

Article

Simulation Study on Switching Overvoltage of Submarine Cables in Flexible DC Transmission System

Youcong Huang¹, Wenqi Li¹, Junfeng Zhang^{1,*}, Zhiwei Fu², Ying Zhang¹, Ziqi Lin¹, Zhongnan Zheng¹, Tongtong He³ and Yuesheng Zheng³ 

¹ State Grid Fujian Electric Power Research Institute, Fuzhou 350007, China; hyoucong@163.com (Y.H.); 372869196@qq.com (W.L.); panpanaiyouyong@163.com (Y.Z.); l_zqfjdky@163.com (Z.L.); zhengzhongnan@hotmail.com (Z.Z.)

² State Grid Fujian Electric Power Co., Ltd., Fuzhou 350003, China; xyfzw@163.com

³ College of Electrical Engineering and Automation, Fuzhou University, Fuzhou 350108, China; hett@fzu.edu.cn (T.H.); yueshengzheng@fzu.edu.cn (Y.Z.)

* Correspondence: 15638293798@163.com

Abstract

With the rapid development of wind power generation, submarine cables have become a critical transmission channel for delivering offshore wind energy to onshore power stations. Because of the difficulty of submarine-cable maintenance, particular attention should be paid to their overvoltage characteristics during operation. Taking a ± 200 kV DC submarine-cable project as the research background, this paper establishes a PSCAD/EMTDC model of a two-terminal MMC-HVDC submarine-cable system and compares the conductor-to-ground overvoltages caused by faults at different electrical locations. Among the investigated AC-side cases, single-line-to-ground faults on the valve sides of the connecting transformer and bridge-arm reactor produce relatively high cable overvoltages, with the bridge-arm-reactor valve-side fault reaching a maximum of 2.48 p.u. (496.48 kV). Among all investigated cases, the grounding fault on the valve side of the DC reactor produces the highest overvoltage, reaching 2.93 p.u. (586.18 kV) at approximately 30 km along the cable. After the initial transient associated with the DC-side grounding faults, the healthy-pole conductor-to-ground voltage remains at approximately 2.0 p.u. The results identify the relatively severe fault locations and cable sections requiring particular monitoring attention and provide a case-specific reference for DC submarine-cable monitoring and subsequent project-specific insulation-coordination studies.

Keywords: flexible DC transmission; modular multilevel converter; switching overvoltage; submarine cable



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1. Introduction

The Hellsjon project in Sweden is the world's first high-voltage direct current transmission project based on voltage source converters (VSC-HVDC). It effectively addresses the core problems of conventional HVDC transmission, including commutation failure risks, heavy reliance on reactive power compensation, and high complexity in system control and fault isolation [1]. The Transbay project in the United States pioneered the application of modular multilevel converters (MMC) in VSC-HVDC systems. Owing to its prominent advantages in high-voltage and large-capacity power conversion scenarios, MMC-HVDC has rapidly evolved into the mainstream technology in the field of flexible DC power transmission [2–4]. In recent years, the large-scale grid integration of renewable

energy far away from load centers, along with the growing number of isolated island power supply projects, has further accelerated the application and advancement of MMC-HVDC technology [5,6]. Among various renewable power generation technologies, wind power has achieved rapid development and played an increasingly vital role in energy supply by virtue of its low cost, mature technology and high operational reliability [7–10]. Compared with onshore wind energy, offshore wind energy features higher energy density and greater annual utilization hours, possessing broad market prospects. For the power delivery from offshore wind farms to onshore substations or AC power grids, flexible DC transmission stands out as a superior option in both technical and economic aspects when compared with high-voltage AC transmission [11]. With the rapid exploitation of nearshore wind energy resources, offshore wind power integrated via flexible DC transmission will become a dominant development trend in the future [12]. Accordingly, high-voltage flexible DC transmission projects are being actively planned and put into operation worldwide [13].

In offshore wind power flexible DC transmission projects, submarine cables are generally adopted as the DC transmission lines connecting rectifier stations and inverter stations. Restricted by the special submarine operating environment, submarine cables have more sophisticated manufacturing processes and internal structures than terrestrial cables. Their structural design incorporates water-blocking, anti-corrosion and armoring components to adapt to undersea conditions, and their laying difficulty and construction cycle also differ greatly from those of land cables.

As flexible DC transmission and DC cable manufacturing technologies become increasingly sophisticated, high-voltage direct current cables with crosslinked polyethylene (XLPE) insulation have become the preferred type of plastic-insulated DC cables thanks to their outstanding electrical and mechanical properties. They have been widely applied in cross-strait power transmission, tunnel power delivery, renewable energy power generation and other fields, and have gained extensive practical applications at home and abroad in recent years [14,15].

Submarine cables adopt solid insulation structure. Once electrical breakdown occurs, the insulation cannot recover, which will trigger the outage of the entire DC power system. In addition, DC submarine cables are costly with complicated construction and emergency maintenance works, so it is essential to guarantee their safe and stable operation. The overvoltage withstand level serves as a core evaluation indicator for the operational reliability of DC submarine cable systems. Therefore, it is necessary to adopt electromagnetic transient simulation to simulate various overvoltage conditions that may occur during the operation of DC submarine cables [16,17], so as to determine the required insulation level for over-voltage protection of submarine cables in advance.

