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Fast temperature sensing for GaN power devices using E-field probes

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***Abstract*—The material properties of GaN enable high-voltage devices to be manufactured in very small packages. This reduces device footprint and parasitics. However, it also increases thermal impedances which makes thermal management increasingly challenging, negatively affecting reliability. One way to increase reliability is to monitor device junction temperature, and subsequently modify converter operation to hold the temperature in safe bounds. This paper demonstrates a method of sensing the instantaneous junction temperature of GaN power devices, using a low-cost capacitive E-field probe and analogue circuitry. For the first time, the use of the extremely fast turn-on *dv/dt* of GaN devices to determine instantaneous junction temperature is reported. The dependency of the sensor output on load current is shown, and a circuit demonstrated that provides an alert for temperatures above a chosen threshold. The circuit detail, operation, response times, and alternative approaches to take care of the dependency on load current are presented, with a view to helping designers to develop integrated and discrete temperature sensing methods for GaN devices. This new temperature sensing technique could be integrated into a smart power module or added to large power devices as an auxiliary circuit.**

Keywords—wide band gap, GaN, turn-on dv/dt, indirect temperature sensing, Over-temperature protection, TSEPs

I. Introduction

Protection circuits are essential parts of power converters to increase their robustness and reliability [1]–[3]. The protection circuits and the control scheme of the power converter should be able to protect the power converter switching devices against over-temperature. Different sensing methods, direct [4], [5] and indirect [6] are reported in the literature. Direct measurement uses a physical sensor to measure the temperature whereas the indirect methods use temperature-sensitive electrical parameters (TSEPs) to infer the device temperature. A range of TSEPs have been reported for a variety of power devices in [6], [7]. These TSEPs are on-state resistance, drain to source current gradient, gate threshold voltage, drain to source voltage gradient, and gate leakage current. Reference [8] proposes the use of turn-off *dv/dt* in IGBTs as a temperature indicator.

Generally, with direct sensing, sensors are introduced to the circuit as close as possible to the devices, to measure the device temperatures. In systems using modules, the modules will often include a thermistor attached to the substrate. The readings are sent to the controller and calibrated for critical temperature point. This method is suited for slow temperature rise and has significant error for sharp rises of temperature. There are also devices with temperature sensors built-in, for instance Texas Instruments has launched 600 V GaN devices with integrated gate driver, over-current and over-temperature protection [9]. However, the response time of the over-temperature protection is not reported.

This paper demonstrates, for the first time, the use of the turn-on dv_{DS}/dt in GaN devices to determine instantaneous junction temperature. The significant contributions are:

- The presentation of an online temperature-sensing method, which can respond to rapid heating, for GaN devices. The concept, illustrated in Fig. 1, leverages the variation of the GaN device dv_{DS}/dt with temperature. In Section II, the theory of this fundamental approach to junction temperature sensing is developed and it is shown how the variation of dv_{DS}/dt with temperature can be sensed using a capacitive E-field probe.
- Development of an architecture in Section III, and implementation in Section IV, of accurate temperature-threshold sensing circuitry that includes an E-field probe and processes the probe output signal to generate an alert if the junction temperature is higher than a pre-set reference temperature.
- The load current dependency of the temperature sensing is demonstrated and a reference adjusting circuit is presented that minimises the current dependency.
- Experimental results from a 2 kW, 400 V half bridge GaN-based power converter in Section V showing switching as a function of temperature and load current, and further results that demonstrate the effectiveness of the proposed protection method.

The proposed GaN over-temperature protection method has several benefits: It is non-invasive, having no effect on converter efficiency or switching waveforms. There are little or no layout compromises; the probe is placed over the switch-node track leading to the output inductor filter, where parasitic inductance is not critical. The sensor is galvanically isolated from the power traces, reducing complexity and cost of transferring signals to a control system. The sensor is inexpensive, as it can be integrated into the main PCB layout, or added as a separate component implemented in low-cost two-layer PCB technology. In the future, it could even be integrated into device packages. The probe output signal is processed by simple low-cost analogue hardware. No computation is required; response time can be as low as a single power-stage switching cycle.

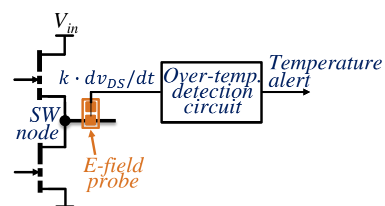

Fig. 1 Temperature alert concept using an E-field probe to sense dv_{DS}/dt.

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II. Temperature Sensing in GaN FET using dv/dt

A. Benefits of employing dv/dt to infer temperature

As discussed in the introduction, there are a handful of TSEPs that could potentially be used to determine the junction temperature of GaN devices. Online measurement of any of these TSEPs, including *dv/dt*, is challenging from signal extraction (many TSEPs such as V_{TH} or R_{dson} cannot be directly measured and must be somehow inferred), computational, isolation and signal sensitivity point of views.

