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A Fault Protection Method for Avoiding Overvoltage in Symmetrical Monopole HVDC Systems by Half-Bridge MMC

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ABSTRACT It is known that the pole-to-ground fault in the symmetrical monopole HVDC transmission system causes overvoltage in the non-faulted pole. The overvoltage increases the required insulation level of the converters and transmission lines. To suppress the overvoltage, this paper proposes a protection method for symmetrical monopole HVDC systems. The proposed method introduces novel protection modes ''lower arm short protection'' and ''upper arm short protection'' to the modular multilevel converter (MMC) being composed of half-bridge (HB) submodules. In addition, blocking diodes are inserted to the DC terminal of the inverter. As a result, the method enables to clear the DC fault currents and to avoid the voltage increase in the non-faulted pole. Experimental results obtained by a 5.5-kW HB-MMC HVDC system demonstrate that the proposed protection method enables to suppress the voltage increase to 106 % of the rated voltage, while the conventional protection method caused overvoltage of 200 %. The proposed method is also effective to the multi-terminal HVDC systems. Even if a fault occurs in one of the transmission sections, the fault does not cause the overvoltage in the other non-faulted section. Therefore, the non-faulted section can continue the power transmission both during and after the DC fault.

INDEX TERMS Fault protection, modular multilevel converter (MMC), HVDC transmission, symmetrical monopole, overvoltage, blocking diode.

I. INTRODUCTION

High voltage DC (HVDC) transmission systems have expanded their application by using a modular multilevel converter (MMC) being composed of half-bridge (HB) submodules. One of the typical applications is the subsea cable transmission for offshore wind power plants. There are several system configurations in the HB-MMC based HVDC systems: Asymmetrical monopole system, symmetrical monopole system, and bipolar system. The asymmetrical monopole system grounds one of the poles. Thus, the other non-grounded pole holds the full DC transmission voltage V_{dc}. In the symmetrical monopole system, neither pole of the system is grounded. The system instead applies a high impedance grounding in the converter's AC side. The line-to-ground voltage of the poles becomes $\pm V_{dc}/2$, resulting in mitigation of the insulation level of the transmission line. The bipolar system uses two sets of HB-MMCs, and also holds $\pm V_{dc}/2$ in each pole. The system has the DC neutral point, thus the neutral point can be grounded.

This paper focuses on the symmetrical monopole system among them. In the symmetrical monopole system, neither pole of the system is grounded. Therefore, the pole-to-ground faults increase the voltage of the non-faulted pole to the double of the rated value if no measures are applied [1]–[4]. The non-faulted cable and other equipment have to be designed to withstand the overvoltage to prevent them from damaging. Mitigation of the overvoltage enables to reduce their insulation level and contributes to the reduction of their cost. A major method to suppress the overvoltage is connecting surge arresters between the DC pole and the ground, or the neutral point of the converter transformer [5]–[7]. Because the voltage increase continues for tens of milliseconds until the AC circuit breaker disconnects the converter, the arresters have to absorb a large amount of energy. Even with the arresters, some amount of voltage increase still remains. Dynamic braking system is used for pole rebalancing after detecting the overvoltage or pole voltage imbalance [8].

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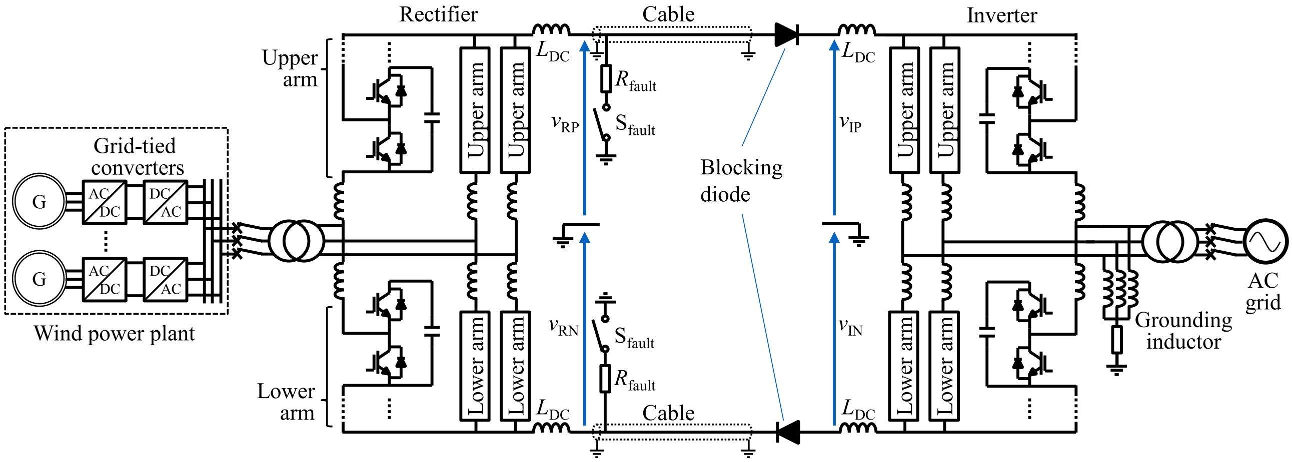

