Thermal model of the IGBT module

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Abstract. In the paper the dynamic compact thermal model of the IGBT module is proposed. This model makes it possible to calculate internal temperatures of diodes and transistors included in the considered IGBT module with selfheating in each device and mutual thermal couplings between them taken into account. The form of this model and the method of estimation of its selected parameters are described. Some results of measurements and calculations illustrating the usefulness of this model are shown and discussed.

1. Introduction

The aspiration to miniaturize electronic and power electronic equipment causes that more and more subcircuits of these equipment are realized as integrated circuits. Power modules are commonly used in switch-mode power supplies [1, 2]. These modules contain in the common case semiconductor devices indispensable to construct one branch of inverters [2]. Typically there are two transistors and two diodes. From the point of view of technology such a module can be treated as a hybrid integrated circuit [3].

During the operation of semiconductor devices contained in power modules, heat is generated [4, 5]. The considered devices are situated on the common basis near each other, which results in thermal interactions between them [6], and finally non-uniform distribution of temperature in such a module is observed [7]. For the purpose of calculating temperature distribution in the considered module estimation of the internal temperature of every semiconductor device is desirable [3, 4, 5]. To realize this task it is necessary to use the thermal model of the power module. Such a model should take into account both self-heating in each semiconductor device and mutual thermal coupling between these devices.

The problem of modelling thermal properties of electronic devices is considered in many papers [4, 8, 9, 10, 11, 12, 13, 14]. The cited papers are devoted to thermal properties of discrete devices. In turn, the problem of modelling mutual thermal couplings between semiconductor devices are described e.g. in [3, 5, 15].

In the paper the compact thermal model of the IGBT module Power Sem PSI 25/06 and the manner of estimating the parameters values of this model are proposed. The correctness of the model is verified experimentally.

2. Investigated module

The power module used in investigations contains two IGBTs and two diodes connected electrically into the branch of the inverter [16]. The diagram of this module is shown in Fig. 1a.
The considered module has 5 terminals, and transistors contracted in it are characterized by the maximum collector current equal to 18.5 A and the maximum reverse voltage reaching 600 V. With the same maximum conduction current the diodes are characterized, and the catalogue value of their forward voltage amounts to 2.58 V at the current equal to 15 A. The described module is situated in the plastic case of the dimensions 34.3x51x8mm shown in Fig.1b, whereas the top part of the case is the metal heat-sink. The values of the junction-to-case thermal resistance given by the manufacturer are equal to 1.52 K/W for the transistor and 3 K/W for the diode, respectively.

3. Model form

As it is visible in Fig. 1, the considered module contains 4 semiconductor devices situated in the common case, but there are four separated semiconductor chips. Therefore the mutual thermal couplings between these devices occur.

In order to calculate the internal temperature of electronic devices their thermal model is indispensable. The thermal model of the considered IGBT module elaborated by the authors belongs to the group of compact thermal models [3, 4, 5, 17]. This model makes it possible to calculate internal temperatures of both the transistors and both the diodes included in the considered IGBT module with a selfheating phenomenon and mutual thermal couplings between all the components of this module taken into account.

The value of the internal temperature of these devices depends on the value of the ambient temperature $T_a$ and the temperature excess caused by self-heating phenomena and by mutual thermal couplings between the semiconductor devices contained in the module. Using the idea of compact thermal modelling [3, 4, 5], the compact thermal model of the IGBT module can be described with convolution integrals [18]. For example, the internal temperature of the transistor $T_1$ can be described with the following equation:

$$ T_{th1}(t) = T_a + \int_0^t Z'_{th11}(\tau-t) \cdot p_{T1}(\tau) d\tau + \int_0^t Z'_{th2T1}(\tau-t) \cdot p_{T2}(\tau) d\tau + \int_0^t Z'_{thD1T1}(\tau-t) \cdot p_{D1}(\tau) d\tau + \int_0^t Z'_{thD2T1}(\tau-t) \cdot p_{D2}(\tau) d\tau $$

(1)

where $Z'_{th11}(t)$ denotes the time derivative of self transient thermal impedance of the transistor $T_1$, $Z'_{th2T1}(t)$, $Z'_{thD1T1}(t)$, $Z'_{thD2T1}(t)$ - time derivatives of mutual transient thermal impedances between the transistors $T_2$ and $T_1$, between the diode $D_1$ and the transistor $T_1$, between the diode $D_2$ and the transistor $T_1$, respectively; whereas $p_{T1}(t)$, $p_{T2}(t)$, $p_{D1}(t)$, $p_{D2}(t)$ - power dissipated in transistors $T_1$ and $T_2$ and in the diodes $D_1$ and $D_2$, respectively.