Measuring the drain-source voltage and taking the derivative would be challenging as derivative circuit outputs are very noisy and are not recommended in practice. However, with an E-field probe, *dv/dt* is directly measured and its output is galvanically isolated. A further benefit is high signal to noise ratio: the peak output from the sensor is between −5.85 V to −5.27 V and has sensitivity of about 11.7 mV/°C, which makes it easier to subsequently process robustly. This compares favourably with many other TSEPs, as summarised in Table I.

B. Temperature dependency of drain to source voltage gradient dv_{DS}/dt

In a hard-switched scenario, temperature has adverse effects on switching performance of GaN devices and results in sluggish turn-on switching and increased power loss. The datasheet of the 650 V, 50 mΩ GS66508T from GaN Systems [10] indicates that temperature rise of 100 °C results in slower turn-on switching by about 32%.

This is because increasing temperature results in electron mobility and transconductance reduction [11], [12], and in gate-drain capacitance (C_{GD}) increase [13]. These in turn lead to slower switching by the following mechanism:

In a hard-switched turn-on transition, first the drain current will rise and then the drain-source voltage will fall, both transients occurring when the device is in the active region, where current is approximately proportional to the overdrive voltage:

$$i_D \approx k(v_{GS} - V_{TH}) \quad (1)$$

Where k is a device characteristic related to the transconductance g_m (g_m being a small-signal parameter and k being a related large-signal parameter). Once the current transition is over, the gate voltage reaches a plateau, during which C_{GD} is discharged by the gate current, and the drain-source voltage transition occurs. Not only is C_{GD} larger at higher temperature, but also from (1), if i_D and V_{TH} are fixed, a lower transconductance (lower k) forces a higher v_{GS} which in turn leads to a lower gate current during the plateau period (higher gate voltage means less voltage dropped across the gate resistor). The lower current then discharges the larger C_{GD} at a lower rate, resulting in a slower v_{DS} transition.

TABLE I Typical Signal Magnitudes and Sensitivities of Various TSEPs

TSEP	Signal derived from	Signal magnitude	Signal sensitivity
Turn-on rise time [10]	High-bandwidth measurement of i_D	3.7 – 4.9 ns	12 ps/°C
R_{dson} on-state resistance [10]	Measurement of i_D and v_{DS} and computed by v_{DS}/i_D	50 – 128 mΩ	0.62 mΩ/°C
R_{gint} gate internal resistance [7]	Measurement of i_G and v_{GS} and computed by v_{GS}/i_G	2 Ω	2.9 mΩ/°C
Gate threshold voltage [7]	Time-synchronised measurement of v_{GS} and i_D	1.4 V	2.9 mV/°C below 60 °C; −3.9 mV/°C above 60 °C
dv/dt	Directly measured by E-field probe	−5.85 – −5.27 V	11.7 mV/°C

The top two waveforms of Fig. 2 illustrate the dependency of GaN device v_{DS} transition on temperature. The higher temperature is seen to force the turn-on switching to be slower and hence generation of lower *dv/dt*. The lower two waveforms in Fig. 2 illustrate the time-derivative of the voltages v_{DS}. Here, it can be seen that higher temperature results in lower negative peak voltage gradient $dv_{DS}/dt|_{min}$. The proposed over-temperature method in this paper is based on this property of the GaN devices and measures the negative peak voltage gradient $dv_{DS}/dt|_{min}$.

The speed of switching, i.e. the drain to source voltage gradient dv_{DS}/dt, also depends on load current. This dependency affects the detection circuit and results in some degree of inaccuracy in temperature measurement. In applications with constant load current this is not an issue however, in applications with varying loads, the load dependency needs to be addressed.

C. Temperature sensing of GaN FET using E-field probe

Online measurement of v_{DS} and subsequent application of a time-derivative function have practical issues such as high voltage measurement, galvanic isolation, and noisy differentiation. Instead of directly measuring the v_{DS} and differentiating it to obtain the dv_{DS}/dt signal, it is proposed to use a capacitive electric-field (E-field) probe.

Capacitive E-field probes consist of two conductive plates, as shown in Fig. 3, that are galvanically isolated. One of these plates is used as a reference ground for measurement (i.e. the plate in Fig. 3(a)), the other one is picking up the measurement signal (i.e. the plate in Fig. 3(b)). The probe is placed near the circuit with high *dv/dt*. Parasitic capacitances are formed between the probe plates and nearby circuitry. The generated *dv/dt* injects currents through these parasitic capacitances and

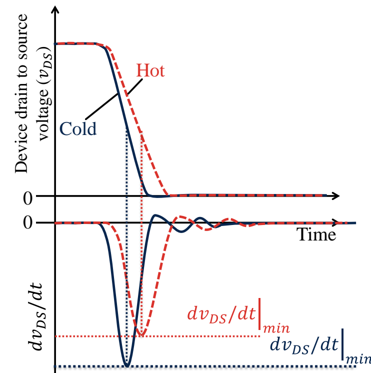

Fig. 2 Illustrative waveforms, at the instant of device turn-on, of GaN device drain to source voltage v_{DS} and its time-derivative at two different temperatures i.e. cold and hot.

