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Study on short circuit effect of silicon carbide power devices

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Abstract. SiC can provide better material properties when the performance of Si - based power devices is almost developed to the limit. But compared with Si material, the reliability of SiC device is poor under ultimate stress. The short circuit capability of SiC MOSFET has been the main area of attention in this paper's study. Through the analysis of SiC MOSFET short-circuit capability, it is mainly represented by the time that the device can withstand short-circuit stress and the time it takes for the device to be safely turned off in the event of a short circuit fault. Secondly, the detection circuit and protection circuit under the SiC MOSFET short-circuit fault are briefly studied, and the optimization ideas and working principles are summarized.

Keywords: SiC MOSFET, short circuit characteristic, protection circuit.

1. Introduction

In the current society, with the continuous progress of science and technology, there are higher requirements for power electronics technology. The performance of traditional silicon-based power semiconductor devices has been developed almost to its limit, and higher performance materials are needed to reach new market demands. At present, the known wide band gap semiconductor materials have the characteristics of wide band gap, large breakdown electric field strength, strong radiation resistance, high temperature resistance, high saturated electron mobility and excellent switching performance. Silicon carbide (SiC) and gallium nitride (GaN) are prominent representatives of them [1]. And has been the most extensively applicated, the most successful industrialized device is SiC MOSFET (metal oxide semiconductor field effect transistor, MOSFET). SiC MOSFET is a normally-close (NC) type voltage driver. Compared with silicon devices, SiC MOSFET has poor robustness and reliability, and its lifetime is much lower than that of silicon devices [2]. However, the normal operation of the power system cannot be separated from the power device, and the reliability of the device directly determines the operating life of the system. Once the power device degrades or even fails, it will cause serious economic losses and safety problems.

The robustness of the device refers to the limit that the device can withstand in a harsh working environment, the most common of which is the short-circuit capability. In contrast to Si MOSFET, SiC MOSFET has a smaller oxide layer thickness and can produce higher electric field strength under the same conditions. Tunnel current generation is one of the main failure mechanisms of sic power MOSFET gate oxide [3]. High current density and high electric field in oxide will aggravate the tunneling effect. At the same time, long - term short-circuit stress may lead to thermal failure of the device, and both drain source and gate source have penetration phenomenon. Therefore, to improve

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the short-circuit capability of SiC devices, the research of short-circuit mechanism and fast response protection circuit is an essential step.

Qin, H.et al. The SiC MOSFET devices' short circuit properties are outlined. When analyzing the influence of circuit parameters, grid resistance, grid source voltage, DC bus voltage and other factors are considered [4]. Sadik, D.P. conducted experimental analysis on SiC MOSFET devices, JFET devices and BJT devices under 1200V short-circuit circumstances. Three power devices' short circuit behavior is carefully examined. They optimize the traditional SiC JFET driver to realize short circuit protection by integrating short circuit detection circuit [5]. Wang Y. A short-circuit detection circuit and short-circuit protection circuit based on drain-source voltage integration were proposed after classifying five different types of short-circuit detection circuits. In the mean time, she shares the circuit parametric design method, enabling SiC MOSFET to achieve self-adaptive short circuit protection [6]. G. Romano et al mainly studied the short-circuit failure behavior caused by thermal runaway, and studied the influence of some parameter mismatches on hot spot formation and failure through TCAD simulation [7]. S. Ji. et al A short-circuit protection circuit on the basis of FPGA with response time of 1.5μs is introduced. It also makes up a grid driver. Furthermore, they tested and discussed the short-circuit behavior of hard switch fault (HSF) and fault under load (FUL) at various DC voltages (500v to 6kv) [8]. Z. Wang et al The short-circuit capability of three commercial SiC MOSFETs was tested under a variety of different conditions. They compared and analyzed the experimental short-circuit behavior through numerical thermodynamic simulation. According to the simulation results, SiC MOSFET short circuit failure may be brought on by thermal runaway which caused by an increase in internal junction temperature or by gate oxide failure associated with high temperature [9]. T. Horiguchi. et al introduced a fast short circuit protection circuit which can monitor both gate voltage and gate charge and has high anti-noise ability. This circuit mainly monitors the hard switch failure of silicon carbide MOSFET. The proposed protection circuit can detect short- circuit fault under HSF within 1 μs [10]. Yin S. et al compared SiC MOSFET with Si IGBT in the case of slower gate driver and designed a gate driver with desaturation protection. They proposed a method of charging the blanking capacitor with an external current source, and realized the short-circuit protection in 0.91μs [11].

