DC Microgrid Protection System Based on Positive Channel Metal Oxide Semiconductor

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Abstract: DC microgrid has received extensive attention and research because of its natural advantages of improving the consumption efficiency of distributed power sources, and in line with the development trend of clean environment and intelligent operation of power grids in the future. However, short-circuit fault protection of DC microgrid is a major challenge for the development of microgrid. Therefore, the author proposes a DC solid-state circuit breaker with a positive channel metal oxide semiconductor as the main switch, and through simulation, it is verified that this solid-state circuit breaker is feasible. The experimental results show that when the proposed solid-state circuit breaker is normally turned on, the positive channel metal oxide semiconductor is completely turned on, which has no effect on the power flow in the DC microgrid; when a short-circuit fault occurs in the DC microgrid system, the short-circuit current is used to couple the energy, the positive channel metal oxide semiconductor is reliably turned off. The stability and reliability of the system are improved, and it can be applied to the short-circuit protection of the DC microgrid, and has a good application prospect.

1. Introduction

DC circuit breakers are generally classified into three types: mechanical, solid-state, and hybrid [1]. Mechanical DC circuit breakers in the breaking due to its inherent action time and the existence of arc, will lead to the entire segmentation process takes a long time, reaching tens of milliseconds or even longer, too long breaking time will make power electronics out of work, reducing the stability and reliability of the grid; solid-state DC circuit breakers use semiconductor power devices as the main switching elements, with no arc, breaking fast and other advantages, however, its cost is high, the through-state loss is large [2], and it often needs to be used in conjunction with control strategies, short-circuit current detection and other modules, which enhances the complexity of the system; the hybrid DC circuit breaker consists of a combination of mechanical switching branches, solid-state switches, buffer absorption circuits and current limiting circuits, which can achieve both controlled opening and low through-state loss, but its structure is complex, electromechanical synergy is difficult, and the breaking speed is limited by mechanical switches [3]. Since the bus voltage of DC microgrid is generally below 1500 V, mostly around 750 V. Power semiconductor devices such as IGBTs and MOS tubes are more mature and reliable in this voltage range, so solid-state circuit breakers have become an important research direction for DC microgrid with their advantages of speed and flexibility [4]. The literature [5] proposed a solid-state DC circuit breaker structure based on power electronics, which contains a set of anti-parallel fully-controlled power electronics, which are connected in parallel with energy absorbing...
branches to improve the open-end speed, but suffers from large through-state losses and complex structure. The literature [6] proposed a solid-state DC circuit breaker structure based on power electronics composed of thyristor and IGBT in parallel, which reduces the large through-state losses, but the size of the breaker is too large. The literature [7] proposed a technical solution for a DC solid-state current-limiting circuit breaker based on IGCT and SCR to improve the interrupting capacity of the breaker by improving the reliability of the main switching tube IGCT working in parallel. The literature [8] proposed a high-voltage DC circuit breaker topology with current-limiting function, which uses IGBT as the main switching device with both breaking and current-limiting functions and has the advantages of low on-state losses, high turn-off current, and high voltage level, but with a high number of switching tubes and complex control logic. The design advantages of the above circuit breaker technology is that: compared with mechanical circuit breakers, no arc break operation and the breaking time used is significantly shorter, but there are shortcomings: the operation of such circuit breakers must be based on very precise and strict timing to carry out the need for detection, control with consistent, and circuit breakers in addition to the power circuit requires additional control and drive circuit, this part of the circuit work requires an external power supply. Increases the complexity of the system, especially in the event of a failure of the grid itself, the power supply may also be unstable, reducing the reliability of the circuit breaker.

To address the above deficiencies, this paper proposes a Positive channel Metal Oxide Semiconductor (PMOS)-based self-taking DC solid-state circuit breaker that works in series in the power grid. When no short-circuit fault occurs, this solid-state circuit breaker conducts normally and has no effect on the original line flow; when a short-circuit fault occurs, the short-circuit current coupling energy is used to make the PMOS shut down reliably without additional power supply. The PMOS-based self-powered DC solid-state circuit breaker uses devices that can be adjusted according to voltage levels, effectively reducing manufacturing costs, and the simple structure eliminates the need for additional auxiliary circuits or complex control strategies, effectively speeding up the response time and improving the reliability of grid operation.