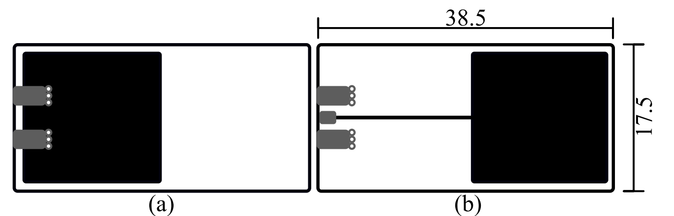

Fig. 3 2D renders of the PCB-based capacitive E-field probe used in this work. (a) bottom view, (b) top view, with all dimensions in mm. An SMA connector is soldered to the left-hand side of the board.

charge them which results in a voltage developed between the plates of the E-field probe. The probe output voltage is proportional to the *dv/dt* generated by the switching action.

Fig. 2 illustrates that the turn-on switching action generates higher negative dv_{DS}/dt when the device is cold, and lower negative dv_{DS}/dt as the device temperature increases. This voltage gradient is picked up by the E-field probe and hence, the probe output voltage also changes with the device temperature. These changes on the probe output voltage can be detected in an analogue circuit, and based on the variation in this signal, the device temperature is estimated.

III. System Architecture of the Proposed Temperature Protection Method

In this section the basics of the proposed method are presented. The proposed over-temperature protection circuit peak-detects the E-field output voltage and compares it with a reference, which is corresponding to a threshold level set by the user, to determine if the device temperature is higher than a threshold temperature. Key challenges are:

- The sensor output presents only during the switching events and is zero outside of the switching events as illustrated in Fig. 4. Hence, continuously comparing the probe output voltage to a threshold is not sufficient.
- The output of the probe is negative during the turn-on event. This needs to be converted to a suitable voltage range of the high-speed comparator.
- The total duration of these pulses are about ten nanoseconds, with narrow peaks lasting only a few nanoseconds.

The solution adopted here to address these challenges is shown in Fig. 5. There are four sub-systems: latching high-speed comparator, sampling and reset, scaling and biasing, and the alert generator blocks.

The probe output voltage ($k \cdot dv_{DS}/dt$), where *k* is a constant of proportionality inherent to the sensor, is proportional to the drain to source voltage gradient. The scaling and biasing block first divides the $k \cdot dv_{DS}/dt$ signal and then adds a biasing voltage. So, the measured signal from the probe is shifted into the positive measurement range of the high-speed comparator chip. The scaled and biased signal, denoted $K_{sb} \cdot dv/dt$, is shown in Fig. 6.

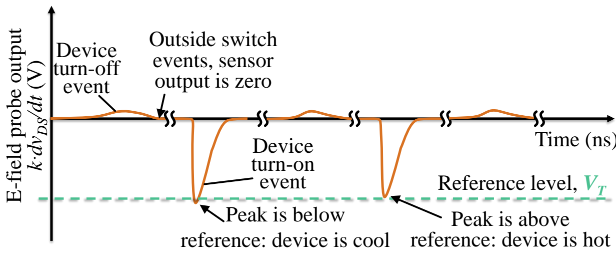

Fig. 4 Idealised output from E-field probe as GaN device heats up.

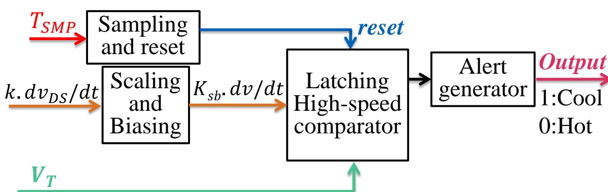

Fig. 5 Over-temperature alert architecture using an E-field probe.

The Sampling and reset block generates a reset signal that releases the latch of the high-speed comparator. Once the latch is released, the high-speed comparator starts sampling the $K_{sb} \cdot dv/dt$ signal. The period of this reset signal, T_{SMP}, is set by the user and depends on how fast temperature sampling is needed. In this paper the temperature sampling is carried out every 1 ms.

The operating principle of the latching high-speed comparator block is illustrated in Fig. 7, the signal $K_{sb} \cdot dv/dt$ is compared against a reference level V_T which is corresponding to a threshold temperature level. In case the device is cool, then there exist instances where the $K_{sb} \cdot dv/dt$ signal goes below the reference level V_T, as shown in Fig. 6. The latching high-speed comparator is regularly reset by the reset signal, and is followed by an alert generator block which in turn drives a slow-response protection relay. When reset, the high-speed comparator output goes low. Subsequently, a *dv/dt* event whose peak is below the threshold (device is "cool") causes the comparator output to latch to high, whilst for a *dv/dt* event above the threshold (device is "hot"), the output will stay logic low. Under normal operation with "cool" devices, the comparator output is therefore normally high, with brief low-going pulses occurring on each reset pulse. The reset signal is not synchronised to the power converter switching events. As such, the maximum duration of this low-going pulse is equal to the converter switching period. The response time of the protection relay following the alert generator circuit is chosen such that the output signal has to stay logic low for at least 1 ms in order to generate the trip signal.

