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Simple and Precise Calorimetry Method for Evaluation of Losses in Power Electronic Converters

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Abstract—As power converters become more compact and more efficient, precisely measuring their efficiency becomes increasingly difficult. Calorimetry is an attractive solution to overcome the limits of electrical measurements (poor accuracy, complex integration of voltage and current probes). Although simple in its principle, calorimetry can be complex to implement. Here, we describe a simple adiabatic calorimeter, which only uses low-cost equipment and yet offers good sensitivity (it can be used to measure losses in the $\approx 1\text{--}20$ W range).

I. INTRODUCTION

Measuring the power losses of a converter becomes increasingly difficult as conversion efficiency rises. Yet, as converters have become more and more compact, this measurement remains essential to ensure proper thermal management.

Losses can be calculated by subtracting the output power of the converter from its input power. This is an obvious solution, which unfortunately is very sensitive to the accuracy of the power measurements [1]. For dc-dc converters, this method may be acceptable, as dc measurements can be performed with an accuracy better than 0.1%. However, for converters connected to an ac link, or those generating non-negligible levels of EMI, such measurement is much less accurate [2].

The “opposition” method is an alternative measurement technique where two identical converters circulate power from one another [3]. This method is commonly used, as it allows the converters to operate at their full rated power, without requiring a large power source, nor any load. A low power source, connected to the converters, compensates for the power lost in operation. The power losses in each converter are then equal to half of the power supplied by the source. This makes the losses measurement easier, and more accurate. This method, however, requires reversible converters (one acting as a generator, the other as a receptor) and a dedicated control system. Furthermore, it obviously requires two converters.

Calorimetric methods have been explored by many authors to overcome the limits of electric measurements [1], [2]. Most of them rely on flow calorimetry, in which all the heat generated by a converter is collected using a cooling fluid (air, water). The fluid flow-rate and temperature rise at the equilibrium are measured, and the power transferred is calculated as

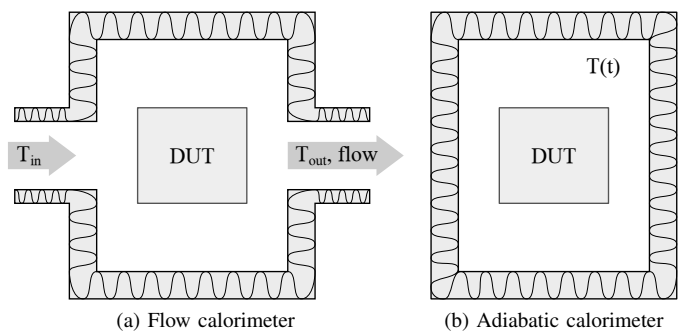


Fig. 1: (a) Basic principle of the flow calorimeter: a fluid (e.g. air) flows through a chamber with insulating walls; the power dissipated by the DUT is calculated from the fluid inlet and outlet temperatures and the flow-rate. (b) in an adiabatic calorimeter, no heat exchange is allowed with the environment; the temperature rise in the chamber is directly proportional to the energy dissipated by the DUT.

$$P_{losses} = \Delta T C_p \dot{m} \quad (1)$$

with C_p the specific heat of the fluid, \dot{m} its mass flow, and ΔT the temperature difference of the fluid before and after it passed through the converter. While its principle is simple (Fig. 1a), the implementation of such calorimeter requires considerable care regarding the heat collection. Because all the power dissipated by the Device Under Test (DUT) must be collected by the cooling fluid, it is important to ensure that no heat flows through the walls of the chamber. This is usually ensured using thermal insulation material as well as a double-wall structure in which the inter-wall temperature is actively controlled [2]. When using air (or any gas) as the cooling fluid, accurate mass-flow measurements may be difficult, so some calorimeter designs consist in two successive chambers, one being used for continuous calibration (dissipation of a set power level), and one for measurement [1]. This way, there is no need to measure the mass-flow. Another solution is to use a liquid coolant to collect the power, so that mass-flow is easier to monitor. By combining these improvements, an

accuracy of 1 % or better can be achieved [1], [2], at the cost of an increased complexity.

