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# A New Control Algorithm to Improve Transient Performance of HVDC Systems

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***Abstract***

*Application of the high voltage direct current (HVDC) system has been gradually extended due to many advantages compared to the high voltage alternate current (HVAC) system. Basically, the HVDC system has the current controller and voltage controller at the terminals of the rectifier and inverter, respectively. The control system should be properly applied to operate stably the HVDC system that depends on the system condition. That is, improving the characteristics of the control system may be needed during the transient state. In this paper, a new algorithm for improving the transient state of the HVDC systems under fault condition is proposed. The proposed control algorithm can change the control strategy of the converter. From simulations, the performance of the proposed algorithm is verified under the fault condition in the AC system.*

***Keywords****: High voltage direct current (HVDC) system, Constant current (CC) control, Constant extinction angle (CEA) control.*

## Introduction

The high voltage direct current (HVDC) system can reduce the transmission loss and the transmission cost compared with the high voltage alternate current (HVAC) system in case of bulk and long-distance transmission of electrical power, typically more than 600 km for overhead lines and more than 50 km for underwater cables [1, 2]. For this reason, the HVDC system has been applied to interconnection between the mainland system and offshore wind farms, and between counties systems such as the super grid [3–5]. Many researches have been conducted on how to operate the HVDC system more stably. Basically, there are two control modes in the HVDC system. The first control mode is a constant current (CC) control for rectifier and constant extinction angle (CEA) control for inverter. The second control mode is a constant ignition angle (CIA) control for the rectifier and CC control for the inverter. These control modes should be suitably selected to stably operate the HVDC system depending on the system condition.

In this paper, the CIGRE Benchmark HVDC system with an auxiliary control is modeled by using PSCAD/EMTDC. A new control algorithm is proposed for the auxiliary control that can improve the performance of the control system. The outline of this paper is as follows. Section 2 explains the configuration and control scheme of the CIGRE Benchmark HVDC system. Section 3 introduces the proposed control algorithm that is developed by considering the control characteristics of the HVDC system. In section 4, the simulation condition for testing the HVDC system with the proposed algorithm is mentioned. In addition, the performance of the proposed algorithm is verified by comparing the simulation results with those of the conventional control scheme. Finally, conclusions are summarized in Section 5.

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# 1. CIGRE Benchmark HVDC System

## 1.1. CIGRE Benchmark HVDC System model

Figure 1 shows the CIGRE benchmark HVDC system that was proposed in 1985 [6]. The HVDC system is a mono-polar 500 kV type and the power transfer is 1,000 MW. The CIGRE benchmark HVDC system consists of the AC and DC sides. The AC side of the HVDC system consists of an AC power supply, AC harmonic filters, and transformers whereas the DC side consists of converters, and a DC transmission line. The AC power supply with the short circuit ratio (SCR) of 2.5 and a rated frequency of 50 Hz is connected to the converters by two transformers [7]. That are based on Y-Δ and Y-Y connection. The converters are rectifier and inverter, which are based on 12-pulse bridge converter using thyristors [8]. A DC transmission line is represented as a T-type that includes resistors, inductors, and a capacitor. In order to reduce the DC harmonics and fault currents, the smoothing reactors are used at two terminals of the DC line [9].