IV. Circuit Level Design

A. E-field probe

An off the shelf PCB-based capacitive E-field probe , from Unit 3 Compliance [14] is used in this paper. It is a low-cost probe which can be integrated into the power board, which is one of the main advantages. The probe PCB layout with the

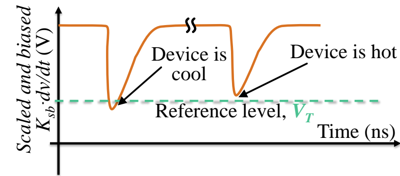

Fig. 6 Scaled and biased idealised output from E-field probe for cool and hot device conditions.

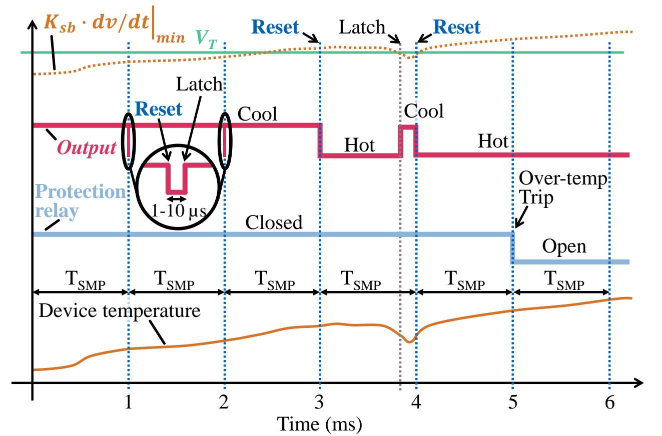

Fig. 7 The operating principle of the proposed temperature alert system for the case of a GaN device gradually heating up.

dimensions are shown in Fig. 3. Another advantage of this probe is the galvanic isolation of the measurement and there is no need to have additional isolation circuitry. Last but not the least is the direct measurement of voltage gradient which does not require any complicated signal processing. Depending on the size and placement of the probe, the magnitude of the probe output voltage changes. In this paper, the probe is directly placed on the switch node cable leading to the filter inductor where the high level of voltage gradient presents.

B. *Circuit design*

The electrical circuit for the proposed over-protection method is given in Fig. 8. Each part of the circuit is explained here. Reference setting is a user control that determines the reference temperature level using a potentiometer. The output voltage of the probe ($k{\cdot}dv_{DS}/dt$) during the turn-on switching is negative, as shown in Fig. 4, and its magnitude is higher than the high-speed comparator input voltage range, hence conditioning is needed for this signal. The signal conditioning is performed by the Scaling and Biasing circuit; the signal $k{\cdot}dv_{DS}/dt$ is divided by three using a resistive voltage divider and is biased with +3.3 V. The output of the scaling and bias circuit is denoted $K_{sb}{\cdot}dv/dt$ and is within the range of the high-speed comparator input voltage.

The high-speed comparator ADCMP553, with differential output voltage (v_{CMP}), compares the signal $K_{sb}{\cdot}dv/dt$ against V_T. If the valley of this signal goes below V_T, i.e. the device is cold, as shown in Fig. 6, the Q output of the high-speed comparator goes high. The $\overline{Latch}$ pin is connected to the $\bar{Q}$ pin via a MOSFET; this latches the comparator as soon as the output goes high. In case of a hot device, the signal $K_{sb}{\cdot}dv/dt$ is always above the reference level V_T, as shown in Fig. 6, and the comparator output stays low.

To release the latch, the sample and reset signal, $reset$, is pulled down. The reset period T_{SMP} is set with a potentiometer in a timer circuit, which in turn generates the $reset$ signal, which is a square pulse train with a 99.8% duty.

The alert generator block is an output buffer that limits the loading of the high-speed comparator. A falling edge at the output indicates an over-temperature alert. The buffer comprises a low-speed comparator LM311 driving a solid-state protection relay TLP227G in the Protection relay circuit. The state of the protection relay is open when the switching device is cool and, in the case of over-temperature detection the relay state changes to closed. The relay is used to shut down the power converter when over-temperature is detected.

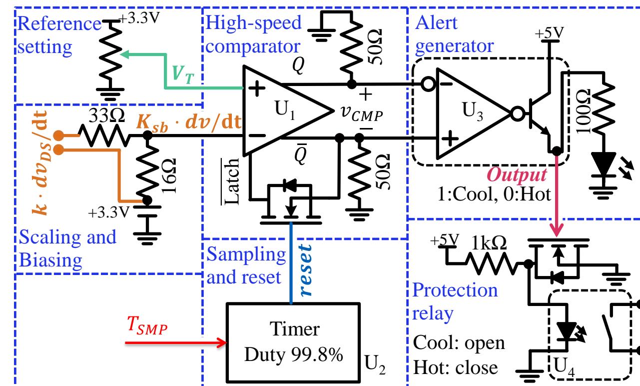

Fig. 8 Proposed over-temperature circuit diagram of the block diagram shown in Fig. 5.

