

Over-Temperature protection for IGBT modules

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Abstract

This paper will summarize the approaches and applications of temperature sensor for IGBT modules, including direct measurement of mounting a sensor on the chip and the NTC inside IGBT modules. Additionally, the calculation methods of the maximum junction temperature T_{jmax} for low output frequencies are introduced. This paper will also show how to design temperature sensing circuit and set over-temperature protection for Mitsubishi CM450DX-24S1.

1. Introduction to the approaches of temperature sensor for IGBT modules

1.1. Diode as a temperature sensor on IGBT chip

Forward voltage of diode linearly varies with temperature. By utilizing this characteristic, we can use diode as a temperature sensor. For Mitsubishi J-Series T-PM IGBT, diode integrated on IGBT chip is used to detect chip temperature directly and enable to turn off IGBT safely and fast for over-temperature protection. Fig.1 shows the IGBT chip integrated temperature sensing diode used for T-PM IGBT.

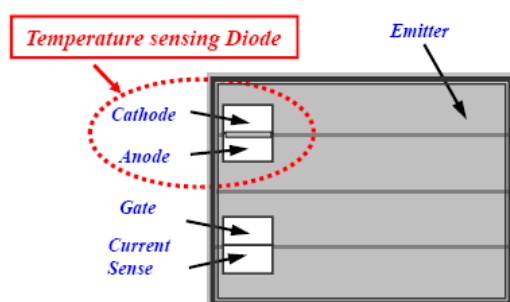


Fig. 1. Temperature sensing diode inside T-PM IGBT

1.2. NTC integrated as a temperature sensor inside IGBT

Fig.2 shows the NTC inside IGBT modules, which is used in Mitsubishi NX6 and NX6.1 IGBT modules. The NTC mounted on the ceramic substrate makes the thermal measurements simple in inverter.

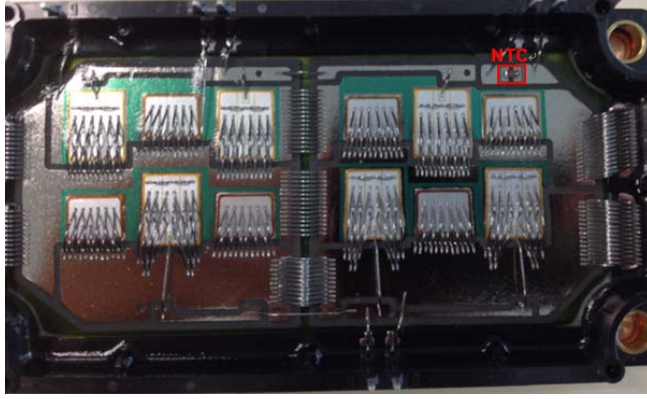


Fig. 2. NTC inside IGBT module

2. Using the NTC as a temperature sensor and OT protection

2.1. Definition of the NTC

The NTC is negative temperature coefficient thermistor, which is located on the same ceramic substrate as the IGBT and diode chips for Mitsubishi NX6 and NX6.1 IGBT modules. The IGBT chip temperature can be calculated by using a thermal model and measuring the temperature of NTC in steady state.

2.2. The approaches of calculating T_{jmax} for low output frequencies

The NTC is designed for detection of a long term overload conditions, while it is not suitable for OT protection during short circuit condition or very short term overload. The principle of calculating the maximum junction temperature T_{jmax} under short pulse is shown as the follow.

2.2.1. How to calculate T_{jave} and T_{jmax}

Refer to Fig.3, with the aid of the thermal resistances defined by reference points (h - heat sink, c - case, j - junction), the average junction temperature T_{jave} and the maximum junction temperature T_{jmax} are calculated using the following two equations Eq.1 and Eq.2. The average losses can be calculated using Mitsubishi's Melcosim Ver.5.0.1

$$T_{jave} = T_h + P_{ave} * R_{th(c-h)} + P_{ave} * R_{th(j-c)} \quad \text{Eq.1}$$

$$\begin{aligned} T_{jmax} &\doteq T_h + P_{ave} * R_{th(c-h)} + \Delta T_{j-c_max} \\ &= T_C + \Delta T_{j-c_max} \end{aligned} \quad \text{Eq.2}$$

with $R_{th(j-c)}$ as thermal resistance junction to case for the IGBT, $R_{th(c-h)}$ as thermal resistance case to heat sink.

