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Active Thermal Control of Isolated Soft Switching DC/DC Converters

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Abstract—Power Semiconductors undergo thermal stress during operation, which is caused by thermal cycling. This refers to heating up and cooling down of the junction temperature and leads to aging and finally failures. Active thermal control can reduce the thermal stress of power semiconductors by regulating the power losses. Most algorithms proposed so far are only applicable to hard switching power converters and implement a regulation of the switching frequency, which is not applicable for the isolated DC/DC converters. This work proposes to regulate the duty cycle of the DC/DC converter to control the semiconductor losses, aiming at influencing the consequent thermal stress. The proposed algorithm is analyzed analytically and a thermal controller is designed, which is capable of reducing thermal cycles during operation without prior knowledge about the mission profile. The capability and the limitations of the proposed algorithm are demonstrated with simulations and the effectiveness is validated on a laboratory prototype with junction temperature measurement.

I. INTRODUCTION

Isolated DC/DC converters are used in new application areas like offshore wind turbines, electric aircraft and solid-state transformers [1]. The necessity of the isolated DC/DC converters comes with the need for flexible voltage level adaption and galvanic isolation [2], [3]. The new applications challenge the engineers to design reliable and cost effective power converters [4], whereby thermal stress is still considered as one of the main reasons for wear out and failures of power electronic modules [5].

Active thermal control offers an opportunity to reduce the thermal stress by means of software by regulating the power losses [6]. This reduction of thermal stress comes without an increase in the manufacturing costs or footprint. Thermal control algorithms have been proposed for electric drives, where severe thermal cycling has been detected and regulated during low speed and high torque [7]. For a reduction of the thermal stress, the existing algorithms apply a variation of the switching frequency. This idea has been extended to the control of the switching frequency for regulating the thermal fluctuations caused by the mission profile during normal converter operation [8]. Further active thermal controllers have been proposed based on circulating the reactive power [9] or rerouting the power in redundant paths [10]. However, none of these thermal controllers is applicable to the emerging high power DC/DC converters. The commonly used dual active bridge (DAB) or even multi pole DC/DC converters, such as the Quadruple Active Bridge (QAB) [11] operate under soft switching conditions and interact with a medium frequency

transformer. A reduction of the switching frequency increases the flux in the transformer, leading to saturation, while an increase of the switching frequency reduces the power and thus the losses of the power semiconductors, while the magnetizing losses of the transformer are increased. Preliminary studies did show that in a three-stage smart transformer structure, the isolated DC/DC converter is subjected to a medium thermal stress, that can still be critical [12]. For improved reliability, active thermal control can be applied. However, considering a switching frequency variation in the the system design, the transformer needs to be overdesigned. This increases the system size and costs, which is not acceptable and calls for an specifically tailored algorithm for the application of isolated DC/DC converters.

This work proposes to control the duty cycle of the isolated high DC/DC converter, which is operating with phase shift modulation for regulating the junction temperature of the power semiconductors during operation. When the power decreases, the duty cycle is reduced, which increases the peak current. Instead, for increasing power and during constant operation conditions, the converter is operated with minimal losses. As a consequence, the approach does not require knowledge of the profile, but compensates thermal cycles shorter than the time periods it is tuned for. The strategy to reduce thermal cycling in operation is demonstrated in simulations and validated on a DAB converter prototype with an open IGBT module and junction temperature measurement. The need for the algorithm is stated and the capability of the proposed algorithm to reduce the thermal swing during operation is demonstrated.

The operation principle of isolated DC/DC converters is illustrated for a dual active bridge in section II, while the third section introduces the applied control algorithm and its controller structure. Section IV shows simulation results to demonstrate the principle for a power cycle. In section V these results are reproduced on a laboratory setup and finally, the the conclusions are made in section VI.

