Over-Current Protection Scheme for SiC Power MOSFET DC Circuit Breaker

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Abstract—The electronic circuit breaker used in DC microgrids are required to work within their safe operating areas bounded by temperature, voltage and current limits. Traditional approach managed to protect these switches through rapid current cut-off operations at over-load or fault situations, but failing to avoid the disturbance induced by transient current surges or noises which are not harmful to the grid operations. Aiming to increase the quality of circuit breaker operations and furthermore improve its reliability, this paper proposed a SiC MOSFET based DC circuit breaker based on the variable time-delay protection scheme. The cut-off operations only take place after proper delay time, which are precisely catered according to the transient thermal properties of SiC devices and the properties of DC loads. The proposed scheme has been implemented with hardware prototype and experimentally verified under different fault situations.

I. INTRODUCTION

DC microgrids are used in modern buildings, vessels and vehicles as efficient delivery interconnects between DC energy sources and loads. Similar to AC grids, circuit breakers in DC microgrids carry the function on grid protection. Therefore, these breakers not only do endure grid normal operations but also be capable of cutting off currents under various fault levels. Solid-state DC circuit breakers made of the modern wide bandgap power semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN) MOSFETs can largely enhance the switching performance much better than the mechanical counterparts [1,2]. These wide bandgap power devices have higher voltage sustainability, higher temperature tolerance and faster switching speed with simple driving requirements [3]. For the voltage level of 400V for the DC microgrids, the use of SiC power devices is a prominent choice for the circuit breaker due to their remarkable performance merits [4,5].

Besides protecting loads, electronic circuit breakers also need to protect themselves from large fault current. The possible risks faced are in two conditions. In moderate fault situation, the breaker may suffer from thermal stress caused by joint overheating [6] if the fault current is not cleared in time. In serious conditions like short-circuit faults, the electromagnetic force induced by large fault current cracks the bond wires of electronic switches and causes physical damage to the semiconductor dies[7].

Several schemes had been proposed to protect SiC devices from thermal and mechanical damage [8-10]. In [8], it came out with a method to collect temperature information by thermal coupler in order to prevent the SiC devices from overheating damage. However, the use of thermal coupler is not welcomed since it increases the cost and complexity of the control circuit. Some achieved rapid fault isolation function for SiC devices based on technique of micro-controllers [9]. The fault current can be interrupted within a few micro-seconds. Such a rapid interruption scheme may result in premature current interrupt on transient surge or noise. In practice, in moderate fault situations with relatively low fault current level, SiC devices will not be burned out immediately until a few milliseconds later. This indicates that smaller fault current can be cut off after an allowable delay time, in order to avoid the false alarm on current surge or noise.

In this paper, a solid-state circuit breaker based on SiC power MOSFET with variable time-delayed protection scheme for DC microgrids is developed. The turn-off delay time varies according to the transient thermal property of the SiC power MOSFET device, as well as the load protection delay time according to user’s preset requirements. The introduction of variable delay time ensures the circuit breaker function with high reliability under various overcurrent transient situations.

II. VARIABLE TURN-OFF DELAY TIMES FOR PROTECTION

A. Three Different Fault Conditions

Large current caused by overloading or faults in DC microgrids will need to be interrupted and isolated in order to preserve the grid integrity. If fault current $I_f$ exceeds the load current limitation $I_{LD}$, load may suffer and break down. If $I_f$
exceeds the continuous current rating \( I_{OC} \) of semiconductor switch, the switch will suffer thermal stress and damage. If \( I_D \) exceeds the pulsed current rating \( I_{SC} \), electromagnetic damage might happen to the semiconductor switch [7].

Three different fault levels showed in Fig. 1 are protected in DC microgrid. The corresponding protection operations in these three fault situations have different assigned turn-off delay time as shown in Fig. 2.

1. **Overload fault** \(( I_{LD} \leq I_D < I_{OC} )\): As shown in Fig. 1(a), fault current \( I_D \) should be interrupted with the allowable turn-off delay time to ensure the safety of DC load. Both load current limitation \( I_{LD} \) and turn-off delay time are adjustable according to the load protection requirement. Usually, delay time varies from a few milliseconds to a few seconds for different DC load types [11].