2.2.2. The methods of measuring T_h and T_C

The heat sink temperature T_h is measured underneath the module in a borehole of up to 2mm into the heat sink surface. The case temperature T_C is measured directly beneath the chip via a drill hole in the heat sink as described in Fig.3. Besides, T_C can also be measured by digging a hole of Ø0.8mm at just under the chip on the base plate of the modules as described in Fig.4, and this special sample can be customized by Mitsubishi.

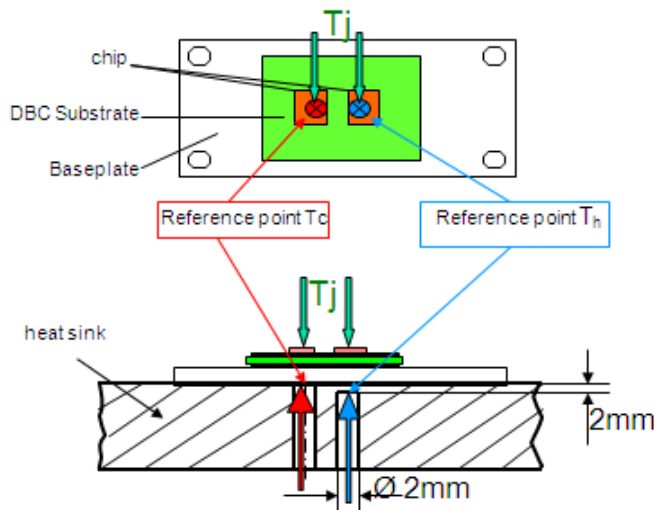


Fig. 3. Measuring points of T_h and T_c

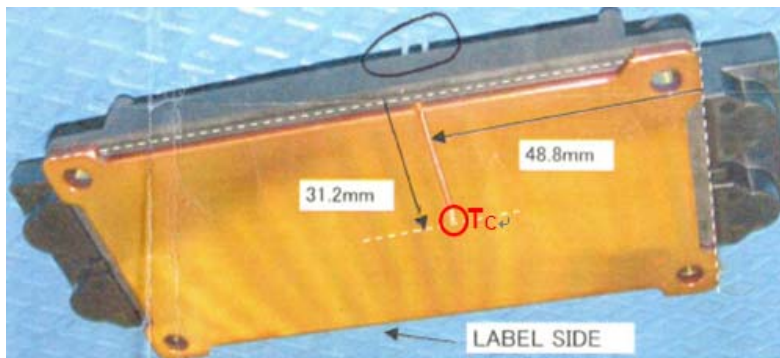


Fig. 4. Sample with thermo couple supplied by Mitsubishi

2.2.3. The principle of calculating $\Delta T_{j-c_{max}}$

Under the actual operation for IGBT modules, the chips inside the modules are heated and cooled by the different amplitude and pulse duration in a PWM chopped current. The junction temperature $T_{j_{max}}$ oscillates with the frequency of the output current. The principle of calculating the maximum temperature difference between junction and case $\Delta T_{j-c_{max}}$ is shown in Fig.5.

