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**Junction temperature control for more reliable power electronics**

Markus Andresen  
Ke Ma  
Giampaolo Buticchi  
Johannes Falck  
Frede Blaabjerg  
Marco Liserre

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# Junction temperature control for more reliable power electronics

Markus Andresen, *Student Member*, IEEE, Ke Ma, *Member*, IEEE, Giampaolo Buticchi, *Member*, IEEE, Johannes Falck, *Frede Blaabjerg, Fellow*, IEEE, and Marco Liserre, *Fellow*, IEEE

**Abstract**—The thermal stress of power electronic components is one of the most important causes of their failure. Proper thermal management plays an important role for more reliable and cost-effective energy conversion. As one of the most vulnerable and expensive components, power semiconductor components are the focus of this paper. Possible approaches to control the semiconductor junction temperature are discussed in this paper, along with the implementation in several emerging applications. The modification of the control variables at different levels (modulation, control, system) to alter the loss generation or distribution is analyzed. Some of the control solutions presented in literature, which showed experimentally that the thermal stress can be effectively reduced, are reviewed in detail. These results are often mission-profile dependent and the controller needs to be tuned to reach the desired cost-benefit trade-off. The paper analyzes also the many open questions of this research area. Among them, it is worth highlighting that a verification of the actual lifetime extension is still missing.

## I. INTRODUCTION

Power semiconductor modules are built of different layers of copper and substrate to ensure electrical insulation on one hand and a good thermal conductivity on the other hand [1]. For the electric connection between chips and terminals, aluminum bond wires are typically used [2], although copper has seen an increasing interest [3]. The scheme of a power electronics module with the different materials stacked on a direct-bond-copper (DBC) substrate is shown in Fig. 1.

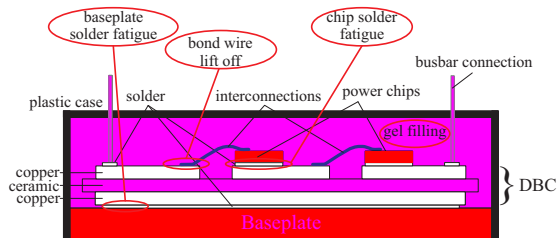


Fig. 1: Structure of a power electronic module.

Variations of the ambient temperature and power variations create cyclic heating and cooling processes, also called thermal

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Markus Andresen, Giampaolo Buticchi, Johannes Falck and Marco Liserre are with the Chair of Power Electronics, Christian-Albrechts University of Kiel, Germany, e-mail: {ma, gibu, jofa, ml}@tf.uni-kiel.de

Ke Ma is with the Department of Department of Electrical Engineering, Shanghai Jiao Tong University, China, e-mail: kema@sjtu.edu.cn

Frede Blaabjerg is with the Department of Energy Technology, Aalborg University, 9220 Aalborg East, Denmark, e-mail: fbl@et.aau.dk

cycles. Due to different thermal expansion coefficients (CTE) of copper and the ceramic of the substrate, mechanical stress between the material layers occurs when the temperature changes [4]. Although all interfaces experience stress due to different CTE, it has been observed that a large difference affects the aluminum and the silicon chip and the solder between ceramic substrate and base plate [5]. For frequent repetition of thermal cycles, the resulting expansions and contractions of the material lead to fatigue of solder joints [1] and thus cause aging [6]. Therefore, thermal cycles are an important cause of failures and destruction of the power modules [7]. The thermal cycle magnitude is the most critical parameter for the scale of the aging [8]. In [9] the advancing degradation of a base plate solder in a power module has been observed for increasing amount of applied thermal cycles using acoustic microscopy. After 4000 cycles with a magnitude of 80 K about a quarter of the solder has been cracked, leading to dramatic increment of thermal resistances within the module. The consequences are increased temperatures in the chips and thereby increased losses. This forms a positive feedback loop which accelerates the aging process [10]. Especially short-term thermal cycling in the order of a second that is mostly evoked by power cycling leads to fatigue of the bonds and therefore may cause bond wire lift off [11]. Many manufacturers of power electronic devices, such as power semiconductors or capacitors, have developed their reliability models, which normally are based on accelerated or aging tests, and are able to evaluate the lifetime information according to certain thermal behaviors of the components. Therefore, the thermal stress of the power devices needs to be assessed and properly controlled. In the energy conversion system, the power or current flowing through the converter is normally designed according to the available electrical or mechanical power level. As a result, if the available power processed by the converter system is not constant, as in the renewable energy or motor drive applications, the complicated and variable mission profiles will be directly reflected by the loading variation in the power electronics components, which results in complicated thermal cycling that can quickly trigger the wear-out of the components.

