC network on pole-ground faults was analysed. Three possible grounding schemes are presented in Fig. 3. The simulation model presented in Fig. 7 was adapted to the AC grounding through the transformer star-point and to the AC grounding with the star-point reactor (SPR). These grounding schemes are not feasible with the 3-winding transformer, so the transformer was replaced with a 2-winding one and there was only one NPC converter rated at full power and voltage. For the simplicity of analysis, the fault at DCCB terminals was considered and there was only one DC station (number 3). The value of the grounding resistance R_n was kept the same at $1 \text{ k}\Omega$. The simulation results under pole-ground faults are presented in Fig. 13. The DC line current collapses

to approximately 10 A after the converter blocks. The pole-ground voltage of the faulty pole collapses to zero following a rapid transient. The ground current exhibits similar behaviour for three grounding schemes and it reaches approximately 10 A in the steady state. It is concluded that as far as the grounding resistance is high, the grounding scheme does not influence the pole-ground faults. The protection strategy presented in this article remains valid for any grounding scheme with the high value grounding resistance. However, the fault localization requires highly sensitive differential current measurements.

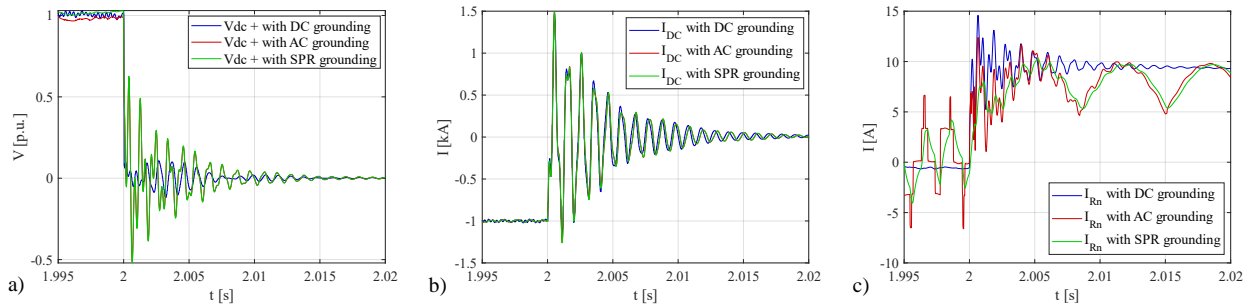


Fig. 13. Simulation results for pole-ground faults with different grounding schemes (DC grounding, AC grounding through transformer star-point and AC grounding with star-point reactor - SPR): pole-ground voltage (a), DC line current (b) and ground current through R_n (c)

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