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제주 HVDC No. 2의 극간 상호작용 경험과 분석: 무정전 전력 송전을 위한 실용적 해결방안

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Experience and Analysis of Pole Interaction for Jeju HVDC No. 2: Practical Solution for Non-Interruptible Power Transfer

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Abstract

The pole interaction of the line-commutated converter high-voltage direct current (HVDC) is analyzed, and a practical solution that uses a surge arrester is proposed. Jeju HVDC No. 2 is a double-monopole HVDC link that has a rated power capacity of 2 × 200 MW and was commissioned in 2012. During normal operation, Jeju HVDC No. 2 is operated in the bipolar mode to minimize the loss caused by the dedicated metallic return. However, when one pole of the inverter valve is bypassed, a commutation failure can occur in the other pole. This phenomenon is called pole interaction in this work. This pole interaction interrupts the HVDC power transfer for almost 2 s and may affect the stability of the power system. This research proposes the installation of a surge arrester at the inverter neutral, which can be an effective and practical solution for pole interaction. The HVDC system is analyzed, and the residual voltage of the surge arrester is determined. Detailed simulation using PSCAD/EMTDC demonstrates that the proposed method eliminates the pole interaction of the bipolar-operated HVDC.

Key words: Jeju HVDC No. 2, LCC-HVDC, Pole interaction

1. Introduction

The line-commuted converter (LCC)-high-voltage direct current (HVDC) is a mature technology that has mainly been used for point-to-point bulk power transmission over long distances. LCC-HVDC provides advantages over high-voltage alternating current (AC), such as higher efficiency and lower loss per 1,000km, no contribution to the short-circuit current of the AC, controllability of the power transmission, no skin effect, and less right-of-way. In particular, LCC-HVDC is the key solution for ultrahigh-voltage DC application[1],[2]. To integrate LCC-HVDC into the AC grid successfully, HVDC interaction studies should be conducted. A possible interaction of the HVDC system is depicted in Fig. 1 [3]. HVDC interaction studies are classified as steady-state voltage/power interactions, commutation failure interactions, electro-mechanical stability interactions, control mode stability interactions, and electromagnetic stability and nonlinear interactions [3]-[14]. The interactions of the HVDC system should be investigated to ensure the reliable and satisfactory performance of the DC links and the AC system. Although analysis and study methodologies of HVDC interactions are well-established for grid planners and operators, the pole-interaction case has not been reported. Recently, Jeju HVDC No. 2 was commissioned, and the pole interaction was observed.

The observed pole interaction of Jeju HVDC No. 2

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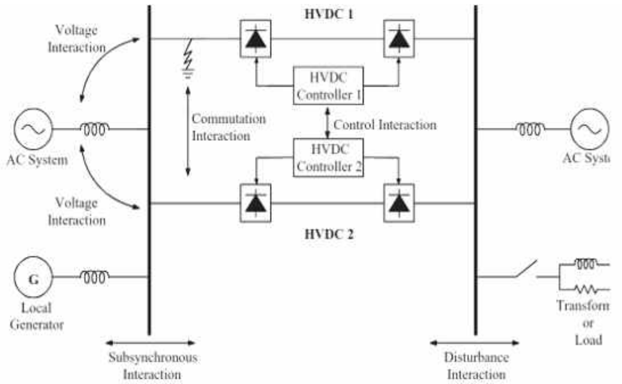


Fig. 1. Interaction of the HVDC system (Figure adopted from [3]).

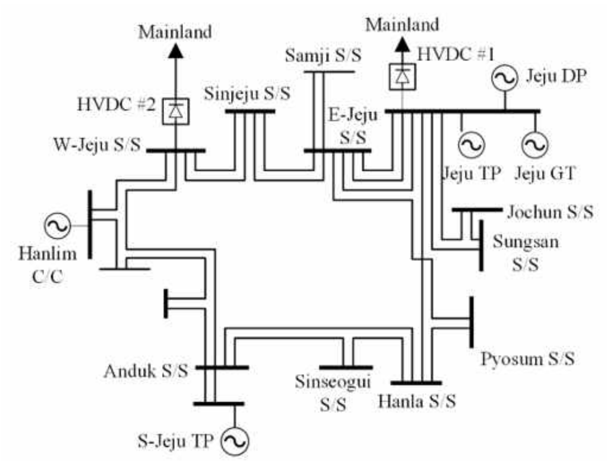


Fig. 2. Simplified diagram of the Jeju transmission network.

is an interaction phenomenon occurring between pole 1 and pole 2, where the HVDC exhibits bipolar operation. Jeju HVDC No. 2 has a double-monopole configuration with a dedicated metallic return and is grounded at the rectifier neutral cable. To reduce the loss of the metallic return cable, Jeju HVDC No. 2 operates in the bipolar mode. When one pole is faulted, the inverter valve of the pole is bypassed to stop the operation, and the over-current in the DC line is returned to rectifier through the inverter bypass valve and the return cable. At this time, the current flowing from the DC line to the valve is three to six times the DC rated current. This over-current induces overvoltage at the neutral point of the HVDC inverter. The induced overvoltage distorts the DC voltage of the other pole, and consequently commutation failure cannot be avoided at the other pole.

In this study, the root cause of the pole interaction of Jeju HVDC No. 2 is investigated. Methods are proposed for reducing the overvoltage at the neutral cable of the HVDC inverter as an effective, economical, and practical solution for the pole interaction.