Adiabatic calorimetry (see Fig. 1b) is an attractive alternative, in which the converter is placed in (ideally) fully adiabatic conditions. It involves no flow of any sort. Instead, power is measured as

$$P_{losses} = \frac{\Delta TC_{Th}}{t} \quad (2)$$

where C_{Th} is the total heat capacity inside the adiabatic enclosure, and t the amount of time during which power is dissipated. Note that (2) is true under the assumptions of constant power dissipation over time, uniform temperature in the calorimeter, and constant heat capacity (in particular, no change with calorimeter temperature). Implementations of such calorimeters include devices under test attached to a simple metal block [4] or immersed in an oil bath [5]. Such calorimeters are easy to design and can therefore be customized for each DUT. Their main drawback is that they do not allow for continuous operation of the DUT (as the temperature in the calorimeter would increase indefinitely). As for flow calorimeters, the accuracy of adiabatic calorimeters can be improved by careful thermal insulation and by controlling the temperature of their environment [6].

This paper focuses on a very simple implementation of an adiabatic calorimeter, describes the main design considerations and presents some experimental results.

II. ADIABATIC CALORIMETER DESIGN

While calorimeters based on a solid heat storage (in general a metal block attached to one or more components) are useful for very local measurements, such as measuring the losses of a single transistor [7], they are more complex to use on an entire converter. Indeed, it is difficult to ensure that the heat generated by all components is collected by the heat storage element. For such cases, immersing the converter under test in a liquid bath is a more convenient solution.

Various heat transfer liquids have been used in the literature: transformer oil in [5], sunflower oil in [6], Fluorinert FC-40 in [1]. All have drawbacks such as toxicity (for transformer oil), environmental concerns (Fluorinert has a global warming power –GWP– of more than 9000 and an atmospheric lifetime of 3000 years [8]), or practical issues (oil residues on the converter, chemical compatibility with PCB solder resist). Here, we propose to use Novec 7500 (3M), a dielectric fluid with a GWP of 90, an atmospheric lifetime of 2.5 years, a reasonable cost (<50 \$/L), no noticeable toxicity, a good chemical compatibility with most materials used in power electronics, and which does not leave any residue after drying.

Tab. I summarizes the main properties of some possible fluids, chosen for their low toxicity and because they leave no residues on the devices under test after drying. Compared to Fluorinert FC-40, Novec has a comparable density and specific heat. It is almost as fluid as water (i.e. little power is required to stir it). It has relatively low resistivity, approximately 10 times that of de-ionized water, but it should remain high

TABLE I: Example of dielectric fluids (manufacturer’s data).

	DI Water	Fluorinert FC-40 (3M)	Novec 7500 (3M)
viscosity (Pa · s)	0.89×10^{-3}	4.1×10^{-3}	1.24×10^{-3}
resistivity ($\Omega \cdot \text{cm}$)	1.8×10^7	1×10^{15}	2.2×10^8
GWP	-	> 9000	90
toxicity	none	low	low
residues	none	none	none
spec. heat ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)	4.2	1.1	1.1
density ($\text{kg} \cdot \text{L}^{-1}$)	1	1.865	1.614
boiling point ($^{\circ}\text{C}$)	100	165	128

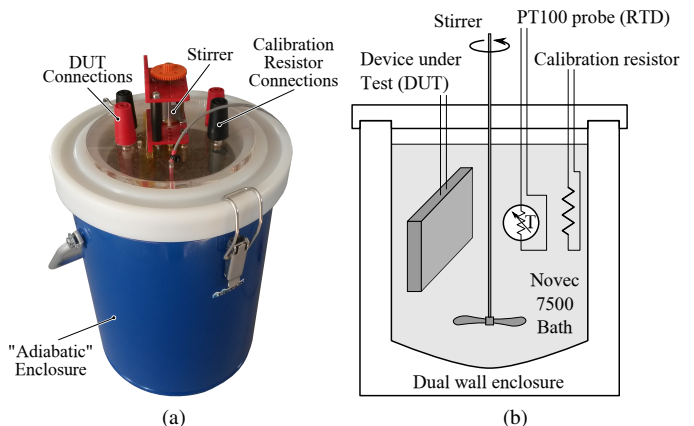


Fig. 2: Photograph (a) and diagram (b) of the calorimeter. The external dimensions of the enclosure are $\Phi = 170 \text{ mm}$, $h = 215 \text{ mm}$. Internal volume: 700 mL.

enough for most applications (if a higher electrical resistivity is needed, other variants such as Novec 7200 have better performance in that regard).

