Power losses calculation and thermal modelling for a three-phase inverter power system is presented in this paper. Aiming a long real time thermal simulation, an accurate average power losses calculation based on PWM reconstruction technique is proposed. For carrying out the thermal simulation, a compact thermal model for a three-phase inverter power module is built. The thermal interference of adjacent heat sources is analysed using 3D thermal simulation. The proposed model can provide accurate power losses with a large simulation time-step and suitable for a long real time thermal simulation for a three phase inverter drive system for hybrid vehicle applications.

Keywords: power losses; thermal modelling; inverter drive system; PWM reconstruction, IGBT junction temperature.

1. INTRODUCTION

Inverter Power Modules (IPM) based on Insulated gate bipolar transistors (IGBT) power modules, are more and more popular for automotive industry. However, due to the confined volumes and high temperature environment, high power density and huge power dissipation, make the power package exposed to high thermal constraints, especially in system transients and very harsh electrical environments [1]. Since the reliability of the power modular very depend on the device junction operating temperature, so effective power losses and thermal simulation is necessary for designer.

A accurate approach to determine the losses is to simulate a circuit by using physically matched device model [2-4], however, due to the complicate physical switching process, the determination of power losses and thermal performance need a very detailed device model and very small simulation time steps, this will result in a massive computing time and memory requirement for a complex power electronics system, especially in the case of long real time electro-thermal simulations. Another approach to determine the losses is to calculate the power losses analytically by using device data sheet provided from manufactures [8]. This method is simple, but less accurate.
To overcome the difficulties, a novel power losses calculation method for a three-phase inverter power module thermal simulation using PWM reconstruction technique is presented in this paper. Initially a temperature-dependent conducting and switching characteristics of power devices are set up by measurement, in which, the turn-on and turn-off switching losses are represented as a function of device voltage, current, and junction temperature.

Next, a system level of the complete inverter drive electrical simulation and temperature coupled power losses and power module thermal simulation are carried out. Here the key feature that allows a significant speed-up of the simulation CPU time is this simplified representation of the inverter during the system level modelling. We have taken the approach that the inverter can be described by a unity gain amplifier. This allows the system to work on effective voltages and currents, which are continuous quantities (rather than the actual PWM switching waveforms). By using PWM reconstruction technique, device current in time-domain can be reconstructed and accurate power losses and thermal simulation can be carried out.

2. TEMPERATURE DEPENDENT POWER LOSSES CHARACTERISTICS OF POWER DEVICES

The power loss of each PWM switching cycle for each power device is divided into conduction losses, turn on loss and turn off loss, the total power loss is the sum of these three portions.

For an IGBT power device, the conduction loss can be calculated using the device collect current and the forward saturation voltage by

\[ P_{\text{cond loss}}(t) = V_{ce}(t)i_c(t) \]  

where \( V_{ce} \) and \( i_c \) represent the forward saturation voltage, collector current of an IGBT, respectively. The measured \( V_{ce} - I_c \) characteristic of the IGBT is shown in Figure 1. It can be seen that the saturation voltage \( V_{ce} \) is a function of collector current and junction temperature.

\[ V_{ce}(t) = f_{\text{cont}}(i_c(t), T_j(t)) \]  

where \( T_j \) represents the junction operating temperature. In an inverter drive system, where significant inductance exists in load circuit, it is reasonable to assume the conduction current being constant over the on-time period of each switching cycle. So based on this assumption, the average conduction loss of each PWM switching pulse can be calculated by:
where, $t_{on}$, represents the conduction time; $k$ denotes the $k^{th}$ PWM switching cycle. The same method can be applied for calculating conduction loss of power diodes.