The notion of a SiC MOSFET short circuit fault and the short circuit behavior under various fault conditions are introduced in the first section of this study. The second section examines various factors that affect a device's ability to withstand a short-circuit as well as some issues that must be resolved when designing a short-circuit protection circuit. The third section lists some SiC MOSFET short circuit detection and protection circuits with high performance or low cost and examines the pertinent findings. The final section presents a summary and draws conclusions.

2. Principle

2.1. Short-circuit fault classification

2.1.1. Hard switching fault (HSF). The SiC MOSFETs are in a short circuit loop in their initial state. When the switch is closed and the device enters the conduction state, the SiC MOSFET short-circuit fault occurs.

Figure 1 shows the response waveform of the SiC MOSFET to the hard switch fault condition, and also the short-circuit behavior of the device under the hard switch fault. We divide it into four stages and introduce the situation and reasons of parameter changes in each stage.

Stage 1 (t_1-t_2) : At t1, the working state of SiC MOSFET transitions from blocking state to short-circuit conduction state, and the value of gate voltage approaches the standard of threshold voltage. Because the main power circuit impedance is small, the drain current of SiC MOSFET increases rapidly. Further, the total inductance of the main power supply circuit will generate a voltage, whose existence relationship is shown in Equation 1, and the direction is opposite to the busbar voltage. The appearance of reverse induced voltage causes the drain source voltage of SiC MOSFET

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to drop briefly. But then gradually tends to DC bus voltage. The relationship between the two is shown in Equation 2. On the other hand, the continuous increase of drain current increases the power loss caused by short circuit fault of SiC MOSFET, which further leads to the rapid increase of junction temperature. Finally, as the on-resistance of SiC MOSFET increases, the drain current growth rate decreases. However, with the increase of orbital mobility and temperature, the drain current of SiC mosFETs continues to increase.

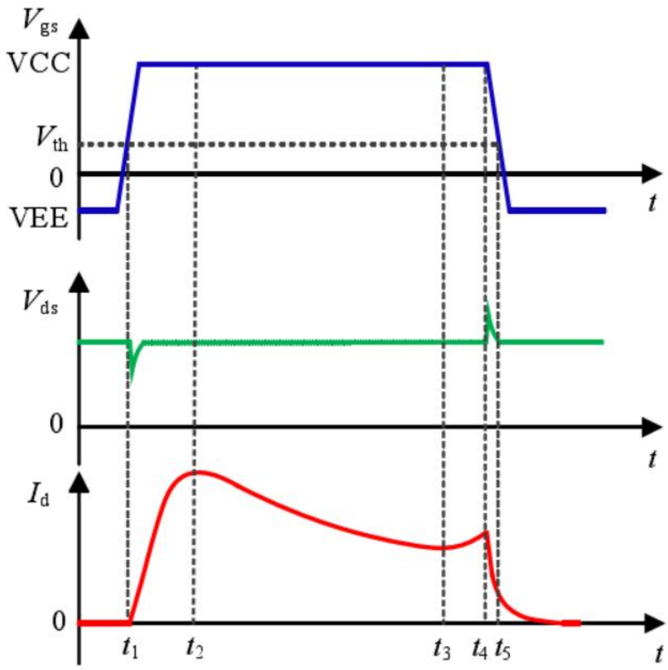

Figure 1. Waveform generated by the SiC MOSFET when the HSF occurs [6].

$$U_{loop} = L_{loop} \times \frac{di}{dt} \tag{1}$$

$$U_{DS} = U_{DC} - U_{loop} \tag{2}$$

L_{loop} is the total inductance of the wire in the loop, U_{loop} is the voltage generated by the wire induction, $\frac{di}{dt}$ is the change rate of the drain current, U_{DS} is the drain source voltage, U_{DC} is the DC bus voltage.