The adiabatic enclosure used here is a simple Dewar jar, depicted in Fig. 2 (Pierron, France). The topside of the jar is closed using a 10 mm-thick PMMA board with cutouts for the electric connections and the mechanical stirrer depicted in Fig. 2b. In the experiments presented here, this level of thermal insulation was found satisfying. A better adiabaticity can be achieved using glass wool or extruded polystyrene [5].

A key element of this setup is the temperature measurement. The main sensor technologies are thermocouples, thermistors, and Resistive Temperature Detectors (RTDs) [9]. Thermocouples have a low cost, wide temperature range, but relatively low accuracy (1 – 2 K). Thermistors and RTDs are usually much more accurate, with thermistors offering the best sensitivity, but are strongly non-linear. Platinum RTDs (PT100) have an almost linear and standard dependency with the temperature ($385 \text{ m}\Omega \cdot \text{K}^{-1}$). Here we use a class A PT100 (D00539/PS3/30, Correge Sensors) connected to a Keithley 2700 precision multimeter [10] using a 4-wire configuration. The absolute accuracy of this temperature measurement is 0.25°C and the resolution (considered to be equal to the relative accuracy) is 0.001°C .

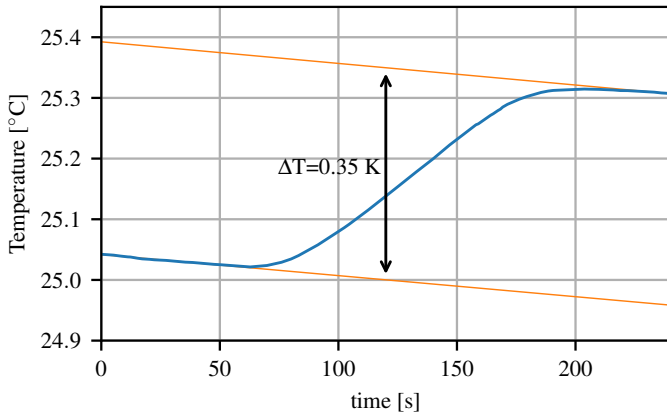


Fig. 3: Example of a temperature transient caused by the dissipation of 4.52 W for 60 s in the calorimeter

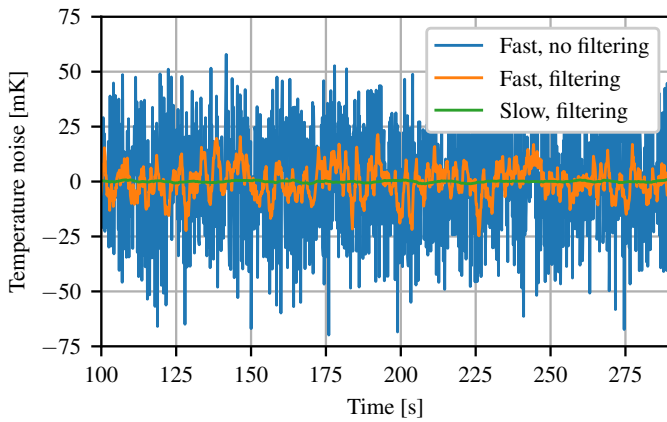


Fig. 4: Temperature acquisitions for three different settings of the Keithley 2700 precision multimeter, at thermal equilibrium (no power dissipated in the calorimeter). “Fast” corresponds to an integration time of 2 ms per acquisition, while “Slow” corresponds to 100 ms per acquisition. “Filtering” is a 10-sample moving average [10].

III. PERFORMANCE EVALUATION

A. Typical measurement

A typical example of a calorimetric measurement is given in Fig. 3: 60 s after temperature recording started, the device under test was operated for 60 s. Recording was stopped after 240 s. The slope of the orange lines in Fig. 3 correspond to heat leaking out of the adiabatic enclosure. Because ΔT is only 0.35 °C, the leaking heat flux can be considered constant for the entire duration of the experiment (i.e the orange lines can be considered parallel). Note that in some cases, the temperature inside the calorimeter could be lower than the temperature of its environment. In such cases, the orange lines in Fig. 3 would have a positive slope.

