A Prognostics Framework for Power Semiconductor IGBT Modules through Monitoring of the On-State Voltage

Nicolas Degrenne[1], Chihiro Kawahara[2] and Stefan Mollov[3]

[1,2,3]*Power Electronic System Division, Mitsubishi Electric R&D Centre Europe, Rennes, France*
n.degrenne@fr.merce.mee.com
c.kawahara@fr.merce.mee.com
s.mollov@fr.merce.mee.com

Abstract

This paper presents a literature review and an overview of original contributions on diagnostic and prognostic technologies for IGBT power modules based on the monitoring of the on-state voltage (Von). First, different kinds of Von sensing circuits are discussed in terms of specifications, implementation, performance and cost. A low-cost and practical circuit is experimentally demonstrated. Then, a method is presented and evaluated for estimating wire-bond degradation. Wire-bond lift-off is the most observable wear-out mechanism for industrial power semiconductor IGBT modules subject to active power cycling (Lutz et al., 2011). It is effectively detected by measuring Von at the Zero Temperature Coefficient (ZTC) current value. Next, a method is presented to estimate the die temperature. Knowing the die temperature allows estimating the thermo-mechanical stress imposed to the wire-bonds. It is demonstrated to be feasible with ±3°C accuracy/precision using after careful calibration of Von as a Temperature Sensitive Electrical Parameter (TSEP). Finally, an algorithm is presented to process the information generated from the monitoring of Von and estimate the Remaining Useful Life (RUL). It considers Von evolution prior the first wire-bond lift-off and it combines both condition-based and damage accumulation based predictions. The major contribution of this paper is to present, for the first time, a complete framework for diagnostics and prognostics of power semi-conductor IGBT modules.

1. Introduction

When designing for life-cycle cost, the power electronic designer faces the trade-off of reliability versus cost (Fig. 1). For increasing number of applications, lifetimes longer than e.g. 30 years is unnecessary due to excessive acquisition cost and lifetime limitation of other components in the system.

Prognostics is defined as an engineering discipline focused on predicting the time at which a system or a component will no longer perform its intended function (Goebel et al., 2017). Prognostics technologies offer a paradigm shift to the power electronic designer: estimation and communication of the Remaining Useful Life (RUL) permit predictive maintenance and reduce the negative impact associated with reduced over-design margin (e.g. security, availability, failure and unplanned maintenance cost) (Degrenne et al., 2015).

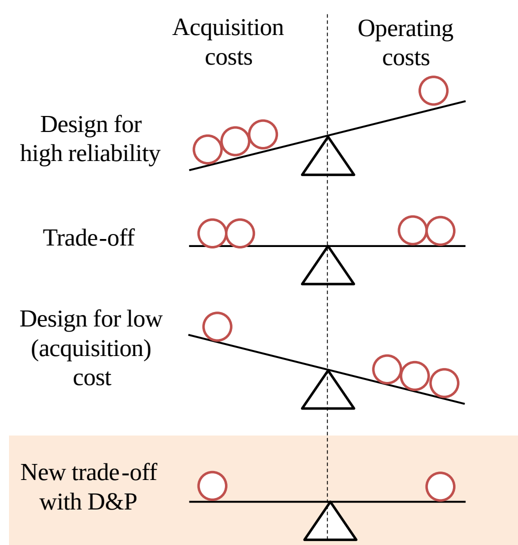


Figure 1. New design trade-off permitted by diagnostics and prognostics.

Condition-based predictions and Damage Accumulation Model (DAM) as defined in Goebel et al. (2017) respectively rely on the monitoring of failure precursors and stressors. When traditional wire-bonded power semi-conductor modules are concerned, these are typically the on-state voltage (Von) at high current and the die temperature Tj. In the case of traditional power semi-conductor modules, Von mainly consists of the on-resistance of semiconductor dies and the resistance of bonding wires. Typical interconnection of power semi-conductor die in the power module and the equivalent circuit is shown in Fig. 2.

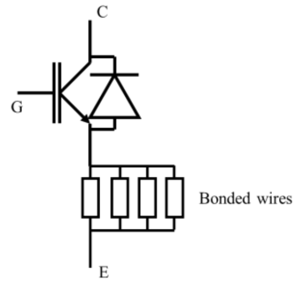


Figure 2. Schematic illustration of equivalent circuit of semi-conductor dies and bonded wires in power modules.

The on-state voltage of IGBT is a Temperature Sensitive Electrical Parameter (TSEP), and it thus can conceivably address both prognostics indicators through the same Von sensor in a low-cost and reliable manner.