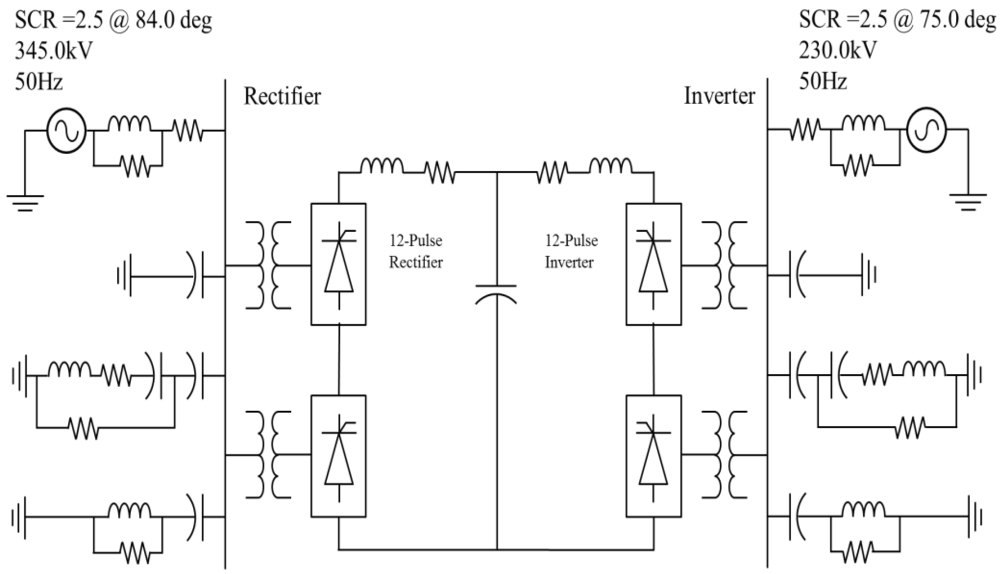


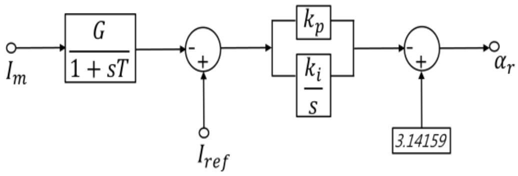

**Figure 1. CIGRE Benchmark HVDC System Model**

## 1.2. HVDC Control Block Diagram

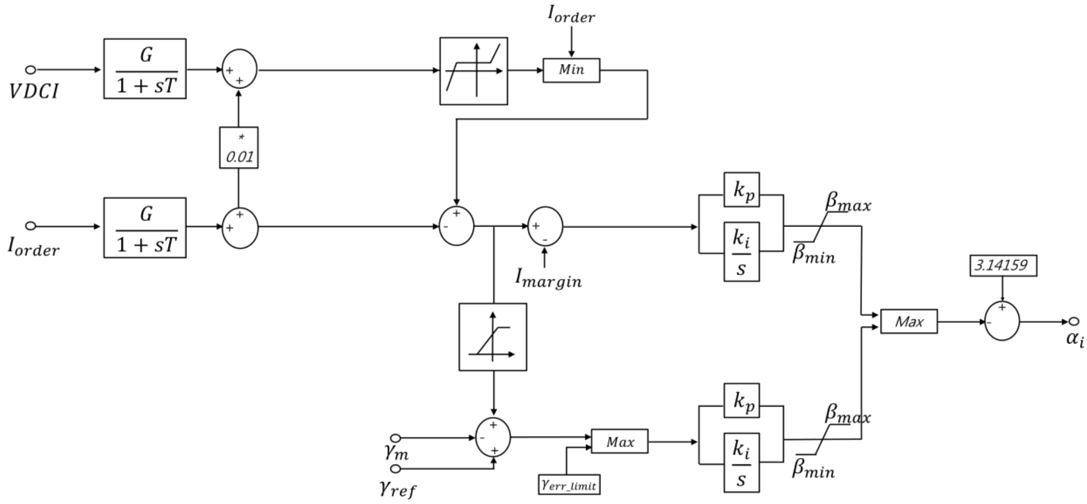
The control block diagrams of the rectifier and inverter are shown in Figures 2(a) and 2(b), respectively. The control modes of two converters can be changed according to the operation condition of the HVDC system. The controller of the rectifier generates an ignition delay angle $\alpha_r$ to maintain a constant current as shown in Figure 2(a). The proportional-integral (PI) controller is used to minimize the error between the reference and the measured current of the DC line. Besides, the controller of the inverter generates the ignition advance angles $\beta_{inv\_C}$ and $\beta_{inv\_\gamma}$ to maintain the constant current and constant extinction angle, respectively. The ignition advance angle $\beta_{inv\_C}$ is the output by the constant current controller of the inverter side and ignition advance angle $\beta_{inv\_\gamma}$ is controlled by the constant extinction angle controller [10, 11]. The maximum value between ignition advance angle $\beta_{inv\_C}$ and ignition advance angle $\beta_{inv\_\gamma}$ is used as $\alpha_i$ that is ignition delay angle at the inverter for generating the gate pulse of the thyristors.

In addition, a voltage dependent current order limit (VDCOL) is used to improve the problems associated with under low-voltage conditions such as commutation failure and voltage instability [12].




(a) The controller of the rectifier side.




(b) The controller of the inverter side.

