Aliyu, Attahir and Castellazzi, Alberto (2016) Extracting structure functions of power devices in induction motor drives. In: 22nd International Workshop on Thermal Investigations of ICs and Systems (THERMINIC 2016), 21-23 Sept 2016, Budapest, Hungary.

Extracting Structure Functions of Power Devices in Induction Motor Drives

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Abstract

This paper proposes the extraction of structure function from power devices on-board induction motor drives. 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 the derivation of the structure function despite issues related to freewheeling current due to energy stored as a result of motor inductance.

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 Figure 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.

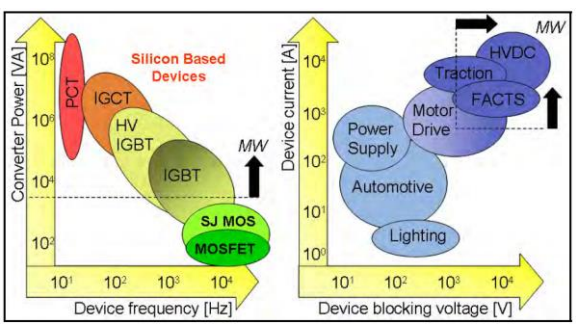

Figure 1: Power Semiconductor Devices and Applications[2]

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 Figure 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.

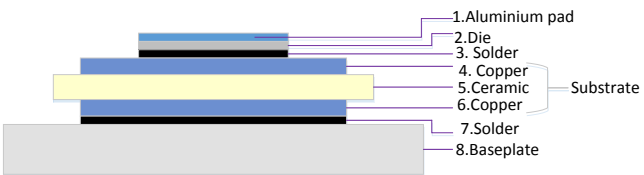

Figure 2: Conventional Power Module Cross Section

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 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 Figure 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.

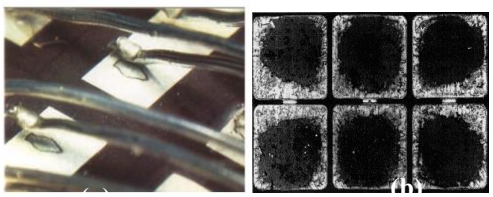

Figure 3: Failure mechanisms (a) wire-bond lift-off (b) solder delamination[5]

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.

1.1 Measuring Thermal Transients

The basic concept for measuring the cooling temperature curve by using temperature sensitive electrical parameters is shown in Figure 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 Figure 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 derive the structure function (from cooling curve) of the power devices in a 2-level 3-phase inverter as seen in Figure 5 without dismounting or changing the connections [8]. As seen from the basic measurement in Figure 4(b) a current source is provided 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.

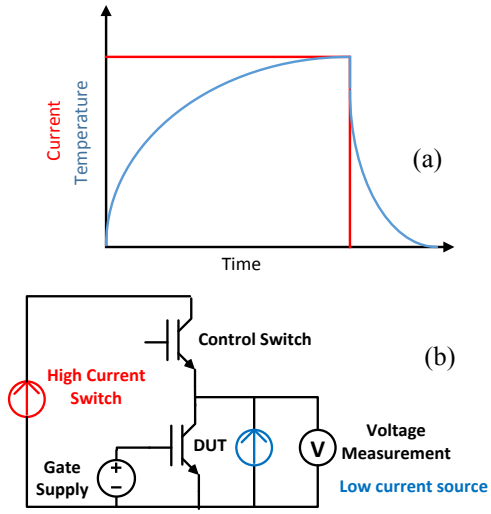

Figure 4: (a) Junction Temperature & Heating Current Pulse (b) Basic Concept of Junction Temperature Measurement Using vce

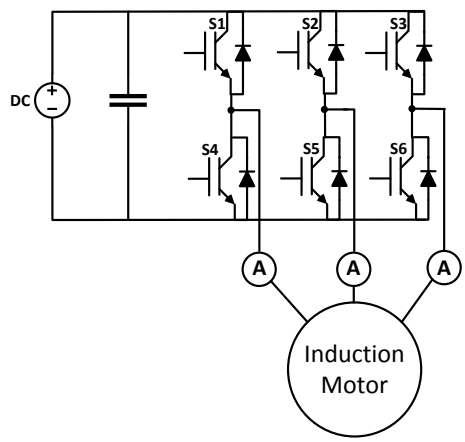

Figure 5: 2- Level 3-Phase Inverter with an Induction Motor Load

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.

