Evaluation of Frequency and Temperature Dependence of Power Losses Difference in Parallel IGBTs

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ABSTRACT With the development of high power converters, safe operation of IGBT modules with parallel chips is of increasing importance. IGBT can work normally in safe range in the initial operation even if current imbalance is happening. However, if the uneven current state lasts too long, it is difficult to keep a uniform junction temperature, which can further lead to uneven distribution of the power losses. In severe cases, the device and converter may be damaged due to overheating. This paper studies the stability of such an interactive process with mathematical modelling backed by experiment. Because of the opposite sensitivities of switching and conduction losses to temperature under high current injection, the concept of ‘inflection point frequency characteristic’ is introduced to evaluate the trend of junction temperature mismatches between the parallel IGBT chips. The inflection point frequency at different current and temperature levels is tested to verify the model prediction, and the applicability of this approach in multi-chip parallel module is discussed. By establishing the relationship between the switching frequency and the thermal stability limit of parallel IGBTs, it can provide a feasible reference for improving the reliability of multi-chip parallel power devices.

INDEX TERMS Insulated gate bipolar transistor (IGBT), parallel connection, switching loss, conduction loss, power losses.

I. INTRODUCTION

High-power IGBT modules are one of the core components in solid state circuit breaker/transformer and frequency converter technologies [1]. The system power level can now reach 100’s of MW to 1 GW, with the module voltage rating up to 6.6kV and current rating up to 3kA [2], [3]. The gap between the output capacity of high-power IGBT modules and the capacity level required in high-power converter applications is increasing day by day. In combination with reliability, economy and other factors, it is sometimes not the best scheme to select the highest level IGBT [4]. Therefore, multiple IGBT chips are used in parallel to achieve the required current rating and power level [5]–[8]. With the rapid development of permanent magnet direct drive wind power generation technology, the number and quality of IGBT parallel connection required by machine side converter is higher and higher, so as to meet the strict requirements of high efficiency and high reliability of wind power converter [9]. At present, the 1800A/1700V power module widely used in MW level wind power converter is composed of 12 IGBTs in parallel.

For commonly used IGBT, the switching process is an important source of device loss, which needs to be strictly controlled under high frequency and large current conditions. At the same time, the consistency of current and junction temperature distribution between parallel IGBTs need to be paid special attention. However, discreteness of IGBT’s own parameters, asymmetry of drive and main circuit loop layout and other factors will affect the current balance in
parallel IGBTs. As a result, it is difficult to keep a uniform junction temperature, which can further lead to uneven distribution of the power losses [10]–[12]. Therefore, junction temperature of the parallel IGBTs will be further unbalanced. In severe cases, the semiconductor device and converter may be damaged due to overheating [13]–[15].

Most existing studies regarding the influence of temperature on power loss focus on a single IGBT, and there are few reports on the interaction between multiple parallel IGBTs. However, with the development of high power converters, safe operation of IGBT modules with parallel chips is of increasing importance [16]. Therefore, it is important to highlight the effect of junction temperature on the power loss of parallel IGBTs to improve its reliability.

In this context, some preliminary research has been conducted regarding the parallel IGBTs, which could be further classified into two categories. The first category of studies is to establish the mathematical model of IGBT power loss and temperature. The mathematical model of IGBT power loss has been studied in some literatures. Xu et al. proposed a newly developed electrothermal calculation method to estimate the power loss and working temperature of IGBT [17]. Das et al. studied the effect of current on switching loss of IGBT, and established the mathematical relationship between switching loss and device current based on experimental data [18]. Das et al. also studied the variations in switching losses of IGBTs under DC link voltage, and established a simple mathematical relationship between switching losses and DC link voltage based on experimental data [19]. Zou et al. introduced a functional model of transient loss, analyzed the switching process in detail, and established a mathematic expressions of power loss considering stray inductance [20]. Xu et al. proposed an improved behavioral transient model of IGBT with anti-parallel freewheeling diode, and further proposed a power loss estimation approach for switching cell [21].

