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A Novel Circuit Breaker Topology for DC Grid Applications

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Abstract

The development of large scale direct current (DC) transmission system with high efficiency and stability of DC grids has been studied widely. The dc circuit breaker (DCCB) is introduced to ensure the stability of DC grids. Among different types of DCCB, hybrid DCCB has gained more attention. This paper proposes a novel hybrid DCCB topology based on inverse current injecting method. The proposed DCCB topology is able to perform the operation duty of reclosing and rebreaking. In addition, this paper also considers the bidirectional topology of dc circuit breaker with bidirectional current breaking capability. The operating characteristics of the proposed DCCB topology are verified by simulations in Matlab/Simulink environment.

Keywords*: DC circuit breakers, Reclosing and rebreaking operation, Bidirectional operation.*

1. Introduction

In order to develop any power grid, whether ac or dc, the circuit breaker is the main component required that can interrupt quickly and reliably to prevent damage to power when a fault occurs [1]. The technical challenges of dc circuit breakers for the dc grid are larger than the traditional ac system. It is understood that the dc fault levels very high is caused by low dc impedances and the absence of a natural current zero-crossing point [2]. Therefore, the target of developing of a dc circuit breaker is to provide breaker with the ability to reduce current to zero rapidly [3-4]. Furthermore, after the initial breaking operation by faults, it is necessary for the power grid to supply the loads as quickly as possible. If the duration of interruption after initial breaking operation sustains for longer durations, it will result in serious economic losses to the operators. Therefore, the operating duty of the DCCB topology must be able to implement the reclosing and rebreaking repeatedly, as mentioned in IEC-62271-100 Standard [5].

On the other hand, bidirectional topologies of DCCBs are widely applied instead of using a single direction DCCB topologies [6]. It was explained that the output power is controlled by charging the dc system current, thus the DCCB topology should be able to break the current in both the direction of forward and reverse sides [7]. In multi-terminal DC grids during the fault, the normal power flow terminates and current from all the nodes flow towards the fault point. Hence, the DCCB topology must have bidirectional current breaking capability [8]. Therefore, in order to improve the reliability of DC power systems and to prevent damage to DC grids, a DCCB with bidirectional capability is required.

Based on these key points, several new DCCB topologies are developed recently. In [9-10-11], the hybrid DCCBs are proposed to achieve reclosing and rebreaking capability because of recharging the capacitor by using an auxiliary power supply. However, those topologies are costly for applications of DC grids. Meanwhile, the proposed solid state DCCB topologies are improved to reclose and rebreak without using the auxiliary power

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supply, but these topologies do not have bidirectional current breaking capabilities [12-13-14].

To overcome such drawbacks, this paper proposes a novel DCCB topology which is not only capable of reclosing and rebreaking without using the auxiliary power supply but also can implement bidirectional current breaking when a fault occurs. The proposed DCCB topology and operation principle is described in Section 2 in detail. Section 3 illustrates the simulation results to verify the validity of the proposed topology in Matlab/Simulink software. Finally, conclusions are presented in Section 4.

2. Proposed DCCB Topology

2.1. DCCB Topology Considering Unidirectional Operation

The injection current method has considered for the proposed DCCB topology. Basically, the main branch with a mechanical switch is for normal operation in the circuit. The auxiliary branch with an inductor, capacitor, and switch is to make resonance current when the switch is turned-on. The current in the main branch can be zero by the injected inverse current from the resonance circuit. The DCCB topology proposed in this paper is based on the conventional injection current method. Figure 1 represents the simple structure of the DC circuit with the proposed DCCB. It is for unidirectional operation of DCCB and consists of three mechanical switches and three thyristors. The branch with the resistor R_1 and the switch S_3 is used for recharging the capacitor C. The branch with the resistor L_2 and the switch T_2 is used for reversing the polarity of the capacitor voltage. And the branch with resistor R_2 and the thyristor T_3 is to charge capacitor.