II. DUAL ACTIVE BRIDGE AND MULTIPLE PORT DC/DC CONVERTERS

The dual active bridge has been proposed as an isolated DC/DC converter with high input/output ratio and bidirectional power flow capability. The equivalent circuit of the DAB, consisting of the medium frequency transformer and two full bridge converters, is shown in Fig. 1 (a). A possible

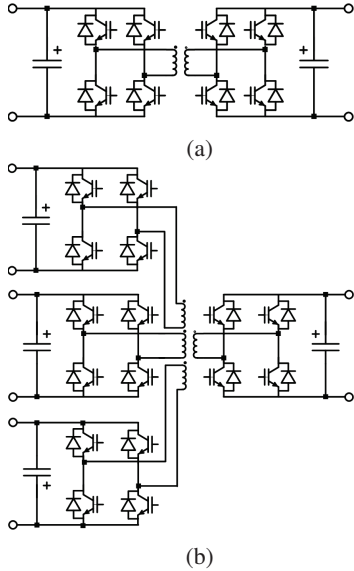


Fig. 1: Isolated DC/DC converter topologies: (a) Dual active bridge (DAB), (b) Quadruple active bridge (QAB).

extension of the DAB can be done by adding multiple windings on the transformer, which enables power transfer between all ports of the converter. Exemplary, this is shown for the extension to a Quadruple Active Bridge QAB with three ports on the medium voltage side in Fig. 1 (b). While the dual active bridge has been proposed for battery systems, the QAB has been proposed for voltage level adaptation from high voltage to lower voltage as it is required in Solid-State-Transformer applications.

The current and voltage waveforms of the DAB converters with the commonly applied phase shift modulation are shown in Fig. 2. Primary and secondary full bridge switch with a constant duty cycle of 0.5, while the phase shift determines the direction and the quantity of the transferred power. The power transfer from primary side to secondary side can be described with (1) in dependence of the primary side voltage, V_P , the secondary side voltage V_S , the switching frequency f_s , the leakage inductance of the transformer L , the transformer ratio n and the phase shift $\phi_{i,k}$ between primary and secondary side.

$$P = \frac{V_p \cdot P_s}{2\pi f_s L n} \phi \left(1 - \frac{\phi}{\pi}\right) \quad (1)$$

The voltage control of the DAB is done with an PI controller, which is setting the phase shift for the applied phase shift modulation as shown in Fig. 3. In case of multiple bridges, the balancing of the secondary cells needs to be performed, which can be done by control of the phase shift between the different secondary bridges.

III. THERMAL STRESS REDUCTION OF THE DAB CONVERTER

Power semiconductors suffer from thermal stress, which is caused by heating up and cooling down of power semicon-

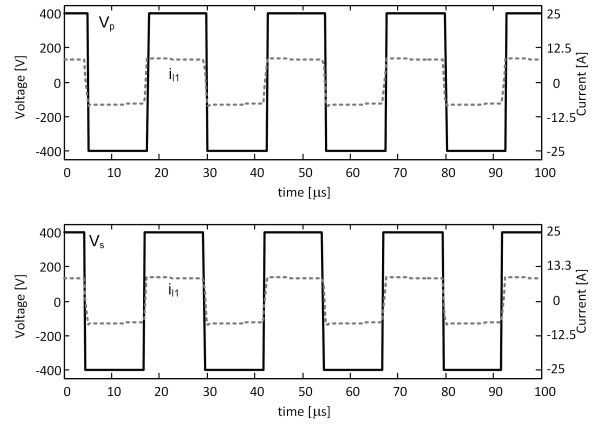


Fig. 2: Operation of the DAB with phase shift modulation.

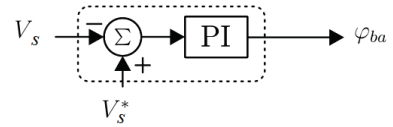


Fig. 3: Phase shift control of the DAB converter.

ductors during operation. This section introduces a model for lifetime estimation of power semiconductors, describes why the switching frequency adaptation is no appropriate solution for the problem and finally proposes a new active thermal control algorithm.