Stage 2 (t_2-t_3) : At this stage, SiC MOSFET is still in saturation conduction state. On the contrary, due to the continuous power loss caused by short circuit, the excessive high temperature causes the channel carrier mobility to decrease from increasing, so the short circuit current also changes from increasing to decreasing.

Stage 3 (t_3-t_4) : The leakage current occurs in the device loop, and the rate of leakage current increase is greater than the rate of channel current decrease. Therefore, at this stage, the drain current briefly rises, and we can use equation 3 to estimate the leakage current.

$$I_{leak} = \frac{qSn_i}{\tau_g} \sqrt{\frac{2\varepsilon_s}{q} \left(\frac{N_d + N_a}{N_d N_a} \right) U_{DC}} \tag{3}$$

q represents the total charge, S represents the active area of MOSFET, n_i represents the intrinsic carrier concentration, τ_g represents the excited state lifetime, ε_s represents the dielectric constant, N_a represents the doping concentration of the P trap region, N_d represents the doping concentration of the N drift region.

Stage 4 (t_4-t_5) : At this stage, in the first case, the drain current value is reduced to 0 and the device is safely shut down. In the second case, the device does not shut down properly, resulting in the following two types of degradation: (1) The device is out of control and its internal structure degrades. The drain-source electrode and gate source electrode are penetrated, and the gate source oxide layer is also broken down; (2) the leakage current still exists, which eventually leads to the thermal effect out of control and the device failure.

2.1.2. Fault under load (FUL). The SiC MOSFET begins operating in the normal conduction state. In working condition, a short circuit fault occurs on a load in the loop.

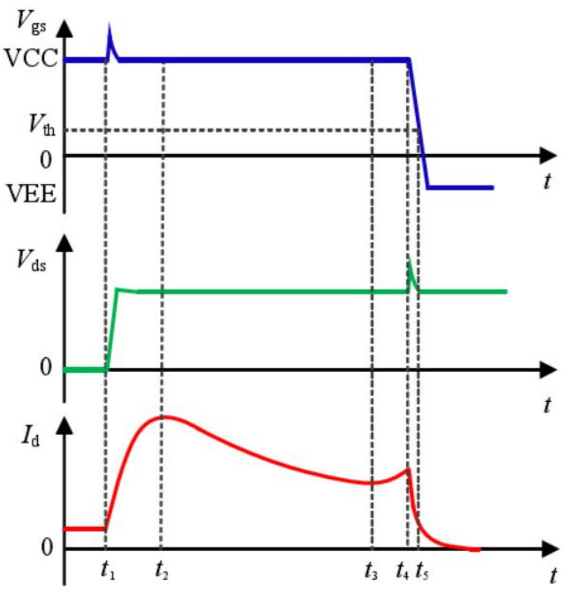

Figure 2. Waveform generated by the SiC MOSFET when the fault under load occurs [6].

Figure 2 shows the response waveform of SiC MOSFET to the fault under load condition and the short-circuit behavior of the device under FUL. Because the (t2-t5) stage is similar to the short-circuit behavior under hard switching fault conditions, the first stage is mainly introduced. At the same time, the hard switching fault will produce greater power loss, resulting in additional energy and temperature stress. At present, most short-circuit characteristic tests choose the hard switch fault condition. Stage 1 (t1-t2): Before t1, the switch is closed and the SiC MOSFET is normally on. The short circuit fault occurs at t1. The drain current is equal to the load current before t1 and rises rapidly after t1. Meanwhile, the value of drain-source voltage also rises rapidly to catch the standard of DC bus voltage. The displacement current generated by drain-source voltage in the loop charges the grid capacitor. This also causes voltage spikes in the waveform.