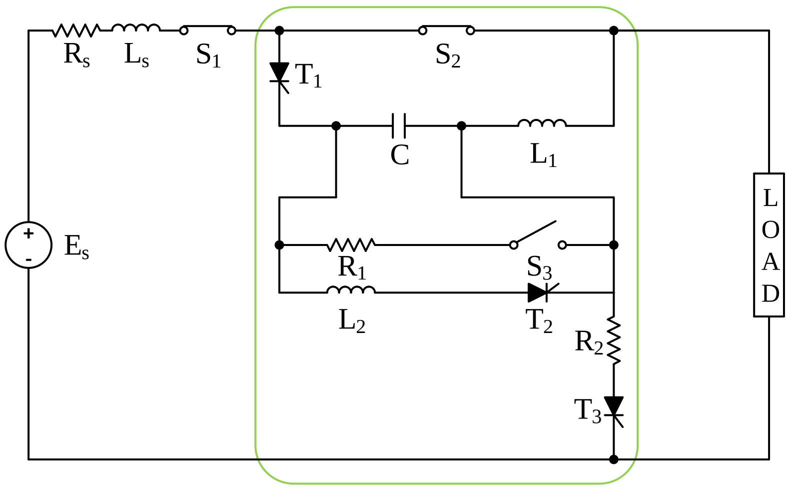


Figure 1. Proposed DCCB Topology

2.2. Operation Mode Considering Unidirectional Operation

The operation of the topology shown in Fig 1 can be classified as six parts. Figure 2 shows the full sequence of the operation modes in the proposed DCCB topology. The six operation modes consists of one charging mode (t_1 ~ t_2), one normal mode (t_2 ~ t_3), two breaking modes (t_3 ~ t_5), and two recharging modes (t_5 ~ t_7). In order to explain the operation of the proposed DCCB topology, it is assumed that the direction of the normal current flow is from the left to the right side. Meanwhile, a short circuit occurs at load side.