Previous studies have investigated DC-cable overvoltages in VSC- and MMC-HVDC systems from different perspectives. Reference [11] systematically evaluates cable-voltage stresses caused by station-internal and DC-side faults in long-cable MMC-HVDC systems. Based on the ± 160 kV Nan'ao multiterminal flexible DC project, Reference [18] examined transient cable overvoltages under different fault conditions and reports the influence of fault resistance on terminal overvoltage. Reference [19], using the ± 200 kV Zhoushan multiterminal flexible DC project, investigated the effects of converter-blocking delay, cable length, and neutral-grounding resistance. Reference [20] analyzes switching overvoltages under different fault scenarios using the calculated impedance and admittance parameters of coaxial HVDC cables. Reference [21] further examined the voltage stresses between the cable conductor, metallic sheath, armor, and ground and discusses their implications for cable-insulation design.

These studies establish the importance of electromagnetic-transient analysis for HVDC cable systems and demonstrate that cable overvoltages are affected by the fault condition,

cable parameters, grounding arrangement, converter response, and protection settings. However, their numerical results are obtained using different system topologies, rated voltages, cable lengths, grounding arrangements, fault parameters, and converter-control or protection settings. Consequently, the reported peak values cannot be directly compared without accounting for these differences. In addition, the published studies place different emphasis on parameter sensitivity, terminal overvoltage, cable-layer voltage stress, or insulation coordination, leaving a need for a consistent comparison of representative fault locations across the continuous electrical path from the AC network to the DC submarine cable within one fixed system configuration.

Against this background, a two-terminal MMC-HVDC submarine-cable model is established based on a ± 200 kV flexible DC transmission project. The research object is the conductor-to-ground overvoltage of the 50 km DC submarine cable. The selected cases cover the main electrical boundaries through which disturbances may propagate to the cable, including the grid and valve sides of the connecting transformer, the valve side of the bridge-arm reactor, different locations along the DC cable, and the valve side of the DC reactor. Under the same system configuration and fixed model parameters, the maximum overvoltage, its location along the cable, and the post-fault voltage behavior are compared among the investigated cases.

The work presented in this paper comprises three aspects. First, representative AC-side and DC-side fault cases are compared within the same system and cable model. Second, for the DC-cable grounding cases, the fault location on the faulted pole is distinguished from the voltage-observation position on the healthy-pole cable. Third, the observed spatial and temporal characteristics are interpreted by considering pole-to-ground voltage displacement, distributed traveling-wave propagation, boundary reflections, and electromagnetic coupling among the cable conducting layers. The results are used to identify relatively severe fault cases and cable sections requiring particular monitoring attention within the investigated system.

The present study focuses on fault-induced overvoltages in the submarine-cable section of the investigated MMC-HVDC system. Lightning surges, circuit-breaker restrikes, multiple simultaneous faults, detailed surge-arrester coordination, thermal aging, and the transient characteristics of onshore cable sections are beyond the scope of this study.

The remainder of this paper is organized as follows. Section 2 describes the MMC-HVDC system and submarine-cable model. Section 3 presents the AC-side and DC-side fault-overvoltage results. Section 4 discusses the comparative results, physical interpretation, applicability, and limitations. Section 5 summarizes the main conclusions.

2. System Parameters of Simulation Model

All electromagnetic-transient simulations were performed using PSCAD/EMTDC (Manitoba Hydro International Ltd., Winnipeg, MB, Canada). The converter stations at both ends of the simulation model established in this paper are equipped with MMC, and the whole model features a symmetric structure of the AC power grid. To further investigate the overvoltage borne by DC transmission lines under transient fault conditions, it is known that a longer transmission distance between the two converter stations corresponds to a larger cable length and higher line capacitance, which intensifies the capacitance rise effect and leads to more severe overvoltage after faults occur [11,22,23]. Such research objects are of typical representative significance. Accordingly, this paper establishes the simulation model focusing on long-distance submarine cable transmission terminals at the corresponding voltage level, and its simplified topological structure is shown in Figure 1.

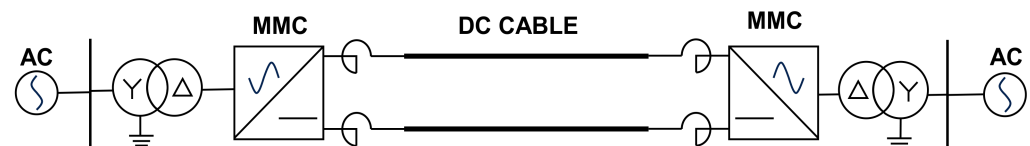


Figure 1. Topology of the ± 200 kV two-terminal MMC-HVDC submarine-cable system used for the electromagnetic-transient study. AC denotes the alternating-current system; MMC denotes the modular multilevel converter; and Y and Δ denote star- and delta-connected transformer windings, respectively.