All results presented in this paper were processed in the same way: temperature recording was started 1 – 5 min before the activation of the DUT (or of the calibration resistor), and was stopped 1 – 5 min after the DUT had been stopped. The

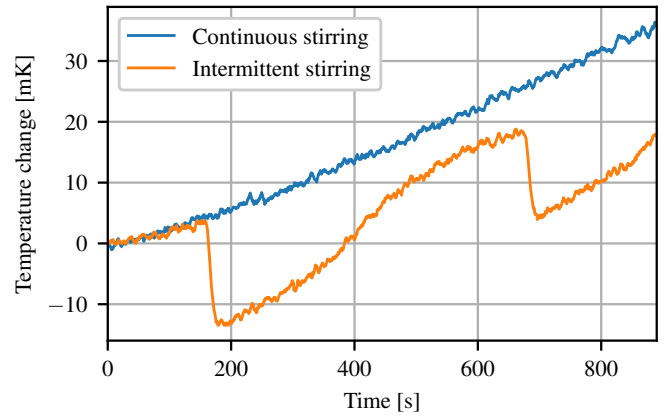


Fig. 5: Effect of bath stirring on the temperature change: When stirring continuously (blue curve), the temperature increases slowly ($\approx 2.4 \text{ mK} \cdot \text{min}^{-1}$), because of the power dissipated by the stirring system. When the stirrer is operated intermittently (orange curve, the stirrer being turned on at $t=160$ and 680 s), noticeable temperature swings occur because of the changes in the temperature distribution.

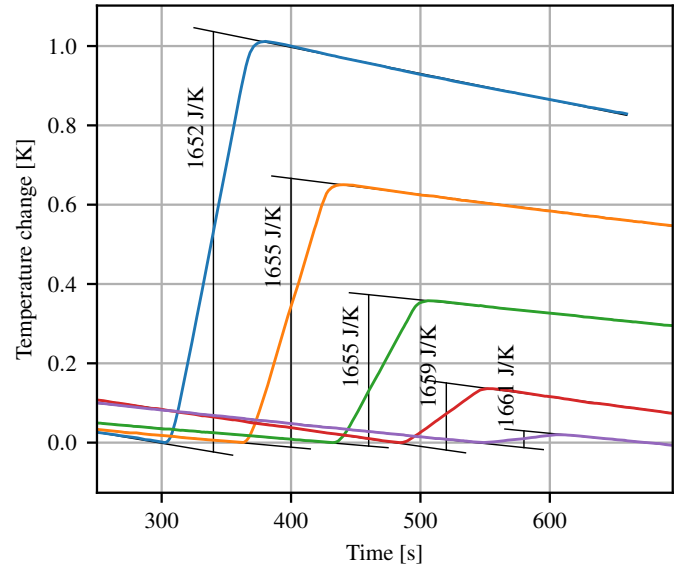


Fig. 6: Dissipation of different amounts of energy over a constant duration (60 s). The measurements are shifted horizontally and vertically for readability (the minimum temperature of each curve is considered to be 0).

temperature slopes for the periods before and after power dissipation were each fitted with a linear function and the temperature increase ΔT was calculated as the difference between the two functions at a time corresponding to the middle of the temperature rise.

B. Exploring the limits of the measurement setup

Fig. 4 illustrates temperature recordings acquired for three different settings of the multimeter. A large integration time (100 ms) and a 10-point moving average filter allow to achieve

