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Improved Reliability of Power Modules: A Review of Online Junction Temperature Measurement Methods

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Improved Reliability of Power Modules via Online Temperature Measurements

I. INTRODUCTION

Power electronic systems play an increasingly important role in adjustable-speed drives, power quality correction, renewable energy systems, energy storage systems, and electric or hybrid electric vehicles. They can provide highly efficient forms of power conversion; however these applications often present demanding operating environments and challenge the reliability aspects of power electronic techniques. For example, power electronic systems are desired for operation in increasingly thermally stressful environments, such as electric vehicles where ambient temperatures under the hood may exceed 150°C; while some wind turbine applications can place large temperature cycling conditions on the system. On the other hand, aerospace and automotive applications place rigorous demands on reliability due to safety requirements in these industries.

Power semiconductor devices are often ranked as the most fragile components in overall systems [1], of which, temperature and temperature cycling conditions form a considerable influence on their reliability and performance. Figure 1 displays a typical multilayer structure and the associated materials used in conventional power modules. Common failure locations often occur around the semiconductor die – notably bond wire lift off and degradation in the solder joints (highlighted in red in Figure 1). These failures are primarily attributed to the temperature swings in the power module coupled with large differences between coefficients of thermal expansion of the different materials in its construction. These differences are exploited by a module's temperature profile, which results from both the environmental and functional thermo-mechanical stresses due to the applicative mission profile (Figure 1).

Thus, the junction temperature (T_j) must be considered in the design of a converter system to ensure optimal reliability and operation. Traditionally, this is performed via analytical estimations based on simplified electrical and thermal models combined with semiconductor datasheet values. Several semiconductor manufacturers now provide software tools for this purpose [2]. Figure 2

demonstrates the T_j parameters generally considered in a design. The average junction temperature, $T_{j(\text{avg})}$, is generally determined using stationary thermal models based on the use of thermal resistances. Taking into account non stationary phenomena, it is possible to estimate the junction temperature swing ΔT_j and then the maximum junction temperature $T_{j(\text{max})}$, which must be respected for safe operation.

Although these modelling techniques using manufacturer data are widely used, significant questions remain regarding their accuracy and limitations. For instance, thermal characteristics given in the datasheet may often account for worst case scenarios, while power loss data is only valid for standard converter design and cannot necessarily be applied accurately to a variety of topologies. Bruckner and Bernet [3] attempt to experimentally verify the accuracy of these estimations when applied to a real power electronic converter. They find that calculated junction temperatures using datasheet values are typically higher than real temperatures as measured with an infra-red camera – with realistic errors in the region of $\pm 11\%$. This uncertainty can lead to oversizing of cooling systems, common in many applications, to guarantee a proper level of reliability – albeit at the expense of increased volume, weight and cost. Furthermore, the thermal and electrical characteristics of a power module alter over the lifetime of a converter [4][5], and therefore these calculations are not valid during the entire lifecycle of the product.

Frequently, only average junction temperatures ($T_{j(\text{avg})}$) are calculated and a safety margin for the maximum junction temperature ripple is included in the design. Thus, interest in developing methods for real-time estimation in order to prevent thermal overloads and provide enhanced chip utilisation currently exist [6][7].

An accurate method for the measurement of junction temperature during the operation of a power electronic converter has benefits for both its design and operation: real time temperature information can improve condition monitoring techniques that concern failure mechanisms that are primarily

dominated by temperature, and temperature based control algorithms that seek to improve reliability and chip utilisation could be further enhanced.

In this article, a brief outline of the potential for junction temperature information to be used in condition monitoring and active thermal control of power electronic systems is provided. Following this, a review of online junction temperature measurement methods is carried out. A specific focus is paid to temperature measurements via Thermo-Sensitive Electrical Parameters (TSEP), which are thought to be the most promising way to conduct online temperature measurements on fully packaged devices.

II. CONDITION MONITORING

Reference [8] defines three conceptions for the implementation of condition monitoring (CM) in power electronics:

- 1. Monitoring of electrical parameters indicative of degradations in the power device*
- 2. Dedicated sensors embedded in the device to explicitly observe degradations*
- 3. Model-based CM: the response of the system is compared to a 'healthy' model*

An ideal CM strategy would not require any electrical or dedicated sensor to observe degradations in the power module, and is therefore based on the use of physical models. However, a perfect models including thermal, electrical, electro-thermal, thermo-mechanical and aging aspects do not exist. Implementation of electrical sensors is already necessary to provide accurate control of a converter, and is one reason why CM research has extensively focused methods without the requirement for dedicated sensors inside the power device. Several investigations exist on the use of on-state voltage drop (or on-resistance) to monitor bond wire degradation and ultimately lift-off [9]-[13]; evaluation of switching parameters has been suggested for identification of several failure mechanisms [14]-[16] in IGBTs, along with gate voltage [17]; and attempts have also been made to

determine the change in a device's internal thermal resistance primarily to indicate solder degradation [4][18][19].

However, interpreting parameters of this nature that are garnered from external measurements requires a thorough understanding of the relationship between the parameter, device condition, and operational profile. As a first principle, accurate real-time junction temperature knowledge can remove the masking effect that normal load variation may have on a chosen degradation parameter. Moreover, since the common failure mechanisms of power devices are intrinsically linked to temperature, an awareness of its value and behaviour could be considered a prerequisite in the development of prognostic systems – especially since junction temperature is likely to influence the value of any extracted precursor.

