Transient thermal measurements and thermal equivalent circuit models

Replaces AN2008-03

About this document

Scope and purpose of AN2015-10

The basis of a power electronic design is the interaction of power losses of an IGBT module with the thermal impedance of the power electronic system.

Using a precise model, the system can be designed for high-output current without exceeding the maximum junction temperature limit, while remaining reliable in terms of power cycling.

To meet this requirement, Infineon has optimized the measurement method.

This application note AN2015-10 describes how to characterize the thermal properties of a power electronic system and how to model it for application-oriented investigations.
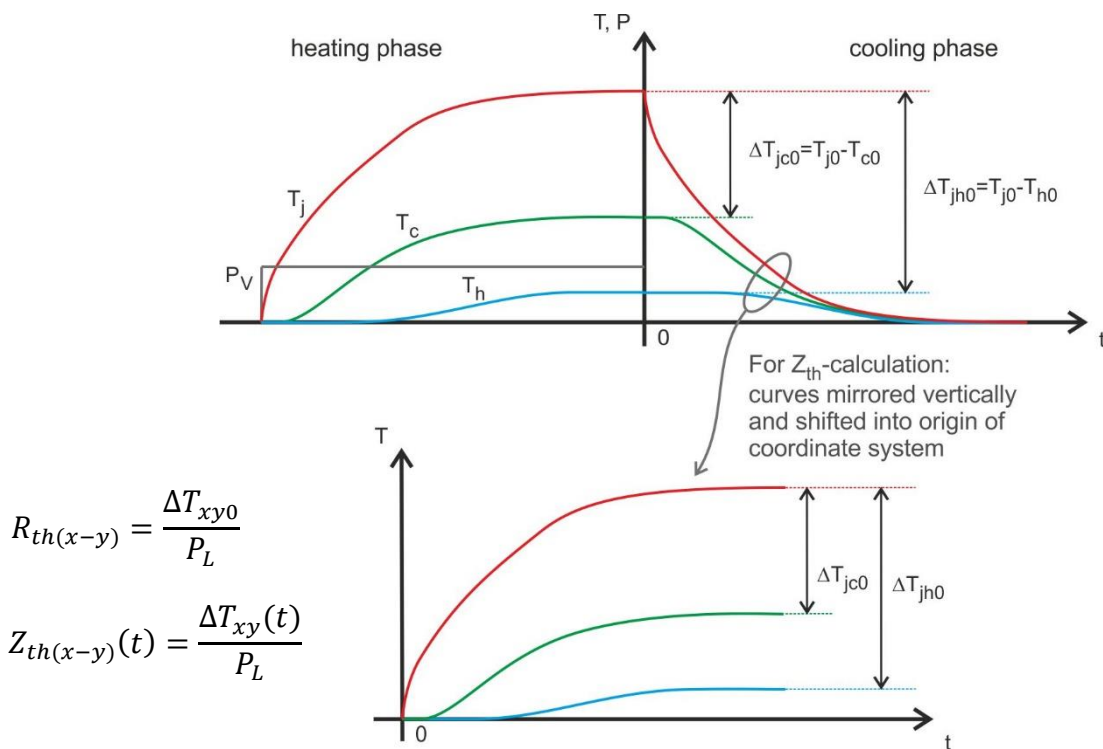
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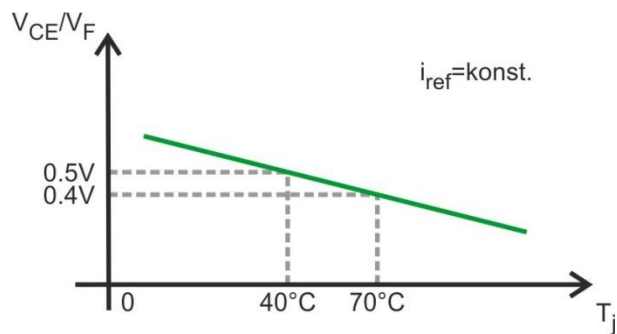
1.1 Principle of measurement – R_{th}/Z_{th} basics

The basic principle of measurement is described in IEC 60747-9 Ed. 2.0 (6.3.13.1) [1].The approach of determining thermal impedance is shown in Figure 1. A constant power P_L is fed into the IGBT module by a current flow, so that a stationary junction temperature T_j is reached after a transient period. After turning off the power, the cooling down of the module is recorded.