Another problem is that the temperature of the device is normally hard to access and it is difficult to monitor it during operation as well as it is difficult to validate thermal models; this calls for estimators/observer in order overcome the direct measurement problem. One effective way to extend the lifetime and improve the reliability of components is to push the overall stress range of the components to a lower

level.

In the case of a converter system, active thermal control reduces the thermal cycling of the components either by reducing the fluctuation amplitude or by reducing the mean level of the temperature, while the design of the converter does not need to be changed, meaning that there is no additional cost for the enhancement of the converter design or components [12], [13], [14]. These topics have not yet been comprehensively summarized and this paper serves to give a review on these topics.

Section II describes the lifetime estimation of power modules and the most common causes of failure, section III discusses the basics of temperature estimation and control, section IV details the possibilities of active thermal controls, section IV presents its applications and section V draws the conclusions.

## II. LIFETIME OF POWER ELECTRONIC MODULES

Failures in power modules impact safety in operation and cause downtimes, giving extra cost for the operators of the system.

For manufacturers and operators of power electronic modules, it is of interest to estimate the impact of certain usage on the lifetime of the modules [15]. The lifetime of a system is an important parameter, as cost calculations for purchase, maintenance and replacement depend on it. The aim of a lifetime prediction is to assess how long a module can be used without expecting to see a failure for a particular application. In the 1950s, the first relationship between the plastic strain amplitude and the number of cycles to failure were established by Coffin and Manson in studies on fatigue in material science caused by cyclic plastic deformations [16]. Since all materials expand and shrink due to thermal cycles, nowadays modified relationships are also used to estimate the capability of power semiconductors to withstand thermal cycles. The parts more susceptible to thermal cycling are highlighted with red color in Fig. 1. Based on this, a well-known approach to estimate the module's lifetime is the Coffin-Manson-Arrhenius model [17]: The number of cycles to failure  $N_f$  is described in dependency of the amplitude of thermal cycles  $\Delta T_j$  and the average temperature  $T_{jm}$ . Other coefficients  $a$ ,  $\alpha$  and  $E_a$  are extracted from a data set of multiple reliability experiments and they are adjusted for best match to the module [18] and  $k_B$  is the Boltzmann constant. Its analytical equation is:

$$N_f = a \cdot \Delta T^{-\alpha} \cdot e^{\frac{E_a}{k_B T_{j,m}}} \quad (1)$$

Other researchers have modified this relationship, recognizing for instance the frequency of thermal cycles, heating and cooling times as well as more electrical parameters in the Bayerer model [19]. Manufacturers of semiconductors use this relationship to determine the thermal cycle capability of their modules. Fig. 2 shows this for a Semikron module with coefficients matched to IGBT4 modules [18]. To rate the impact of a certain mission profile on the module's lifetime, first a temperature profile is created from the power profile, calculating the losses in the semiconductors, thermal related

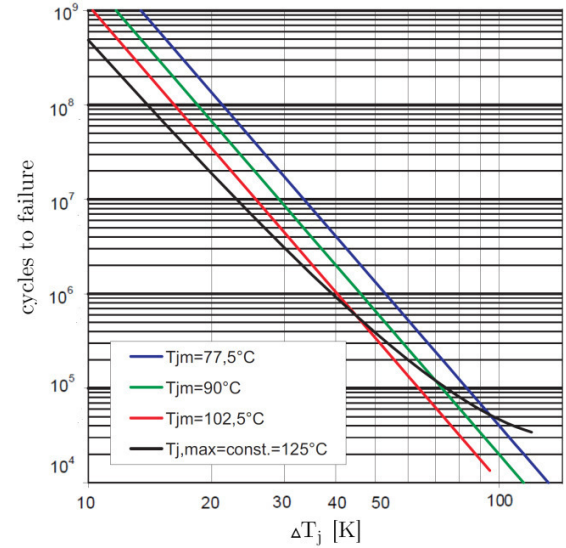


Fig. 2: Temperature cycle capability characteristic  $N_f$  for Standard SEMIKRON IGBT modules [18].

characteristics and environmental influences. This thermal profile contains normally thermal cycles of different magnitudes at different average temperatures, so a direct derivation of the accumulated damage with (1) is not possible. In order to combine the damage caused by these different thermal cycles, Miner's cumulative damage rule can be adopted [4]. Miner's rule is written as:

$$C = \sum_i \frac{n_i}{N_i} \quad (2)$$

Here  $C$  is the cumulative damage,  $n_i$  the number of cycles in the stress range  $i$  and  $N_i$  the number of cycles to failure in the  $i$ -th stress range. Thus, the more thermal cycles occur in the mission profiles the more the cumulative damage will rise. If the cumulative damage reaches 1, the module will fail according to the model [20].