For example, it is acknowledged that the on-state voltage drop (V_{on}) of a device is significantly influenced by T_j [13]. Fluctuations in V_{on} can therefore occur even if no bond-wire degradation is present, which is unacceptable if V_{on} is observed with the specific intention of evaluating bond wire fatigue. Figure 3 displays a generalised evolution of V_{on} throughout an accelerated life test consistent with what is commonly reported in literature. It can be seen that V_{on} tends to increase despite the non-existence of bond wire lift-off, therefore in order to make a correct observation, a precise knowledge of T_j is necessary to make proper compensation of the V_{on} measurement. Some previous studies attempt to compensate for T_j using electrothermal models [20], while others have sought to use case temperature as a substitute [21]. A temperature sensitive parameter, has also been implemented in accelerated life tests [13][22][23] where V_{on} is used to monitor bond wire condition.

For thermal resistance measurements, the main challenge is the determination of T_j : without a method for external measurement, internal sensors are required and data is combined with power loss models [24], or accessible external temperature points such as case temperature are used as an alternative [18].

Finally, since one of the major causes of failure in power electronics is the junction temperature swings, precise knowledge of their amplitude and frequency allows better specification of thermo-mechanical models to predict lifetime [25]. Cycle counting methods that attempt to assess the remaining lifetime in the device could then be improved [26].

The application of real time junction temperature information in this manner can aid the development of unique indicator systems for specific failure mechanisms. As failures such as bond wire or solder fatigue occur independently [27], this can have a significant impact on prognostic systems and improve understanding of power module failure modes.

III. ACTIVE THERMAL CONTROL

The thermal analysis of power systems reveals that some power semiconductor devices in the same converter can be more stressed in respect to others. This discrepancy can be especially pronounced in conditions such as those caused by system faults. Therefore, the ability to modify modulation and control of a power converter using junction temperature as feedback is appealing (Figure 4).

A common approach is to manipulate the switching frequency and current limit to regulate power loss and control both steady state and transient thermal stresses [7][28][29]. [28] implements a region-based controller that contains predefined thermal operating modes, as seen in Fig. 5 – operating modes are assigned according to the junction temperature swing (ΔT_j) and maximum junction temperature – for example an excessive ΔT_j activates a ‘Power Cycling High’ strategy. These control strategies could be further extended to include control profiles for specific health conditions of the module.

In particular, junction temperature knowledge can prove especially useful in the control of systems that present redundancies, such as parallel, multicellular or interleaved power converters, where it is possible to share the load among different units with a view to control temperature swings

[30]. Another alternative is the circulation of reactive power among different power converters connected in parallel in a high-power converter, such as in a wind or photovoltaic park, in order to reduce the temperature swing in the most stressed power semiconductor devices [31]. These specific applications such as wind can frequently present stressful circumstances (e.g. during a wind gust [32]) that exacerbate uneven temperature distributions between devices or paralleled converter units.

Lastly, there is also noteworthy interest in the development of intelligent gate drivers, of which temperature measurement is a key enabling concept in their development [33][34].

A key challenge in the realisation of active thermal control and CM systems is the accurate measurement of junction temperature: without this, internal sensors like thermocouples or thermistors are once again required which increase the complexity of power modules; or alternatively electrothermal models are used that may often only provide estimations within a given tolerance range.

IV. ONLINE TEMPERATURE MEASUREMENTS

A. Main methods of online temperature evaluation

Sensing junction temperature during converter operation is notoriously difficult, and the selection of a measurement method must be made with careful consideration. The main dilemmas in the selection or design of a temperature measurement system for a specific application are displayed in Figure 6 and entail: whether a good correlation with the thermal stress (non-uniform temperature distribution in one chip and between different power chips) is demonstrated, what degree of time resolution can be provided (ability to track temperature swings, sampling frequency) and the level of degradation introduced to converter performance versus the design-to-cost objective.

Direct access to chips is prevented by module packaging and dielectric gel, which therefore limits the use of optical and physical contact methods such as infrared cameras or optical fibres. These solutions are also limited by temperature range and have a relatively low response time. Electrical

methods are therefore preferred for online temperature measurements in power electronic converters. These techniques use the dependence of an electrical parameter with temperature. Two families are outlined in scientific literature: the use of supplementary sensors located on the chip surface, and the use of thermo-sensitive electrical parameters of the chip.

One solution is outlined by Brekel [35], who proposes modifying the substrate layout of an IGBT chip to provide room for additional sensing equipment that facilitates the measurement of the internal gate resistance. The temperature dependence of this resistance is then used to evaluate semiconductor temperature. This gate resistor method is shown to give accurate results with an ample time resolution that enables tracking of the temperature ripple in the IGBT due to the alternating output current in an inverter application. Nonetheless, this method still requires alteration to a packaged device.