3. Short circuit problem

3.1. Influencing factors of short circuit characteristics

Among the circuit parameters, the driving voltage is the main factor affecting the short circuit characteristics of SiC MOSFET devices. When the SiC MOSFET is short-circuited, the gate voltage of the device increases. This also causes the change rate and peak value of short circuit current to increase obviously. At the same time, a similar trend of parameter variation can also be found when the voltage of DC rice noodles increases. For short circuit energy, the influence of DC bus voltage and gate voltage is positive. Second, the grid resistance will affect the switching speed, and the relationship is negative, which will affect the overshoot current and may damage the device. It has little effect on short circuit current.

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3.2. Short circuit detection circuit

Short circuit detection circuit determines whether the SiC MOSFET short circuit protection circuit can be accurate and fast protection. According to the principle, it can be divided into five categories: drain-source voltage detection, drain-current detection, short-circuit current change rate detection, grid voltage charge detection and power detection.

Drain source voltage detection: In the detection, the conduction voltage is easily affected by temperature. Under the same current condition, the increase of temperature is usually accompanied by the increase of SiC MOSFET's breakover voltage. This will affect the design of the threshold voltage. Secondly, the voltage spike after conduction is easy to make the protection circuit shut off by mistake.

Drain current detection: In the detection, the sampling resistor may produce large power loss. The circuit is more complicated when designing Hall element and Rogowski coil, and some detection circuits are not universal.

Short-circuit current change rate detection: In the detection, if the inductance in the short-circuit circuit is large, the current change rate will become smaller, and it may be difficult to reach the protection threshold. If the Rogowski coil is used, the protection circuit structure will become complicated and difficult to be widely used.

Gate voltage and charge detection: The principle of this method is based on the gate charge characteristics of SiC MOSFET at the moment of opening. This method can only detect hard switch faults, but not load short-circuit faults. Secondly, the change of parasitic parameters of short circuit is also easy to interfere with the detection circuit.

3.3. short circuit protection circuit

To increase the short circuit reliability of SiC MOSFETs, the following four issues must be taken into account while designing the short circuit protection circuit: 1. Can the short circuit problem be found as soon as possible? 2. If the detector circuit can correctly identify the short circuit signal. If it can prevent a wrong shutdown, it can function even when there is interference in the loop. 3. Can the detection circuit produce a regular short-circuit signal? 4. Can the SiC MOSFET's switching speed be limited? Faster switching speeds could lead to current overshoot and harm the device.

4. Short-circuit protection circuit design

4.1. Detection circuit

It is necessary to design the detection circuit so that it can detect short circuit signal quickly and accurately within 2-3μs to meet the requirements of protection circuit. Improve the short circuit capability of the SiC MOSFET.

The following will list some optimized short-circuit detection circuits.

The circuit in figure 3 is optimized by short circuit detection prior to desaturation, which effectively avoids the effect of the closing temperature when detecting drain-source voltage. Simultaneously, the circuit sets two separate detection thresholds for hard shutdown faults and load short-circuit faults, with two different short-circuit response paths. The results show that the detection circuit can accurately detect the drain source voltage and overshoot current.

The detection circuit in figure 4 is based on the principle of detecting the gate charge of the gate source voltage and transient conduction. The optimization part of the circuit is that the threshold of the gate voltage can be set to the Miller platform voltage, and the circuit does not need to set the blanking time. The results show that the circuit can detect the hard switching short circuit fault within 1μs, which is faster than the traditional protection circuit. At the same time, the circuit does not require high-voltage diodes and current sensors for sensing, and is a cost-effective detection circuit.

The point of the circuit in figure 5 optimization is that when detecting the current change rate, the traditional detection circuit needs to set different detection thresholds for hard switching faults and fault under load. The results show that the detection circuit can detect the short-circuit signal accurately and quickly, and provide accurate and consistent results under different load and fault

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conditions.