FIGURE 1. Configuration of a symmetrical monopole HVDC system. The blocking diodes are required only for the proposed protection method.

MMC being composed of full-bridge (FB) submodules [9] and DC circuit breakers [10] are also options to suppress the overvoltage because they can immediately clear the DC fault currents causing the overvoltage. However, these methods require additional equipment, which increases the system cost.

In this paper, the authors propose a protection method of the symmetrical monopole HVDC systems with the HB-MMC to suppress the overvoltage resulting from the pole-to-ground faults. The method consists of the combination of two approaches. The first approach is to apply new protection modes for the HB-MMC operating as a rectifier. There are blocking protection and overall short protection [11] as existing major protection modes. Instead of them, this paper proposes the "lower arm short protection" and "upper arm short protection" for the HB-MMC. These protection modes are novel and original methods in this paper. The proposed protection modes generate a short circuit either in the upper arms or lower arms, and contribute to suppress the DC fault currents of the rectifier. The second approach is to apply blocking diodes for the inverter side HB-MMC. The blocking diodes are inserted to the DC terminal of the HB-MMC. This blocking diodes have been used for fault clearing of the hybrid HVDC transmission being composed of a voltage-source converter (VSC) and a line-commutated converter [12]–[15]. The authors apply the blocking diodes not only for fault clearing but also for suppressing the DC fault currents from the inverter. Combination of the aforementioned two methods realizes immediately clearing the fault current and also suppressing the voltage increase of the non-faulted pole.

The previous paper [16] by the authors presented the basic concept and the preliminary simulation results. However, the method has not been verified by experiments. This paper verifies the proposed protection methods by the experiment using a 5.5-kW HB-MMC HVDC system for the first time. The experimental results in this paper will demonstrate that the proposed method enables to suppress the overvoltage to 106 % of the rated voltage, while the conventional blocking protection causes overvoltage of 200 %. In addition, this paper discusses the applicability to the multi-terminal HVDC systems. A drawback of the multi-terminal HVDC system exists in the spread of the overvoltage to the whole system [8]. The proposed method can suppress the overvoltage even in the multi-terminal system and enables the continuous power transmission in the non-faulted section. Transient simulations verify the operation of the multi-terminal HVDC system.

II. SYMMETRICAL MONOPOLE HVDC SYSTEM

A. SYSTEM CONFIGURATION

Fig. 1 depicts the system configuration of an HVDC system for interconnecting an offshore wind power plant. The system configuration and system level control is based on the existing system [17]. The AC voltage of the wind power plant is formed by the rectifier consisting of the HB-MMC. Each generator in the power plant is equipped with a full-scale back-to-back grid-tied converter, and it controls the AC current. The current flows to the rectifier. The rectifier converts the power to DC, and the subsea cables deliver the DC power to the inverter. Then the inverter, consisting of the HB-MMC, converts the power to AC. The DC voltage of the HVDC system is controlled by the inverter.

Symmetrical monopole HVDC is adopted to the system. DC lines consist of two cables for positive and negative poles. The center conductor of the cables are not grounded, whereas the sheath is grounded in both ends of the cable. The cable has a relatively large capacitance between the DC lines and the ground. The high impedance grounding inductor is connected to AC side of the inverter for monitoring and protection.

B. OVERVOLTAGE CAUSED BY THE CONVENTIONAL PROTECTION METHOD

DC line faults are categorized to a pole-to-ground fault and a pole-to-pole fault in the symmetrical monopole system.

TABLE 1. Protection scheme for the HB-MMC under pole-to-ground faults.