Thermal resistance $R_{th(x-y)}$ is the difference between two temperatures T_{x0} and T_{y0} at t=0, divided by P_L. For calculating time-dependent thermal impedance $Z_{th(x-y)}(t)$, the recorded temperature curves need to be vertically mirrored, and shifted to the origin of the coordinate system. Then $Z_{th(x-y)}(t)$ is calculated by dividing the difference of $T_x(t)$ and $T_y(t)$ by P_L.
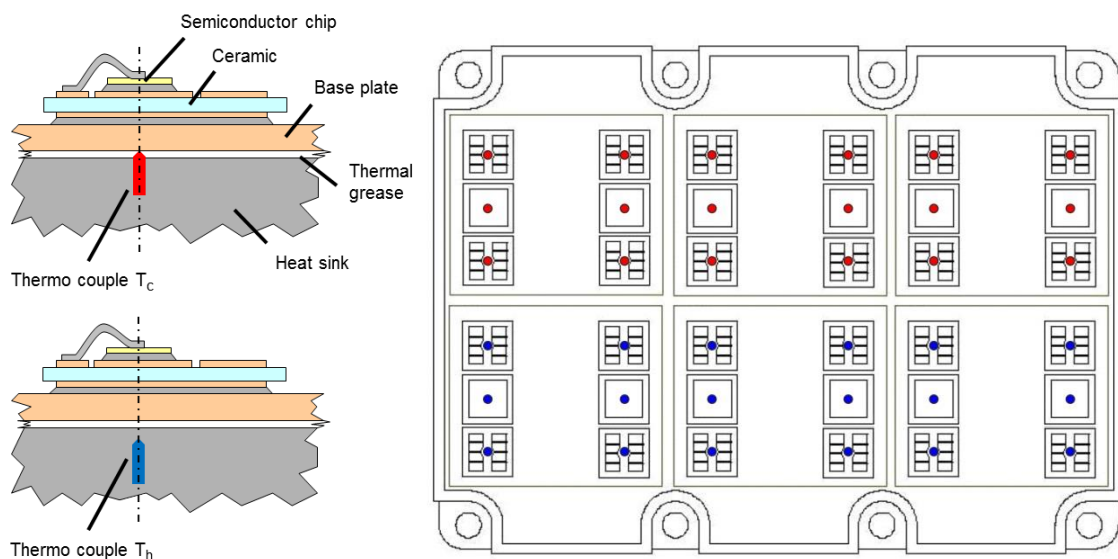
$$R_{th(x-y)} = \frac{\Delta T_{xy0}}{P_L}$$

$$Z_{th(x-y)}(t) = \frac{\Delta T_{xy}(t)}{P_L}$$

Figure 1   Principle approach of thermal impedance measurement

For determining the junction temperature in the cooling phase, a defined measurement current (I_{ref} approx. 1/1000 I_{nom}) is fed to the module, and the resulting saturation or forward voltage is recorded. The junction temperature $T_j(t)$ can be determined from the measured forward voltage with the aid of a calibration curve $T_j = f(V_{CE}/V_F @ I_{ref})$. Its reverse curve $V_{CE}/V_F = f(T_j @ I_{ref})$ (see Figure 2) is recorded earlier by means of external, homogenous heating of the tested module.

Figure 2   **Example of a calibration curve used to determine the junction temperature by measuring the saturation voltage at a defined measuring current**

The case temperatures T_c and the heat-sink temperatures T_h are determined by means of thermocouples. The thermocouples are thermally isolated except at the top. This is where they come into contact with the base plate of the module and the heat sink, respectively (Figure 3, left). In both cases, the projected thermocouple axis is located in the center of each chip (Figure 3, right).
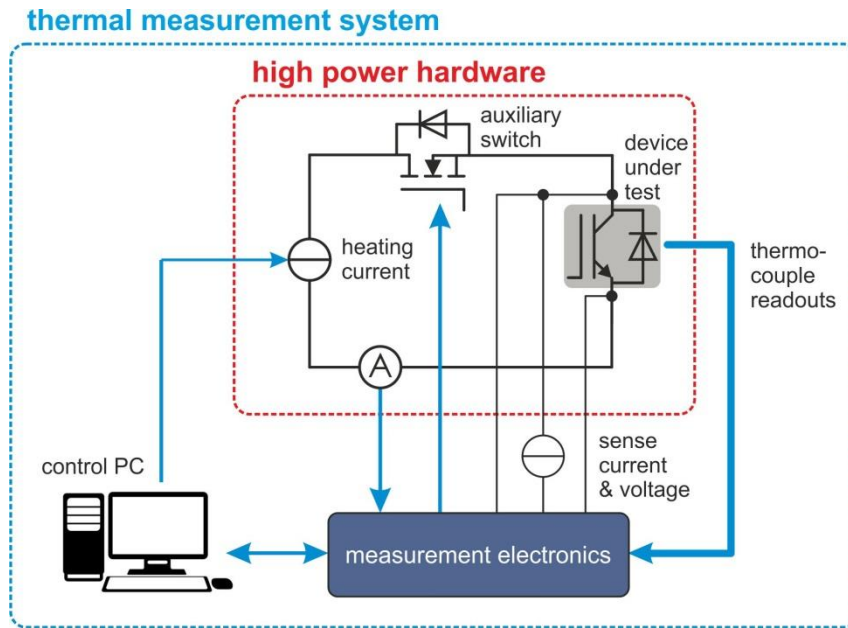