The second category of studies is to explore the interaction effect of temperature on the power loss between parallel IGBTs. Aiming at the temperature characteristics of IGBT, the mechanism and application of it have been studied in some literatures. Based on the one-to-one correspondence between the internal physical parameters and the temperature, [22]–[29] established the temperature-dependent functionality expression of IGBT electrical parameters, and used it to estimate the junction temperature of IGBT. Dupont et al. presented an experimental evaluation of two new thermo-sensitive electrical parameters (TSEPs) based on forward voltage measured at different injection current levels, which could be used during operation of the converter [30]. Singh et al. pointed out that the temperature characteristic of IGBT is related to the injection current level in steady-state conditions [31]. At high frequency, the trend of parallel IGBTs power loss affected by temperature remains unclear. At this time, the switching loss of IGBT becomes an important part of power loss, and further affects the junction temperature of the device. However, most of the research on the influence of temperature on power loss focuses on a single IGBT, and very little was found in the literature on the question of interaction between parallel IGBTs.

In this paper, taking the IGBT discrete devices as the research object, studies the stability of parallel IGBTs electrothermal interactive process with mathematical modelling backed by experiment. The work of this paper lies in the second category of studies as described above, focusing on the trend of switching loss and conduction loss to temperature. Based on the relationship between switching frequency and temperature difference, the concept of ‘inflection point frequency characteristic’ was proposed to evaluate development trend of junction temperature difference of parallel IGBTs. The inflection point frequency at different current and temperature difference levels is tested to verify the model prediction, and the applicability of this approach in multi-chip parallel modules is discussed. By establishing the relationship between the switching frequency and the thermal stability limit of parallel IGBTs, it can provide a feasible reference for improving the reliability of multi-chip parallel power devices.

The paper is organized as follows. Section II introduces the temperature loss characteristics of single IGBT, and establishes the mathematical model of power loss and temperature. Section III presents the ‘inflection point frequency characteristic’ of parallel IGBTs and verified by experiment in Section IV. Section V discusses the applicability of inflection point frequency in multi-chip parallel modules. Finally, Section VI concludes the paper.

II. TEMPERATURE LOSS CHARACTERISTICS OF SINGLE IGBT

The loss of IGBT in working process is determined by the nature of its material and the structure of device [32]. As the material parameters change with temperature, the electrical characteristics of IGBT also change with temperature. Therefore, there is a correlation between temperature and power loss. Considering that the off-state blocking loss of IGBT accounts for a relatively small proportion of the total loss [33], this paper only considers switching and conduction losses [34].

A. EFFECT OF TEMPERATURE ON TURN-ON SWITCHING LOSS

Fig. 1 shows collector-emitter voltage $u_{ce}$ and collector current $i_c$ waveforms during IGBT turn-on. According to the analysis of the internal mechanism of turn-on process, which can be separated into three stages: collector current rising stage; diode reverse recovery stage; diode reverse recovery blocked stage.

1) COLLECTOR CURRENT RISING STAGE $t_{1n}$ – $t_{2n}$

After IGBT is turned on, the gate-emitter voltage $u_{ge}$ begins to rise. At $t_{1n}$, $u_{ge}$ begins to threshold voltage $u_{th}$, and then the collector current $i_c$ begins to rise. As the rise of $i_c$, the stray inductance of the IGBT loop result in sag of $u_{ce}$, which leads to the rapid drop of $u_{ce}$. The data sheet of IGBT will provide...
The collector current of IGBT drops sharply, and then it is the free carriers in the drift region are extracted, forming a depletion region that can withstand high electric fields [35]. The collector current of IGBT drops sharply, and then it decays as exponential function, while the tail current in this process is not obvious. Therefore, assuming that the duration of this phase is the same as that of the reverse recovery phase, and the collector current remains unchanged, and the duration of this stage can be obtained [20]:

\[
\begin{align*}
  u_{ce} &= I_{dc} - L_s \frac{di_c}{dt} t \\
  i_c &= \frac{di_c}{dt} 
\end{align*}
\]

where \( L_s \) is stray inductance of the whole IGBT loop, including stray inductance of DC busbar and DC capacitors, lead inductance of the IGBT as well as each connection. \( U_{dc} \) is the DC-link voltage. \( t_{on1} \) is the duration in this stage.

The turn-on switching loss during collector current rising stage:

\[
E_{on1} = \int_0^{t_{on1}} u_{ce} i_c dt = U_{dc} I_{c n}^2 / 2 \left( \frac{L_s}{3} \right) + L_s I_{c n}^2 / 3 
\]

where \( I_c \) is the load current.