Instead of using a model-based approach, another possibility to detect the aging of a module during operation is the measurement of a physical parameter such as the collector-emitter voltage  $v_{ce}$ . An increment of  $v_{ce}$  is observed for bond wire lift-off [21]. However,  $v_{ce}$  is also sensitive to the applied power level and changes in the temperature. It is worth noting that the measurement of  $v_{ce}$  shows marked variation when the device is approaching the end-of-life, while it is fairly constant during the normal conditions. Due to this fact, although  $v_{ce}$  measurement could be used to get a lifetime indication, it is more suitable to detect an incipient fault than to estimate the residual lifetime. By knowing the influencing factors and indicators for the lifetime of the power semiconductors, it is possible to control some of the influencing variables during converter operation to influence the lifetime of the power semiconductors. This is referred to as active thermal control and will be discussed in the next section.

### III. SEMICONDUCTOR JUNCTION TEMPERATURE ESTIMATION AND CONTROL

Active thermal control is a new concept recently introduced to regulate power losses and control the thermal stress. The general principle is to vary temperature related control variables of the system to influence its junction temperature in order to reduce damage caused by thermal cycling [22]. Since the junction temperature is difficult to measure, an important part of the active thermal control algorithms is the temperature estimation. These parts will be detailed in the next paragraphs.

#### A. Temperature estimation

An accurate real-time estimation of the junction temperatures of a power module is of interest for active thermal control. Measurements of the junction temperatures are possible as well, but the sensors need to have a bandwidth in the order of a magnitude higher than the expected thermal cycles. Usually thermocouples connected to the chips cannot reach the necessary bandwidth demand for their detection. High-bandwidth temperature measurement equipment is expensive and only used in specialized or experimental setups. For commercial product solutions, junction temperature estimations on the basis of electrical measurements are more realistic as there is no need to increase complexity of power modules [23]. Electro-thermal models for this purpose consist of three parts: A device model that holds the dynamic characteristics of the used power module, a power losses model for the semiconductors, and a thermal model to estimate the heat propagation in the module [22]. Another way to estimate the junction temperature is the use of Thermo-Sensitive Electrical Parameters (TSEP) in the module. Classical TSEPs are the collector-emitter voltage drop at low current, the threshold voltage and saturation current of metal-oxide semiconductor gated devices [23] and the short circuit current [24]. However, measurements of TSEPs require additional circuitry.

#### B. Temperature control

A simple approach to achieve temperature control is to adjust the switching frequency as it has a direct influence on the power losses without notably affecting the operating point of the application when adjusted within system constraints. The switching frequency control is done using linear control [13] or hysteresis control [14], [25]. A dynamic limit of the inverter current under thermal constraints is proposed in [13]. This enables low-power operation of nearly overheated systems to prevent further rise in temperature and thereby a complete shutdown or damage of the module due to over temperature. Another approach is to manipulate the loss distribution between IGBTs and diodes, by adjustment of the dc link voltage which influences the modulation index [26]. This can be used to relieve specific semiconductors on the cost of additional losses in the inverter caused by a higher current magnitude. In modular multilevel converters (MMC) the modules are stressed unequally in specific conditions, leading to higher thermal stress in particular modules. An algorithm is proposed in [27], [28] and for active balancing

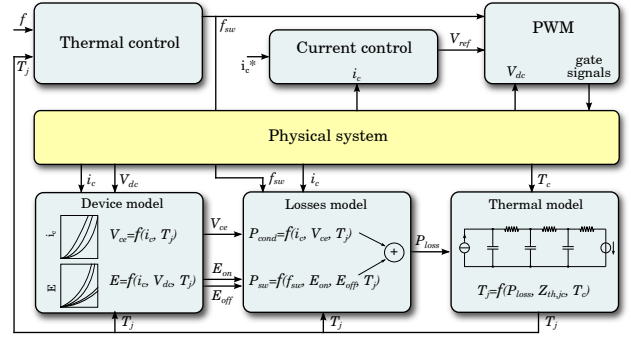


Fig. 3: Example of a model-based active temperature control scheme.

the junction temperatures of the MMC cells. In [29] power routing is used to balance uneven loading of cells in the smart transformer. In [13] and [14] the used active thermal controllers decrease the switching frequency below that of the uncontrolled system at the price of an increase in the current ripple. In a comparison in [25] the active thermal controller is reducing the current and is therefore influencing the mission profile.

Since the thermal behavior is changed via the control, there are as many possibilities as control layers and variables. The lowest level is the gate driver, that can be used directly to influence the losses of the power devices. Also modified modulation patterns can be employed to this aim. The converter's control level generates the reference signals for the modulator and in this case active de-rating can be performed, or modification to some control variables (DC link, switching frequency) can be realized without altering the normal converter's operation. At the highest level there is system control, where the presence of multiple power converters can be exploited to alter the losses distribution or to create additional losses without affecting the main converter's goal. In the following sections the possibilities for each control level will be explored and an analysis on how these techniques can be applied to specific applications will be carried on.