2. **Large overcurrent fault** \(( I_{OC} \leq I_D < I_{SC} )\): Switch is short circuited through the impedance \( Z_f \) [12] as in Fig. 1(b). Protection operation is required within the Safe Operation Area (SOA) thermal limit to avoid overheating. As shown in Fig. 2, the allowable delay time varies exponentially with the overcurrent magnitude \( I_D \) according to the transient thermal property of the semiconductor switch in the ranges of milliseconds.

3. **Short-circuit fault** \(( I_D \geq I_{SC} )\): This is the most serious situation with almost zero fault impedance shown in Fig. 1(c). Fault current \( I_D \) should be cut off as soon as possible to avoid electromagnetic force damage to the power semiconductor devices. The maximum turn-off delay time is usually in microseconds for rapid operation.

\[
\text{Fault current (A)} \quad \text{overload fault} \quad \text{large overcurrent fault} \quad \text{short-circuit fault}
\]

**B. Transient Thermal Response of SiC Switch**

At large fault current, SiC device is heated with temperature gradually rising on thermal capacitance [10]. The transient thermal response of SiC MOSFET can be derived based on the equivalent thermal circuit shown in Fig. 3(a), in which thermal capacitance and resistance are modelled by electric capacitor and resistor. The resistance \( R_J \) and capacitance \( C_J \) between junction and case, and resistance \( R_{CA} \) and capacitance \( C_{CA} \) between case and ambient are used in the circuit model. Temperatures of junction, case and ambient are equivalent by node voltages assigned as \( T_J \), \( T_C \) and \( T_A \) respectively. Power dissipation by semiconductor junction is equivalent to a current source signed as \( P_D \). Transient thermal response can be treated as the process that temperature \( T_J \) varying with power \( P_D \). Normally, the time constant \( \tau_{CA}=R_{CA}C_{CA} \) is a few seconds if a heatsink is used, which is much larger than the time scale of transient thermal response considered in this paper. Thus it is reasonable to ignore the effects of \( R_{CA} \) and \( C_{CA} \), and analyze the simplified model in Fig. 3(b) with constant case temperature \( T_C \).

\[
T_J(t) = P_D Z_{JC}(t) + T_C \quad (1)
\]

where \( Z_{JC} \) is the transient thermal impedance related to \( R_J \) and \( C_J \), \( T_C \) is a constant value depending on the initial operating condition as

\[
T_C = P_{DO} R_{CA} + T_A \quad (2)
\]

where \( P_{DO} \) is the initial dissipation power; \( R_{CA} \) is the case-to-ambient thermal resistor; \( T_A \) is the ambient temperature.

In (1), the value of power dissipation \( P_D \) depends on the on-state resistance \( R_{DS} \) and drain current \( I_D \) as

\[
P_D = I_D^2 R_{DS} \quad (3)
\]

where \( R_{DS} \) changes with \( I_D \) according to

\[
R_{DS} = R_{DS0} + 0.001(I_D - 20) \quad (4)
\]

\( R_{DS0} \) in (4) is temperature-dependent and is at \( I_D=20A \). Its value is described in the datasheet of SiC MOSFET [13] as following.
where coefficients $a_1$, $a_2$ and $a_3$ are 0.00006, 0.0044 and 1.04.

$Z_{jc}$ in (1) can also be obtained from datasheet as

$$Z_{jc} = \begin{cases} 10^{-b_1c^2-b_2e^2-b_3c-b_4} & \text{for } 0.40 \leq t < 0.14s \\ 0.53 & \text{for } t \geq 0.14s \end{cases}$$ (6)

where coefficients $b_1$, $b_2$, $b_3$ and $b_4$ are 0.01, 0.20, 0.38 and 0.40; $c$ is the common logarithm of duration $t$ with fault current.

Based on (1)-(6), the allowable time for SiC MOSFET to exceed its maximum junction temperature can be derived using numerical iteration method and obtained as depicted in Fig. 2. This delay-time value is treated as the maximum turn-off delay time on overcurrent fault, within then the fault current has to be interrupted [14]. Here the maximum junction temperature is set to be 200ºC to maintain thermal reliability [15], and pulsed current rating $I_{SC}$ is set at 78A according to the datasheet [13].

III. PROPOSED CIRCUIT FOR TIME-DELAYED PROTECTION

Since the allowable turn-off delay time of three fault types are in different time scale, the proposed circuit is designed for load protection and device protection respectively.