A. Lifetime estimation of power semiconductors

Power semiconductors are failing due to several mechanisms. The most common failures due to wear out are bond wire lift off and chip solder fatigue, whereby both mechanisms are caused by thermal cycling of the power semiconductors. This thermal cycling is referring to cooling down and heating up during operation. The thermal swing is causing mechanical stress between layers with different coefficients of thermal extension, commonly found in power electronic modules. The thermal cycling capability of power semiconductors is quantified by the manufacturer in dependence of the number of junction temperature swings N_f with the magnitude ΔT_j and the average junction temperature $T_{j,av}$ as shown in (2) with the fitting parameters a_1, a_2, a_3, a_4 .

$$N_f = a_1 \cdot (\Delta T_j)^{a_2} \cdot \exp((T_{j,av} + a_3) \cdot a_4) \quad (2)$$

The mission profile, the system design and particularly the cooling system determine the number and the magnitude of the thermal cycles, which the system is undergoing. Counting of these thermal cycles is commonly done by means of Rainflow counting, which is extracting the maximum thermal swings from the temperature profile of the power semiconductors. These cycles are used to derive the consumed and the remaining lifetime of the power semiconductors with linear damage accumulation. The accumulation is expressed with (3). In this

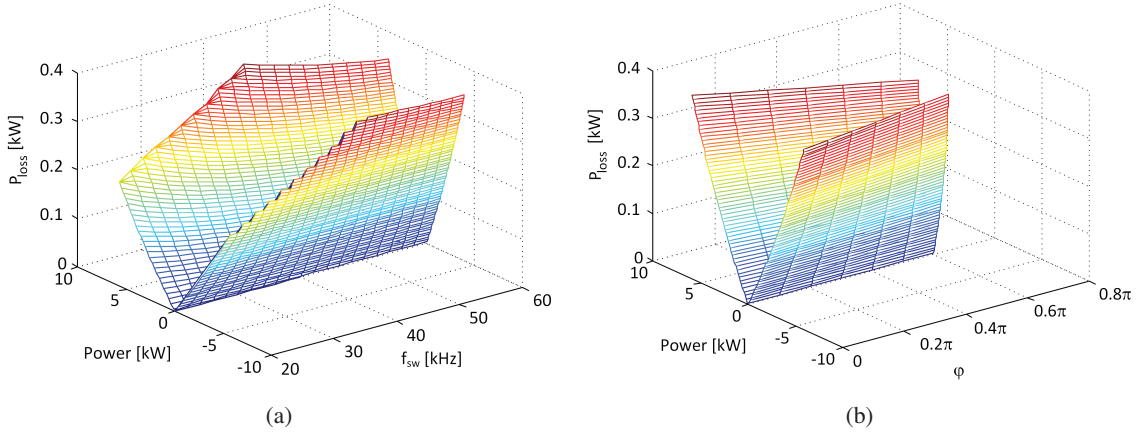


Fig. 4: Demonstration of the losses of the DAB for bidirectional power flow with the parameters of Tab. I: (a) for the control of the switching frequency $f_{sw} = [20, 60]kHz$ (b) For the proposed thermal controller with $\phi = [0; 0.6 \cdot \pi]$.

equation n_i is the number of cycles in the stress range i with the number of cycles to failure N_i . As $c \geq 1$, the device fails.

$$\sum_{i=1}^k \frac{n_i}{N_i} = c \quad (3)$$

B. Active thermal control for isolated DC/DC converters

With respect to the described lifetime model, a reduction of the thermal swing can increase the lifetime of power semiconductors. The most commonly applied algorithm in literature is to control the switching frequency for the regulation of the junction temperature. If no snubbers are used, the DAB converter's transistors operates in ZVS turn-on and hard turn-off. This causes switching losses, which are dependent on the switched current, the voltage, the switching frequency and the power semiconductor characteristics. However, the control of the switching frequency is not a solution for the application in isolated DC/DC converters, which is demonstrated in Fig. 4 (a). The losses for the control of the switching frequency are shown in dependence of the power, whereby similar colors indicate similar losses. It can clearly be seen that an increase of the switching frequency reduces the transferred power. A decrease of the switching frequency is limited by the current rating of the power semiconductors and the rated transformer flux. Consequently, for a reduced switching frequency, the maximum phase shift between primary and secondary side cannot be reached without overloading components and the system needed to be highly overrated to apply this algorithm.