This paper introduces the most recent state of the art and provides an overview of original contributions in the field on prognostics based on Von sensor. The paper presents in order (Fig. 3):

- Von sensors
- Estimation of electrical resistance increase
- Estimation of junction temperature
- Prediction of damage, EoL(End of Life) and RUL

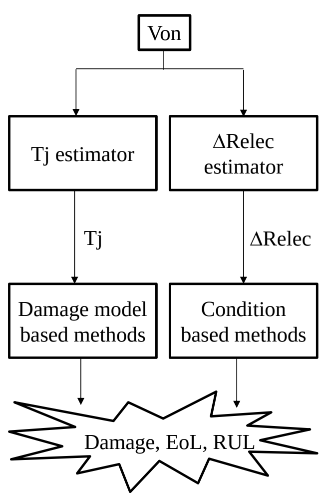


Figure 3. Von is used both as a temperature sensor and a damage sensor to perform diagnostics and prognostics with damage model based and condition based methods.

2. VON SENSOR

2.1. Literature review

The most critical and original part of the Von sensor is the high-voltage protection. It disconnects the low-voltage sensor from the power switch when high voltage is across it. Four main types of clamp circuits can be found in the literature (Ghimire, 2015), (Asimakopoulos, 2018), as classified and illustrated in Table 1 and Fig. 4.

Table 1. Classification of protection circuits for Von sensors

Nb	Clamp method	Pros	Cons
a)	De-sat style with 2 thermally-coupled HV diodes in series	Fast	- Fundamental issue with dispersion in diode thermal sensitivity
b)	Active MOSFET clamp	Fast	- Requirement of (SiC) HV switches which are necessarily high-cost - Complex control
c)	Depletion mode MOSFET	Fast	- Requirement of HV depletion mode MOSFET which is not common
d)	R-D clamp	Simple	- Trade-off rapidity/ power consumption

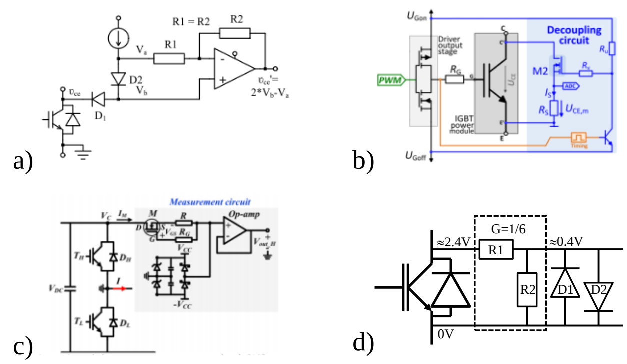


Figure 4. Examples of clamp circuits compared in Table 1.

The most important criteria for comparing Von sensors are low temperature drift, low-cost and component availability. The circuit d) with R-D clamp is performing better in this regards. Its main drawback is its relatively long time response caused by the RC time constant and the reverse-recovery charges in the clamping diodes. Decreasing the resistor value increases the power losses of the sensor when subject to high-voltage.

2.2. Proposed Von sensor

A Von sensor using a diode clamp was presented in (Degrenne & Mollov, 2018a), that is capable of monitoring devices operating at high switching frequency (i.e. above 20kHz under typical extreme modulation depth). In this paper, the cost is mitigated through low/top-side multiplexing (Fig. 5). This circuit is demonstrated in Fig. 6 on the high and low-side pairs of a full-bridge. Its evaluation shows a precision of ±3.5mV and a time-response of 11µs. Such a prototype can be built with a MOQ (multiple Order Quantity) BOM (Bill of Material) of less 8€ per monitored switch.