This paper is organized as follows. The Jeju HVDC No. 2 system is described in detail in Section 2. The pole interaction of Jeju HVDC No. 2 is explained and analyzed in Section 3. In Section 4, the countermeasures of the pole interaction are presented, and the installation of the surge arrester at the inverter neutral cable is proposed. In Section 5, the efficacy of the proposed method is validated using simulations in PSCAD/EMTDC. Finally, Section 6 concludes the paper.

2. Jeju HVDC No. 2 System

2.1 Configuration of Jeju HVDC No. 2 system

Fig. 2 shows a simplified transmission diagram of the Jeju power system. Jeju is the biggest island of Korea, and the peak load level will be 853 MW in 2020, according to the 7th power system planning of Korea. Two LCC-HVDC stations were installed for the reliable and stable operation of the Jeju power system in 1997 and 2012, respectively. Seven synchronous generators are in operation. Two synchronous condensers were installed nearby, in Jeju HVDC No. 1. The must-run generators and synchronous condensers provide sufficient short-circuit capacity for the operation of the LCC-HVDC systems in Jeju. Jeju HVDC No. 1 has a bipolar configuration, and the power rating is 300MW.

The detailed configuration and specifications of Jeju HVDC No. 2 are shown in Fig. 3 and Table I, respectively. The power rating of Jeju HVDC No. 2 is 400MW with a 250kV DC voltage. Jeju HVDC No. 2 has a double-monopole configuration to reduce the possibility of a pole fault causing a bipolar outage. Jeju HVDC No. 2 is operated in the bipolar mode to reduce the conduction loss of the return cable. As shown in Fig. 3, the HVDC system is grounded at the neutral of the rectifier. HVDC No. 2 is operated under constant power control.

2.2 Jeju HVDC No. 2. cable parameter and configuration

The cable specifications are shown in Table II. Two mass-impregnated (MI) cables are used for high voltage (HV), and one MI cable and one cross-linked polyethylene (XLPE) cable are used for dedicated

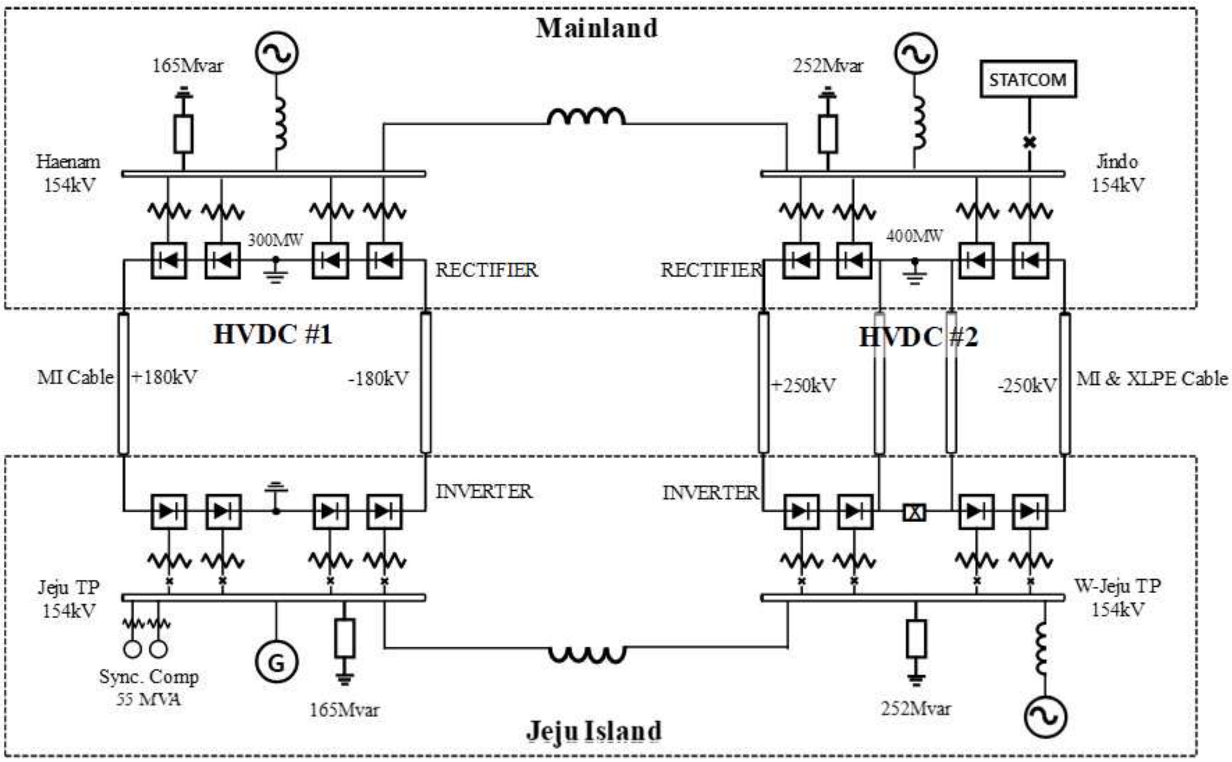


Fig. 3. HVDC system configuration on Jeju Island of South Korea.

