A Method to Extract the Accurate Junction Temperature of an IGCT During Conduction Using Gate–Cathode Voltage

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***Abstract*—In this paper, we propose a novel method to extract the accurate junction temperature of an integrated gate commutated thyristor (IGCT) during device conduction (on-state mode), by measuring the gate–cathode voltage of the device. We have shown that the gate–cathode voltage is a function of anode current and junction temperature T_{vj}. Indeed, the gate–cathode voltage of the device can be easily accessed in real-time operation of the device from its gate-unit without the need of any external power supply or thermal sensors. The method has been tested by both the simulations (semiconductor device simulations) and experiments (static and load cycling tests) for two different types of IGCTs. This method will enable us to continuously monitor the T_{vj} of the device during real-time operation of the power electronic converter, and hence, to predict and evaluate the remaining lifetime of the device.**

***Index Terms*—Gate–cathode voltage, integrated gate commutated thyristor (IGCT), junction temperature, method, power semiconductor, RB-IGCT, real-time operation.**

I. INTRODUCTION

THE integrated gate commutated thyristor (IGCT) was established since its evolution from the gate turn-off thyristor (GTO) in the mid 1990s, as the device of choice for industrial medium voltage drives (MVD) and also for other applications such as wind–power conversion, pumped hydro, STATCOMS, power quality, and railway interties, to name a few [1]–[4]. The IGCT acts like a thyristor in the on-state resulting in low on-state voltage drop and turns-off like a transistor in open base transistor mode (hard switching turn-off capability due to the integration of the low inductive gate-unit). Therefore, the IGCTs have optimum plasma distribution in the conduction mode to achieve low on-state voltage drop compared to that of the insulated gate bipolar transistors (IGBT) as shown in Fig. 1.

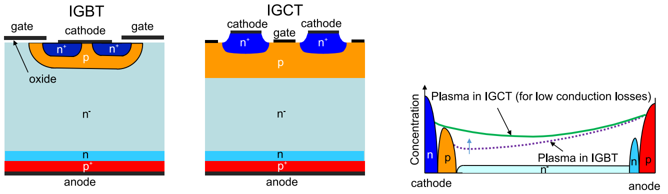

Fig. 1. Schematic structures of IGBT and IGCT and their plasma distribution during conduction.

Today, however, IGCTs have voltage ratings ranging from 4.5 up to 6.5 kV for enabling two to five-level voltage source inverters. Hence, such devices are normally optimized for relatively high switching frequencies in the range of few 100 Hz. With the recent trend toward employing multilevel topologies in many power electronic applications [5]–[7], demands are now being made for more application specific devices with a shift in focus toward lower conduction losses for operating efficiently at lower switching frequencies with higher power capabilities. In these applications (where the multilevel topologies are employed and/or solid state dc-breaker), the semiconductor device is in conduction state continuously for a longer time compare to two-level topologies and it is important to extract the accurate junction temperature during device conduction (on-state mode) to achieve the maximum output power of the system or converter. The maximum output power of a power electronic converter is limited by the maximum junction temperature of the semiconductor devices or modules.

The conventional method to estimate the maximum junction temperature of the semiconductor device is done by calculating the total switching losses plus the conduction losses of the device and its thermal impedance to ambient [8], [9]. Since most of the data are not accurate, one has to work with a lot of margin to allow for error, losing much of the theoretical possible output power of the power electronic converter or system. Additionally, in real-time operation, it is very difficult or might not be possible to get the conduction and switching losses of the device. Several authors [10]–[12] proposed or discussed methods or techniques to estimate the T_{vj} of the IGBT in real-time operation, for example, based on dv/dt during device turn-off or V_{GE} waveform during device turn-off (the width of the Miller plateau in the gate–emitter voltage V_{GE} waveform which depends linearly on the T_{vj} of the IGBT chips). There are also methods proposed [13], [14] to extract the accurate junction temperature of the GTO (could also be valid for IGCTs), but these methods could only be applied during device turn-off or just after device turn-off event and not during the device conduction. In low switching frequency and high power applications, the IGCT is conducting

Manuscript received June 9, 2015; revised July 30, 2015 and September 10, 2015; accepted October 9, 2015. Date of publication October 26, 2015; date of current version March 2, 2016. Recommended for publication by Associate Editor T. M. Lebey.

