Research on IGBT Limit Frequency Based on Heat Balance Analysis
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Abstract. Insulated gate bipolar transistor (IGBT) is the most widely used fully-controlled power electronic device at present. Its limit frequency is generally determined by the maximum junction temperature and maximum power consumption given in the manual, and it is difficult to reflect the nature of thermal failure. Based on the thermal balance analysis of IGBT power consumption-temperature curve and heat transfer curve, the thermal stability point, unstable point and critical point of junction temperature are obtained, thus the IGBT limit power consumption at the critical point is obtained, the design method of IGBT limit frequency is obtained from the tangent of the two curves, and finally the experimental verification is carried out.

Introduction
IGBT is a kind of compound power semiconductor device which combines the structure of field effect transistor and bipolar power transistor. It has the advantages of high input impedance, fast switching speed, low driving power, reduced saturation voltage, large current bearing, etc. It is widely used in various medium and high power electronic devices and is currently the most widely used full control power electronic device [1].

In the existing power electronic devices, IGBT safe operating area is generally designed based on experience and parameters and curves provided by device manufacturers, and a large margin is usually reserved for ensuring reliability in application. At present, the basic idea of studying IGBT limit frequency at home and abroad is based on the steady-state thermal resistance calculation formula, which is realized through the maximum junction temperature given in the manual. Literature [2] studied the IGBT operating limit according to the relationship between maximum junction temperature, thermal resistance and limiting power consumption. Literature [3] analyzed the on-state limit current and the on-state limit power consumption, and points out that the on-state limit power consumption is the power consumption corresponding to the maximum junction temperature. Literature [4] calculated IGBT switch power consumption and conduction power consumption, and estimated the junction temperature at switch works by using the relationship between power consumption and thermal resistance.

Based on the thermal balance analysis of IGBT power consumption-temperature curve and heat transfer curve, this paper obtains the stable point, unstable point and critical point of junction temperature, obtains the limit power consumption of IGBT at the critical point, obtains the limit frequency under certain circuit conditions from the limit power consumption, and finally carries out experimental verification.

Theoretical Analysis
IGBT thermal failure mainly includes long-term thermal accumulation failure and short-term thermal shock failure. Among them, thermal accumulation failure is mainly caused by poor heat dissipation, excessive current and frequency, and there is a process of thermal accumulation.

Heat Balance Analysis of IGBT
The internal structure of IGBT is shown in fig. 1. inside the dotted line frame is a cellular structure of a through-type planar gate.
According to the working mechanism of IGBT, the switching and conduction process of IGBT are electron and hole currents formed by the continuous movement and recombination of carriers in the base region, and the heat generated is mainly concentrated in the active base region of IGBT. In the actual reverse PN junction curve, the reverse current will increase slightly with the increase of the reverse voltage and will increase exponentially with the increase of temperature due to the influence of the generated current in the space charge region and the surface leakage current. When the reverse bias voltage of the PN junction increases, the heat loss caused by the reverse current causes the junction temperature to rise, and the rise of the junction temperature causes the reverse current to increase. If the heat sink cannot transfer heat in time, the junction temperature rise and the increase of the reverse current will cycle alternately, and eventually the PN junction will break down. This breakdown caused by thermal effect is called thermal breakdown. In the same principle, the thermal failure mechanism of IGBT can also be analyzed from the heat balance relationship between the generated heat and the heat that can be dissipated, so IGBT power consumption curve and heat transfer curve need to be obtained.

