An IGBT short-circuit protection method using variable $V_{CE}$ detection threshold

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Abstract. When mine fan is driven by power inverter, the high-power inverter maybe used to drive low-power motors, so the short-circuit protection threshold of the IGBT needs to be adjusted online. Firstly, the principle of DESAT function of IGBT driver chip is analyzed, then the detection threshold adjustment circuit is designed by using precision voltage reference and voltage comparator, and the method of real-time threshold adjustment by PWM wave with different duty ratio is designed. Experiments show that the IGBT overcurrent detection circuit can respond and act quickly and accurately, so that the IGBT can be protected in time and effectively under different overcurrent conditions.

1. Introduction
Electrical equipment used in coal mines is becoming more and more intelligent and integrated, and variable frequency driving is widely used in this area. The frequency converter plays an important role in the intellectualized reconstruction. IGBT is an important power device in the inverter bridge, and its stability is closely related to the reliability of the entire equipment. Due to the limited overcurrent that the IGBT can hold, the overcurrent protection shall be rapid and accurate. The overcurrent of IGBT can be divided into two types: 1) overload (current value is 1.2 ~ 2 times of the rated value), which is allowed in a short time; 2) a large multiple of overcurrent short circuit. The short faults of IGBT can be divided into Category I and Category II.

The short-circuit through the bridge arm is called as the Category I short circuit, in which the inductance is nH level, and the current rises rapidly. Similar inter-phase short circuit or relative ground short circuit that occurs when the IGBT has been turned on is called Category II short circuit [1-4]. The IGBT is in the saturation region during its normal operation, and the voltage drop $V_{CE}$ between the collector and the emitter is very small (about 2V). When a short circuit occurs, the current value quickly reaches 4-8 times that of the rated current, and $V_{CE}$ rises rapidly and then exits the saturation zone. This process is called desaturation. If the IGBT is not turned off in time, $V_{CE}$ may rise to the bus voltage value, causing irreversible damage to the IGBT. Therefore, the working state of IGBT can be judged based on the voltage value of $V_{CE}$ [5-7].

The overcurrent detection methods of IGBT include current sensor detection, di/dt detection, $V_{CE}$ saturation voltage drop detection, etc. [8-9]. The current sensor detection mainly uses closed-loop Hall current sensor for sampling. However, limited by the bandwidth of the Hall sensor and the delay of the sampling circuit of the control system, the real-time performance is yet to be improved. The di/dt detection mainly uses the parasitic inductance of the power E pole and driving E pole of the IGBT to judge the size of the current, but this inductance parameter is not easy to be obtained. $V_{CE}$ saturation
voltage drop is detected using the desaturation DESAT detection function of the IGBT driver chip. The detection threshold of the available IGBT driver chips are within the range of 6.5 V ~ 10V, in which the overcurrent multiple of IGBT is high, requiring for further optimization.

Literature [10] designed an IGBT overcurrent protection circuit using HCPL-316J optocoupler chip based on built-in saturation voltage drop \( V_{CE} \), which has the aforementioned deficiencies. Literature [11] proposed an IGBT overcurrent protection strategy of level 4 \( V_{CE} \) detection, which requires a CPLD for each IGBT for overcurrent logic judgment, leading to complication and higher circuit cost. Literature [12] proposes a multi-threshold protection IGBT drive circuit, which, however, is too complicated and inconvenient for production and debugging.

Based on the above, this paper proposes an IGBT desaturation overcurrent detection scheme with an adjustable threshold.

2. Working principle of DESAT overcurrent protection

This paper uses the IGBT optocoupler driver chip FOD8332 produced by ON Semiconductor, which integrates the functions of PWM optocoupler isolation, DESAT desaturation detection, soft shutdown, and push-pull output. The typical threshold of DESAT detection function voltage is 6.5V, and the detection principle is shown in Figure 1.

![Figure 1. Principle of desaturation DESAT detection](image)

The DESAT detection function is only effective when the IGBT is turned on. When the IGBT is turned off, the MOS tube inside the chip is turned on to release the charge of the C1 capacitor and clamp it to the \( V_E \) to prevent false fault signals. When the IGBT is turned on, the MOS tube is quickly turned off, and the internal 250uA constant current source charges C1. At the same time, the current flows back to the \( V_E \) end through the resistor, diode, and the collector as well as emitter of the IGBT. The pin voltage at the DESAT terminal is:

\[
V_{DE SAT} = V_{R1} + V_{D1} + V_{CE}
\]

In the formula, \( V_{R1} \) refers to the voltage of the series resistance \( R_1 \) and \( V \); \( V_{D1} \) is the forward conduction voltage drop of the reverse blocking high-voltage diode \( D_1 \); \( V \); \( V_{CE} \) is the voltage between the collector and the emitter when the IGBT is turned on, which can be expressed as \( V \).