2) DIODE REVERSE RECOVERY STAGE \( t_{2n} \rightarrow t_{3n} \)

At \( t_{2n} \), \( i_c \) has risen to the rated value determined by the load. According to the analysis of the internal mechanism of reverse recovery, \( i_c \) keeps rising. Assuming that \( u_{ce} \) is fixed and the rise slope of collector current remains unchanged, and the duration of this stage is:

\[
t_{on2} = \frac{I_{rrm}}{\frac{di_c}{dt}} 
\]

where \( I_{rrm} \) is the peak value of reverse recovery current. It is approximately proportional to the load current at a definite.

The turn-on switching loss during diode reverse recovery stage:

\[
E_{on2} = \int_0^{t_{on2}} u_{ce} i_c dt = \left( U_{dc} - L_s \frac{di_c}{dt} \right) \left( \frac{I_{rrm}}{3} + I_{rrm}I_c \right) 
\]

3) DIODE REVERSE RECOVERY BLOCKED STAGE \( t_{3n} \rightarrow t_{4n} \)

At \( t_{3n} \), the diode completed the transition from the forward conduction to the reverse blocking state. The high concentration free carriers in the drift region are extracted, forming a depletion region that can withstand high electric fields [35]. The collector current of IGBT drops sharply, and then it decays as exponential function, while the tail current in this process is not obvious. Therefore, assuming that the duration of this phase is the same as that of the reverse recovery phase, and the collector current remains unchanged, and the duration of this stage can be obtained [20]:

\[
\begin{align*}
  u_{ce} &= U_{dc} - L_s \frac{di_c}{dt} - U_{dc} - L_s \frac{di_c}{dt} \\
  i_{c} &= U_{dc} - L_s \frac{di_c}{dt} 
\end{align*}
\]

So the turn-on switching loss during diode during reverse recovery blocked stage is:

\[
E_{on3} = \int_0^{t_{on3}} u_{ce} i_c dt = \left( U_{dc} - L_s \right) \left( \frac{I_{rrm}}{3} + I_{rrm}I_c \right) 
\]

To sum up, the turn-on switching loss of IGBT is:

\[
E_{on} = E_{on1} + E_{on2} + E_{on3} = U_{dc} \left( \frac{I_{c n}}{3} + I_{rrm}I_c \right) + L_s \left( \frac{I_{rrm}}{3} + I_{rrm}I_c \right) 
\]

Among the parameters involved in the turn-on switching loss, only the current rise slope is related to IGBT temperature, so

\[
E_{on} = \frac{K_{on}}{\frac{di_c}{dt}(T)} + o 
\]

where, \( o \) and \( k_{on} \) are constant independent of temperature.

From the relation between the current rise slope and temperature [36], the relationship between IGBT turn-on switching loss and temperature can be obtained:

\[
E_{on} \propto \left( \frac{T}{300} \right) \phi 
\]

where, \( \phi \) is the temperature coefficient of switching loss.

B. EFFECT OF TEMPERATURE ON TURN-OFF SWITCHING LOSS

Fig.2 shows the \( u_{ce} \) and \( i_c \) waveforms during IGBT turn-off. According to the analysis of the internal mechanism of turn-off process, which can also be separated into three stages: \( u_{ce} \) voltage rising stage; \( i_c \) current drop stage; current tailing stage.

1) \( u_{ce} \) VOLTAGE RISING STAGE \( t_{1f} \rightarrow t_{2f} \)

At this stage, \( i_c \) keeps the load current \( i_c \) constant, and \( u_{ce} \) linearly rises to the DC link voltage. The rise time at this stage is:

\[
t_{off1} = \frac{U_{dc}}{\frac{du_{ce}}{dt}} 
\]

The turn-off switching loss during \( u_{ce} \) voltage rising stage:

\[
E_{off1} = \int_0^{t_{off1}} i_c \cdot \frac{du_{ce}}{dt} dt = \frac{U_{dc}^2 \cdot I_{c n}}{2 \frac{du_{ce}}{dt}} 
\]
Since the turn-off switching loss and temperature are related to IGBT temperature, so the relationship between IGBT turn-off switching loss and temperature can be obtained by combining equation (9)

$$E_{off} < 2 \approx k_2 \left( \frac{T}{300} \right)^{\phi}$$

where, $k_2$ is constant independent of temperature.