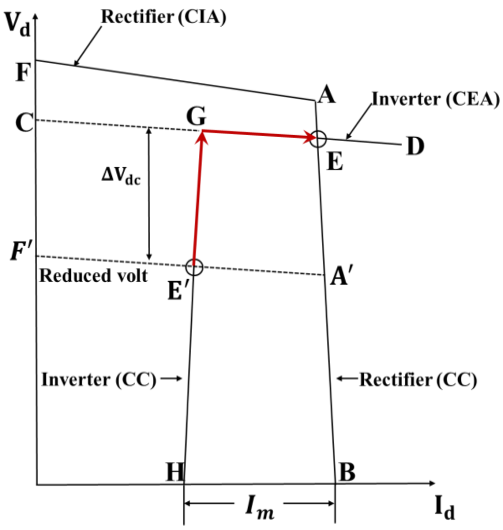
**Figure 2. The Control Block Diagrams of the Converters**

## 2. The Proposed Control Algorithm

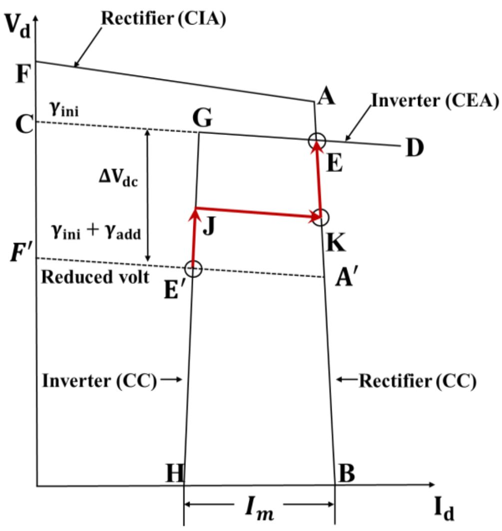
Figure 3(a) represents the conventional voltage-current (V-I) characteristics of the HVDC system. There are three control modes in the conventional control system: CC control, CIA control, and CEA control. The rectifier operates on the CC and CIA control modes whereas the inverter operates on the CC and CEA control modes.

Under steady state condition, the rectifier is on CC mode whereas the inverter is on CEA mode. The operation point of the HVDC system is point E as shown in Figure 3(a). In case of abnormal condition such as fault or load change, the DC voltage of the rectifier side is reduced~~,~~ the operation point of the HVDC system to a new point E′. In such condition, the rectifier is on CIA control mode and the inverter is on CC control mode. When the DC voltage recovers after clearing the fault, the operation point is returned to point E following the red line as shown the Figure 3(a).

This study proposed a new control algorithm to improve the performance of HVDC control system. The proposed control algorithm is based on the converter control system as shown in Figure 3(b). In the process of restoring the DC voltage, the main purpose of the proposed control algorithm is to make sure that the current control and voltage control are distinct and assigned to terminals of the rectifier and inverter respectively. The reference angle of the CEA control is increased to regulate the voltage of the inverter. Thus, the operation point of HVDC system is returned following the red line as shown the Figure 3(b).




(a) Conventional control characteristics




(b) Improved control characteristics.

**Figure 3. Converter Control Characteristics**

Figure 4 shows the flowchart of the proposed control algorithm. The procedures of the proposed algorithm are as follows:

Measure the ignition delay angle $\alpha_{rec\_C}$, ignition advance angles $\beta_{inv\_C}$, and $\beta_{inv\_\gamma}$.

A comparator checks whether the control mode at the inverter is switched from CEA control mode to CC control mode. This means that the control angle at inverter is from CC controller.

Check the minimum ignition delay angle $\alpha_{min}$.

If the ignition delay angle $\alpha_{rec\_C}$ is more than the minimum ignition delay angle $\alpha_{min}$ and the control angle at inverter is from CC controller, the final reference of the extinction angle $\gamma_{final}$ is equal to the sum of the initial extinction advance angle reference $\gamma_{ini}$ and additional extinction advance angle $\gamma_{add}$.

Otherwise, the final reference of the extinction angle $\gamma_{final}$ is equal to the reference of the initial extinction advance angle $\gamma_{ini}$.

# 3. Simulations

### 3.1 Simulation Conditions

In this paper, the CIGRE Benchmark HVDC system as shown in Figure 1 is used for simulations. In order to test the effectiveness and performance of the proposed control algorithm, the simulation results with and without the proposed algorithm have been compared. In the simulation, it has been assumed that the single line-to-ground fault occurs in the AC system at the rectifier side at 2.0 sec and the fault is cleared after 0.1 sec. The fault resistance is 0.01Ω.