C. Description of the proposed active thermal control algorithm

Instead of controlling the switching frequency, this work proposes to control the duty cycle of the converter due to the fast reaction time and simple implementation. The current and voltage waveforms for the modification of the duty cycles are demonstrated in Fig. 5 and described in the following. The reduction of the duty cycle requires a higher current for transferring the same power and causes higher switching losses

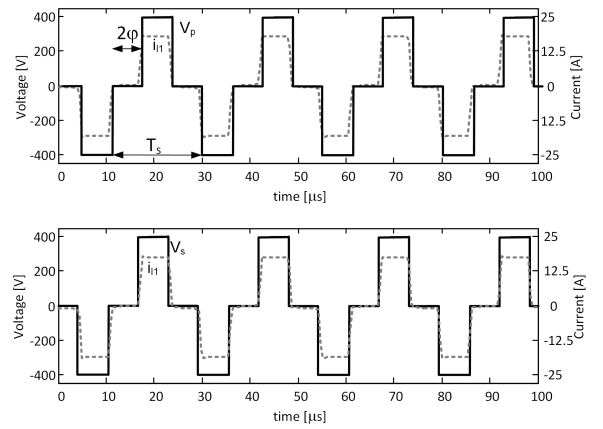


Fig. 5: Voltage and current waveforms for the proposed duty cycle control.

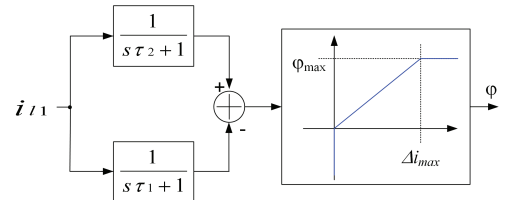


Fig. 6: Control diagram of the QAB converter.

of the power semiconductors. In Fig. 4 (b) the dependence of the power semiconductor losses is shown for different power and duty cycles with the parameters of Tab. I, showing how the losses can be controlled in all operation points. The losses can be controlled for a wide range, making this a promising solution. The only limitation is the maximum current which can flow in the inductor for a requested power transfer. For a limitation of the reactive power, the maximum ϕ is set to $\phi \leq 0.3\pi$. In efficiency optimized systems, the phase shift is usually limited to $\phi_{max} \leq 0.18 \cdot 2\pi$.

The control of the junction temperature needs to be done

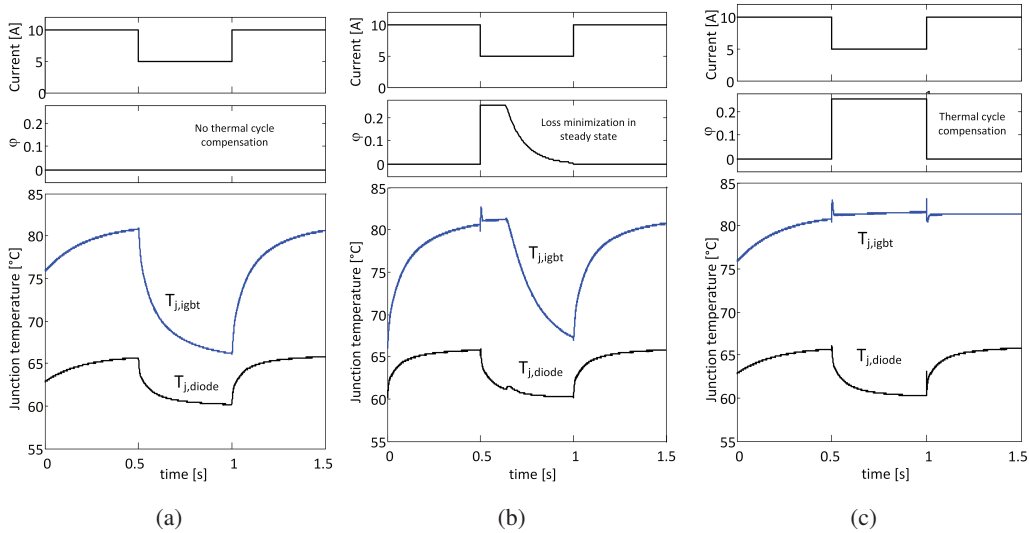


Fig. 7: Simulation results: Power cycle of one power semiconductor in an QAB: (a) Without thermal control, (b) With thermal control and full cycle compensation, (c) With thermal and demonstration of loss minimization in steady state conditions.

