A Method of Power Loss Calculation for RB-IGBT Matrix Converter

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***Abstract*-The calculation and distribution of power losses for RB-IGBT based matrix converter are discussed in this paper. The on-state performance and switching transients of RB-IGBTs are analyzed in detail. According to this analysis, the calculation models of switching losses and conduction loss are established and a power loss calculation method based on the mathematical fit of experimental test data is proposed. Calculation results are presented to validate the proposed method. In addition, this method can also be used for other power converters using RB-IGBT.**

I. Introduction

Reverse blocking IGBT (RB-IGBT) is a power semiconductor with the capability of bi-directional blockings. It is suitable to be used in the bi-directional switches for some power converters, especially for matrix converter [1][2]. As shown in Fig.1, RB-IGBT is employed to construct the bi-directional switch, which replaces the series connection of conventional IGBT and fast recovery diode (FRD). By using RB-IGBT, the number of power device and the power loss in matrix converter can be reduced[1].

Matrix converter is direct power conversion device, which is shown in Fig.2. Since the topology of matrix converter is a configuration without dc link, it has some inherent advantages: (1) easy bi-directional power flow, (2) sinusoidal input/output currents, (3) unity input power factor. The concept of matrix converter has been proposed for more than three decades, and some products have been developed. Some effective calculation methods for power loss of matrix converter have been proposed [3][4]. In addition, the calculation method for the PWM inverters based on conventional IGBT can also be used for matrix converter [5]. However, most of the works focus on the

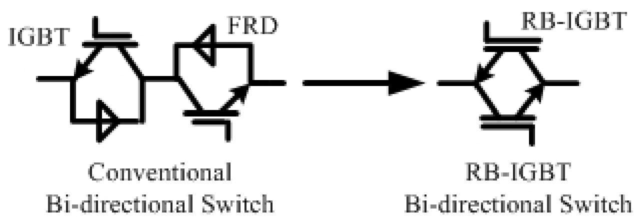


Fig. 1. Topology of bi-directional switch

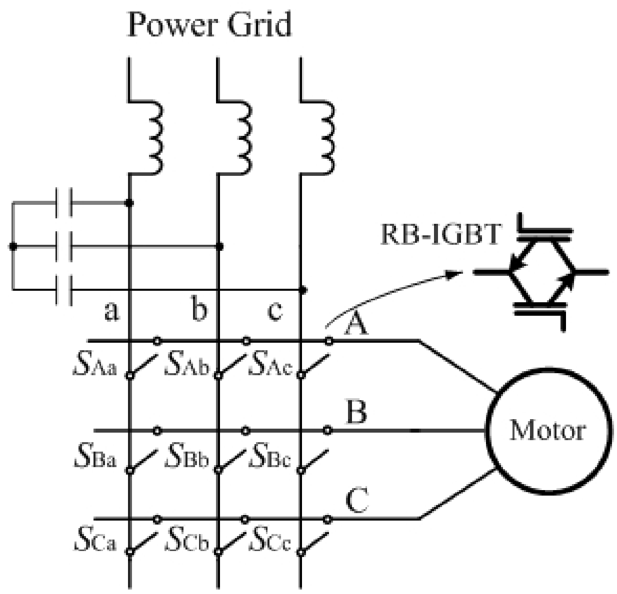
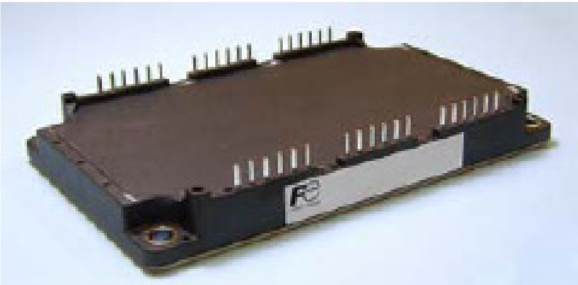


Fig. 2. Topology of RB-IGBT matrix converter

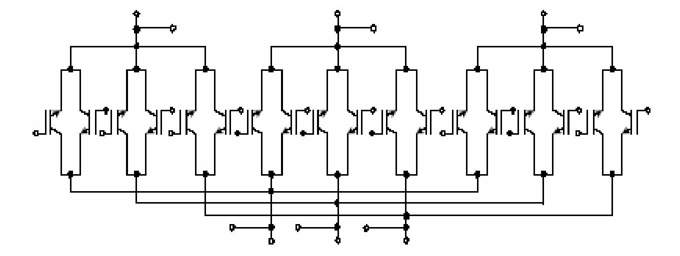
matrix converter using conventional IGBT, while only a few papers took the RB-IGBT matrix converter into account for power loss calculation[6].