Figure 1: Measured $V_{ce} - I_c$ characteristics of an IGBT at different temperature

Figure 2: IGBT total switching energy losses characteristics

Due to the complicated physics process of switching. In this paper, a lookup-table method is utilised, in which, the switching energy loss is defined as a function of collect current and junction temperature (for a constant dc link voltage). The function is represented as
The total switching loss is calculated by

\[ E_{sw}(k) = E_{sw-on}(k) + E_{sw-off}(k) \]  

and represented as

\[ E_{sw}(k) = f_{sw}(i_c(k), T_j(k)) \]  

where, \( k \) denotes the \( k^{th} \) PWM switching pulse. The measured total IGBT switching energy losses against collect current and junction temperature is shown in Figure 2. It can be seen that the total switching energy loss increases with increase of collect current and junction temperature, and can be considered as a function of the collect current and junction temperature. The average switching power loss of a switching cycle is then calculated by

\[ P_{sw-ave}(k) = \frac{1}{T_{sw}} E_{sw}(k) \]  

If the dc link voltage is changed, the the switching losse characteristics will vary to reflect this change. Adding Eq. (3) and (8), the average power loss \( P_{ave\_loss} \) over each switching cycle is calculated by

\[ P_{ave\_loss}(k) = P_{sw-ave}(k) + P_{cond-ave}(k) \]  

3. PWM AND DEVICE CURRENT RECONSTRUCTION FOR POWER LOSSES CALCULATION

The simulation in Figure 3 gives the effective motor voltages and currents, which are continuous quantities (rather than the actual PWM switching waveforms) and cannot directly be used for power losses calculation. Therefore, a PWM reconstruction technique is proposed for the power losses simulation. By using PWM reconstruction technique, device current and the on-time of device can be mathematically reconstructed for power losses calculation. Figure 3 shows the block diagram of the PWM and device current reconstruction.

where, \( V_m \) and \( I_m \) are the effective motor terminal voltage and current vectors. The mathematical method to reconstruct the PWM signals will depend on the actual PWM strategy applied. Figure 4 shows a three-phase PWM inverter circuit.
Figure 3: PWM signals and device conduction current reconstruction process using effective smooth motor stator voltage vector

Figure 4: A three-phase PWM inverter circuit

where T_i, D_i, i = 1, 2, ..6 denote the IGBTs and the anti-parallell diodes, respectively. S_i (i = 1, 2, ..6) represents the switching states of IGBTs (on-state S_i=1; off-state S_i=0). Assuming that the positive current is flowing from inverter to motor, the conduction currents flowing in IGBTs and Diodes can be reconstructed by

\[
\begin{bmatrix}
    i_{T_1} \\
    i_{T_2} \\
    i_{T_3} \\
    i_{T_4} \\
    i_{T_5} \\
    i_{T_6}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
    (1 + \text{sign} S_1) & 0 & 0 \\
    0 & (1 + \text{sign} S_2) & 0 \\
    0 & 0 & (1 + \text{sign} S_3) \\
    (1 - \text{sign} S_4) & 0 & 0 \\
    0 & (1 - \text{sign} S_5) & 0 \\
    0 & 0 & (1 - \text{sign} S_6)
\end{bmatrix} \begin{bmatrix}
    i_{ma} \\
    i_{mb} \\
    i_{mc}
\end{bmatrix}
\]

(10)

\[
\begin{bmatrix}
    i_{D_1} \\
    i_{D_2} \\
    i_{D_3} \\
    i_{D_4} \\
    i_{D_5} \\
    i_{D_6}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
    (1 - \text{sign} S_1) & 0 & 0 \\
    0 & (1 - \text{sign} S_2) & 0 \\
    0 & 0 & (1 - \text{sign} S_3) \\
    (1 + \text{sign} S_4) & 0 & 0 \\
    0 & (1 + \text{sign} S_5) & 0 \\
    0 & 0 & (1 + \text{sign} S_6)
\end{bmatrix} \begin{bmatrix}
    i_{ma} \\
    i_{mb} \\
    i_{mc}
\end{bmatrix}
\]

(11)
where, \( \text{sign} \) can be either +1 or -1, depend on the direction of load current; \( i_{ma}, i_{mb}, i_{mc} \) represent the three phase load currents. By using the reconstructed PWM signals, and the power loss characteristics described in section 2, the average power loss of each PWM switching cycle can be calculated accurately. Based on the reconstructed on-time and conduction current for power devices, the power losses calculation and the thermal simulation can then be carried out, the block diagram is shown in Figure 10. Based on the reconstructed PWM and device conduction current, the power losses calculation and the thermal simulation can then be carried out, the block diagram is shown in Figure 5

![Block diagram of the power losses and thermal simulation model](image)

Figure 5: Block diagram of the power losses and thermal simulation model

where \( I_c, T_j \) represents the device current and junction temperature. The average power losses of each PWM switching cycle is then calculated using equation (9). Feeding this average power losses into the thermal network, the junction temperature can be calculated. The temperature predicted at the end of one time step is assumed to be the temperature for the next time step, this means the there is a small delay which is insignificant at the switching frequencies used. In an inverter drive system, where significant inductance exists in load circuit, the current in the load circuit is continuous, since the time constant of the load circuit is large compared with the PWM switching waveform.

