Simultaneous online estimation of junction temperature and current of IGBTs using emitter-auxiliary emitter parasitic inductance

Vinoth Kumar Sundaramoorthy, Enea Bianda, Richard Bloch, Franz Zurfluh
ABB Switzerland Ltd, Corporate Research, 5405 Baden, Switzerland
vinoth.sundaramoorthy@ch.abb.com

Abstract

A novel method is presented for online estimation of the junction temperature (Tj) of semiconductor chips in IGBT modules, based on the voltage drop ($V_{EE'}$) across the parasitic inductor that exists between the main emitter (E) and auxiliary emitter (E') terminals. The peak amplitude of the voltage drop ($V_{EE'}$) was found to depend on the junction temperature at a known current and DC link voltage. Also, the collector current can be estimated simultaneously, by integrating $V_{EE'}$ without the use of any additional sensors. Measurement circuits were implemented to estimate Tj and the current, and their results are discussed. The results of these measurement circuits when implemented in a real power electronic (PE) converter to estimate Tj and current in real time are also presented. This method opens up a full set of new opportunities for engineers and designers to better understand the behavior and performance of high power modules in real PE applications.

1. Introduction:

The junction temperature (Tj) of semiconductor chips in IGBT modules during operation of a power electronic converter is an important parameter, which provides information on the operating status of the IGBT module. Information about the thermal cycles of the IGBT modules during operation could be thus directly available. From this, important information could be extracted e.g., prediction and evaluation of the remaining lifetime of IGBT modules [1-2]. Normally, the junction temperature of the IGBT modules is measured using either optical or physical contact techniques that involve direct access to the chips inside the package or require specially designed IGBT chips & modules [3]. Most of these existing methods presented in the literature are not suitable to determine the Tj in real time or when the converter is in operation. Alternatively, there are also methods reported to estimate Tj based on complex thermal network models [4]. However, these methods are prone to evaluation errors and do not include the aging effects of modules.

The most suitable approach to extract the junction temperature is to focus on "external" electrical parameters that can be measured at the gate driver level. Electrical characteristics of IGBTs change with Tj of the device due to their dependence on basic material properties (e.g., electron mobility, carrier lifetime, intrinsic carrier concentration) [5]. Although these basic material characteristics are not easily accessible, they lead to macroscopic changes of electrical parameters called temperature sensitive electrical parameters (TSEP), which can be measured. The most commonly reported TSEPs are turn-on and turn-off delay times, transconductance (g_m), threshold voltage (V_{th}), dV_{ce}/dt, dI_{ce}/dt, on-state voltage drop (V_{ce-on}) and saturation current [6-12]. Most of these TSEPs require either complex circuitry for measurement and are very difficult to implement or are not suitable for real-time estimation of Tj [10-11]. This paper introduces a novel approach for determining the Tj using a method, which can be implemented easily at the gate drive level, thus being suitable for use during converter operation. By measuring the voltage drop ($V_{EE'}$) across the parasitic inductance between the main emitter terminal (E) and auxiliary emitter terminals (E') of the IGBT, the junction temperature can be estimated.

The junction temperature depends on the operating conditions of the IGBT, and becomes highly dependent on the switching current. Hence, the simultaneous measurement of the switching current and the junction temperature becomes significant in estimating the remaining lifetime of the IGBT modules. The load current of the IGBT module during operation is normally measured using expensive, bulky sensors such as Rogowski coil, current transformers etc. It is not practical to install these types of sensors in converters for the measurement of the current of the IGBT modules during operation. On the other-hand the IGBT load current could be estimated directly from the electrical measurements at the IGBT terminals. The proposed method in this paper can be used to estimate the IGBT current and the junction temperature, simultaneously.

2. Physical background

Normally the emitter terminal of the IGBT is split into power-emitter or the main emitter (E) that is connected to the power circuit and, the auxiliary emitter (E') that is connected to the gate drive unit (figure 1). The internal connections of the IGBT module cause parasitic inductances (L_e and L_σ in figure 1) between the main emitter terminal (E) and auxiliary emitter terminals (E') of the IGBT. This is due to the bonding wires and the screwed terminals. During switching operation of the IGBT, the collector current I_C flows only through L_σ and the gate current flows through L_e. Hence, the voltage drop across the parasitic inductance L_σ is dominant during switching. This voltage drop can be used for the estimation of both current and junction temperature.