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Digital Object Identifier 10.1109/TPEL.2015.2492621

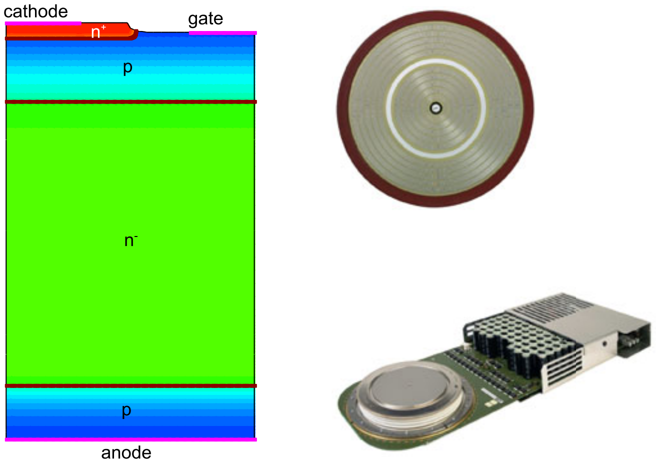

Fig. 2. 2.5-kV RB-IGCT. Left: The structure used in the semiconductor device simulations. Top Right: Fabricated 91 mm, 2.5-kV RB-IGCT device. Bottom Right: The device in a hermetic package and with its integrated gate-unit (the device which is used in the static experiments).

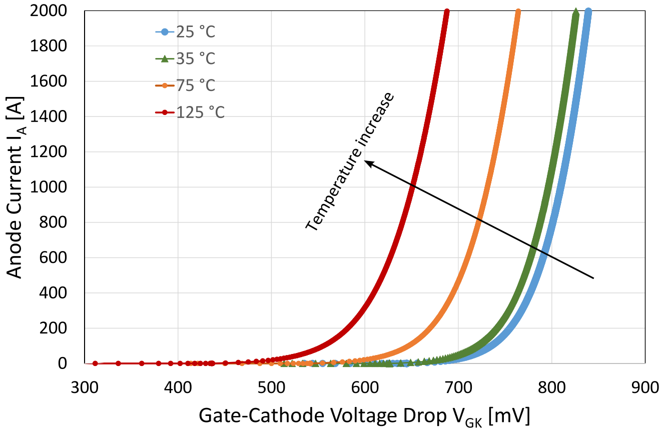

Fig. 3. Simulation results of the 2.5-kV RB-IGCT: The gate–cathode voltage against anode current as a function of device temperature.

TABLE I
EXTRACTED GATE–CATHODE VOLTAGE FROM THE SIMULATIONS AT DIFFERENT T_{vj} FOR A GIVEN ANODE CURRENT

Anode Current	V_{GK} at 25° C	V_{GK} at 75° C	V_{GK} at 125 ° C	Sensitivity
2 A	656.3 mV	554.0 mV	450.9 mV	2.05 mV/°C
200 A	755.3 mV	669.1 mV	581.8 mV	1.73 mV/°C
400 A	777.0 mV	694.0 mV	609.7 mV	1.67 mV/°C

continuously for a longer time and it is important to extract the accurate junction temperature during device conduction.

The extraction of the accurate junction temperature of the semiconductor during the converter operation plays a significant role in designing as well as in operation of the power converter. For example, the thermal resistance values of the module or semiconductor calculated based on the thermal networks are not accurate and may change during the converter operation and, therefore, one has to work with certain safety margins and has to overdesign the cooling system to guarantee a reliable operation of the power converter. This leads to increased volume, weight, as well as cost and also limits the exploiting of the full output power of the converter.

In this paper, we propose a method to extract the accurate junction temperature of an IGCT during the conduction by measuring the gate–cathode voltage of the IGCT. This gate–cathode voltage drop can be measured from the IGCT gate-unit without the need of any external measurement equipment and power supply (no added current or voltage source is required). We found out that the gate–cathode voltage is a function of anode current and junction temperature. This can be clearly seen from the simulation and experimental results as shown in Figs. 3 and 6, respectively.