4. INVERTER POWER MODULE THERMAL MODEL

The inverter power module consists of 12 IGBT modules (every arm contained two IGBT modules in parallel to share the current) and each of them paired with an anti-parallel diode. The IGBT has a chip area of 133 mm\(^2\) (13.7mm×9.7mm) per one chip and the diode has a chip area of 41mm\(^2\) (6.4mm×6.4mm) per one chip, they are separated by 6mm. The rating of the IGBTs and diodes is 850V/200A. The circuit connection is shown in Figure 7.

A cross sectional view of each single IGBT module is shown in Figure 6. Silicon IGBT and diode are mounted on the top of an insulative layer, and that is fixed on a base-plate, the IGBT module is mounted on a laboratory heat-sink.
A compact thermal model composed of thermal resistance and thermal capacitance, is strongly required as a thermal model for carrying out the thermal simulation, because the compact thermal model can be implemented using a circuit simulator easily.

In this paper, a compact thermal model [2] is employed, in which, each physical layer domain represented by a "cell" composed by two parallel thermal resistance and capacitance sub-circuits connected in series as shown in Figure 8

\[
Z_{th}(t) = R_1 \{1 - \exp(t/R_1C_1)\} + R_2 \{1 - \exp(t/R_2C_2)\}
\]

Where, \(Z_{th}(t)\) represents the cell thermal impedance. To determine the parameters \(R_1\), \(R_2\), \(C_1\) and \(C_2\), a transient heat 3D-FEM simulation of the IGBT module with a laboratory heat-sink is carried out. The transient response of temperature at each layer of a single IGBT module with heat-sink is shown in Fig 9, where, a 100W step changed heat source is applied. The transient thermal impedance corresponding to each physical layer can be calculated by...
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$$Z_{thi}(t) = \frac{(T_{thi}(t) - T_{thi(i-1)}(t))}{P_c}$$  \hspace{1cm} (13)

where, $T_i(t)$ represents the temperature at the $i^{th}$ layer of the module ($i=0, 2, \ldots, 10$); $P_c$ is the heat source applied in the 3D-FEM simulation. The transient thermal impedance corresponding to each physical layer is shown in Figure 10.

Figure 9: Step response of temperature at each layer of the power module (FEM)

Figure 10: Equivalent thermal impedance for each layer of the compact model

By using a curve fitting approach, the parameters $R_1$, $R_2$, $C_1$ and $C_2$ can be extracted for each layer. So the compact IGBT thermal model can be...
represented by a number of series connected cells, and each cell of the thermal network can correspond to a physical layer of the IGBT module from the layer temperature point of view.

For a multi-IGBT modules mounted on a common heat-sink system, the thermal model considering thermal interference among chips can be expressed as

\[
\begin{bmatrix}
T_{j1} \\
T_{j2} \\
\vdots \\
T_{jm}
\end{bmatrix} =
\begin{bmatrix}
Z_{11} & Z_{12} & \cdots & Z_{1m} \\
Z_{21} & Z_{22} & \cdots & Z_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
Z_{ml} & Z_{m2} & \cdots & Z_{mm}
\end{bmatrix}
\begin{bmatrix}
P_{L1} \\
P_{L2} \\
\vdots \\
P_{Ln}
\end{bmatrix}
\]

where the diagonal elements \((i = j)\) correspond to the self-impedance of each chip, whereas off-diagonal elements \((i \neq j)\) are mutual-impedances. \(P_{Li}, T_{ji}\) \((i = 1, 2, \ldots, m)\) represent \(m\) heat sources and junction temperatures. As visible in Figure 7, the number of the heat sources is \(m = 24\). The elements in EQ. (11) can determined by a 3-D numerical simulation. For the purpose of illustrating the power loss and thermal simulation approach proposed in this paper, a relative simple thermal model is utilised, in which, considering the sufficient distance between the adjacent chips (more than 6mm), the thermal interference of the heat flux from different heat sources along the layers of IGBT module is relative small as shown in Figures 11-14 and is ignored in this paper.