Another solution is the use of temperature sensors which are directly integrated in the power chip structure. In fact, some commercial solutions exist [36]. For example, Moto and Donlon [37] use an IGBT chip including a string of diodes fabricated on the IGBT chip's surface. Because the forward voltage drop of this string of diodes has a linear relationship with temperature, it is possible to use it as a temperature indicator. However, this temperature measurement is only local which presents some issues. For instance, figure 7 displays a map of temperature distribution in an IGBT chip. The peak temperature in the junction is due to a solder void in the backside of the chip – a local measurement is unable to detect the presence of these peaks if the sensor is distant from the solder void. Therefore, local measurements are seen to be limited in their ability to detect thermo-mechanical degradations of this character. As the temperature distribution of a junction is non-uniform, measurements that supply the average temperature across the junction are preferred.

In order to have a good representation of the global surface temperature, Thollin et al. [38] present a functional power chip with several temperature sensors on its surface. They are made with a

deposition of a thin thermo-sensitive polysilicon layer. In this case, multiple external wires are needed to obtain the temperature value given by each sensor. Therefore, the active surface of the chip is reduced and the setup becomes more complex.

Finally, the online observation of chip temperature without modification to the active surface of the device can be achieved using thermo-sensitive electrical parameters (TSEP). In fact, these approaches generally give an average temperature across the die and thus allow for observation of thermo-mechanical degradations. Moreover, TSEPs have been used to perform thermal characterisation of devices for a number of decades [39], that is – the validation of thermal resistance or thermal impedance of datasheet values provided by manufacturers. Recent reviews of the variety of TSEPs are provided by [39] in 1988, and more recently in 2012 [40]. However, their use in online temperature measurements is not well developed at present.

There are only limited attempts to feasibly incorporate the use of TSEPs for the measurement of junction temperature during the operation of a power electronic converter. Three main concepts have however been proposed for this purpose:

- The use of classical TSEPs with the addition of supplementary elements in the converter structure, and/or modifying the control strategy in order to introduce time windows for the temperature measurements to take place
- The variation of the static characteristic $I(V)$ with the temperature of the device
- The variation of dynamic characteristics with the temperature of the device

Table I displays a synthesis of publications where a TSEP has been employed or investigated in order to evaluate online junction temperature. The various concepts will be outlined in the following subsections.

B. Use of Classical TSEPs

Traditionally, the voltage drop at low current, threshold voltage and saturation current of MOS gated devices have been used as TSEPs – with the voltage drop at low current most predominantly selected. Classically used TSEPs are attractive for investigation as significant knowledge is already available which allows for the realisation of proficient and robust systems. However, these temperature measurements have to be done in specific electrical conditions and often necessitate an alteration to the structure or operation of a power electronic converter.

Regarding the commonly used TSEP, the voltage drop at a low current, temperature measurement using this technique can be used in inverters when the output current crosses zero [22][41]. A supplementary delay is consequently necessary in order to have enough time to perform the measurement [22]. In the case of a chopper, Nowak [42] alternatively proposes to add supplementary power devices in the circuit in order to isolate the characterised devices during the temperature measurement.

For MOS gated devices, it is possible to use the saturation current under a given gate-emitter (gate-source) and a given collector-emitter (drain-source) voltages. In the case of an IGBT in a chopper, Bergogne et al. [43] use this technique when the chip is in off-state. However the main problem is the need of a current sensor able to measure a low current level in order to have accurate temperature measurements. Xu et al. [44] studied the short circuit current as a TSEP in a chopper and in a 2-level inverter. The main problem is a very high thermal dissipation during the short circuit which can cause a fast thermal runaway of the device. Moreover, supplementary IGBTs are necessary for the implementation of this method in a converter.

As a conclusion, these studies demonstrate that temperature measurements are possible during the operation of a converter using classical TSEPs. However, the modification of the structure of the converter and/or its operation can be seen as a serious drawback. It is therefore important to find

TSEPs that are specifically adapted to online temperature measurements – the use of static or dynamic characteristics are both potential answers to this problem.

C. Static Characteristic $I(V)$

Because the static characteristic $I(V)$ of all power devices depends on the temperature, a natural way to estimate the junction temperature of a device is to measure simultaneously its forward voltage and the current crossing it. Generally, the use of this method does not require any additional current sensor because the current in the devices can be measured at load level. This method is used by several different authors [45-47]. However, the actual implementation of this method encounters numerous issues that will be highlighted in succeeding sections.

D. Dynamic Characteristics

Another way to estimate the junction temperature during the operation of a converter is the measurement of dynamic parameters of power devices. In the case of MOS transistors, several different TSEPs are proposed: the turn-on delay [48]-[50], the turn-off delay [48][49][51][52], and the current slope during turn-on [48][54]. These measurements are constrained by the need for very fast current sensors as the sensitivity of these TSEPs can be in the range of several nanoseconds, or even picosecond, per degree. In order to bypass this issue, it may be possible to observe changes in these electrical parameters indirectly. For example, it has been demonstrated in an IGBT inverter that monitoring harmonics in the output can be indicative of changes in the IGBT turn-off mechanism due to its relationship with temperature [53].

V. TSEP IMPLEMENTATION ISSUES

The development of a temperature measurement system using TSEPs is hindered by a number of issues. These include: the dependence of electrical parameters on other variables outside of temperature, such as current and voltage; parasitic and aging influences throughout a power

electronic converter lifetime; and the practicality of conducting the measurement of a TSEP without interruption to regular operating cycles. The key issues are briefly outlined in the following paragraphs.