Parameter	Value
Rated Output Power	$P = 6kW$
LV DC link voltage	$V_p = 400 V$
MV DC link voltage	$V_s = 400 V$
Switching frequency	$f_s = 20 kHz$
Leakage inductance	$L = 22.5 \mu H$
Transformer turn ratio	$n = 1 : 1$
IGBTs	<i>Infineon fs50r12kt4_b11</i>

TABLE I: Simulation parameters of the QAB

by controlling the power semiconductor losses, which are affecting the temperature variations. If the losses are kept constant for all components, there is no thermal swing, which is stressing the power semiconductors. In (4) the dependence of the switching losses on the electrical parameters is expressed in an approximated form for an IGBT and in (5) the conduction losses are expressed. The losses are dependent on the semiconductor current I , the voltage V and the turn on time, expressed with the duty cycle D .

$$P_{SW,T} = f(I, U^{1.3}) \quad (4)$$

$$P_{Cond,T} = f(I^2, I, D) \quad (5)$$

With the proposed duty cycle control, the peak current can be increased, which affects higher switching losses and conduction losses. The active power remains constant, while the power factor is reduced. In normal operation with phase shift modulation, the current magnitude is the only quantity which is varying and consequently, it is the only influencing factor on the power semiconductor losses. A reduction of a potential junction temperature swing, occurring for decreasing current magnitude, requires to increase the peak current. In order to have another parameter, which is influencing the power semiconductor losses, the duty cycle is modulated.

For simplicity and the target of not using direct junction temperature measurement controller, the magnitude of the current is used as shown in Fig. 6. The current is low pass filtered to detect power variations, whereby the controller has to be tuned for two different goals:

- Compensation of thermal cycles imposed from the mission profile
- Reversal to normal operation with minimal losses in long term steady state operation.

The tuning of the controller depends on the operation conditions and requires knowledge of the mission profile. The first low pass filter with the time constant τ_1 detects the power variations as explained and enables to revert to normal operation after the reduction of power is permanent. This is important because the system should operate with maximum efficiency, when a reduction of thermal stress is disproportionate with respect to additional losses for the compensation of a thermal cycle. For an appropriate tuning of τ_1 , the mission profile should be known and evaluated. The second low pass filter needs to be tuned to delay the controller response to a variation in the current. Otherwise, a fast controller response might cause an increase in the junction temperature and thus an additional increase of the thermal swing. For the tuning of this parameter, the time constants of the cooling system need to be known.

IV. SIMULATION RESULTS

To demonstrate the capability of the proposed controller, a system with the parameters of Tab. I is simulated. The low pass filter is tuned with $\tau_1 = 0.1 s$ and $\tau_2 = 0.002 s$ to compensate thermal cycles with periods smaller than $100 ms$. Simulations are run for $1.5 s$ with a power cycle for $0.5 s$ during which the power is decreased. First, this is run without the thermal controller to demonstrate the resulting thermal swing, and the results are shown in Fig. 7 (a). The step in the current causes

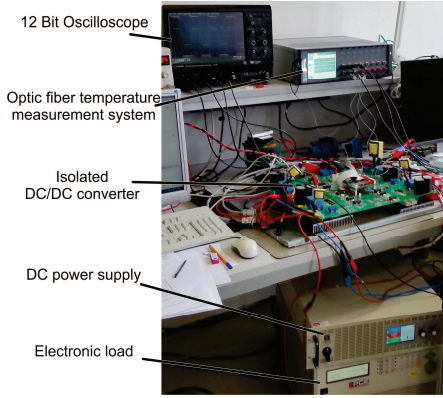


Fig. 8: Picture of the laboratory setup with the QAB prototype and temperature measurement with an open IGBT module.