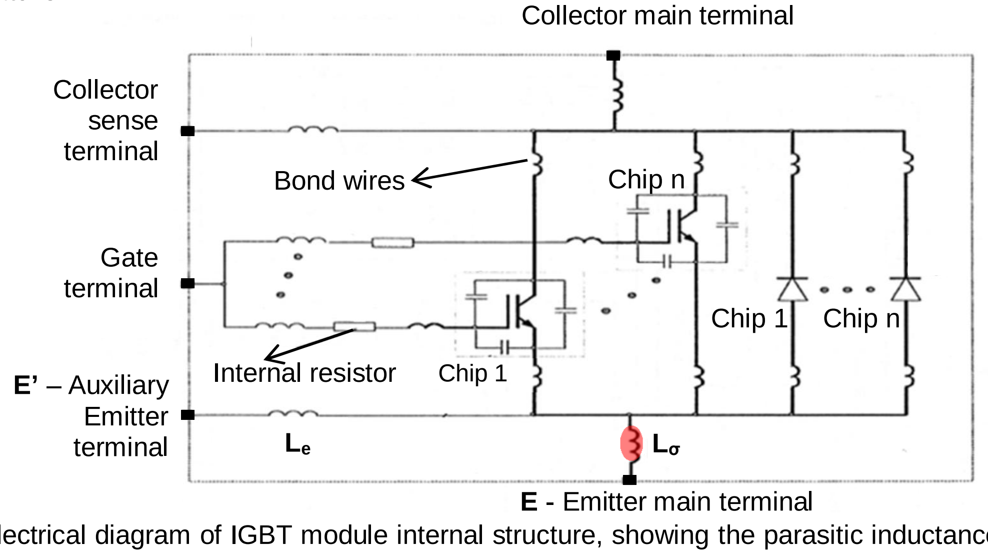

Fig.1. Electrical diagram of IGBT module internal structure, showing the parasitic inductance between the main emitter (E) and auxiliary emitter (E').

The parasitic inductance L_σ between the auxiliary emitter (E') and the main emitter (E) terminals (shown in figure 1) can be used as a sensor to extract the current flowing through the IGBT. The derivative of the collector current flowing through this parasitic inductance (L_σ) generates a voltage drop given by equation (1),

$$V_{EE'} = L_\sigma \frac{dI_c}{dt} \tag{1}$$

Where $V_{EE'}$ is the voltage drop measured between auxiliary emitter and main emitter, L_σ is the parasitic inductance across which $V_{EE'}$ is measured, I_C is the collector current. The parasitic inductor L_σ is shown in figure 1 between the auxiliary emitter (E') and the main emitter terminal (E).

By integration of this voltage drop, the collector current during turn-off can be estimated using equation (2),

$$I_c = \frac{1}{L_\sigma} \int V_{EE'} \cdot dt \tag{2}$$

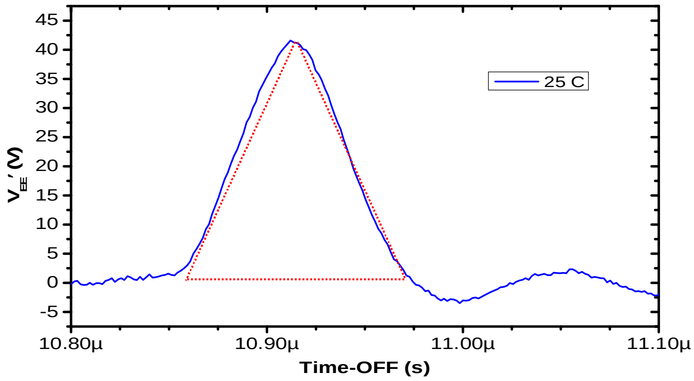

Fig.2. The measured differential voltage ($V_{EE'}$) across the parasitic inductance between the auxiliary (E') and main emitter terminal (E).