Protection scheme	Upper arm	Lower arm	Fault current interruption	Overvoltage in non-faulted pole
Blocking protection [1]–[4]	Block	Block	Unable	Overvoltage up to 2 pu
Overall short protection [11], [16]	Short	Short	Able	Negative overvoltage
Lower arm short protection (proposed)	Block	Short	Able	No overvoltage
Upper arm short protection (proposed)	Short	Block	Able	No overvoltage

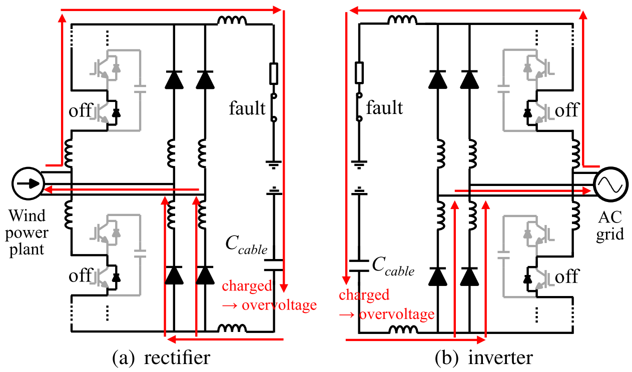

FIGURE 2. Conventional protection method (blocking protection).

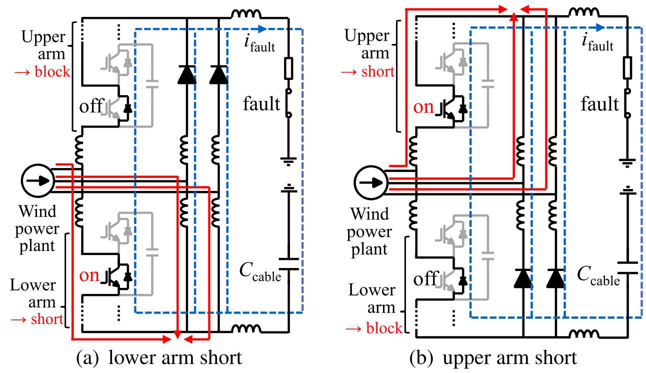

FIGURE 3. Proposed protection modes for the rectifier.

Normally, the DC cables for each pole are laid separately. Thus, the pole-to-pole faults are relatively rare faults, and in addition they do not cause the overvoltage. Most of the faults in the DC cable are the pole-to-ground fault. Moreover, the pole-to-ground faults cause the voltage increase in the non-faulted pole.

Fig. 2 shows the operation of the rectifier and the inverter when applying the conventional blocking protection in the symmetrical monopole configuration. The lines indicate the routes of the fault current. When a fault occurs in the DC line, the MMC turns off all the gate signals in the rectifier and inverter (blocking protection). It makes the rectifier and the inverter behave as a diode rectifier. Thus, the wind power plant or AC grid continuously supply the fault current to the DC side over the MMC. Then, the cable's line-to-ground capacitance C_{cable} is charged in the non-faulted pole in several milliseconds. The fault is usually removed by the AC circuit breakers between the AC power sources and the MMC in several tens of milliseconds. During the period, C_{cable} is charged to be almost twice of the rated voltage. Even if surge arresters are inserted between the pole and the ground to mitigate the overvoltage, it is unavoidable to cause some amount of voltage increase [5], [7].

III. PROPOSED PROTECTION METHOD

The proposed protection method combines two measures. Firstly, arm short protection mode is applied to the HB-MMC operating as a rectifier. Secondly, blocking diodes are inserted to the DC terminal of the inverter. Combination of these methods realizes to avoid the voltage increase in the non-faulted pole under pole-to-ground faults. The detail of the method is described in this section.

A. ARM SHORT PROTECTION FOR THE RECTIFIER

Fig. 3 depicts the proposed protection modes applied to the HB-MMC for the rectifier. Table 1 summarizes the existing and proposed protection schemes for the HB-MMC. The rectifier carries out either ''lower arm short'' as shown in Fig. 3 (a) or ''upper arm short'' as shown in Fig. 3 (b) under a pole-to-ground fault in the DC terminal. In the lower arm short, all the modules forming the lower arms turn on the low-side IGBT switch, while the modules forming the upper arms turns off all the IGBT switches. On the other hand, the upper arms are shorted and the lower arms are blocked in the upper arms short. These arm short protections make a short circuit between the three-phase AC terminals of the MMC. As a result, AC currents circulate in the MMC. Even if the wind power plant flows the AC currents continuously, the currents do not flow into the DC circuit. The AC currents can be cleared afterward by halting the grid-tied converters in the power plant or opening the AC circuit breaker. During the lower arm short or the upper arm short, the submodule capacitors are disconnected from the current path. Thus, the submodule capacitors maintain their voltage and they do not cause voltage unbalance or overvoltage.