II. SIMULATION RESULTS

The aim of the simulation study (Sentaurus numerical device simulations) is to show that the gate–cathode voltage is a function of anode current and junction temperature of the IGCT. The simulation structure used in this study is 2.5 kV reverse blocking-IGCT (RB-IGCT) as shown in Fig. 2. The device was designed and optimized to have very low conduction losses for low switching frequency applications [15]. Fig. 3 illustrates the gate–cathode voltage V_{GK} characteristics of a 2.5-kV RB-IGCT as a function of anode current for different junction temperatures of the device. It can be seen from Fig. 3 that the gate–cathode voltage varies with the junction temperature of the device, for a given anode current. The decrease of the V_{GK} with increasing temperature is mainly due to the decrease of the built-in voltage V_{bi} of the gate–cathode junction. The temperature dependency of the V_{bi} is approximately linear [9] and this can be expressed as follows:

$$V_{\mathrm{bi}} = \frac{E_{\mathrm{g}}}{q} - \frac{kT}{q} ln \frac{N_{\mathrm{C}} N_{\mathrm{V}}}{N_{\mathrm{A}} N_{\mathrm{D}}} \tag{1}$$

where E_{g} is the band gap energy, q is elementary charge, k is the Boltzmann constant, T is the absolute temperature, N_{A} and N_{D} are the acceptor and donor concentrations, respectively, and N_{C} and N_{V} are effective density of the states in the conduction and valence bands, respectively.

Table I depicts the temperature sensitivity of the gate–cathode voltage at a given anode current of the device and it is 2.05 mV/°C at very low currents (2 A) and 1.67 mV/°C at high currents (400 A). The extracted temperature sensitivity values from the simulation results are quantitatively in good agreement with the experimental values, which are discussed in the next section. It is worth mentioning that the V_{GK} depends on gate current I_{G} at very low anode current ($I_{\mathrm{A}} < I_{\mathrm{G}}$) and at high anode current, V_{GK} does not depend on I_{G} ($I_{\mathrm{A}} >> I_{\mathrm{G}}$). In the simulations as well as in the experiments, a constant gate current of 4 A is applied to turn on the device.

III. EXPERIMENTAL RESULTS

In order to confirm the simulation results, static and load cycling experiments have been performed. Static characterization consists of measuring the gate–cathode voltage as a function of the anode current flowing through the IGCT at different temperatures. The package of the IGCT is thermally conductive on

TABLE II
SUPPLY ANODE AND GATE CURRENT CHARACTERISTICS

	Pulse width	Repetition rate	Rise/Fall Time
Supply Anode Current	$250\ \mu s$	12.5 Hz	$40–120\ \mu s$
Supply Gate Current	$500\ \mu s$	12.5 Hz	$<40\ \mu s$

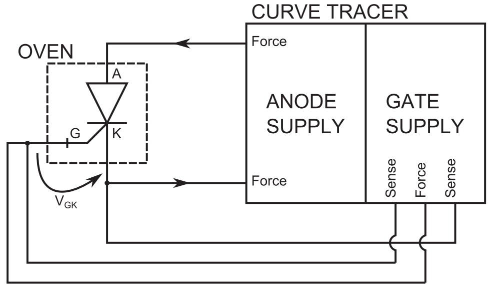

Fig. 4. Schematic of the setup.

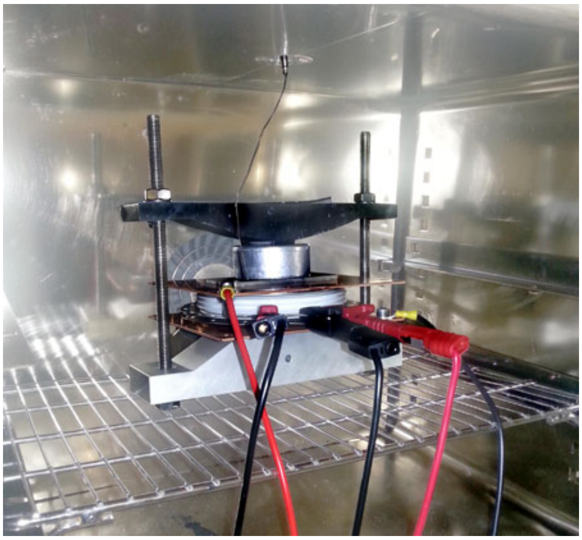

Fig. 5. Picture setup.

both the anode side and cathode side, hence the device is put into a ventilated oven in order to have homogeneous temperature distribution. The IGCT is connected to a Sony Tektronix 371, a curve tracer, which can provide a maximum current of 400 A at a power of 3 kW. The curve tracer has a supply for the anode current and one for the gate current and both inject pulses of current with a duty cycle below 1% (Table II), such that the device is not self-heating while conducting high current and, therefore, the junction temperature is equal to the temperature in the oven. The IGCT is kept in the on-state with a gate current of 4 A (pulsed) and the gate–cathode voltage is measured accurately using Kelvin 4-point measurement technique in order to avoid measuring the voltage drop caused by the current flowing in the cables supplying the gate (Fig. 4 schematic of setup, Fig. 5 picture of setup).