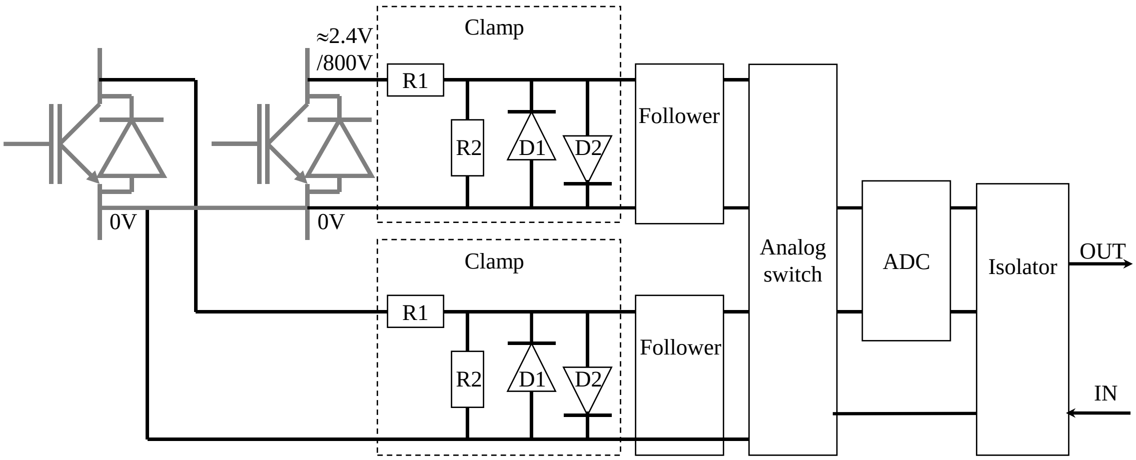


Figure 5. Multiplexed R-D clamp circuit

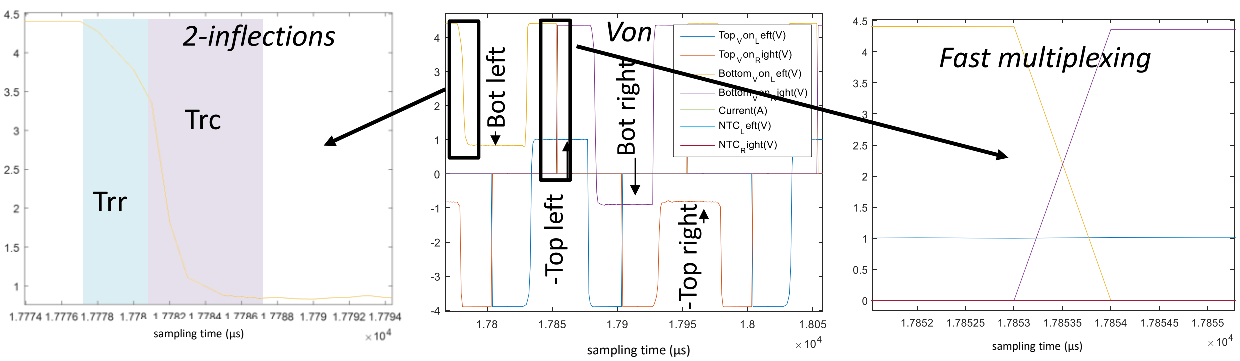


Figure 6. Von sensor output voltage waveforms monitoring a full bridge.

3. ESTIMATION OF ELECTRICAL RESISTANCE INCREASE

3.1. Method

The typical method for estimating the electrical resistance increase due to the degradation of wire-bonds is by performing Von measurement at high current and constant temperature. In (Degrenne & Mollov, 2018a), the electrical resistance increase is assessed by performing Von measurements at ZTC (Zero Temperature Coefficient) current at any temperature, thus eliminating the effort to remove the influence of temperature variations due to variable field operating conditions. ZTC point is typically present in most IGBTs as illustrated by the static characteristic in Fig. 7.

3.2. Results

As compared with estimation at high load current, the sensitivity at ZTC current is proportionally decreased with the current value. For example, in Fig. 8, the static characteristics of an IGBT were acquired on-line with the previously described Von sensor for different scenario of degradation. In order to emulate degradations, wire-bonds were sectioned one by one (out of a total of 15 wire-bonds).

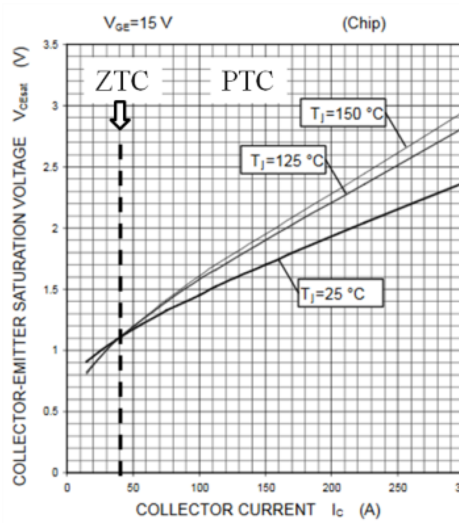


Figure 7. Typical static characteristic of an IGBT (CM150TX-24S)

The sensitivity is thus reduced by a ratio of 2.6 between measurements at 90A and at ZTC current of 35A. However, the sensitivity at ZTC current is sufficient to detect the lift-off of 1/5th of the wire-bonds of a 1.2KV/150A IGBT module (Fig. 8). As shown in Table 2, the detection of a 5% Von increase at high current, that is typically used as a failure criteria in power cycling tests, corresponds to 35mV increase at ZTC current, is an order of magnitude higher than the experimentally observed precision of the Von sensor, and can thus be easily detected. The detection of finer and earlier increases such as evolution prior to the first lift-off, as used in (Degrenne & Mollov, 2018b) and first Von jump is still a challenge at ZTC current.

