Development of Countermeasures for Transient Phenomena in Low-Voltage DC Distribution Systems due to ACCB Operation

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***Abstract*—As low-voltage DC (LVDC) distribution systems attract more attention, studies and standardization work are being conducted on various aspects, including protection schemes. However, many studies focus on the perspective of DC faults, even though LVDC distribution systems are supplied from AC distribution systems. Thus, in this paper, countermeasures are proposed for transient phenomena in LVDC distribution systems due to AC faults and the operation of the AC circuit breakers (ACCB) on the AC side. To this end, transient characteristics of an LVDC distribution system resulting from AC faults and ACCB operation are analyzed first. From the analysis results, corresponding countermeasures are developed and are verified by simulation using the Electro-Magnetic Transients Program.**

***Keywords*: AC circuit breaker, Low-voltage DC distribution system, Protection scheme, Transient characteristics.**

I. INTRODUCTION

LOW-voltage DC (LVDC) distribution systems are considered a solution for the challenges of conventional power systems. In particular, this novel power system concept is expected to improve energy efficiency by reducing the number of power conversions when supplying digital loads. However, there is still a lack of standards and research results for building LVDC distribution systems, even though various studies are being carried out. Protection schemes for LVDC distribution systems are involved. Transient characteristics by DC faults have been analyzed and corresponding protection schemes discussed in many papers [1–3]. Some of them have dealt with the case of AC faults, but they proposed countermeasures against the problems resulting from distributed generation [4, 5]. In the concept of the LVDC distribution system, however, power is supplied from an AC distribution system and the voltage is rectified through an AC/DC converter. Thus, a protection scheme for an LVDC distribution system considering only DC faults cannot ensure the reliability of the LVDC distribution system. This study therefore analyzed the transient characteristics resulting from AC faults and the operation of the AC circuit breaker (ACCB), and then developed corresponding countermeasures. Finally, the countermeasures were verified with the Electro-Magnetic Transients Program (EMTP). To this end, Section II discusses the concept of the LVDC distribution system as well as transient characteristics caused by AC faults and ACCB operation. In Section III, the corresponding countermeasures are described, and EMTP verification results are discussed. The paper is concluded in Section IV.

II. TRANSIENT CHARACTERISTICS OF LVDC DISTRIBUTION SYSTEMS

Low voltage means a voltage level less than or equal to 1500 VDC according to the IEC standard. Therefore, an LVDC distribution system is one that operates at the corresponding voltage range. This system includes two important components, the AC/DC converter and the DC/DC converter, as shown in Fig. 1. The AC/DC converter rectifies AC voltage supplied from the AC distribution system. In this study, an AC voltage of 22.9 kV is rectified to a DC voltage of 1500 V through this component. The DC/DC converter converts this DC voltage to a voltage level that customers require; in this paper, it reduces the 1500 VDC to 380 VDC. In addition, the various circuit breakers (ACCB, CB_{IT}, and DCCB) are considered to protect the LVDC distribution system. The ACCB and DCCB protect the AC and DC distribution system, respectively. CB_{IT} is used to protect the converter station with the DCCB by using the unit protection

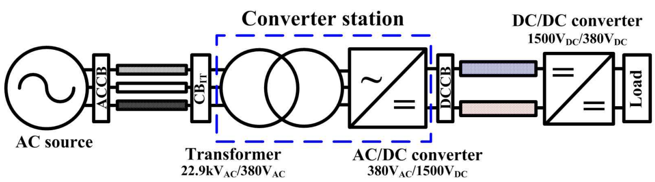

Fig. 1. Concept of the LVDC distribution system

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scheme. The LVDC distribution system could be significantly affected by AC faults and the operation of the ACCB, judging from the structure in Fig. 1. Thus, in this section, transient characteristics of LVDC distribution systems caused by these faults are analyzed.

A. AC Line Fault

In this section, the transient characteristics of LVDC distribution system are analyzed for AC line faults. When a fault occurs, most of the current flows towards the fault because the fault resistance is extremely small compared to the system impedance. Thus, the downstream parts are not greatly affected in the prospective of current. It is the same with the LVDC distribution system. Although an AC/DC converter operates under unbalanced voltages when ac AC fault occurs, LVDC distribution system can still operate correctly with somewhat lower efficiency and power quality.