Considering the previously reviewed active thermal control approaches, a control scheme using the switching frequency to influence the junction temperature, as it is the most common temperature control parameter, is depicted in Fig. 3. In the scheme the load current  $i_c$ , the DC-link voltage  $V_{dc}$  and a small bandwidth measurement of the modules case temperature  $T_c$  are sensed in the physical system. In addition the semiconductor's characteristic curves are taken to determine the collector to emitter voltage drop  $V_{ce}$  and the switching energies  $E_{on}$  and  $E_{off}$ . They are used to achieve an estimation of the conduction losses  $P_{cond}$  and the switching losses  $P_{sw}$  which are given to the thermal network to calculate the resulting junction temperature. The thermal controller sets the switching frequency independent from the current reference  $i_c^*$ , but to achieve the selected target, that could be temperature limitation (then the maximum allowable junction temperature can be used as reference) or thermal cycle reduction. To filter the junction temperature's fluctuation of the fundamental frequency,  $f$  is used as an input.

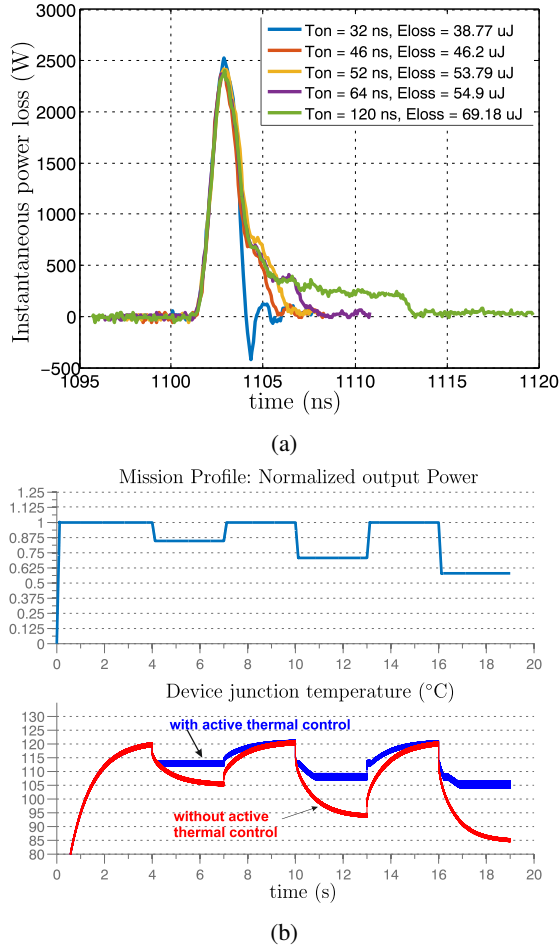


Fig. 4: Two-step gate driver applied to a GaN Enhancement Mode High Electron Mobility Transistor (E-HEMT). (a) Energy loss variation depending on the duration of the intermediate gate voltage step. (b) Simulation of active thermal control of the junction temperature variation of the switching loss energies for 400V and a switching frequency of 100kHz [31].

Another strategy to perform active thermal control relies on the active control of the cooling system. In [30] the authors control the speed of the fan in order to reduce the power cycling of the estimated junction temperature. Although this technique can be adopted in all system that feature a controllable cooling, the focus of this paper is on the solutions which modify the electrical parameters of the control

#### IV. IMPLEMENTATION POSSIBILITIES FOR ACTIVE THERMAL CONTROL

##### A. Thermally-conditioned gate driver

Active gate control is a possibility to control the semiconductor losses, without affecting the functionality of the device. As the gate drive voltage influences both conduction and switching losses of the semiconductors, it can be used to decrease the thermal cycling [32]. In the literature an active gate driver has been reported that is applied for counteracting variations in the on-state resistance of the IGBTs [33]. Another

active gate control has been used to balance the currents among parallel connected IGBT devices [34]. By adjusting the control parameters in these active gate controls, they can also be applied to reduce the thermal cycling in the semiconductors. Active gate control in the context of GaN power semiconductors is of particular interest. Compared to Si-devices, GaN-devices provide a much higher switching speed and possibly higher operating temperature. As a consequence, they have an increased power density, which makes the temperature management critical, especially for the PCB and components to which the GaN is connected. Therefore, active gate control has been applied in [31] to reduce the thermal cycling in a GaN-based DC/DC converter. In Fig. 4(a) the variation of energy loss during turn off of the device is shown dependent on the tunable parameter ( $T_{on}$ ) of the active gate driver, that represents the time during which the gate is fed with an intermediate voltage level. Having a three-level gate driver with controllable on-time allows controlling the slew rate and the conduction losses of the device. In Fig. 4(b) the impact of a variation of the switching losses of a GaN device on its junction temperature is shown. This simulation shows the possibility of reducing the thermal cycling by varying the device losses using the gate driver.