V. Hardware Implementation and Experimental Results

Fig. 9 shows a schematic of a GaN-based bridge-leg power converter used to demonstrate the proposed over-temperature protection method. The E-field probe is placed on the switch node cable just before the filter inductor, where the *dv/dt* is high.

Photographs of the constructed 2 kW-rated power converter are shown in Fig. 10 and Fig. 11. The 650 V GS66508T from GaN Systems [10] is used for the power devices. Underneath each device a hole is placed to enable measurement of the device case temperature using a TESTO 875-1i thermal camera. A heat plate is thermally attached to the devices and an Inkbird ITC-100RL controller controls the temperature of the heat plate. The circuit is a DC-DC power converter which converts 400 V to 200 V. An EA-EL 9500-60B electronic DC load is connected from after the output inductor I_L up to the positive supply rail (so load current flows into the switched node), and is used to vary the load up to 2 kW.

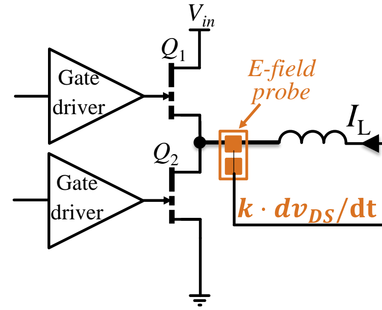

Fig. 9 Schematic of experimental GaN bridge-leg power converter with temperature sensing, using an E-field probe to obtain $k{\cdot}dv_{DS}/dt$.

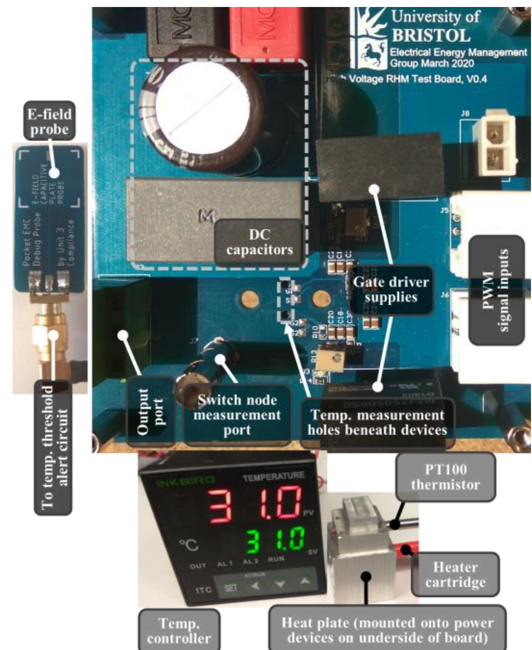

Fig. 10 Top side of the power board, showing temperature measurement holes beneath the devices, E-field probe from Unit 3 Compliance Ltd [14], and temperature-controller setup. The power devices are mounted on the bottom side of the board as shown in Fig. 11.

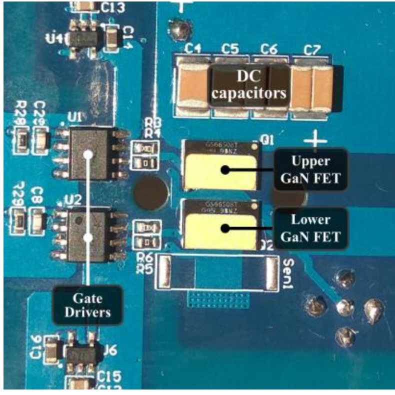

Fig. 11 Underside of the power board. A 2 kW GaN bridge leg power converter utilising top-side cooled GS66508T devices from GaN Systems.

A. E-field probe output measurement and over-temperature protection test results

The power converter is operated at 10 A, 2 kW as a DC-DC buck converter. The GaN devices temperature is initially at ambient (23 °C). The power loss in the devices results in a gradual temperature rise; the results are captured at desired temperatures from 70 °C to 120 °C in steps of 10 °C. The case temperature of the GaN device is monitored using the thermal camera, through the holes placed beneath the devices. The scaled and biased E-field probe output voltage $K_{sb}{\cdot}dv/dt$, at different device temperatures is shown in Fig. 12. It can be seen that as the temperature of the switching device increases, the measured $K_{sb}{\cdot}dv/dt$ signal's valley shifts up. This shift has an average sensitivity of around 3.92 mV/°C. The proposed over-temperature protection circuit detects this shift and based on the set reference temperature level generates an alert correspondingly.