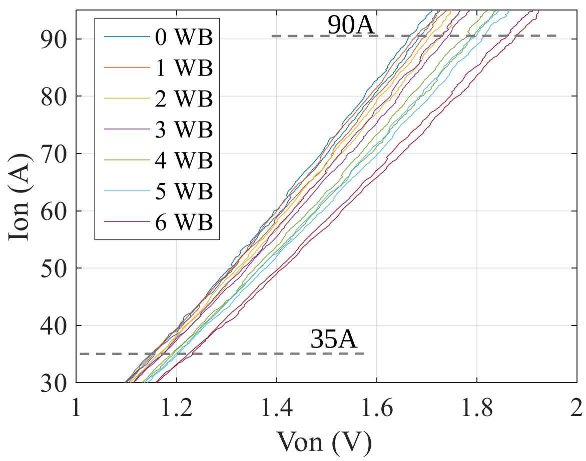


Figure 8. On-line Ion(Von) at with sectioned wire-bonds

Table 2. Typical requirements on Von sensitivity

	1% Von increase (at high current)	**Average Von jump**	**5% voltage increase (at high current)**
@ High current of 90A	18mV	33.2mV	90mV
@ ZTC of 35A	7mV	12.8mV	35mV

3.2.1. Calibration of ZTC current

ZTC can generally be approximated using the datasheet of the power IGBT module (Fig. 7). However, dispersions of more than 5A were observed between two 1.2kV/150A switches of the same reference. On-line calibration may thus be necessary in order to increase the accuracy. Two calibration methods based on the on-line acquisition of the static curves were demonstrated in (Degrenne & Mollov., 2018a). The first method is performing 2 static curves at different heat-sink temperatures (Fig. 9). The second method is applied in an inverter by performing one bi-directional curve at low modulating frequency (Fig. 10). In this last case, the accuracy is reduced and filtering of the local static characteristics is necessary.

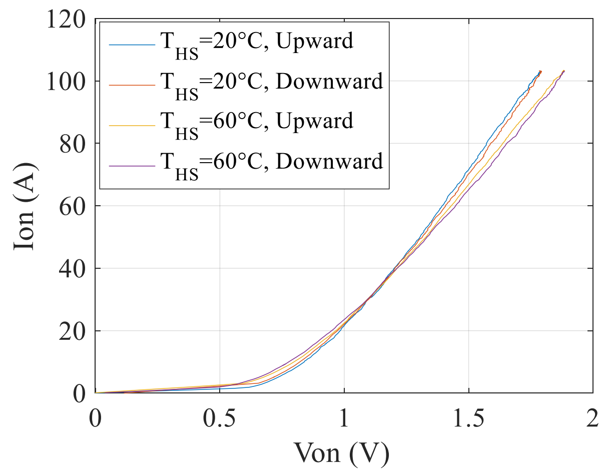


Figure 9. On-line Ion(Von) at 2 heatsink temperatures of 20°C and 60°C

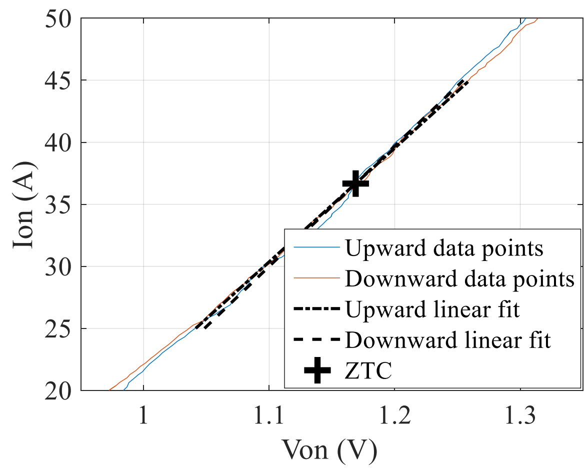


Figure 10. On-line Ion(Von) at a same heatsink temperature and during increasing and decreasing current with linear fit

