Analysis on the Influence of IGBT Dead Time Setting

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Abstract. The dead time setting of Insulated Gate Bipolar Transistor (IGBT) is usually determined by the calculation formula in Infenion technical documents. The parameters in the calculation formula are often obtained according to manual or empirical values, without considering actual application conditions, which inevitably leads to unreasonable setting. In this paper, several main factors affecting the dead time setting are analyzed. Based on the working principle of semiconductor devices, the influence laws of bus voltage, current and temperature on IGBT dead time setting are analyzed, and then the design experiment is carried out to verify.

Introduction

Insulated gate bipolar transistor (IGBT) is a composite device which combines the structure of field effect transistor and bipolar transistor, and absorbs the advantages of both at the same time. It is widely used in various high-power power conversion devices. As an important parameter in the use of electric energy conversion device, IGBT dead time setting has an important influence on inverter performance[1-2]. Therefore, IGBT dead time setting needs to take into account the reliability of the device and the quality of the output waveform for reasonable design[3-5].

At present, the dead-time setting of IGBT in power conversion devices is usually determined by the calculation formula in Infenion technical documents, or calculated according to the parameter values of IGBT under rated working conditions, and then given a certain margin, usually no more than 50% is taken as the set value. Its essence is still an estimation method based on experience and the set value given in the manual[6]. In addition, IGBT dead time is closely related to turn-off time, which is affected by bus voltage, current and temperature. Therefore, it is of theoretical and practical significance to study the influencing factors of IGBT dead time for reasonable design of dead time.

Starting from the main factors that affect the dead time setting of IGBT and based on semiconductor physics theory, this paper analyzes the influence of bus voltage, current and temperature on the dead time, which is verified by experiments.

Theoretical Analysis

Calculation of Dead Time Setting

At present, the dead time setting of IGBT is usually based on the calculation formula in Infenion technical documents:

\[ t_{\text{dead}} = \left( t_{\text{d,on,\text{max}} - t_{\text{d,on,\text{min}}} + t_{\text{PDD,\text{max}} - t_{\text{PDD,\text{min}}} \right) \times r \]  \tag{1}

Among them, \( t_{\text{dead}} \) is set for the dead time of IGBT, \( t_{\text{d,on,\text{max}}} \) is the maximum turn-on delay of IGBT, \( t_{\text{d,on,\text{min}}} \) is the minimum turn-on delay of IGBT, \( t_{\text{PDD,\text{max}}} \) is the maximum input-output delay of IGBT drive, \( t_{\text{PDD,\text{min}}} \) is the minimum input-output delay of IGBT drive, and \( r \) is the margin coefficient, which is generally 1.2-1.5.

In equation (1), the first term describes the IGBT device itself and the gate resistance characteristics, and the second term describes the signal delay propagation characteristics determined...
by the drive. Usually, it can be found in the drive manual. For the driver of opto-coupler signal, the delay is large and cannot be ignored.

It is known from equation (1) that the main factors affecting the dead time setting are: IGBT’s off time, on time, maximum input and output delay of IGBT drive circuit, and minimum input and output delay of IGBT drive circuit. The turn-off time and turn-on time are mainly affected by voltage, current and junction temperature, and the turn-off time is usually much larger than the turn-on time due to the presence of trailing current, so the turn-off time is dominant.

**Analysis on the Influence of Voltage**

The influence of voltage on dead time is mainly realized by affecting the turn-off time and turn-on time. Fig. 1 is a structural diagram of a standard NPT IGBT. Among them, J₁ is the P+/N- junction, J₂ is the N-base/P-well junction, and J₃ is the P-well/N+ junction.

![Figure 1. Basic structure diagram of IGBT.](image1)

![Figure 2. IGBT current shutdown waveform.](image2)

When the gate voltage of IGBT is greater than the threshold voltage of IGBT, the inversion layer charge will be generated in the P-well region under the gate. Under the action of Collector and Emitter direct voltage, this part of charge will move from the emitter to the N-base region and generate current through base recombination. When the transistor is turned off, the conductive channel under the gate rapidly disappears, a process time is very short, as shown in stage 1 in fig. 2, while electrons accumulated in a large amount on the side of the N-base region close to the conductive channel recombine through base carriers to generate current tailing, as shown in stage 2. The turn-off time of IGBT is mainly determined by this trailing current.

When IGBT works normally, Collector-Emitter is applied with positive bias voltage and J₂ junction is reverse biased. When IGBT is turned off, electron-hole pairs will be generated in the space charge region of J₂ junction. Since the concentration of electrons and holes in the space charge region is zero and the recombination center energy level generates electrons and holes, these electrons and holes attempt to reestablish thermal equilibrium. Therefore, once electrons and holes are generated, they will be swept out of the space charge region by the electric field, as shown in fig. 3.

![Figure 3. Carrier motion diagram of reverse bias junction.](image3)
Holes are swept into the P collector region, electrons are swept into the N-drift region. With the increase of bus voltage, the width of the $J_2$ junction space charge region increases, generating more electron-hole pairs, and more carriers are swept into the P collector region and the N-drift region from the depletion layer, thus increasing the carrier concentration in the two regions. Therefore, the recombination time of carriers is prolonged, the trailing current is prolonged, and furthermore, the turn-off time is prolonged with the increase of bus voltage.