The voltage measured between the auxiliary and main emitter terminal for module A (1.2 kV, 300 A module) at 600 V, 200 A and 25 °C switching condition is shown in figure 2. It could be seen that there is a voltage drop with a peak at ~1.09 µs corresponding to the differential voltage. The integration of this voltage peak would give rise to the corresponding current. The measurement of differential voltage ($V_{EE'}$) for the module A at a defined switching condition as a function of temperature is shown in figure 3. It can be seen that the differential voltage between the auxiliary and main emitter terminals when measured at different temperatures gives rise to different peak amplitudes of voltage $V_{EE'}$. The difference in peak amplitude of this voltage at a particular current can serve as indicator for the device junction temperature. It can be seen from figure 3 that the peak amplitude of $V_{EE'}$ is higher (~42 V) at 25 °C and it starts to decrease with temperature (~35 V at 100 °C). However, the area of the curve at each measurement temperature is the same, as the curves are wider with increased temperature. Hence, the switching current should remain approximately the same at all the temperatures for this measurement condition (using equation 2). To verify this, the switching current was calculated using the measured differential voltage ($V_{EE'}$) at different temperatures and the parasitic inductance (measured externally) using equation (2).

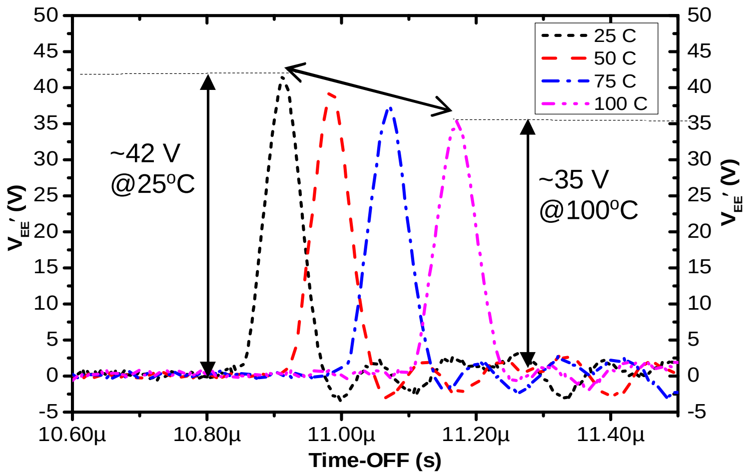

Fig.3. $V_{EE'}$ across the parasitic inductance for Module A at 600 V, 200 A switching condition for different temperatures.

The parasitic inductance (L_σ) was measured externally as a function of temperature and it was found to be constant at ~10 nH at 1 MHz at all measured temperatures from 25 °C to 100 °C for this module. The evaluated current was approximately the same as that of the switching current (i.e., 200 A) at each measurement temperature. Hence, the operating conditions are the same at each measurement temperature and the observed change in peak amplitude of $V_{EE'}$ is only due to the change in temperature. The decrease in peak amplitude of $V_{EE'}$ with temperature is due to the decrease in the dI_C/dt with temperature as per equation 1 (as the other parameter L_σ remains constant at all measurement temperatures).

The variation of dI_C/dt with temperature can be analyzed using the equation 3 [13],

$$\frac{dI_c}{dt} = \left[\frac{1}{(1-\alpha_{PNP}(T))}\right].\left[\mu(T).C_{ox}.\frac{W}{L}.(V_{GE} - V_{th}(T))\right].\frac{dV_{GE}}{dt} \quad (3)$$