TABLE I
HVDC SPECIFICATIONS FOR JEJU HVDC NO. 2
(ADOPTED FROM [15])

Parameter	Jeju HVDC No. 2 System
Power Rating	200 [MW] × 2 (bipoles)
Voltage	250 [kV]
Current	800 [A]
Firing Angle (Rectifier)	12 [deg] - Alpha
Firing Angle (Inverter)	23 [deg] - Gamma
Short-Circuit Capacity (SCC)	Rectifier : 2,199 [MVA] Inverter : 800 [MVA]
Reactive Power Rating	105 [Mvar] × 2
Operation Mode (Rectifier)	Current Control
Operation Mode (Inverter)	Voltage Control
Minimum Gamma in Inverter	12 [deg]
% Impedance of Transformer	15 [%]
Smoothing Reactor	60 [mH]
AC Voltage Variation	3 % (5.5 [deg])
Return Cable Surge Arrester	70 [kV]

metallic return. One of the MI cables is a redundant cable to be used if one of the HV cables is broken. This spare HV cable increases the reliability and availability of the Jeju HVDC No. 2 system. The DC short-circuit current and the neutral voltage can be determined using the cable parameters at the inverter during the inverter bypass condition.

TABLE II
JEJU HVDC NO. 2 CABLE SPECIFICATION

Parameter	HV Cable (MI)	MV Cable (XLPE)
Resistance (Ω)	2.4424	3.5372
Inductance (mH)	16.179	11.3
Capacitance (uF)	65.03	26.25

2.3 Electrode line insulation to ground

There are two criteria that usually determine the protective level of the metallic return cable surge arrester:

- The maximum continuously applied voltage (MCAV) during normal operation
- The peak neutral voltage due to a flashover on one of the delta winding bushings

Both of these conditions are influenced by the neutral line impedance. The neutral MCAV on the rectifier is 0 V because the neutral bus is directly grounded. The neutral MCAV on the inverter can be obtained as follows:

$$MCAV_{\in \mid er} = I_{dc,\max} \times R_{dc,\neq utral} + V_h \tag{1}$$

where $I_{dc,\max}$ is the maximum continuous DC, $R_{dc,neutral}$ is the maximum metallic return resistance, and V_h is the maximum harmonic voltage. For the Jeju HVDC No. 2 system, $I_{dc,\max}$ is 813A, $R_{dc,neutral}$ is 4.69Ω, and V_h is assumed to be 25% of the neutral DC voltage. Thus, $MCVA_{\in \mid er}$ is 4.766kV.

Furthermore, the impedance of the neutral line is such that the resulting flashover voltage at the neutral busbar is a small part of the valve winding voltage. If the insulation level at the neural busbar of the inverter is coordinated with this value, the insulation requirements for the same DC side insulations are low.

However, for consistency with standard low-cost electrical equipment, the protective level of the electrode line surge arrester is set to 105 kV at a coordinating current of 1kA. The Lightning Impulse Protective Level (LIPL) is coordinated with the cable basic insulation level (BIL) of 150kV.

The following protective levels are used:

- Switching Impulse Protective Level (SIPL) with 1kA: 105kV
- LIPL with 1kA: 1.037 × SIPL = 107kV
- Front of Wave Protective Level (FWPL) with 1kA: 1.11 × SIPL = 115kV

The LIPL and FWPL are calculated using data from the manufacturer of the surge arrester.

3. Pole Interaction of Jeju HVDC No. 2

The pole interaction of Jeju HVDC No. 2 was recognized during a pole-transfer test in 2014. Fig. 4 shows the dynamic response obtained in the pole-transfer test during the commissioning of Jeju HVDC No. 2. This test was conducted under the following scenario.

1) The HVDC system transfers 30MW of power per pole.
2) The bypass valve of pole 2 is closed.
3) Pole 1 takes 30MW and transfers 60MW.

As shown in Fig. 4, the neutral voltage of inverter

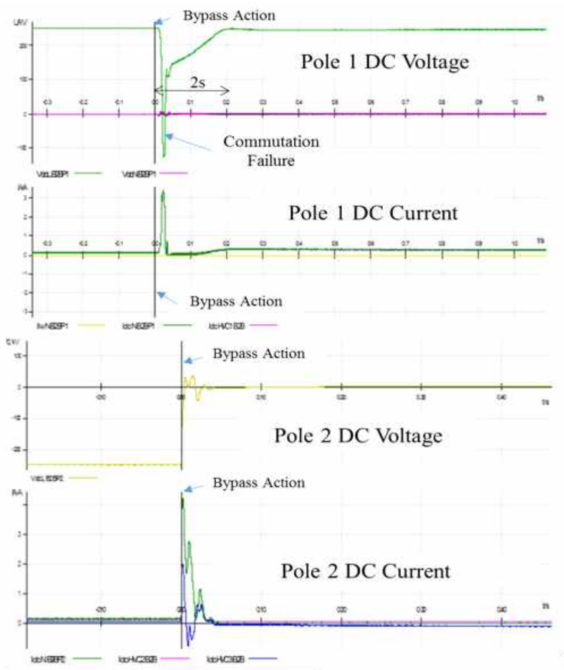


Fig. 4. Dynamics response obtained in the Jeju HVDC No. 2 pole transfer test of 2014.

is distorted by the bypass action of pole 2, and a commutation failure occurs on pole 1. Because of the commutation failure, the power transfer is interrupted for almost 2s.

3.1 Procedure of pole interaction

The neutral of the rectifier is grounded, and the DCs of poles 1 and 2 are balanced. The DC on the metallic return cable is close to zero, and the neutral bus of the inverter has almost zero potential in the bipolar operation, which means that the neutral point is common for poles 1 and 2. The harmonic voltage can be observed on the neutral point of the inverter. However, this is beyond the scope of the paper.