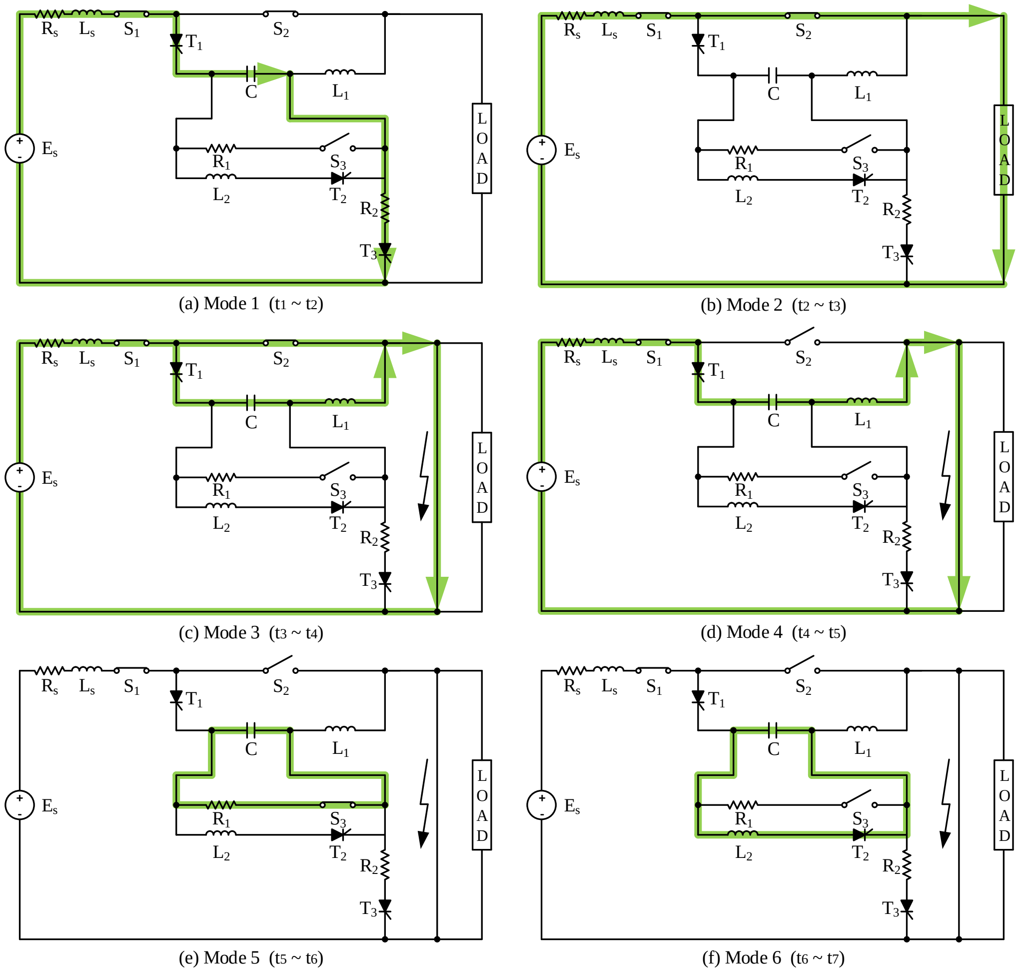


Figure 2. Operation Modes of the Proposed DCCB Topology

a. Mode 1 – Charging operation (t_1 ~ t_2)

The capacitor in the DCCB should be pre-charged before the occurrence of the fault in the circuit. It means that the pre-charged capacitor of the proposed DCCB topology is required to generate resonance current by L_1 – C circuit. At this time, the injected current into the main branch should be bigger than the fault current. During the charging mode, as shown in Figure 2(a), the current flows through the path of T_1 – C – R_2 – T_3. During this time interval, the capacitor is charged until the required voltage is achieved by turning-on the thyristor T_1. If the charging of the capacitor is finished at t_2, the thyristor T_1 is naturally turned-off.

b. Mode 2 – Normal operation (t_2 ~ t_3)

In the normal mode as shown in Figure 2(b), the DC source current i_s flows directly to the load through the switch S_2. The capacitor voltage V_c should be kept at $V_c(t_2)$. This ensures that its the ability to break the current cause by a short circuit fault using L_1 – C resonance current.

c. Mode 3 – Breaking operation (t_3 ~ t_5)

When short circuit fault occurs on load side, the fault current is increasing during the third interval (t_3 ~ t_4) as shown in Figure 2(c). If the fault current is as high as a preset reference current, the breaking mode is selected as the operation mode of the DCCB.

Meanwhile, if the magnitude of the fault current is smaller than the preset reference current, the status of thyristor T_1 is kept as the turned-off condition. In the breaking mode, if the thyristor T_1 is turned-on, the resonance current i_c in the L_1 – C circuit is increased gradually. When the magnitude of the resonance current is equal to short circuit current i_{s1}, the switch S_2 is turned-off and all current in the circuit only flow through auxiliary branch as shown in Figure 2(d). After that, the fault current is decreased gradually, the thyristor T_1 is naturally turned-off.

d. Mode 4 – Recharging operation (t_5 ~ t_7)

The recharging of the capacitor is required for reclosing and rebreaking of the DCCB after isolating the fault current. On the other hand, the capacitor should be recharged to the required voltage for next operation. The recharging mode is divided into two operation modes. The capacitor is discharged until the required voltage through the branch with the C – R_1 – S_3 as shown in Figure 2(e). However, the polarity of the capacitor is different from the polarity of the precharged voltage initially. Therefore, the operation for reversing the polarity is required as shown in Figure 2(f). During the reverse mode, the capacitor voltage can be changed from $+V_{max}$ to $-V_{max}$ by equation (1). When the operation in the reverse mode is finished, the thyristor T_2 is naturally turned-off.