2. Topology and working principle

2.1. System composition and topology analysis

Figure 1 shows the system structure diagram of the solid-state circuit breaker designed in this paper in the DC microgrid. According to the functional modules, it can be divided into the main switch module, the drive module, and the power acquisition module. The S1 branch is used to simulate the short circuit of the line in the experiment. state, there is actually no S1 branch. Block A in Figure 1 is the main switch module, which mainly includes the main switch tube PMOS Q1 that controls on and off; Block B is the driving module, which mainly includes a Zener diode D1 and a resistor R1, and the driving module is mainly used to connect the PMOS gate. The effect of the pole voltage pull-down makes the gate and source of the PMOS form a sufficient voltage difference, so that the main switch tube is completely turned on under the normal operation of the line; Block C is the power taking module, which mainly includes transformer T1, resistor R2, diode D4 and electrolytic capacitor C1. When a short-circuit fault occurs in the line, an instantaneous large current will be generated at the output end. This current is short-circuit current. Transformer T1 uses short-circuit current. The coupling energy is generated, and the energy is stored by the capacitor C1. After the charging is completed, the capacitor C1 discharges and transmits the disconnection signal to the main switch module to cut off the circuit and limit the short-circuit current.
2.2. Operating mode and switching process

The working process of the PMOS-based self-taking DC solid-state circuit breaker topology in the paper is divided into the turn-on process and the turn-off process. Each of the main operating states is analyzed separately in the following section.

1) Opening process

Figure 2(a) shows the equivalent circuit diagram of the DC solid-state circuit breaker circuit topology when the blocking function is not activated.

![Equivalent circuit diagram for normal conduction](image)

Based on the P-type MOSFET without additional power supply short-circuit current blocking circuit connected in series in the DC power line, do not start the blocking function, the role of the voltage regulator diode D1 in the driver module is when the circuit works normally, so that the drive signal along D1-R1 to the P-type MOSFET gate power supply, so that the P-type MOSFET gate voltage and the source voltage to form a voltage difference, the P-type MOSFET conduction, at this time the current flows along the path of P1-Q1-P2, transformer T1 can be equated to an inductor L1, fully conduction state, ignoring the voltage drop of the main switching tube Q1 and transformer T1, to obtain a simplified circuit diagram as shown in Figure.2(b), in which E is the supply voltage; L1 is the transformer series connected in the circuit equivalent inductor; Rload is the load resistance; the initial value of the load current is 0.

According to the KVL and KCL laws, the system of equations can be obtained as:

\[
\begin{align*}
ir_1 + L_1 \frac{di}{dt} &= E \\
i_0 &= i_0.
\end{align*}
\]

The solution is:

\[i_{\text{Load}} = \frac{E}{R_1} \left(1 - e^{\frac{t}{L/R_1}}\right)\]

It can be seen that when the circuit breaker designed in this paper is on normally, the current will rise exponentially to the normal operating current. The gate voltage of the main switching tube forms a sufficient voltage difference with the source voltage due to the role of the drive module, and the main switching tube is fully on with almost zero voltage drop, which has no effect on the normal operation of the line.

2) Fault shutdown process

Figure 3 shows the equivalent circuit diagram of the DC solid state circuit breaker circuit topology after activating the fault blocking function.
A short-circuit current blocking circuit based on PMOS without additional power supply as described herein, when a short circuit occurs in the line, switch S1 closes to simulate a short-circuit situation, at which time the current surge at the primary coil end of transformer T1 in the power extraction module, the secondary coil will generate coupling energy, and then the energy extraction module uses the coupling energy to charge capacitor C1, after charging is complete capacitor C1 discharges, and the drive signal along T1-D4-C1-Q1 to the main switching tube gate power supply, so that the P-type MOSFET gate voltage rises until it reaches the PMOS shutdown conditions, the PMOS automatically shut down, the excess voltage through the diode D2 back to the grid, to achieve the short-circuit current blocking effect without additional power supply.

3. Simulation Analysis

Based on the above analysis of the structure and modules of the proposed solid-state circuit breaker, a circuit simulation model is constructed in Multisim platform, The model includes the main switch module, the driver module, the power extraction module and the energy extraction module. The specific parameters of the simulation are set as follows: input DC voltage $U_{in}=480V$ (DC microgrid low voltage level), resistor $R1=10K\Omega$, $R2=1\Omega$, transformer primary inductance $L1=20\mu H$, transformer secondary inductance $L2=100\mu H$, leakage inductance $W_{leakage}=100hm$, and resistor $R3=100\Omega$. Two states are simulated: steady-state and short-circuit state.

