Research on Current Transfer Characteristics of Hybrid Circuit Breaker in Low Voltage DC Micro-grid

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Abstract. The analysis of current transfer characteristics of hybrid DC circuit breakers is of great significance for improving their breaking capacity and implementing control strategies. This paper analyzes the principle of hybrid DC circuit breakers. The hybrid circuit breaker simulation model is built based on the Mayr arc model in Matlab/Simulink using IGBT, RCD snubber circuit and arrester model. The current simulation waveforms under different external circuit parameters and transfer branch parameters with a voltage of 400V and breaking fault current less than 200A are mainly studied. Through the analysis of the current transfer characteristics, a series of theoretically supported breaking characteristics are obtained, which provide a reasonable and effective reference for the fast and reliable breaking of DC micro-grid hybrid circuit breaker.

1. Introduction
In recent years, DC micro-grid has received extensive attention with its unique advantages, which is the development trend of distributed power sources in the future\[1\]. DC circuit breaker is an important protection device for DC micro-grid, which plays a vital role in the safe and reliable operation of micro-grid. However, unlike the AC system, there is no natural zero-crossing in the DC transmission. In fault condition, a special method must be used to create the zero-crossing point. On the other hand, the DC short-circuit current rises fast and the peak value is high, the circuit breaker must complete the breaking task within a few milliseconds to meet the protection needs of the DC power system\[2\]. The hybrid DC circuit breaker combines the excellent dynamic performance of the power electronic device on the basis of maintaining the good static characteristics of the mechanical switch, and can simultaneously meet the requirements of short breaking time, fast action and low on-state loss\[3\].

Nowadays, many university research institutes and electrical equipment manufacturing companies are studying DC circuit breakers that can break current without arc\[4-13\]. However, the research of domestic and foreign scholars still focuses on the performance improvement of power electronic units and the circuit design of mechanical switches and semiconductor devices. There are few studies on the details of the hybrid switch current transfer in fault condition. The article first proposes a hybrid circuit breaker model, and then analyzes the process of transferring the current from the mechanical switch branch to the solid-state switching phase and the solid-state switch to the energy absorption branch when breaking the fault current. Based on the Mayr arc model in Matlab, a suitable hybrid
circuit breaker model is built to simulate and analyze the factors that may affect the current transfer. Finally, the current transfer characteristics of the hybrid switch under different factors are obtained, which provides a theoretical basis for fast breaking of the hybrid circuit breaker.

2. Hybrid DC circuit breaker topology and working principle

The DC circuit breaker topology is shown in Figure 1, which consists of mechanical switch S<sub>1</sub>, semiconductor branch IGBT, arrester MOV and RCD snubber circuit. As shown in Figure 1, \( R_L \) and \( L \) in the figure are the system equivalent resistance and the external circuit inductance.

![Figure 1. DC hybrid circuit breaker topology](image1)

During normal condition, the mechanical switch S<sub>1</sub> carries load current. At this time, the power electronic unit is in the trigger conduction state, but the on-resistance of the mechanical switch is generally slightly lower than the on-resistance of the power electronic switching element (milliohm level). Therefore, there is almost no current flowing through the power electronic branch. When the circuit is overloaded or short-circuited, actual current of the line can reach 10 times of rated current. At this time, the hybrid DC circuit breaker measures the line current through a current detecting unit (such as a shunt or a Hall transformer), and calculates a line current magnitude and a rising rate thereof through a control unit (including a microprocessor or an FPGA). A trip command is issued according to a predetermined trip time limit request, and the mechanical switch S<sub>1</sub> is disconnected by the trip unit. As the switch S<sub>1</sub> is opened, an arc voltage drop occurs at both ends of the fracture. When the voltage drop meets the conduction of power electronic switch, the current will be transferred to the power electronics branch, and the mechanical switch S<sub>1</sub> will break without arc. Finally, the energy stored in the equivalent inductor of the line is absorbed by the RCD snubber circuit and the MOV overvoltage protection device (such as a varistor), which is related to the system time constant.

3. Construction of circuit breaker model

3.1. Selection of arc model

The generation, combustion and extinction of the arc in the arc extinguishing chamber of the circuit breaker is a process that is affected by many factors. Research on the establishment of appropriate mathematical models has always received much attention. Mayr arc model based on Matlab platform is used commonly. The lower layer file of the Mayr arc model is shown in Figure 2. Its structure consists of differential equation editor (DEE), step signal (Step), constant value detection (Hit Crossing) and controllable current source (Controlled-Current Source).

![Figure 2. Underlying file of Mayr arc model](image2)
In fact, the process of arc burning is extremely complicated and has different mathematical characteristics at different stages. Some existing arc models, such as the Cassie model, are mathematical modeling descriptions based on arc dynamics after zero. The Mayr model selected in this paper is the model that is closest to the arc shape before the zero point and is suitable for small current applications. In the simulation, the difference of the arc before and after the zero point is neglected, so that the current transfer characteristic curve will not have a large influences.