A. Calibration Need

Before the use of a TSEP, it is necessary to make a preliminary calibration. The goal is to obtain the variation of the TSEP as a function of temperature. During this step, the temperature is controlled by an external system and the self-heating of the device is kept as low as possible. Thus, the measurement of the TSEP has to be completed in a very brief period.

Difficulties arise due to the dependence of dynamic characteristics on the threshold voltage, while the $I(V)$ characteristic depends on the electrical interconnection configuration. This presents issues when dealing with power modules where multiple devices may be connected in parallel: the threshold voltage will be distinct for each device due to manufacturing processes, and the electrical connections associated with each device will alter depending on its position in the module. Therefore a calibration procedure is required for each individual chip inside a power module.

B. Validity of the $I(V)$ Static Characteristic as a TSEP

Electrical methods of junction temperature measurement are generally thought to give an average temperature across the die. However, in a packaged device it is not possible to directly measure the voltage drop across a junction – individual dies are connected through a series of interconnections or bond-wires. Typically, these interconnections materials will be at different temperatures to the die during operation and can introduce large errors in a temperature measurement via TSEP. This is specifically encountered by Perpina [45] when using the forward voltage drop under a high current in an IGBT. Perpina hypothesises that during calibration, the temperature of the die and interconnections are the effectively homogenous as the characterisation takes place in a temperature

controlled environment and self-heating effects are kept to a minimum. However, during operation the temperatures of the die and interconnections begin to diverge and cause inaccuracies.

One other important issue is the aging of the power module. In fact, an increase in voltage drop across a device is commonly seen as it ages [9]. Consequently this causes a natural variation of the TSEP throughout the lifetime of a device. The possibility of making several calibrations during the life of a converter, or introducing methods to discount the influence of aging and bond-wire interconnections should perhaps therefore be studied.

Finally, the accuracy of the current sensors presents an issue: we have carried out temperature measurements on an IGBT (Infineon SIGC100T60R3) while lightly varying the current level. Table II shows the effect of the small current variation on the temperature measurements. A current variation of only 0.5% introduces a temperature measurement discrepancy of close to 4°C. The current sensor therefore requires excellent accuracy and synchronisation with voltage measurement in order obtain reliable temperature values.

C. Use of Dynamic Characteristics

Dynamic characteristics (switching parameters) are particularly susceptible to influences of operating conditions as well as parasitic components within a converter setup. The rise time for example of an IGBT or MOSFET may be influenced by: temperature, voltage, current, gate resistance, control strategy, as well as fluctuations in gate driver performance and parasitic inductances in the circuit. The calibration of the device has to be done in the commutation cell and with the same driver as in the final application in order to reduce temperature measurement errors. A higher number of dependents would seemingly suggest increased complexity in the task of developing a viable strategy for use in a power electronic converter.

Threshold voltage, which is linked with turn-on and turn-off delays, has also been shown to have variance with aging [55]. Methods to discount the influence of aging processes or a recalibration after aging are therefore required to maintain the accuracy of these measurements.

D. Temperature Non-Uniformity

Temperature non-uniformity within the die itself, and between dies in the case of paralleled chips, also presents issues. Discrepancies between the measured ‘average’ temperature via TSEPs and the actual temperature peak in the device have been identified as far back as 1966 [56] as well as in more recent studies [57]-[59]. It has also been demonstrated that alternate TSEPs can give varying temperature measurements on the same device under the same conditions, as well as having a dependence on dissipation mode [60][61].

E. Generacity

An ideal TSEP solution would be applicable to any device type, any converter topology, suitable for any application, and representative of the chip temperature distribution. However in a first iteration this may not be achievable.

For example, some TSEPs have advantageous qualities but due to implementation issues may only be able to be sampled periodically without causing unacceptable disruption to normal converter operation. A temporary increase in gate resistance for instance is suggested to slow switching speeds so that switching parameters can be assessed more easily [50] – the viability of performing this increase with high frequency should perhaps be assessed. Cases like this could indicate suitability for health monitoring in a device, but not for control purposes which may require frequent sampling.

For the case of conventional TSEPs adapted to online measurements, the proposed solutions may only be adaptable to particular converter topologies. For example, the voltage at low current method has been employed in inverters when the load current comes close to 0A [22][41], while a method

has been proposed to implement the use of saturation current on IGBTs in a chopper [43]. Figure 8 [22] visualises a potential control strategy for the implementation of an online V_{on} prognostic system with junction temperature measurement via TSEP in a single phase inverter. However, this system cannot successfully obtain the junction temperature swing, or the exact temperature at which the V_{on} measurement is taken.

At the device level, the selection of a particular device will narrow or broaden the potential TSEPs available. Voltage drop across the junction can be applied to any bipolar transistor or diode, whereas TSEPs that are dependent on the threshold voltage are only applicable to transistors. Furthermore, TSEPs that are specific to IGBTs or MOSFETs also exist – the turn-off mechanism in an IGBT has been hypothesised for use [48][51], as well as experimented with [52][53], however this cannot be applied to MOSFETs which have no current tail. The voltage drop of the internal body diode in a MOSFET can also be used as a temperature sensitive parameter but the junction used in the chip is not located where the maximum power dissipation is.