##### B. Thermally-modified Modulation

Another way is to explore the modulation methods. The Discontinuous PWM (DPWM) in two-level three-phase converter is a well-known strategy for the device loading control, as it is shown in Fig. 5. The principle of discontinuous PWM is to clamp the voltage reference of the converter output to the upper or lower DC-link potential in a certain interval so that the corresponding power device will keep its status without switching, and the switching loss is thereby mitigated in that interval. Since the total loss of the power device during this clamping period is reduced, the mean value and variation of the junction temperature are therefore both reduced. The thermal control by using DPWM can also be a benefit in the thermal optimization of multi-level converters. A case study on a three-level NPC converter can be found in [35], where several different modulation methods in terms of Optimal Zero Sequence Injection (Opt-ZSSPWM) [36], Conventional  $60^{\circ}$  Discontinuous PWM (CONV- $60^{\circ}$  DPWM) [37], and Alternative  $60^{\circ}$  Discontinuous PWM (ALT- $60^{\circ}$  DPWM) [37] are applied to the converter. It has been reported in [36] that with CONV- $60^{\circ}$  DPWM and ALT- $60^{\circ}$  DPWM the junction temperature of the device with the highest temperature (Cl. Diode1) can be reduced significantly.

Besides the switching losses, the PWM strategies can also alter the conduction losses of power devices and thereby achieve the thermal control target. The space vector diagram for a 3L-NPC converter is shown in Fig. 6. It is composed of 27 switching states/state vectors, which can be grouped into 3 zero vectors, 12 short vectors, 6 medium vectors and 6 long vectors according to the length in the diagram. The numbering "2", "1", "0" of the state vectors represent that a certain phase is connected by the converter to the positive DC bus, the neutral point and the negative DC bus respectively.



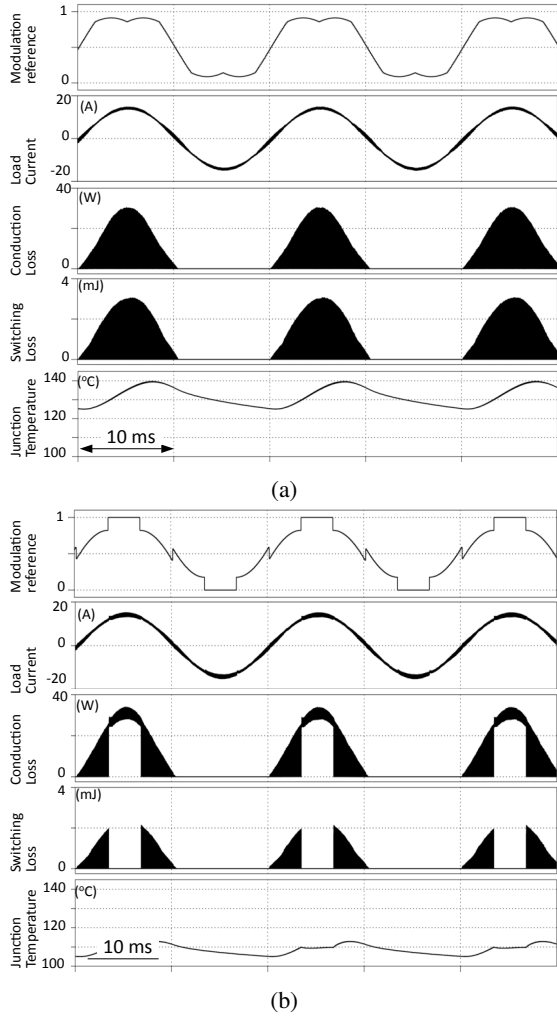


Fig. 5: Power loss and junction temperature of the IGBT in a B6 converter with different modulation schemes: (a) SVPWM (b) DPWM. (switching loss: conduction loss = 3.56:1).

By looking at the Space Vector Diagram (SVD) of the 3L-NPC converter, as shown in Fig. 6, which is used for the Space Vector Modulation (SVM) of the three-phase converter, it can be seen that all state vectors at the inner hex of the SVD have switching redundancies. These switching redundancies provide the control flexibility to modify the current paths flowing in the power devices, and thereby modifying the conduction losses of the device. This feature is especially interesting for the ride-through operation during the grid faults for grid-tied converters [38], or the start-up operation of motor drives, where the voltage reference vector is normally low in amplitude and it is located in the inner hexagon in Fig. 6 [38], [39].