For the common sinusoidal pulse width bipolar modulated two-level H-bridge inverter circuit, IGBT conduction power consumption, switching power consumption and off-state power consumption are respectively obtained as follows.

\[
\begin{align*}
P_{on} &= \frac{1}{2} \left( \frac{V_{T0} I}{\pi} + \frac{R_{CE} I^2}{4} \right) + m \cdot \cos \phi \cdot \left( \frac{V_{T0} I}{8} + \frac{R_{CE} I^2}{3\pi} \right) \\
P_{SW} &= \frac{1}{\pi} f_{SW} \left( E_{on} (I_{nom}, V_{nom}) + E_{off} (I_{nom}, V_{nom}) \right) \frac{I \cdot V_{dc}}{I_{nom} \cdot V_{nom}} \\
P_{off} &= V_{dc} I_{leak} \left( \frac{1}{2} - \frac{m \cdot \cos \phi}{\pi} \right)
\end{align*}
\]

where: \(V_{T0}\) is the threshold voltage; \(R_{CE}\) is the slope resistance when conducting; \(\cos \phi\) is the load power factor; \(m\) is modulation index; \(I\) is the load current peak value; \(f_{SW}\) is the switching frequency; \(E_{on} (I_{nom}, V_{nom})\) and \(E_{off} (I_{nom}, V_{nom})\) is the switching-on energy and the switching-off energy under the given current and voltage conditions in the device manual; \(V_{dc}\) is the DC voltage value; \(I_{leak}\) is the collector leakage current.

Considering the influence of temperature from equation (1), the IGBT power consumption-temperature relation is obtained:

\[
P_{heat}(T) = P_{on}(T) + P_{SW}(T) + P_{off}(T)
\]

IGBT is generally packaged in modules, and the cross-sectional structure of heat sink is shown in Figure 2.
During IGBT work, most of the heat generated by the internal silicon chip is transferred to the substrate through the direct copper layer under the chip, and then transferred to the surrounding environment through the heat dissipation device. When the heat dissipated is equal to the heat generated, the system reaches a thermal equilibrium state and the temperature of each part remains stable. For a certain combination consisting of IGBT module, radiator and cooling medium, its steady heat transfer power consumption can be expressed as follows\(^5\):

\[
P_{\text{cool}}(T) = \left( T_J - T_C \right) \frac{1}{R_{th-JC}}
\]  

(3)

where: \(R_{th-JC}\) is the junction-shell steady-state thermal resistance, \(T_J\) is the junction temperature, \(T_C\) is the shell temperature and \(P_{\text{cool}}(T)\) is the conduction power consumption.

The IGBT power consumption curve and junction-shell heat transfer curve are plotted in the same coordinate system as shown in fig. 3, where \(P_{\text{heat}}\) is the temperature curve of IGBT power consumption and \(P_{\text{cool}}\) is the temperature curve of IGBT heat transfer power consumption. The abscissa is temperature, and the ordinate is power consumption.

When power consumption changes due to changes in IGBT electrical conditions, the curve will move up and down; When the shell temperature changes due to the change of the heat dissipation device, the heat transfer curve will move left and right.

Heat balance analysis is carried out by combining IGBT power consumption curve and heat transfer power consumption curve. It can be seen from fig. 3 that the IGBT power consumption curve increases exponentially with temperature at high temperature stage, while the slope of the temperature curve of heat transfer power consumption remains unchanged, and the two curves have different changing trends with temperature. Assuming that the shell temperature increases, the heat transfer curve when reaching the heat balance shifts in the positive direction of the axis, intersecting, tangent and without intersection with IGBT power consumption curves respectively.

If the two curves intersect at points A and B, there are:
Below the first intersection point A, it means that the generated power consumption is greater than that taken away by the heat dissipation device, and $T_j$ will continue to rise to point A. IGBT will reach thermal equilibrium and maintain stable temperature;

(2) Between point A and the second intersection point B, it means that the generated power consumption is less than the power consumption taken away by the heat dissipation device and will fall back to the equilibrium point A;

(3) Above point B, it means that IGBT power consumption is greater than that taken away by the heat sink and $T_j$ will rise and cannot reach thermal equilibrium again.

Therefore, point A is the stable operating point of IGBT junction temperature and point B is the unstable point of IGBT junction temperature.

If the two curves are tangent, point A and point B coincide with point C, then the system is in a critical thermal equilibrium state, and the power consumption corresponding to point C is the IGBT limit power consumption at the shell temperature $T_c$.