Two 2.5-kV RB-IGCTs from ABB semiconductors have been investigated. Each one is clamped between two copper busbars, which are used for cable connections, with a force of 40 kN and they have been characterized using the above described experimental setup. The gate–cathode voltage as a function of the anode current at three different temperatures is shown in Fig. 6 for both devices. The temperatures sensitivity (from 21 to 130 °C) of both the devices at zero current is the same (1.98 mV/°C), while the sensitivity at 400 A differs between the devices (1.49 mV/°C device 1 and 1.54 mV/°C device 2) even if they are the same type, due to a small difference in the on-state voltage. This means that each device has to be calibrated in order to obtain its gate–cathode voltage versus anode current characteristic at different temperatures, before being installed in a converter. Such characteristic can then be used in a look-up table format in order to estimate the junction temperature of the IGCT during operation (see next section).

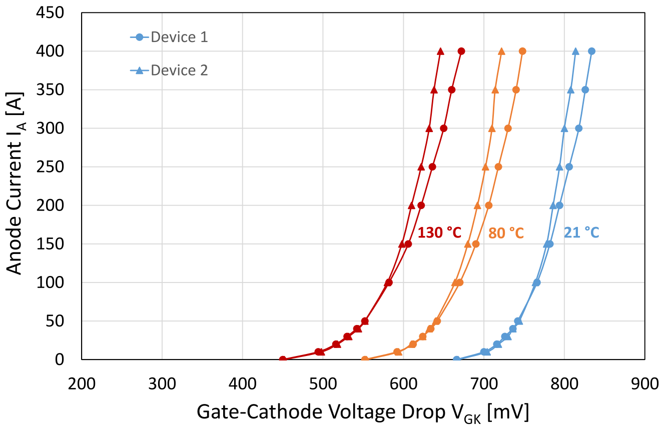

Fig. 6. Experimental results: Gate–Cathode voltage drop as function of anode current at three different temperatures.

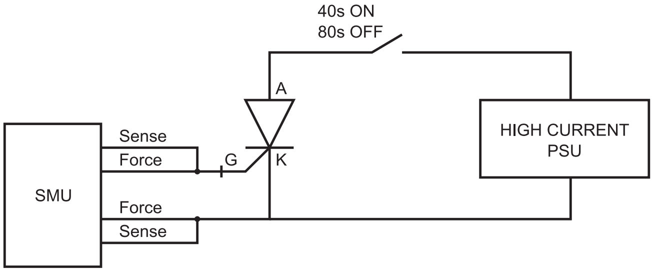

Fig. 7. Load cycling setup.

The gate–cathode voltage has also been measured during load cycling test of a 4.5-kV asymmetric IGCT from ABB Semiconductors. The device is water cooled and it has no current flow for 80 s (cooling phase) and 1000 A of dc current for 40 s (heating phase). The IGCT is kept in the on-state with a power supply injecting 4 A of dc current through the gate and the gate–cathode voltage is monitored during the whole experiment using Kelvin 4-point measurement technique (see Fig. 7).

The water temperature measured at the end of the cooling phase is around 21 °C, while the temperature at the end of the heating phase is around 67 °C. Table III shows the gate–cathode voltage measured at the beginning and at end of both the heating and cooling phase at 0 and 1000 A with the respective temperature sensitivity, while the gate–cathode voltage over time is shown in Fig. 8. It is clear that the gate–cathode voltage increases

TABLE III
EXPERIMENTAL RESULTS: EXTRACTED GATE–CATHODE VOLTAGE AT DIFFERENT T_{vj} FOR A GIVEN ANODE CURRENT

	I_{A}	V_{GK}	T_{vj}	Sensitivity
Before turning on current	0 A	669 mV	21 °C	1.43 mV/°C
After turning off current	0 A	603 mV	67 °C	
After turning on current	1000 A	859 mV	21 °C	0.85 mV/°C
Before turning off current	1000 A	820 mV	67 °C	