When pole 1 of the bipolar HVDC system is faulted, pole 1 activates bypass action and stops operation. After the inverter of pole 1 is bypassed, over-current occurs on the HVDC line of pole 1 and the metallic return cable. At this time, the surge current on the DC is three to six times the rated current. The procedure of the pole interaction is illustrated in Fig. 5 and is summarized below.

4. Countermeasures Against Pole Interaction

4.1 Methods of preventing pole interaction

The DC smoothing reactance must be increased to reduce the bypassed DC on the neutral cable.

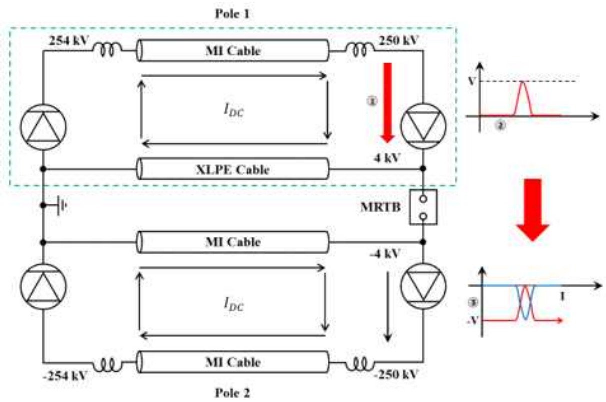


Fig. 5. Procedure of the pole interaction.

However, the DC smoothing reactor value is determined from an economic viewpoint considering various factors, such as the prevention of discontinuous current, DC line resonance, and di/dt limitation. The impedance of the return cable must be reduced. To reduce the impedance of the cable, the diameter of the conductor of the cable is increased, and the insulation rating may decrease. However, the installation of a new cable is not an economical or efficient solution for pole interaction. The installation of a neutral bus ground switch instead of a metallic return transfer breaker has also been considered. However, this is not a viable method, because of the switching speed. Although double-monopole operation can avoid the pole interaction, it is not an economical solution. The conduction loss of the return cable is increased during double-monopole operation, which is not the preferred condition for utility. The installation of neutral surge capacitors was also considered[2]. The overhead line or cable used as the return line has its capacitance. However, the cable capacitance cannot absorb the surge current directly and change to the voltage, because the cable capacitance is distributed through the total length of the overhead line or the cable. The installation of the surge capacitor at the neutral busbar of the inverter is not an economical or efficient solution. The capacitor must be large enough to prevent overvoltage, and additional protective devices such as arresters are needed. In addition, the harmonics, which are generated by the inverter valve during normal operation, pass through the large capacitance at the neutral busbar and may cause telecommunication interference.

4.2 Installation of surge arrester

Hingorani proposed the installation of a surge

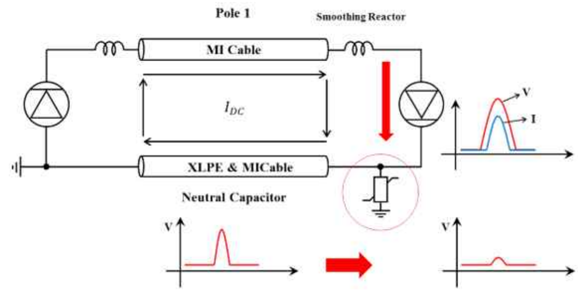


Fig. 6. Effect of the surge arrester on the neutral cable.

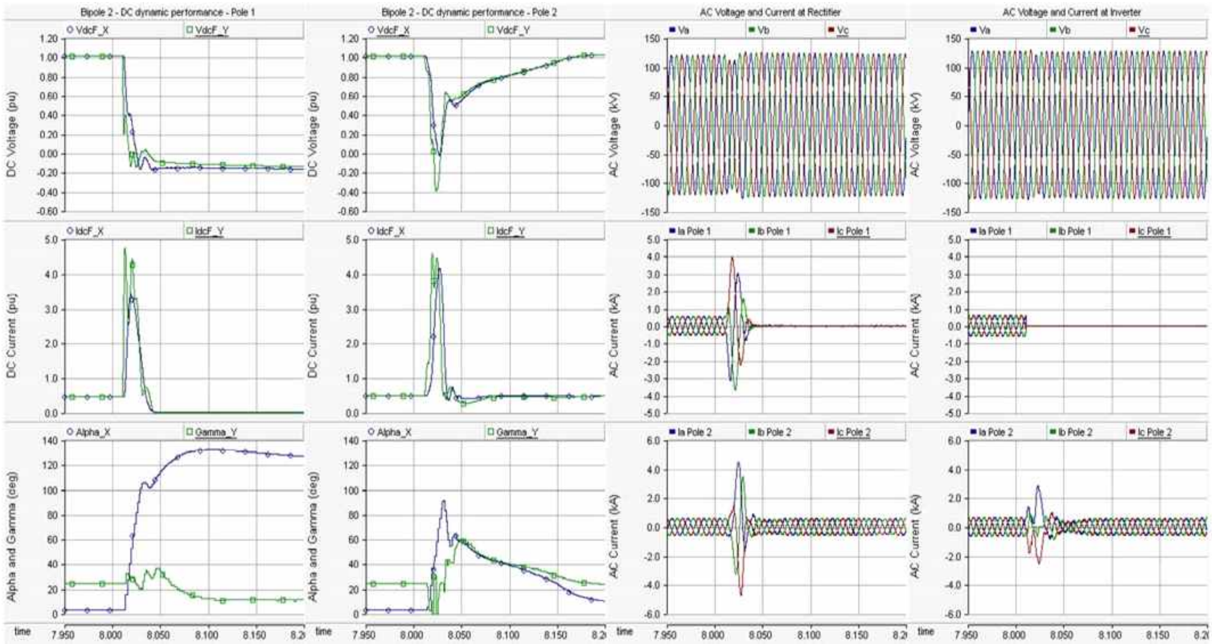
arrester at the floating neutral point to protect the overvoltage of the return cable during the monopolar metallic return operation of a long-distance HVDC system in [16]. However, the pole interaction of the bipolar HVDC was not mentioned in [16], [17]. Fig. 6 illustrates the effects of the surge arrester on the neutral bus at the inverter. An arrester exists in neutral busbar of the monopole and bipolar HVDC system to protect the overvoltage of the return cable. The general design criterion is that when the HVDC system causes commutation failure owing to a ground fault in the inverter-side AC system, a voltage 0.3 times the DC voltage is induced at the neutral point; thus, the rating of the arrester is based on this value. The BIL and SIPL of the return cable are considered. Thus, a 70kV surge arrester is installed on the neutral bus of the inverter of the present Jeju HVDC No. 2 system. However, this surge arrester cannot prevent the pole interaction.