3) CURRENT TAILING STAGE $t_3 f \sim t_4 f$

At $t_3 f$, the collector current drops to the tailing current $I_{tail}$, after which it no longer decreases as fast as before, and the slope will gradually slow down. Under the action of external voltage, it usually takes several microseconds to remove the remaining carriers in the IGBT to completely turn off the IGBT. In practice, the determination of the turn-off energy per pulse is mostly done with an oscilloscope; the product of current waveform and voltage waveform is executed and integrated over the turn-off time interval. So, a simplified estimation can be made with [27]

$$E_{off} = \frac{1}{2} U_{dc} I_{tail} t_{tail}$$

The duration of the tailing current increases with increasing temperature [19], which greatly affects the turn-off switching loss. Finally, the relationship between the turn-off switching loss and temperature during the current tailing stage can be obtained:

$$E_{off} = E_{off1} + E_{off2} + E_{off3} \propto \left( \frac{T}{300} \right)^{\phi}$$

From (9) (23), the relationship between switching loss and temperature of IGBT can be obtained

$$E_{sw} = E_{on} + E_{off} \propto \left( \frac{T}{300} \right)^{\phi} \approx k_{sw} \left( \frac{T}{300} \right)^{\phi}$$

where, $k_{sw}$ is constant independent of temperature.

For Infineon trench-gate IGBTs IHW20N120R2, are chosen as the devices under tests (DUTs), according to the $E_{sw}$ data obtained from the experimental results, the model parameter $\phi = 2.263$ can be obtained from equation (24) fitting, and the model fitting effect shows in Fig. 3.

C. EFFECT OF TEMPERATURE ON CONDUCTION LOSS

The static characteristics of Non Punch Through(NPT) IGBT are affected by temperature, which is related to the injection current level. At low current, the temperature coefficient of NPT IGBT is governed by the characteristics of the diode voltage drop; as current level increases, the voltage drop across MOSFET becomes predominant [31]. This causes NPT IGBT characteristics to shift from NTC to PTC, as shown in Fig. 4(a).
For Infineon trench-gate IGBTs IHW20N120R2, the static characteristics of IGBT at different temperatures are measured by Agilent B1505 power device analyzer, and the temperature characteristics of collector current can be obtained by data fitting

\[ I_c = m_1 U_{ce} + (m_2 - m_3 U_{ce}) T + m_4 U_{ce}^2 - m_5 \]  

(25)

where, \( m_1 = 52.34, m_2 = 0.096, m_3 = 0.952, m_4 = 1.2856, m_5 = 47.5136 \), the model data and experimental results fit better, as shown in Fig. 4(b).

Therefore, the relationship between the conduction loss and temperature of IGBT in a cycle can be obtained

\[ E_{cond} = D U_{ce} \left( m_1 U_{ce} + (m_2 - m_3 U_{ce}) T + m_4 U_{ce}^2 - m_5 \right) \left( T / K \right) \]  

(26)

where, \( D \) is duty cycle of IGBT switching, \( f \) is the switching frequency.

The power loss of IGBT in a switching cycle is composed of switching and conduction losses. The effect of temperature on conduction loss is related to on-state collector-emitter voltage \( U_{ce} \). IGBT has a relatively large \( U_{ce} \) under high current injection, so \( m_2 \ll m_3 U_{ce} \). It can be seen from (24) and (26) that \( E_{sw} \) and \( E_{cond} \) have opposite temperature characteristics in a switching cycle, and the \( E_{cond} \) is directly related to the switching frequency. It should be noted that higher switching frequency leads to higher junction temperature. Therefore, the temperature characteristics in the switching state need to introduce frequency factor. Because current sharing and junction temperature of the parallel IGBTs were unbalanced, the switching process and conduction behavior will be more combined with the temperature characteristics. In order to keep the junction temperatures of parallel IGBTs more consistent, the temperature characteristics of them will be further studied below.

### III. “INFLEXION FREQUENCY CHARACTERISTIC” OF PARALLEL IGBTS

#### A. LOSS DIFFERENCE AT DIFFERENT TEMPERATURES

When IGBTs operate in parallel, the magnitude of the total parallel current is determined by the load to keep the load current \( I_c \) constant, but the junction temperature difference will affect the current distribution of each parallel IGBT. The degradation rate of parallel IGBTs is not uniform, which results in different aging degree and makes them work at different junction temperature. According to the effect of temperature on power loss, different junction temperature will produce different power loss, further forming feedback effect on junction temperature.