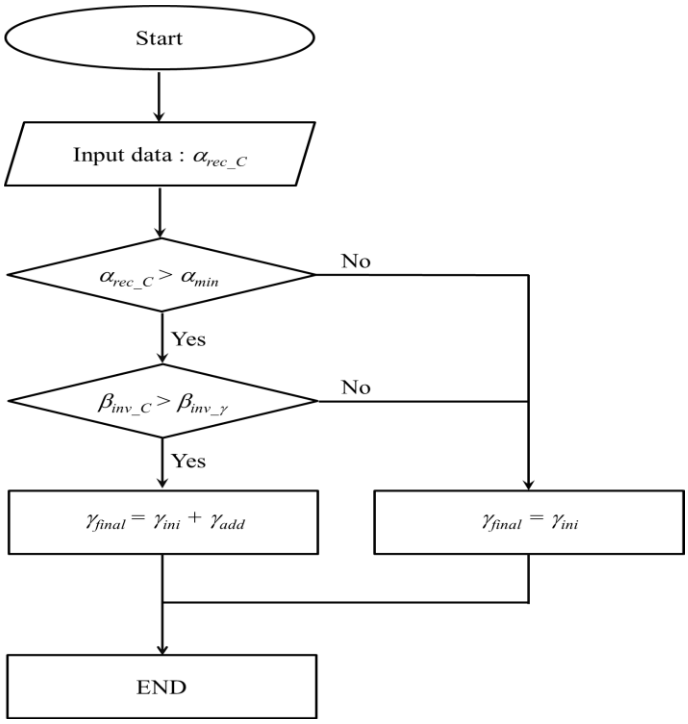
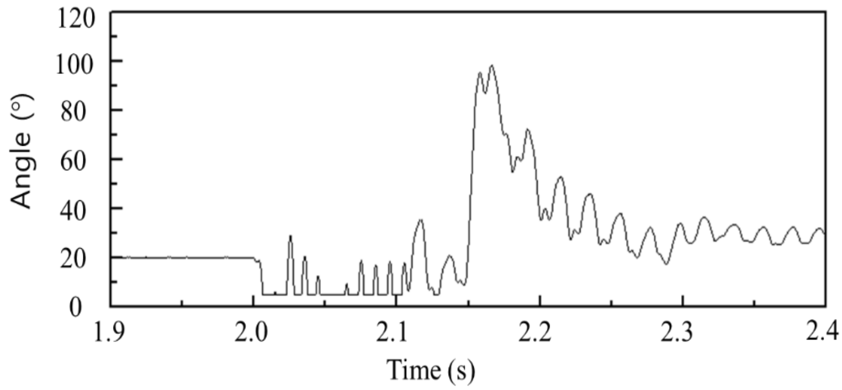



**Figure 4. The Flowchart of Proposed Control Algorithm.**

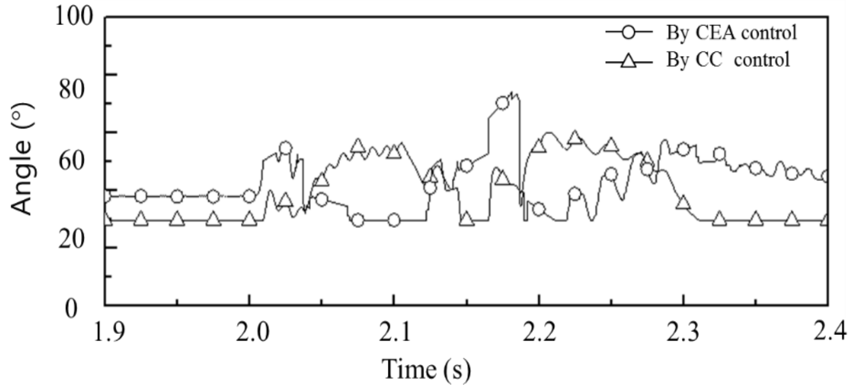
### 3.2 Simulation Results

Figure 5 shows the ignition angle, extinction angles, and the final reference of the extinction angle in case of the conventional control algorithm. When the fault occurs in the rectifier side at 2.0 sec, the ignition angle is decreased to recover the DC current that is reduced by the AC fault at rectifier side as shown in Figure 5(a). At this time, the control mode of the inverter is switched from CEA control to CC control operation as shown in Figure 5(b). This is due to the compensation of the DC current by CC control of the inverter side. After clearing the fault, DC voltage of the rectifier side recovers gradually. The final change of control mode from CC control to CEA control is at 2.28 sec. The reference of the extinction angle is always 15° as shown in Figure 5(c).