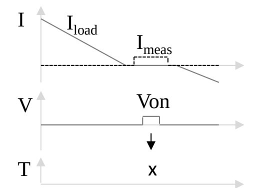
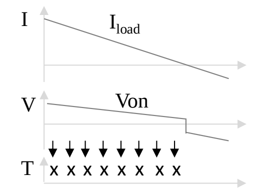
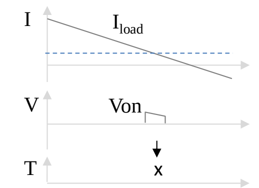
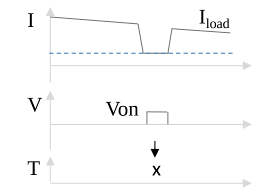
4. ESTIMATION OF JUNCTION TEMPERATURE

4.1. Literature review

Von is a TSEP that can be exploited in different manners in order to estimate the junction temperature. As opposed to other TSEPs, the advantage of Von are:

- Applies to both IGBTs and Diodes
- Provides condition monitoring as well

Table 3. Methods for Tj estimation with Von as a TSEP (method 4 is developed in the present paper)

	Method 1: Von @ low measurement current	**Method 2: Von @ any load current**	**Method 3: Von @ low load-current**	**<u>Method 4: Von @ low load-current pulses</u>**
Features				
Cost and calibration effort	★☆☆☆☆ - Von sensor - Specific current source - By-pass circuit	★★★☆☆ → ★★★★☆ (this paper demonstrates the use of a reduced calibration data) - Von sensor - Current sensor - High calibration effort (calibration versus both temperature and current)		
Intrusiveness and bandwidth	★★☆☆☆ - Disconnects the power-device from power during measurement	★★★★★ - Does not interact with normal operation - Can be performed at each switching period	★★★☆☆ - Does not interact with normal operation - Can be performed twice per modulating period of an inverter	★★★☆☆ - Modifies the load current during 100µs to 200µs - Each temperature estimation impacts load current and EMI
Accuracy	★★★★☆ - The main issue is the cool-down during the delay before measurement	★★☆☆☆ - Self-heating in calibration - High influence of the interconnect temperature - Low sensitivity for some current values close to ZTC - Uncertainty on current	★★★★☆ - Uncertainty on current	
Robustness	★★★★★	★☆☆☆☆ - High sensitivity to wire-bond degradation	★★☆☆☆ → ★★★★☆ (this paper demonstrates a means to estimate and compensate for the wire-bond degradation) - Medium sensitivity to wire-bond degradation	
References	(Rashed et al., 2013) (Hiller et al., 2014) (Aliyu et al., 2018)	(Kim et al., 1998) (Ji et al., 2013) (Choi et al., 2015)	-	(Brandelero et al., 2016)

The Table 3, originally presented and discussed in (Degrenne & Mollov, 2019) provides a literature review for implementing Tj estimation with Von. The selection criteria for choosing a most suitable method are the cost, the calibration effort, the intrusiveness (i.e. the on-line and in-situ capability), the bandwidth, the accuracy and the robustness. In this paper, results obtained with the method 4 are presented with a way to increase the robustness to wire-bond degradation.

4.2. Proposed Method 4 and results

The methodology for on-line temperature estimation as detailed in (Degrenne & Mollov, 2019) includes the phases of calibration, modeling, degradation assessment, and temperature estimation as illustrated in Fig. 11.

The calibration phase is performed under low load current pulses (Fig. 12).

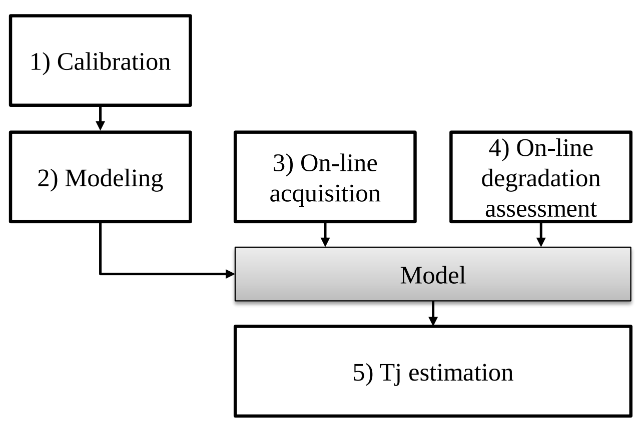


Figure 11. Proposed methodology for Tj estimation based on Von measurement at low load current pulses.

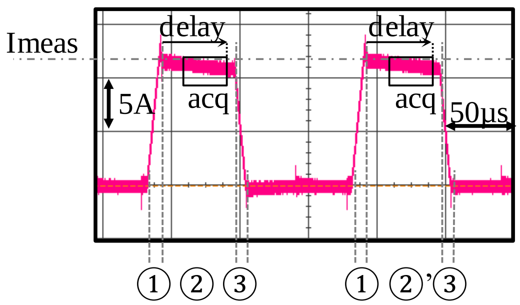


Figure 12. Example of couple of current pulses for estimation of the Tj of two IGBTs and two diodes of a H-bridge. ILinit=0 and Imeas>0.