Based on this concept, a series of optimized modulation sequences have been proposed in [38], and one of the SVM sequences within one switching cycle is shown in Fig. 7. It can be seen that the state vector 111, which connects the three-phase output of the converter to the neutral point of the DC bus, is eliminated, indicating that the time of the converter state when the current is flowing through the clamped diode and inner switch of 3L-NPC will be reduced. The simulation

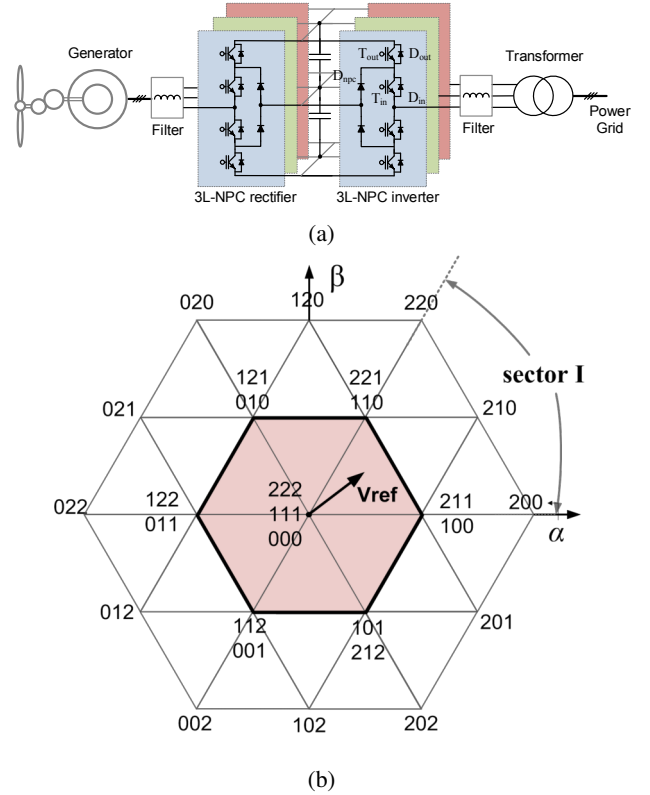


Fig. 6: 3L-NPC converter. (a) back-to-back topology and configuration for a wind turbine application, (b) space vector diagram.

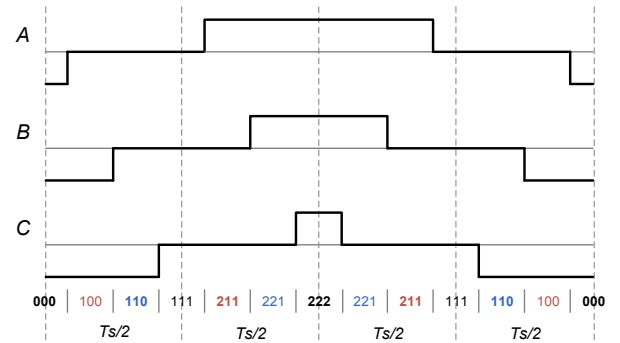


Fig. 7: Optimal modulation sequence for relieved device temperature under LVRT.

results of the device temperature in the 3L-NPC converter under a low voltage output is shown in Fig. 8. It can be seen that when applying the optimized modulation sequence, the thermal loading among the devices is more symmetrical, and the thermal loading of the most stressful devices are also reduced.

### C. Thermally-oriented control of the power converter

The converter controller generates the reference for the lower-level systems that implement the modulation, meaning that at this level the active thermal control can be used to modify the control variables. The goal can either be the junction temperature limitation, in order to perform an active