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 CΣ (cumulative thermal capacitance) in the function of the sum of the thermal resistances RΣ (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

$$K(R_\Sigma) = \frac{d\,C_\Sigma}{d\,R_\Sigma} \qquad (1)$$

From Figure 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

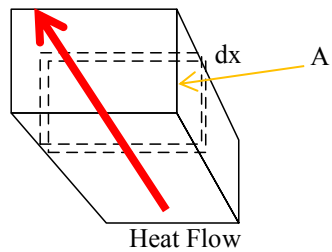

Figure 6: One Dimensional Heat Flow Model

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

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 related to the structure of the system. In other words: this function provides a map of the square of the heat-flow cross section area as a function of the cumulative resistance. The differential function is shown in Figure 7, the local peaks indicate reaching new surfaces (materials) in the heat flow path, and their distance on the horizontal axis gives the partial thermal resistances between these surfaces. More precisely the peaks point usually to the middle of any new region where both the areas, perpendicular to the heat flow and the material are uniform

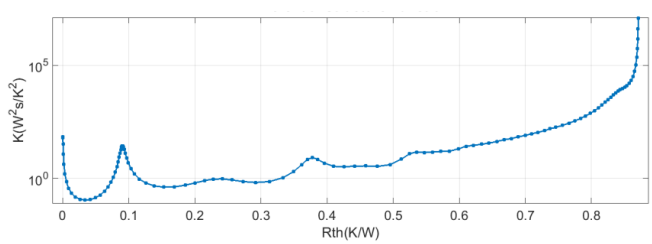

Figure 7: Differential Structure Function

3 Extracting Structure Function On-Board

One of the challenges of extracting the structure function from the inverter is heating the devices with constant current. A control technique called vector control is introduced to heat up the devices and at the same time keeps the induction motor stationary, as test is to be carried out during maintenance routines. Vector control is used because it provides the opportunity to control the torque current (I_{sq}) and field current I_{sd} which analogous to the armature current and the field current in DC motors respectively. By making the torque current (I_{sq}) 0 and giving the required current as the field (I_{sd}) reference, current flows in the devices hence heating the devices up without moving the rotor. These conditions make it suitable for maintenance routine. The details of this process are presented in [15]. The resulting phase currents during heating can be seen in Figure 8. From

the phase currents it is evident that the motor will be stationary due to absence of rotating fields.

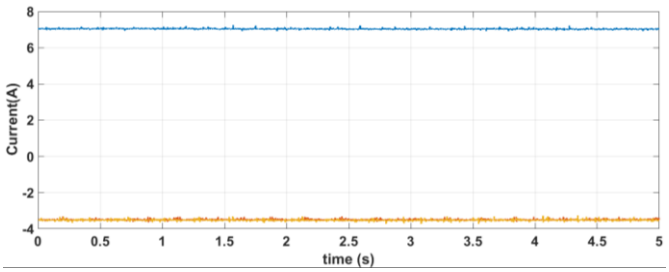

Figure 8: Three Phase Currents During Heating

The next step after heating is measuring the V_{ce}, which has to be carried out on the inverter in the presence of high voltages. The measurement circuitry is based on the work in [6]. Two diodes D1 and D2 shown in Figure 9 are connected in series and a current source forward-biases them during the IGBT on time. When the IGBT is off, the D1 diode is blocking the V_{ce} voltage, protecting the measurement circuitry from damage. Assuming the two diodes are identical ($V_{D1} = V_{D2}$), the V_{ce} voltage may be measured by subtracting the voltage drop on diode D2 from the V_b potential. This mathematical function can be realized using the circuit shown in Figure 9.

$$V_{ce} = V_b - V_{D2} = V_b - (V_a - V_b) = 2V_b - V_a \quad (3)$$

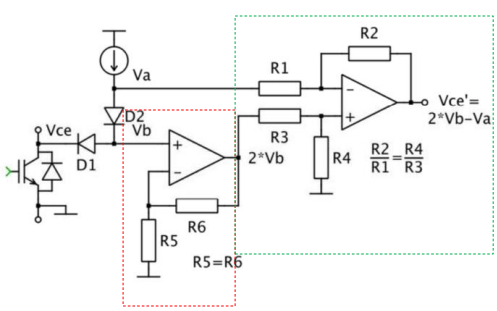

Figure 9:Schematic of measurement circuit [6]

The circuit in Figure 9 makes it possible to implement the equation above. The first op-amp (highlighted in red) does the mathematical function of producing $2V_b$ in (3). The second part (highlighted in green) of the circuit completes the mathematic function using a differential amplifier to obtain V_{ce} ($2V_b$-V_a). Extra stages have been added to the measurement circuit, such as conditioning the signal to utilize the full range of the FPGA and increase resolution. An isolation stage has also been added to protect the control board. The measurement circuit and the isolation can be seen in Figure 10.