**IGBT Thermal Failure Mechanism**

In order to keep IGBT in thermal equilibrium, in addition to requirements $P_{heat} = P_{cool}$, it is also required that the increment of power consumption generated by IGBT with temperature must be smaller than the increment of heat transfer power consumption, namely:

$$\frac{dP_{heat}}{dT_j} < \frac{dP_{cool}}{dT_j} = \frac{1}{R_{th-JC}}$$  \hspace{1cm} (4)

Therefore, the heat accumulation failure mechanism of IGBT is summarized as follows. When the heat increment generated by IGBT is greater than the heat increment that can be dissipated, the heat accumulation formed in the active area of the chip leads to the junction temperature rise, which in turn leads to the aggravation of the thermal imbalance state. A positive feedback relationship is formed between the junction temperature and the heat, and the continuous rise of the junction temperature leads to the local occurrence of thermal breakdown.

**IGBT Frequency Limit Design Method**

The thermal balance simulation method based on IGBT electrothermal model can not only obtain the shell temperature when IGBT breaks down, but also design the IGBT parameters to be used to the limit under this shell temperature condition. Taking the limited use of IGBT switching frequency as an example, the design steps are as follows:

(1) Selecting different modeling methods according to IGBT types and circuit conditions to obtain conduction power consumption, switching power consumption and off-state power consumption, thereby obtaining an IGBT total power consumption model;

(2) Considering the relationship between semiconductor physical constants and internal parameters and temperature, IGBT power consumption-temperature curve reflecting temperature characteristics is obtained;

(3) Obtaining a junction-shell heat transfer curve from the junction-shell steady-state thermal resistance;

(4) Heat balance analysis is carried out by combining the IGBT power consumption-temperature curve and the heat transfer curve, and the IGBT power consumption-temperature curve is moved by changing the IGBT working frequency until tangent to the heat transfer curve.

(5) The switching frequency when the two curves are tangent is the limit frequency under this application condition.

**Experimental Verification**

The IGBT model selected is GD50HFL120C1S, which is a soft through two-cell half-bridge module. The experimental conditions are: DC voltage 600V, effective value of load current 75A, load power
factor 0.9, modulation index 0.9, load current frequency 20Hz, shell temperature 80 ℃, initial switching frequency assignment 5kHz.

The IGBT module is fixed on a water-cooled heat dissipation bottom plate capable of adjusting the water flow speed in a large range, and a thermocouple for measuring the shell temperature is arranged directly below the working chip. The initial use of large water flow speed, after a period of time IGBT reach the thermal equilibrium state, the shell temperature rises until it remains stable. Then, adjust and reduce the water flow speed, and the shell temperature will continue to rise and reach the steady state again. Continue to adjust and reduce the water flow speed, and the stable shell temperature gradually increases to around 80 ℃. Finally, adjust and increase the switching frequency, and record the shell temperature and switching frequency when failure occurs. Repeated experiments show that IGBT switching frequency is 6.6kHz and shell temperature is 80 ℃ when failure occurs. Draw IGBT power consumption-temperature curve and heat transfer curve as shown in fig. 4. The dashed line ① is the power consumption curve at the switching frequency of 5kHz, and the solid line ② is the power consumption curve at the switching frequency of 6.6kHz.

![Figure 4. IGBT switching frequency limit limit curve.](image)

As can be seen from fig. 4, when the IGBT switching frequency increases to make the two curves tangent, the limit value of the switching frequency is 6.6kHz, which verifies the IGBT switching frequency limit method based on heat balance analysis.

**Summary**

Through the analysis of the heat balance relationship between IGBT power consumption-temperature curve and heat transfer curve, the maximum power consumption of IGBT when the two curves are tangent is obtained, thus the IGBT switching frequency limit design is carried out. This design method has clear principle and can be analogized to IGBT current limit design.

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**References**


