Research on on-line monitoring technology of IGBT module junction temperature based on Kalman filter

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Abstract. IGBT is the core device of energy conversion and transmission, commonly known as the CPU of power electronic devices. However, with the continuous improvement of IGBT power density, its reliability is increasingly concerned by industry and academia. The failure of IGBT module is mainly related to the average junction temperature and the amplitude of junction temperature fluctuation, and with the increase of the amplitude of junction temperature fluctuation, the number of failure cycles of IGBT module will sharply decrease. It can be seen that the change of junction temperature in power module is the key to affect its fatigue life. In this paper, an on-line junction temperature monitoring method based on Kalman filter is proposed, which combines the actual temperature measured by IGBT module with the junction temperature obtained by RC thermal network, so it has the advantages of high reliability and real-time on-line monitoring. The simulation results show the effectiveness of the method.

1. Introduction

Insulated gate bipolar transistor (IGBT) is a fully controlled power semiconductor device with the advantages of high input impedance, fast switching speed, small driving power, simple driving circuit, high current density and low saturation voltage drop. IGBT is widely used in new energy, high-speed rail, military and other fields [1].

At present, some research has been carried out on the acquisition method of IGBT module junction temperature in domestic and foreign literature, which can be divided into two categories, namely experimental measurement and simulation analysis. For example, the junction temperature of IGBT chip is measured directly by using temperature sensor and infrared thermal imager [2,3]. In reference [4], the junction temperature of IGBT chip is measured directly by establishing thermal sensitive parameters and IGBT chip. Aiming at the simulation calculation and analysis method of IGBT module junction temperature, there are many approaches have been proposed. For example, the heat transfer process of IGBT is modeled based on the physical structure of the device through the finite element analysis method [5]. In reference [6], the loss and junction temperature of IGBT are analyzed by establishing the coupled model.

However, the above methods only focus on one aspect of theoretical analysis or practical measurement. A method is needed to combine the junction temperature data obtained by the two parts, so that the noise of the junction temperature data obtained is less, and it will not bring greater error due to the model parameter offset. The junction temperature monitoring method based on Kalman filter can not only combine the advantages of the two methods, but also effectively overcome their shortcomings.
2. IGBT Module loss calculation

2.1. Conduction loss calculation
When there is current flowing through the power semiconductor, the conduction voltage drop will be generated, and then the conduction loss will be generated, as shown in (1). Although the on-off voltage of power semiconductor devices is not a constant, it is a function of on-off current. In this paper, the on-off voltage of IGBT and diode are modeled respectively by using the third-order polynomial fitting method.

\[
\begin{align*}
P_{\text{con loss IGBT}} &= V_{ce} \cdot i_c \\
P_{\text{con loss FWD}} &= V_f \cdot i_f
\end{align*}
\]

(1)

The on-off voltage drop of power semiconductor devices can be related to \(V_{ce}, V_f, \) current \(i_c \) and \(i_f \) by looking up the product manual of IGBT module, and then through the curve fitting toolbox in MATLAB, where the third-order polynomial is used for fitting, and its expression is shown in (2).

\[
\begin{align*}
v_{ce}(i_c) &= a_0 + a_1 \cdot i_c + a_2 \cdot i_c^2 + a_3 \cdot i_c^3 \\
v_f(i_f) &= b_0 + b_1 \cdot i_f + b_2 \cdot i_f^2 + b_3 \cdot i_f^3
\end{align*}
\]

(2)

2.2. Switch loss calculation
During the working period of the actual power device, the current commutation can not be completed in an instant, so when the device is turned on or off, it will bear high voltage and current, in this case, there will be switch loss. The datasheet of the product usually gives the information of switching loss, such as \(E_{\text{on}}-i_c, E_{\text{off}}-i_c, \) and \(E_{\text{rec}}-i_f, \) which can be expressed by (3). The coefficients in the formula can also be obtained by curve fitting. Because the switch loss information given in the data book is measured under the rated voltage, and in the actual operation process of IGBT module, the voltage borne by both ends of the power device is constantly changing, so on the basis of the obtained switch loss, according to the actual operation voltage, carry out the normalization processing.

\[
\begin{align*}
E_{\text{on}}(i_c) &= (c_0 + c_1 \cdot i_c + c_2 \cdot i_c^2 + c_3 \cdot i_c^3) \cdot \frac{V_{ce}}{v_{nom}} \\
E_{\text{off}}(i_c) &= (d_0 + d_1 \cdot i_c + d_2 \cdot i_c^2 + d_3 \cdot i_c^3) \cdot \frac{V_{cw}}{v_{nom}} \\
E_{\text{rec}}(i_f) &= (e_0 + e_1 \cdot i_f + e_2 \cdot i_f^2 + e_3 \cdot i_f^3) \cdot \frac{V_{re}}{v_{nom}}
\end{align*}
\]

(3)

Based on the loss of each part of IGBT and DIODE during operation, the junction temperature can be obtained by using the loss calculation expression. The calculation expression of IGBT and DIODE loss is as follows

\[
\begin{align*}
P_{\text{loss IGBT}} &= P_{\text{con loss IGBT}} + P_{\text{sw loss IGBT}} \\
P_{\text{loss FWD}} &= P_{\text{con loss FWD}} + P_{\text{sw loss FWD}}
\end{align*}
\]

(4)