$$V_c(t) = V_{max}\left(1 - cos\frac{1}{\sqrt{LC}}t\right)$$
(1)

2.3. Considering of Bidirectional Current Flow in the DCCB Operation

Base on the unidirectional DCCB topology shows in Figure 1 with single direction, the bidirectional DCCB topology is proposed as shown in Figure 3. Compared with the unidirectional DCCB topology, the thyristor T_1 is replaced by two pairs of thyristors. Figure 4(a) assumes that the fault occurs at the right side of DCCB. The normal current flows from the left to the right through the thyristor T_{1a} and T_{1b}. In contrast, Figure. 4(b) assumes that the fault occurs at the left side of DCCB. The normal current flows from the right to the left through the thyristor T_{2a} and T_{2b}. In this topology, the polarity of the precharged capacitor is same although the direction of the current flow for breaking is changed.

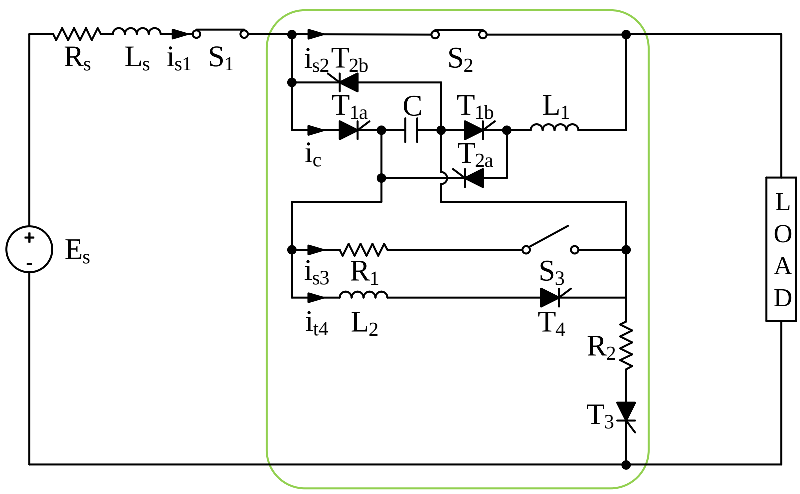
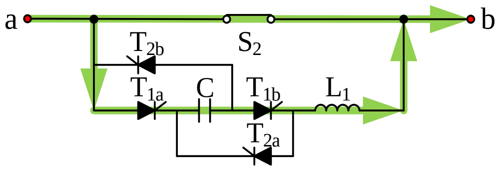
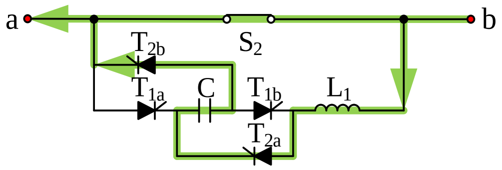


Figure 3. Proposed Bidirectional DCCB Topology



a) From the left side to the right



b) From the right side to the right

Figure 4. Bidirectional Current Flow in the Proposed DCCB Topology

3. Simulation Results

3.1. Test Scenario

In order to test the proposed DCCB topology, Figure 3 is used in the simulation and its parameters are shown in Table 1. The simulation is based on two scenarios such as breaking the positive current and the negative current in bidirectional DCCB topology. In addition, the number of operations of the DCCB are limited to two time because it is enough to verify the capability of the reclosing and rebreaking. The fault condition is considered as the short circuit without any load.