This paper proposes a simple method to calculate the power losses of RB-IGBT matrix converter, including switching losses and on-state conduction loss. The conduction loss is calculated based on the operation principle of matrix converter and the I-V curve of RB-IGBT. The switching losses are calculated by using the simplified calculation models, which are developed from experimental waveforms. Some unmeasurable variables in calculation models can be obtained from measurable data through mathematical fit. Thus, the power losses calculation of RB-IGBT matrix converter is achieved and the calculation results are presented.

In this paper, a matrix converter prototype using 600V/100A 18-in-1 RB-IGBT module is implemented and the experimental test data on it are used as the base of power loss calculation. The photo and equivalent circuit of RB-IGBT module are shown in Fig.3. There are 18 RB-IGBTs inside this module, which make up 9 bi-directional switches by anti-paralleled connection. This matrix converter prototype is applied to drive an induction motor.



a. Photo of RB-IGBT module



b. Equivalent circuit of RB-IGBT module

Fig. 3. RB-IGBT module

II. Conduction Loss Calculation

The instantaneous conduction loss of a RB-IGBT in three-phase to three-phase matrix converter $P_{\text{cond}}(t)$ can be calculated by,

$$P_{\text{cond}}(t) = V_{\text{ce\_on}}(t) \cdot I_{\text{c}}(t) \tag{1}$$

where $V_{\text{ce\_on}}(t), I_{\text{c}}(t)$ are the on-state collector-emitter voltage drop and collector current of RB-IGBT respectively.

According to the I-V characteristic of RB-IGBT, which is shown in Fig.4, $V_{\text{ce\_on}}(t)$ can be considered as a function of $I_{\text{c}}(t)$,

$$V_{\text{ce\_on}}(t) = f_1(I_{\text{c}}(t)) \tag{2}$$

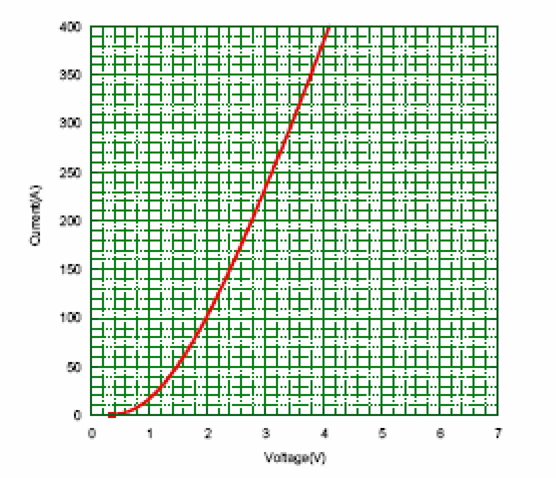


Fig. 4. I-V curve of RB-IGBT module ($T_{\text{j}} = 125^{\circ}\text{C}$)

The function $f_1(I_{\text{c}}(t))$ is obtained by means of mathematical fit from the I-V curve shown in Fig.4.

$$\begin{aligned} V_{\text{ce\_on}}(t) = f_1(I_{\text{c}}(t)) &= 0.403938 + 0.0448708 I_{\text{c}}(t) \\ &\quad -0.000204671 I_{\text{c}}^2(t) \end{aligned} \tag{3}$$

While setting the output period of matrix converter is T_{o}, the conduction energy loss related to one output phase in one output period is,

$$E_{\text{cond}} = \int_0^{T_{\text{o}}} V_{\text{ce\_on}}(t) \cdot I_{\text{c}}(t) dt = \int_0^{T_{\text{o}}} f_1(I_{\text{c}}(t)) \cdot I_{\text{c}}(t) dt \tag{4}$$