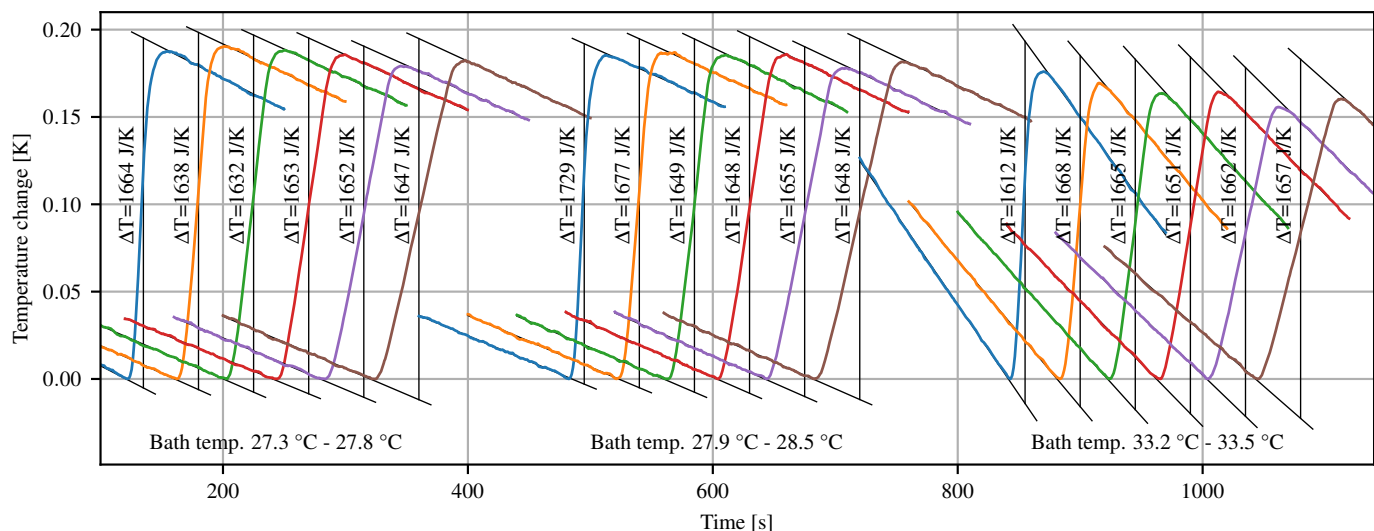


Fig. 7: Dissipation of a constant amount of energy over periods ranging from 10 s to 60 s (with 10 s increments). Three series of measurements are performed, for different bath temperatures ranging from 27.3 °C to 33.5 °C. The measurement are shifted horizontally and vertically for readability (the minimum temperature of each curve is considered to be 0).

a noise level of ≈ 1 mK, while keeping acceptable signal dynamics.

Another parameter which may affect the accuracy of the measurements is the temperature uniformity of the bath. A motorized stirrer (part #238-9822, RS) is used to homogenize temperature distribution. The blue curve in Fig. 5 shows that even without any power dissipation from the DUT or the calibration resistor, the temperature of the bath increases because of stirring (and because of the small amount of power dissipated for reading the PT100 probe). This evolution remains slow (≈ 2.4 mK \cdot min $^{-1}$, corresponding to 70 mW being injected in the bath) and occurs during the entire measurement period, so it has the same consequences as heat leakages. Discontinuous stirring (orange line in Fig. 5), however, has stronger consequences as it changes the temperature distribution in the bath. All other measurements presented in the paper were obtained with continuous stirring.

Two sets of data in which the calibration resistor was used to dissipate energy are presented in Figs. 6 and 7: in Fig. 6, various energy levels were dissipated for the same duration (60 s); In Fig. 7, the same amount of energy (330 J) was dissipated for durations ranging from 10 to 60 s.

For the constant time operation, the dissipated power levels (electrical measurement across the calibration resistor) ranged from 1.17 to 29.18 W (note that power dissipation was found to remain constant over the duration of each calibration test, indicating that thermal steady state of the resistor was reached rapidly). The heat capacitance (calculated using (2)) was found to be (1657 ± 5) J \cdot K $^{-1}$, i.e. less than 0.3 % difference between measurements. Repeated measurements (not presented here for the sake of brevity) yielded similar results.

Regarding the constant energy operation, three series are presented in Fig. 7, for slightly different bath temperature

conditions (ranging from 27 to 34 °C, hence the different slopes in the linear parts of the curves). The heat capacitance of the calorimeter is then found to be (1670 ± 59) J \cdot K $^{-1}$, i.e. a 3.5 % error. Discarding the measurements corresponding to a 10 s power dissipation (the blue curves in Fig. 7) reduces the error down to 1.4 %. This highlights the sensitivity of the setup to the duration of the power dissipation, which may be caused by insufficient stirring or poor control of the duration (see next section). On the contrary, the bath temperature, although it has obvious consequences on the shape of the curves, is not found to introduce additional error.