Table 1. System Parameters

Parameters	**Specification**
DC Network Voltage	100 [V]
Interruption Current	3 [kA]
R_s	0.001 [Ω]
L_s	5 [uH]
C	20000 [µF]
R_1	0.5 [Ω]
R_2	0.77 [Ω]
L_1	0.02 [uH]
L_2	0.1 [uH]

3.2. Test of Interrupting Positive Current in Bidirectional DCCB Topology

For interrupting the positive current in the DC circuit, it is assumed that the capacitor is not precharged initially. The operation of the DCCB starts after a time delay of 0.05s. DC currents in each branch and DC voltage of capacitor are represented in Figure 5 to Figure 7. In addition, Figure 8 shows the control signals in each switch including thyristor. During the charging mode, the charging current flows through the branch with switch S_1, thyritosr T_{1a} and T_3. The capacitor was fully charged to 100V within 0.05s as shown in Figure 7. The thyritosr T_{1a} and T_3 are naturally turned-off at the end of the charging mode. As mentioned in the section 2.2, the negative capacitor voltage is required for normal operation of the DCCB. This operation is possible by turning-on the thyristor T_4 at 0.15s. The condition of the short circuit starts right after changing the polarity of capacitor voltage. During the normal mode, DC current can be increased on the branch with switch S_1 and S_2. When the DC current reaches to the setting value for interrupting DC current, the inverse current by $L_1 – C$ resonant circuit is injected to main circuit by turning-on thyristor T_{1a} and T_{1b}. When the current on switch S_2 is reduced to zero, the switch S_2 is turned-off. After that, the current i_{s1} is fully interrupted within 12ms. However, the voltage of capacitor is very high during the breaking operation and the discharging of the capacitor is required to perform the reclosing and rebreaking capability in the next operation. Therefore, the capacitor voltage is discharged by turning-on the switch S_3 until its voltage is equal to the required magnitude. If the operation for discharging the capacitor voltage is finished, the reclosing and rebreaking is possible after reversing the capacitor voltage. As a result, the sequential process of the DCCB can be repeated until the fixed number of times.