Thus, the average conduction loss related to one output phase in one output period can be obtained by,

$$P_{\text{cond}} = E_{\text{cond}} / T_{\text{o}} \tag{5}$$

Assuming the output frequency is 20Hz, while $T_{\text{o}} = 50\text{ms}$, and the load torque of induction motor is $T_{\text{L}} = 8\text{Nm}$. By the simulation for matrix converter operation, the one phase output current is,

$$I_{\text{c}}(t) = 5.5 \sin(2\pi \cdot 20 \cdot t) \tag{6}$$

Hence, the conduction energy loss related to one output phase under the set working condition can be obtained by using (3),(4), and (6),

$$\begin{aligned} E_{\text{cond}} &= \int_0^{0.05} [0.403938 I_{\text{c}}(t) + 0.0448708 I_{\text{c}}^2(t) \\ &\qquad - 0.000204671 I_{\text{c}}^3(t)] dt \\ &= 0.0339335\text{J} \end{aligned} \tag{7}$$

The average conduction loss related to one output phase in one output period and the total conduction loss of matrix converter under set working condition are,

$$P_{\text{cond}} = E_{\text{cond}} / T_{\text{o}} = 0.0339335\text{J} / 0.05\text{s} = 0.67867\text{W} \tag{8}$$

$$P_{\text{cond\_total}} = P_{\text{cond}} \times 3 = 2.03601\text{W} \tag{9}$$

III. Switching Loss Calculation

The switching loss of RB-IGBT matrix converter consists of turn-on loss, turn-off loss and tail current loss.

A. Turn-on Loss Calculation

The experimental data of the turn-on transient of RB-IGBT are shown in Fig.5. According to the experimental waveforms, the calculation model of turn-on loss is simplified and summarized as shown in Fig.6. The energy loss of one turn-on switching can be calculated by,

$$E_{\text{on}} = \frac{1}{2}(I_{\text{rr}} + I_{\text{c}}) \cdot V_{\text{ce\_plat}} \cdot t_{\text{on}} \tag{10}$$

The definitions of $I_{\text{rr}}, I_{\text{c}}, V_{\text{ce\_plat}}, V_{\text{ce}}, t_{\text{on}}$ are shown in Fig.6.

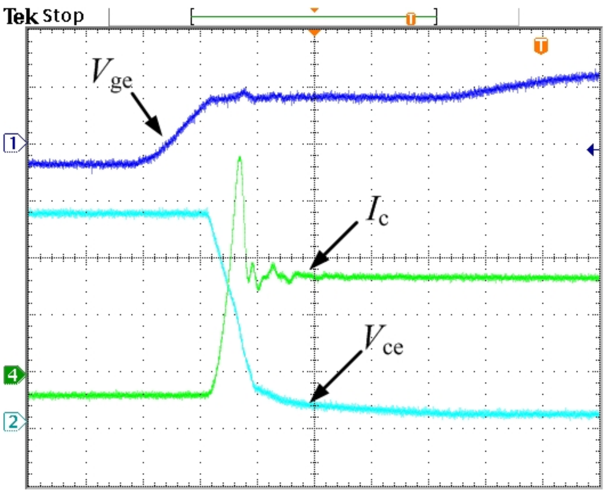


Fig. 5. Experimental waveforms of the turn-on transient of RB-IGBT

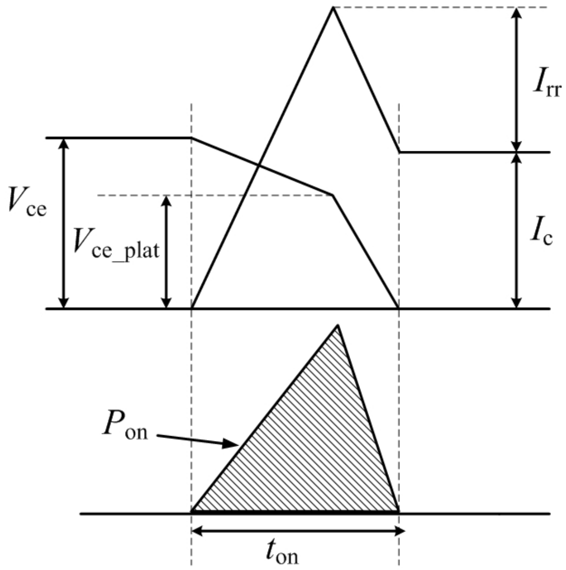


Fig. 6. Calculation model of the turn-on loss of RB-IGBT

I_{rr}, V_{ce_plat} can be considered as the functions of I_c, V_{ce}. These functions are obtained by using mathematical fit from experimental data,

$$I_{rr} = -0.614067 - 0.0592995V_{ce} + 1.74721I_c \tag{11}$$

$$V_{ce\_plat} = 4.72269 + 0.156296V_{ce} + 6.34866I_c \tag{12}$$

And t_{on} can be considered as a constant since its variation is not obvious.