2.1. Parameters of Two-Terminal Converter Stations

The grid sides of the two converter stations are connected to 220 kV AC systems. Three-phase two-winding transformers with Yn/ Δ connections convert the grid-side voltages to the valve-side voltages required by the converter stations. Each MMC consists of six arms, and an arm reactor is installed in each arm to suppress internal circulating currents. Each arm contains 20 half-bridge submodules (SMs) [24]. Nearest Level Control (NLC) is adopted as the internal modulation strategy of the MMC. In addition, a proportional-control-based capacitor-voltage-balancing strategy and Circulating Current Suppression Control (CCSC) in the dq reference frame are employed [25]. DC reactors are installed between the converters and DC cables to stabilize the DC current and suppress resonant components. The principal converter-station parameters are listed in Table 1 [26–28].

Table 1. Parameters of both converter stations.

Equipment	Parameters	Sending-End Converter Station	Receiving-End Converter Station
Interface Transformer	Rated Capacity/MVA	450/450	350/350
	Rated Voltage/kV	230/205.13	230/204.12
	Connection Mode	Yn/ Δ	Yn/ Δ
Bridge Arm Reactor	Inductance Value/mH	90	120
DC Reactor	Inductance Value/mH	20	20
Sub-module Capacitor	Number of Sub-modules per Bridge Arm	20	20
	Sub-Module Capacitance Value/mF	12	9
	Sub-Module Capacitor Rated Voltage/kV	20	20
Equivalent Star-Point High-Impedance Branch	Equivalent Inductance Used in the EMT model/H	5000	5000
	Branch Resistance/ Ω	6000	6000
DC Side Outlet Terminal	Rated DC Voltage/kV	± 200	± 200
	Rated DC Power/MW	400	300

Note: Yn/ Δ denotes a grounded-star/delta transformer winding connection.

This two-terminal flexible DC transmission system supports four-quadrant operation of active and reactive power. As the active power balancing node of the DC system, the sending-end converter station maintains the DC voltage stably at ± 200 kV by adjusting the phase angle of the modulation wave. The receiving-end converter station adopts constant active power control, and keeps the active power at the outlet of the connecting transformer at the set value via phase angle regulation of the modulation wave [29]. Accordingly, the

sending-end converter station applies AC voltage control and DC voltage control, while the receiving-end converter station adopts reactive power control and active power control.

The value of 5000 H listed in Table 1 is not the rated inductance of a physical star-point reactor. It is an equivalent numerical setting used in the PSCAD/EMTDC model to represent a high-impedance neutral-point boundary condition. At 50 Hz, its inductive reactance is approximately 1.57 M Ω , and the corresponding branch therefore behaves approximately as an open circuit at the fundamental frequency. This parameter is kept unchanged in all comparative simulation cases.

2.2. DC Submarine Cable Parameters

In the established model, the transmission distance of submarine cables between the two converter stations is 50 km with a rated DC voltage of ± 200 kV, and the pseudo-bipolar connection mode is adopted for the main wiring of the DC field. The type of DC submarine cable is HVDC-YJQ41-200 kV – 1 $\times$ 1000 mm² + 2 $\times$ 10B1 + 2 $\times$ 2B4 [19]. Its longitudinal section consists of six layers, namely conductor, primary insulation layer, lead sheath, secondary insulation layer, armor layer and tertiary insulation layer. The parameters of each layer are presented in Table 2. The burial depth of the cable is set to 1 m underground. To accurately reflect line characteristics within a wide frequency range and take all frequency-dependent parameters into account, the Frequency-Dependent (Phase) Model is selected as the equivalent model for submarine cable simulation.

Table 2. DC submarine cable structural parameters.

DC Submarine Cable Structure	Outer Radius/m	Resistivity/($\Omega \cdot \text{m}$)	Relative Permittivity	Relative Permeability
Conductor	0.0191	1.75×10^{-8}		1
Insulation 1	0.0351		2.30	1
Lead sheath	0.0380	2.20×10^{-7}		1
Insulation 2	0.0490		2.25	1
Aarmor	0.0550	5.50×10^{-7}		500
Insulation 3	0.0590		2.50	1

The dimensions listed in Table 2 are the outer radii of the individual cable layers used in the PSCAD/EMTDC line-constants calculation. In particular, the conductor outer radius of 0.0191 m represents its geometrical outer boundary, whereas the value of 1000 mm² in the cable designation represents the nominal metallic cross-sectional area. For a stranded or compacted conductor, the area enclosed by the geometrical outer boundary is not necessarily identical to the nominal metallic conducting area.

A homogeneous equivalent ground medium is used in the line-constants calculation, with a ground resistivity of 100 $\Omega \cdot \text{m}$ and a relative permeability of 1. The horizontal coordinate of each individual cable is set to $x = 0$ m, and the burial depth is 1.0 m. A separate seawater layer is not represented; therefore, the specified resistivity represents the equivalent surrounding soil medium used in the calculation. The positive and negative pole cables are represented by two separate single-core coaxial cable components with identical parameters, and their line constants are calculated separately. Coupling among the conductor, lead sheath, and armor within each cable is included, whereas mutual electromagnetic coupling between the two pole cables is not explicitly represented. Consequently, pole-to-pole spacing is not an input parameter of the present model.

