Thermal Equivalent Model of IGBT Modules

I. Purpose

In order to ensure a sufficient life time of power electronics application systems, proper thermal design is indispensable and one of the critical items to be considered. The thermal equivalent model of power semiconductors, including IGBTs, is generally utilized for the design. In this document, selecting IGBT modules as a representative example is presented. Thereafter a modelling process is reviewed.

II. Definition of temperatures

Before describing the model, the temperatures related to the model need to be defined. Herein are the definitions:

A) Virtual junction temperature, T_{vj}

A junction temperature basically means the temperature in the junction area of an IGBT or a Diode chip. It should be noted at an early stage that the temperature is not uniform in the chip. Furthermore, where multiple chips are mounted in a module, the temperature may differ from chip to chip. Therefore, the idea of a virtual junction temperature T_{vj} is introduced to define the thermal resistance or impedance junction to case ($R_{th(j-c)}$ or $Z_{th(j-c)}$). The virtual junction temperature does not precisely coincide with the junction temperature of each chip, but it is useful for the estimation of a junction temperature. As the temperature is measured indirectly and does not have a precise value, it is appropriate to be termed a “Virtual junction temperature”. The measuring method of the temperature is presented in the international standard IEC 60747-9.

B) Case temperature, T_c

The case temperature T_c is defined as the surface temperature of a base plate in an IGBT module and is generally measured by means of a thermocouple for each device chip, as shown in Fig. 1. The symbols T_c_IGBT and T_c_diode in Fig. 1 stand for the case temperatures for an IGBT chip and a diode chip respectively.

C) Heat sink temperature, T_h

The heat sink temperature T_h is the surface temperature of a heat sink and is measured on the surface where an IGBT module is mounted. Depending on the measuring position, the measured temperature has a certain deviation. But, in Fig. 1 the temperature T_h is measured at the point just under an IGBT chip.

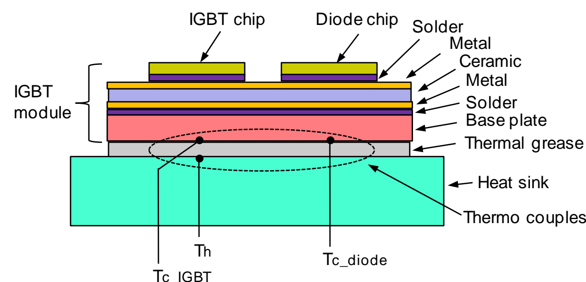

Fig. 1 Schematic cross section of an IGBT module and heat sink

III. Transient thermal impedance $Z_{th(j-c)}(t)$

The transient thermal behaviour of an IGBT module is characterized by a transient thermal impedance $Z_{th(j-c)}(t)$. The impedance for an IGBT chip or a diode chip is defined by the following equation (1)

$$Z_{th(j-c)}(t) = \frac{T_{vj}(t) - T_c(t)}{P_{loss}} \quad \text{------} \quad (1)$$

where $T_{vj}(t)$ and $T_c(t)$ are defined in chapter II. P_{loss} is the power loss of an IGBT or a diode chip.

IV. Thermal equivalent model

The thermal characteristic of an IGBT module with a heat sink, shown as a cross section in Fig. 1, is modelled as a thermal equivalent circuit and shown in Fig. 2. In the thermal circuit, the power loss of an IGBT or a diode chip is converted to a current source. Thermal capacity and thermal resistance are expressed as a capacitor and a resistor respectively. The symbol T_a stands for an ambient temperature. The partial models for an IGBT and a diode chip can be obtained by employing either the “Cauer Model” or “Foster Model”. In the model of Fig. 2, if P_{loss}_IGBT, P_{loss}_diode and T_a are given, then T_{vj}_IGBT and T_{vj}_diode can be deduced. Fig. 3 shows a simplified thermal circuit model in which $R_{th(c-h)}$ and C_{grease} are defined for a whole module. It depends on the data available in the data sheet as to which model, Fig. 2 or Fig. 3, is appropriate to apply to the thermal design of the application system(s).