A test is carried out to evaluate the effectiveness of the proposed over-temperature protection method; the results are depicted in Fig. 13. The reference threshold temperature is set to 120 °C and the power converter operates at 10 A, 2 kW, 100 kHz, converting 400 V to 200 V. The devices temperature is initially at ambient i.e. 23 °C. The converter is switched on at time zero with heatsink fan turned off. The devices are cool initially and hence the protection circuit outputs a high signal indicating cool device. The power loss gradually increases the temperature of the devices and after around 50 seconds the switching device temperature reaches 120 °C. At this point, the protection circuit detects high temperature and its output goes low indicating hot devices. To cool the devices down, the heatsink fan is turned on at time t = 60 s. The device temperature reduces and once it goes below 120 °C the protection circuit indicates cool again. With the fan turned on the switching device temperature settles at 96 °C. This is repeated once more to check the repeatability of the protection temperature levels.

B. Current dependency of the E-field probe output voltage and reference level adjustment

As mentioned in Section II, the voltage gradient depends also on the load current, hence dependency of the probe output on the load current. A set of tests are carried out to evaluate dependency of the probe output voltage on load current at different temperatures. For these tests, the power converter is operated at a known load current and results are captured once the temperature is settled at desired levels. The signal $K_{sb}{\cdot}dv/dt$ is measured in each test and the minimum value at the valley of these signals are measured and plotted against the load

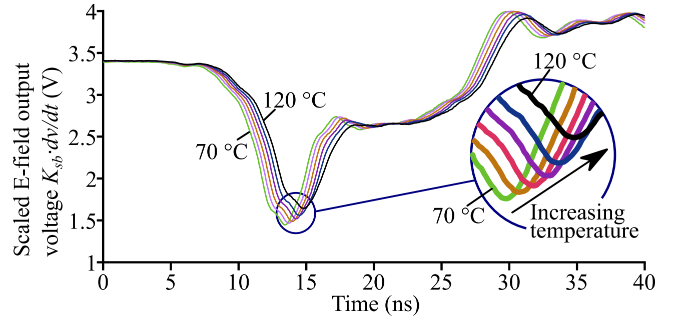

Fig. 12 Scaled and biased E-field output voltage $K_{sb}{\cdot}dv/dt$ at different temperatures from 70 °C to 120 °C with steps of 10 °C. The power converter is operating at 10 A load current i.e. 2 kW output power.

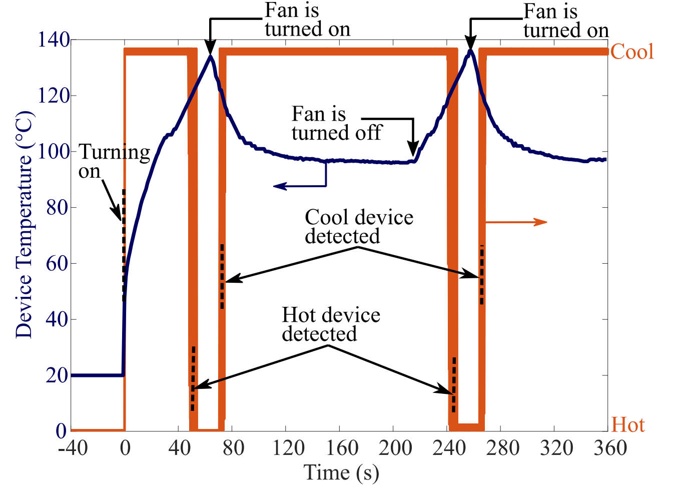

Fig. 13 Over-temperature protection alert signal using E-field probe, and device case temperature measured using thermal camera. The power converter operates at 2 kW, 100 kHz, converting 400 V to 200 V, with reference temperature set to 120 °C.

current in Fig. 14, for different device temperatures. It is apparent that probe output voltage depends on the device temperature as well as the load current. However, the dependency on the temperature is dominant. Fig. 14 shows that the $K_{sb}{\cdot}dv/dt$ signal valley voltages for the cases of 100 °C at 10 A and 110 °C at 4 A are the same. This means if the reference level is set to the green dashed line, shown in Fig. 14, the protection circuit would trip at 100 °C and 110 °C for load currents of 10 A and 4 A, respectively.

A test is carried out to evaluate the effects of the current dependency on the over-temperature protection accuracy. For these tests, the relay provided in the protection circuit is connected to the remote control of the main power supply. If a hot device is detected, the relay closes and shuts down the main power supply. The temperature of the switching device is monitored and the last temperature, just before the trip, is noted. In the first test a reference level V_T is set corresponding to 100 °C at 10 A load current. The power converter is operated at different load current from 3 A to 10 A (i.e. 0.6 kW to 2 kW). At each current the temperature of the devices increases gradually until the protection circuit trips. The results are shown in Fig. 15 using a solid line. It can be seen at 10 A the trip temperature is 102 °C which, at only 2 °C higher than the set reference level, can be acceptable. However, at 3 A the trip temperature is 110 °C. This is 10 °C higher than the set reference level and may not be acceptable for some applications. The trip temperatures are between 102 °C and 110 °C, over the full range of load current, i.e. a tolerance of 8 °C.