VI. CONCLUSIONS

Many applications for power electronic systems demand operation in increasingly thermally stressful environments. Temperature can impact both the efficiency and reliability of power electronic devices: it is known that temperature swings in the active parts of the device form one of the main failure factors in power converters. Knowledge of junction temperature and these temperature swings can facilitate significant improvements to the current avenues of research in condition monitoring and active control of power electronic converters.

This article presents a short review of potential uses for accurate junction temperature knowledge in present condition monitoring efforts and temperature based control strategies. Techniques to achieve accurate measurements of junction temperature on packaged power devices during functional use are then discussed. Specific attention is paid to the use of Thermo-sensitive Electrical

Parameters, which are seen to be the most promising way to acquire temperature measurements during the operation of a power electronic converter. However, no simple and generalised solutions exist today for online junction temperature measurements. It is therefore necessary to direct research efforts in this domain in order to continue progression of condition monitoring and temperature based control of power converters.

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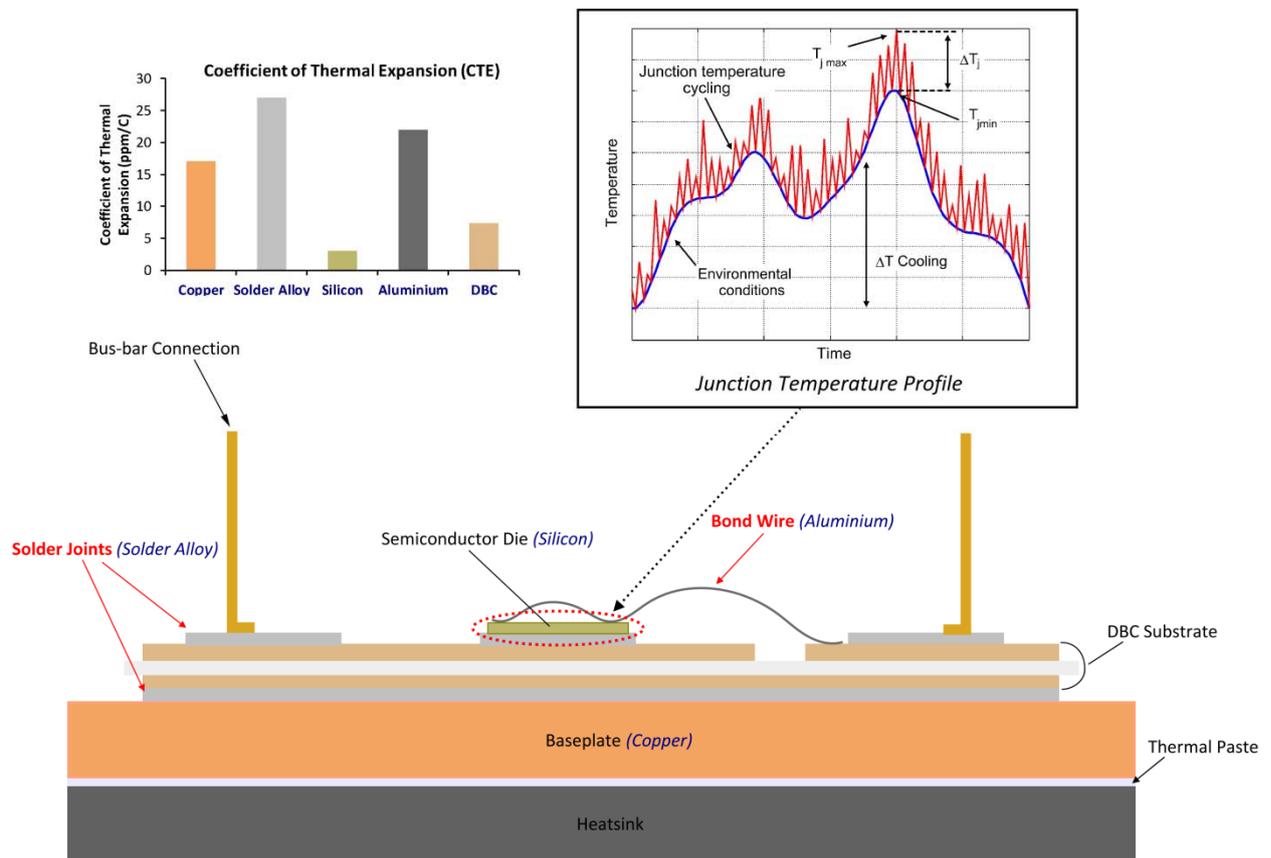