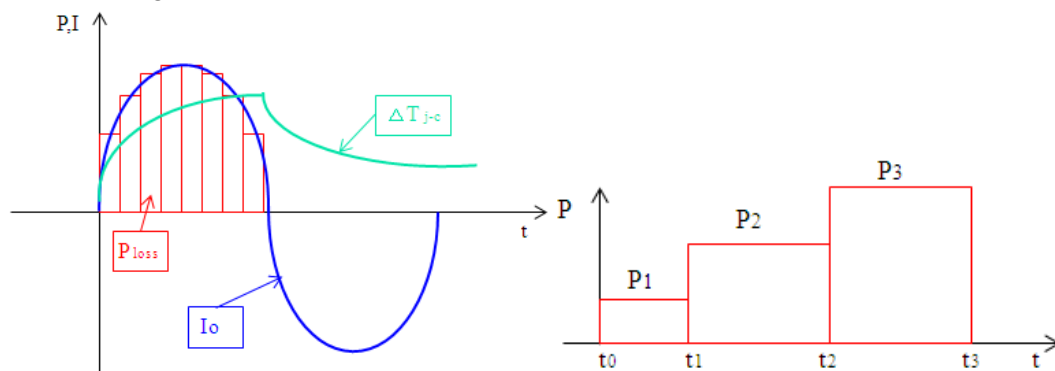
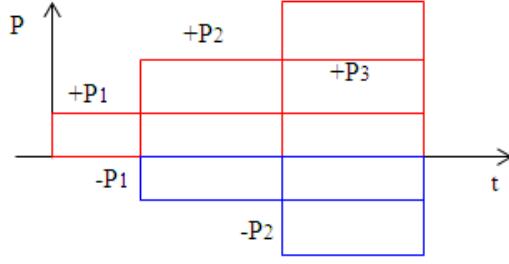
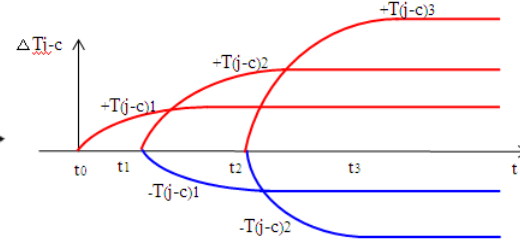


Fig. 5. (a) PWM chopped current

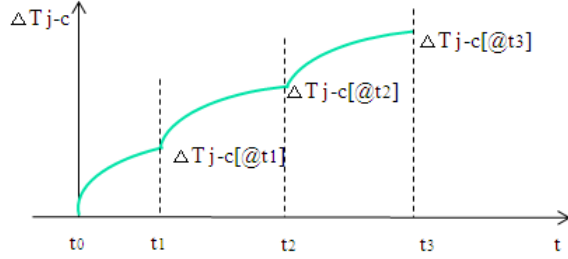
(b) Input power pulses



(c) Power pulses separated into positive and negative pulses



(d) T_{j-c} change caused by positive and negative pulses



(e) ΔT_{j-c} composite

Based on the above superposition principle, the following equation Eq.3 is used to calculate the temperature at the end and start of every pulse.

$$\Delta T_{(j-c)}[@t1] = P1 * R_{th(j-c)}[@t1]$$

$$\Delta T_{(j-c)}[@t2] = P1 * R_{th(j-c)}[@t2] - P1 * R_{th(j-c)}[@t2 - t1]$$

$$\Delta T_{(j-c)}[@t3] = P1 * R_{th(j-c)}[@t3] - P1 * R_{th(j-c)}[@t3 - t1] + P2 * R_{th(j-c)}[@t3 - t2]$$

Eq.3

$$R_{th(j-c)}[@t] = \sum_{i=1}^n r_i (1 - e^{-t/\tau_i}), t = t1, t2 - t1, t3 - t2$$

$$\tau_i = r_i * c_i$$

The r and c can be easily extracted from a measured cooling curve of the IGBT modules, and the coefficients of τ_i and r_i are provided in the datasheet.

At output frequencies higher than 5Hz, an approximation of using rectangular shaped block to calculate the average losses. A simple method of calculating ΔT_{j-c_max} , as a function of the output current frequency f_o , is as the following formula Eq.4.

$$\Delta T_{j-c_max} = 2 * P_{av} * \sum_{i=1}^n r_i \frac{1 - e^{-\frac{1}{2*f_o*\tau_i}}}{1 - e^{-\frac{1}{f_o*\tau_i}}}$$