Figure 3   **Determination of case temperature T_c and heat-sink temperature T_h and example for the projected sensor positions based on a 3.3 kV 140x190 mm^2 module**

1.2   Challenges and optimization of R_{th}/Z_{th} measurement

Precise measurements are required for determining T_j and T_c exactly at the time the cooling phase begins. It should be pointed out that directly after turn-off, the smallest thermal time constants lead to big changes in the T_{vj}, so this is a very important time period to measure. On the other hand, oscillations also occur at this time, which make the measurement very difficult. The parasitic effects lead to transient disturbances in the measured signals.

In order to overcome the hurdles mentioned above, a modified measurement system (see Figure 4) is being used.
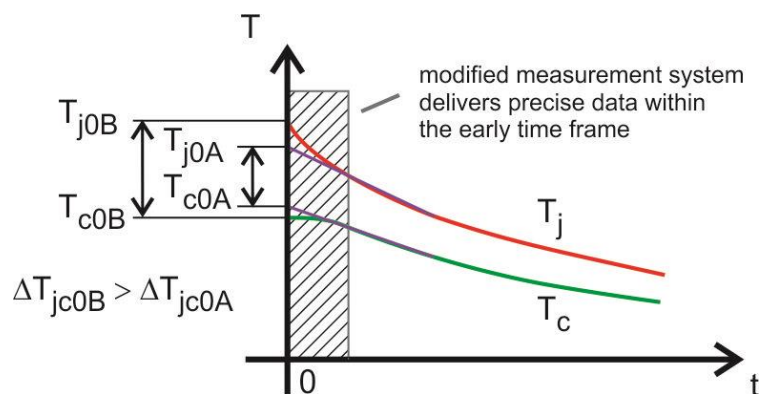
Determination of thermal impedance curves

Figure 4   Optimized analog/digital measurement equipment

Owing to advancements in technologies and products, Infineon has reviewed the R_{th}/Z_{th} measurement method and simulation approach. R_{th}/Z_{th} measurements have been modified accordingly. By using the new measurement equipment, it is now possible to determine more precise R_{th}/Z_{th} values of IGBT modules. This is depicted in a simplified manner in Figure 5. The difference between T_j and T_c at t=0 is larger for the modified measurement system "B" in comparison to the former measurement system "A". As seen in Figure 1, this temperature difference is proportional to the thermal resistance R_{th}, and also affects the thermal impedance Z_{th}.

The modified measurement system is able to determine precise data even at an early stage.

Due to the thermomechanical behavior of modules, the thermal impedance between case and heatsink (Z_{thCH}, but also Z_{thJH}) is temperature dependent. Modules are optimized to have best thermal heat transfer to the heat sink for high operating temperatures at which the semiconductors are typically best used. Therefore, data sheet conditions reflect high temperature operation only. If the modules run at low case temperatures, the users themselves should measure whether the specific thermal impedance has increased noticeably.
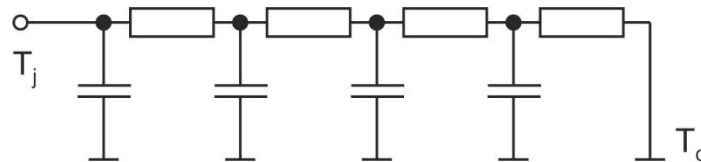