The measurement is carried out by passing the low current used to calibrate the device. This is carried out by switching on only S1 in Figure 5 and switching off S2-S6, in order to prevent high current paths. Due to the energy stored in the motor inductance current free wheels through the device switched on for measurement and the top 2 diodes in the 2 other phases as shown in Figure 11.This means that the low current measurement cannot be carried out during the free-wheeling period due to high current flowing in the device. A voltage (collector-emitter) and current measurement of the device was carried out at this stage and it can be seen in Figure 12 that the current decays slowly.

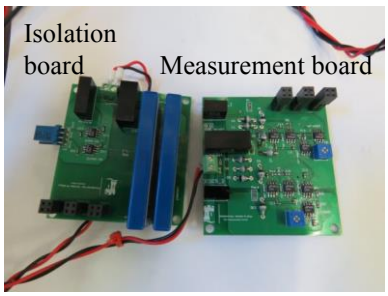

Figure 10: Measurement Circuit and Isolation Board

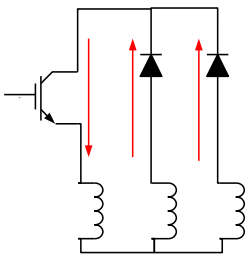

Figure 11: Inverter during Measurement Phase

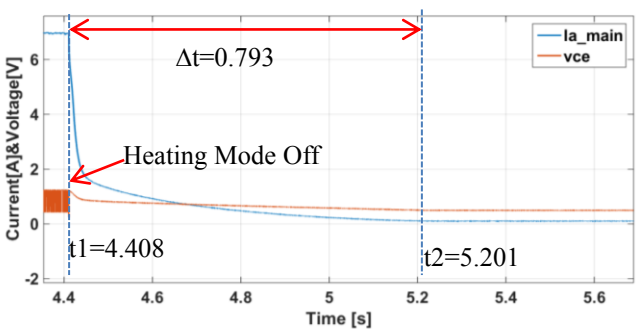

Figure 12:Current and Voltage (collector-emitter) of DUT

The magnetising inductance of the motor is considerable; it takes time for the current to decay to the measurement current used for calibration. This means that by this time, a lot of information is lost in the cooling curve which means information on the structure of the device is lost. From Figure 12, it can be observed that it takes 0.793s for the current to reach the level of the measurement current. If the measurement is to start at 0.793s most information of the structure of the device will be lost; as the die, solder and substrate faster time constants. The data sheet gives information about the junction to case thermal resistance of the device (Magna Chip MPMB75B120RH) which is typically 0.2 °C/W. By matching this information to the derived normalized temperature (divided by the power dissipation) shown in Figure 13. The approximate time

constant from the junction to the case can be obtained. In this case the obtained time constant from the graph is 0.2512s. This means that any measurement that starts past this time constant is measuring the heat sink. Therefore any degradation present in the device will not be recorded

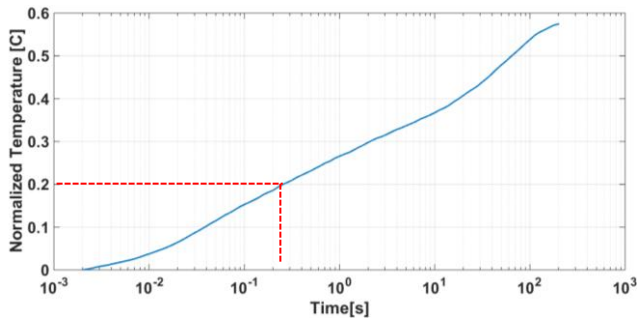

Figure 13: Normalized Temperature Curve

To solve this problem, the methodology will be outlined. Since the current stored in the inductor flows through the device and the voltage is always measured. The collector current against the collector emitter voltage (I-V curves) at different temperatures can be used to measure the temperature by creating a look-up table. In Figure 14, the maroon line is the measured voltage and current passing through the device. However this curve passes through a point on the IV curves where there is no difference in voltage and current for all the temperatures. This means that it is impossible to measure at this point (Inflexion Point). But above the and below this point the sensitivity (to noise) gradually decreases. The highlighted area in Figure 14 below the Inflexion point has a lower sensitivity (to noise) of about 2mV/°C and the highlighted area above this region has a higher sensitivity(to noise) of 0.9mV/°C This methodology exploits the point below the inflexion point. One of the reasons for this is that the region has a lower sensitivity (to noise) and also it is known that there is negligible self-heating in this region as the current is low.