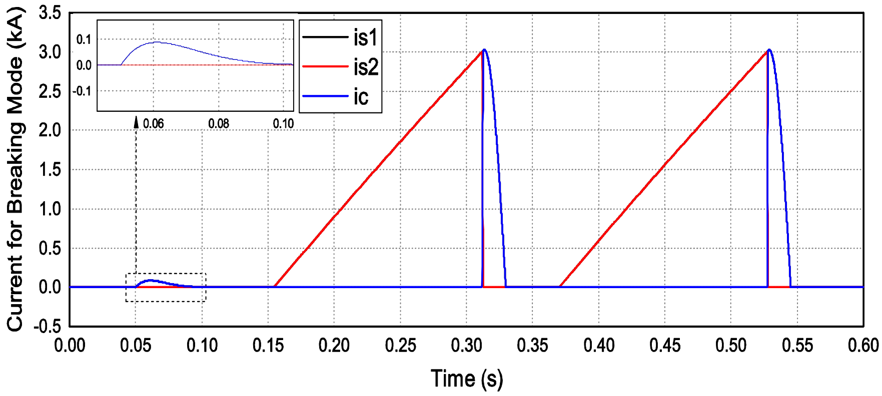


Figure 5. Simulation Waveform of Current Flow in the Breaking Mode

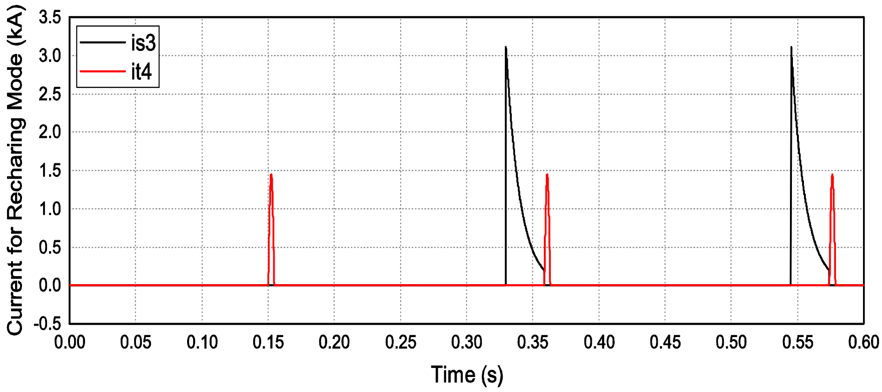


Figure 6. Simulation Waveform of Current Flow in the Recharging Mode

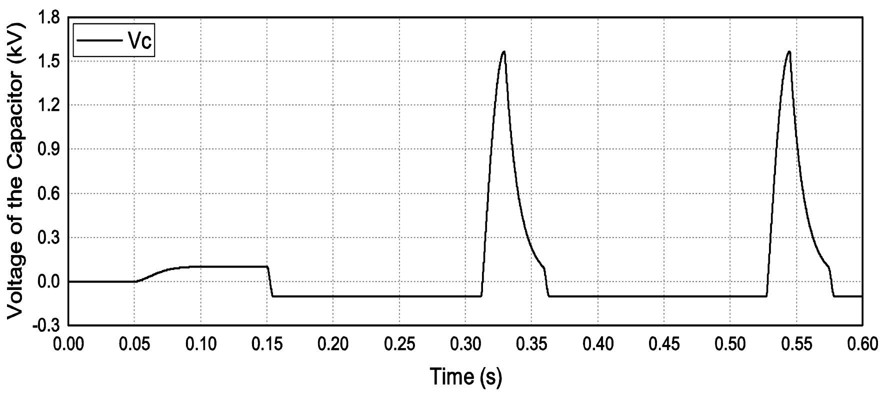
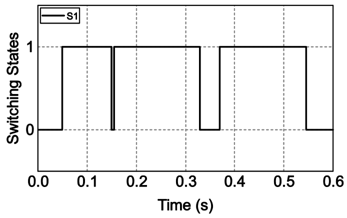
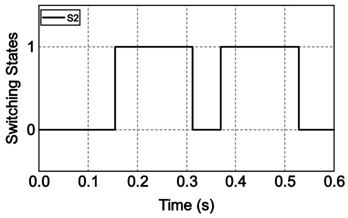


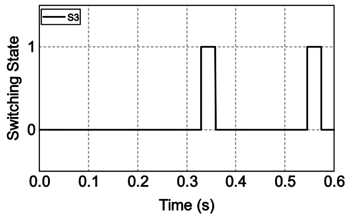
Figure 7. Simulation Waveforms of the Capacitor Voltage V_c