where α_{PNP} is the gain of inherent bipolar PNP transistor, µ is the electron mobility, C_{ox} is the intrinsic gate oxide capacitance, W/L is the gate width/length ratio, V_{th} is the threshold voltage and T is the temperature. The temperature dependency of inherent PNP transistor of the IGBT is given by the gain α_{PNP} in the first term of equation 3 and the temperature dependency of the MOS transistor of the IGBT is taken into account by the mobility (µ) and the threshold voltage (V_{th}) in the second term of equation 3. Both mobility (µ) and threshold voltage (V_{th}) decrease with temperature causing the dI_C/dt to decrease with temperature [6]. The decrease of mobility (µ) with temperature directly translates to a decrease in dI_C/dt, according to equation 3. The reduction of V_{th} with temperature would increase the dI_C/dt (equation 3). However, this effect is dominated by the mobility degradation with temperature, especially at higher currents, eventually causing the dI_C/dt to decrease with temperature. Hence, the dI_C/dt decreases significantly with temperature causing the voltage $V_{EE'}$ (across the parasitic inductor L_σ) to decrease with temperature.

3. Experimental results

To measure the peak amplitude of voltage $V_{EE'}$ and current during online converter operation, a peak detector and an integrator circuit have been implemented. The peak detector contains 5 elements, an input voltage divider, an active diode, a memory capacitance, a reset switch and an output buffer (figure 4).

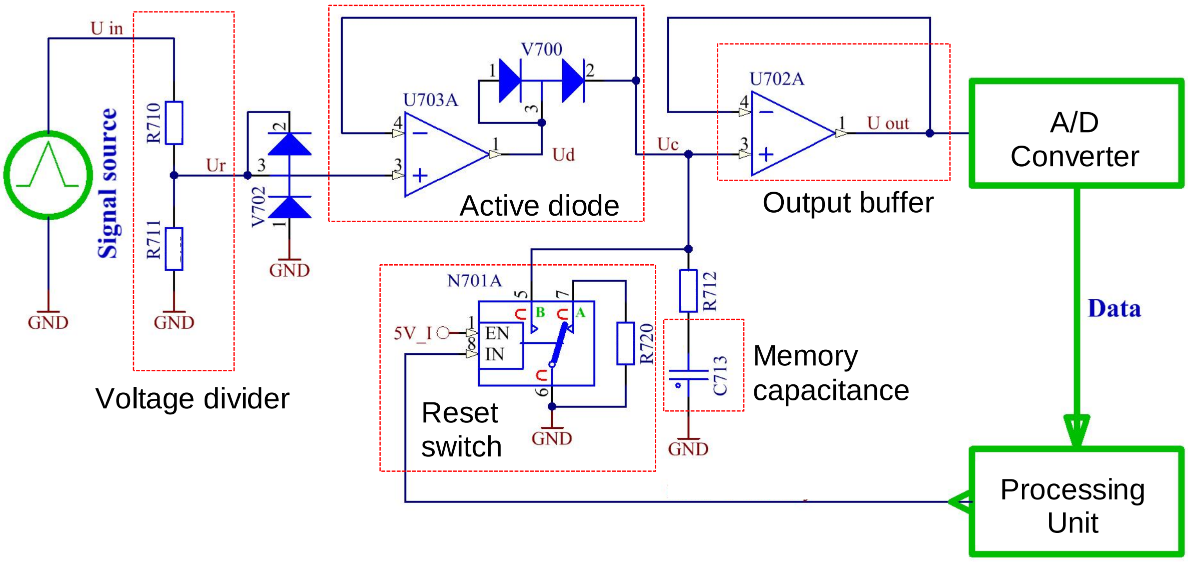

Fig.4. Circuit description of the peak detector.

Referring to the figure 4, the input voltage divider (R710 and R711) fits the input value (0 to ~80 V) to the working range of the active diode (~4.5 V). The diode V702 next to the voltage divider protects it against negative signal. The active diode is composed of the operational amplifier U703A and the diode V700. The purpose of the circuit is to transmit the input voltage to the memory capacitance through a diode with a theoretical zero voltage drop. The active diode also provides the load current to the memory capacitance C713. The capacitance cannot discharge due to the presence of the diode V700 and therefore, keeps the higher voltage value. The active diode is fast enough in order to capture the small spike (or the voltage peak $V_{EE'}$). After reading the memory capacitance with the output buffer, the memory capacitance would be set to the initial state (zero volts) with the reset switch N701A in order to allow the next measurement. The output buffer U702A has a high impedance input to avoid the discharging of the memory capacitance. The measured voltage $V_{EE'}$ at the output buffer would be converted into a digital value using a A/D converter and fed to the processing unit, which can then process the data to estimate the junction temperature.