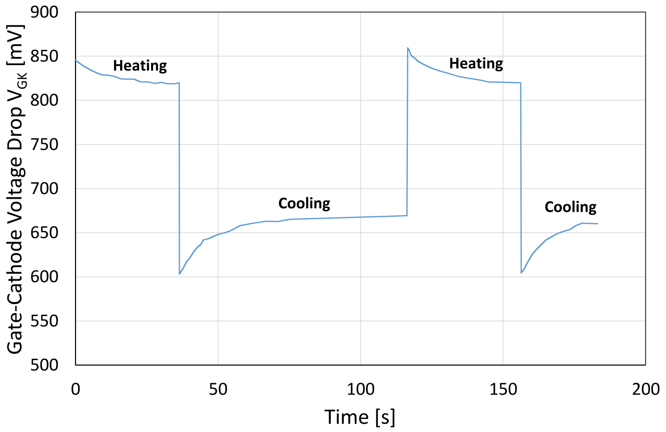

Fig. 8. Experimental results: Gate–Cathode voltage over time during load cycling test.

during the cooling phase as the IGCT temperature is decreasing and it decreases during the heating phase as the IGCT is heating up. Both performed experiments have shown the temperature dependence of the gate–cathode voltage and they confirm the simulation results obtained in the previous section. Therefore, the gate–cathode voltage can be used as a parameter to estimate the junction temperature of an IGCT. In the next section, the implementation of a method to estimate the junction temperature based on the gate–cathode voltage measurement of an IGCT in a power electronics converter is presented.

IV. IMPLEMENTATION IN A CONVERTER

As shown in the previous section, each IGCT requires a gate–cathode voltage characterization as a function of temperature before being installed in a converter. The data can then be used to extract a polynomial function $f(V_{\mathrm{GK}},\ I_{\mathrm{A}})$ to estimate the junction temperature T_{vj}. The polynomial function was chosen as (2) and the coefficients a_{i} can be extracted via least squares method using classical algebra tools [16]. The set of measurements shown in Fig. 6, which includes three different temperatures and several anode current points from 100 to 400 A, has been fitted with the function shown in (2). An almost linear behavior is present over the selected current range. Results are presented for two devices and the resulting prediction error, which is difference between the calculated and measured temperatures, is shown in Fig. 9 and it is less than ±2 °C for all the data points in the set of measurements

$$T_{\mathrm{vj}} = f(V_{\mathrm{GK}}, I_{\mathrm{A}}) = a_0 + a_1 I_{\mathrm{A}} + a_2 I_{\mathrm{A}}^2 + a_3 V_{\mathrm{GK}} + a_4 V_{\mathrm{GK}}^2 + a_5 I_{\mathrm{A}} V_{\mathrm{GK}}. \tag{2}$$

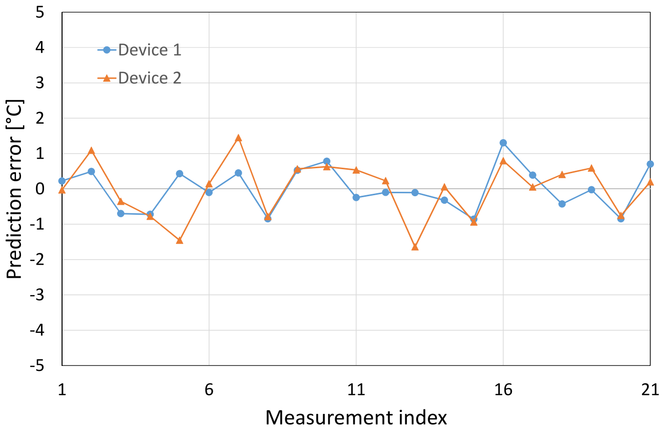

Fig. 9. Prediction error using extracted function.

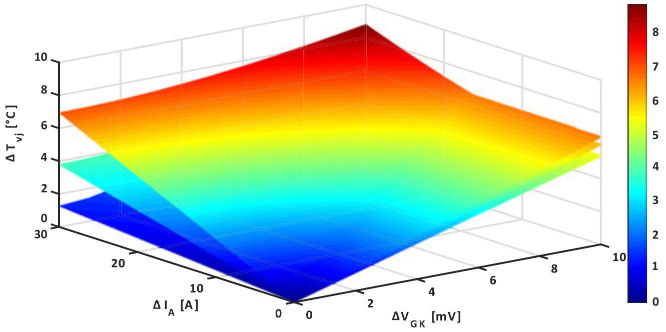

Fig. 10. Uncertainty analysis of T_{vj}.