Under the working condition described in Section II ($f_o = 20\text{Hz}$, $T_o = 50\text{ms}$, $T_L = 8\text{Nm}$), furthermore the switching frequency is 5kHz, the average turn-on loss of RB-IGBT matrix converter in one output period is,

$$P_{on} = \frac{\sum E_{on}}{T_o} = 3.3606\text{W} \tag{13}$$

B. Turn-off and Tail Current Loss Calculation

The experimental data of the turn-off transient of RB-IGBT are shown in Fig.7. According to the experimental waveforms, the calculation model of turn-off loss and tail current loss are simplified and summarized as shown in Fig.8. The energy losses of one turn-off switching can be calculated by,

$$E_{off} = \frac{1}{2}V_{ce\_peak} \cdot I_c \cdot t_{off} \tag{14}$$

$$E_{tail} = \frac{1}{2}V_{ce} \cdot I_{tail} \cdot t_{tail} \tag{15}$$

The definitions of $I_c, I_{tail}, V_{ce\_peak}, V_{ce}, t_{off}, t_{tail}$ are shown in Fig.8.

I_{tail}, V_{ce_peak} can be considered as the functions of I_c, V_{ce}. These functions are obtained by using mathematical fit from experimental data,

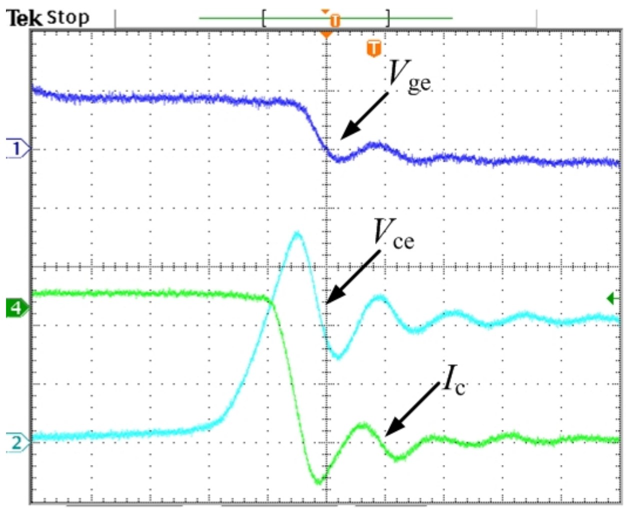


Fig. 7. Experimental waveforms of the turn-off transient of RB-IGBT

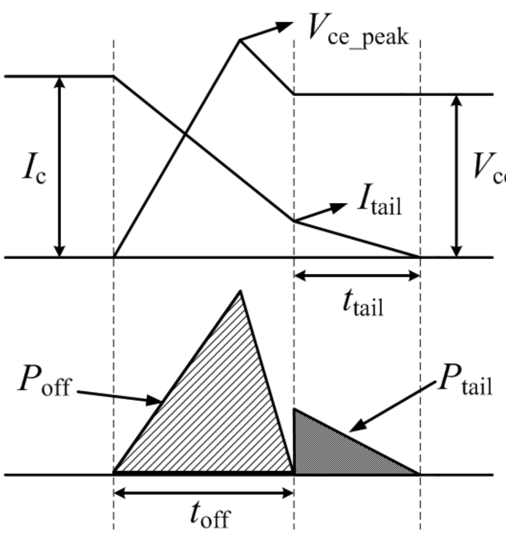


Fig. 8. Calculation model of turn-off and tail current loss

$$I_{\text{tail}} = 0.1 I_c \tag{16}$$

$$V_{\text{ce\_peak}} = -1.13843 + 1.44557 V_{\text{ce}} + 4.78795 I_c \tag{17}$$

And $t_{\text{off}}, t_{\text{tail}}$ can be considered as constant since their variations are not obvious.

Under the same working condition as described in Section II and Section III A ($f_o = 20\text{Hz}$, $T_o = 50\text{ms}$, $T_L = 8\text{Nm}$, $f_s = 5\text{kHz}$),the average turn-off loss and average tail current loss of RB-IGBT matrix converter in one output period are,

$$P_{\text{off}} + P_{\text{tail}} = \frac{\sum E_{\text{off}}}{T_o} + \frac{\sum E_{\text{tail}}}{T_o} = 9.2035\text{W} \tag{18}$$

IV. Calculation Results

The power losses of RB-IGBT matrix converter have been calculated by using the proposed method. The operation of matrix converter is simulated by MATLAB, and the mathematical fit is conducted by Mathematica.