Von values are monitored at various low load current levels and various heat-sink temperatures. The 3-column array of acquired data (Ths / Iload / Von) is used to fit the model of Eq. (1):

$$Von = (a \cdot Tj + b) \cdot Ion + (c \cdot Tj + d + e \cdot Tj^2) \qquad (1)$$

During the on-line acquisition, low-load current pulses are generated. In Fig. 13, heating and cooling of the die is performed by alternating 4s sinusoidal current and 8s zero current. Low-load current pulses are generated at the end of the heating and cooling phases.

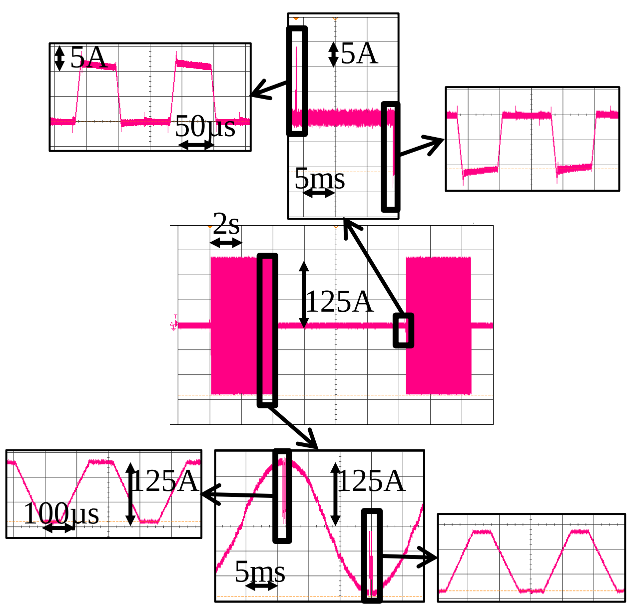


Figure 13. Low load current pulse on-line generation for Tj estimation at the end of the cooling phase (top) and heating phase (bottom).

The monitored Von and load current values are used together with the inverted equation for Eq. (1) and Tj is estimated. Experimental results demonstrate an accuracy within ±3°C (Fig. 14).

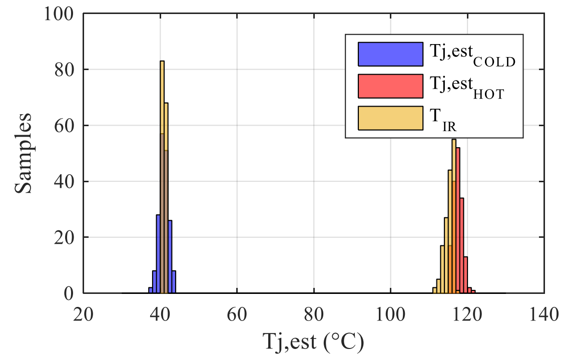


Figure 14. Cold and hot temperature estimates and IR camera values during PWM temperature cycles under 110Apk at 50Hz.

When wire-bonds lift-off, the monitored Von is slightly increase for a same effective temperature, which relates into the under-estimation of the temperature (Fig. 15)