The 50 km submarine cable is represented by five identical 10 km sections connected in series. All sections use the same cross-sectional configuration and Frequency-Dependent

(Phase) Model parameters. The conductor-to-ground voltages are recorded at 0, 10, 20, 30, 40, and 50 km along the cable.

The distributed-parameter representation of the submarine cable is governed by the telegrapher's equations:

$$\partial u(x,s)/\partial x = -Z(s)i(x,s) \quad (1)$$

$$\partial i(x,s)/\partial x = -Y(s)u(x,s) \quad (2)$$

where $u(x,s)$ and $i(x,s)$ are the voltage and current vectors at cable position x , respectively. The per-unit-length series-impedance and shunt-admittance matrices are expressed as

$$Z(s) = R(s) + sL(s) \quad (3)$$

$$Y(s) = G(s) + sC(s) \quad (4)$$

where $R(s)$, $L(s)$, $G(s)$, and $C(s)$ denote the frequency-dependent per-unit-length resistance, inductance, conductance, and capacitance matrices, respectively.

Based on the geometrical dimensions and material properties of the cable layers, the Frequency-Dependent (Phase) Model calculates the per-unit-length impedance and admittance matrices over a specified frequency range and incorporates the resulting frequency-domain responses into the time-domain simulation through rational-function fitting. The model represents both the frequency dependence of the cable parameters and the electromagnetic coupling among the central conductor, metallic sheath, and armor. It is therefore suitable for analyzing the propagation and reflection of fault-induced transients in multi-layer DC submarine cables.

In the present model, the curve-fitting frequency range is set from 0.5 Hz to 1 MHz using 100 frequency points. The maximum fitting orders for the characteristic admittance and propagation function are both set to 20, and the prescribed maximum fitting errors are both 0.2%. According to the Line Constants Program log, the actual maximum fitting errors of the characteristic admittance and propagation function are 0.1851% and 0.1825%, respectively, both below the specified tolerance.

To check the principal propagation characteristic of the cable model, an approximate analytical calculation is performed for the conductor-to-sheath propagation mode. For a coaxial insulation structure, the per-unit-length inductance and capacitance can be approximated as

$$L' = [\mu_0/(2\pi)] \ln(r_2/r_1) \quad (5)$$

$$C' = 2\pi\epsilon_0 \epsilon_r / \ln(r_2/r_1) \quad (6)$$

where r_1 is the conductor outer radius, r_2 is the outer radius of the main insulation, and ϵ_r is the relative permittivity of the main insulation. Using $r_1 = 0.0191$ m, $r_2 = 0.0351$ m, and $\epsilon_r = 2.3$, the calculated per-unit-length inductance and capacitance are 0.1217 mH/km and 0.2103 μ F/km, respectively. The corresponding wave velocity and characteristic impedance are

$$v = 1/\sqrt{L'C'} = 1.977 \times 10^8 \text{ m/s} \quad (7)$$

$$Z_c = \sqrt{L'/C'} = 24.06 \Omega \quad (8)$$

For a 10 km cable section, the analytical one-way travel time is 0.05059 ms, whereas the minimum travel time calculated by the PSCAD Line Constants Program is 0.05063 ms. The relative difference between the two values is approximately 0.092%, indicating good consistency between the analytical result and the principal propagation characteristic calculated by the Line Constants Program.

No metal-oxide surge arresters are installed at the DC-cable terminals in the present model, and no additional overvoltage-limiting control is introduced. The DC-reactor parameters, cable parameters, grounding arrangement, converter control, and fault-clearing settings remain fixed throughout the comparison unless otherwise stated. The results therefore represent the fault-induced overvoltages under the adopted model settings.

All faults are applied at 1.00 s after the system reaches steady-state operation, and the fault resistance is $0.01\ \Omega$. The AC-side fault elements are removed at 1.06 s after a duration of 0.06 s, whereas the DC-side fault elements are removed at 1.50 s after a duration of 0.50 s. The DC-side grounding cases are treated as non-self-clearing permanent fault scenarios because the conductor-to-ground voltage does not recover to its pre-fault steady state within the subsequent observation interval after removal of the fault element.

No circuit-breaker operation occurs during the investigated fault sequences. The fault components are applied and removed through predefined timing signals. The MMC blocking signal remains unchanged, and converter blocking is not triggered within the investigated cases and observation interval.

3. Analysis on Simulation Results of Overvoltage of DC Cable

Unless otherwise stated, cable positions are measured from the sending end, with 0 km and 50 km corresponding to the sending and receiving ends, respectively. In Figures 2–4, the value at each observation position is the maximum conductor-to-ground overvoltage selected from the positive and negative poles. For the single-pole DC-cable grounding faults shown in Figures 5 and 6, the negative pole is the faulted pole and the positive pole is the healthy pole. The fault position on the negative-pole cable and the voltage observation position on the healthy positive-pole cable are defined separately.