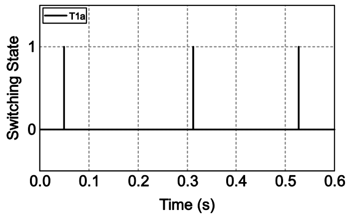
(a) S_1 signal



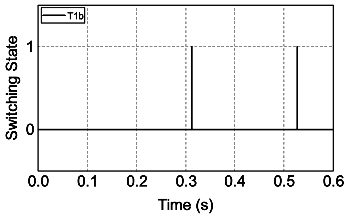
(b) S_2 signal



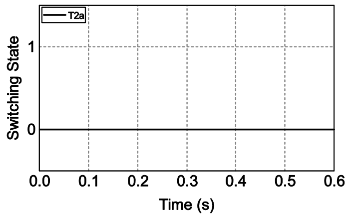
(c) S_3 signal



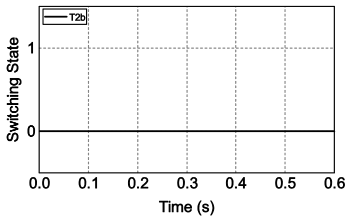
(d) T_{1a} signal



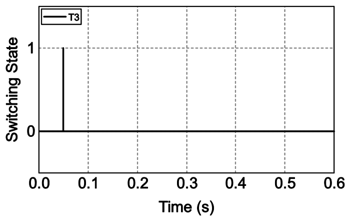
(e) T_{1b} signal



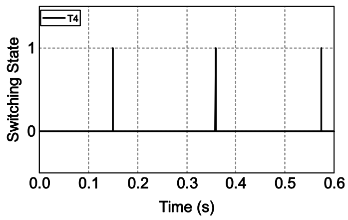
(f) T_{2a} signal



(g) T_{2b} signal



(h) T_3 signal



(i) T_4 signal

Figure 8. Simulation of Controlling and Status Signals

3.3 Test of Interrupting Negative Current in Bidirectional DCCB Topology

In order to charge the capacitor in proposed DCCB, the DC source should be connected to left side of the DCCB as shown in Figure 3. Therefore, for interrupting the negative current in the DC circuit, it is assumed that the capacitor is precharged to the required voltage and the polarity of the DC source is only changed to consider negative current in the topology. In other words, there is no charging mode at initial time. For interrupting the negative current, the DC currents in each branch and DC voltage of capacitor are represented in Figure 9 to Figure 11 and the control signals in each switch including thyristor are shown in Figure 12. The overall operation of the DCCB is similar to the results in positive current. However, the inverse current is generated by turning-on thyristors T_{2a} and T_{2b}. Furthermore, the direction of the injected current to the main branch is opposite. The full sequential process of the DCCB are represented in Figure 12.