Note that the proposed method is different from the overall short protection [11], which is applied to the pole-to-pole faults. The overall short protection applies the short mode to both the upper and lower arms together. Thus, the DC terminal is also shorted in the HB-MMC. It has been confirmed that the use of the overall short protection against pole-to-ground faults discharges the non-faulted cable [16]. This discharge results in the overcurrent in the rectifier and overvoltage in the blocking diodes or MMC.

Because the AC currents from the wind power plant are always regulated by the full-scale back-to-back grid-tied

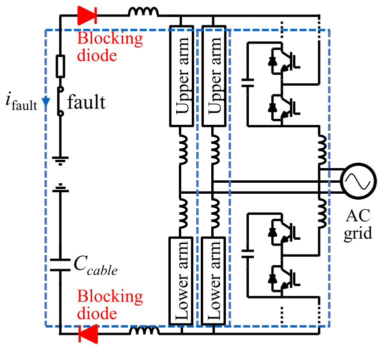

FIGURE 4. Protection circuit in the inverter.

converters, the lower/upper arm short protection does not significantly increase the AC currents. Therefore, in this configuration, the system may remove the bypass switches in parallel with the submodules as shown in [11] where the AC currents reach eight times larger than the rated value.

While the AC current continues to flow, the protection mode can immediately suppress the DC fault current i_{fault} to zero. The DC terminal of the MMC is still connected to the capacitance of the non-faulted cable C_{cable}. Then, the remaining voltage of C_{cable} is applied to the blocked arms of the MMC, which behave as diodes. The diodes are reversely biased by the voltage of C_{cable}. Thus, the diodes are in the off state, and C_{cable} retains its charge. As a result, i_{fault} is maintained to be zero. Therefore, the voltage of the negative pole maintains the same voltage as before the fault even during the protection mode. It is also noted that the upper arm short and the lower arm short have the same effect on the fault current. Therefore, both protection modes can be applied to the both positive and negative pole-to-ground faults.

For the pole-to-pole fault, the line-to-ground capacitances of both positive and negative poles are discharged together. Therefore the overvoltage does not occur. The pole-to-pole fault can be cleared by applying the overall short protection, which is investigated in the previous studies [11], [16]. Because this paper deals with the overvoltage, the following verification focuses on only the pole-to-ground fault.

B. BLOCKING DIODES IN THE INVERTER

Fig. 4 depicts the protection circuit in the HB-MMC for the inverter. The DC terminal of the inverter is equipped with blocking diodes in series with the DC lines. The blocking diodes were originally known as a fault clearing method of hybrid HVDC transmission systems being composed of a voltage-source converter and a line-commutated converter [12], [13]. This system uses the blocking diodes to prevent the fault current from the inverter. When a DC fault occurs, DC voltage of the inverter reversely biases the diodes. Thus, the diodes block the fault current from the inverter before it charges the C_{cable} of the non-faulted cable. Therefore, the voltage of C_{cable} is maintained to the rated voltage.

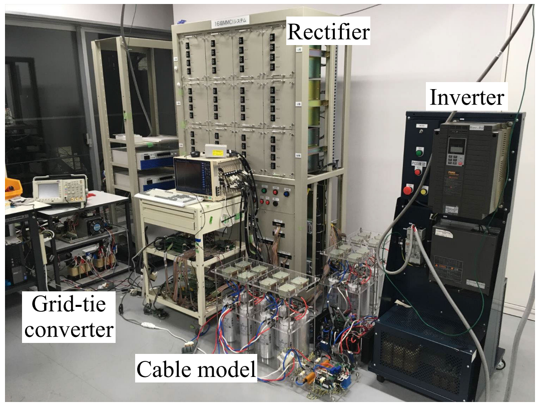

FIGURE 5. Experimental setup.

TABLE 2. Circuit parameters of the experimental setup.

DC voltage rating		±170 V
DC line current rating		16.3 A
DC line inductance	L_{cable}	0.25 mH
DC line capacitance	C_{cable}	1.0 mF
Fault resistance	R_{fault}	3.3 Ω
AC grid voltage	V_{s}	200 V
Power rating of the grid-tied converter		5.5 kVA
Power rating of the rectifier		5.5 kVA
Power rating of the inverter		13 kVA

The insertion of the blocking diodes prohibits the reverse power flow. The reverse power flow does not occur during the operation of offshore wind power plants, however it happens when starting up the power plants or maintenance of the system. Thus, an auxiliary power supply or an initial charging resistor is used to start up the system.