Unless otherwise stated, the severity of a fault case in the following analysis refers to its relative overvoltage level among the investigated cases under the same simulation conditions rather than a direct assessment of insulation failure. The cases are compared using the maximum conductor-to-ground overvoltage normalized by the rated pole voltage, the location of the maximum along the cable, and the post-fault voltage behavior.

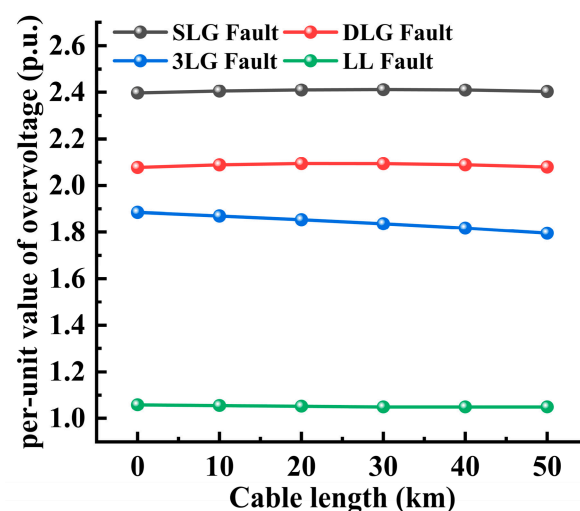


Figure 2. Maximum conductor-to-ground overvoltage along the DC submarine cable under four faults on the valve side of the connecting transformer. The value at each observation position is the maximum selected from the positive and negative poles. SLG, DLG, 3LG, and LL denote single-line-to-ground, double-line-to-ground, three-line-to-ground, and line-to-line faults, respectively. The faults are applied at 1.00 s and removed at 1.06 s, with a fault resistance of $0.01\ \Omega$; 0 km denotes the sending end.

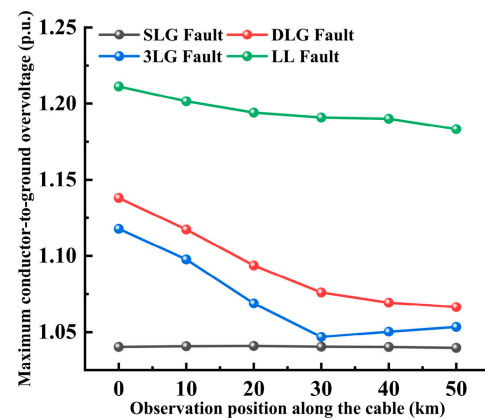


Figure 3. Maximum conductor-to-ground overvoltage along the DC submarine cable under four faults on the grid side of the connecting transformer. The value at each observation position is the maximum selected from the positive and negative poles. The fault abbreviations are defined in Figure 2. The faults are applied at 1.00 s and removed at 1.06 s, with a fault resistance of 0.01 Ω ; 0 km denotes the sending end.

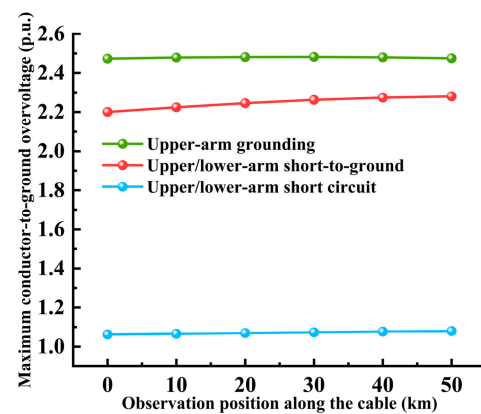


Figure 4. Maximum conductor-to-ground overvoltage along the DC submarine cable under faults on the valve side of the bridge-arm reactors. “Upper-arm grounding” denotes a grounding fault on the valve side of the upper-arm reactor; “upper/lower-arm short-to-ground” denotes a short circuit between the valve sides of the upper- and lower-arm reactors with grounding; and “upper/lower-arm short circuit” denotes a short circuit between the valve sides of the upper- and lower-arm reactors without grounding. The plotted value at each observation position is the maximum selected from the positive and negative poles. The faults are applied at 1.00 s and removed at 1.06 s, with a fault resistance of 0.01 Ω ; 0 km denotes the sending end.

3.1. AC Side Fault

3.1.1. Valve-Side Fault of Connecting Transformer

When four typical faults occur on the valve side of the connecting transformer at the AC side of the converter station, the surge-overvoltage distribution along the DC submarine cable is illustrated in Figure 2. The selected faults include a single-line-to-ground fault, a double-line-to-ground fault, a three-line-to-ground fault, and a line-to-line fault. Under all fault conditions, the peak overvoltage varies only slightly along the cable. The line-to-line fault produces little overvoltage on the DC submarine cable. Among the four investigated fault types, the single-line-to-ground fault produces the highest overvoltage, with a maximum value of 2.41 p.u., corresponding to 482.25 kV.