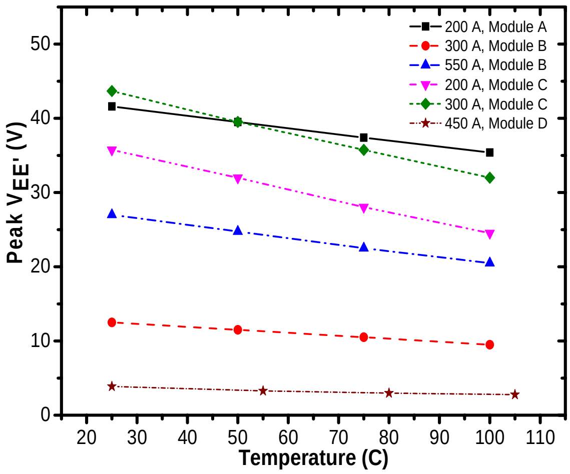

Fig.5. The peak amplitude of voltage $V_{EE'}$ as a function of temperature measured using peak detector at 600 V for modules A, B, C and at 900 V for module D.

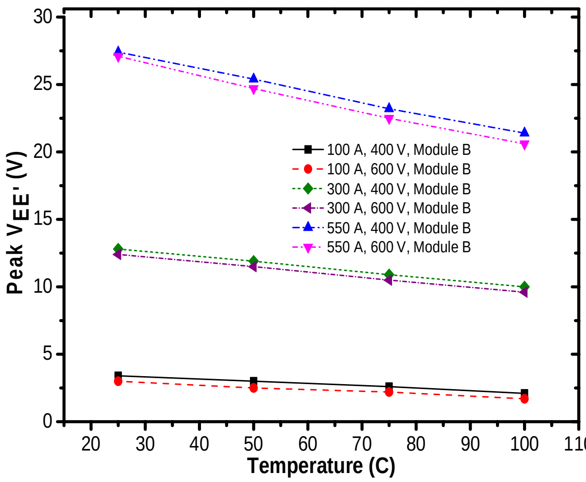

Fig.6. The peak amplitude of voltage $V_{EE'}$ as a function of temperature measured using peak detector at 400 V and 600 V for module B.

The peak amplitude of voltage $V_{EE'}$ measured using the peak detector circuit for different types of modules A (1.2kV, 300A module), B (1.7kV, 650A module), C (1.2kV, 300A module – different type from module A) and D (1.7kV, 1.6kA module) are shown in figure 5. It can be seen that the measured peak amplitude of $V_{EE'}$ decreases linearly as a function of temperature at all measured currents for all the types of modules measured. It can also be seen that the peak amplitude values are higher for higher currents at a given temperature (comparing peak amplitudes at 300 A and 550 A for Module B; and peak amplitudes at 200 A and 300 A for Module C). It should be also noted that the peak amplitude is different for different types of modules for the same switching condition (comparing Module A and C at 200 A).

The peak amplitude of voltage $V_{EE'}$ measured using the peak detector circuit as a function of temperature at various current and DC-link voltages for module B is shown in figure 6. It can be seen that the peak amplitude of voltage $V_{EE'}$ is higher at higher current levels for any given temperature, as also observed in figure 5. However, the peak amplitude of voltage $V_{EE'}$ does not show significant variation with different DC-link voltages for all measurement conditions. Hence, it shows higher dependency on current and temperature, when compared with DC link voltage. It can also be seen that the peak amplitude of voltage $V_{EE'}$ has higher temperature sensitivity at higher current levels. By benchmarking the peak amplitude of voltage $V_{EE'}$ for a given module type at different switching conditions (i.e., current, voltage and temperature), the junction temperature of the IGBT could be estimated.