The susceptibility to commutation failure can be calculated using the maximum permissible voltage drop ΔV, as follows:

$$\Delta V = 1 - \frac{I_d'}{I_d} \cdot \frac{(I_d/I_{dFL}) \cdot X_{cpu}}{(I_d/I_{dFL}) \cdot X_{cpu} + \cos\gamma_0 - \cos\gamma} \tag{2}$$

where Id is the pre-fault DC, I_d' is the post-fault DC, I_{dFL} is the nominal current, X_{cpu} is the transformer percentage impedance, γ is the operation extinction angle, and γ_0 is the absolute minimum extinction angle at which commutation fails. According to (2) and Table Ⅰ, the commutation failure possibility index of Jeju HVDC No. 2 is 0.2776, where $I_d = I_d'$ = 1pu. This means that a DC voltage drop of 70kV causes commutation failure. Therefore, the protective level of the arrester should be less than 70kV.

Therefore, we propose that the protective level of the surge arrester is set as 10kV (MCAV) for Jeju



(a) (b) (c) (d)

Fig. 7. Dynamic response of AC/DC system without surge arrester when inverter bypass occurs at 8.01s while all cables are secured. (a) Pole 1 rectifier DC voltage and current, inverter DC voltage and current, rectifier alpha and inverter gamma, (b) Pole 2 rectifier DC voltage and current, DC voltage and current, rectifier alpha and inverter gamma, (c) AC voltage and current (pole 1 and pole 2) at rectifier, (d) AC voltage and current (pole 1 and pole 2) at inverter.

HVDC No. 2. Section 2.3 mentions that the neutral $MCVA_{\in \mid er}$ of Jeju HVDC No. 2 is 4.766kV. The protective level of the surge arrester should be larger than the MCAV value. As indicated by the metal-dioxide surge arrester V-I characteristic, the arrester draws very little current until the voltage approaches its protective level. Moreover, the arrester voltage returns to the rated voltage when the overvoltage drops to the protective level and the arrester current becomes zero. Consequently, we propose that the protective level of the surge arrester is set as 10 kV for Jeju HVDC No. 2.

5. Simulation Results

5.1 Simulation setting

To validate the efficacy of the surge-arrester installation, a simulation is performed for Jeju HVDC No. 2 using a detailed PSCAD/EMTDC model the manufacturer provides. The detailed specifications and configuration of the HVDC system and cable are provided in Section 2. The surge arrester is modeled as a nonlinear resistor. The default PSCAD surge-arrester model (ASEA XAP-A) is used for the 10kV surge arrester. The number of the 10kV surge arrester installed in the simulation is 40 in order to distribute the energy capability of the surge arrester.

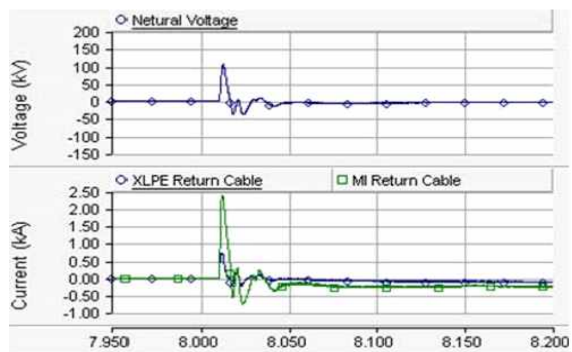
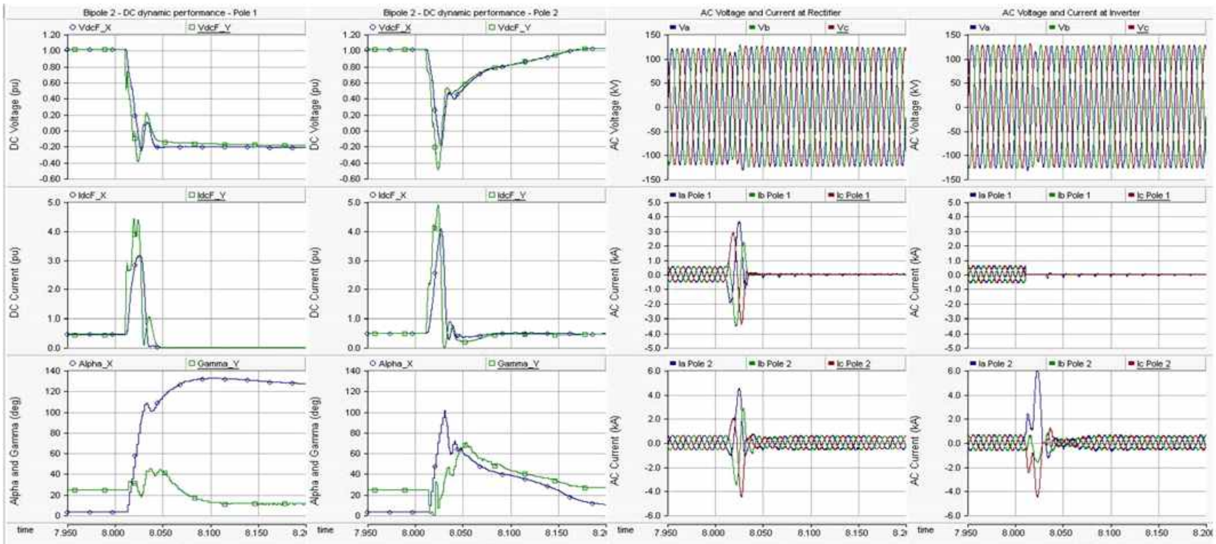


