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Study of Reliability-Efficiency Tradeoff of Active Thermal Control for Power Electronic Systems

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Abstract: Active thermal control for power modules can potentially extend the lifetime of the converter. This paper investigates the trade-off between the lifetime extension or de-rating and its cost due to the efficiency reduction. A short review on the existing approaches using control to reduce thermal stress of power modules is presented. Based on a given junction temperature profile, a method to evaluate the active thermal control's trade-off is presented. The concept is validated on a laboratory setup, where active thermal control is implemented by adapting the switching frequency. A discussion of the possible lifetime extension at the efficiency's expense is finally given.

Keywords: Reliability, thermal cycling, thermal control, thermal management

I. Introduction

Power electronics is today a key component in new application fields like transportation or the electrical grid [1],[2]. Beside the advantages of a potentially better controllability and flexibility of the system, the reliability has to be guaranteed. Failures need to be minimized to reduce the associated costs. For power electronics the thermal cycling and spatial temperature gradients are affecting aging and the related failure mechanisms are well known in literature [3],[4]. The manufacturers of power electronic modules and capacitors aim at increasing the reliability of the system by improving the single components [5],[6],[7]. Usually, from the users point of view, reliability is part of the design process, which is iterated until the reliability targets are fulfilled [8],[9]. To fulfill the requirements, the system can be designed for a reduced maximum junction temperature or for higher current ratings.

It is also possible to use active thermal control to increase the reliability. The controller reduces the thermal swing of the power semiconductors and thus the thermal stress in operation. This increases the expected lifetime and consequently improves the reliability of the system. Possible implementations of active thermal control are: variable forced cooling [10],[11],[12], thermoelectric cooling [13] and electric parameters' variation [14],[15],[16]. This study focuses on active thermal control by means of the latter one.

The control of the temperature by means of active thermal control leads to the problem of increased losses and reduced efficiency of the system. Since efficiency directly influences the operation cost, an estimation of the reduced system efficiency is mandatory before the system is designed and a thermal controller is tuned. This estimation has to be based on the system design and on the real operation of the module, referred to as mission profile. Several works calculate the temperature profile of the system based on the mission profile and the system parameters [17],[18],[19],[20],[21]. The procedure is well known and several simulations have been presented, which analyze different applications. In these studies critical ambient and operating conditions have been detected, which limit the lifetime of the power semiconductors [22].

This work assumes the temperature profile due to the operating condition as a starting point to investigate the potential for active thermal control. Based on this junction temperature profile, a qualitative method is introduced to analyze the tradeoff between reduced thermal stress and increased system loss. For the quantification of the conflicting goals, a system without thermal control and with thermal control are considered. The implemented thermal controller applies an adaptation of the switching frequency in a full bridge converter to show the resulting lifetime enhancement or possible de-rating and the related increase in energy loss.

In section II a review on active thermal control in literature is given, while in section III guidelines are given how the potential of active thermal control can be estimated. Section IV presents a thermal controller design and shows the results of the controller on a laboratory setup. Finally, in section V the results are concluded.

II. Review on Active thermal control

In order to achieve high power density and low leakage inductance, semiconductors are assembled in power module configurations. To ensure electrical insulation and good heat dissipation at the same time, several layers of different materials need to be used, which is usually done in the DBC (Direct Bonded Copper) structure [23]. These materials obtain different coefficients of thermal extension [24],[25] and consequently temperature gradients and temperature swings caused by the losses of the power semiconductors affect mechanical strain within the module and especially at the interconnections. This mechanism is regarded as the main reason for power modules aging [1] and leads to failures. At the bond wires, which interconnect different chips, the state of the art soldered connection can be improved with improved interconnections, i.e. sintered connections [26]. Also the gel that fills the power module, used to reduce the risk of corrosion and environmental influences [27], can be source of aging, in particular due to the presence of partial discharges [28]. However, apart from vibration, cosmic rays and humidity caused failures, the failure mechanisms are dependent on the junction temperature and especially the temperature swing [3].