The blocking diodes generates some amount of conduction loss. However, the diodes do not generate switching loss because they are kept to be on-state. Previous papers has reported that the estimated power loss is 0.02 % [12] or 0.05 % [14] of the transmission capacity. The loss is much smaller compared to the rectifiers or inverters.

IV. VERIFICATION OF THE PROTECTION METHOD BY EXPERIMENTS

A. EXPERIMENTAL SETUP

Experiments were carried out to verify the effectiveness of the proposed protection method. Fig. 5 shows the experimental setup, and Fig. 6 is the circuit configuration. Parameters of the experimental setup are listed in the Table 2. The aim of the experiment is to verify the protection scheme. Therefore, the experimental setup was designed to be a downscaled model of the actual system to reproduce the transient characteristics. Specifically, the parameters of passive components were designed to have the same percentage impedance based on the rated transmission capacity. Therefore, the downscaled experimental system can sufficiently emulate the dynamic characteristics during system faults and the protection scheme. The rectifier is the MMC consisting of six arms. Each arm

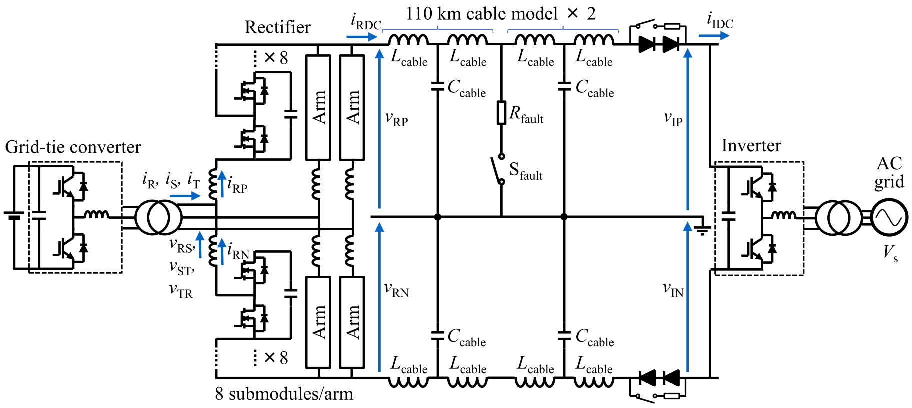

FIGURE 6. Circuit configuration of the experimental setup.

consists of eight half-bridge submodules. The paralleled grid-tied converters are simplified by a single current-controlled three-phase PWM inverter with a DC power supply. The 220-km subsea cables are modeled by two T-type lumped-element models with L_{cable} and C_{cable}. A pole-to-ground fault is caused by closing S_{fault} in the middle of the cable. Blocking diodes are inserted between the cable model and the inverter. Initial charging circuits consisting of a switch and a resistor are connected in parallel to the blocking diodes. The switch is closed only for starting up the rectifier and converter, and maintained to be open during the experiment. The inverter is a three-phase PWM inverter connected to the AC grid. The inverter regulates the DC voltage to the nominal value.

B. BLOCKING PROTECTION

Fig. 7 demonstrates the experimental waveforms when applying the conventional blocking protection. The results are expressed by per-unit values based on the rated power and rated voltage. The blocking diodes were inserted in this measurement. The switch S_{fault} closed at $t = 0$ ms, and a pole-to-ground fault occurred in the positive pole. The fault caused the drop of the positive pole voltages v_{RP} and v_{IP}. Then, the rectifier executed the blocking protection at $t = 0.7$ ms after detecting the increase of the DC current i_{RDC}. Whereas the rectifier was blocked, the AC currents i_R, i_S, and i_T continued to flow into the rectifier. As a result, the DC current i_{RDC} also flowed continuously. This DC current charged the line-to-ground capacitance of the non-faulted negative pole, resulting in the voltage increase at v_{RN} and v_{IN} up to 2.0 pu.

C. ARM SHORT PROTECTION

Fig. 8 illustrates the experimental waveforms when applying the proposed lower arm short protection. The pole-to-ground fault occurred in the positive pole cable at $t = 0$ ms. As a result, the DC current i_{RDC} increased to 1.3 pu. The rectifier detected the increase of DC current i_{RDC} and conducted the lower arm short protection when $t = 0.7$ ms. This operation caused the drop in the AC voltages v_{RS}, v_{ST}, and v_{TR}. The