3.2. Semiconductor devices and arresters
The IGBT can usually turn off its own rated current 4 times, and the IGBT is equipped with an anti-parallel fast diode package, which can meet the needs of the actual circuit. The function of the overvoltage protection device MOV is mainly to absorb the overvoltage generated when the IGBT is turned off, so as to prevent high voltage breakdown when the IGBT is turned off. The model of the arrester in Matlab simulation is similar to the nonlinear resistor.

3.3. RCD buffer circuit
The role of the RCD snubber circuit is to absorb the energy stored in the stray inductance of the circuit, reduce losses during turn-off, and limit the rate of rise of current and voltage to ensure that the power electronics operate in a safe area. Therefore, the selection of the capacitor C only needs to consider the absorption of energy in the loop - the energy storage of the inductor L in the line. Inductive energy storage and capacitance energy absorption calculation formula is:

\[ E_1 = \frac{1}{2} LI^2 \]  
\[ E_2 = \frac{1}{2} C \cdot \Delta U^2 \]

In equations (3) and (4), L is the line inductance, C is the absorption capacitance, I is the system loop current, and \( \Delta U \) is the overvoltage generated by the inductance. From (3) and (4):

\[ C = \frac{L}{\Delta U^2} \]

In which, the capacitance C of the inductor energy in the fully absorbed line can be obtained. However, since the circuit is supplemented with a branch of the arrester, the energy storage in the line does not need to be completely absorbed by the capacitor C. When selecting the capacitor, only a few microhenries can be selected to avoid selecting an excessively large snubber capacitor.

4. Analysis of simulation results of hybrid DC circuit breaker
Taking the short-circuit fault of the system as an example. The inductor L is used to simulate different line inductances. The simulation simulates the occurrence of short-circuit current directly. Therefore, adjusting the magnitude of the load resistor \( R_L \) results in different short circuit fault currents. In the Mayr arc model, the time constant \( \tau \) and the dissipated power P are selected as default values: \( \tau = 0.3 \text{, } P = 30000 \text{ W} \), and the initial parameters of other components are shown in Table 1:

| parameter                  | Digital simulation |
|----------------------------|--------------------|
| DC system voltage U_s/V    | 400                |
| System resistance R_s/Ω    | 10                 |
| Inductance L/μH            | 100                |
| IGBT on-resistance /mΩ     | 10                 |
| RCD resistance /Ω          | 20                 |
| RCD capacitor C /μF        | 1                  |

Assuming that the Mayr arc model is turned on at \( t_1 = 2 \text{ms} \), the IGBT is turned on at \( t_2 = 2.1 \text{ms} \). After running the simulation, the current transfer curve in the initial state is shown in Figure 3:
It can be seen from Figure 3 that the process of zero current interruption is mainly divided into two stages, that is, the process of transferring current to the IGBT branch and the process of turning off the IGBT short-circuit current to the RCD and the arrester circuit.

4.1. Transfer of mechanical switch to power electronic device branch

From the circuit analysis, the factors affecting the current transfer are mainly divided into two categories: external factors and internal factors. External factors refer to the influence of external circuit parameters on current transfer, such as fault current magnitude, external circuit line parameters, and so on. The internal factor include the transfer branch resistance and the line inductance component.

4.1.1. External factors

1) Breaking fault currents of different sizes

When the other parameters are unchanged, the current transfer waveform of the short-circuit current of 40-200A is obtained by changing the line resistance value. As shown in Figure 4.

Figure 4. Different breaking current curves

It can be seen from the figure that for short-circuit currents of different sizes, the time for the current to completely transfer to the IGBT branch is the same, about 2.3 milliseconds. However, as the current increases, the moment that the current begins to shift will continue to advance, resulting in the time of the first phase current transfer process will increase with the increase of current.

2) Influence of inductance component of external circuit line

In the simulation model, keep the other line parameters unchanged, and the current transfer characteristics is obtained by simulating different line inductances under the condition of 40A breaking current. As shown in Figure 5. It can be seen from Figure 5 that when breaking the fault current, the current transfer is basically unchanged as the line inductance increases. Although the simulation is run under ideal conditions, it can be concluded that the size of external circuit inductance has no effect on the time taken for the current to be transferred from the switch to the IGBT branch.

4.1.2. Internal factors

1) Transfer branch resistance size

Since the on-resistances of different types of IGBTs are different, the size of the transfer branch resistor mainly depends on the internal resistance of the IGBT. Therefore, the remaining circuit parameters are kept unchanged during the simulation, and the on-resistance of the IGBT is selected to be simulated from 10 to 1000 milliohms. The result is shown in Figure 6.
Figure 6. Simulation of transfer slip resistance

It can be seen from Figure 6 that internal resistance of the IGBT has no influence on the start time of the fault current transfer, but the time for the completion of the transfer is continuously increased. The larger the internal resistance of the IGBT is, the longer the fault current is transferred from the mechanical switch to the IGBT. Therefore, when selecting a module, try to select an IGBT module with a small internal resistance to reduce the impact on the breaking speed. In addition, it should be pointed out that the conclusions obtained are based on the Mayr arc model. The Mayr arc model specifies that the fault current begins to be transferred when the power $P > P_0$. The turn-off power $P$ is not affected by the IGBT on-resistance, so there is no change in the current transfer timing of the first stage of the simulation. However, in the actual breaking, the current transfer is based on the principle of natural commutation, which is achieved by comparing the equivalent arc resistance of the arc with the internal resistance of the IGBT. In the case of a constant breaking current, when the arc resistance is bigger than the resistance of transfer branch, the current begins to shift. Therefore, the first conclusion of the simulation has no practical significance, but the second conclusion is correct.