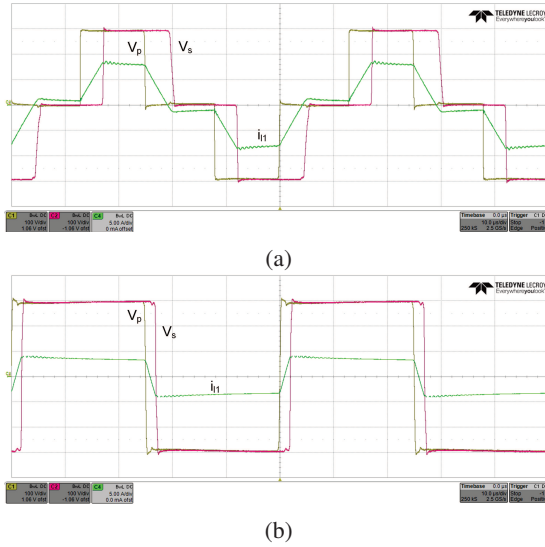


Fig. 9: Laboratory measurements for similar voltage ($U_{dc} = 300V$), similar power ($P_{load} = 1kW$) and different φ : (a) $\varphi = 0.25$, (b) $\varphi = 0$.

the cooling down of the IGBT and the diode. In Fig. 7 (b) the thermal control is activated, but the time period of the thermal cycle is too long to be compensated with the controller tuning. However, the cooling down is delayed and the cooling is slower than in the case without thermal control. Here, the thermal controller is reducing the efficiency without reducing the thermal stress. However, this demonstrates the steady state optimization of the efficiency of the controller.

In the third case, shown in Fig. 7 (c), the thermal controller is tuned with $\tau_1 \rightarrow \infty$ to fully compensate the thermal cycle. As expected, the thermal swing during the power cycle for the IGBT is compensated. However, the junction temperature of the diode is not affected by the thermal control. The diode is not cooling down, because the losses are only caused by the conduction losses, which are reduced for the smaller duty cycle. Consequently, the thermal swing of the diode is not reduced. As explained, the losses should only be increased

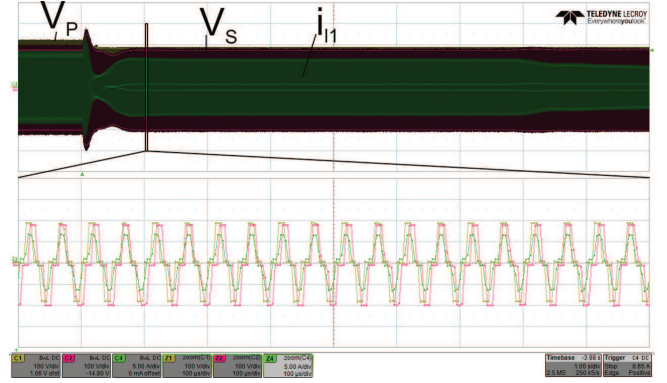


Fig. 10: Laboratory measurement of a step in the output power.

temporally to compensate thermal cycles below certain periods. Nevertheless, the cross coupling within the module will also prevent the cooling down of the case temperature and thus indirectly reduce the thermal swing for the diodes in the module.

V. LABORATORY RESULTS

A DAB prototype has been built to validate the proposed algorithm with junction temperature measurement on an open IGBT module with the setup shown in Fig. 8. The junction temperature is measured with an optic fiber measurement system, whose sensors have a response time of 7 ms . The parameters of the setup are similar to the parameters of the simulation system in Tab. I. A mission profile with fast varying power is realized by using an electronic load (Chroma 63800), which is operating with varying resistances. The controller is tuned with $\tau_1 = 10\text{ s}$ and $\tau_2 = 0.1\text{ s}$.

To demonstrate the functionality of the converter, Fig. 9 demonstrates the operation of the converter. In both cases, the same power $P = 1\text{ kW}$ is transferred by the converter. In Fig. 9 (a), the duty cycle is reduced by $\varphi = 0.25\phi$, while the second case is applying standard phase shift operation. It can clearly be seen, that the peak current is increased for the reduction of the duty cycle.