The operating voltage threshold of \( V_{DE SAT} \) is less than 6.5V when the IGBT is working normally. After IGBT exits the saturation region due to overcurrent, \( V_{CE} \) rises and the \( V_{DE SAT} \) voltage rises above the threshold of 6.5V. The drive output of the chip is slowly pulled down in a controlled manner within 4us to turn off the IGBT so as to reduce peak voltage on the IGBT collector.

After the IGBT is turned on, \( V_{CE} \) decreases slowly. \( C_1 \) provides some blind spot time for detection, which can prevent the DESAT function from being falsely triggered when the IGBT is turned on.

When the IGBT is turned off, the diode \( D_1 \) with high dielectric strength can block the high voltage of the DC bus. In order to ensure the response speed of the circuit, it is necessary to use a diode with a reverse recovery time of less than 75ns.

Multiple diodes can be used to lower the trigger threshold. However, too many diodes will occupy
too much board space. The diodes are inconsistent in terms of volt-ampere characteristics, turn-on time, and reverse recovery charge, leading to uneven voltage of the diode, which may damage a diode under excessive reverse voltage [13]. In actual application, no more than 4 diodes can be used.

The IGBT (with a rated output current value twice that of the inverter) is generally used as the power device. Take a 660V / 160kW flameproof inverter for the local fan as an example, the inverter's rated output current is set as 170A, and the inverter bridge uses FF400R17KE4 IGBT produced by Infineon (VCE of the IGBT at 170A is about 1.6 V). Using the overcurrent detection circuit shown in Figure 1 and four BYG23T diodes, the VCE of the IGBT is about 4.9V when a fault is detected by DESAT. According to the IGBT data book, the current of the IGBT under this saturation voltage drop is much greater than 800A, posing a great risk to the load and therefore requiring optimization.

3. Trigger level adjustment

TL431 is a three-terminal adjustable shunt reference source with good thermal stability. Its output voltage can be set as any value in the range of VREF (2.5V) to 36V through two voltage-dividing resistors [14-15]. Therefore, this device can be used to form different voltage thresholds and its overcurrent trigger level can be conveniently adjusted with a voltage comparator.

The principle is shown in Figure 2. Ds is a low-temperature drift-type voltage comparator LM2903. By adjusting the resistance of R1 and R2, the required threshold voltage Vth can be obtained at the 2-pin end of Ds. When the IGBT is working normally, the 3-pin voltage of Ds is lower than Vth, and the output of the comparator is at a low level. The output of the comparator is the output of the triode OC gate, so the voltage of the DESAT terminal is clamped at a low level (about 0V) without any overcurrent fault. When the VCE of IGBT rises due to overcurrent and the 3-pin voltage of Ds is higher than Vth, the comparator outputs a high level, the OC gate turns off, and the voltage of the DESAT terminal rises to +15V, higher than the comparison threshold inside the chip (6.5V), leading to overcurrent faults.

![Figure 2. Trigger level adjustment circuit](image)

The over-current protection circuit using voltage reference source TL431 and voltage comparator LM2903 can adjust the resistance values of R1 and R2 for different IGBTs, which is more convenient for production and debugging.

4. Overcurrent protection with the online adjustable threshold

In actual application, when the inverter of the local fan is replaced or used for other purposes after the underground tunneling is completed, a large-capacity inverter may bear a low power load. For example, the 660V / 160kW local fan inverter may be used to drive a 2 x 22kW counter-rotating fan with a rated current of 45A. The load carrying capacity of the motor is limited when there is an inter-phase short circuit or relative short circuit. To better protect the motor, it is necessary to enable the inverter to make real-time adjustment of the overcurrent protection trigger level according to the
load (for example, 4 ~ 4.5 times of the load rated current $I_e$). Considering that PWM waves of different duty ratios can produce different voltage values after filtering, this method can be used for real-time adjustment of the overcurrent protection trigger threshold.

Figure 3. Online-adjustable DESAT detection circuit

The circuit is shown in Figure 3. TL431 and $R_1$, $R_2$, and $C_1$ form a precise 10V/50mA power supply. The PWM waves with different duty cycles are filtered by $R_4$, $C_2$, $R_5$, and $C_3$ to obtain a stable voltage threshold.