C. Error estimation

As presented above, the relative accuracy on the temperature measurement is estimated to be ≈ 1 mK. Another source of error, which is more difficult to estimate, is related to the linear fitting performed to calculate ΔT . Here, we estimate that this fitting adds 2 mK to the estimation, hence ΔT is supposed to be known within a ± 3 mK error margin.

Another major source of error is the control of the duration for which the DUT (or the calibration resistor) dissipates power. As this is controlled manually, a 1 s error is considered on this duration. The error associated with the electrical measurements (voltage and current across the calibration resistor) are considered negligible here.

As a consequence, the error associated with $\Delta T = 0.2$ K and a duration $t = 60$ s is $0.003/0.2 + 1/60 = 3.2$ %. Note that the error associated with t represents more than half of the total error. This could be reduced virtually to zero by using an automated control.

The measurements presented in the previous sections are consistent with the error estimation.

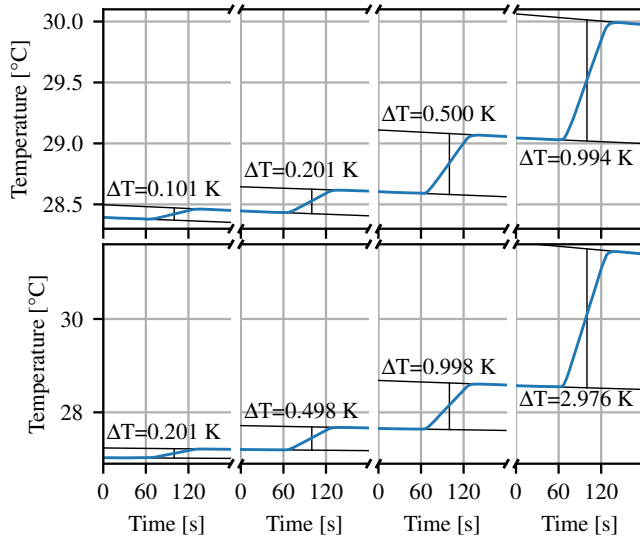


Fig. 8: Example of calibration runs: different amounts of heat are dissipated for 60 s (from $t=60$ s to $t=120$ s) using a resistor supplied with dc current. The corresponding temperature rise is monitored and used to calculate the heat capacity of the calorimeter. Top and bottom curves correspond to two different calorimeter configurations (see text).

TABLE II: Calibration data for two configurations of the calorimeter. For each series, the first line is discarded from the average calculation.

Energy (J)	ΔT (K)	C_{Th} ($J \cdot K^{-1}$)
Series 1		
16.13	0.005	3226
84.81	0.051	1663
166.3	0.101	1647
333.5	0.201	1659
831.8	0.500	1664
1675.	0.994	1685
5005.	2.997	1670
Average		$1665 \pm 1\%$
Series 2		
32.23	0.025	1289
84.48	0.062	1363
165.4	0.124	1334
268.1	0.201	1350
672.4	0.498	1350
1343.	0.998	1346
4030.	2.976	1354
Average		$1350 \pm 1\%$

D. Calibration

Fig. 8 and Tab. II present the results of two calibration runs (corresponding to two slightly different quantities of Novac 7500 in the calorimeter). Note that not all the data from Tab. II are shown in Fig. 8. It is found that very low ΔT values (< 50 mK) tend to produce inconsistent results. They were discarded for the averages calculated in Tab. II.

IV. LOSSES MEASUREMENTS ON A CONVERTER

The converter used here is presented in more details in [11]. It is a SiC-based half-bridge structure, which includes

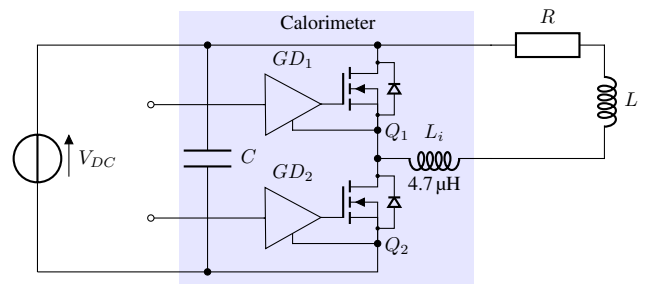


Fig. 9: Circuit diagram of converter test, highlighting the elements enclosed in the calorimeter.