Eq.4

2.2.4. Temperature difference between junction and case for low output frequencies

For example, using CM450DX-24S1 to develop 110kW two-level G/P inverter, the rated application conditions are that: $V_{DC}=540V$, $I_o=210Arms$, overload=315Arms, $f_c=3\text{ kHz}$, $R_{g(on)}=R_{g(off)}=5\Omega$. The average loss for upper or bottom IGBT is 306.53W. Based on this loss,

ΔT_{j-c_max} is calculated at low output frequencies (Table.1). ΔT_{j-c_max} can be calculated using the following formula Eq.5.

$$T_{j_max} \doteq T_C + \Delta T_{j-c_max} = T_C + f_{corr} * P_{ave} \quad \text{Eq.5}$$

The factor f_{corr} can be obtained using the following formula Eq.6.

$$f_{corr}(f_o) = \frac{\Delta T_{j-c_max}}{P_{ave}} \quad \text{Eq.6}$$

$f_o(\text{Hz})$	ΔT_{j-c_max}	f_{corr}	$f_o(\text{Hz})$	ΔT_{j-c_max}	f_{corr}
0.1	60.37	5.08	2	53.30	5.75
0.2	60.21	5.09	3	50.06	6.12
0.3	59.97	5.11	4	47.44	6.46
0.4	59.66	5.14	5	45.29	6.77
0.5	59.31	5.17	6	43.51	7.05
0.6	58.92	5.20	7	42.00	7.30
0.7	58.52	5.24	8	40.70	7.53
0.8	58.11	5.27	9	39.57	7.75
0.9	57.69	5.31	10	38.57	7.95
1	57.27	5.35			

Table.1. ΔT_{j-c_max} and f_{corr} for low output frequencies

For output frequencies above 10Hz, ΔT_{j-c_max} can also be calculated using Melcosim Ver.5.0.1.

2.2.5. The differences between T_{NTC} and T_C

For IGBT modules and heat sink, the below picture Fig.6 shows the thermal distribution and positions of different reference points for T_{NTC} and T_C .

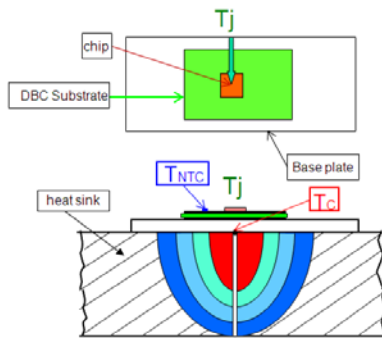


Fig. 6. Thermal distribution and positions of T_{NTC} and T_C

Under constant average losses, T_{NTC} and T_C are slightly influenced by output frequencies, so the differences between T_{NTC} and T_C can be calculated with equation Eq.6.

$$T_{NTC} - T_C = k * P_{ave}$$

$$T_C = T_{NTC} - k * P_{ave}$$
Eq.7

The factor k can be obtained by testing T_{NTC} and T_C under different P_{ave} .

2.2.6. Using the NTC as over-temperature protection for IGBT modules

Based on Eq.5 and Eq.6, Eq.7 is derived as the following.

$$T_{jmax} \doteq T_{NTC} + (f_{corr} - k) * P_{ave}$$
Eq.8

Taking CM450DX-24S1 as an example, T_{jmax} has to be less than 150°C to ensure SCSOA and RBSOA.

$$T_{NTC} \leq 150^{\circ}\text{C} - (f_{corr} - k) * P_{ave}$$
Eq.9

Using the NTC temperature T_{NTC} as OT protection, this OT protection value can be finally achieved by checking the relation of f_{corr} , k and P_{ave} in software.

3. Design details of temperature sensing circuit using diode and the NTC

3.1. Using diode as a temperature sensor to design temperature sensing circuit

To minimize the influence of the flowing current inside diode, a small current is employed. Fig.7 shows the application circuits for T-PM IGBT.