Therefore, the elements \(Z_{ij}(i \neq j) = Z_{bhs}\). All the self-impedances \(Z_{ij}(i = j)\) can be determined by the 3D-FEM simulation in Figure9-10. The proposed thermal model has the capability to represent the interference of the heat flux from different heat sources that are adjacent to each other. Specifically, the interference of the heat flux can be represented by merging the individual thermal models at individual points where the different heat fluxes interfere with each other. The bottom of heat-sink represented by \(Z_{bhs}\) is chosen as the fully thermal interference part in the compact thermal model.

The corresponding equivalent thermal network of the inverter power module and heat-sink is shown in Figure 15, where \(T_a = 50^\circ\text{C}\).

Where, the thermal parameters of the bottom heat-sink are chosen by reference a Semikron water-cooled heat-sink thermal model (SKiiPPACK 3, 6 liter/ min flow rate), and employed in the simulation. The parameters are given in the table-1 and table-2 [10].
Figure 11: a 2 in 1 IGBT 3D model simulation module.

Figure 12: Heat transfer along cross section of the IGBT module with a single heat source (100W).

Figure 13: Surface temperature of the IGBT module with a single heat source (100W).

Figure 14: Surface temperature of the IGBT module with two heat sources (both 100W)
Table 1: Thermal resistance

<table>
<thead>
<tr>
<th>$R_1$ (K/W)</th>
<th>$R_2$ (K/W)</th>
<th>$R_3$ (K/W)</th>
<th>$R_4$ (K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.143 \times 10^{-3}$</td>
<td>$3.818 \times 10^{-3}$</td>
<td>$9.045 \times 10^{-3}$</td>
<td>$2.535 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 2: Time constant

<table>
<thead>
<tr>
<th>$t_1$ (s)</th>
<th>$t_2$ (s)</th>
<th>$t_3$ (s)</th>
<th>$t_4$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.204 \times 10^{-1}$</td>
<td>$2.911$</td>
<td>$2.0 \times 10^1$</td>
<td>$1.355 \times 10^2$</td>
</tr>
</tbody>
</table>

5. SIMULATION RESULTS

Simulation program is developed in Matlab/Simulink. Simulation of the power losses and thermal performance for the inverter drive system shown in Figure 7 is carried out. The specified torque and speed profiles are shown in Figure 16, the corresponding continuous effective motor stator currents and voltage are shown in Figure 17. The power losses in IGBT1 and diode D1 and the corresponding junction temperature are shown in Fig 18-19 respectively. The temperature of inlet water is set to 50°C.

The PWM switching frequency is set to 2 kHz, and simulation time step is 0.5ms. The total simulation time takes about 1hr with a 3.12 GHz CPU, 1Gbyte memory PC.

6. CONCLUSIONS

A fast power losses simulation model for a three-phase inverter power module (IPM) thermal simulation using PWM reconstruction technique is proposed in this paper. In this model, an inverter drive system simulation model with the aim of fast and efficient power loss and thermal analysis for inverter power devices in electrical vehicle applications. This approach has a very fast simulation speed and produces the voltages and currents associated with each of the semiconductor switches in real-time by using PWM reconstruction. This information is then used in conjunction with detailed device switching models,
to describe the heat-source terms for a thermal solver, this allows electro-thermal performance of the inverter to be predicted over long periods of real time. This simulation methodology brings together accurate models of the electrical systems performance, state of the art-device compact models and a realistic simulation of the thermal performance in a useable period of CPU time.

Figure 16: Motor torque (Nm) and speed (rpm).

Figure 17: Motor stator three phase currents and voltages.
Figure 18: power losses of IGBT (W).

Figure 19: Junction temperature of IGBT (°C).
Acknowledgment

The authors would like to thank Toyota Motor Corporation for their financial support and technical advice.

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