The uncertainty of the proposed method can be calculated according to the principle of uncertainty propagation as shown in

$$\Delta T_{\mathrm{vj}} = \sqrt{\left(\frac{\partial T_{\mathrm{vj}}}{\partial V_{\mathrm{GK}}}\right)^2 \cdot \Delta V_{\mathrm{GK}}{}^2 + \left(\frac{\partial T_{\mathrm{vj}}}{\partial I_{\mathrm{A}}}\right)^2 \cdot \Delta I_{\mathrm{A}}{}^2}. \tag{3}$$

A representation of the uncertainty is given in Fig. 10 for three operating points of anode current and gate–cathode voltage. The three-dimensional planes include the minimum and maximum uncertainty for both devices. The desired uncertainty of ±5 °C can be achieved with an uncertainty in the gate–cathode voltage measurement of about ±5 mV and an uncertainty in the anode current measurement of about ±20 A, which is feasible with state-of-the-art current sensors.

The gate–cathode voltage can directly be measured at the gate drive level, since the gate-unit is directly connected to the gate and cathode terminals. This voltage can then be translated in digital value with a ADC, which has the required accuracy. For example, a 10-bit ADC supplied with 2.7 V and ±1 Least Significant Bit of accuracy would have an accuracy of 2.64 mV calculated from

$$\text{Accuracy} = \frac{2.7\ \text{V}}{2^{10}} = 2.64\ \text{mV}. \tag{4}$$

The digital value can then be processed by a microcontroller which has implemented the polynomial function to extract the junction temperature from the measurement of the gate–cathode voltage and the anode current. Typically IGCT are operated in

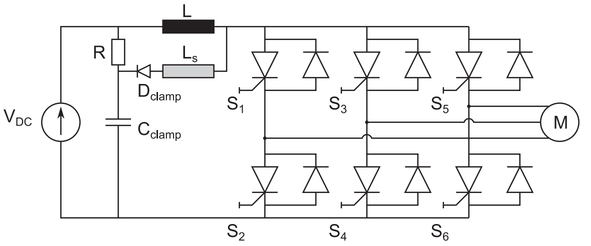

Fig. 11. Topology of a typical inverter unit in a MVD.

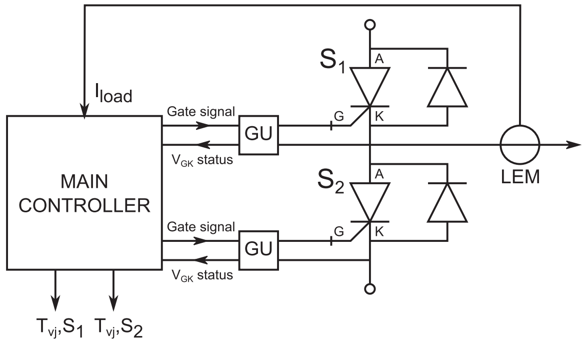

Fig. 12. Implementation of the method in one leg of the inverter unit.

the inverter unit of MVD, which typically have a topology as shown in Fig. 11. Fig. 12 shows a possible implementation of the junction temperature estimation method, where the digital value of the gate–cathode voltage is sent to the main controller of the converter, which then estimates the junction temperature using the polynomial function of the IGCT of interest based also on the current flowing through the device at that moment. The measurement of the load current in the three phases is always available in such converters and by knowing the switching pattern it is possible to know through which IGCT the load current is flowing.

The aforementioned implementation works in principle for any application where the anode current flowing through the IGCT can be measured, hence, a temperature profile of the IGCT during operation can be traced and its remaining lifetime can be estimated [17], [18]. From an industrial standpoint, an accurate prediction of the component lifetime enables an efficient scheduling of the converter maintenance, hence a reduction of the operation downtime and consequently an increase of the whole availability can be achieved.

V. CONCLUSION

A method to estimate the junction temperature of an IGCT during its conduction state by measuring the gate–cathode voltage has been presented. The concept has been proven with both simulations and experimental results. Additionally, a possible implementation of the method in an MVD application has been shown. The presented solution does not require additional hardware, which would increase the volume of the converter, and can be implemented directly on the gate-unit of the device. Therefore, it is a low-cost solution, which enables an on-line estimation of the IGCT junction temperature during on-state. Since the presented method provides an accurate estimation of the junction temperature, the power electronic converter or system can be operated at a output power closer to the theoretical limits as the margin to allow for error is reduced compared to conventional methods. With this method, the temperature profile of the IGCTs in operation can be monitored, and thus, the reliability of the devices can be assessed.

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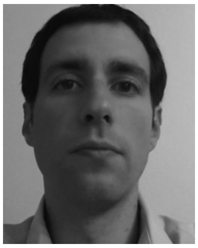

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