Any change in current will induce a voltage spike on the parasitic inductance between the emitter and the auxiliary emitter. This differential current signal in the form of a voltage would be integrated using the integrator circuit, as shown in figure 7. Thus the output signal will be a voltage proportional to the IGBT current. The output of the implemented integrator circuit as a function of measurement current is shown in figure 8 for modules A, B, C and D. It can be seen that the output voltage of the integrator is ~ 1 V at 100 A for module A. Using the value of measured parasitic inductance L_σ (~10 nH) in equation (2) and considering the gain of the integrator circuit, the measured value of 1 V corresponds to 100 A (which is the measurement test current). It can be seen from figure 8 that the integrator output is linear with respect to the measured current for all the modules. The integrator output voltage varies for different types of modules at a given measurement current, depending on their parasitic inductance value. Hence, with the prior information on parasitic inductance L_σ, the operating current of the IGBT can be obtained directly using this integrator circuit during operation for any given module.

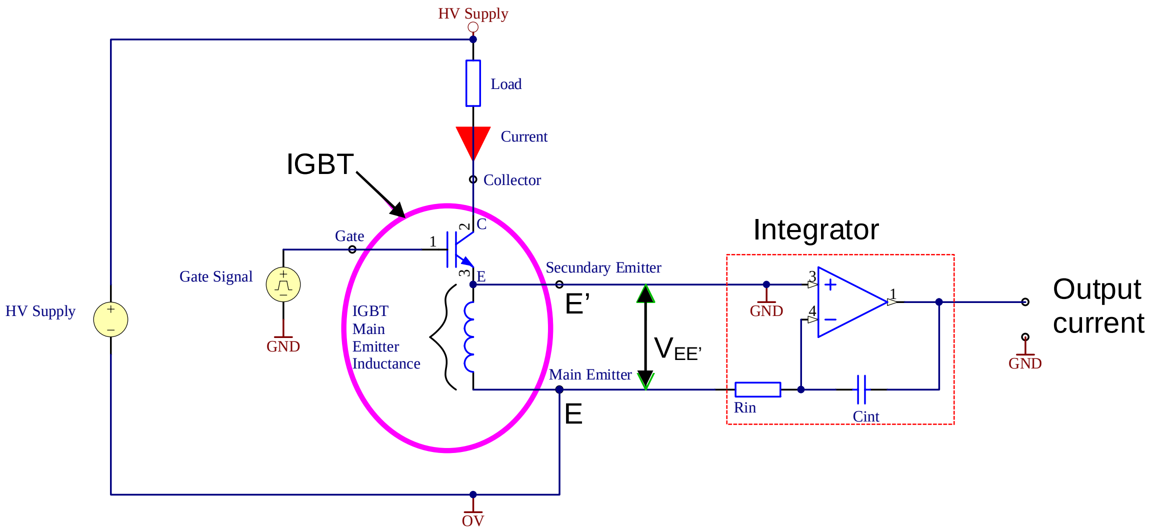

Fig.7. Current measurement using the integrator circuit.

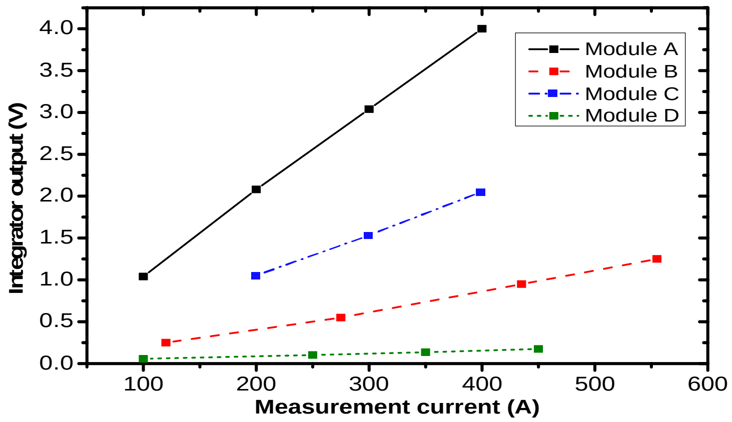

Fig.8. The integrator output as a function of current measured for modules A, B, C and D.