B. ACCB Opening

When an AC fault occurs, the ACCB should interrupt the fault current to protect the AC distribution system. The operation of the ACCB prevents AC input from supplying the downstream LVDC distribution system. Simultaneously, the DC-link capacitor in the AC/DC converter begins to discharge along with the fault loop on the left side in Fig. 2, which shows a circuit diagram simplified from the original. The current initially becomes quite high because of the abrupt discharge of the DC-link capacitor and gradually decreases until full discharge of the DC-link capacitor. Because the fault loop is a series RLC circuit, the current has a damping form. It could be one of three types of damping according to the values of the constants in the fault loop, but it usually has the underdamped sinusoidal form in a power system as shown in (1) [2]. B_x represents a constant, α is the damping factor, and ω_d is the resonant frequency.

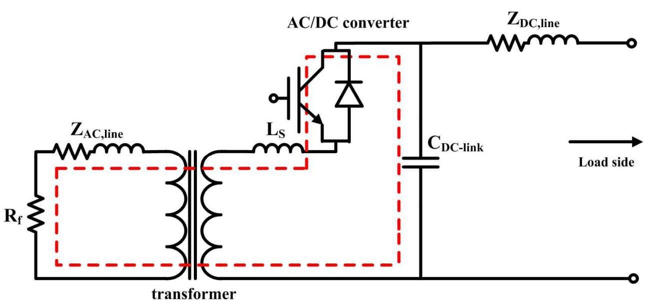

Fig. 2. Current flow caused by ACCB opening

$$I_{fault1} = B_1 e^{-\alpha t} \cos\omega_d t + B_2 e^{-\alpha t} \cos\omega_d t \qquad (1)$$

Because this current flows through a semiconductor switch in the AC/DC converter, the semiconductor switch could be opened and uncontrollable. In other words, the AC/DC converter acts like a six-pulse diode rectifier. This means that the LVDC distribution system is abnormally operated with a lower voltage level even if the AC distribution system is restored later. The whole LVDC distribution system must be collapsed, because this system includes many sensitive components such as converters and digital loads that are vulnerable to voltage sag. Therefore, a countermeasure is required to prevent underdamped current from flowing through the semiconductor switches.

C. ACCB Reclosing

After the AC fault is cleared, the LVDC distribution system should be operated normally by reclosing the ACCB. When the ACCB is operated, however, sudden injection of AC input could result in inrush current. This current flows toward the AC/DC converter, and then abruptly charges the DC-link capacitor that was discharged during the ACCB opening, as shown in Fig. 3. Fig. 3 also shows a circuit diagram simplified from the original. This process causes the charging current as in (2).

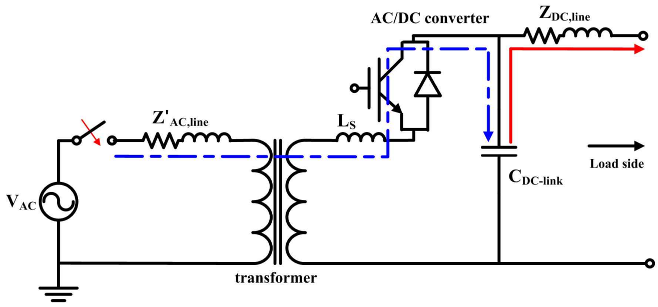

Fig. 3. Current flow caused by ACCB reclosing

$$I_C = C_{DC-link}(dV_C / dt) \qquad (2)$$

The high inrush current could make the semiconductor switches uncontrollable even though the countermeasure for the problem in Section II.B is applied to the LVDC distribution system. Furthermore, the magnitude of the current I_C must be high within short time because the voltage across the DC-link capacitor v_C is changed rapidly by the inrush current. The charging current could result in the malfunction of the DCCB after the AC/DC converter, because the representative transient characteristics of the current under a DC fault become very high within short time [6]. Therefore, a countermeasure should be considered to solve both of problems simultaneously by reducing the effect of the inrush current.

III. COUNTERMEASURES FOR THE TRANSIENT PHENOMENA

In this section, the countermeasures for the transient phenomena in an LVDC distribution system due to ACCB operation are discussed.