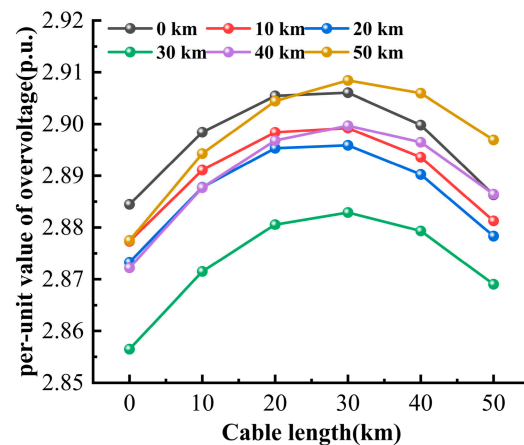


Figure 5. Maximum conductor-to-ground overvoltage along the healthy positive-pole cable under single-pole grounding faults at different locations of the negative-pole cable. The horizontal axis denotes the observation position on the healthy positive-pole cable, whereas the legend denotes the fault position on the negative-pole cable. The faults are applied at 1.00 s, and the fault elements are removed at 1.50 s, with a fault resistance of 0.01 Ω ; 0 km denotes the sending end.

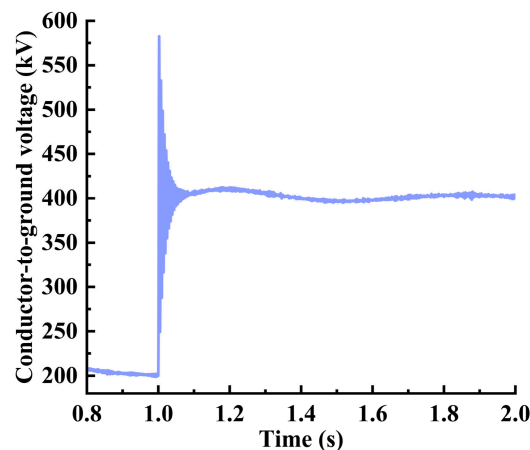


Figure 6. Time-domain conductor-to-ground voltage at the 30 km observation position on the healthy positive-pole cable under a single-pole grounding fault at the 50 km receiving-end terminal of the negative-pole cable. The fault is applied at 1.00 s, and the fault element is removed at 1.50 s, with a fault resistance of 0.01 Ω .

3.1.2. Grid-Side Fault of Connecting Transformer

The surge-overvoltage distribution along the DC submarine cable under four AC faults on the grid side of the connecting transformer is shown in Figure 3. The calculated overvoltage decreases slightly from the cable head end toward the far end. The line-to-line fault produces the highest value among these four cases, reaching 1.21 p.u. (242.25 kV) at the cable head end. Overall, faults on the grid side of the connecting transformer produce lower overvoltage levels than the other relatively severe fault cases investigated in this study.

3.1.3. Valve-Side Fault of Bridge Arm Reactor

Figure 4 presents the surge overvoltage along the DC submarine cable when grounding and short-circuit faults occur on the valve side of the bridge-arm reactor. The overvoltage varies only slightly among the monitoring positions. The single-side grounding fault produces the highest overvoltage among the investigated bridge-arm-reactor cases, reaching 2.48 p.u. (496.48 kV) in the middle section of the cable, whereas the short-circuit fault between the upper and lower arms produces a much lower voltage variation.

In summary, faults on the grid side of the connecting transformer produce relatively small overvoltages in the investigated cases. By contrast, the peak overvoltages caused by single-line-to-ground faults on the valve side of the connecting transformer and bridge-arm reactor approach 2.5 p.u., or approximately 500 kV, representing the highest AC-side overvoltage levels among the investigated cases. These locations should therefore receive particular monitoring attention during operation and fault diagnosis.

3.2. DC Side Fault

3.2.1. Grounding Fault Along DC Cable

Single-pole grounding faults are applied at 0, 10, 20, 30, 40, and 50 km along the negative-pole cable, and the resulting maximum conductor-to-ground overvoltages are observed at the same six positions along the healthy positive-pole cable, as shown in Figure 5. The horizontal axis represents the observation position on the healthy positive-pole cable, whereas the legend represents the fault position on the negative-pole cable. Regardless of the fault position, the highest monitored voltage occurs in the middle region and decreases toward the cable terminals. This spatial distribution results from traveling-wave propagation and reflections at cable and metallic-layer boundaries, together with electromagnetic coupling among the conductor, sheath, and armor. Faults at the 0 km sending end and 50 km receiving end of the negative-pole cable produce higher healthy-pole overvoltages than faults near the cable middle. When the fault occurs at the 50 km receiving end, the maximum overvoltage reaches 2.908 p.u. (581.68 kV) at the 30 km observation position on the healthy positive-pole cable.