4. Implementation in a converter

The peak detector and the integrator circuit to measure peak amplitude of voltage $V_{EE'}$ and the operating current were implemented in a converter (ABB 1MW compact converter) to estimate junction temperature of IGBT modules in real time. Prior to the implementation in the converter set up, the IGBT modules were benchmarked at various load conditions by performing measurements in a separate double pulse set-up using a gate driver that includes the peak detector and the integrator circuit. From these measurements, calibration curves for voltage $V_{EE'}$ and current were obtained at different controlled switching conditions and baseplate temperatures.

The converter was switched from 50 A to 550 A in steps of 100 A at a constant DC link voltage of 800 V. The output of the peak detector circuit at a switching current of 250 A is shown in figure 9. It can be seen that the digital output given by the peak detector closely follows the shape of the voltage ($V_{EE'}$) across the auxiliary emitter and main emitter terminal. The digital value of peak amplitude of $V_{EE'}$ is 4380, which corresponds to peak amplitude of 1.173 V. The temperature corresponding to this peak amplitude from the calibration curve was found to be ~72 ^{o}C, which is the junction temperature of the IGBT modules at this operating condition. The junction temperature was also verified using another TSEP – Miller plateau duration in Vge curve, which we have reported elsewhere [10]. The Vge measurement circuit was also implemented in the converter set up. The temperature directly given by this method using the implemented Vge measurement circuit and Tj extraction model was ~75 ^{o}C. Hence, the junction temperature estimated using the peak detector circuit in real time was validated.

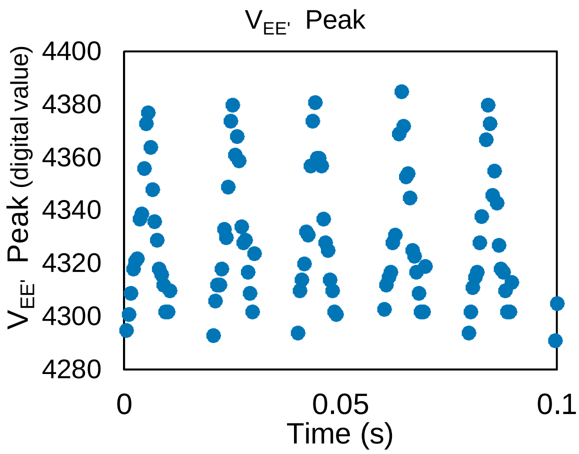

Fig.9. The output of peak detector implemented in a converter at a switching current of 250 A.

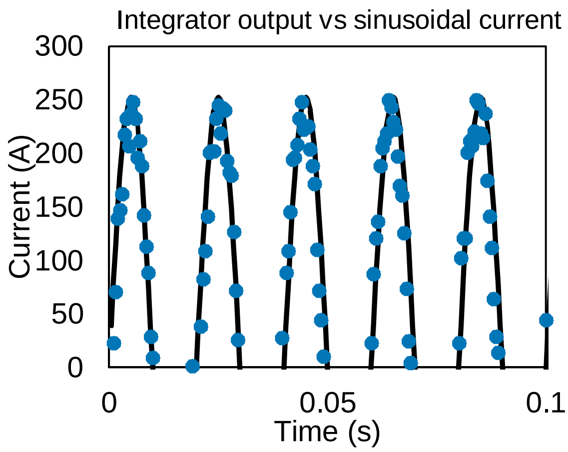

Fig.10. The output of integrator implemented in a converter at a switching current of 250 A.

The output of the integrator circuit during the converter operation is shown in figure 10. It can be seen that the measured current output during switching closely follows the shape of the sinusoidal current. The peak current measured using the integrator is ~245 A, which corresponds to the actual load current. Hence, the integrator output corresponds to the switching current of the converter as expected.