A reduction of the temperature swing increases the lifetime of the power semiconductors. If this is achieved with control actions, it is referred to active thermal control. There are several possibilities to apply active thermal control approaches on different layers of the overall control system, addressing different time periods of thermal cycles, which is summarized in Fig. 1. The short thermal cycles can be addressed with the loss control in the gate driver or the modulator, i.e. with the placement of pulses or the control of the switching frequency. These controllers are application invariant and can only be limited by regulations of hardware limitations. While the loss control acts directly on the hardware, the power electronics controller can modify the electrical parameters (voltage/current), while system controllers can implement longer-term actions by performing the energy managing/routing. In the following, examples from literature for loss control and energy routing are presented.

a. Control of power losses (stress reduction)

Several approaches are reported in literature where the frequency of the pulse width modulation (PWM) for drive application is changed in order to limit the maximum junction temperature [29],[30],[31]. The

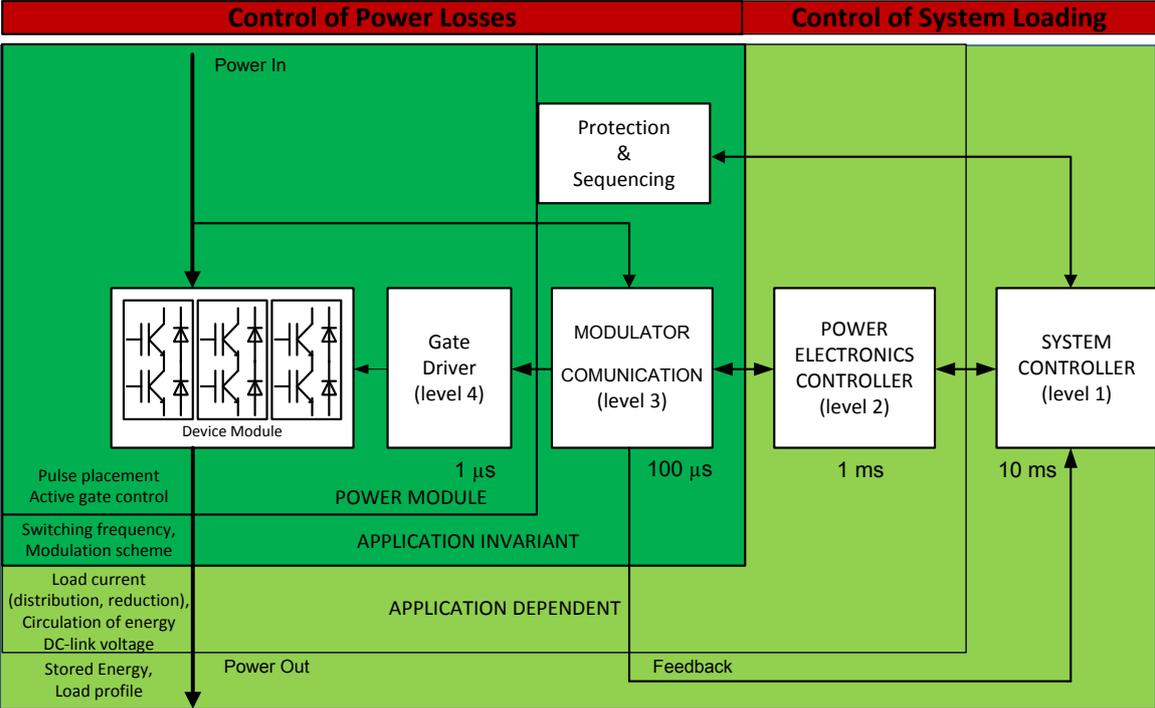


Figure 1: Active thermal controllers in different layers of a system.

same technique is adopted in [15], where the aim is reducing the thermal cycling. The thermal controller can also influence multiple parameters, i.e., maximum current and switching frequency, while system constraints by means of an electrical machine are taken into account [32].