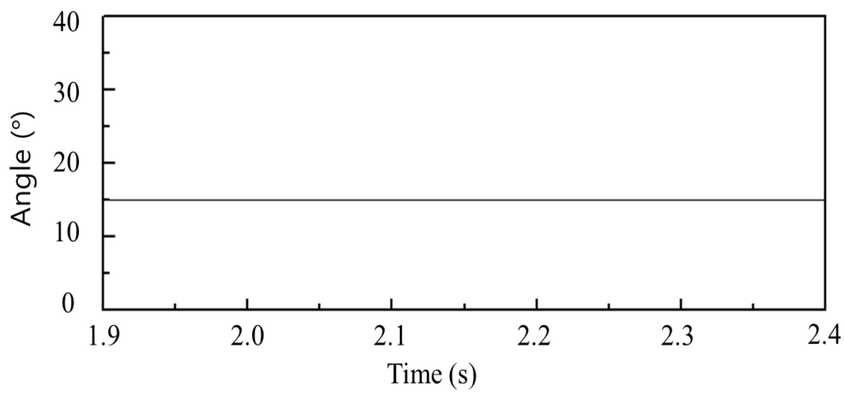
Figure 6 represents the ignition angle, extinction angles, and the final reference of the extinction angle when the proposed control algorithm is applied. The rectifier operates at the minimum ignition angle and the inverter operates on CC control during the fault. These characteristics are identical to results without the proposed algorithm. However, the final reference of the extinction angle is increased by the algorithm as shown in Figure 6(c). In particularly, the reference of CEA controller maintains an increased extinction angle as 35°. For the period, the ignition angle of rectifier side is not at the minimum angle and the control angle of the inverter is from the CC controller. As a result, both the rectifier and inverter operate on CC control. At this time, DC system can be unstable because there is no the responsibility of the voltage regulation. For this reason, the proposed algorithm can regulate the terminal voltage of the inverter. Figure 6(a) represents the extinction angles of the inverter and the final switch of control mode from CC control to CEA control is at 2.13 sec. This time is shorter than the result without the proposed algorithm. In addition, it can be seen that the extinction angle has shown relatively more stable recovery characteristics compared to the result shown in Figure 5(b).




(a) The firing angle of the rectifier side.

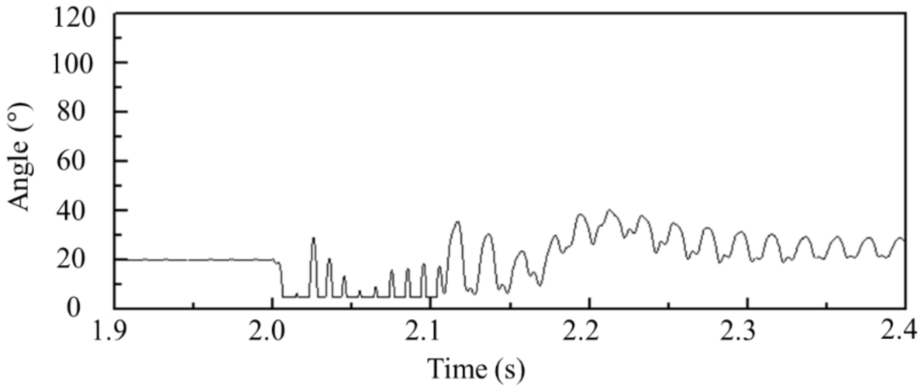



(b) The beta angle of the inverter side.

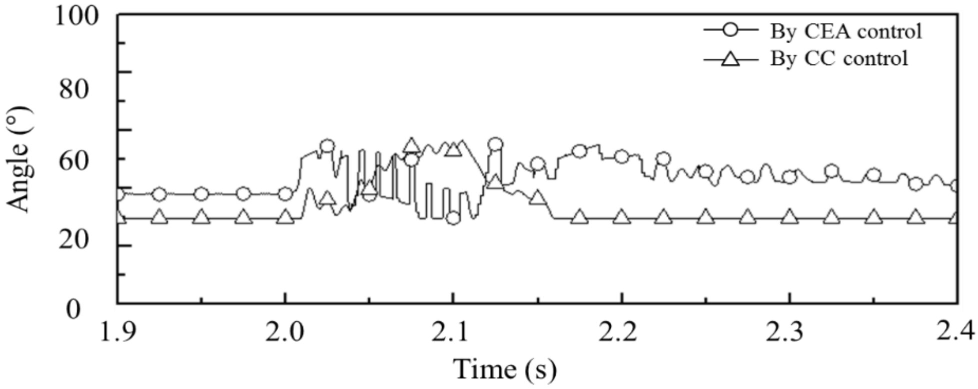



(c) The gamma reference of the inverter side.