5. Conclusion

A novel method using electrical characteristics has been proposed for the online simultaneously estimation of the junction temperature and the operating current of chips in IGBT modules. The differential voltage ($V_{EE'}$) between the auxiliary and main emitter of IGBT modules during turn-off can be used to estimate Tj as the peak amplitude of voltage $V_{EE'}$ can be directly related to the IGBT chip temperature. The differential voltage ($V_{EE'}$) can also be integrated to estimate the operating current directly. Hence, this method can yield both current and junction temperature of the IGBT, simultaneously. Measurement circuits have been implemented to extract both the peak amplitude of $V_{EE'}$ across the parasitic inductance and the operating current for various IGBT modules. The measurement circuits have also been implemented in a real converter set-up and were found to successfully measure Tj and current in real time. With the help of these measurement circuits, and a look up table for a particular module type acquired under controlled switching conditions, the junction temperature of the IGBT could be estimated directly at the gate drive or at the controller level. We expect that this novel method will open up a new world of opportunities for understanding the behavior and performance of high power modules in real PE applications, with long term impact on improving the PE system reliability and availability.

References

[1] M. Musallam, C. Johnson, “Real-time compact thermal models for health management of power electronics”, *IEEE Transactions on Power Electronics*, vol.25, pp.1416-1425, 2010.

[2] M. Ciappa, F. Carbognani, P. Cova, W. Fichtner, “A novel thermo mechanics-based lifetime prediction model for cycle fatigue failure mechanisms in power semiconductors”, *Microelectronics Reliability*, vol.42, pp.1653-1658, 2002.

[3] W. Brekel, T. Dütemeyer, G. Puk, O. Schilling, “Time resolved in situ chip temperature measurements during inverter operation”, *Proceedings of Power Conversion Intelligent Motion Conference (PCIM Europe)*, Nuremberg, Germany, May 12-14, 2009, pp. 808-813.

[4] A. Ammous, S. Ghedira, B. Allard, “Choosing a thermal model for electrothermal simulation of power semiconductor devices”, *IEEE Transactions on Power Electronics*, vol.14, pp.300-307, 1999.

[5] S. M. Sze, *Semiconductor Devices-Physics and Technology*, John Wiley & Sons, New York, 1985.

[6] D. Barlini, M. Ciappa, A. Castellazzi, M. Mermet-Guyennet, W. Fichtner, “New technique for the measurement of the static and of the transient junction temperature in IGBT devices under operating conditions”, *Microelectronics Reliability*, vol. 46, pp.1772- 1777, 2006.

[7] Y-S. Kim, S-K. Sul, “Online estimation of IGBT junction temperature using on-state voltage drop”, *Proceedings of IEEE IAS Industry Applications Conference*, St.Louis, USA, October 12-15, 1998, pp.853-859.

[8] R. Schmidt, U. Scheuermann, “Using the chip as a temperature sensor – The influence of of steep lateral temperature gradients on the Vce(T)-measurement”, *Proceedings of European Conference on Power Electronics and Applications (EPE)*, Barcelona, Spain, September 8-10, 2009, pp. 1-9.

[9] V. Sundaramoorthy, E. Bianda, R. Bloch, I. Nistor, G. Knapp, A. Heinemann, “Online estimation of IGBT junction temperature (Tj) using gate-emitter voltage (Vge) at turn-off”, *Proceedings of European Conference on Power Electronics and Applications (EPE)*, Lille, France, September 3-5, 2013, pp.1-10.

[10] A. Bryant, S. Yang, P. Mawby, D. Xiang, L. Ran, P. Tavner, P.R. Palmer, “Investigation into IGBT dV/dt during turn-off and its temperature dependence”, *IEEE Transactions on Power Electronics*, vol.26, pp.3019-3031, 2011.

[11] Y. Avenas, L. Dupont, Z. Khatir, “Temperature measurement of power semiconductor devices by thermo-sensitive electrical parameters - a review”, *IEEE Transactions on Power Electronics*, vol.27, pp.3081-3092, 2012.

[12] H. Kuhn, A. Mertens, “Online junction temperature measurement of IGBTs based on temperature sensitive electrical parameters”, *Proceedings of European Conference on Power Electronics and Applications (EPE)*, Barcelona, Spain, September 8-10, 2009, pp. 1-10.

[13] Jayant Baliga, *Power Semiconductor Devices*, International Thomson Publishing, Boston, 1996.