According to the IGBT data book, when the driving voltage of FF400R17KE4 $V_{GE} = 15V$, the current of IGBT is within 100 ~ 800A (more than 800A is not available here) and $V_{CE}$ shows an approximately linear relationship:

$$V_{CE} = 3.8 \times 10^{-3} \times I_e + 0.84$$ (2)

The data book shows that when there is a 400A through current, the $V_{CE}$ is 2.35V, and the calculated result based on Formula (2) is 2.36V, indicating a referable relationship.

The following relationship can be obtained based on Figure 3:

$$\begin{align*}
V_a & \approx 10D \\
V_a & = V_{CE} + 4 \times V_{Diode}
\end{align*}$$ (3)

In the formula, $D$ refers to the duty cycle of the PWM wave, which can be expressed as %; $I_e$ is the rated current of the load motor, which can be expressed as A; $V_{Diode}$ is the diode voltage drop, which can be expressed as V.

According to Formulas (2) and (3), the duty cycle calculation result can be obtained:

$$D = (0.0152 \times I_e + 2.44)/10$$ (4)

Since there is a microsecond delay in the on and off the optocoupler, the frequency of the PWM wave can be set to 5 ~ 10kHz. There is a slight difference between the calculated value and the actual value of the duty cycle, which can be corrected using the experimental method.

Therefore, the inverter can adjust the trigger level of IGBT overcurrent protection in real time according to the inputted rated load current value.

5. Experimental results

In order to verify the correctness and timeliness of this IGBT overcurrent protection circuit with an adjustable threshold, this paper verifies the circuit of Figure 3 using experiments. Firstly, the delay time of the IGBT drive output is about 0.25us; $C_4$ is 100pF, and the blind spot time for detection is 2.6us. The IGBT drive input is 50kHz/50% square wave, and the $V_{CE}$ voltage of the IGBT is simulated using the ramp voltage of 3V/100kHz. Threshold adjustment PWM wave is set to a square wave of 10kHz with different duty cycles, respectively simulating the fan load of 2×5.5kW, 2×22kW, 2×37kW, 2×55kW. The overcurrent protection value is set as 4 times that of the rated current. The average value of the 10 test results is as follows:
Table 1. Overcurrent protection test data

| Overcurrent protection value /A | Duty cycle /% | Calculated action moment /μs | Actual action moment /μs | Deviation /μs |
|-------------------------------|--------------|-----------------------------|-------------------------|--------------|
| 60                            | 38.5         | 3.85                        | 3.7                     | 0.14         |
| 180                           | 43.2         | 5.08                        | 5.0                     | 0.08         |
| 320                           | 49.0         | 6.85                        | 6.7                     | 0.15         |
| 445                           | 53.6         | 8.43                        | 8.3                     | 0.13         |

Plot the test data curve as follows:

![Curve of overcurrent protection test data](image)

Figure 4. Curve of overcurrent protection test data

From Figure 4-1, it can be seen that the simulated ramp voltage at 3.91μs is 1.17V, reaching the comparator threshold (3.85V); the comparator output switches, and the IGBT drive is turned off. There is a certain error between the theoretically calculated value and the measured value, which is caused by the difference in the reaction time of the voltage comparator and the voltage drop of the diode. At the same time, the $V_{CE}$ at different temperatures and the calculated value are slightly different. In actual application, the overcurrent protection value can be changed by adjusting the duty ratio according to the temperature detected by the built-in NTC of the IGBT.

![Test waveform of overcurrent protection](image)

Figure 5. Test waveform of overcurrent protection

According to the research results of literature [16], there is a certain linear relationship between $V_{CE}$ of IGBT and current $I_C$ and junction temperature $T_j$:

$$V_{ce} = f(T_j, I_c) = a + b T_j + c I_c + d T_j I_c + e I_c^2 + f T_j I_c^2$$  \hspace{1cm} (5)

The correlation coefficient in the formula can be determined by the experimental method. The
experimental method can refer to the literature [16].

6. Conclusion
This paper analyzes in detail the working principle of the IGBT overcurrent protection circuit with an adjustable threshold based on $V_{CE}$ detection, and verifies the feasibility of the circuit through experiments. Compared with the protection circuit that only uses the DESAT detection function of the IGBT driver chip, the threshold-adjustable IGBT desaturation detection circuit has the following advantages: 1) flexible application: the trigger level of the overcurrent protection circuit can be adjusted in real time according to the inputted motor rated current, especially when the high-power inverter is used for a small power load; 2) sensitive and accurate protection action: the added circuit part does not significantly change the original response time; 3) simple and reliable circuit: the cost does not increase much, and there is no need for complicated debugging. According to the application feedback, the circuit can effectively guarantee the normal operation of IGBT, and is especially suitable for the load with a poor insulation performance in a poor operating environment, such as the underground fan for mining.

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