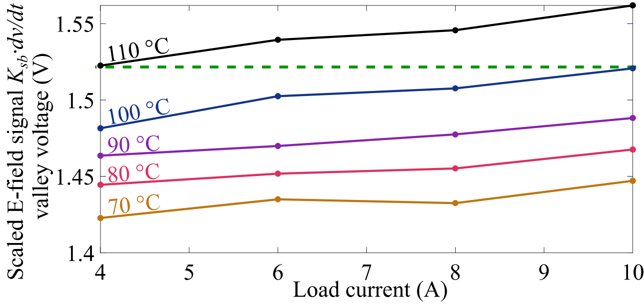

Fig. 14 Dependency of probe output on temperatures and load currents.

Another set of tests with variable (3 tier) reference level is carried out. The load current is divided into three groups: $I_L \leq 5$ A, 5 A< $I_L \leq 8$ A, and $I_L > 8$ A. For each group, a different reference level is manually selected based on the load current information. A circuit that could be used to change the reference level automatically based on the load current information (v_I), from a load current sensor, is shown in Fig. 16(a). There are two comparators which switch between the reference levels. Here, V_{i1} and V_{i2} are DC voltages corresponding to 5 A and 8 A respectively. The adjusted reference level is calculated using (2). The resistances are selected based on the data shown in Fig. 14 to generate the desired reference levels.

$$V_{T_{adj}} = \begin{cases} 5\frac{R_2+R_3+R_4}{R_1+R_2+R_3+R_4} & v_I > \mathrm{V_{i2}} \\ 5\frac{R_2+R_3}{R_1+R_2+R_3} & \mathrm{V_{i1}} < v_I < \mathrm{V_{i2}} \\ 5\frac{R_2}{R_1+R_2} & v_I < \mathrm{V_{i1}} \end{cases} \quad (2)$$

The reference levels selected here are corresponding to 100 °C at 5, 8, and 10 A. The results are shown in Fig. 15 (dashed line). The trip temperatures are between 101 °C and 104 °C, which has a tolerance of only 3 °C, over the full current range. It can be seen that by using three reference levels it is possible to reduce the trip temperature tolerance by 75%. It is possible to reduce the tolerance even more if more reference levels are selected.

Another option to eliminate the load current dependency of the over-temperature protection circuit is to actively adjust the reference level using the load current feedback as given in equation (3), where v_I is a voltage proportional to the load current (v_I=k·I_L). Using the data shown in Fig. 14, and the scaling factor k, the compensation factor k_{adj} is calculated. In this way the reference level is adjusted automatically according to the load current information (v_I).

$$V_{T_{adj}} = V_T + k_{adj} \times v_I \quad (3)$$

This can be implemented either in an analogue circuit or microcontroller. For microcontroller implementation the compensation factors k_{adj} and the reference levels V_T from Fig. 14 are calculated and used in equation (2) accordingly. Another way to implement in microcontroller is to have the data in Fig. 13 as a lookup table and select a suitable reference level based on the current level and desired trip temperature.

An analogue circuit for continuous reference level adjustment is shown in Fig. 16(b). Two potentiometers are provided; *PT1* is used to adjust V_T and *PT2* adjusts the compensation factor k_{adj}. This circuit is simulated in LTspice and in Fig. 17 the simulated waveforms are shown using solid lines. Circles, diamonds, and squares show the measured values of the valley of signal $K_{sb}\cdot dv/dt$. The simulated results

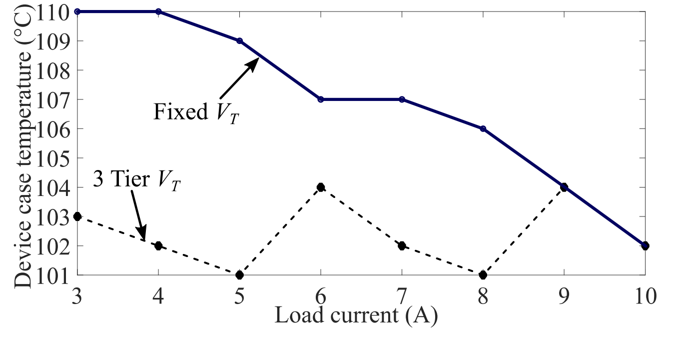

Fig. 15 Measured trip temperature against load current for fixed reference level, and 3 tier reference levels.

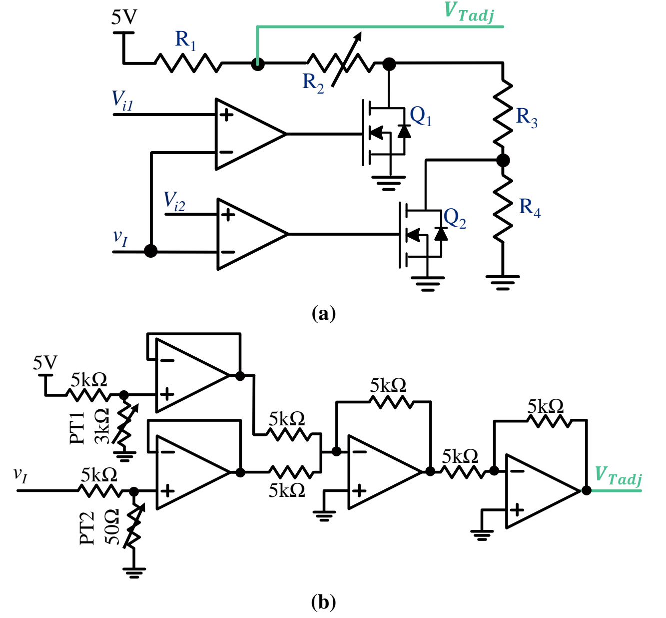

Fig. 16 Reference level adjustment analogue circuit. (a) three level reference adjustment, (b) continuous reference adjustment.