Internal temperatures of the remaining components of the considered module are described by equations of the form analogous to the equation (1). Therefore, in the description of the thermal model of the considered module four self transient thermal impedances and twelve mutual transient thermal impedances appear. Because the two-way heat transfer between each pair of semiconductor devices exists, the considered module is characterized by the same mutual transient thermal impedances. Hence, only six (instead of 12) mutual transient thermal impedances are needed in the model.
4. Estimation of the model parameters values

In order to apply the presented model in practice, it is indispensable to estimate the values of all its parameters. This process is performed in two steps. First, the waveforms of self and mutual transient thermal impedances occurring in the considered model are measured. Next, for each of them the parameters values of the classical \( Z_{th}(t) \) model are calculated. This model is given by following equation [3, 4, 5, 18]:

\[
Z_{th}(t) = R_{th} \left[ 1 - \sum_{i=1}^{N} a_i \cdot \exp \left( -\frac{t}{\tau_{thi}} \right) \right]
\]  

(2)

In Eq. (2) \( R_{th} \) denotes thermal resistance, \( a_i \) - the weight coefficient corresponding to \( i \)-th thermal time constant \( \tau_{thi} \), while \( N \) is the number of thermal time constants. For each self and mutual transient thermal impedance the values of parameters \( R_{th}, a_i, \tau_{thi} \) must be estimated.

Due to electric connections between semiconductor devices contracted in the considered module, special methods of measurements of self and mutual transient thermal impedances have to be used. The measurement method of each transient thermal impedance requires a different measuring set-up, whereas the measurement procedure is identical. The measurement is realized with the use of the indirect electrical method and the conception of the so called cooling curve [19]. Thermally sensitive parameters are the voltage between the gate and the emitter of the transistor at the small constant value of the collector current or the forward voltage of the diode operating with the constant current of the small value. For example, the measurement set-up to measure self transient thermal impedance of the transistor \( T_1 \) \( Z_{thT1}(t) \) is shown in Fig. 2, whereas the set-up to measure mutual transient thermal impedance between the diodes \( Z_{thD1D2}(t) \) is presented in Fig. 3.

![Figure 2. Measurement set-up to measure transient thermal impedance \( Z_{thT1}(t) \)](image)

The measurement of transient thermal impedance of the transistor \( T_1 \) is realized in four steps. First, thermometric characteristics \( V_{GE1}(T) \) of the transistor \( T_1 \) are measured at the collector current \( I_M \). During calibration the tested module (DUT) is situated in the thermostat, the switch \( S_1 \) is closed and the switch \( S_2 \) is opened. As a result of calibration the slope of the thermometric characteristic \( \alpha_V \) is calculated. The characteristic \( V_{GE1}(T) \) is linear only for the selected values of \( I_M \) current. The value of this current must be much higher than the sub-threshold current and simultaneously so small that selfheating phenomenon could be omitted.

In the second step the transistor \( T_1 \) operates in the active normal mode. The switch \( S_1 \) is opened and the switch \( S_2 \) is closed. In the transistor the dissipated power is equal to \( I_H V_{CE} \). As a result of selfheating, the internal temperature of this transistor increases until the steady state is obtained. Then, the values of the current \( I_H \) and the voltage \( V_{CE} \) are measured. At time \( t = 0 \) the switch \( S_1 \) is closing and the switch \( S_2 \) is opening. Next, the waveform of the voltage \( V_{GE1}(t) \) is registered while cooling the tested module until the steady state is obtained. Finally, the waveform of transient thermal impedance is calculated with the formula:

\[
Z_{thT1T2}(t) = \frac{V_{GE1}(t) - V_{GE1}(t = 0)}{\alpha_V \cdot I_{C1} \cdot V_{CE1}}
\]  