Figure 5   Comparison of former measurement system (A) and modified one (B)
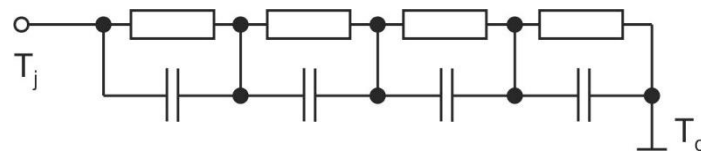
2 Thermal equivalent circuit models

2.1 Introduction

The thermal behavior of semiconductor components can be described using various equivalent circuit models:

Figure 6   Continued-fraction circuit, also known as Cauer model, T-model or ladder network

The continued-fraction circuit (Figure 6) reflects the real, physical setup of the semiconductor based on thermal capacitances with intermediary thermal resistances. The model can be set up where the material characteristics of the individual layers are known, whereby, however, the correct mapping of the thermal spreading on the individual layers is problematic. The individual RC elements can be assigned to the individual layers of the module (chip, chip solder, substrate, substrate solder, and base plate). The network nodes therefore allow access to the internal temperatures of the layer sequence.

Figure 7   Partial-fraction circuit, also known as the Foster model or Pi model

In contrast to the continued-fraction circuit, the individual RC elements of the partial-fraction circuit no longer represent the layer sequence. The network nodes do not have any physical significance. This illustration is used in datasheets, as the coefficients can be easily extracted from a measured cooling curve of the module. Furthermore, they can be used to make analytical calculations.
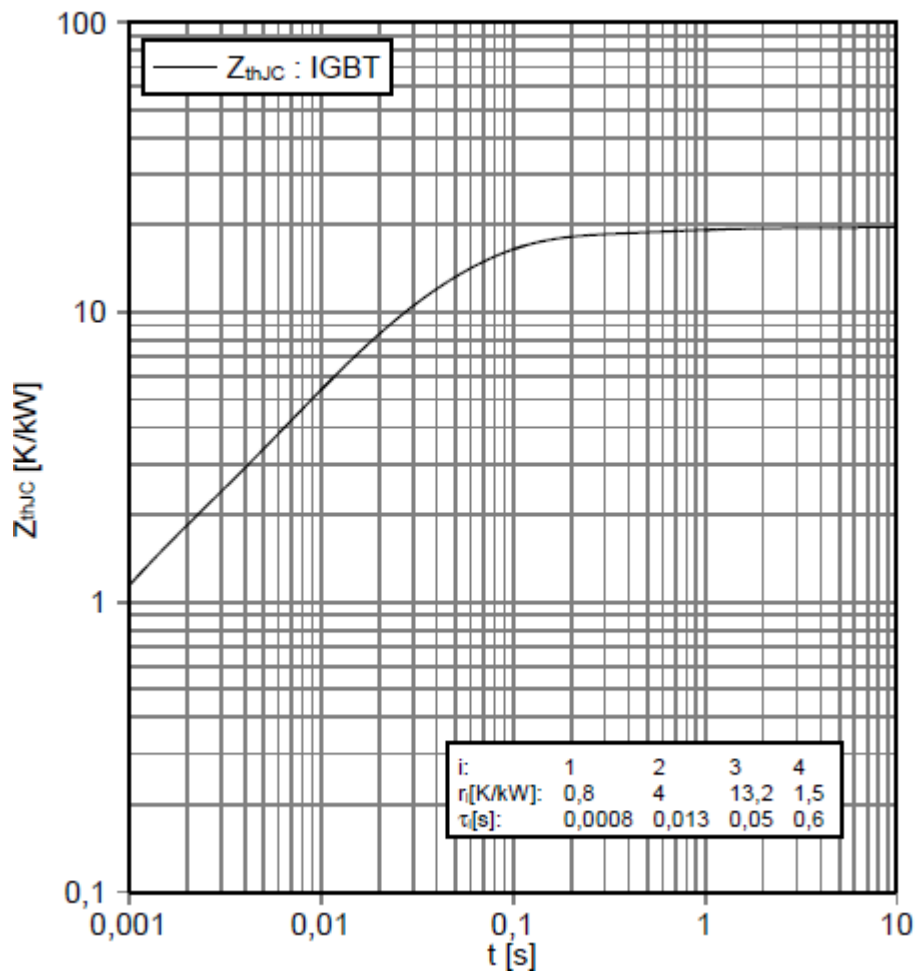
The thermal impedance of a partial fraction model can be expressed as:

$$Z_{th}(t) = \sum_{i=1}^{n} r_i \left(1 - e^{-\frac{t}{\tau_i}}\right) \tag{1}$$