Fig. 8. Dynamics response of inverter neutral busbar voltage and current without surge arrester when inverter bypass occurs at 8.01s while all cables are secured. (a) Neutral busbar voltage, (b) Current of XPLE cable (circle), and current of MI cable on the neutral (square).

The simulation conditions are as follows:

- The current control mode is activated at the rectifier.
- The voltage control mode is activated at the inverter.
- The initial current order is set to 0.5p.u.
- The inverter bypass for pole 1 occurs at 8.01s.
- The frequency phase-dependent model is used for the DC cable.

Four scenarios are presented to clearly explain the adverse impact of the HVDC system without the



(a) (b) (c) (d)

Fig. 9. Dynamic response of AC/DC system without surge arrester when inverter bypass occurs at 8.01 s while MI return cable is disabled. (a) Pole 1 rectifier DC voltage and current, inverter DC voltage and current, rectifier alpha and inverter gamma, (b) Pole 2 rectifier DC voltage and current, inverter DC voltage and current, rectifier alpha and inverter gamma, (c) AC voltage and current (pole 1 and pole 2) at rectifier, (d) AC voltage and current (pole 1 and pole 2) at inverter.

arrester and the effectiveness of the surge arrester that conserves the HVDC system through prevention of the pole interaction.

- Scenario 1: Pole interaction without surge arrester while all cables are secured
- Scenario 2: Pole interaction without surge arrester while the MI return cable is disabled
- Scenario 3: Elimination of the pole interaction with the surge arrester while all cables are secured
- Scenario 4: Elimination of the pole interaction with the surge arrester while the MI return cable is disabled

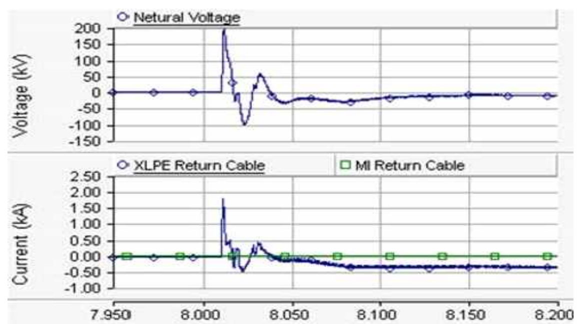


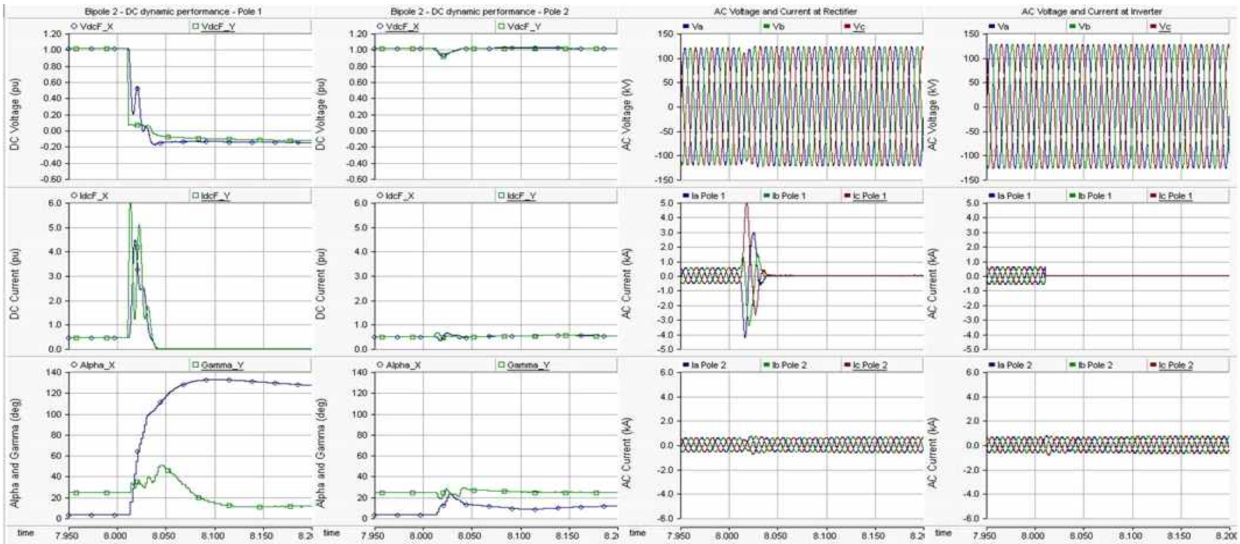
Fig. 10. Dynamic response of inverter neutral busbar voltage and current without surge arrester when inverter bypass occurs at 8.01s while MI return cable is disabled. (a) Neutral busbar voltage, (b) Current of XLPE cable (circle) and current of MI cable on the neutral (square).