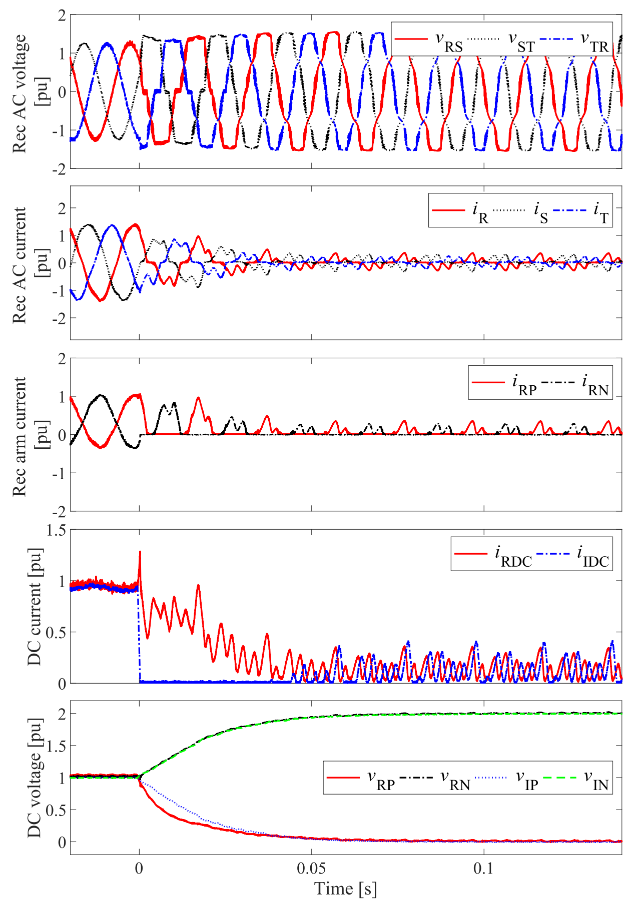

FIGURE 7. Experimental waveforms with the conventional blocking protection.

AC currents i_R, i_S, i_T continued to flow into the AC side of the rectifier until the grid-tied converter detected the voltage drop and blocked its operation at $t = 60$ ms. The circulating current of MMC is defined as $(i_{RP} + i_{RN})/2$. Fig. 8 demonstrates that i_{RP} becomes zero and i_{RN} becomes equal to the negative of the AC current $-i_R$. Thus, the circulating current becomes half of i_R during the lower arm short protection. On the other hand, the lower arm short protection immediately decreased

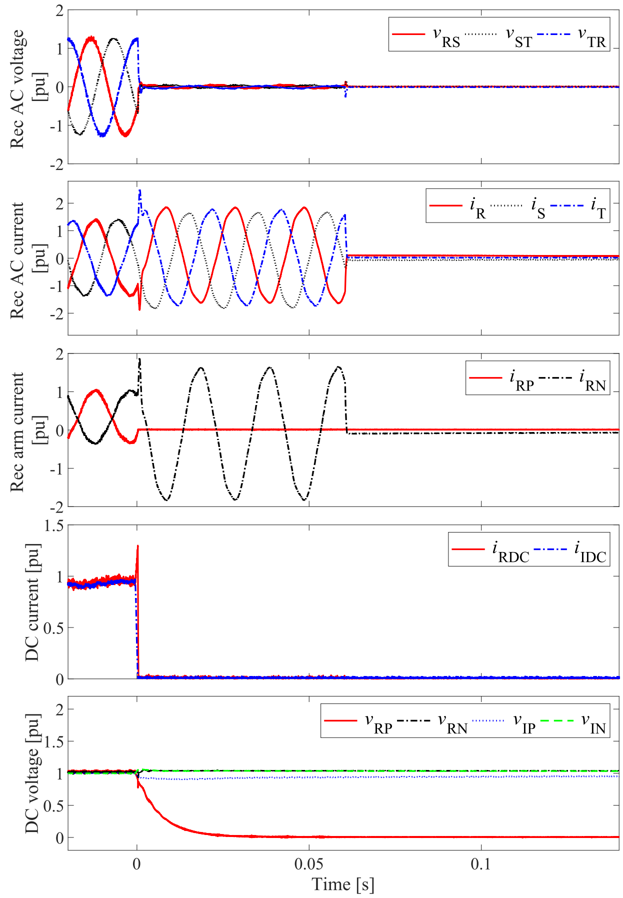

FIGURE 8. Experimental waveforms with the proposed lower arm short protection.