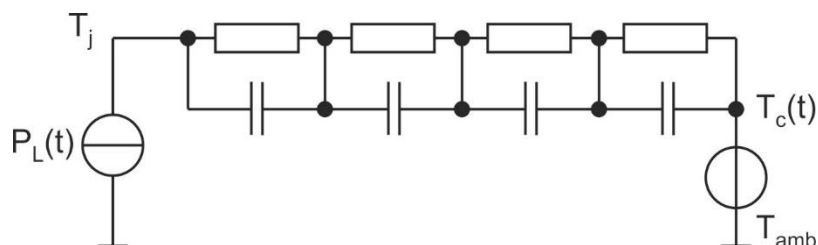whereas,

$$\tau_i = r_i \, c_i \tag{2}$$

As an example in Figure 8, the module datasheet Z_{th}(j-c) of an IGBT is specified based on a partial-fraction model. The corresponding coefficients are provided in tabular form as resistance (r) and time constant (τ) pairs.

Figure 8 Example of how thermal impedance is specified in a datasheet based on a partial-fraction model

With specific switching and forward losses $P_L(t)$, and assuming a known case temperature $T_c(t)$, the junction temperature $T_j(t)$ can be determined as follows:

$$T_j(t) = P_L(t) * \dot{Z}_{th(j-c)}(t) + T_c(t) \tag{3}$$

Figure 9 Partial-fraction model for determining $T_j(t)$ for given semiconductor losses $P_L(t)$ under the assumption of a known case temperature $T_c(t)$

The simplified assumption of a constant case and heat-sink temperature is not always given in practice, as the load duration is not negligibly short compared to the time constants of the heat sink. For considering non-stationary operating conditions, either $T_c(t)$ should be measured, or the IGBT model should be linked to a heat-sink model.

2.2 Taking thermal paste into account

In both models, the use of R_{th} instead of the usually unknown Z_{th} for thermal paste, is conceivable for a worst-case assessment. Neglecting the capacitances in the partial fraction model, a fed-in power step causes an immediate temperature drop across the whole resistor chain. The junction temperature and thermal paste temperature both rise immediately to a constant value, which does not represent the physical behavior of the system. There are two ways to bypass this problem:
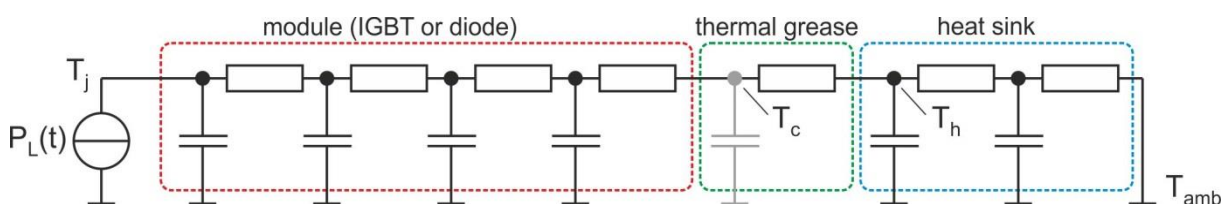
- If the Z_{th} of the heat sink is to be determined by measurement, the case temperature T_c should be used instead of the heat-sink temperature T_h. In this case, the thermal paste is included in the heat-sink measurement and is no longer to be considered separately.
- If an IGBT setup is available, where the fed-in power loss $P_L(t)$ is known, the case temperature $T_c(t)$ can be measured directly, and included in the calculation in accordance with Figure 9.

2.3 Merging the semiconductor module and the heat sink into a system model

The user often will avoid the expense of measurements, and will create a thermal system model from the existing IGBT/diode model and the desired heat-sink data. Both the continued-fraction and the partial-fraction model can depict the respective transfer functions "junction-to-case" of the IGBT and "heat sink-to-ambient" of the heat sink. If the IGBT and heat-sink models are to be combined, the question arises as to which of the two models should be used, especially if the IGBT and heat sink have been characterized separately from each other.

2.3.1 Thermal system model based on continued-fraction model

The continued-fraction model and the linking of individual models of this type visualize the physical concept of individual layers which are sequentially heating one another. The heat flow – the current in the model from Figure 10 – reaches, and therefore heats, the heat sink with a certain delay. A continued fraction model can be achieved by simulation or transformation from a measured partial-fraction model.