Changing between continuous and discontinuous 60 degree PWM to reduce losses was also applied in [33],[34], but needs to be considered carefully for application because of the different impact on the current ripple. A loss reduction can also beneficially affect the lifetime by decreasing the average operating temperature [35]. Furthermore, for grid-connected applications, the modulation strategy was modified to address specific problems, like the low voltage ride through (LVRT) [36], which normally increases the stress of the anti-parallel diodes of the power modules.

The smallest accessible time constants are achieved by gate driver control, which was applied in [37],[38],[39],[40], mainly to balance the stress between parallel semiconductors. However, the potential to reduce the thermal cycling by increasing the power losses was also exploited.

b. Control of system loading (Stress redistribution)

If the system is composed of multiple cells or multiple converters, additional high-level controls can be implemented. In [41] commutation counting was performed to select the cell to switch in a cascaded H-bridge structure. Intelligent management of the power in micro-grid has also been an object of interest in [42]. In [43] the control of parallel converter is optimized for lifetime extension, while the applied lifetime model increased the thermal stress for the components. Another approach to control the thermal cycling with multiple grid-connected inverters in a wind farm was proposed in [44], where reactive power was circulated in order to prevent excessive cooling down of the power modules during abrupt output power changes. For photovoltaic application, a maximum power point tracking algorithm has been proposed, which does not only consider the harvested energy, but also considers the damage caused by thermal cycling during fast changing irradiation [45]. In a modular multilevel converter (MMC) with redundant cells, the effect of the transition to the cold reserve was also analyzed [46] and could be extend to junction temperature control with the reserve cells.

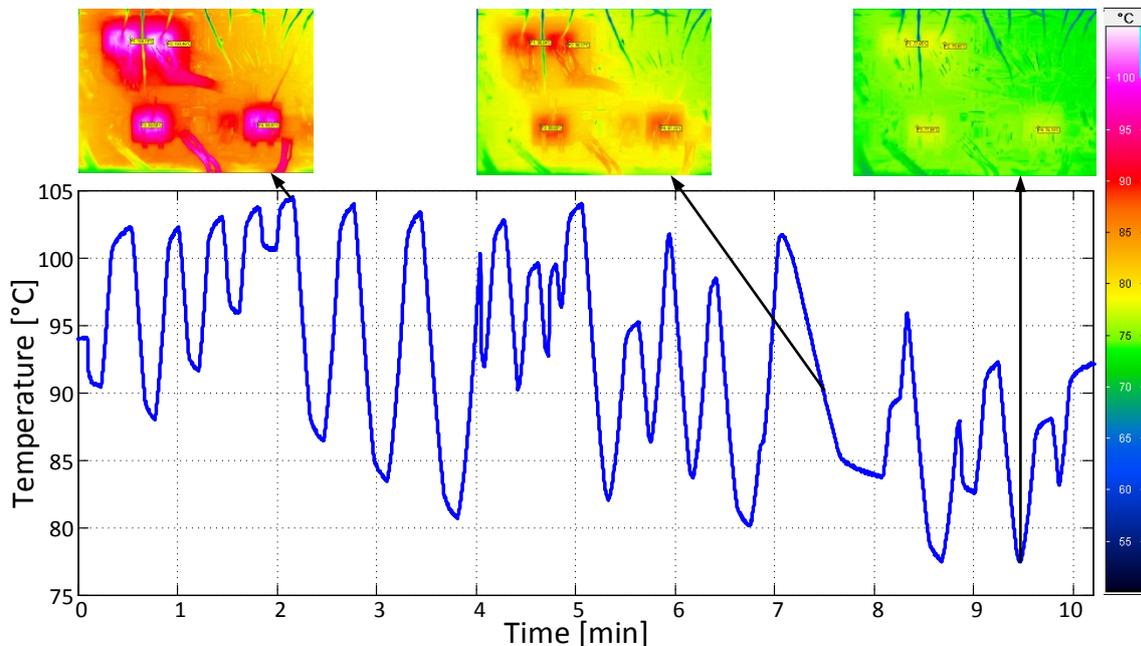


Fig. 2: Junction temperature profile and infrared camera images for different conditions in a full bridge converter.