Fig. 1: Cross-section and construction materials of a typical power module

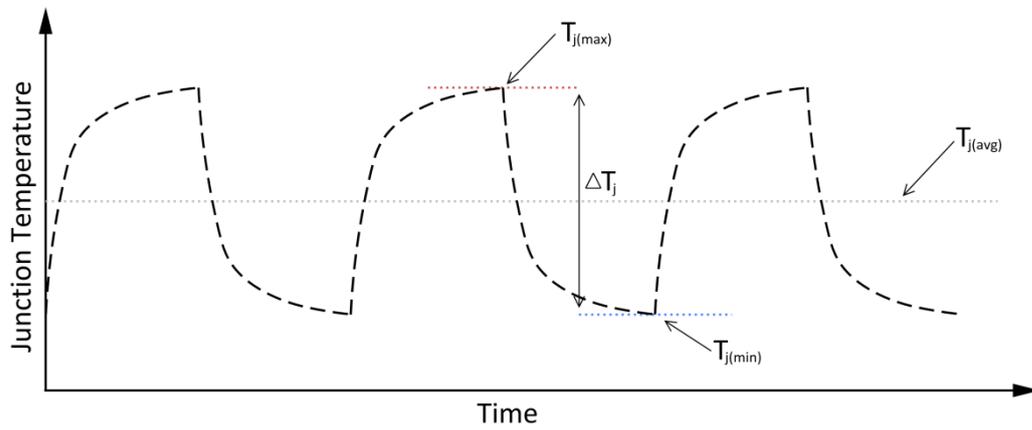


Fig. 2: Example of junction temperature evolution in a power device

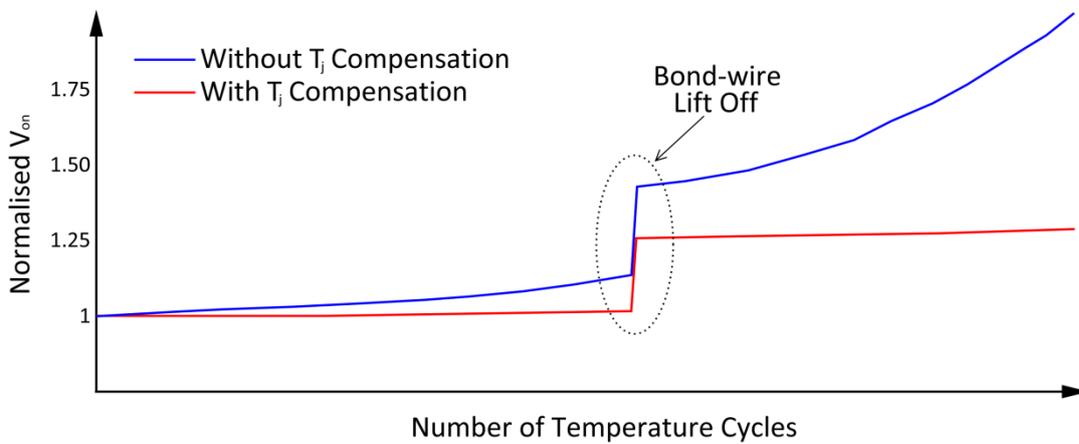


Fig. 3: Evolution of V_{on} with and without temperature compensation

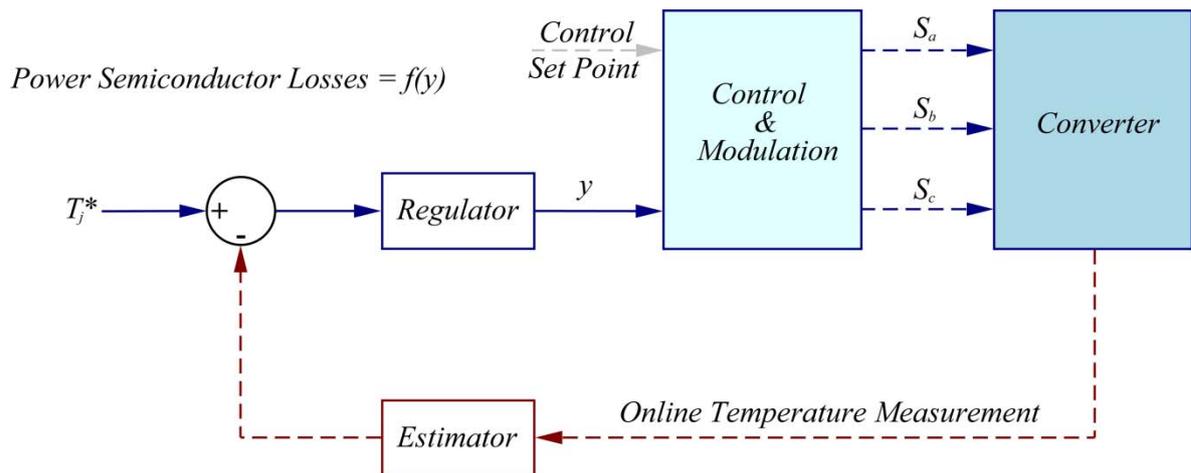


Fig. 4: Example of active thermal control of power semiconductor junction temperature, T_j , by means of y (switching frequency, reactive power or any other quantity that can modify the power semiconductor losses). T_j is obtained using an estimator based on an online temperature measurement method.

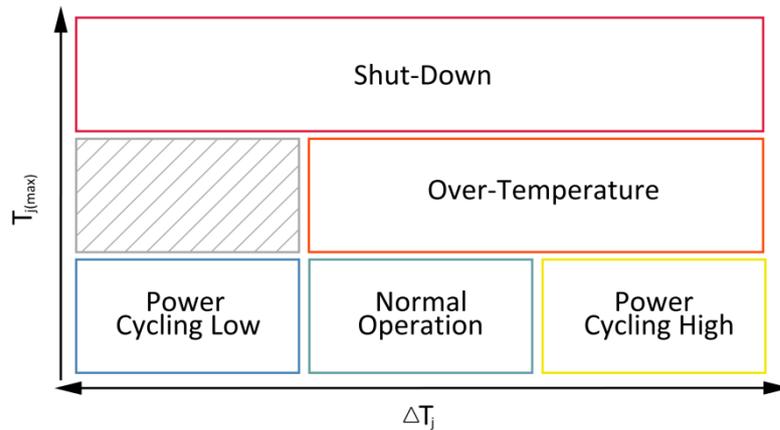


Fig. 5 [28]: Control strategies defining different thermal operating regions based on junction temperature swing (ΔT_j) and maximum junction temperature ($T_{j(max)}$)