Four cases are considered in the calculation: 1) Condition1, $f_o = 20\text{Hz}$, $T_L = 8\text{Nm}$, $f_s = 5\text{kHz}$; 2) Condition2, $f_o = 40\text{Hz}$, $T_L = 8\text{Nm}$, $f_s = 5\text{kHz}$; 3) Condtion3, $f_o = 20\text{Hz}$, $T_L = 8\text{Nm}$, $f_s = 10\text{kHz}$; 4) Condtion4, $f_o = 20\text{Hz}$, $T_L = 32\text{Nm}$, $f_s = 5\text{kHz}$. The calculation results are illustrated in Fig.9. These results show that the output frequency of matrix converter has a little influence on the power loss, while the switching power loss of RB-IGBT is proportional to its switching frequency. In addition, the higher load torque is, the more power loss is, due to the higher output currents of matrix converter. These reasonable results demonstrate the proposed calculation method.

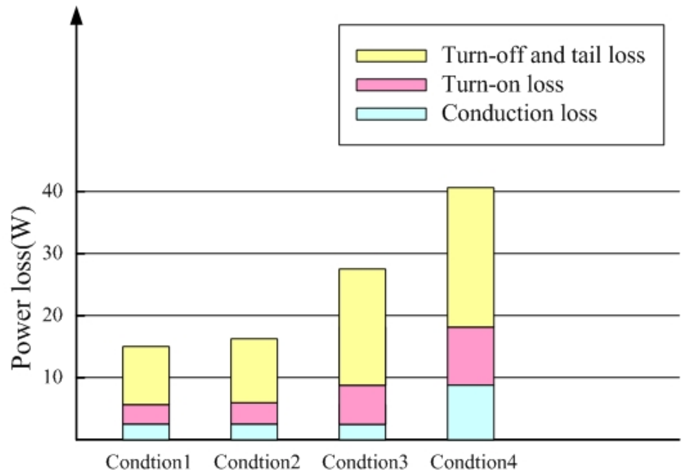


Fig. 9. Power losses of RB-IGBT matrix converter

V. Summary

In this paper, a calculation method of power loss for RB-IGBT matrix converter is proposed. The mathematical models of power loss calculation are established based on the analysis of experimental waveforms. The calculations are conducted by using MATLAB and Mathematica.

The calculation results under different working conditions are presented, which are reasonable and verify the effectiveness of the proposed method.

Furthermore, this method can also be used for other RB-IGBT power converters since it is developed based on the particular characteristic of RB-IGBT.

Acknowledgment

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References

[1] C. Klumpner, F. Blaabjerg, "Using Reverse Blocking IGBTs in Power Converters for Adjustable Speed Drives," *Proceedings IEEE IAS'03,* vol.3, pp.1516-1523, 2003.

[2] Kai Sun, Daning Zhou, Lipei Huang, Kouki Matsuse, Kiyoaki Sasagawa, "A Novel Commutation Method of Matrix Converter fed Induction Motor Drive using RB-IGBT," *IEEE Transactions on Industry Applications,* vol. 43, No. 3, pp.777-786, May 2007.

[3] S. Bernet, S. Ponnaluri, R. Teichmann, "Design and Loss Comparison of Matrix Converters and Voltage-Source Converter for Modern AC Drives," *IEEE Transactions on Industry Electronics*, vol. 49, No. 2, pp. 304-314, Apr 2002.

[4] J.K Kang, H. Hara, E. Yamamoto, E. Watanabe, "Analysis and Evaluation of Bi-directional Power Switch Losses for Matrix Converter Drive,“ *Proceedings of IEEE IAS2002*, vol. 1, pp. 438-443, 2002.

[5] Dewei Xu, Haiwei Lu, Lipei Huang, S. Azuma, M. Kimata, and R. Uchida, "Power Loss and Junction Temperature Analysis of Power Semiconductor Devices," *IEEE Transactions on Industry Applications*, vol. 38, No. 5, pp. 1426-1431, Sep 2002.

[6] A. Odaka, J. Itoh, I. Sato, H. Ohguchi, "Analysis of Loss and Junction Temperature in Power Semiconductors of the Matrix Converter using Simple simulation Methods,“ *Proceedings of IEEE IAS2004*, vol. 2, pp. 850-855, 2004.