III. Cost and benefit analysis for active thermal control

Depending on the mission profile, a lifetime extension of the power module with active thermal control can be achieved with associated costs in terms of additional losses, higher current ripple or higher stress for passive components. Remarkably, the potential and the cost-benefit tradeoff of active thermal control varies with the mission profile and the thermal characteristics of the power converter system. The determination of the related optimum is a difficult topic, especially if no known periodic power cycle is applied, such as in renewable energy applications, where the weather is unpredictable. To overcome the complex interaction between mission profile and thermal behavior, it is suggested to start the analysis with a given junction temperature profile as shown in Fig. 2, which can either be measured or simulated. An indication of the lifetime enhancement is shown in (1), where the cycles to failure for

$$N_{f1} = K \cdot (\Delta T)^{\beta_1} \cdot e^{\frac{\beta_2}{T_{j,av}+273}} \cdot t_{on}^{\beta_3} \cdot I_1^{\beta_4} \cdot V^{\beta_5} \cdot D^{\beta_6} \quad (1)$$

a specific IGBT is expressed by various influencing factors, such as the thermal cycles magnitude ΔT , the average junction temperature $T_{j,av}$, the power on-time t_{on} , the blocking voltage V , the diameter of the bond wire D and the current per wire I_1 .

Beside the well-known dependence of the lifetime to the thermal cycles, this equation can be used to describe the relationship between lifetime and current rating. Considering the topic from another point of view, the goal of active thermal control can shift to increased expected lifetime to a reduced current rating per bond wire I_1' under the constraint of equal lifetime expectation. This is shown in (2) for a similar number of bond wires and visualized in Fig. 3 with the additional indication of a higher or lower

$$\frac{N_{f1}'}{N_{f1}} = \left(\frac{I_1'}{I_1} \right)^{-0.717} \quad (2)$$

number of bond wires [47].

Beside the lifetime enhancement of active thermal control, the reduced efficiency has to be considered. An accurate derivation requires taking the dynamic behavior of the thermal impedance into account. In (3) the derivation is shown for the junction temperature $T_j(t)$ in dependence of the starting temperature $T_{j,0}$ added to the convolution integral of the losses $P(t)$ and the derivative of the thermal impedance $\dot{Z}_{th}(t)$ [48]

$$T_j(t) = T_{j,0} + \int_0^t P(\tau) \dot{Z}_{th}(t - \tau) d\tau \quad (3)$$

Since this equation is too complex to analyze the mitigation of power losses and thus for the efficiency, this work proposes to only give a qualitative estimation based on the distribution of thermal cycles.

An effective way to analyze the potential of an application based on a thermal profile is to identify the thermal cycles, which are most responsible for the degradation. This is done by applying thermal cycle counting, which leads to a histogram with the thermal swing ΔT_j , the time period of the cycle T , the mean temperature of the thermal swing $T_{j,mean}$ and the number of cycles in a defined interval of these variables. Even if there are several ways to count thermal cycles, in reliability literature Rainflow counting [49] has been preferred and it is also applied in this case study. The 10 min temperature profile of a power semiconductor during operation in Fig. 2 is used to present the proposed method. The Rainflow histograms for the aforementioned temperature profile are derived. The x-axis displays the cycles period T , the y-axis the thermal swing ΔT_j and the z-axis the number of thermal cycles N . This is shown in Fig. 4 (a). Here, thermal cycles with a magnitude lower than $\Delta T_j < IK$ are neglected. The most severe cycles have high thermal swings, which make their reduction most important [3]. However, beside the magnitude, the time period is important, because a long period affects high additional losses for the compensation of the cycle and thus a high drop in efficiency. According to this this, high potential for a cost effective thermal controller design is existing for profiles with high thermal swings, which occur in short time periods.