2) Influence of the size of the inductance component of the branch circuit

In order to analyze the influence of the inductance component of the transfer branch on the current transfer characteristics. In the simulation, 20-200μH inductor is selected for simulation, and the obtained waveform is shown in Figure 7.

Analysis of Figure 7 can get two conclusions. First, as the inductance of the transfer branch increases, transfer time continues to grow. Second, the presence of the inductance component causes the breaking current to generate an overcurrent pulse point higher than the normal breaking current which may damage the power electronic device in practical applications. Therefore, it is necessary to reduce the inductance of the branch circuit to protect effective and reliable operation of the IGBT.

4.2. IGBT to RCD transfer and current drop to zero

4.2.1. External factors. 1) Breaking fault currents of different sizes

For the second phase, the main purpose is to reduce the short-circuit current to zero. The short-circuit current is simulated at a current of 20-200A, and the waveforms are obtained as shown in Figure 8:

Figure 8. Breaking current and time waveforms

It can be seen from Figure 8 that in the second stage, the time when the breaking fault current drops to zero will be shortened as the current gradually increases. To analyze this process, it is necessary to clarify that for the second stage, the commutation of the IGBT to the RCD snubber circuit is very fast, which is about nanosecond. Its main process is an LC resonant discharge circuit composed of an inductor and a snubber capacitor in the circuit. When the IGBT is completely turned off, the LC...
resonates until the voltage across capacitor C rises to a peak, at which point the current in the loop drops to zero. The diode D is turned off and the voltage $U_C$ is clamped, so the current drop is considered to be zero as long as the voltage $U_C$ reaches the maximum value. Figure 9 shows the waveform of the shutdown voltage at different breaking currents. It can be seen from the figure that the larger the breaking current, the shorter the time at which the voltage $U_C$ reaches the maximum value, and the shorter the time when the current drops to zero.

2) External circuit inductance component

The simulation process is the same as the first phase to investigate the effect of the external circuit inductance component on the transfer current. The effect of the inductance component on the transition time is shown in Figure 10. It can be seen from the figure that the change of the line inductance has no obvious effect on the current drop to zero, and the time when the current drops to zero is basically constant.

![Figure 10. Second stage current simulation waveform under different inductances](image)

4.2.2. Internal factors.

1) Transfer branch parameters

The second stage of the transfer branch mainly refers to the transfer of current from the IGBT branch to the RCD snubber circuit. The diode in the RCD snubber circuit is unidirectional, which provides a unidirectional path for current. The role of resistor R is to provide a path for capacitor discharge after breaking the fault current. These two parameters have basically no effect on the current transfer. Therefore, it mainly affects the current transfer of the second stage by changing its internal parameter capacitance C. The simulation of the snubber capacitor of 1-20μF is performed without changing other parameters, and the curve of the current transfer characteristic is obtained as shown in Figure 11.

![Figure 11. RCD current transfer and turn-off voltage waveform under different capacitance](image)

It can be seen from Figure 11(b) that the increase of the snubber capacitor reduces the rate of increase of the turn-off voltage. Its overvoltage is gradually disappearing. This is very beneficial for IGBT protection and reliable operation. However, as can be seen from Figure 11(a), the increase of capacitance in RCD will cause the shutdown current to drop to zero for a longer period of time, which can adversely affect the system. Therefore, in order to meet the requirements of IGBT breaking, the snubber capacitor with the smallest possible capacity should be selected to minimize the time. Therefore, in the actual circuit, under the requirement of IGBT breaking, the snubber capacitor with the smallest possible capacity should be selected to reduce the time when the RCD current drop is zero.

5. Conclusion
Through simulation and theoretical analysis, a series of conclusions on current transfer characteristics are obtained, which provides a theoretical basis for rapid breaking of hybrid circuit breakers.

1) The increase of the fault current will affect the transfer time of the first stage, and the longer the current, the longer the transfer time. The transfer of the second phase current and the time to zero will be shortened as the fault current increases.

2) The change of the inductance of external circuit has no influence on the transfer characteristics of the first stage. There is no obvious influence on the transfer speed of the second stage.

3) The internal resistance of the IGBT and the inductance of the transfer branch will increase the transfer time of the first stage, and the presence of the line inductance causes the breaking current to generate an overcurrent pulse point which may damage the power electronic device in practical applications. Therefore, in practical applications, an IGBT module with a small on-resistance should be selected, and the parasitic inductance of the transfer branch should be minimized.

4) The increase of the RCD snubber circuit C will make the current drop to zero for a long time, but it can reduce the overvoltage of IGBT. Therefore, in practical applications, due to the presence of the arrester branch, the capacitor C in the RCD snubber circuit should be selected as small as possible while satisfying the reliable and safe operation of the IGBT.

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