A. Countermeasure for Underdamped Current

In order to prevent underdamped current from flowing through the semiconductor switches when an ACCB is opened, an intertripping scheme is introduced. An intertripping scheme is the controlled tripping of a circuit breaker so as to complete the isolation of a circuit or piece of apparatus in sympathy with the tripping of another CB [7]. The concept of an intertripping scheme is shown in Fig. 4. When one of the CBs at both ends is tripped by a disturbance, the tripping signal is conveyed to the other CB through a communication link.

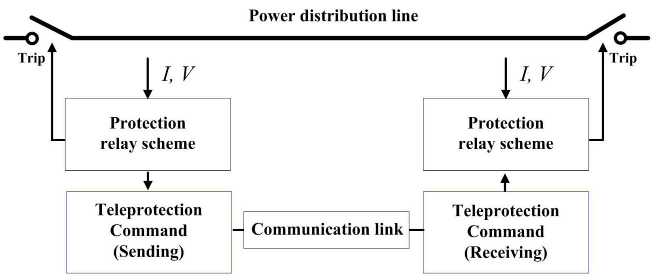

Fig. 4. Concept of an intertripping scheme [7]

To protect important components such as transformers, a conventional AC distribution system generally uses a unit protection scheme. It is equally applied to an LVDC distribution system. To protect the converter station, two CBs should be installed before and after: CB_{IT} and DCCB. Thus, an intertripping scheme between ACCB and CB_{IT} in front of the converter station is established as the countermeasure for the underdamped current. An intertripping scheme can be classified into three types: direct tripping, permissive tripping, and blocking tripping [7]. If a direct tripping scheme is applied, the corresponding CB is tripped whenever the signal is detected at the receiving end. On the other hand, in the application of permissive tripping, the signal is checked for appropriateness before the corresponding CB is tripped. Finally, a blocking scheme prevents the specified CBs from tripping either directly or after the check. In the application in an LVDC distribution system, permissive tripping is used because of the reclosing of the ACCB. When the ACCB is tripped by the overcurrent relay, the tripping signal is conveyed to CB_{IT}, and then CB_{IT} is directly tripped. However, ACCB and CB_{IT} should not be synchronized with each other during the reclosing of the ACCB as long as the AC fault is not cleared. After an instantaneous fault is identified by reclosing the ACCB, the tripping signal can be transmitted to the receiving end to close CB_{IT}. In other words, CB_{IT} should ignore the tripping signal from the ACCB during ACCB reclosing. That is why permissive tripping is applied to the LVDC distribution system as the countermeasure for preventing underdamped current from flowing into the AC/DC converter.

B. Countermeasure for Inrush Current

As discussed in Section II.C, the inrush current can result in both the opening of semiconductor switches and the malfunction of the DCCB when the ACCB is reclosed. As the countermeasure for these problems, a modified inrush current limiter (ICL) circuit is applied to the AC/DC converter in the LVDC distribution system. Typical ICL circuits can be classified into two solutions. The first solution uses a negative temperature coefficient (NTC) thermistor whose resistance changes according to temperature [8]. In the normal state, the NTC thermistor is heated so that the resistance becomes low. When the power is supplied, however, the resistance becomes high because the NTC thermistor is cooled. The other solution is a bypass solution that uses a relay. In this solution, a switch is operated according to the voltage level across the DC-link capacitor [8]. If the DC-link capacitor is fully charged, the switch in the bypass circuit is closed. If not, the switch is open and current flows through a resistor. A MOSFET can be used instead of a relay, but it increases the cost. Because an NTC thermistor causes more losses in normal state than a bypass solution, a bypass solution using an undervoltage relay is applied in this study.