In the second step Rainflow counting is repeated based on $T_{j,mean}$ instead of the time period. This identifies if the thermal controller should rather reduce or increase the losses for the compensation of the thermal cycles. In general, both ways are possible, but regulations of device ratings might set limits. If no limitation is violated in case of high average temperatures the losses should be reduced and in case of low average temperatures, the losses should be increased. In Fig. 4, (b), this Rainflow histogram is

shown. These histograms can be used to estimate the lifetime of the power semiconductors with a simplified form of (1):

$$N_{f1} = K \cdot (\Delta T)^{\beta_1} \cdot e^{\frac{\beta_2}{T_{j,av}+273}} \quad (4)$$

This histogram can be used to estimate the lifetime of the power semiconductors with a simplified form of (1), which is shown in (4). Since this equation is only valid for a specific ΔT , the Palmgren Miner rule is commonly applied (5).

$$\sum_{i=1}^k \frac{n_i}{N_i} = c \quad (5)$$

If the sum of the number of cycles n_i divided by the lifetime N_i in the stress range i exceeds c the module fails. This expression is known to lack of precision, because it assumes linear damage accumulation. Nevertheless, it is applicable with the power cycling data commonly published by the module manufacturers, which makes it a practical solution in combination with the Rainflow histograms.

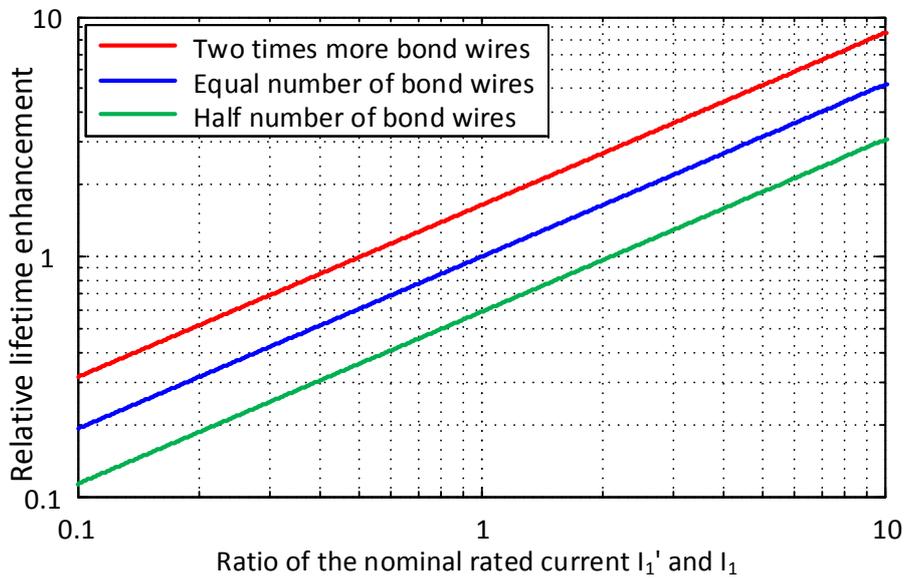


Fig. 3: Power module lifetime dependence on current rating and number of bond wires.