Figure 10   Merging continued-fraction models to a system model

It is common to set up a model by material analysis and FEM simulation of the individual layers of the entire setup. But this is only possible if specific heat-sink data is used, as the heat sink has a reverse effect on the thermal spreading within the semiconductor module, and therefore on the time response and the resulting $Z_{th}(j\text{-}c)$ of the module. If the heat sink in the application deviates from the simulated heat sink, the model will not take this into consideration.
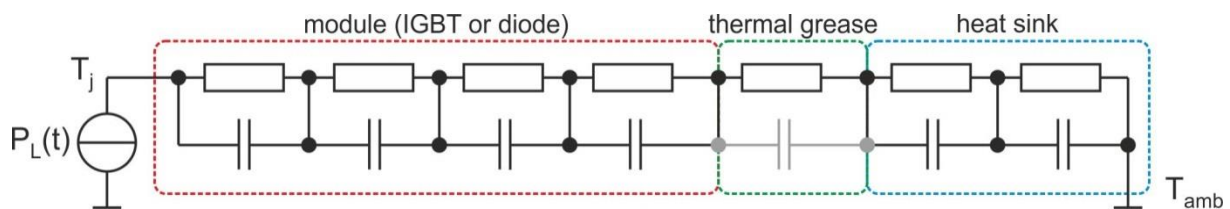
Usually the partial-fraction model is used in datasheets, as this is the result of a measurement-related analysis, with the $Z_{th}(j\text{-}c)$ being provided advantageously as a closed solution. A mathematical transformation of a partial-fraction model into a continued-fraction model is possible. This transformation is not unambiguous. Various thermal resistance (R_{th}) and thermal capacitance (C_{th}) value pairs are possible. Also the individual R_{th} and C_{th} elements, as well as the node points of the

new continued-fraction model, do not have any physical significance after the transformation. A merging of continued-fraction models that are not coordinated with one another can therefore result in many different errors.

2.3.2 Thermal-system model based on partial-fraction model

The semiconductor module, partial-fraction model, as it appears in the datasheet, is based on a measurement in combination with a specific heat sink. While an air-cooled heat sink results in a wide spread of heat flow in the module, and therefore leads to better, i.e. lower R_{th}(j-c) in the measurement, the limited heat spreading in a water-cooled heat sink results in a comparably higher R_{th}(j-c) value in the measurement. By using a water-cooling bar for the characterization, the partial-fraction model provided in the Infineon datasheets represents a comparably unfavorable operation mode, which means an appraisal on the safe side, i.e. in favor of the module.

Due to the connection of networks in series (Figure 11), the power fed into the junction – in the equivalent circuit represented by the current – reaches the heat sink without delay. Therefore, already at an early stage, the increase of junction temperature depends on the type of heat sink model.

Figure 11   Merging partial-fraction models to a system model

However, with air-cooled systems, the time constants of the heat sinks range from around 10 s to several 100 s, which is far above the value for the IGBT itself with only approximately 1 s. In this case the calculated heat-sink temperature rise distorts the IGBT temperature only to a very small degree. On the other hand, water-cooled systems are critical, since they have comparably low thermal capacitances, i.e. correspondingly low time constants. For "very fast" water-cooled heat sinks, i.e. systems with direct water cooling of the semiconductor module base plate, a Z_{th} measurement of the complete system of semiconductor module plus heat sink should be performed.

Because of the reverse effect on the thermal spreading in the module, it is not possible to link the semiconductor module and the heat sink in a fault-free way, neither in the continued-fraction nor in the partial-fraction model. A way to overcome this issue is to model or measure the Z_{th} of the semiconductor module and the heat sink interdependently. A complete fault-free thermal system model can only be obtained by measuring the thermal impedance Z_{th}(j-a), i.e. with simultaneous measurement of the complete thermal path - from junction via semiconductor module, thermal grease, heatsink to ambient. This delivers a partial-fraction model of the entire system, with which the junction temperature can be calculated fault-free.

3 References

[1]   IEC 60747-9 Ed. 2.0 (6.3.13.1) 'Semiconductor devices - Discrete devices - Part 9: Insulated-gate bipolar transistors (IGBTs) [3]

Revision history

Document version	Date of release	Description of changes
Rev 1.0	2015-12-08	First release
Rev 1.1	2018-10-16	Horizontal mirrored -> vertically mirrored on page 3 Formula (3) on page 7
V 1.2	2020-04-14	Thermomechanical behavior of modules on page 5

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