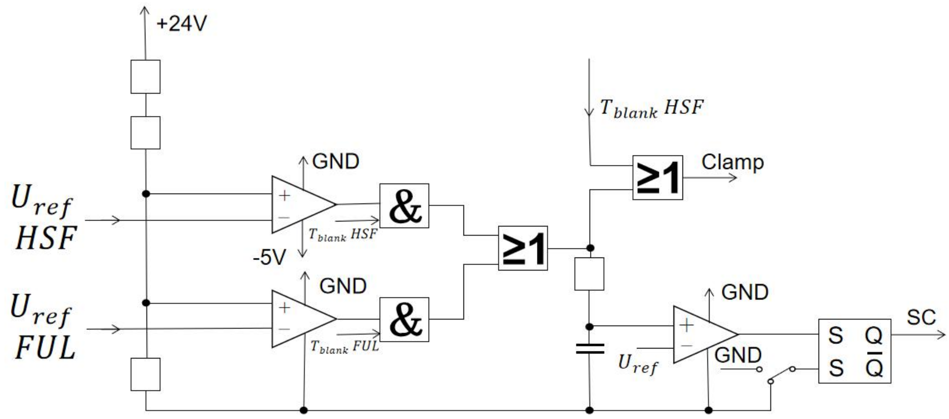

Figure 3. Optimized desaturation detection circuit [12].

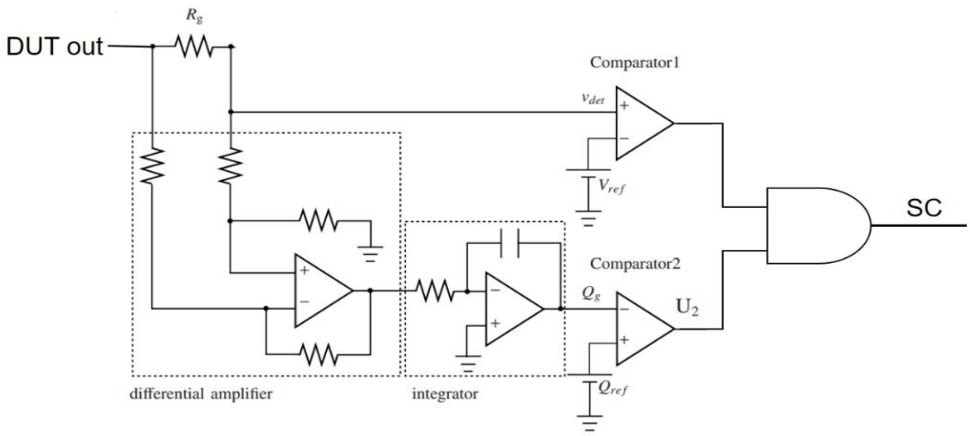

Figure 4. Optimized grid voltage charge detection circuit [10].

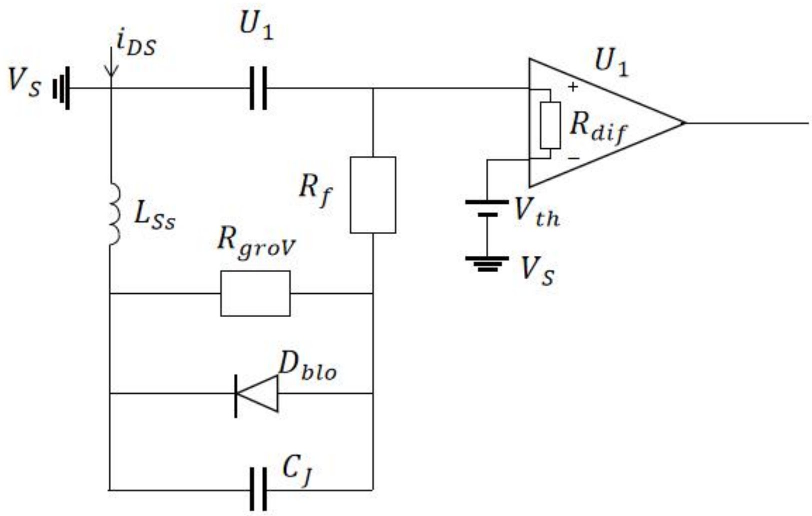

Figure 5. optimized current change rate detection circuit [13].