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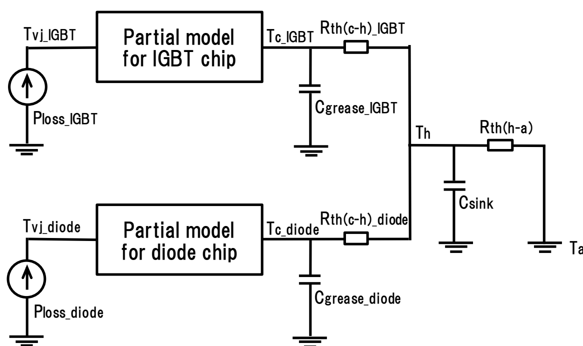

Fig. 2 Thermal circuit model of the IGBT module

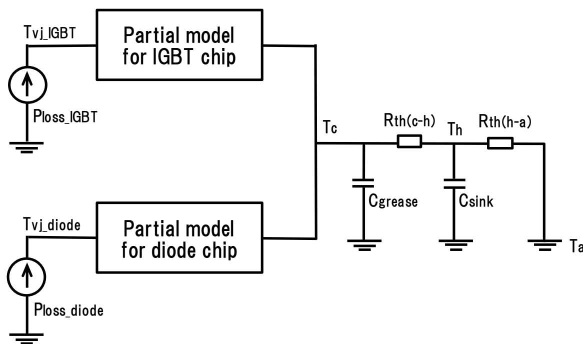

Fig. 3 Simplified thermal circuit model

A) Cauer Model

Fig. 4 shows the Cauer Model for the IGBT module of Fig. 1. Employing the Cauer Model, the thermal behaviour of an IGBT module can be understood. This model is effective to get a physical image of the internal behaviour for an IGBT module. Please note that in order to realize the model, it is necessary to acquire the material properties of each layer inside and the module construction. It is therefore not always practical for IGBT users to employ this model in designing application systems because it can be difficult for the users to ascertain the detailed information needed to realize the model.

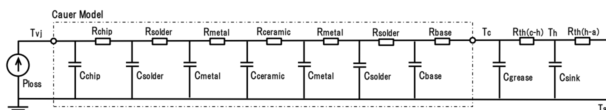

Fig. 4 Cauer Model

B) Foster Model

The Foster Model, Fig. 5, consists of series connected RC elements, where each element is the parallel circuit of a resistor and a capacitor. In contrast to the Cauer Model, the element does not have any physical significance, but the model is an effective tool to design application systems, because in contrast to the Cauer Model, it can be realized without detailed information about the material characteristics of the individual layers in an IGBT module. The thermal impedance of the model is derived from the circuit of Fig. 5. The equation of the thermal impedance $Z_{th(j-c)}(t)$ is as follows.

$$Z_{th(j-c)}(t) = \sum_{i=1}^{n} R_i \left(1 - e^{-t/\tau_i}\right) \text{ ------ } \quad (2)$$

where $\tau_i = R_i \times C_i$. This model is realized by tuning the model's characteristics to the transient thermal impedance described in a data sheet.

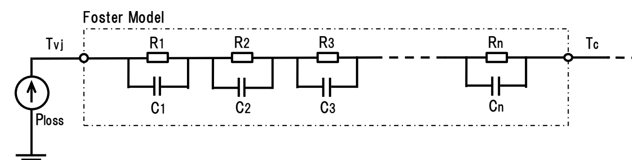

Fig. 5 Foster Model

V. Modeling process of the Foster Model

In this chapter, the modelling process of the Foster Model is reviewed using the IGBT type MBN1200E33E as a working example. Fig. 6 shows the transient thermal impedance of the module.

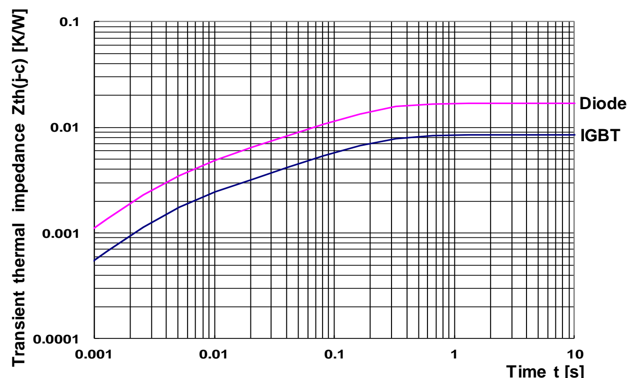

Fig. 6 $Z_{th(j-c)}$ of an IGBT module MBN1200E33E

The Foster Model is tuned to the impedance curve of Fig. 6. The greater the number of terms in equation (2) is, the more accurate the tuning of the model will become. However, if the number of the terms is too large, the tuning becomes complicated because of the large number of parameters to be tuned. On the other hand, in order to keep the practical accuracy of the model's characteristics, the number of the terms should ideally be more than or equal to 4. For the algorithmic tuning, there are various methods possible. The least-squares method is generally employed. Fig. 7 shows the tuned results for IGBT chips. Lines i = 1, 2, 3, and 4 show the impedance characteristics of four terms in $Z_{th(j-c)}(t)$. Fig. 8 shows

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the tuned results for diode chips. The tuned data is input into Table 1.

