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Measuring structure functions of power devices in inverters

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ABSTRACT

This paper proposes the measuring of structure function from power devices on-board induction motor drives and multilevel converters. It puts forward the issues and methodology related to on-board measurement of the cooling curve and derivation of the structure function during idle times in induction motor drives for maintenance purposes. The structure function uses the thermal resistances and capacitances in the Cauer form to identify changes in the device structure. The advantage of the structure function is that it does not only reveal the value but also the location of the thermal resistance and capacitance in the heat flow path. The novelty in this work is the methodology used to achieve the measurement of the cooling curve and obtaining the structure function despite issues related to freewheeling current due to energy stored as a result of motor inductance. A detailed description of the measurement circuit is presented. The possibility of applying this technique to multilevel converters in different application is also elaborated.

1. Introduction

Power Semiconductors are central to a number of key societal infrastructures. They are the basic building blocks of power (electrical) conversion applications. From Fig. 1, the various silicon based semiconductor devices can be observed to be used for a wide range of power levels. Also the various possible applications for the semiconductor devices have been illustrated. Most of these applications are integral to daily life. In fact, according to [1], electric motors and the systems they drive are the single largest electrical end-use, consuming more than twice as much as lighting, the next largest end-use. It is estimated that electric motor driven systems account for between 43% and 46% of all global electricity consumption. Over 90% of this is represented by induction motors. About 25–30% of induction motor drives are driven by power switched converters. This number is growing in motor drive applications, automotive, renewable and other applications.

Power converters that use insulated gate bipolar transistors (IGBT) modules are becoming more common in automotive, rail-traction, aerospace, renewable energy and several other applications where the combination of environmental and load-derived thermal cycling can result in large and unpredictable fluctuations in junction temperature [3]. The power module is made up of different layers and several materials. This is designed to provide mechanical stability, electrical insulation and thermal conductivity [4]. The conventional power module is usually made up of eight layers as seen in Fig. 2. The numbers indicate the different layers and the colors are indicative of the materials used. Table 1 enumerates some of the different materials used and the coefficients (CTE) of thermal expansion. The CTE indicates change of a component's size with a change in temperature.

The different values of CTE will make the different materials expand and contract at different rates which will lead to mechanical stresses resulting in various failure mechanisms, such as wire-bond lift off and cracking, solder delamination and aluminium reconstruction [4]. Wire-bond lift off and solder delamination are shown in Fig. 3. The failure mechanisms need to be detected in order to prevent abrupt destruction of the devices. Therefore to detect the impending failure, cursor/cursors of detecting the failure mechanisms need to be defined. Some parameters related the device or device structure will be related to the failure mechanisms. The thermal response function (cooling or heating curve) as a result of power step excitation contains information of structure of the device. Hence by measuring the thermal response function a change in the structure can be detected. The junction temperature then is an important parameter to monitor degradation; the power modules are enclosed and provide no opportunity for a direct measurement of the junction temperature.

A common method to detect the temperature in enclosed devices with no direct contact is with temperature sensitive electric parameter (TSEP). TSEPs are electrical parameters like collector-emitter voltage (V_{ce}) [6–9] which have a mathematical relationship to temperature. V_{ce} is chosen in this work based on the fact that the aim is to measure the dynamic temperature of the device. Therefore a continuous measurement of the temperature is needed. This eliminates the use of the threshold voltage, turn-off time as regular switching is needed in order to obtain the temperature. The V_{ce} as presented in [10], exhibits the favourable characteristics such as a high repeatability, linearity.

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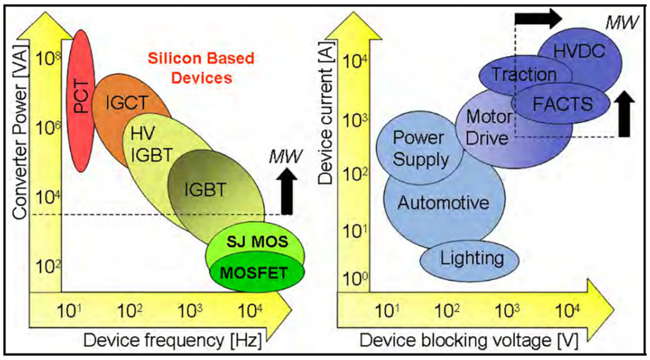

Fig. 1. Power semiconductor devices and applications [2].