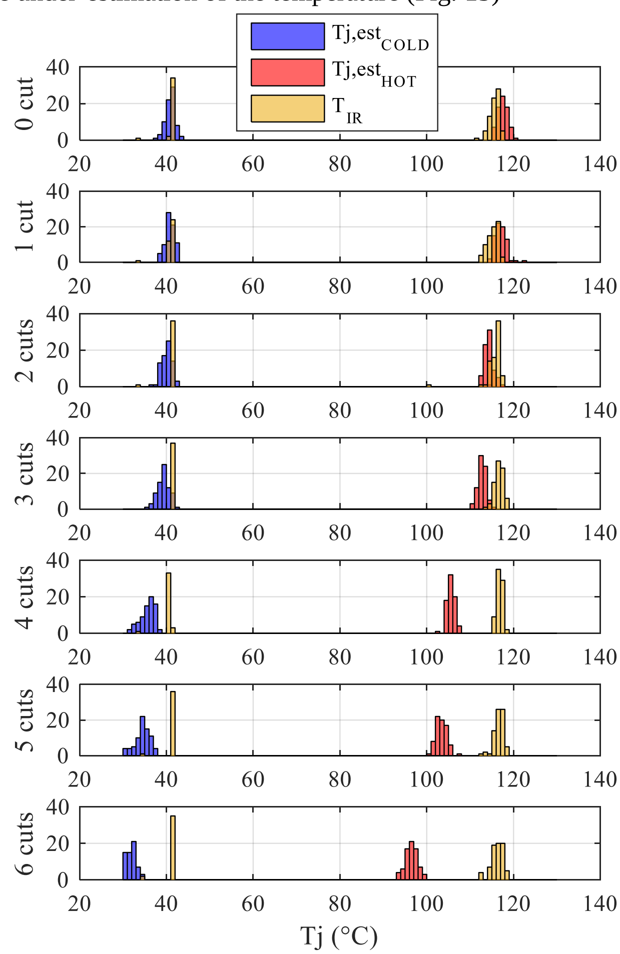


Figure 15. Cold and hot, estimated and measured temperatures with different number of sectioned wire-bonds for an IGBT.

The estimation of the electrical resistance increase at ZTC can be used to correct the model (1) and the robustness of the temperature estimations is increased (Fig. 16). The demonstrated Kelvin-range accuracy and precision make it suitable for both protection and remaining useful lifetime estimation.

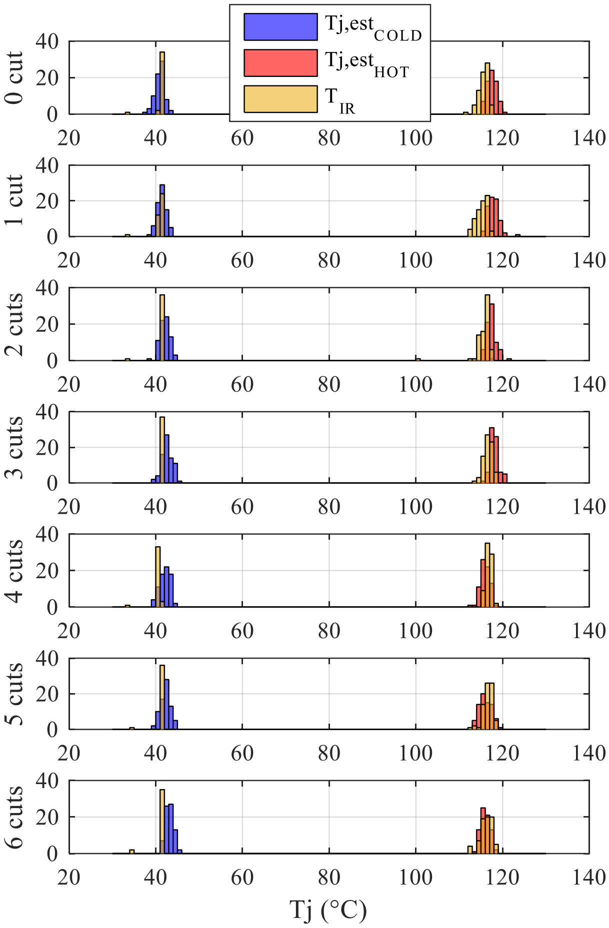


Figure 16. Cold and hot corrected temperature estimated and measured temperatures with different number of sectioned wire-bonds for an IGBT.

5. PREDICTION OF DAMAGE, EOL AND RUL

Now that the methods for estimating the electrical resistance increase (failure precursor) and the junction temperature (stressor) were developed, this section provides an example on how to process the information in order to generate a diagnostic and prognostic of the IGBT module.

5.1. Literature review

The data processing step requires a multi-disciplinary approach to combine expert knowledge in the fields of power electronics, mechanical failure propagation, and signal processing. Almost all methods in the literature require models that can either be pre-defined or auto-learned (e.g. machine learning). Physics-based models are generally preferred because they offer a logical understanding of the results and can be modified to adapt to different power modules (Yang et al., 2013), though the literature is dominated by examples of (exponential) empirical models (Celaya et al., 2011) (Dusmez et al., 2015) (Biglarbegian et al., 2018) such as Eq. (2):

$$\Delta R = \alpha\left(e^{\beta t} - 1\right) \tag{2}$$

5.2. Proposed Diagnostics and Prognostics algorithm

The algorithm presented in Fig. 17 is detailed extensively in (Degrenne & Mollov, 2018c). The inputs of the algorithm are Von,meas which is independent of temperature (i.e. such as electrical resistance increase) and Tj,meas, the junction temperature measured and estimated from Von. The algorithm counts the temperature cycles with a rainflow algorithm, and uses a degradation model (or damage model) to estimate the damage (in %) and two corresponding physical parameters which are the crack length in the wire-bonds and the metallization resistivity increase. The relation between damage and physical parameters was established with FMEA (Failure Mode and Effect Analysis) and is detailed in (Degrenne et al., 2018b). An electrical model translates these parameters and the current value into an estimate of Von. This estimate is compared and combined with the measured Von in the re-sampling block. In the forecasting phase (i.e. RUL estimation phase), similar models are used but the temperature cycles are forecasted based on past observations, and no comparison and combination is performed since no measurement of Von is available.