The dynamical performance of the controller is demonstrated with an variation of the power, which is shown in Fig. 10, where the primary side voltage, the secondary side voltage and the current are recorded. The variation of the power is done by a step in the resistance, which is emulated by the electronic load. Caused by the voltage balancing controller, the power is increasing first, and reduced quickly. Then, the thermal controller is reducing the duty cycle and the peak current is increasing. Over time, the duty cycle is increased again, because the power is kept constant and the operating point is shifted back to normal operation. This behavior is operating as expected.

For the proof of the thermal performance of the algorithm, the optic fiber temperature measurement system is used and a temperature sensors is attached on the surface of one IGBT in the open module. Additionally, the power consumption of the electronic load is measured and the results of a power

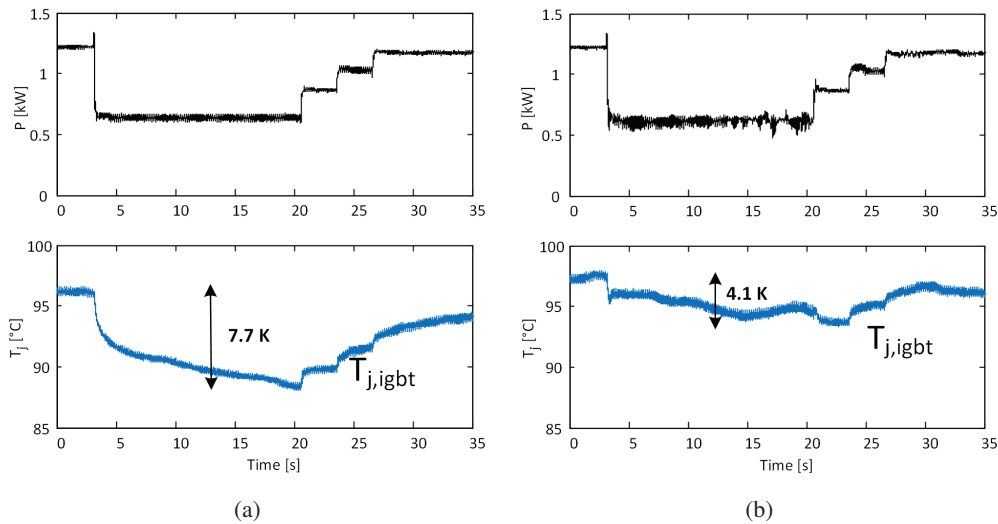


Fig. 11: Laboratory measurements for a variation in the output power and measurement of the power and the junction temperature of one IGBT: (a) with standard phase shift modulation , (b) with the proposed active thermal control algorithm.

reduction from $P = 1.2 \text{ kW}$ to $P = 600 \text{ W}$ is shown. In Fig. 11 (a) no thermal control is applied and in Fig 11 (b) the thermal controller is activated. Without the controller, the thermal swing in the profile has a magnitude of $\Delta T = 7.7 \text{ K}$, which is significantly reduced to $\Delta T = 4.1 \text{ K}$, which is a reduction by almost 50%. Here, the tuning of the controller can be modified to optimize the trade off between a higher reduction for the cost of higher power semiconductor losses or a lower thermal swing reduction for lower increase of the losses. Beside the reduction of the thermal swing, the average temperature $T_{j,av}$ is increased. However, as shown in (2), this reduction of the thermal swing has a bigger impact on the lifetime than the increase of $T_{j,av}$.

VI. CONCLUSION

An active thermal control algorithm for isolated DC/DC converters has been proposed for reducing the thermal stress of power semiconductors. Thermal cycling is reduced by control of the power semiconductor losses to reduce thermal swing caused by power variations without prior knowledge of the profile. The proposed strategy to control the duty cycle of isolated soft DC/DC converters is introduced and investigated analytically. Simulation results demonstrate the effectiveness of the algorithm and give guidelines for the tuning of the thermal controller. The results are validated on a laboratory setup with high speed junction temperature measurement and the capability to reduce the thermal swing with the proposed controller is demonstrated.

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