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4.2. Protection circuit

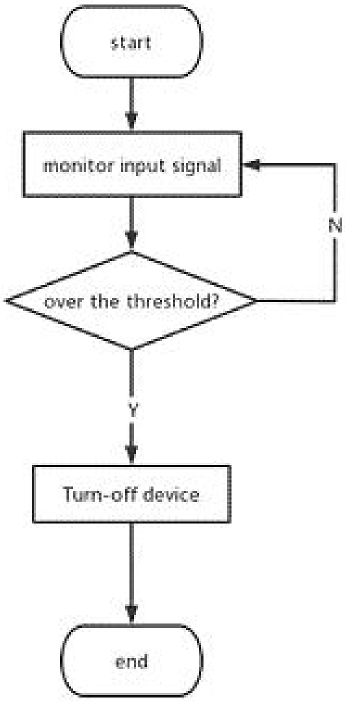

Figure 6. The basic strategy in developing SiC short circuit protection circuit.

Figure 6 is the basic design idea of the protection circuit design for SiC short circuit problem. Determine whether a short circuit fault is occurring by setting the threshold of the detection circuit. Then the short circuit signal is output to the turn-off circuit to turn off the device, so as to complete the protection action. While designing a circuit, it is necessary to consider the time spent in detecting and turning off behaviors and the anti-interference ability of the detection circuit. In this way, the short-circuit capability of SiC power devices can be effectively improved. Some SiC short circuit protection circuits with good protection performance are listed below.

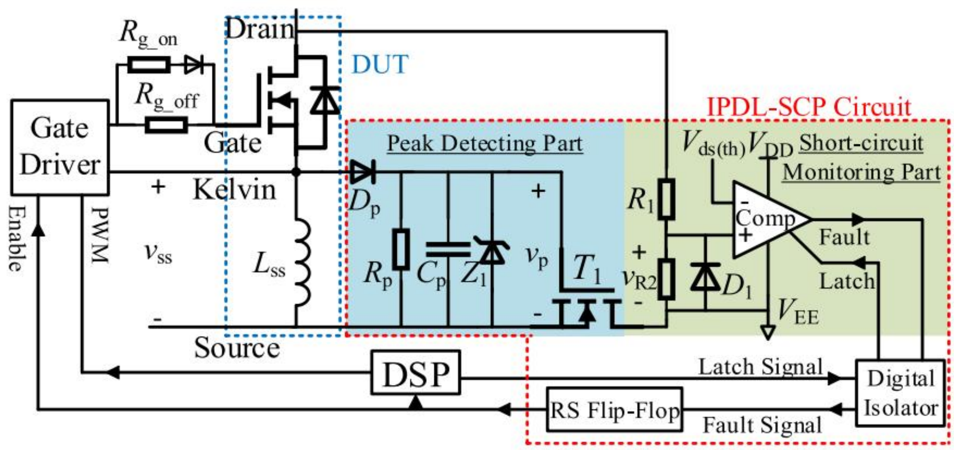

Figure 7. The SiC MOSFET short-circuit protection circuit is designed based on the principle of detecting drain-source voltage [14].

Short power level protection is the main idea of the short circuit protection circuit design in figure 7. Triggered by the voltage oscillation of the parasitic inductor, the short-circuit signal is detected by the drain-source voltage, and the circuit is completed with the least number of components. The experimental results show that the response delay of the protection circuit is 75ns under the condition of HSF and 170ns under the condition of FUL. Compared with the desaturation method, no blanking

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time is required (cancel blanking capacitance), and the response time is shorter. Compared with the current change rate detection method, this method only takes Vss as the wake-up signal. The drain-source voltage of the measured device is directly monitored, which solves the reliability problem of low dids/dt rate caused by low pass filter in the dids/dt detection circuit. The short-circuit capability of SiC MOSFET has been effectively improved.