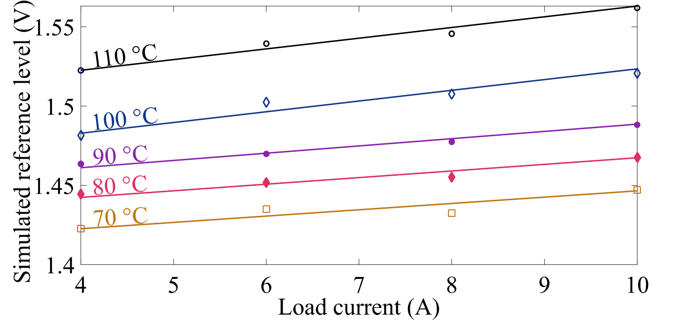

Fig. 17 Simulated reference adjustment using the circuit shown in Fig. 16 (solid lines) along with measured values of the valley in signal $K_{sb}\cdot dv/dt$ (circle, diamond, and square).

show that the threshold is adjusted in such a way that it stays within ±5 mV of the valley value of signal $K_{sb}\cdot dv/dt$. As such, it can be expected that using the circuit shown in Fig. 16(b), the actual trip level would be within ±1.27 °C of the set threshold, across the load current range, for a trip level of 100 °C.

C. *Over-temperature protection circuit response time*

The aim of this study is to evaluate the response time of the protection circuit. For this test, the power converter switching frequency is increased to 500 kHz to highly increase the switching loss. The power converter is operated

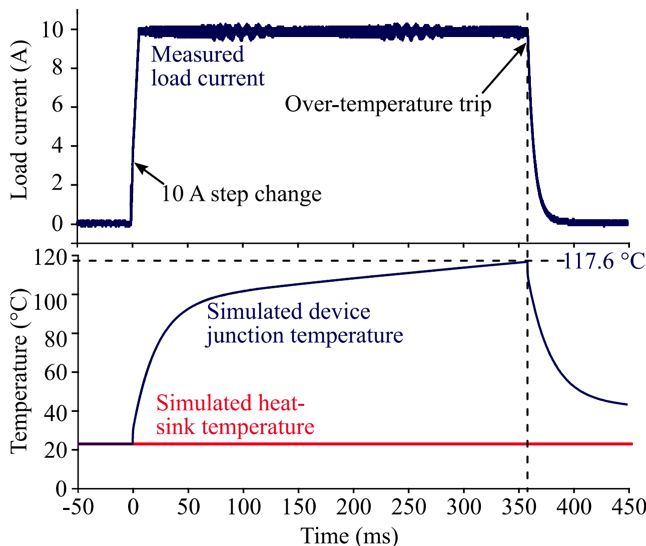

Fig. 18 Demonstration of safe shutdown on highly overloaded GaN bridge-leg power converter operating at 10 A, 2 kW, and 500 kHz. The high switching losses at 500 kHz result in rapid heating of the GaN devices.

at 10 A, and 2 kW. The power loss of this operating point is well beyond the steady-state handling for the GaN devices and their cooling arrangement, and can be withstood for less than a second before the specified maximum operating temperature of the devices is reached. The over-temperature protection method should be capable of detecting the rapid heating of the GaN devices and shut down the power converter safely. The reference level is set to 120 °C. The results are shown in Fig. 18. The power converter is turned on at time zero, the load current ramps up and settles at 10 A. 358 ms after first turn-on, the protection circuit detects an over-temperature state and the converter is shut down. The junction and heat-sink temperatures are simulated, and it is found that at 358 ms, the junction temperature has risen to about 117.6 °C, as shown in Fig. 18. This confirms that the protection circuit is fast enough to protect the devices even at this high rate of switching loss.

VI. Conclusions

A temperature-sensing and over-temperature protection method, using a non-contact E-field probe, has been implemented and validated. The method detects the negative peak of the E-field probe output voltage and based on that, determines if the junction temperature is higher than a reference level, in which case an alert is generated and the power converter is shut down. It is shown that the reference level can be automatically adjusted to compensate for the dependency on the load current. The response time for this protection method to detect an over-temperature is of the order of milliseconds. This is likely to be faster than direct sensing concepts that use a physical temperature sensor. Experimental evaluation on a 2 kW power converter is presented and it is shown that the protection circuit safely trips the converter even under extreme conditions with a tolerance of the order of ±5 °C.

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