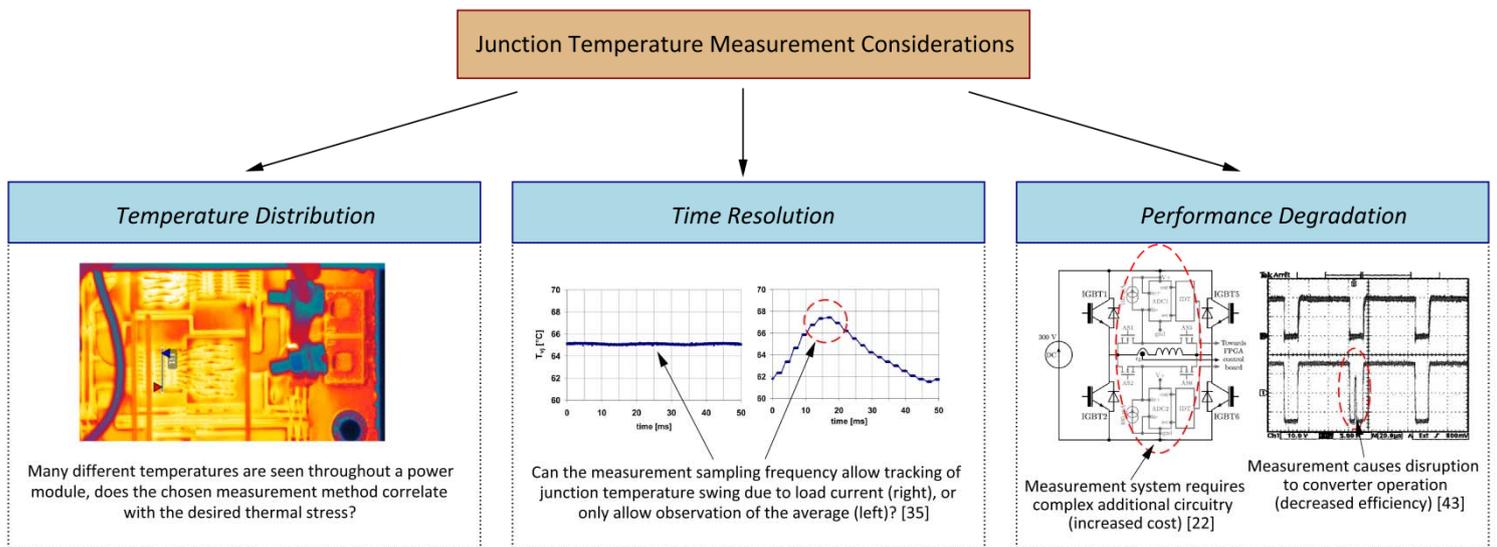


Fig. 6: Considerations for selection and design of a junction temperature measurement system

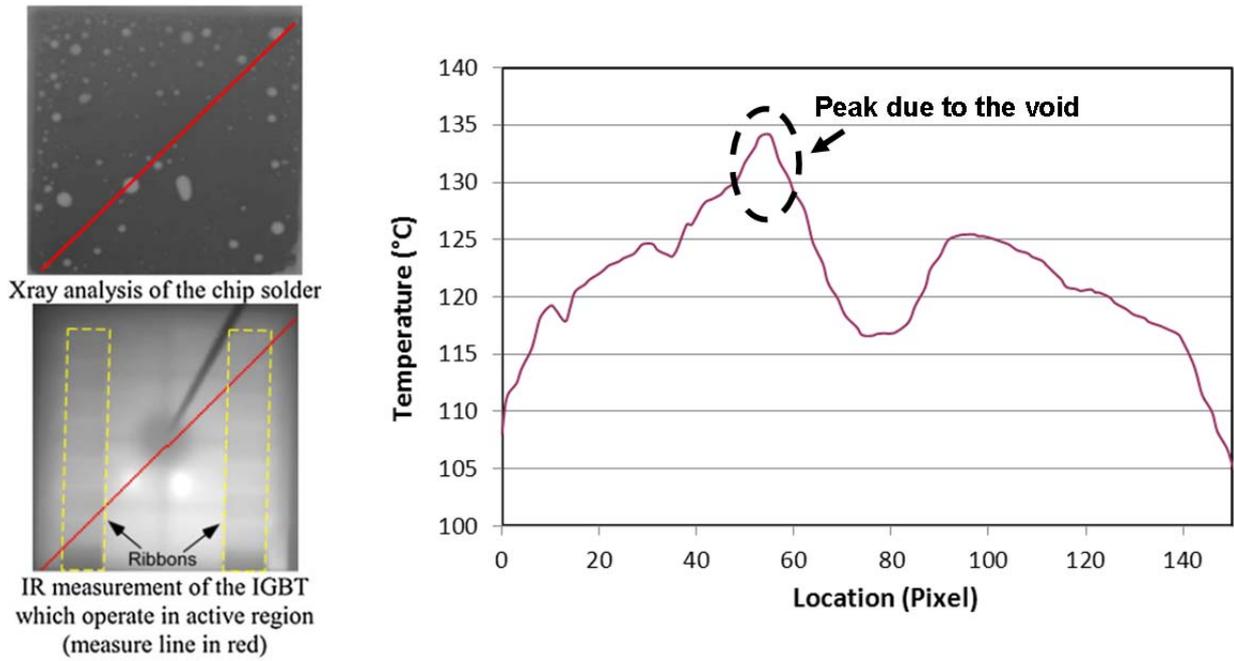


Fig. 7: Temperature distribution in an IGBT chip with peak temperature caused by a solder void