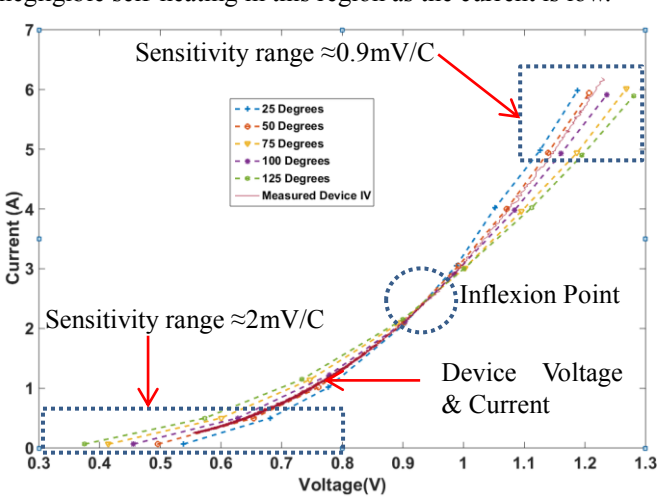

Figure 14: I-V Curves and Measured Device current and Voltage

4 Results

The methodology is to use the controller (vector control) used to heat the devices to force the current to a low value so that the region in the IV curves will be of a low sensitivity. It can be seen in Figure 15 that the reference changes from 7A to a low value (0.2 amps in this case). The current changes faster (from 7Amps to 0.2 A in 2ms) than in the previous case. This means that the self-heating is negligible, faster time constants will be recorded. In this case the measurement starts when the current falls below 1A. As it can be seen from figure 6, the sensitivity(to noise) of the IV curves reduces as the current approaches zero therefore less error in the measurement.

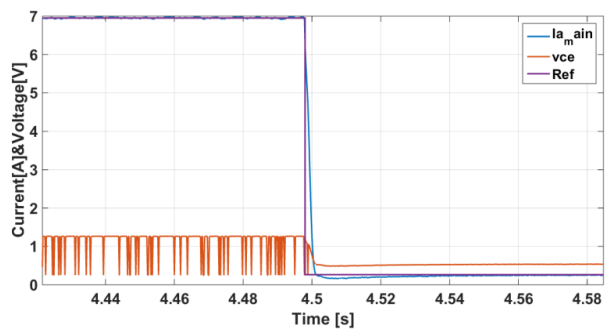

Figure 15: Current and Voltage During Measurement Using Vector Control.

The Junction Temperature measurements taken in this case are shown in Figure 16. An averaging technique was used to derive the two averaged curves (Blue and Orange). The two curves are presented here to show that this process is repeatable. This is important because the process is carried out to check for degradation in power modules; making sure changes are due to degradation not measurement. The differential structure function of the temperature curves can be seen Figure 17 also showing repeatability.

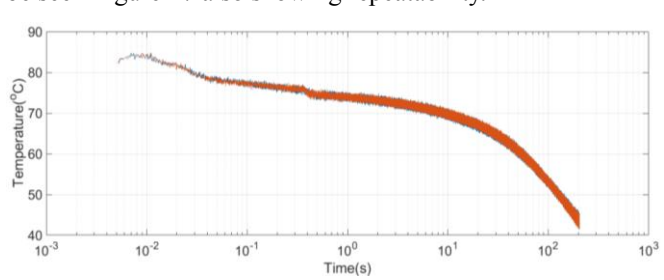

Figure 16: Junction Temperature Curves

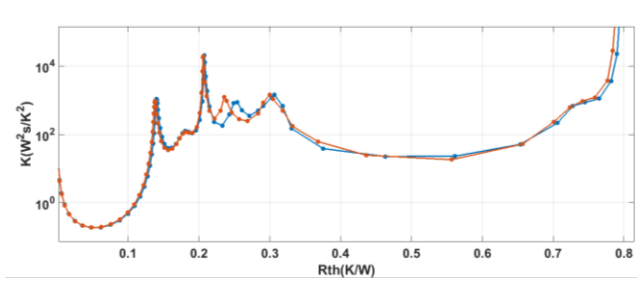

Figure 17: Differential Structure Function

5 Conclusion

This work has shown a method of extracting the junction temperature and structure function of power modules for health monitoring purposes. It introduces the use current controller to measure junction temperature. It also shows how to avoid the stored energy in the induction motor that disrupts temperature measurement. Experimental results of junction temperature and the structure function have been provided. The system is carried without additional components or changes to the inverter system except the analog measurement circuitry. Future work will entail cycling of devices to induce degradation so the difference can be identified by a measurement carried out at time 0 using the structure function.

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