1.1. Measuring thermal transients

The basic concept for measuring the cooling temperature curve by using temperature sensitive electrical parameters is shown in Fig. 4(a). A high current (red) is passed through the device under test to heat up the device using a high current source; the temperature profile (blue) of the device heating and cooling can be observed. A basic set-up to obtain the aforementioned temperature profile can be seen in Fig. 4 (b). A control switch is placed in the high current path to turn on and off the high current during heating and measurement respectively. The device under test (DUT) is left on, so during the measurement the low current passes through the DUT to create a voltage drop proportional to temperature. The relationship between the voltage and temperature is obtained from the device calibration. The calibration process is carried out by heating the device to a certain temperature and applying the low current (measurement current) and measuring the corresponding voltage. By measuring at different temperatures a relationship between the temperature and the voltage can be established.

The aim of this paper is to present the challenges and methodology used to extract the cooling curve and obtain the structure function (from cooling curve using a dedicated software program on-board) of the power devices in a 2-level 3-phase inverter as seen in Fig. 5 without dismounting or changing the connections [8]. As seen from the basic measurement in Fig. 4(b) a current source is needed in order to heat up the DUT. However in the inverter setup, the current (constant) has to be taken from the DC voltage supply without exceeding the current ratings of the devices.

As opposed to the real-time monitoring solutions, which take measurements of the TSEP of the device during operation of the inverter, in the methodology proposed here, measurements are taken when the system is not operation in order to measure the cooling curve. In [11, 12] real-time monitoring is presented, which compares physical measurement with a model estimate to accurately track the junction temperature of the device under consideration. The limitations of this method are that the collector emitter voltage is noisy and intermittent due to the non-linearity of the I-V characteristic of the IGBT, low temperature sensitivity and the variable phase current in an inverter. A quasi real-time method was also proposed in [13] which uses the RMS collector emitter voltage and current to detect fault just before start in vehicles.

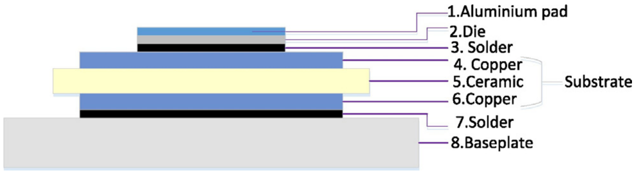

Fig. 2. Conventional power module cross section. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1
Power module materials and CTE.

Material	CTE ppm/°C
Aluminium	~22
Silicon (Die)	~3
Ceramic (Al_2O_3)	~7
Copper (Cu)	~17

The in-situ method in [14] works by injecting external currents into the power unit during idle times. Both high currents (heating) and low currents (measuring) are injected externally. Moreover, in [14] a set of relays need to be inserted to select which device undergoes test, with severe limitation of the applicability of such solution and considerable complication of the testing methodology. The method [15], mainly made reference to in this work introduces the use of vector control to heat up the power devices making use of the DC voltage supply as opposed to [14] which uses external high current source. An original approach in this paper is extraction of structure function (on-board) which can be carried out between operational phases of the equipment, such as in trains once a week/month in the depot for maintenance routines.

2. Structure function

The structure function uses the thermal resistances and capacitances in the Cauer form (because Cauer networks have a link with the physical structure) to identify changes in the devices structure. The structure functions are obtained by direct mathematical transformations from the heating or cooling curves [16]. These curves may be obtained either from measurements or from the simulations of the detailed structural model of the heat flow path. In both cases a unit step function powering has be applied on the structure, and the resulting increase (or decrease, in case of switching off) in the temperature at the same location has to be measured in time, following the switching on [17].

The advantage of the structure function is that it does not only reveal the value but also the location of the thermal resistance and capacitance in the heat flow path. There are two types of structure function, differential and cumulative. The cumulative structure function is also known as the Protonotarios-Wing function [18]. This is a function that presents a graphical representation of the structure of the device by using the thermal capacitance and thermal resistance. The cumulative structure function is sum of the thermal capacitances $C\Sigma$ (cumulative thermal capacitance) in the function of the sum of the thermal resistances $R\Sigma$ (cumulative thermal resistance) of the thermal system, measured from the point of excitation towards the ambient. In [17], the differential structure function is defined as the derivative of the cumulative thermal capacitance with respect to the cumulative thermal resistance, by

$$K(R_\Sigma) = \frac{dC_\Sigma}{dR_\Sigma} \tag{1}$$

From Fig. 6, considering a dx wide slice of a single matter of cross section A, we can calculate this value. Since for this case $dC\Sigma = cAdx$, and the resistance is $dR\Sigma = dx/\lambda A$, where c is the volumetric heat capacitance, λ is the thermal conductivity and A is the cross sectional area of the heat flow, the K value of the differential structure function is

$$K(R_\Sigma) = \frac{cAdx}{\frac{dx}{\lambda A}} = c\lambda A^2 \tag{2}$$

This value is proportional to the c and λ material parameters, and to the square of the cross sectional area of the heat flow, consequently it is

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