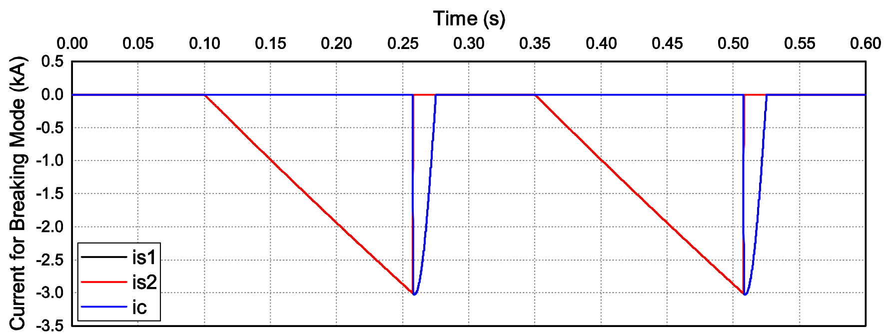


Figure 9. Simulation Waveform of Current Flow in the Breaking Mode

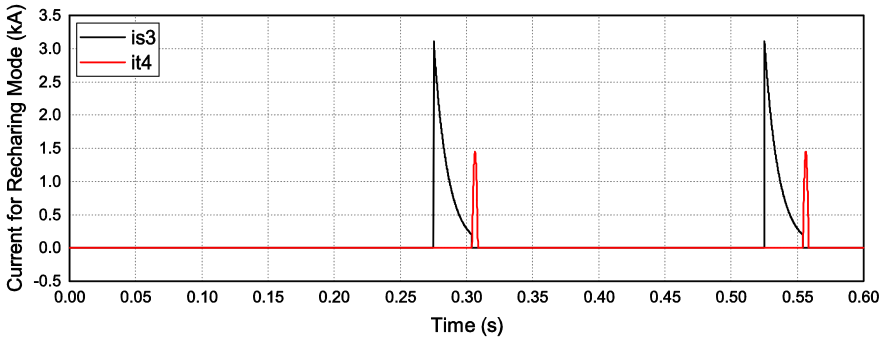


Figure 10. Simulation Waveform of Current Flow in the Recharging Mode

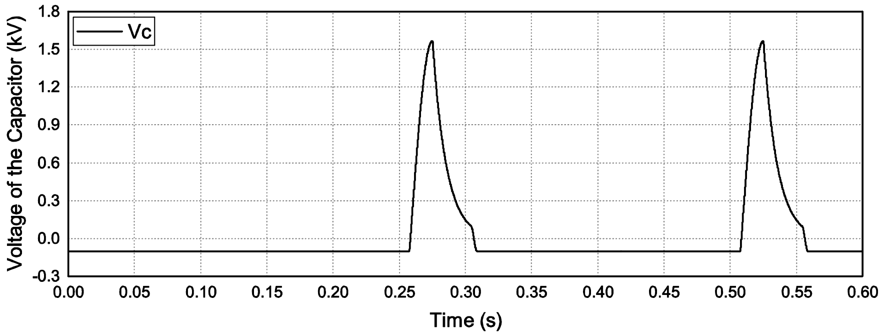
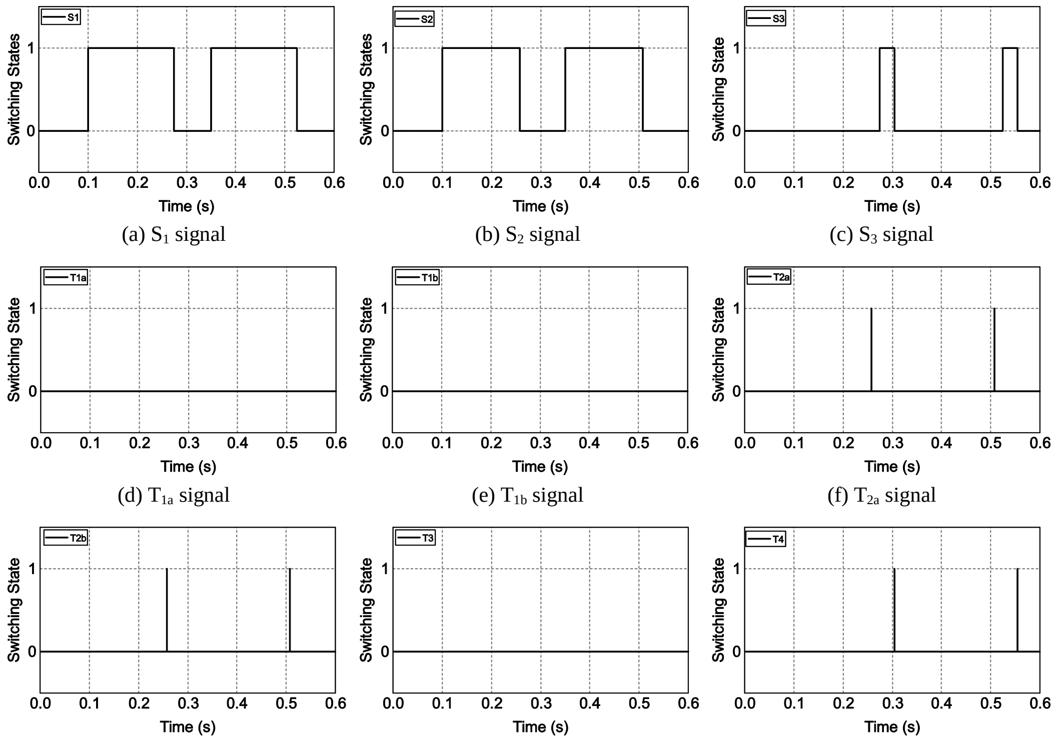


Figure 11. Simulation Waveforms of the Capacitor Voltage V_c



(a) S_1 signal
(b) S_2 signal
(c) S_3 signal
(d) T_{1a} signal
(e) T_{1b} signal
(f) T_{2a} signal
(g) T_{2b} signal
(h) T_3 signal
(i) T_4 signal

Figure 12. Simulation of Controlling and Status Signals

4. Conclusions

This paper proposed a novel circuit breaker topology for breaking the dc fault current. The DCCB is capable of the reclosing and rebreaking because of the recharging of the capacitor. In addition, it is possible to interrupt the positive and negative dc fault current in the circuit. The simulation results showed that the performances of this proposed topology is suitable for the bidirectional operation.

Acknowledgments

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