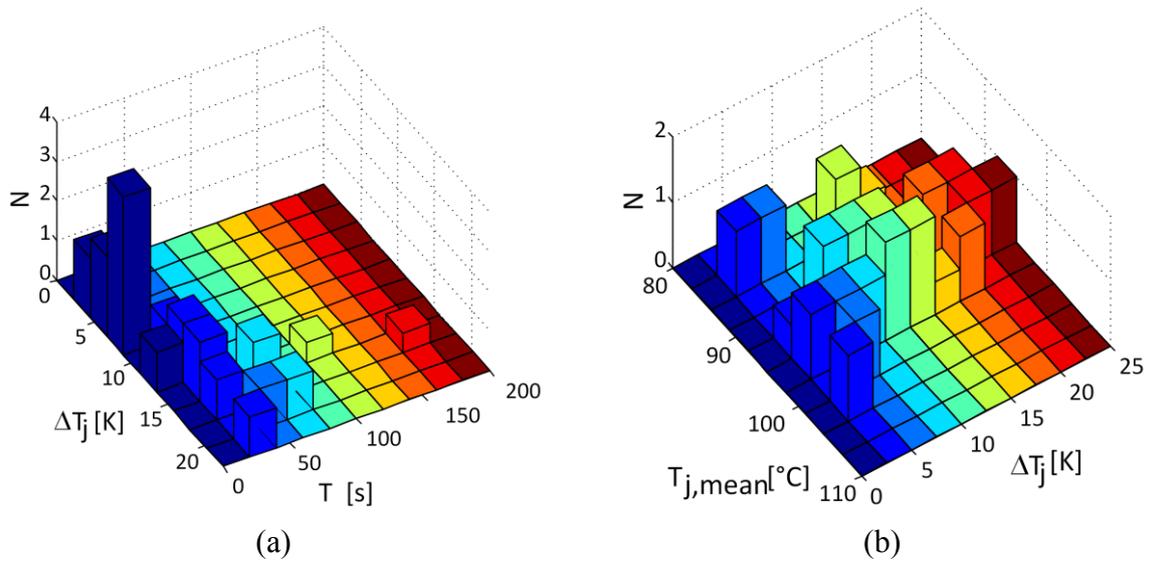


Fig. 4: Rainflow Counting of the thermal cycles: a) in dependence of the cycles period and magnitude, b) in dependence of the cycles mean temperature and magnitude.

IV. Study on laboratory setup

For demonstration of the concept in a study case, a mission profile composed by active and reactive power profiles is considered and simulated with constant switching frequency $f_{sw} = 10 \text{ kHz}$, constant voltage $U_{dc} = 300 \text{ V}$ and constant output frequency $f = 50 \text{ Hz}$ on a full bridge IGBT converter built with a Danfoss module (DP25H1200T101667-101667, $V_{ce} = 1200 \text{ V}$, $I_c = 25 \text{ A}$). An equivalent circuit is shown in Fig. 5 (a) and a photo of the measurement setup in Fig. 5 (b) with a high speed infrared camera and a power analyzer. The resulting temperature profile is shown in Fig. 2. To reduce the temperature fluctuations, a thermal controller is designed as shown in Fig. 6 to vary the switching frequency between $10 \text{ kHz} < f_{sw} < 30 \text{ kHz}$.

Based on the electrical parameter, the losses are derived and filtered by a low pass filter. A lookup table sets the switching frequency, which increases for decreasing losses. Consequently, during steady state operation and during increased output power the losses are being minimized. Appropriate tuning of this controller is essential and explained in [50], but will not be investigated deeper in this work.

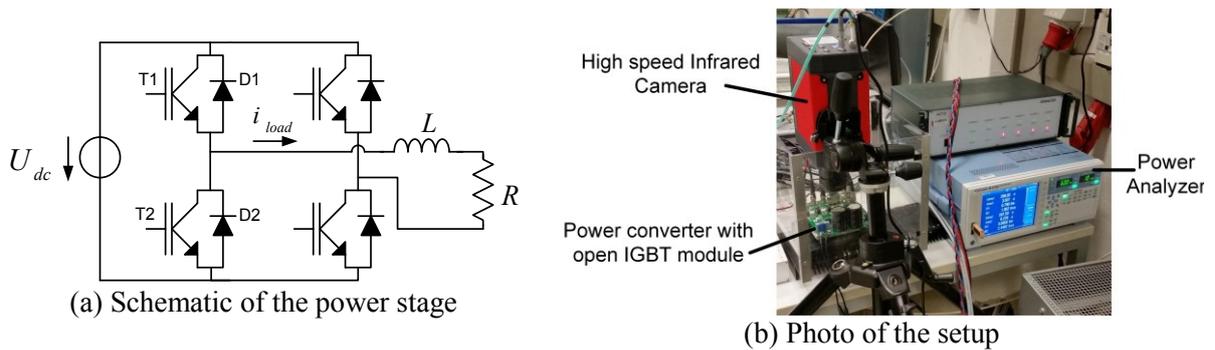


Fig. 5: Setup with a power converter equipped with an open module infrared camera temperature measurement.