5.2 Scenario 1

Fig. 7 presents the dynamic response for poles 1 and 2 when the pole 1 inverter is bypassed at 8.01s and all cables are secured. As shown in Fig. 7(b), a commutation failure occurs on pole 2 when the pole 1 inverter is bypassed because the gamma angle instantly falls to 0°. When the rectifier alpha angle grows larger than 90°, the rectifier DC voltage drops below 0kV, and the DC falls to almost 0kA within two cycles. The difference between the rectifier DC and the inverter DC arises from the charged DC voltage of the HV cable. Fig. 8 presents the neutral voltage and current. The neutral voltage is induced more than 100kV, and the neutral current is around 2.5kA for the MI cable and 0.75kA for the XLPE cable at 8.011s. This neutral voltage distorts the DC voltage of the pole 2 inverter. Thus, a commutation failure occurs.

5.3 Scenario 2

Fig. 9 presents the dynamic response for poles 1 and 2 when the pole 1 inverter is bypassed at 8.01 s, while the MI return cable is disabled. As shown in Fig. 9(b), a commutation failure occurs on pole 2 when the pole 1 inverter is bypassed, because the gamma angle instantly falls to 0°. When the rectifier alpha angle grows larger than 90°, the rectifier DC voltage drops below 0kV, and the DC drops to almost



(a) (b) (c) (d)

Fig. 11. Dynamic response of AC/DC system with surge arrester when inverter bypass occurs at 8.01 s while all cables are secured. (a) Pole 1 rectifier DC voltage and current, inverter DC voltage and current, rectifier alpha and inverter gamma, (b) Pole 2 rectifier DC voltage and current, inverter DC voltage and current, rectifier alpha and inverter gamma, (c) AC voltage and current (pole 1 and pole 2) at rectifier, (d) AC voltage and current (pole 1 and pole 2) at inverter.

0kA within two cycles. The difference between the rectifier DC and the inverter DC arises from the charged DC voltage on the HV cable.

Fig. 10 presents the neutral voltage and current. Disconnection of the MI return cable increases the impedance of the HVDC system's return path, increasing the neutral voltage. This leads to more severe voltage distortion on the inverter side of pole 2. For the XLPE return cable at 8.011s, the neutral voltage reaches 200kV, and the neutral current reaches nearly 2kA. This neutral voltage distorts the DC voltage of the pole 2 inverter causing a commutation failure. Thus, the high impedance of the return cable increases the possibility of pole interaction.

5.4 Scenario 3

Fig. 11 presents the dynamic response of the bipolar HVDC system with a 10kV surge arrester on the inverter neutral busbar when the pole 1 inverter is bypassed at 8.01s while all cables are secured. In contrast to the HVDC system, without the surge arrester discussed in Sections V-B and C, a commutation failure does not occur on pole 2 when the inverter of pole 1 is bypassed. The inverter gamma of pole 2 decreases from 23° to 20°, and the inverter of pole 2 operates with a stable gamma (see Fig. 11(b), third row). The minimum gamma angle (20°) of the pole 2 inverter in Fig. 11(b) is larger

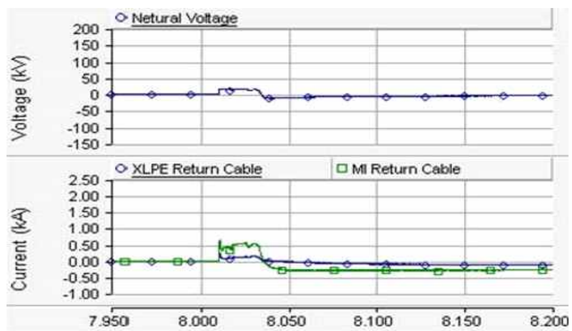
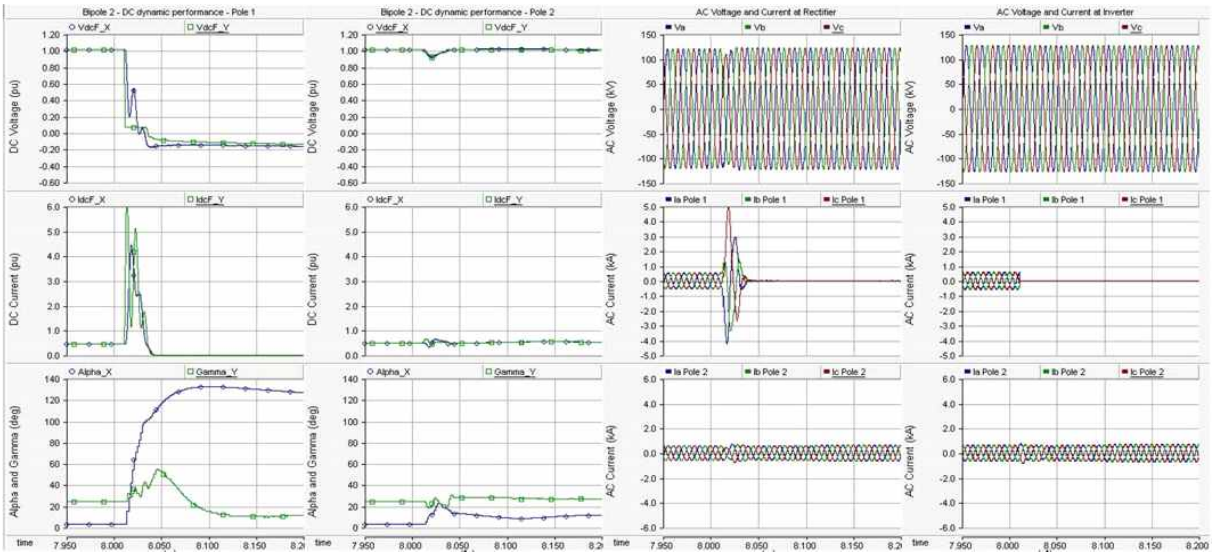