(3)

The measurement of mutual transient thermal impedance between the diode \( D_1 \) and the diode \( D_2 \) is
realized in four steps. First, thermometric characteristics \( V_{D1}(T) \) of the diode \( D_1 \) are measured at the forward current \( I_M \). During calibration the tested module (DUT) is situated in the thermostat, the switch \( S_1 \) is closed and the switch \( S_2 \) is opened. As a result of calibration the slope of the thermometric characteristic \( \alpha_V \) is calculated.

**Figure 3.** Measurement set-up to measure self and mutual transient thermal impedances of the diodes

In the second step the diode \( D_2 \) operates in the forward mode. The switch \( S_1 \) is opened and the switch \( S_2 \) is closed. As a result of mutual thermal couplings the internal temperature of the diode \( D_1 \) increases due to a self-heating phenomenon occurring in the diode \( D_2 \) until the steady state is obtained. Then, the values of the current \( I_{D2} \) and the voltage \( V_{D2} \) are measured. At time \( t = 0 \) the switch \( S_1 \) is closing and the switch \( S_2 \) is opening. Next, the waveform of the voltage \( V_{D1}(t) \) is registered while cooling the tested module until the steady state is obtained. Finally, the waveform of transient thermal impedance is calculated with the formula:

\[
Z_{thD2}(t) = \frac{V_{D1}(t) - V_{D1}(t = 0)}{\alpha_v \cdot I_{D2} \cdot V_{D2}}
\]  

(4)

For all the other thermal parameters the measurement is realized in three steps. The first step includes calibration of thermometric characteristic. The second step - dissipation of the power \( P_H \) in one of the components of the module, which plays the role of a heat source until the thermally steady state is obtained. The third step - cooling this element and recording waveforms of the thermally sensitive parameter from the moment \( t = 0 \) (switching off the power dissipated in the heat source) until the thermally steady state is obtained. On the basis of the measured waveforms of the thermally sensitive parameter and the power \( P_H \), waveforms of transient thermal impedances are calculated using equations of the form similar to Eq. (3) for self transient thermal impedances or similar to Eq. (4) for mutual transient thermal impedances.

Using measured waveforms of self and mutual transient thermal impedances for each of them the values of parameters \( R_{th} \), \( a_i \) and \( \tau_{thi} \) are estimated with the use of the algorithm described in [20]. In this algorithm the value of \( R_{th} \) is equal to mean value of the transient thermal impedance at the steady state. In turn, values of parameters \( a_i \) and \( \tau_{thi} \) are calculated using least square method in approximation transformed Eq. (2) by a linear function starting from the longest thermal time constant.
5. Results of measurements and calculations

Using the methods described in Section 4, self and mutual transient thermal impedances existing in the thermal model of the IGBT module were measured. For example, in Fig. 4a the measured (solid lines) waveforms of self transient thermal impedance $Z_{thT1}(t)$ of the transistor $T_1$ and mutual transient thermal impedance $Z_{thT1D1}(t)$ between the transistor $T_1$ and the diode $D_1$ are shown, whereas in Fig. 4b the measured waveforms of self transient thermal impedance $Z_{thD1}(t)$ of the diode $D_1$ and mutual transient thermal impedance $Z_{thD1D2}(t)$ between the diodes are presented. In the same figures the waveform of transient thermal impedances obtained with the use of Eq. (2) are marked with dashed lines.

![Figure 4](image)

**Figure 4.** Measured and calculated waveforms of the selected self and mutual transient thermal impedances

As it is visible, good agreement between the measured and modelled waveforms was obtained. The differences between results of calculations and measurements do not exceed 0.2 K/W. It is worth noticing that visible differences between the waveforms of self and mutual transient thermal impedances are observed. Particularly, for the waveforms of self and mutual transient thermal impedances $Z_{thT1}(t)$ and $Z_{thT1D1}(t)$ one can observe that differences occur only at the steady state. In turn, the waveform of $Z_{thD1D2}(t)$ is visibly late in comparison with the waveform of $Z_{thD1}(t)$.