5.3. Results

The algorithm is tested using power cycling data. An example of RUL estimate is shown in Fig. 18. The algorithm shows ability to estimate RUL with a reasonable error at 75% of lifetime, e.g. 5 years before End of Life (EoL) if the lifetime is 20 years (Fig. 19). At the moment of writing this paper, the different blocks of the algorithm are only roughly tuned, and the objective is mostly to show a proof of concept, rather than to evaluate its performances quantitatively.

6. CONCLUSION

This paper presents a framework that combines sensors, feature extraction methods, models, estimators and forecasting for remaining useful life estimation of power modules. Each part of this framework is important and challenging for obtaining an accurate estimation on an on-line system. An often overlooked problem is the calibration of the Von sensor as a temperature sensitive electrical parameter. In this paper, a method is presented where the heat-sink temperature is controlled and short current pulses are generated. This is usually not possible to perform such a calibration in the field.
The further steps of this study will be to adapt it to a fully on-line converter environment, and to quantify its performances experimentally.

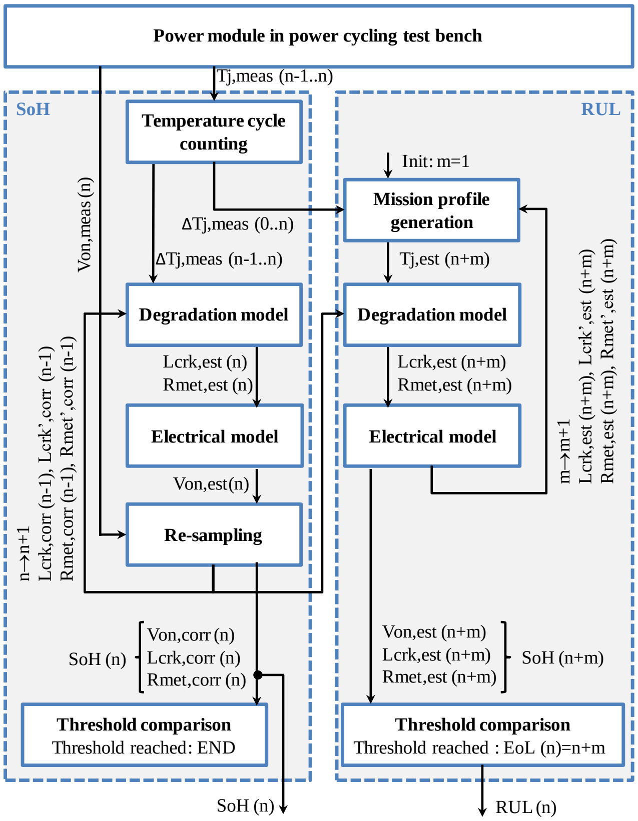


Figure 17. General view of the algorithm for SoH and RUL estimation

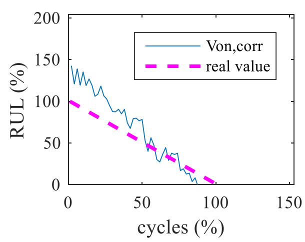


Figure 18. Mean estimation of the RUL as a function of number of cycle for a DUT.

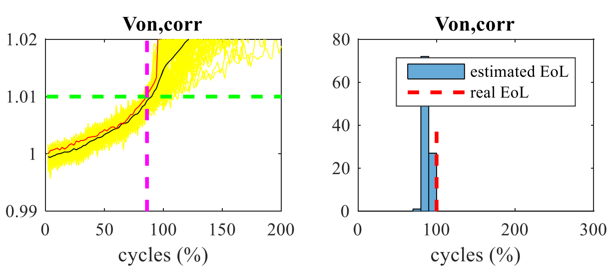


Figure 19. Details of the algorithm activated after 75% cycles. Identification and extrapolation of the SoH states (left) and corresponding EoL estimates (right). On the left, the particles and their mean are yellow and black, the real value is red, dashed curves show the activation time (magenta) and the threshold (green).

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