Figure 6 illustrates the time-domain voltage at the 30 km observation position on the healthy positive-pole cable when a single-pole grounding fault occurs at the negative-pole cable terminal. Following the fault, the faulted-pole voltage rapidly decreases toward ground potential. Since the MMC control maintains the DC pole-to-pole voltage, the conductor-to-ground voltage of the healthy positive pole shifts from approximately 200 kV toward the pole-to-pole voltage level of approximately 400 kV. The initial peak superimposed on this voltage displacement is associated with the redistribution of stored electromagnetic energy and the propagation and reflection of transient waves along the cable. After the initial transient decays, the healthy-pole voltage remains at approximately 400 kV, corresponding to approximately 2.0 p.u. on the rated pole-to-ground voltage base [30].

3.2.2. Grounding Fault on Valve Side of DC Reactor

Figure 7 compares the switching overvoltage along the healthy positive-pole cable during a grounding fault on the valve side of the DC reactor with that during the negative-pole cable-terminal grounding fault. Under the adopted simulation conditions, the DC-reactor valve-side fault produces the higher peak. Because the fault is located between the converter and the DC reactor, the sudden change in the electrical boundary condition is directly coupled to the DC-cable terminal. The resulting pole-to-ground voltage displacement launches a transient wave into the cable. Its propagation and reflection, together with the coupling among the cable conducting layers, produce a higher healthy-pole overvoltage than the investigated cable-terminal grounding fault.

In general, the investigated DC-side grounding faults produce higher overvoltage levels than the investigated AC-side faults. The spatial distribution is characterized by higher values in the middle region and lower values near the cable terminals. Among all investigated cases, the grounding fault on the valve side of the DC reactor produces the highest calculated overvoltage, reaching 2.93 p.u. (586.18 kV) at approximately 30 km along the cable. This value is obtained from the consistent original simulation cases used throughout the manuscript. After the DC fault element is removed at 1.50 s, the healthy-

pole voltage remains at approximately 2.0 p.u. and does not recover to the pre-fault steady state within the subsequent observation interval. These results provide a comparative reference for identifying relatively severe DC-side fault cases and cable sections requiring particular monitoring attention.

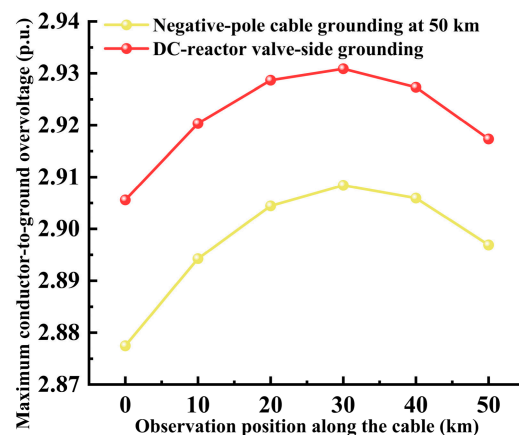


Figure 7. Comparison of the maximum conductor-to-ground overvoltage along the healthy positive-pole cable under a negative-pole cable-terminal grounding fault at the 50 km receiving end and a grounding fault on the valve side of the DC reactor. The faults are applied at 1.00 s, and the fault elements are removed at 1.50 s, with a fault resistance of 0.01 Ω ; 0 km denotes the sending end.

4. Discussion

Table 3 summarizes the representative fault cases using the maximum conductor-to-ground overvoltage, the location of the maximum, the nature of the fault, and the post-fault voltage behavior. These quantities are used for relative comparison among the simulated cases rather than as direct criteria for insulation failure.

Table 3. Summary and comparison of the representative fault cases.

Fault Scenario	Maximum Overvoltage	Location of Maximum	Fault Nature	Post-Fault Voltage Behavior
Transformer valve-side single-line-to-ground fault	2.41 p.u. (482.25 kV)	Middle region, approximately 20–30 km	Temporary AC-side fault	Returns toward rated value after fault clearance
Transformer grid-side line-to-line fault	1.21 p.u. (242.25 kV)	Cable head end, 0 km	Temporary AC-side fault	Returns toward rated value after fault clearance
Bridge-arm-reactor valve-side single-side grounding fault	2.48 p.u. (496.48 kV)	Middle region, approximately 30 km	Temporary AC-side fault	Returns toward rated value after fault clearance
Negative-pole cable-terminal single-pole grounding fault	2.908 p.u. (581.68 kV)	30 km on healthy positive-pole cable	Permanent DC-side fault	Fault element removed at 1.50 s; healthy-pole voltage remains at approximately 2.0 p.u. within the subsequent observation interval
DC-reactor valve-side grounding fault	2.93 p.u. (586.18 kV)	Middle region, approximately 30 km	Permanent DC-side fault	Fault element removed at 1.50 s; healthy-pole voltage remains at approximately 2.0 p.u. within the subsequent observation interval

As summarized in Table 3, the permanent DC-side grounding faults produce higher peak overvoltages than the investigated AC-side faults. Their influence is not limited to the initial transient peak, because the healthy-pole voltage remains elevated at approximately 2.0 p.u. after the transient process. Therefore, both the peak magnitude and the post-

fault voltage state should be considered when comparing the relative severity of the investigated cases.