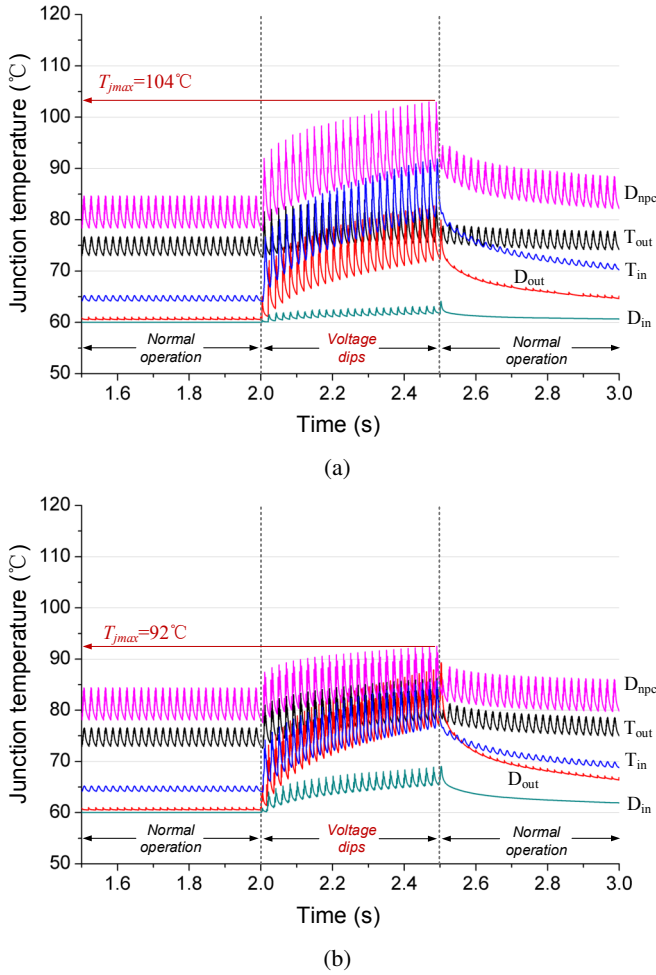


Fig. 8: Device temperature reduction of 3L-NPC under LVRT of 500ms [38]. (a) With normal modulation (b) with optimal modulation.

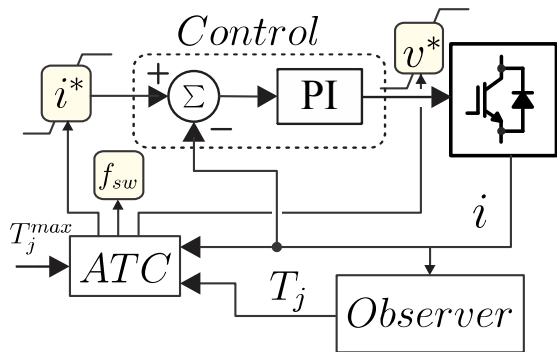


Fig. 9: Basic scheme for active thermal control (ATC) at the converter's control level.

de-rating that pushes the semiconductors close to their limits with a minimum over-design or the thermal cycle reduction, as depicted in Fig. 9. An additional block is used to observe the junction temperature,  $T_j$ . The Junction temperature limitation normally involves the saturation of a control variable (voltage, duty cycle, current) when the temperature reaches a certain level.

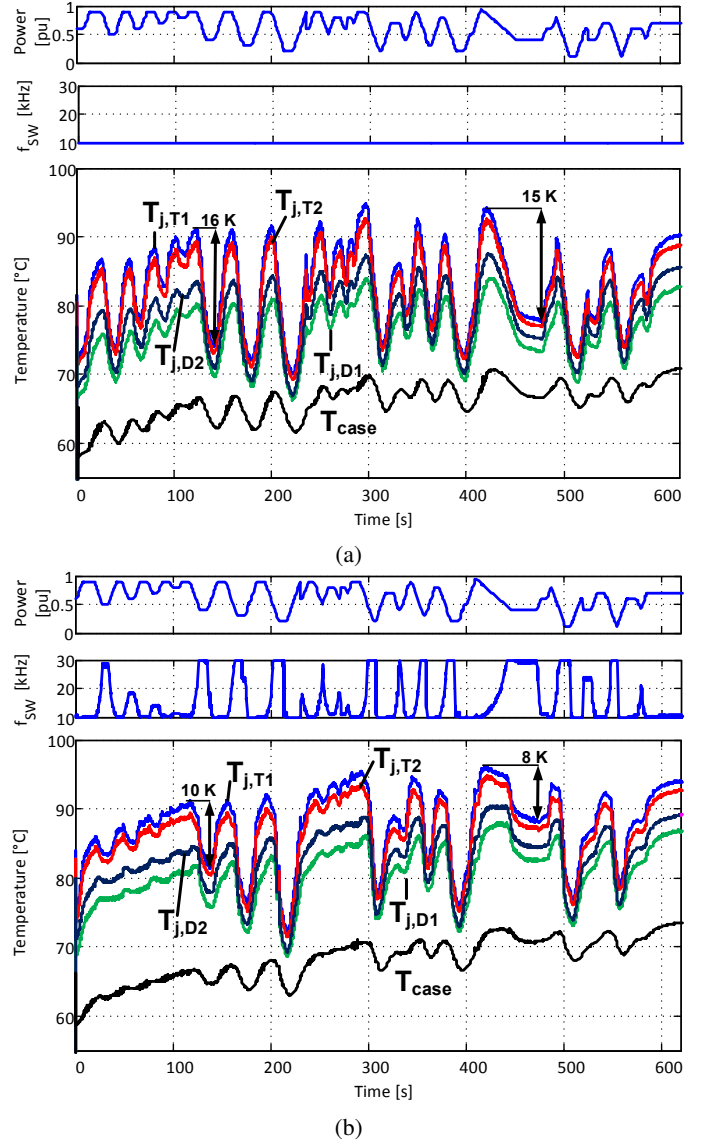


Fig. 10: Experimental results of the ATC using switching frequency variation between 10kHz and 30kHz [40].