Figure 4 shows the voltage and current waveforms under steady-state conditions in normal operation. From the waveform diagram in the figure, it can be obtained that when the PMOS gate voltage is 280V and the source voltage is 480V, the PMOS is fully on and the tube voltage drop is negligible, so the input voltage is nearly equal to the output voltage. At this time, the load current $i_s=48A$. It is proved that the PMOS-based self-powered DC solid-state circuit breaker in this paper has no effect on the original line during normal operation.

Simulate the influence of the capacitor value on the turn-off speed of the PMOS tube in the short-circuit state, and analyze the waveform of the charging current and the PMOS gate voltage under different values of the capacitor C1, as shown in Figure 5 (in the waveform diagram, the upper line is the PMOS gate pole voltage, the lower dotted line is the charging current $I_c$ of capacitor C1).
Figure 5 shows the charging current and PMOS gate voltage for different capacitor values.

(a) capacitor values 1μF

(b) capacitor values 2μF

(c) capacitor values 3μF

The results of the simulation analysis show that the PMOS-based self-taking DC solid-state circuit breaker has no effect on the original line voltage and current during normal conduction; in the event of a short-circuit fault, the coupling energy of the short-circuit current can be used to quickly cut off the circuit and block the short-circuit current, and the blocking process can be completed within 5μs.

4. Conclusion

This paper proposes a solid-state circuit breaker that can be applied to DC microgrid protection without additional power supply, analyzes its working principle and the opening and disconnecting working modes, and conducts corresponding simulation experiments. The experimental results are consistent with the theoretical analysis. The DC solid-state circuit breaker proposed in this paper has the following advantages:

1. Using the working characteristics of PMOS, the rapid turn-off of the circuit breaker is realized, and the solid-state circuit breaker has a simple structure and reliable performance.

2. In the event of a short-circuit fault in the DC microgrid, PMOS is used to cut off the positive electrode to ensure the safety of operation. (NMOS needs to be cut off from the negative pole, there is a risk of electric shock.)

In summary, the DC solid-state circuit breaker proposed in this paper has the advantages of current limiting protection function, low manufacturing cost and low on-state loss, and can be applied to DC microgrid or battery energy storage system and other occasions, and has a good application prospect.

Acknowledgments

National Natural Science Foundation Project (51607060).
References

[1] Dragievi T, Lu X, Vasquez J C, et al. (2015) DC microgrid Part I: A review of control strategies and stabilization techniques[J]. IEEE Trans. power electronics, 31(7): 4876-4891.

[2] M Meyer C, Kowal M, Doncker R. (2005) Circuit breaker concepts for future high-power DC-applications[C]. In: Industry Applications Conference. IEEE. 2: 860-866.

[3] Shimizu H, Yokomizu Y, Goto M, et al. (2003) A study on required volume of superconducting element for flux flow resistance type fault current limiter[J]. IEEE Transactions on Applied Superconductivity, 13(2): 2052-2055.

[4] Strumpler R, Skindhoj J, Glatz-Reichenbach J, et al. (1999) Novel medium voltage fault current limiter based on polymer PTC resistors[J]. IEEE Trans. Power Deliv, 14(2): 425-430.

[5] Savaliya S G, Fernandes B G. (2020) Analysis and Experimental Validation of Bidirectional Z-Source DC Circuit Breakers[J]. IEEE Trans. Industrial Electronics, 67(6): 4613-4622.

[6] Satpathi K, Ukil A, Nag S S, et al. (2019) DC Marine Power System: Transient Behavior and Fault Management Aspects[J]. IEEE Trans. Industrial Informatics, 15(4): 1911-1925.

[7] Dupraz J P, Montillet G F. (2008) New network concepts using electronic hybrid circuit breakers[C]. In: Transmission and Distribution Conference and Exposition. T&D. IEEE/PES. IEEE.

[8] Meyer C, Doncker R D. (2006) Solid-State Circuit Breaker Based on Active Thyristor Topologies[J]. IEEE TRANSACTIONS ON POWER ELECTRONICS PE.