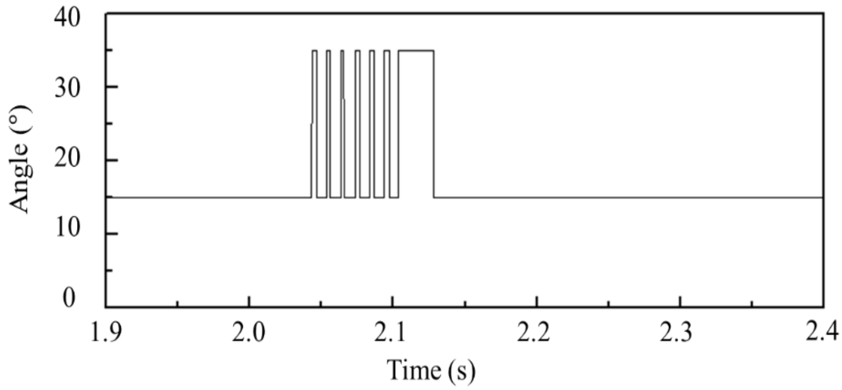
**Figure 5. Without The Algorithm**




(a) The firing angle of the rectifier side.



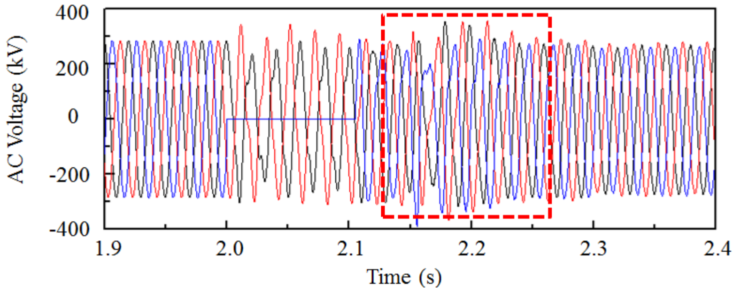

(b) The ignition advance angles of the inverter side.



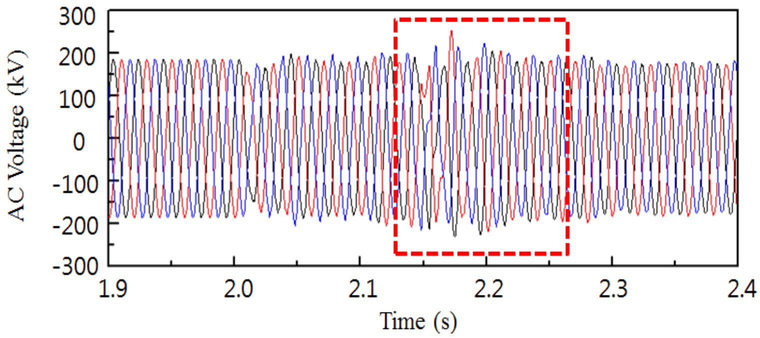

(c) The reference of the extinction advance angle of the inverter side.

**Figure 6. Control Performance with the Proposed Algorithm**

Figure 7 represents the AC voltages of the rectifier and inverter sides in case of conventional control system. Without applying the proposed control algorithm, the AC voltages of the rectifier side range from -386.63 kV to 335.82 kV and the AC voltages of the inverter side range from -226.48 kV to 251.50 kV. The voltage waveform is unstable recovery characteristics. However, the waveform of the rectifier side is more stable after the application of the proposed control algorithm as shown in Figure 8. The voltage waveforms of the inverter side range from -196.03 kV to 213.57 kV after clearing the fault.