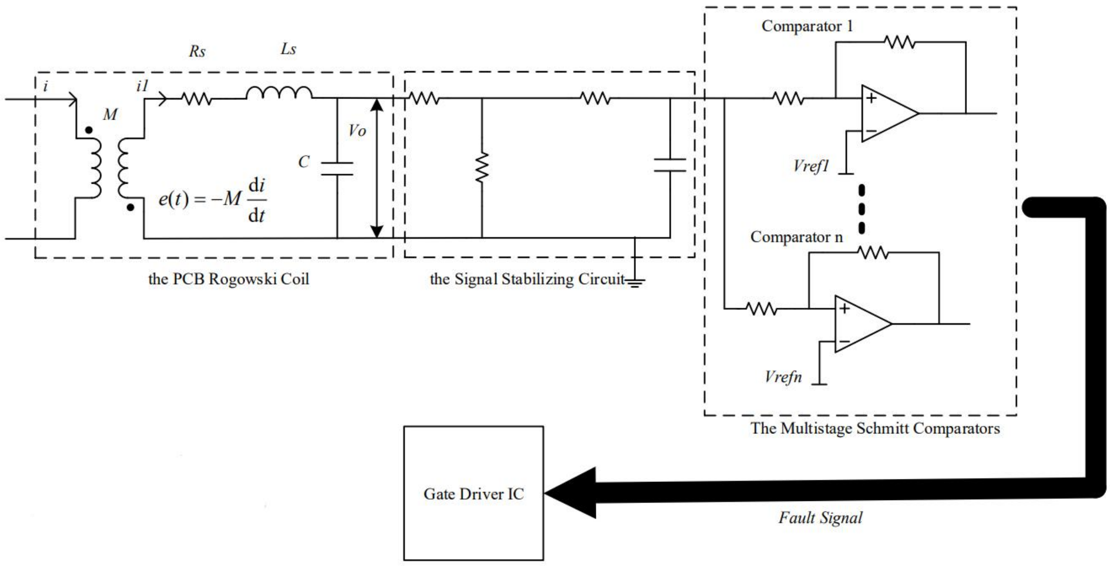

Figure 8. Based on the principle of simplifying the Rogowski coil current sensor structure, the designed SiC MOSFET short-circuit protection circuit [15].

Compared with the traditional protection method, the circuit in figure 8 simplifies the circuit complexity of using Rogowski Coil, has the advantages of low sensitivity to temperature, insulation with power pole, no parasitic parameters and fast dynamic response. This method is also more suitable for practical application than previous ones. At the same time, the circuit has anti-magnetic noise structure, which improves the anti-magnetic noise ability of Rogowski coil in complex magnetic field and optimizes the stability of the signal. The experimental results show that the short-circuit protection can be completed under different short-circuit fault conditions. It provides a reliable and fast short-circuit protection method for SiC MOSFETs, requiring only 430ns from the occurrence of short circuit to the start of protection action.

5. Conclusion

In this paper, the device characteristics of SiC MOSFET under short circuit stress are mainly studied, and then the short circuit protection circuit of SiC MOSFET is studied. The detection circuit is partially optimized on the basic circuit. The first detection circuit optimizes the accuracy of the leakage source voltage detection. The second detection circuit optimizes the blanking time The third detection circuit optimizes the threshold setting. The design of the protection circuit selects a circuit with good short-circuit performance, low line structure complexity, and more effective overall construction cost. The first circuit is directly awakened by the voltage oscillation caused by the parasitic inductor and uses fewer circuit elements to form the protective circuit. The second circuit simplifies the setup of the Rogowski coil and optimizes the anti-magnetic noise capability of the Rogowski coil, making the protection circuit easier to implement in practical applications. The detection circuit and protection circuit mentioned in this paper can effectively deal with the short-circuit problem of SiC MOSFET and improve the short-circuit capability of the device. It has some guiding effect.

References

[1] She, X., Huang, A. Q., Lucia, O., & Ozpineci, B. (2017). Review of silicon carbide power devices and their applications. *IEEE Transactions on Industrial Electronics*, *64*(10), 8193-8205.