In Table 1 the values of parameters describing the considered self and mutual transient thermal impedances by Eq. (2) are collected.

**Table 1.** Parameters values describing the considered self and mutual transient thermal impedances of the considered IGBT module.

| parameter | $Z_{thT1}(t)$ | $Z_{thT1D1}(t)$ | $Z_{thD1}(t)$ | $Z_{thD1D2}(t)$ |
|-----------|---------------|----------------|---------------|----------------|
| $R_{th}$ [K/W] | 10.15 | 9.05 | 10.24 | 8.63 |
| $a_1$ | 0.736 | 0.479 | 0.384 | 0.886 |
| $a_2$ | 0.18 | 0.257 | 0.416 | 0.114 |
| $a_3$ | 0.068 | 0.158 | 0.027 | - |
| $a_4$ | 0.014 | 0.053 | 0.12 | - |
| $a_5$ | 0.002 | 0.038 | 0.053 | - |
| $a_6$ | - | 0.015 | - | - |
| $\tau_{th1}$ [s] | 212.3 | 281.9 | 331.6 | 204.6 |
| $\tau_{th2}$ [s] | 6.64 | 78.25 | 123.6 | 4.57 |
| $\tau_{th3}$ [s] | 0.418 | 7.75 | 12.68 | - |
| $\tau_{th4}$ [s] | 0.336 | 2.06 | 9.68 | - |
| $\tau_{th5}$ [ms] | 0.04 | 163.8 | 0.04 | - |
| $\tau_{th6}$ [ms] | - | 54.33 | - | - |
As it is visible, differences between thermal resistance $R_{th}$ of the transistor $T_1$ and the diode $D_1$ are very small. They do not exceed 1%. In turn, mutual thermal resistances are even 15% smaller than self thermal resistances. The steady state of all the considered waveforms is obtained after nearly 1000 s.

The practical usefulness of the elaborated model is illustrated in Fig.5. In this figure the calculated waveforms of internal temperatures of the selected components of the considered module are shown.

The waveforms shown in Fig. 5a were obtained during power dissipation in the transistor $T_1$ only. This power has the shape of a single rectangular impulse of the amplitude equal to 10 W and duration time equal to 1000 s. In turn, in Fig. 5b the waveforms of the internal temperature of the same devices obtained at dissipation of power of the same shape of a rectangular impulse of duration time equal to 1000s in the transistor $T_1$ (amplitude equal to 10 W) and in the diode $D_1$ (amplitude equal to 5 W) simultaneously.

![Figure 5](image-url)

**Figure 5.** Calculated waveforms of the internal temperatures of components of the considered module at different waveforms of the power dissipated in these components

As it is visible, the internal temperature of all the considered devices changes while heating and cooling the used heat sources. This is a result of mutual thermal couplings between the components of the IGBT module. In both the considered cases the highest value of temperature is observed for the transistor $T_1$, in which the power of the highest amplitude is dissipated. The observed differences in the maximum value of the components internal temperature reach even 30°C and this value is smaller, when the power is dissipated in two devices simultaneously.

6. **Conclusions**

In the paper the compact thermal model of the IGBT module containing IGBTs and diodes was proposed. This model makes it possible to calculate waveforms of the internal temperature of each semiconductor device contracted in this module taking into account both self-heating phenomena in each of these devices and mutual thermal couplings between all the devices. The analytical form of this model and the procedure of estimation of the parameters values of this model are presented.

The measured waveforms of self and mutual transient thermal impedances differ from each other even by 15% and the classical analytical formula makes it possible to accurate approximate results of measurements. It is proved that both self-heating in each component of the module and mutual thermal coupling between them must be taken into account in order to model correctly thermal phenomena in the considered module.

The presented results of calculations illustrate that differences in the values of internal temperatures of the components of the considered module can reach even 30°C. This proves that strong non-uniform temperature distribution occurs in the considered module.

In further investigations some infrared measurements of the considered module operating without this case will be performed in order to measure temperature distribution in this module.
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