The expression of the first stage $\Delta I$ in Fig. 2 is as follows:

$$
\Delta I = I_0 - I_1 = I_{MOS} \left\{ 1 - \beta \left( \frac{1 - x_{dn}}{W_B} \right)^2 - 1 \right\}
$$

$$
x_{dn} = \frac{2e_s (V_{bi} + V_B)}{e} \left( \frac{N_a + N_d}{N_a N_d} \right)^{0.5}
$$

where: $V_s$ is the magnitude of the reverse bias voltage applied to the depletion layer; $\varepsilon$ is the dielectric constant of the semiconductor; $V_s$ is a built-in potential difference in a thermal equilibrium state; $\beta$ is BJT current amplification factor $N_a$ is the atomic density of acceptor impurity; $N_d$ is the donor impurity atomic density.

As can be seen from equation (2), the size of the $\Delta I$ is inversely proportional to the width of the depletion layer $x_{dn}$, and $I_1$ increases if the conduction current is kept unchanged, thus prolonging the turn-off time. Therefore, when the current is constant, the longer the turn-off time is, the longer the dead zone setting time is.

**Analysis on the Influence of Voltage**

The influence of current on dead time is mainly realized by influencing the turn-off time. As can be seen from Fig. 2, $\Delta I$ will also change with the change of $I_0$, so it is difficult to visually see the change of current shutdown time. Therefore, we use the ratio of $\Delta I/I_0$ to judge the change of shutdown time. The larger the value, the faster the shutdown and the shorter the tail. The ratio expression is as follows:

$$
K = \frac{\Delta I}{I_0} = \frac{I_{MOS}}{I_{MOS} + I_{CBT1}} = \frac{I_{MOS}}{I_{MOS} + \beta I_{MOS}} = \frac{1}{1 + \beta}
$$

(3)

From semiconductor physics, we can see the relationship between the rate of change $K$ and the current.

$$
dK \propto \frac{1}{I_c^2}
$$

(4)

Equation (4) shows that the smaller the current, the more significant the change in the off-time and the greater the current, the less obvious the change in the off-time with the current. Therefore, the dead time setting of IGBT decreases with the increase of current.

**Effect of TEMPERATURE**

The influence of junction temperature on turn-on time is mainly reflected in the influence on threshold voltage. When $V_{GE} > V_{th}$, collector-emitter current starts to turn on and increases rapidly with $V_{GE}$. Since $V_{th}$ decreases with the increase of temperature, the turn-on time of IGBT is advanced with the increase of temperature under the same conditions. Since $V_{GE}$ rises from 0 to $V_{th}$ in a short
time and the temperature has a general influence on $V_{th}$ of several mV/°C, the temperature has little influence on the turn-on time of IGBT.

The influence of junction temperature on turn-off time is much larger than turn-on time, which is mainly determined by the influence of temperature on carrier lifetime. As shown in fig. 1, when the IGBT is turned off, the channel under the gate is quickly turned off and the channel current disappears, while a large number of electrons are accumulated near the drift region at the $J_2$ junction. These electrons disappear only through recombination with base carriers, thus generating a longer trailing current. When the temperature rises, the semiconductor theory shows that the carrier mobility decreases and the lifetime increases, resulting in a slower current drop, a longer current tail and a longer turn-off time in the turn-off process. In addition, the lowering of $V_{th}$ also makes the control voltage lower to turn off the IGBT, i.e. the time of stage 1 in fig. 2 is prolonged. however, since this time is much smaller than the trailing time, the effect of temperature on stage 1 can be approximately ignored.

Therefore, the effect of junction temperature on the dead time setting is that the larger the junction temperature is, the larger the dead time setting is.

**Experimental Verification**

In order to verify the analysis of the influence of IGBT dead time setting, the test contents include (1) the influence of on-state current on turn-off time; (2) Influence of bus voltage on shutdown time; (3) Effect of temperature on shutdown time.

The circuit used in the experiment is a two-level half-bridge circuit, and the load is a resistive load. The driving signals of the upper and lower tubes in the circuit are shown in fig. 4. When testing the off time, T2 tube is always off, and the off time of T1 tube is the test result. The complementary pulse signal in the figure will be used in the dead time test. The IGBT model used in the experiment is FF650R17IE4V.

**Experiment on Influence of Voltage**

Using bus voltage of 150V to 900V, IGBT turn-off time was tested under the same current. the turn-off waveform is shown in fig. 5. Since the current turn-off waveform is not easy to observe under the same current, the time when the load resistor voltage is collected and the voltage across the resistor drops from 90% to 10% is the current drop time.

As can be seen from fig. 5, under the same current, IGBT turn-off time increases approximately linearly with bus voltage.
Experiment on Influence of Current

Using bus voltage of 900V, IGBT turn-off time was tested under different currents. The turn-off waveform is shown in fig. 6.

As can be seen from fig. 6, as the current increases, the turn-off time decreases. Under the same voltage, IGBT turn-off time decreases with the current approximately exponentially.

Experiment on Influence of Temperature

In order to reduce the influence of high temperature on the packaging materials of high-power IGBT modules, a thermostatic oven is used to control the working junction temperature. The measured waveforms are shown in fig. 7.

![Shutdown curves under different currents](image1)

![Shutdown curves at different temperatures](image2)

As can be seen from fig. 7, the influence of junction temperature on IGBT turn-off time cannot be ignored.

Summary

The main parameters of IGBT dead time calculation formula are turn-off time, and the main factors affecting turn-off time of IGBT are bus voltage, on-current and temperature of IGBT. The change relation is: IGBT dead time increases with the increase of bus voltage, decreases with the increase of conduction current, and increases with the increase of temperature. And the turn-off time is approximately linear with the bus voltage, and is approximately exponential and hyperbolic with the turn-on current, i.e. the smaller the current, the more obvious the change in turn-off time is, and the turn-off time is much less affected by the temperature than by the voltage and current.

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