Fig. 12. Dynamic response of inverter neutral busbar voltage and current with surge arrester when inverter bypass occurs at 8.01s while all cables are secured. (a) Neutral busbar voltage, (b) Current of XLPE cable (circle) and current of MI cable on the neutral (square).

than the minimum extinction angle in Table I. Thus, the DC voltage in pole 2 is hardly affected, even when pole 1 is bypassed. As can be seen in Fig. 12, neutral voltage is limited to 10kV by the surge arrester, the current of the MI return cable is less than 500A, and the XLPE return cable current is less than 150A. The energy absorbed by surge arrester is around 548kJ.

5.5 Scenario 4

Fig. 13 presents the dynamic response of the bipolar HVDC system with a 10kV surge arrester on the inverter neutral busbar when the pole 1 inverter is bypassed at 8.01s while the MI return cable is disabled. Whereas this scenario is more severe than



(a) (b) (c) (d)

Fig. 13. Dynamic response of AC/DC system without surge arrester when inverter bypass occurs at 8.01 s while MI return cable is disabled. (a) Pole 1 rectifier DC voltage and current, inverter DC voltage and current, rectifier alpha and inverter gamma, (b) Pole 2 rectifier DC voltage and current, inverter DC voltage and current, rectifier alpha and inverter gamma, (c) AC voltage and current (pole 1 and pole 2) at rectifier, (d) AC voltage and current (pole 1 and pole 2) at inverter.

Scenario 3, the HVDC system does not undergo commutation failure on pole 2. The inverter gamma of pole 2 decreases from 23° to 20°, and the inverter of pole 2 operates with a stable gamma (see Fig. 13(b), third row). The minimum gamma angle (20°) of the pole 2 inverter in Fig. 13(b) is larger than the minimum extinction angle in Table I. Thus, DC voltage in pole 2 is barely interfered, even when pole 1 is bypassed. AC and DC dynamics response are almost the same as in Scenario 3.

As can be seen in Fig. 14, neutral voltage is limited to 10kV by the surge arrester, and the current on XLPE return cables is less than 150 A. The energy absorbed by the surge arrester is around 705 kJ. The surge arrester requires higher energy capability in Scenario 4 than in Scenario 3, because a higher neutral busbar voltage is induced in Scenario 4. Therefore, depending on the return cable configuration, the rating, energy tolerance, and discharge capability of the surge arrester must be carefully determined.

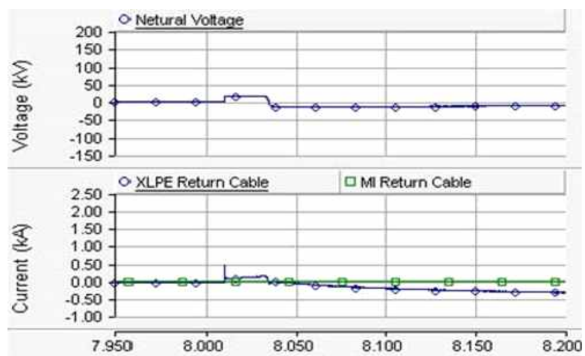


Fig. 14. Dynamic response of inverter neutral busbar voltage and current with surge arrester when inverter bypass occurs at 8.01s while MI return cable is disabled. (a) Neutral busbar voltage, (b) Current of XLPE cable (circle) and current of MI cable on the neutral (square).

6. Conclusion

The pole-interaction phenomenon of the HVDC system was investigated. The HVDC system has various types of interactions, such as that between the HVDC system and the AC system, that between the HVDC system and another HVDC system, and that between poles in the HVDC system. In this paper, we present the interactions between the poles in the HVDC system, along with countermeasures against them. The pole interaction of Jeju HVDC No. 2 occurred during the commissioning field test of 2014; we proposed a practical and economic solution for the pole interaction of HVDC. Pole interaction can only occur in a double-monopole configuration with cable application during bipolar HVDC operation, where the neutral busbar of the rectifier is grounded and the inverter neutral busbar is ungrounded.

This paper proposes the installation of a low-rated voltage surge arrester to prevent pole interaction. Other countermeasures, such as increasing the reactance of the DC, reducing the cable impedance, and installing a surge capacitor, are considered. However, the installation of the low-rated voltage surge arrester is the most efficient and effective method for preventing pole interaction. The efficacy of the proposed method is validated using PSCAD/EMTDC simulation. The results indicate that the proposed method eliminates the pole interaction of bipolar-operated HVDC.

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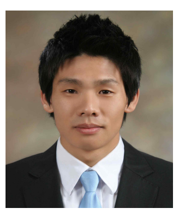

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