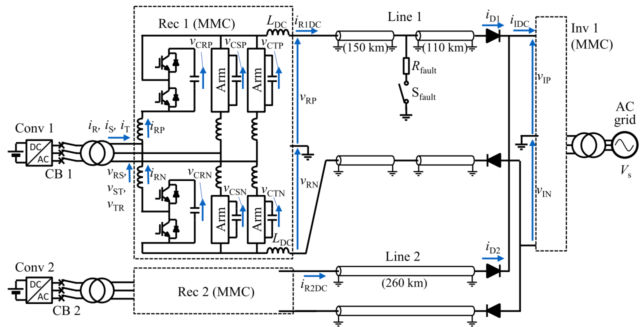

FIGURE 9. Three-terminal HVDC transmission system for the simulation.

TABLE 3. Circuit parameters for the simulation.

DC voltage rating		±500 kV
DC line current rating		1500 A
DC cable length		260 km
Fault resistance	R_{fault}	210 Ω
DC inductor	L_{DC}	32 mH
AC grid voltage	V_{s}	500 kV
Power rating of the grid-tied converters		750 MVA
Power rating of the rectifiers		750 MVA
Power rating of the inverter		1500 MVA

the DC current of the rectifier i_{RDC} to zero at $t = 0.9$ ms. The inverter also diminished its DC current i_{IDC} to zero at $t = 0.8$ ms. Thus, there was no current which charges the line-to-ground capacitance of the non-faulted negative pole cable. The negative pole DC voltages v_{RN} and v_{IN} show that they were suppressed up to 1.06 pu.

Compared to the conventional blocking protection, the lower arm short protection increased the peak value of arm current i_{RN} to 1.84 pu. The power devices of the rectifier have to be designed to withstand the current. However, the arms generate only conduction loss because they stop switching operation while the protection mode. Since the rated current of the power devices is designed based on the total of switching and conduction losses, it is difficult to discuss how much their current rating has to be increased based on these waveforms. However, the result implies that the arm current can be significantly reduced compared to the conventional overall short protection in [11]. Therefore, the proposed method may remove the bypass switches inserted in parallel with each submodule.

V. APPLICATION TO THE MULTI-TERMINAL HVDC SYSTEMS

One of the issues in the multi-terminal HVDC systems is to prevent the spread of faults. The system especially has a difficulty to prevent the spread of the overvoltage to the whole system [8]. The spread of the overvoltage may cause the whole system to shutdown. The proposed protection method is also applicable to the multi-terminal HVDC system. It can effectively suppress the overvoltage and realize the continuous power transfer in the other non-faulted section. The electromagnetic transient (EMT) simulations were carried out to validate the operation after the DC line fault.

A. THREE-TERMINAL HVDC SYSTEM

Fig. 9 shows the three-terminal HVDC system investigated in this section. Table 3 summarizes the parameters of the system. The modeling and simulations were carried out by an EMT simulation program XTAP [18]. The system has two grid-tied converters Conv 1 and Conv 2, which correspond to offshore wind power plants. They are simplified by a single model each. Two HVDC lines are paralleled in the DC terminal of the inverter through the blocking diodes. Each HVDC line applies the symmetrical monopole configuration. The frequency-dependent model based on the Bergeron's equivalent circuits [19] were used for modeling the 260-km DC lines. The pole-to-ground fault is modeled by the switch S_{fault} and the fault resistance R_{fault} in the middle of the line 1. Conv 1 and Conv 2, being the grid-tied converters in the wind power plant, are modeled by the current-controlled inverter with a DC voltage source. The rectifier Rec 1, Rec 2 and the inverter Inv 1 are the HB-MMC. The MMC arm switching function model [20], [21] is used for modeling the HB-MMC to consider the behavior of separated arms.

B. SIMULATION OF A LINE-TO-GROUND FAULT

Fig. 10 shows the simulated waveforms when applying the proposed lower arm short protection after a line-to-ground