A. Load Protection Circuit

Fig. 4 shows the protection circuit for DC load. The input signal $V_{HI}$ comes from the hall-effect sensor which senses current $I_D$ of MOSFET with proportional voltage signal output according to

$$V_{HI} = V_{h0} + k_S I_D$$ (5)

where $V_{h0}$ is the quiescent output voltage of hall-effect sensor when $I_D$ equals to zero; $k_S$ is the sensitivity of the sensor. In this paper, hall-effect sensor with $V_{h0}=0.6V$, $k_S=0.04V/A$ is used.

Under overload situation with $I_D$ exceeding load rating $I_{LD}$, $V_{HI}$ increases accordingly and makes the output signal $V_1$ of comparator jump to a high level. In this situation, the delay time circuit formed by oscillator and counter starts to operate, and produces a positive pulse $V_5$ which induces a positive edge $V_{LD}$.

As mentioned before, the current threshold $I_{LD}$ and turn-off delay time $t_d$ for overload depend on the requirement of the DC load and thus should be adjustable by users. This can be achieved by changing the value of resistance $R_4$ and $R_{11}$. $I_{LD}$ varies its value with $R_4$ according to

$$I_{LD} = \left(\frac{V_{th1}}{1+(R_3+R_4)/R_2} - V_{h0}\right) \frac{1}{k_S}$$ (6)

where $V_{h0}$ and $k_S$ are current sensor’s coefficients shown in (5); $V_{th1}$ is the threshold of comparator set by $A_2$ in Fig. 4.

Turn-off delay time $t_d$ then varies with resistance $R_{11}$ according to

$$t_d = 20(R_{10} + R_{11})C_1$$ (7)

B. Protection Circuit for SiC MOSFET Switches

Fig. 5 shows the protection circuit for SiC switching device. When overcurrent fault happens, fault current $I_D$ exceeds the current threshold $I_{OC}$. $V_{HI}$ surges and makes the output voltage $V_7$ increase. $V_7$ gradually charges capacitor $C_2$ in the time delay circuit. Once voltage $V_8$ of $C_2$ exceeds the threshold value $V_{th2}$ of comparator $A_{10}$ after delay time $t_o$, a positive edge $V_{OC}$ is produced.

The threshold $I_{OC}$ of switch protection is set based on

$$I_{OC} = \left[\frac{V_{th2}R_{18}}{(R_{18}+R_{19})} - V_{h0}\right]/k_S$$ (8)

and the delay time $t_d$ corresponding to fault current level $I_D$ can be represented as

$$t_d = -\tau \ln \left[1 - \frac{V_{th2}-(1+R_{19}/R_{18})R_{21}V_{h0}/(R_{20}+R_{21})}{(1+R_{19}/R_{18})R_{21}V_{h0}+k_S I_D/(R_{20}+R_{21})}\right]$$ (9)

where $\tau$ is the time constant for RC circuit. In overcurrent fault with relatively small $I_D$, $V_7$ is small so that zener diode $Z_1$ does not break down. Thus $\tau$ is larger and can be
estimated as \( \tau = R_{OC}C_1 \), where \( R_{OC} \) is the parallel resistance of \( R_{20} \) and \( R_{21} \). In short-circuit situation with larger \( I_D \), \( \tau \) decreases to \( R_{SC}C_1 \) due to the breakdown of \( Z_1 \). Here \( R_{SC} \) is the parallel resistance of \( R_{OC} \) and the dynamic resistance of \( Z_1 \). The decease of \( \tau \) meets the rapid turn-off action required in short-circuit fault.

C. Control of Gate Driving Circuit

Fig. 6 shows the continuously-on gate driver of the SiC MOSFET high-side switch [16]. As can be seen, the driver is controlled by three signals: \( V_{LD} \) from load protection circuit, \( V_{OC} \) from switch protection circuit, and manual command \( V_{SD} \). At the initial stage, a positive pulse \( V_{SD} \) is required to turn on the SiC MOSFET. Once fault happens, positive pulse \( V_{OC} \) or \( V_{LD} \) is produced after allowable delay time and SiC switch is turned off.

\[ V_{DD}: 15V, V_{DD2}: 5V. \]

A. Load Protection Test

In the load protection test, resistance \( R_4 \) and \( R_1 \) are set to be 2.7k\( \Omega \) and 140k\( \Omega \) respectively. According to (6) and (7), the current threshold \( I_{LD} \) for load protection is 3.4A, while turn-off delay time is about 2.8s. Since the supply DC voltage \( V_D \) in Fig. 6 is 400V, the resistance of DC load is set to be 54\( \Omega \) in order to create the overload fault. Measured waveforms on load protection are shown in Fig. 7. As seen, the SiC MOSFET is turned on at 0.72s when gate voltage \( V_{GS} \) raises to 15V under the function of positive pulse \( V_{SD} \) in Fig. 6. Current \( I_D \) surges to 9.6A and sets at 5.4A exceeding the threshold current level \( I_{LD} \). The turn-off command \( V_{LD} \) is produced after 2.78s and fault current \( I_D \) is cut off at 3.5s.