The same model and the same batch of products are usually selected for parallel connection to improve the reliability of the device. Therefore, the temperature loss characteristic coefficients of the two IGBTs are approximately the same. The difference in collector current at different temperatures is

\[ \Delta I_c = I_{c(T_{max})} - I_{c(T_{min})} \]  

(27)

It can be seen from equation (25) that when IGBT has a relatively large \( U_{ce} \) under high current injection, \( m_2 \ll m_3 U_{ce} \), the collector current is inversely proportional to temperature, \( \Delta I_c \) is negative. The effect of temperature on \( U_{ce} \) is shown in Fig. 4(a), which can be obtained

\[ U_{ce(T_{max})} \approx U_{ce(T_{min})} \]  

(28)

Furthermore, the difference of conduction loss at different temperatures is approximately

\[ \Delta E_{cond} = E_{cond(T_{max})} - E_{cond(T_{min})} = D U_{ce} \Delta I_c / f \]  

\[ = D U_{ce} (m_2 - m_3 U_{ce}) \Delta T / f \]  

(29)
where $\Delta T = T_{\text{max}} - T_{\text{min}}$ is the difference between maximum and minimum temperature.

It can be seen from (24) that the difference of switching loss at different temperatures is

$$\Delta E_{\text{sw}} = E_{\text{sw}(T_{\text{max}})} - E_{\text{sw}(T_{\text{min}})} = k_{\text{sw}} \left( \frac{T_{\text{min}} + \Delta T}{300} \right)^y - \left( \frac{T_{\text{min}}}{300} \right)^y$$  \hspace{1cm} (30)

In a switching cycle, the difference of total loss at different temperatures is

$$\Delta E = \Delta E_{\text{sw}} + \Delta E_{\text{cond}}$$  \hspace{1cm} (31)

Due to the loss difference, the temperature difference between the two IGBTs further changes to

$$\Delta T = E_{(T_{\text{max}})} R_{\text{th}(T_{\text{max}})} - E_{(T_{\text{max}})} R_{\text{th}(T_{\text{min}})}$$  \hspace{1cm} (32)

### B. TEMPERATURE DIFFERENCE-FREQUENCY CHARACTERISTICS OF PARALLEL IGBTs

It can be seen from (29) and (30) that when IGBTs operate in parallel, the switching loss of IGBT increases with the increase of temperature. The effect of temperature on conduction loss is related to on-state collector-emitter voltage $U_{ce}$. When IGBT has a relatively large $U_{ce}$ under high current injection, the conduction loss decreases with increasing temperature, whereas the case of low current injection is the opposite. Therefore, in a switching cycle, the conduction loss of IGBT is affected by temperature in two cases: positive feedback and negative feedback. In case of high current injection, the switching loss and conduction loss have the opposite trend to the temperature, in which the conduction loss is proportional to the switching frequency and temperature respectively. Therefore, the existence of a switching frequency $f_0$ keeps the total power loss in a period constant, so as to ensure that the junction temperature difference between parallel IGBTs will not continue to change, that is,

$$f_0 = \frac{|D U_{ce} \Delta I_c|}{\Delta E_{\text{sw}}}$$  \hspace{1cm} (33)

Define $f_0$ as “frequency inflection point” when junction temperature difference is $\Delta T$ and the injection current level is $I_c$. Thus, the frequency-loss characteristic of parallel IGBTs can be obtained, as shown in Fig.5.

When switching frequency is higher than “frequency inflection point” $f_0$, the impact of switching loss on parallel current sharing and temperature characteristics is dominant, and the junction temperature of high-temperature IGBT will further increase, which will make the device fail or even damage the converter seriously; when switching frequency is lower than $f_0$, the impact of conduction loss on parallel current sharing is dominant, and the temperature of parallel IGBTs tends to be uniform, which makes the device in a thermally stable state; when working at $f_0$, the loss difference of parallel IGBTs is zero, so the junction temperature difference between them remains unchanged.

According to (33), if the temperature difference $\Delta T$ between two IGBTs is 0, the junction temperature has no limiting effect on the switching frequency. Under the current in positive temperature characteristic region, the relationship between $\Delta T$ and $f_0$ is shown in Figure 8. With the increase of temperature difference, the absolute value of conduction loss difference between parallel IGBTs increases linearly, whereas the difference between switching loss increases exponentially, so the frequency inflection point will decrease with the temperature. In actual operation, when the duty cycle is fixed and the switching frequency is higher than $f_0$, without temperature coupling, the device temperature difference will increase from the initial value. Finally, the high-temperature IGBT will first reach the thermal limit failure. Therefore, the frequency inflection point of parallel IGBTs will limit its thermal stability limit.