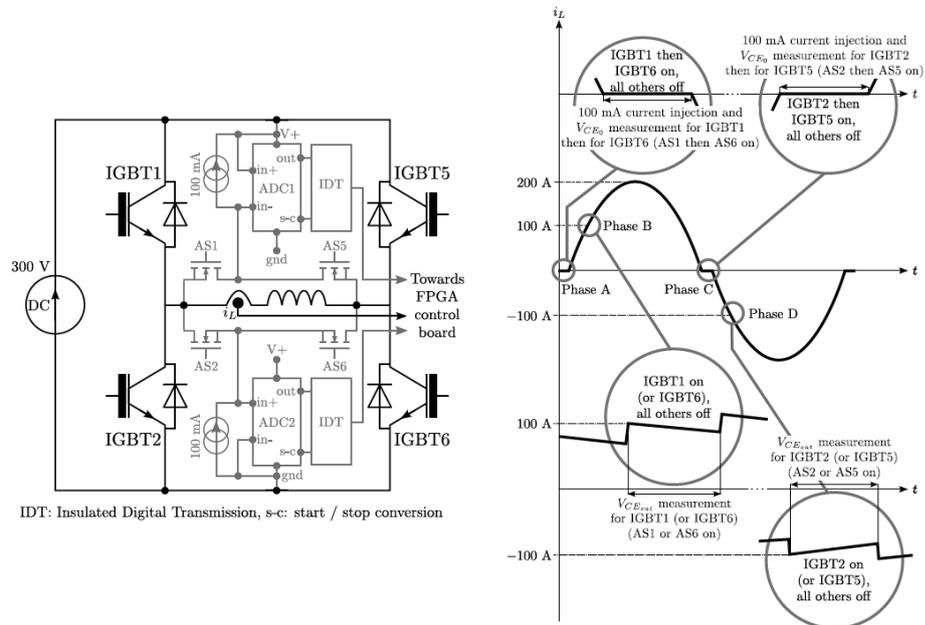


Fig. 8 [22]: Implementation strategy for Voltage at Low Current in a single phase inverter: Temperature measurement is taken when load current crosses 0A

TABLE I. 'ONLINE' TSEP STUDIES

Method		Comments			
		Device	Dependents	Additional Comments	Reference
Classical TSEPs	Short Circuit Current	IGBT	T	Induces a Hard Switching Fault to create short circuit. Prototyped on Buck Converter and 2-level three phase inverter. Possible measurement frequency unknown. Measured current dependent only on temperature.	[44]
	Saturation Current	MOS Transistors	T, V	Implementation strategy applies to 'choppers'. Measurement frequency unknown	[43]
	Voltage at Low Current	Transistors and Diodes	T, I	Requires specific current level to maintain linearity Temperature measurement is able to be taken as output current crosses zero in the case of inverter. Supplementary devices could be added to isolate the characterised devices	[13, 22, 23, 41, 42]
Static characteristic	Voltage at High Current	Transistors and Diodes	T, I	Requires accurate current sensors (small error in current measurement leads to large error in temperature measurement). Measurement influenced greatly by parasitic elements inside modules (bond wires etc.). When verified with Infra-Red Camera, measurements were largely inaccurate – required modified calibration procedure to discount influence of interconnections. Can be measured very frequently (each switching cycle)	[45, 46, 47]
Dynamic characteristics	IGBT Turn-Off	IGBT	T, I, V, R _g	Requires fast sensors with sensitivity in region of nano or picosecond per degree. Changes can be seen in harmonics in the output of an IGBT inverter [53]	[48, 49, 51, 52]
	Turn-On Delay	MOS Transistors	T, R _g	Requires fast sensors with sensitivity in region of nano or picosecond per degree. Increase in gate resistance when measurement is required is proposed to slow down the process. Not affected by current and voltage operating values, however gate resistance and parasitic elements have large influence	[48, 49, 50]
	Rise-Time	MOS Transistors	T, I, V, R _g	Requires fast and accurate sensors with sensitivity in region of nano or picosecond per degree. Increase in gate resistance when measurement is required is proposed to slow down the process. Influenced greatly by parasitic and operating conditions.	[48, 54]

T = TEMPERATURE, I = CURRENT, V = VOLTAGE, R_g = GATE RESISTANCE

TABLE II. EFFECT OF THE CURRENT LEVEL ON I(V) TSEP

	Current close to 80A		Current close to 100A	
Current (A)	79.8	80.2	99.8	100.2
Estimated temperature (°C)	111.2	116	150.5	154