[2] Hu, B., Gonzalez, J. O., Ran, L., Ren, H., Zeng, Z., Lai, W., ... & Mawby, P. (2017). Failure and reliability analysis of a SiC power module based on stress comparison to a Si device. *IEEE Transactions on Device and Materials Reliability*, *17*(4), 727-737.

[3] A. Fayyaz, L. Yang, A. Castellazzi, Transient robustness testing of silicon carbide (SiC)power MOSFETs, 15th Eur. Conf. Power Electron. A

[4] Qin, H. , Dong, Y. , Xu, K. , Xu, H. , Fu, D. , & Wang, S. , et al. (2018). A comprehensive study of the short-circuit characteristics of SiC MOSFETs. IEEE Conference on Industrial Electronics & Applications (pp.332-336). IEEE.

[5] Sadik, D. P. . (2014). Analysis of short-circuit conditions for silicon carbide power transistors and suggestions for protection. European Conference on Power Electronics & Applications. IEEE.

[6] Wang,Y . Research on PSpice Short-circuit Model and Short-circuit Protection Circuit of Si C MOSFET[D].Beijing Jiaotong University,2021.DOI:10.26944/d.cnki.gbfju.2021.001879.

[7] G. Romano et al., "Influence of design parameters on the short-circuit ruggedness of SiC power MOSFETs," 2016 28th International Symposium on Power Semiconductor Devices and ICs (ISPSD), Prague, Czech Republic, 2016, pp. 47-50, doi: 10.1109/ISPSD.2016.7520774.

[8] S. Ji et al., "Short-Circuit Characterization and Protection of 10-kV SiC MOSFET," in IEEE Transactions on Power Electronics, vol. 34, no. 2, pp. 1755-1764, Feb. 2019, doi: 10.1109/TPEL.2018.2834463.

[9] Z. Wang et al., "Temperature-Dependent Short-Circuit Capability of Silicon Carbide Power MOSFETs," in IEEE Transactions on Power Electronics, vol. 31, no. 2, pp. 1555-1566, Feb. 2016, doi: 10.1109/TPEL.2015.2416358.

[10] T. Horiguchi, S. -i. Kinouchi, Y. Nakayama and H. Akagi, "A fast short-circuit protection method using gate charge characteristics of SiC MOSFETs," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 2015, pp. 4759-4764, doi: 10.1109/ECCE.2015.7310332.

[11] Yin S, Wu Y, Liu Y, Pan X. Comparative Design of Gate Drivers with Short-Circuit Protection Scheme for SiC MOSFET and Si IGBT. *Energies*. 2019; 12(23):4546. https://doi.org/10.3390/en12234546

[12] T. Bertelshofer, A. Maerz and M. Bakran, "Design Rules to Adapt the Desaturation Detection for SiC MOSFET Modules," PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 2017, pp. 1-8.

[13] J. Xue, Z. Xin, H. Wang, P. C. Loh and F. Blaabjerg, "An Improved di/dt-RCD Detection for Short-Circuit Protection of SiC MOSFET," in IEEE Transactions on Power Electronics, vol. 36, no. 1, pp. 12-17, Jan. 2021, doi: 10.1109/TPEL.2020.3000246.

[14] W. Ouyang, P. Sun, M. Xie, Q. Luo and X. Du, "A Fast Short-Circuit Protection Method for SiC MOSFET Based on Indirect Power Dissipation Level," in IEEE Transactions on Power Electronics, vol. 37, no. 8, pp. 8825-8829, Aug. 2022, doi: 10.1109/TPEL.2022.3161741.

[15] Y. Xu, Y. Hao, W. Li, X. Bu, P. Xiang and R. Hao, "A Novel Short-Circuit Protect Method for SiC MOSFET Module Based on Simplified Rogowski Coil Current Sensor," 2019 4th IEEE Workshop on the Electronic Grid (eGRID), Xiamen, China, 2019, pp. 1-8, doi: 10.1109/eGRID48402.2019.9092681.