The curve fitted by the data table is shown in Figure 1

2.3. Power loss of IGBT module under working condition
In order to calculate the loss of IGBT in the actual working state, a three-phase three-level inverter based on half bridge structure is established in this paper. The parameters of the simulation model are shown in Table 1.
(a) Figure 1. IGBT Module characteristic curve fitting (a) IGBT (b) Diode

Table 1. Three-phase, three-level inverter model parameter

| Parameters                      | Value   |
|---------------------------------|---------|
| DC-link Voltage                 | 3600V   |
| Rated power                     | 400kW   |
| Nominal frequency               | 50Hz    |
| Line resistance/inductance      | 15mΩ/5mH|
| Transformer ratio               | 2200V/25kV|
| AC voltage                      | 25kV    |
| Reactive capacity of SVC        | 100kVar |

Under operating conditions, the voltage and current of one module of the system and the calculated loss are shown in Figure 2 and Figure 3.

(a) Figure 2. Voltage and current of IGBT module under working condition (a) IGBT (b) Diode
3. IGBT module junction temperature monitoring

3.1. RC thermal network model of IGBT module

As shown in Figure 4 and Figure 5, IGBT modules are made of different materials, and the heat dissipation path from IGBT junction to case is usually defined as

$$Z_{th(j-c)}(t) = \sum_{j=1}^{n} R_j (1 - e^{-t/\tau_j})$$

(5)

Table 2. ABB 5SNG 0250P330300 Thermal Model Parameters

| Term       | Num  | 1       | 2       | 3       | 4       |
|------------|------|---------|---------|---------|---------|
| IGBT       | R(K/W) | 0.0351  | 0.00825 | 0.00385 | 0.00379 |
|            | \(\tau_j\) | 0.2074  | 0.0301  | 0.0076  | 0.0016  |
| Diode      | R(K/W) | 0.0692  | 0.0173  | 0.00779 | 0.00777 |
|            | \(\tau_j\) | 0.2036  | 0.0301  | 0.0075  | 0.0016  |

3.2. Junction temperature monitoring based on Kalman filter

The resulting state-space representation for a Foster network thermal model (Figure 5) is given as in (6), where \(A_{4 \times 4}\) is the system matrix, \(B_{4 \times 2}\) is the input matrix, \(C_{1 \times 4}\) is the output matrix, and \(D_{1 \times 2}\) is the feed-forward matrix. The state vector \(x(t)\) represents the differential temperatures across RC elements, \(u_{0} = [P_{\text{loss}}(t), Tc]\) is the system input vector, where \(P_{\text{loss}}\) is the power dissipation and \(Tc\) is the case temperature.
The output equation gives the junction temperature $T_j(t)$, which is the total sum of system states and the constant case temperature. In order to make the Kalman filter run on the microprocessor, the state space model proposed above needs to be discretized according to the sampling time.

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$T_j(t) = Cx(t) + Du(t)$$

\[
A = \begin{bmatrix}
\frac{1}{R_1C_1} & 0 & 0 & 0 \\
0 & \frac{1}{R_2C_2} & 0 & 0 \\
0 & 0 & \frac{1}{R_3C_3} & 0 \\
0 & 0 & 0 & \frac{1}{R_4C_4}
\end{bmatrix}
\quad B = \begin{bmatrix}
\frac{1}{C_1} \\
\frac{1}{C_2} \\
\frac{1}{C_3} \\
\frac{1}{C_4}
\end{bmatrix}
\quad C = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}
\quad D = \begin{bmatrix} 0 & 1 \end{bmatrix}
\]

By introducing the discrete state space model into the Kalman filter, the form shown in (7) and (8) can be obtained.

**Predict**

$$\hat{x}^+ = F\hat{x}^+_{k-1} + Bu_k$$
$$\hat{T}_j^+ = C\hat{x}^+_k + Du_k$$
$$P^+_k = FP^+_{k-1}F^T + HQH$$

**Update**

$$e_k = T_k - \hat{T}_j^+$$
$$K_k = P_k^+ C^T \left( CP_k^T C^T + R \right)^{-1}$$
$$\hat{x}_k = \hat{x}_k^+ + K_k e_k$$
$$P_k^- = [I - K_k C] P_k^+$$

### 3.3. Simulation Results and Discussion

In this paper, the shell temperature of IGBT module is obtained by setting, instead of using the measured value in practical application.

(a) ![Fig 6. IGBT junction temperature monitoring](image1)
(b) ![Fig 6. IGBT junction temperature monitoring](image2)

(a) ![Fig 7. Diode junction temperature monitoring](image3)
(b) ![Fig 7. Diode junction temperature monitoring](image4)
From the simulation results in Figure 6 and Figure 7, it can be seen that the junction temperature monitoring based on Kalman filter can effectively filter the noise of the measurement system, so as to achieve the most accurate junction temperature. At the same time, it can be seen that the Kalman filter is not sensitive to the initial value, and the convergence speed is very fast. After about 20 seconds, the temperature error can converge to a stable value.

4. Conclusion
On the basis of obtaining the IGBT module loss of three-phase three-level inverter, this paper combines the RC thermal network model with the actual measured shell temperature of IGBT through Kalman filter, so as to realize the on-line monitoring of the junction temperature of IGBT module, which is of great significance to the failure analysis and routine maintenance of IGBT module in practical engineering application.

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