In the application of the ICL circuit to the LVDC distribution system, a reactor is used rather than a resistor that is used in general in many applications. Both a reactor and a resistor can efficiently reduce the magnitude of inrush current. However, it is impossible to prevent the DC-link capacitor from charging rapidly when a resistor is used in the ICL circuit, because a resistor reduces the magnitude of both AC and DC current and voltage. Thus, the voltage across the DC-link capacitor v_C increases rapidly when a switch in turned on. On the other hand, a reactor is responsive only to the rise time of the DC current and voltage as shown in (3). t_r is the rise time, ω_n is the natural frequency, L is the reactance of the ICL circuit, and C is the capacitance of the DC-link capacitor. Therefore, both inrush current and charging current can be reduced by applying the ICL circuit using a reactor as shown in Fig. 5. This figure is simplified, similar to Fig. 2 and Fig. 3. When v_C is discharged below the threshold value, SW_{bypass} is turned off so that the inrush current is limited and the DC-link capacitor is charged gradually. On the other hand, SW_{bypass} is turned on when the DC-link capacitor is almost fully charged, to eliminate losses in the normal state.

$$t_r \propto \omega_n = (1/\sqrt{LC}) \tag{3}$$

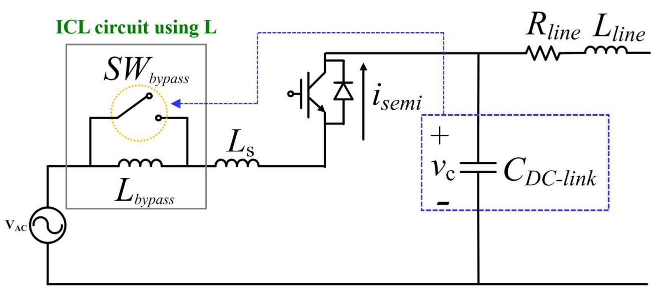

Fig. 5. Schematic of the ICL circuit using a reactor

IV. VERIFICATION BY SIMULATION

This section describes the simulations using EMTP that were conducted to verify the countermeasures for transient phenomena by ACCB operation. First, the LVDC distribution system

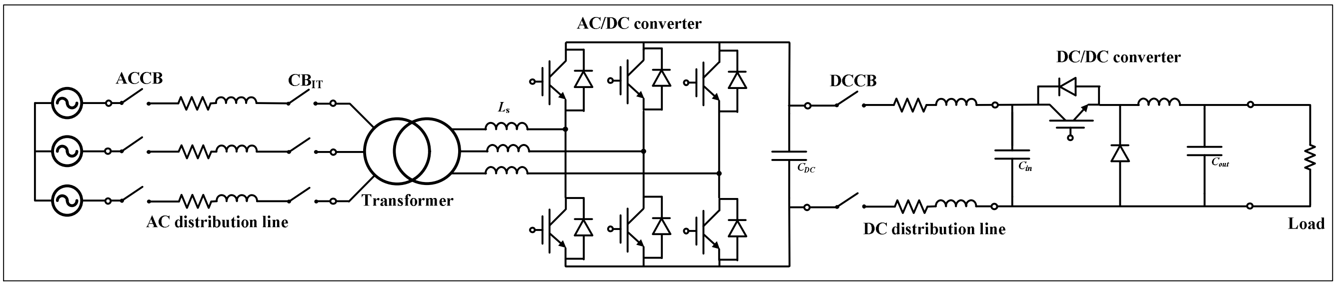

Fig. 6. Circuit diagram of the test LVDC distribution system

was tested, including an intertripping scheme and the ICL circuit using a reactor modeled by using EMTP. Next, simulations with the test system were performed to verify the countermeasures.

A. Simulation Conditions

In this study, a test LVDC distribution system was modeled by using EMTP as shown in Fig. 6. To model the test system, a pulse-width modulation (PWM) AC/DC converter and buck converter were considered. Moreover, it was assumed that the distribution line for a conventional AC distribution system is applied only to the LVDC distribution system. The details of the test system are summarized in Table 1, including data on the countermeasure setups. The proposed countermeasures were applied to the modeled system on the basis of the concepts shown in Fig. 4 and Fig. 5.

The simulations with the modeled system were performed for 3 s and include a ground fault on the AC distribution line and ACCB operation. The occurrence of these faults was arbitrarily assumed to leave enough time to verify the performance of the proposed countermeasures. An AC line fault occurred at 1 s, and then the ACCB was opened at 1.48 s to interrupt the fault current. Next, the AC fault cleared by itself at 1.8 s. Finally, the ACCB was reclosed at 2 s to restore the whole system. Moreover, the function to protect the semiconductor switches from overcurrent was considered in the simulation. However, in the cases without the countermeasures, this function was not applied to the simulation so as to show all the transient phenomena accurately.