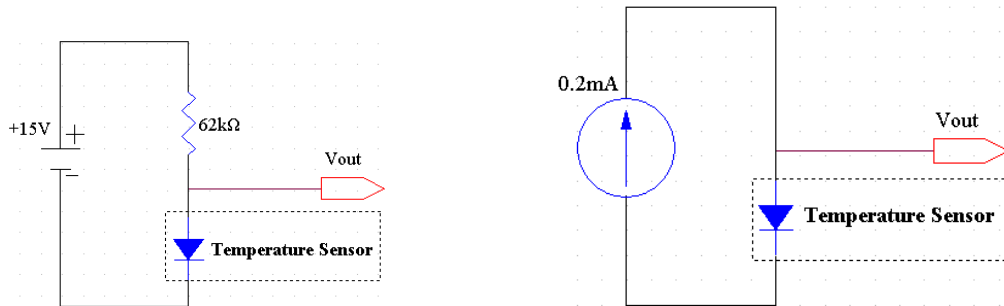


Fig. 7. (a) Using pull-up resistor

(b) Using constant current

3.2. Using the NTC as a temperature sensor to design temperature sensing circuit

3.2.1. The isolation considerations between the NTC and chips

Since the NTC inside IGBT modules could be exposed to a high voltage level during the failure, a functional isolation for the NTC couldn't be sufficient that reinforced isolation is often required in inverter. In accordance with EN 50178, additional isolation has to be done externally.

3.2.2. Design details of temperature sensing circuit

Based on EN 50178, proper isolation levels have to be guaranteed for all parts of a piece of

equipment that can be touched by a person. The isolation against high voltage can be achieved by an opto-coupler to make the NTC isolate from the control logic.

To limit the self heating of the NTC by the flowing current, 3 to 4mA of flowing current are recommended. Fig.8 is a common sensing circuit.

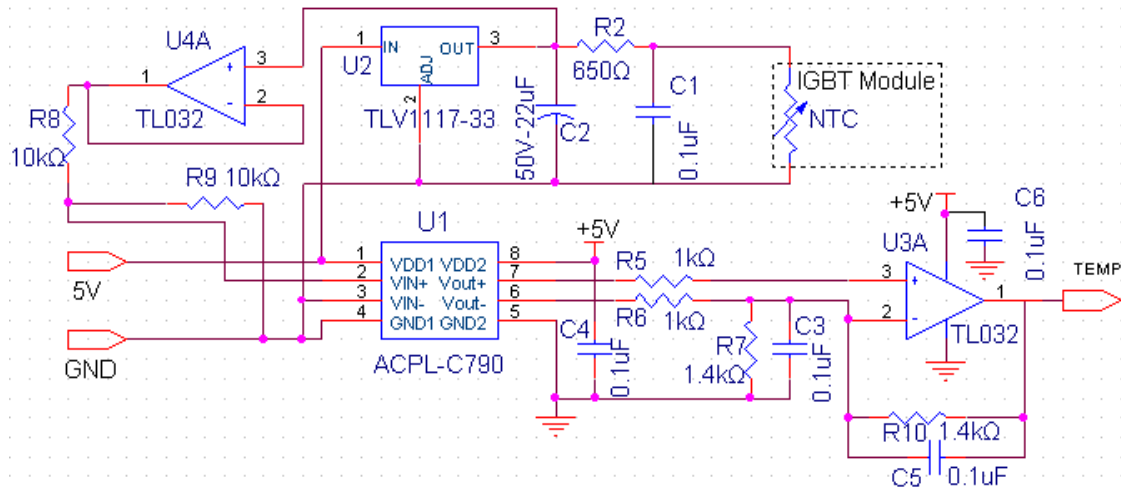


Fig. 8. Application circuit for temperature sensing

4. Conclusion

The NTC is integrated inside IGBT modules as a temperature sensor to make the design of an accurate temperature measurement easy. Based on the relation of T_{jmax} and T_{NTC} , it's easy to set the OT protection point to protect IGBT modules.

5. References

- [1] Tetsuya Ueda, "Simple, Compact, Robust and High-performance Power module T-PM (Transfer-molded Power Module)", in Proc. of the 22nd International Symposium on Power Semiconductor Devices & IC's, Hiroshima, Japan, June 2010, pp.47-50.
- [2] ON Semiconductor, "AN569/D:Transient Thermal Resistance-General Data and Its Use"