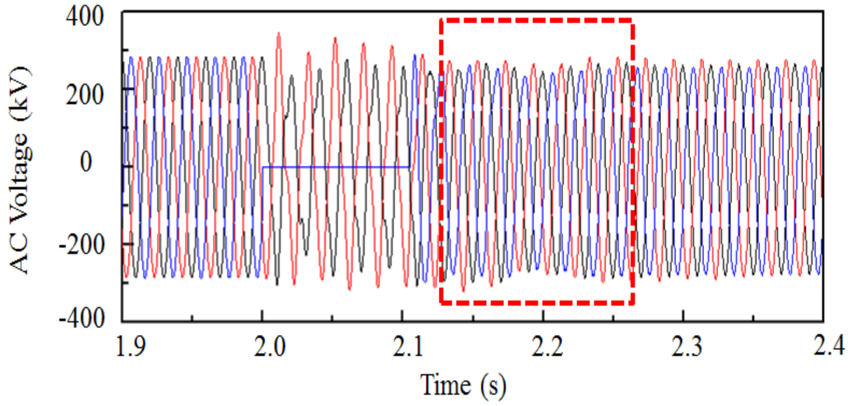

(a) AC voltage of the rectifier side.




(b) AC voltage of the inverter side.

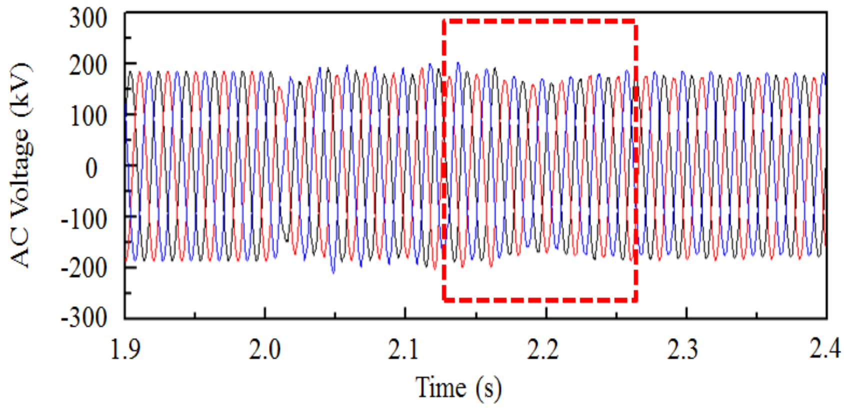
**Figure 7. AC Voltages without the Proposed Algorithm**

Figure 9 represents the measured DC power at inverter. Before applying the proposed control algorithm, the rated power has been observed after about 2.3 sec. However, when the proposed control algorithm is applied, a small drop of power transfer is seen as depicted in Figure 9.




(a) AC voltage of the rectifier side.




(b) AC voltage of the inverter side.

**Figure 8. AC Voltages with the Proposed Algorithm**

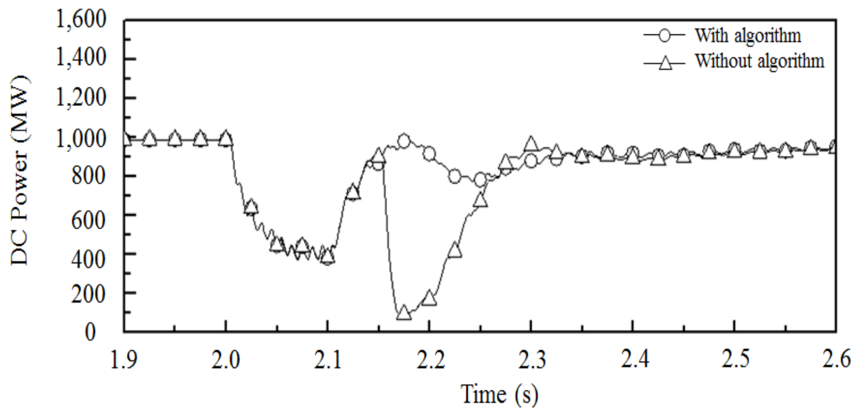



**Figure 9. The Measured DC Power Output at the Inverter Side**

## 4. Conclusion

In order to ensure a stable operation of HVDC system, this paper proposed a control algorithm for improving the performance of the HVDC control during the DC voltage recovery of the rectifier side. The proposed control algorithm has been implemented in the CIGRE HVDC Benchmark system using PSCAD/EMTDC. In order to verify the effectiveness and performance of the proposed control algorithm m, a single line-to-ground fault has been assumed on AC system of the rectifier side. The results showed that the final switch time of control mode from CC control to CEA control could be reduced about 0.1539 sec when the proposed control algorithm is included to the control system. In addition, the stable recovery characteristics have been observed from the voltage waveforms and DC power.

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