TABLE I
SIMULATION CONDITIONS OF THE TEST LVDC DISTRIBUTION SYSTEM

Parameter		Input values	
Distribution line	Line length	AC distribution line: 1,000 m	
		DC distribution line: 600 m	
	Line constant	R	L
		0.164 Ω/km	0.26 Ω/km
Load capacity		50 kW	
AC/DC converter	Input reactance	1 mH	
	DC-link capacitance	5000 μF	
AC line fault	Type	Ground fault	
	Resistance	1 Ω	
	Location	50%	
Delay time for a permissive trip [7]		1.5 ms	
ICL circuit	Reactance	3 mH	
	Threshold value to operate SW_{bypass}	600 V	

B. Simulation Results

This section compares the original system in Fig. 6 with the system with the proposed countermeasures applied, namely, the intertripping scheme and the ICL circuit using a reactor. To this end, the current i_{semi} flowing through the semiconductor switch and the voltage v_C across the DC-link capacitor were measured. Fig. 7 and Fig. 8 show the entire transient without the countermeasures and with them, respectively. The two figures each show four states: (1) steady state, (2) post-fault state, (3) ACCB opening state, and (4) ACCB reclosing state. In the first two states of Fig. 7, any specific transient phenomena are not found in terms of i_{semi} and v_C. However, in the last two states of the same figure, the overcurrent flows through the semiconductor switches, which must result in the opening of the switches. On the other hand,

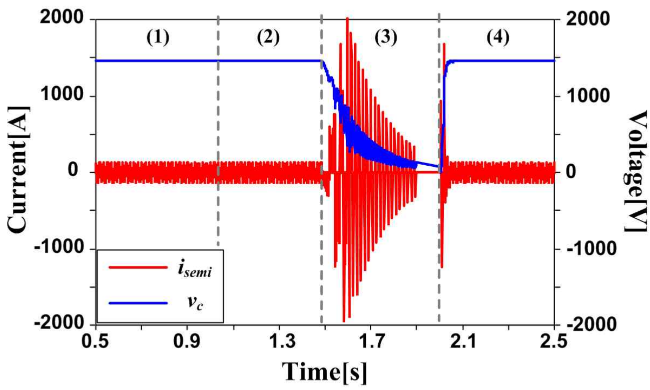

Fig. 7. Entire waveform of i_{semi} and v_C when the countermeasures are not applied

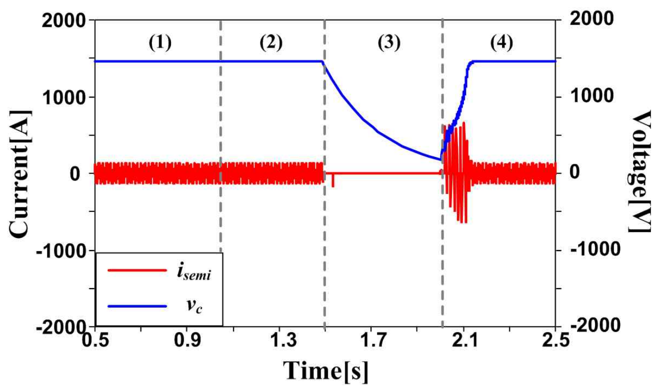

Fig. 8. Entire waveform of i_{semi} and v_C when the countermeasures are applied

in Fig. 8, there are no spectacular transient phenomena except in the last state. However, the possibility of opening the semiconductor switches is low even in the last state because the magnitude of the overcurrent is significantly reduced by the countermeasures.

The next four figures show the detailed transient phenomena resulting from the ACCB operation, which are described in the previous sections. Fig. 9 and Fig. 10 are relevant to the cases without the countermeasures. Fig. 9 represents the current i_{semi} flowing through the semiconductor switch when the ACCB is opened, and Fig. 10 shows the current i_{semi} and the voltage v_C across the DC-link capacitor measured when the ACCB is reclosed.