According to equation (33), $f_0$ is proportional to the duty cycle. As shown in Fig. 7, the frequency inflection point increases as the increase of duty cycle. Therefore, when parallel IGBTs are controlled by chopping control mode, the frequency inflection point characteristic curve should be corrected according to the duty cycle.

### IV. EXPERIMENTAL VERIFICATION

#### A. EXPERIMENTAL PLATFORM

Double pulse test is used to verify the temperature difference-frequency characteristics of parallel IGBTs at different temperatures derived in Section III. The Infineon trench-gate IGBTs IHW20N120R2 are chosen as the DUTs. The test circuit and test bench are shown in Fig. 8, where $U_{dc}$ is DC link voltage, $C$ is DC bus capacitance, the upper leg is silicon PiN diode in parallel with load inductance $L$, and the lower leg is tested device parallel IGBTs T1 and T2. The first pulse is used to control the load current approach the setting value and the second pulse is to measure $u_{ce}$ and $i_c$ during the parallel IGBTs turn on and off. The electric heating plate with temperature control is placed under the basement of T1 to warm it precisely, and T2 is kept at 25°C room temperature to simulate the switching characteristics of parallel IGBTs at different junction temperatures. Before the test, the basement of T1 is warmed for a while until the temperature seems to
be stable, which means the junction temperature and case temperature of T1 are equal to the temperature measured by the heating plate. Then the parallel IGBTs are triggered with the gating pulse and the measurement starts. A series of characteristics of IGBT under different temperature difference can be obtained by adjusting the temperature of electric heating plate.

The same model and batch of products are selected to parallel to eliminate the influence of the discreteness of IGBT’s own parameters on the test results. The circuit layout is symmetrical and the lead wire is shortest as far as possible to eliminate the influence of the layout of external circuits on the test results. Because the frequency inflection point only occurs in high current injection, the experimental verification is discussed for the case of high current injection.

The heating plate is used to control the temperature difference $\Delta T$ between two IGBTs, and the first pulse is used to control the total load current $I_{\text{all}}$ approach the setting value. Repeat the above experiment to gain switching process of different temperature difference and different parallel current level.

**FIGURE 6.** Temperature difference-frequency characteristics of parallel IGBTs.

**FIGURE 7.** Temperature difference-frequency characteristics at different duty cycles.

**FIGURE 8.** Double test circuit and test bench.

**B. EXPERIMENTAL RESULTS OF SWITCHING LOSS CHARACTERISTICS**

The switching process test results of high-temperature IGBT and low-temperature IGBT under 400V DC voltage are shown in the Fig.9. The turn-off loss of high-temperature IGBT is significantly lower than that of low-temperature IGBT. The switching loss difference between high-temperature and low-temperature IGBT is

$$\Delta E_{sw} = \int_{t_{1n}}^{t_{4n}} U_{ce}(i_H - i_L)dt + \int_{t_{1f}}^{t_{4f}} U_{ce}(i_H - i_L)dt$$

And fit to the form of equation (33), as shown in Fig. 10. The fitting results show that the aforementioned model can well characterize the relationship between switching loss. With the increase of temperature difference, the switching loss difference increases significantly.

**C. EXPERIMENTAL RESULTS OF CONDUCTION CURRENT DIFFERENCE**

Similarly, the difference between the conduction currents of parallel IGBTs at different temperature difference is shown in Fig. 11. Although parallel IGBTs voltage clamp, the collector current gap increases with the increase of temperature.
so the total parallel current level affects the inflection point frequency.

As shown in Fig. 10 and Fig. 11, the sensitivity of $\Delta E_{\text{sw}}$ to temperature is greater than $\Delta E_{\text{cond}}$, so the inflection point frequency decreases with the temperature difference increases at a certain total parallel current. When the duty cycle is constant, the smaller the parallel current is, the larger the junction temperature difference is, and the smaller the inflexion frequency is.