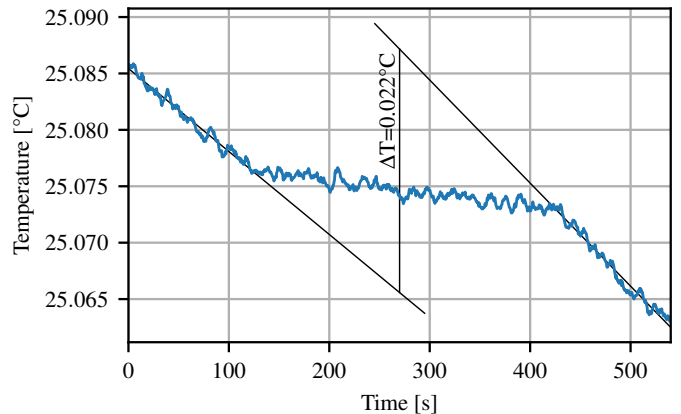


Fig. 10: Temperature transient caused by the operation of the gate driver for 300 s, without any power source connected to the SiC MOSFETs. This illustrates the sensitivity of the calorimeter setup.

decoupling capacitors, output inductor and gate drives (see circuit diagram in Fig. 9). It uses advanced integration techniques (SiC dies embedded in the printed circuit board, molded inductor), which makes measuring electrical signals difficult.

For testing, the converter was connected to an RL load and a power source. Calibration of the calorimeter was performed as described above, after the converter had been placed inside. For the results presented below, C_{Th} was found to be $1601 J \cdot K^{-1}$.

A first result is presented in Fig. 10: it corresponds to the measurement of the temperature rise due to the operation of the gate drivers only (no power source nor any load was connected to the converter). The temperature of the bath increased by $0.022^\circ C$, corresponding to a $35.3 J$ energy dissipation or $110 mW$ power dissipation over 300 s. Because of the very small temperature rise, however, large measurements errors are expected to be any better than 15% (considering a 3 mK error on the temperature measurement and a 1 s error on duration control). This measurement rather illustrates the sensitivity of the calorimeter, and demonstrates the advantage of immersing the converter in a liquid bath, as it measures the contribution of all components in the circuit.

Losses measurements performed with the operating con-

TABLE III: Losses measurements on the converter (I_{max} is the peak output current). E1 is the error estimation taking into account uncertainties on temperature and time, while only temperature uncertainty is considered for E2.

	V_{DC} (V)	R (Ω)	L (μ H)	I_{max} (A)	f_{sw} (kHz)	P (W)	E1 (%)	E2 (%)
1	100	30.	250	3.3	4	0.73	12.6	11.0
2	60	10.	250	6.	4	1.8	6.1	4.4
3	60	5.	250	12.	2	6.42	2.9	1.2
4	60	3.3	250	18.2	1.2	12.9	2.2	0.6
5	60	10.	0	6.	4	2.35	5.1	3.4
6	60	5.	0	12.	2	9.35	2.5	0.9

verter are presented in Tab. III, for different values (arbitrarily chosen) of DC bus voltage, load resistor and inductor, and switching frequency. For all tests, the converter operated during 60 s, resulting in ΔT values ranging from 27 to 480 mK.

V. CONCLUSION

The calorimetric setup presented here is very simple, and is inexpensive (≈ 500 €, excluding the multimeter). It is easy to implement, and does not require extreme precautions to ensure adiabaticity (for example, the lid of the calorimeter is a single PMMA plate with holes for the various wires). Compared to existing adiabatic calorimeters [5], it is designed for much smaller bath temperature rises (<0.5 °C vs. 5 to 20 °C). As a consequence, it is faster, and less sensitive to heat leakages.

The calorimeter uses a fluid which do not cause health or environmental concern, and can easily be adapted to suit larger or smaller converters. A conservative error estimation yields a $\pm 3.2\%$ error for a typical measurement. With suitable (i.e. automatic) control of the duration for which the DUT operates, this error can be reduced to less than 1.5%. The sensitivity of the setup is even sufficient to detect the quiescent power dissipation of the gate drivers.

This measurement method is especially suited to very integrated converters, for which direct electrical measurement is unpractical.

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