As shown in Fig. 9 and Fig. 10 above, the overcurrent flows through the semiconductor switch whenever the ACCB is operated. This current could result in the unexpected opening of semiconductor switches, which brings about the collapse of the entire LVDC distribution system because of damage to its sensitive components. Thus, the countermeasures in Section III should be applied to the LVDC distribution system. The simulation results for the modeled system with both an intertripping scheme and the ICL circuit using a reactor are shown in Fig. 11 and Fig. 12.

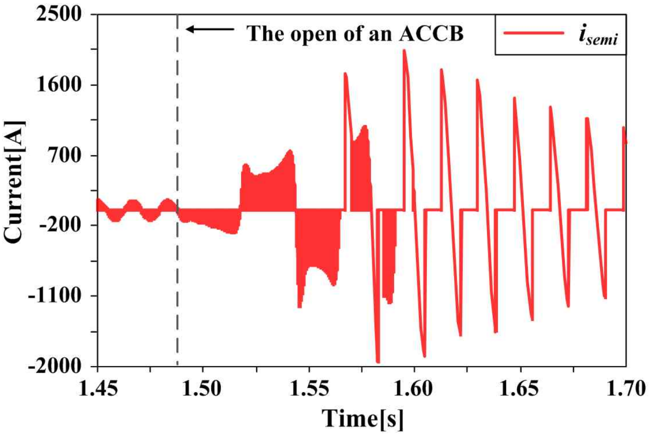

Fig. 9. Waveform of i_{semi} when the ACCB is opened for the modeled system without countermeasures

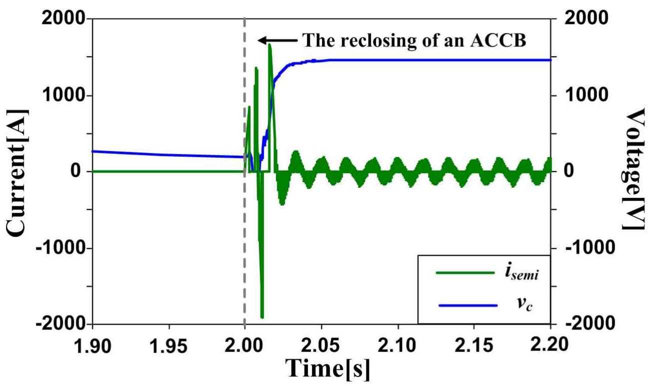

Fig. 10. Waveform of i_{semi} and v_C when the ACCB is reclosed for the modeled system without countermeasures

The underdamped current by the ACCB opening in Fig. 9 does not appear when an intertripping scheme is applied to the modeled LVDC distribution system in Fig. 11, because the CB_{IT} at the front end of the converter station prevents the series RLC fault loop from being formed by the intertripping scheme between the ACCB and CB_{IT}. When the ICL circuit using a reactor is applied as shown in Fig. 12, the magnitude of the inrush current is considerably reduced compared to that in Fig. 10. In fact, the reduced magnitude of i_{semi} is lower than the general pickup value, which is set as 3 times that under the normal state. The rise time of v_C and the magnitude of i_{semi} can vary according to the reactance in the ICL circuit. In conclusion, it is verified through the simulation results that the countermeasures are highly effective in mitigating the transient phenomena resulting from the operation of the ACCB in an LVDC distribution system.

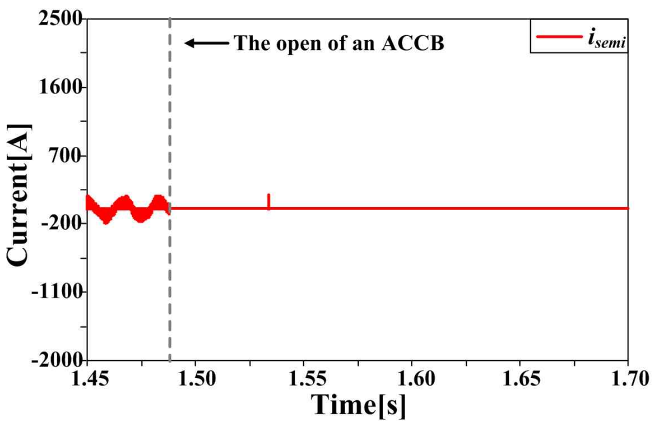

Fig. 11. Waveform of i_{semi} when the ACCB is opened for the modeled system with countermeasures