Figure 5. Protection circuit for SiC MOSFET switch

Figure 6. High-side drive and current sensor for SiC MOSFET switch

IV. EXPERIMENTAL VERIFICATION

To verify the function of time-delayed protection circuit developed in Fig. 4 to Fig. 6, the experimental measurements were taken. The component values in the designed circuits are listed as follows:

- \( R_1, R_2, R_3, R_{10}, R_{17}, R_{13}=1k\Omega, R_6=3.3k\Omega, R_{14}=47k\Omega, \)
- \( R_3, R_9, R_{12}, R_{16}, R_{23}, R_{26}=2.2k\Omega, R_7, R_{13}=4.7k\Omega, \)
- \( R_6, R_{25}=33k\Omega, R_{10}=2.7k\Omega, R_{14}, R_{22}=1.5k\Omega, R_{25}=10k\Omega \)
- \( R_{20}, R_{21}=15k\Omega, R_{28}=1M\Omega, R_{29}=560\Omega, R_{30}=120\Omega; \)
- \( R_4=0.5k\Omega, R_{11}=0.1M\Omega; \)
- \( C_1, C_3, C_5=1\mu F, C_2=0.33\mu F, C_6=10nF, \)
- \( C_3, C_6, C_8=0.1\mu F, C_9=0.033\mu F; \)
- \( D_1, D_2, D_3=1N4002; \)
- \( Z_1: BZX85C11, Z_2: BZX85C15; \)
- \( A_1, A_2, A_7, A_9, A_{10}: LM392, A_3, A_{14}: IC7555; \)
- \( A_4, A_6: CD4049, A_1: CD4029, A_{8}, A_{12}: CD4013, \)
- \( A_{11}: CD4075, A_{13}: IR2117, A_{15}: CMF2012D; \)
- \( V_{DD}: 15V, V_{DD2}: 5V. \)

The relationship between current threshold \( I_{LD} \) and resistance \( R_4 \) is verified and showed in Fig. 8, in which solid line is the calculated outcome based on (6) and dots are the measured data. The relationship between turn-off delay time and resistance \( R_{11} \) is showed in Fig. 9. Both figures verify that the measured data match the prediction closely, which indicates that proposed protection circuit can be adjusted according to different load requirements.

B. Switch Protection Test

In this test, protection circuit is required to respond to large overcurrent and short-circuit faults. The turn-off delay time is measured under different fault current levels ranging from 30A to 90A. The function of zener diode \( Z_1 \) in Fig. 5 is experimentally examined. The relationship between turn-off delay time and fault current level is depicted in Fig. 10. As seen, protection circuit with \( Z_1 \) manages to turn off the fault current \( I_D \) before the maximum allowable turn-off delay time. The threshold current \( I_{OC} \) of overcurrent protection is 32.5A, above which the turn-off delay time decreases from 60.85ms to 0.254ms when \( I_D \) is at 72.5A. The threshold current \( I_{SC} \) of short-circuit protection is 72.5A, above which
the allowable turn-off delay time becomes 75µs. The turn-off delay time exceeds the maximum limitation if zener diode $Z_t$ is not used.

![Figure 8](image8.png)

**Figure 8.** The relationship between overload fault current threshold $I_{LD}$ and resistance $R_t$.

![Figure 9](image9.png)

**Figure 9.** The relationship between overload turn-off delay time $t_{LD}$ and resistance $R_t$.

![Figure 10](image10.png)

**Figure 10.** Turn-off delay time of tested circuit under different fault current level.

V. CONCLUSIONS

This paper describes a variable time-delay overcurrent protection scheme for SiC MOSFET circuit breakers used in DC microgrid. The proposed scheme provides comprehensive protection for all overcurrent conditions with a proper current-dependent turn-off delay time. The proposed scheme is verified through laboratory measurements and the effectiveness of protection scheme is clearly confirmed.

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