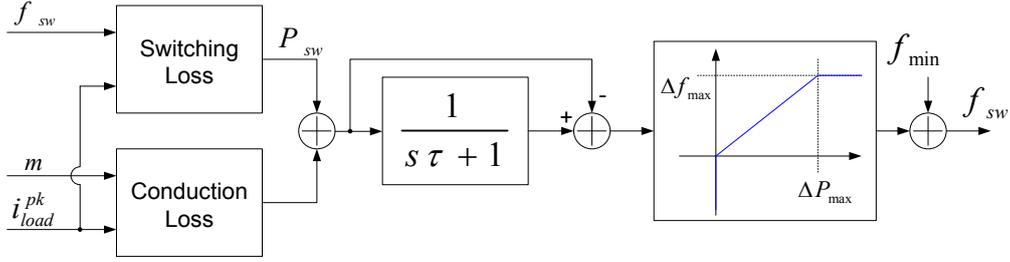


Fig. 6: Controller diagram.

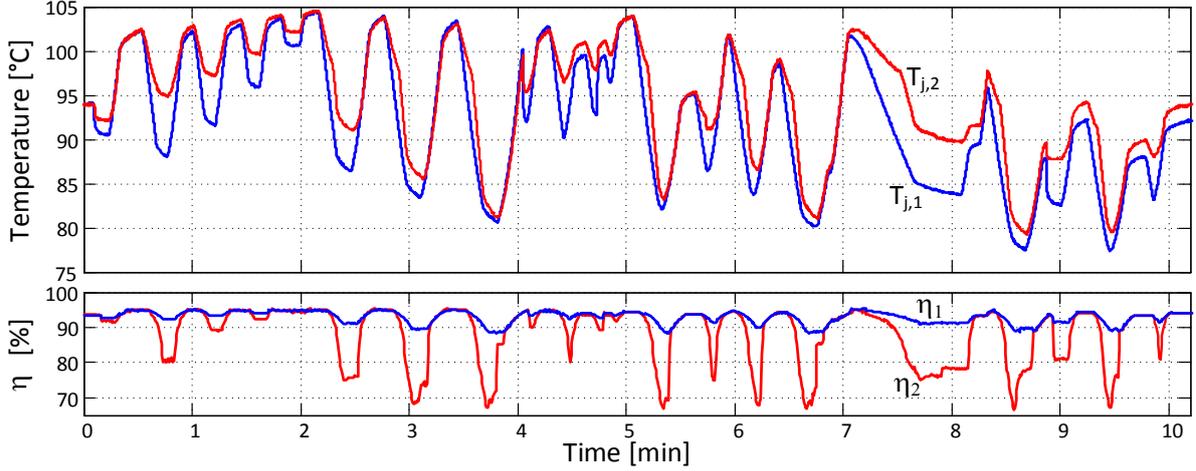


Fig. 7: Measured temperature and efficiency profiles: $T_{j,1}$ without thermal control and $T_{j,2}$ with active thermal control.

The same mission profile of the previous case is now applied to test the thermal controller and results in the temperature profiles of Fig. 7, where also the measured efficiency is shown for both cases. $T_{j,1}$ is the recorded temperature measurement without thermal control and $T_{j,2}$ is the temperature measurement with active thermal control. From the figure it can be seen that several thermal cycles are significantly reduced in magnitude, while others are affected less. The efficiency without thermal control is between 88.5% and 95%. Instead, for the active thermal control it is varying between 67% at decreasing low power and 95% for full power. For a deeper analysis of the thermal cycles and thus the reliability, the Rainflow histograms are shown in Fig. 8. In Fig. 8 (a) the thermal cycles are reduced in magnitude compared to the histogram without thermal control, while the periods of the cycles show only few changes. In Fig. 8 (b) it can be seen that also the average temperature of the cycles has increased. In total fewer cycles are counted than in the previous temperature profile. For the comparison between the cases with thermal control and without thermal control, the lifetime consumption of the profiles is derived as in (4)-(5) with the parameters in [51]:

$$N_f = 4.48 \cdot 10^{14} \cdot (\Delta T_j)^{-5.024} \cdot e^{(-T_{j,\text{mean}} + 77.5) \cdot 0.0555} \quad (6)$$

The data of this experiment is furthermore used to apply the proposed method of section III and the results are shown in Tab. 1. The overall efficiency of the profile is shown for both cases, whereby the thermal controller reduces the efficiency by 1.1%. Remarkably, the cumulated damage with thermal control c_{ctr} is estimated to be 72% of the damage without thermal control for the expense of 9.7% higher loss energy. This can either be used to achieve a lifetime enhancement of 39% or to apply it for de-rating as shown in Fig. 3. De-rating leads to power semiconductors with 78 % current rating compared to no thermal control under equal expected lifetime.