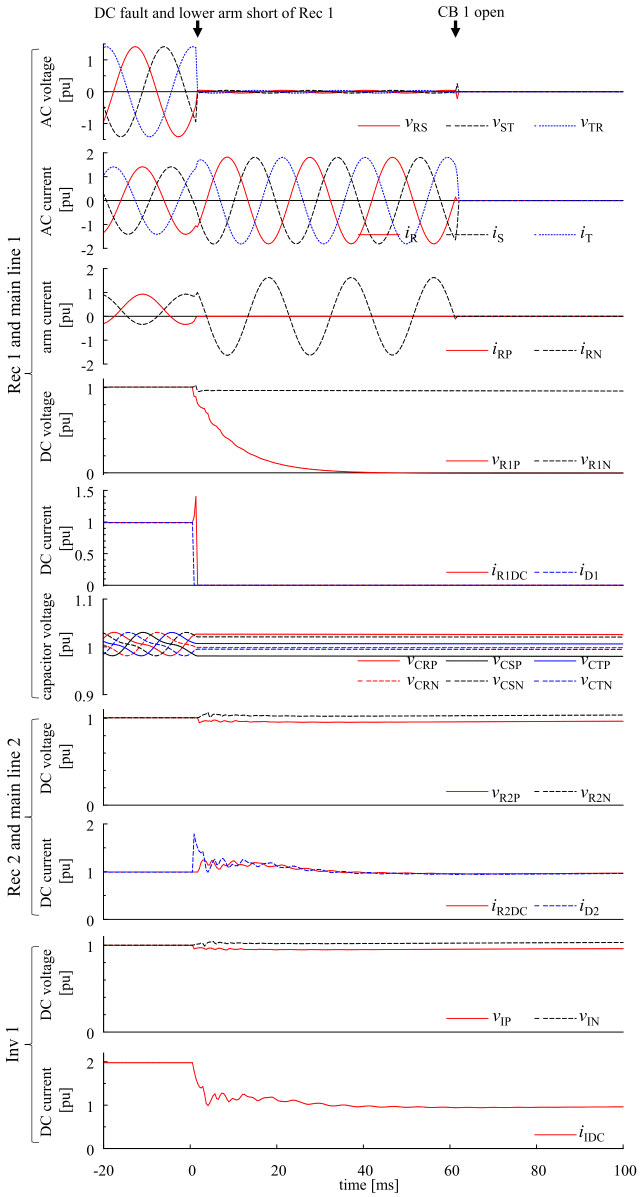

FIGURE 10. Simulated waveforms when applying the proposed lower arm short protection after a line-to-ground fault in the DC line 1.

fault occurs in the line 1 at $t = 0$ s. The results are expressed by per-unit values based on the rated power and rated voltage.

The operation characteristics of the Rec 1 agree well with the experimental result shown in the Fig. 8, which validates the operation of the simulated model. When the DC fault occurred, the DC current i_{R1DC} increased. Then, the Rec 1 carried out the lower arm short protection by detecting the increase of i_{R1DC}. As a result, i_{R1DC} immediately decreased to zero. Although the AC currents i_R, i_S, i_T were continuously controlled by the Conv 1 for a while, they are also cleared by opening the AC circuit breaker CB 1 at $t = 60$ ms. On the other hand, the DC current flowing to the blocking diode i_{D1} immediately decreased to zero and maintained to zero since the diodes are reversely biased. Therefore, the DC bus does not supply any fault current to the faulted main line 1. The line-to-ground voltage of the negative pole v_{RN} was maintained around 1.0 pu, which means that this fault clearing method caused no overvoltage at the non-faulted pole. The submodule capacitors also maintain their voltages v_{CRP}, v_{CRN}, v_{CSP}, v_{CSN}, v_{CTP}, v_{CTN} during the protection.

The line-to-ground voltages of the Inv 1 v_{IP} and v_{IN} are maintained around 1 pu with a slight deviation. The deviation can be removed by high impedance grounding devices or dynamic braking system over a certain amount of time, and does not effect the operation of the system. The Rec 2 and the Inv 1 flowed their DC currents over the line 2 after the fault, and they continuously transferred the power.

This result verifies that the proposed protection method can suppress the overvoltage not only in the faulted sections but also in the other non-faulted sections. Therefore, the method is also effective to the multi-terminal HVDC system.

VI. CONCLUSION

This paper has proposed a protection method for the symmetrical monopole HVDC systems with the HB-MMC to suppress the overvoltage resulting from the pole-to-ground faults. This method applies the upper/lower arm short protection to the HB-MMC operating as a rectifier when the pole-to-ground fault occurs. In addition, blocking diodes are inserted to the DC terminal of the HB-MMC operating as an inverter. The combination of these approaches enables to clear the DC fault currents and to avoid the voltage increase in the non-faulted pole. Experimental results obtained by a 5.5-kW HB-MMC HVDC system demonstrated that the proposed method was able to suppress the voltage increase to 106 % of the rated voltage, whereas the conventional protection method reached 200 %. Therefore, the proposed method contributes to reduce the insulation level of the transmission line, resulting in the reduction of the cost. Applicability to a multi-terminal HVDC system is also discussed. The EMT simulation result verified that the proposed protection method is also effective to suppress the overvoltage both in the faulted section and the non-faulted section. Therefore, the non-faulted section can continue the power transmission during and after the DC fault in the neighboring section.

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