The spatial distribution of the DC-side fault overvoltages reflects the distributed-parameter nature of the submarine cable. A sudden grounding fault changes an electrical boundary condition and launches voltage waves along the cable. These waves propagate with mode-dependent velocities and are reflected where electrical boundary conditions change. The Line Constants Program gives a minimum travel time of 0.05063 ms for each 10 km cable section, which is consistent with the analytically calculated travel time of 0.05059 ms for the principal conductor-to-sheath propagation mode. For a single-pole DC grounding fault, the pole-to-ground voltage displacement and the transient component superimposed on this displacement should be distinguished. Traveling-wave propagation, reflection, and electromagnetic coupling among the conductor, sheath, and armor explain why the maximum monitored voltage may occur in the middle region rather than at a cable terminal. Because a complete modal decomposition and reflection-coefficient calculation are not performed, the respective contributions of individual modes are not quantified in this study.

The qualitative trends obtained in this study are consistent with previously published MMC-HVDC cable studies. Previous investigations have shown that cable-voltage stresses during station-internal and DC-side faults depend on the fault type, fault location, cable length, grounding arrangement, converter response, and protection settings [11,18–21]. Similarly, the present results show that faults at different electrical boundaries produce different overvoltage levels and spatial distributions. Direct numerical comparison of peak values is not attempted because the system voltage, cable length, grounding arrangement, fault parameters, converter control, and surge-arrester configuration differ among the published studies. The numerical values reported here should therefore be interpreted as case-specific results for the investigated ± 200 kV, 50 km system.

The per-unit overvoltages reported in this study are used to compare voltage stresses and identify the fault locations and cable sections requiring particular monitoring attention. In this context, the terms “severe” and “most severe” represent a relative ranking within the investigated cases. They do not indicate that insulation breakdown has occurred or that a specified insulation withstand level has been exceeded. A quantitative insulation-coordination assessment requires the project-specific transient withstand characteristics of the cable and its accessories for the relevant waveforms and durations, together with the protection level, voltage–current characteristics, installation location, and energy capability of the selected surge arresters. These project-specific data are not included in the present study; consequently, no quantitative insulation margin is claimed.

The present model does not include surge arresters at the DC-cable terminals, and the reported values therefore do not represent arrester-protected overvoltage levels. In practical projects, MOV-based surge arresters can limit terminal overvoltages and absorb part of the transient energy, but their quantitative effect depends on the complete voltage–current characteristic, protective level, installation location, lead inductance, and energy capability. The line constants of the positive- and negative-pole cables are calculated separately without explicitly considering mutual electromagnetic coupling between the two pole cables. Complete protection criteria and circuit-breaker interruption processes are also not modeled. Therefore, the effects of pole-to-pole spacing, mutual coupling, and practical protection operation require further investigation.

5. Conclusions

Based on the switching surge overvoltage simulation of the DC submarine cable model established for the ± 200 kV two-terminal flexible DC transmission project, the main conclusions are drawn as follows:

- (1) Among the investigated AC-side cases, single-line-to-ground faults on the valve side of the connecting transformer and bridge-arm reactor produce the highest cable overvoltages, with peak values approaching 2.5 p.u. (approximately 500 kV). For the investigated temporary AC-side faults, the cable voltage returns toward its steady-state operating value after fault clearance. These valve-side locations should receive particular monitoring attention.
- (2) The investigated DC-side grounding faults produce higher overvoltage levels than the investigated AC-side faults, with initial peaks exceeding 2.85 p.u. The maximum values occur in the middle region of the cable under the adopted model settings. After the initial transient, the healthy-pole voltage remains at approximately 2.0 p.u. for the investigated permanent DC-side faults. The spatial distribution is associated with the combined effects of pole-to-ground voltage displacement, distributed traveling-wave propagation, boundary reflections, and electromagnetic coupling among the cable conducting layers. The DC-reactor valve-side grounding fault produces the highest peak among the investigated cases, and this location and the middle cable region should receive particular monitoring attention.

This study comparatively analyzes the switching-overvoltage characteristics and identifies the relatively severe fault cases within the investigated ± 200 kV MMC-HVDC submarine-cable system. The results provide a case-specific reference for identifying monitoring priorities and diagnosing faults and may support subsequent project-specific insulation-coordination studies. The reported peak values should not be regarded as universal insulation-failure criteria.

The reported results are case-specific to the investigated ± 200 kV, 50 km two-terminal MMC-HVDC submarine-cable system and should not be regarded as universal insulation-failure criteria. The present model represents an unprotected baseline configuration without DC-cable terminal surge arresters. No project-specific insulation-coordination assessment is performed, complete protection and circuit-breaker interruption processes are not modeled, and mutual coupling between the two pole cables is not explicitly included. Quantitative validation using field fault records or full-scale experimental data has not yet been conducted. Future work will incorporate project-specific cable-withstand and surge-arrester characteristics, practical protection sequences, a combined multi-cable model accounting for pole spacing and mutual coupling, and available project or experimental data.

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