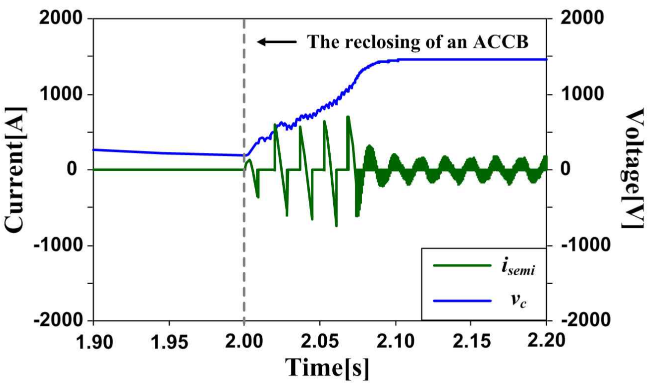

Fig. 12. Waveform of i_{semi} and v_C when the ACCB is reclosed for the modeled system with countermeasures

V. CONCLUSIONS

This paper proposes countermeasures for the transient phenomena in an LVDC distribution system due to ACCB operation. To this end, the transient characteristics resulting from the ACCB operation are analyzed first. From the analysis results, it becomes clear that two main problems can occur in an LVDC distribution system. One problem is that the underdamped current by the ACCB opening can cause abnormal operation of the semiconductor switches in the AC/DC converter when the system is restored. The other problem is that the inrush current by reclosing the ACCB can result in the same issues. Moreover, it could cause a malfunction of the DCCB because of the rapid charging of the DC-link capacitor. These problems can be solved by an intertripping scheme and an ICL circuit using a reactor, respectively. An intertripping scheme operates CB_{IT} at the front end of the converter station simultaneously when the ACCB is opened. Thus, this scheme can prevent the underdamped current from flowing through the semiconductor switch. The ICL circuit provides two paths for inrush current; a path with a switch and a path with high reactance. When the voltage across the DC-link capacitor decreases below the threshold value, the path with a switch is open so that the inrush current is reduced by the reactance. The performance of both countermeasures is verified through EMTP simulations.

VI. References

[1] Jae-Do Park, Jared Candelaria, Liuyan Ma, Kyle Dunn, “DC Ring-Bus Microgrid Fault Protection and Identification of Fault Location”, IEEE Trans. Power Delivery, vol. 28, no. 4, pp. 2574-2584, Oct. 2013.

[2] Jin Yang, John Edward Fletcher, John O'Reilly, “Multiterminal DC Wind Farm Collection Grid Internet Fault Analysis and Protection Design”, IEEE Transactions on Power Delivery, Vol.25, No.4, 2010.10.

[3] K.J. Tseng, Cuomin Luo, “Power Electronic-Based Protection for Direct-Current Power Distribution in Micro-Grids”, presented at The International Power Electronics Conference, Hiroshima, Japan, May. 18-21, 2014.

[4] Sri Raju Bushanam Vanteddu, Ahmed Mohamed, Osama Mohammed, "Protection Design and Coordination of DC Distributed Power Systems Architectures", 2013 IEEE Power and Energy Society Genral Meeting (PES), Nov. 24, 2013.

[5] Shimin Xue, Chaochao Chen, Yi Jin, Yongli Li, Botong Li, YingWang, "Protection for DC Distribution System with Distributed Generator", Journal of Applied Mathmatics, Vol.24, 2014.

[6] Chul-Ho Noh, Gi-Hyeon Gwon, Jong-Il Song, Joon Han, Yun-Sik Oh, Chul-Hwan Kim, "An Analysis on Fault Response Characteristics in Low Voltage DC Distribution System", The transactions of The Korean Institute of Electrical Engineers, Vol.65, No.6, pp.911-917, 2016.6.

[7] Alstom Grid, Network Protection and Automation Guide, 4th ed., 2011.

[8] STMicroeletronics, "Inrush-current limiter circuits (ICL) with Triacs and Thyristors (SCR) and controlled bridge design tips”, STMicroeletronics, Geneva, Switzerland, Tech. Rep. AN-4606, Mar. 2016.