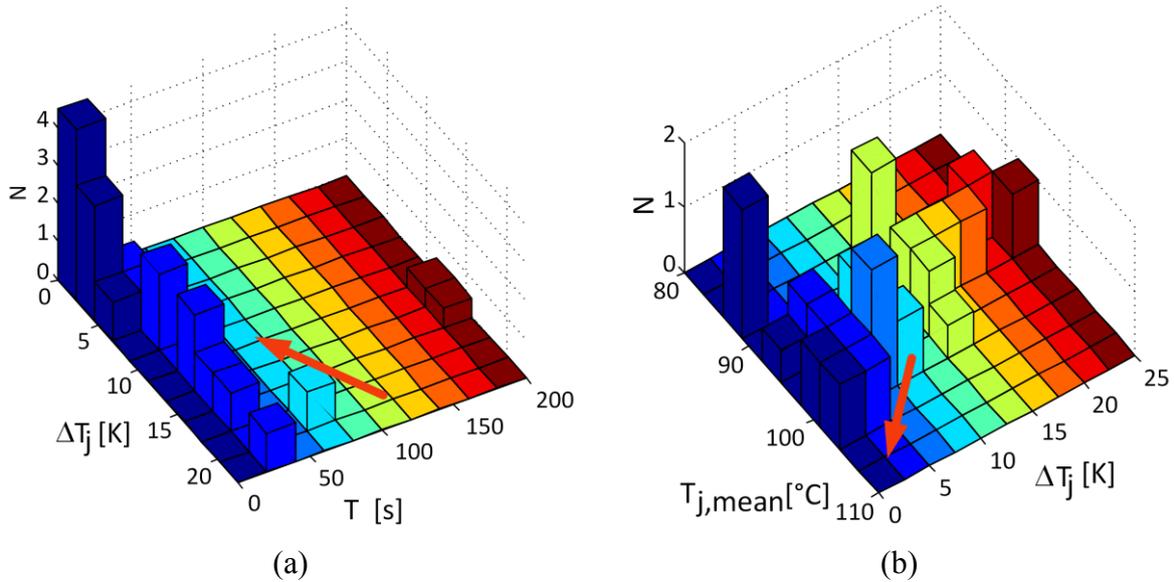


Fig. 8: Rainflow Counting of the thermal cycles after applying active thermal control: a) in dependence of the cycles period and magnitude, b) in dependence of the cycles mean temperature and magnitude.

	Without thermal control	With thermal control
Efficiency η [%]	93.9	92.8
Cumulated damage c	$c = 1.272 \cdot 10^{-7}$	$c_{ctr} = 9.11 \cdot 10^{-8} \approx 0.72 \cdot c$
Lifetime enhancement [%]	0	39
Measured relative losses [%]	100	109.7
Current rating for similar lifetime [%]	100	78

Tab. 1: Comparison of the profile with thermal control and without thermal control.

V. Conclusion

This work has reviewed several active thermal control approaches proposed in literature to reduce the thermal stress of power electronic systems. A method by means of Rainflow counting been introduced to estimate the potential improvements and the related potential for the active thermal control. A study case where switching frequency variation is used to control the losses is analyzed with the proposed tools. The adopted active thermal controller has reduced the accumulated damage by 28% at the expense of 9.7% higher losses. Consequently, for an expected efficiency reduction of 1.1%, the lifetime of the system is significantly increased (by 39%) or alternatively, the current rating can be reduced to 78% under the same lifetime conditions.

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