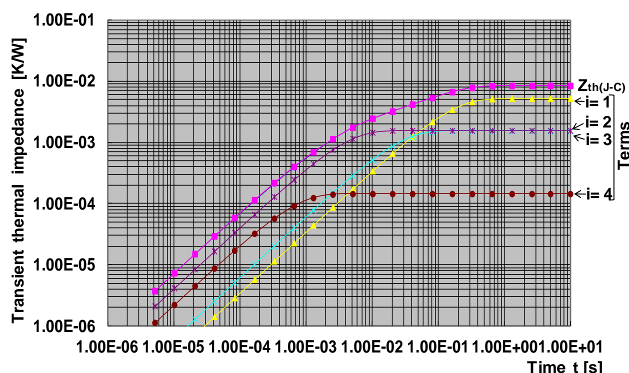

Fig. 7 Tuned results of $Z_{th(j\text{-}c)}$ for IGBT_chips

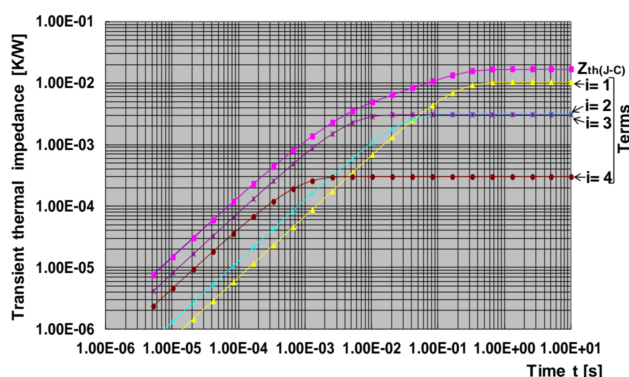

Fig. 8 Tuned results of $Z_{th(j\text{-}c)}$ for diode_chips

Table 1 Tuned data for MBN1200E33E

i	1	2	3	4	Unit
τ [i]	1.51E-01	2.49E-02	3.86E-03	6.61E-04	sec
R [i,IGBT]	5.24E-03	1.54E-03	1.57E-03	1.45E-04	K/W
R [i,Diode]	1.04E-02	3.19E-03	3.08E-03	2.99E-04	K/W

VI. Utilization of the thermal circuit model

The thermal equivalent circuit model is useful in evaluating the thermal performance of power electronic application systems. The block diagram in Fig. 9 shows a general way of considering life time estimation for a system. The circuit model simulates the electrical behaviour of the system, such as an inverter, according to operating conditions and outputs the values: V_{CE}; V_{AK}; I_C; I_A; and a switching frequency, f_{SW}, for the calculation of a power module's power loss. The device loss model calculates the power loss using the aforementioned input and outputs values, P_{loss}_IGBT and P_{loss}_diode. The thermal model simulates the thermal transient behaviour of an IGBT module according to P_{loss}_IGBT, P_{loss}_diode and Ta. T_{vj}_IGBT and T_{vj}_diode are then applied to the device loss model.

The life time model predicts the life time of an IGBT module based on the fluctuation of T_c_IGBT, T_c_diode, T_{vj}_IGBT and T_{vj}_diode. The consideration flow shown in Fig. 9 can be applied to realize a life time simulator of power electronic application systems using general purpose simulation tools.

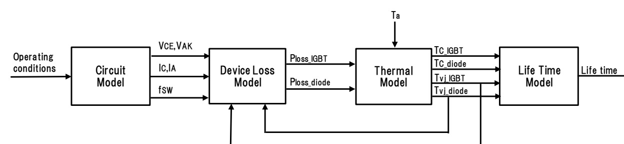

Fig. 9 Consideration flow for life time estimation

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