D. EXPERIMENTAL RESULTS OF INFLECTION POINT FREQUENCY CHARACTERISTICS

The conduction current distribution and switching loss of IGBT can be measured by experiment, so as to extract the inflection point frequency with the junction temperature difference at different current levels, as shown in Fig. 12. It can be seen from Fig. 12 that the inflection point frequency is related to junction temperature difference and load current: with the parallel current of 43A and the duty cycle of 0.99, the inflection point frequency decreases from 20.8kHz to 9.4kHz as the junction temperature difference increases from 25°C to 125°C; with the junction temperature difference of 25°C and the duty cycle of 0.99, the inflection point frequency decreases from 20.8kHz to 3.3kHz as the parallel current decreases from 43A to 16A.
In summary, the relationship between the inflection point frequency and junction temperature difference, current injection level, and duty cycle is proved by experiments. In actual operation, when parallel IGBTs work at the lower point in the positive temperature characteristic region, its inflection point frequency is very low. If the switching frequency exceeds the maximum inflection point frequency, it will easily cause the junction temperature of high-temperature IGBT to further increase, which will cause device failure in serious cases; on the contrary, when parallel IGBTs works at the higher point in the positive temperature characteristic region, its inflection point frequency is higher. The loss difference of parallel IGBTs decreases with the increase of temperature difference, the junction temperature of high-temperature IGBT further decreases, and finally in a thermal stable state.

V. DISCUSSION

Multi-chip parallel power modules are widely used in MW level wind power converter, so it is necessary to discuss and analyze them. According to the above research, when the switch frequency is lower than the inflection point frequency, the parallel IGBTs are in a thermal stability state; when the switch frequency is higher than the inflection point frequency, the parallel IGBTs will enter the thermal runaway state. Furthermore, for the multi-chip parallel IGBT power module, only the switch frequency is lower than the minimum inflection point frequency, it can be in a thermal stable state.

From equation (33), the inflection point frequency is inversely proportional to the switching loss difference and directly proportional to the current difference. Therefore, the larger the switching loss difference is, the smaller the current difference is, and the lower the inflection point frequency is. The switching loss difference is also related to the temperature difference between chips. The greater the temperature difference between parallel chips is, the greater the switching loss difference is. Although the response of thermal coupling between chips will lead to current imbalance, the switching loss difference is mainly determined by the temperature difference, and has little correlation with the collector current. It can be seen from Fig. 6 that the change of temperature difference has more influence on the switching loss difference than on the current difference, so the minimum inflection point frequency appears between the two chips with the highest temperature and the lowest temperature. So, the minimum inflection point frequency is

$$f_{\text{min}} = \frac{DUce}{E_{\text{sw}}(T_{\text{max}}) - E_{\text{sw}}(T_{\text{min}})}$$

From Fig. 13, when the junction temperature difference is 25°C and the duty cycle is 0.99, for the same 1700V/1000A power module, the minimum inflection point frequency of Infineon power module is several kHz, whereas SEMIKRON power module is only a few hundred Hz. The above study shows that the larger the junction temperature difference is, the smaller the inflection point frequency is. Therefore, when the temperature difference increases, the minimum inflection point frequency will further reduce. To sum up, the information of minimum inflection point frequency is very important to improve the reliability of high voltage multi-chip parallel power module.

VI. CONCLUSION

In this paper, taking the IGBT discrete devices as the research object, the effect of temperature on switching and conduction is analyzed when there is junction temperature difference between parallel IGBTs. Because of the opposite sensitivities of switching and conduction losses to temperature under high current injection, the concept of ‘inflection point frequency characteristic’ was proposed to evaluate the trend of junction temperature mismatches between the parallel IGBT chips. The existence of inflection point and the correctness of mathematical model are verified by experiments.
Finally, the applicability of this approach in multi-chip parallel modules is discussed. The following conclusions can be drawn:

1) There is inflection point frequency in parallel IGBTs working in the positive temperature characteristic region, and the loss difference working in different junction temperature is zero at this frequency.

2) The inflection point frequency is related to load current, temperature difference and duty cycle. If the switching frequency is above this frequency, the temperature of high-temperature IGBT will be out of control and eventually thermal instability happens; otherwise, the junction temperatures of parallel IGBTs tend to be consistent, which is beneficial to stable operation. Switching at such frequency, the original junction temperature difference between parallel IGBTs can be maintained.

To sum up, the inflection point frequency should be included in the thermal design index of parallel IGBTs, and its influencing factors should be fully considered. When IGBTs operate above the inflection point frequency, the change of resistance can be used as a means of junction temperature monitoring.

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