Thermal cycle reduction without affecting the system operation can be achieved when the degrees of freedom of the control are used, and they are also application dependent. In particular, in [22] and in [40] for a single-phase H-bridge IGBT converter, thermal cycle reduction was achieved by modifying the switching frequency of the converter to eliminate the fast thermal cycles. This is achieved by increasing the losses, when the output power drops to prevent the system to cool down. To validate the functionality of the proposed method, a mission profile with highly fluctuating power is used and the junction temperature is measured for a fixed switching frequency and afterwards by its adaption for active thermal control. As it can be seen from the measurement in Fig. 10, the active thermal controller allows to strongly reduce the temperature variations during a fast changing power demand. For achieving the compensation of thermal cycles, the thermal controller needs to be tuned in an appropriate

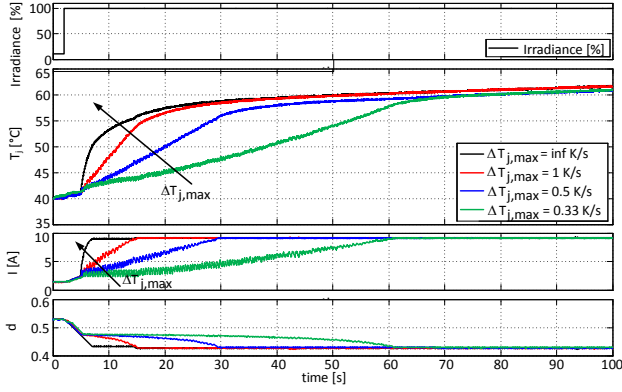


Fig. 11: Behavior of the MPPT for a step in the irradiance from  $P_{PV,rel} = 10\%$  to  $P_{PV,rel} = 100\%$  for different temperature gradients and normalized starting temperature in one IGBT. Irradiance, junction temperature, input current and duty cycle of the boost converter are shown.

way. Otherwise, the risk is to only increase the losses without reducing the thermal cycling. This problem is addressed in [41]. The drawback of this solution is that the increased losses cause an average increase of the mean junction temperature. Depending on the main cause of failure, i.e. thermal cycling or average temperature, the damage due to the slightly higher average mean temperature can not become relevant.

The limit of modulator based active thermal control structures is that they cannot reduce the thermal stress in a specific semiconductor, as the conductivity and switching of the semiconductors in the converter is selected by the modulator. In [42] a thermal controller is presented, that applies a Finite Control-Set Model Predictive Control (FCS-MPC) in order to achieve a more precise junction temperature control. The predictive control selects the optimal switching vector, that fulfills the applications demand and reduces the thermal stress. This switching vector is directly applied to the physical system. The possibility to modify the control variable to limit the maximum junction temperature was first proposed in [13]. Another possibility is to reduce the maximum temperature derivative, which at the same time reduces the thermal cycle. This concept was explored in [41], where the duty cycle of a DC/DC converter for photovoltaic system was actively modified in order to limit the maximum junction temperature derivative in the presence of irradiation changes. This algorithm modifies the Maximum Power Point Tracking (MPPT) embedded in this kind of converters. In Fig. 11 the functionality of the derivative limitation is shown for this thermal-optimized MPPT and it is possible to see that the IGBT temperature can be effectively controlled by actively limiting the duty-cycle variation. In fast varying irradiance environments, it is demonstrated in [41] to reduce the thermal cycling by not tracking very fast irradiance variations, which only slightly increase the harvested energy, but cause damage to the components. If there are no fast variations, the maximum power point is normally tracked by harvesting the maximum energy, as it is commonly done.

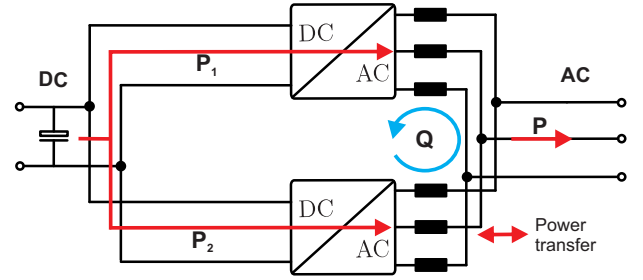


Fig. 12: Active power routing and reactive power routing for low thermal stress.

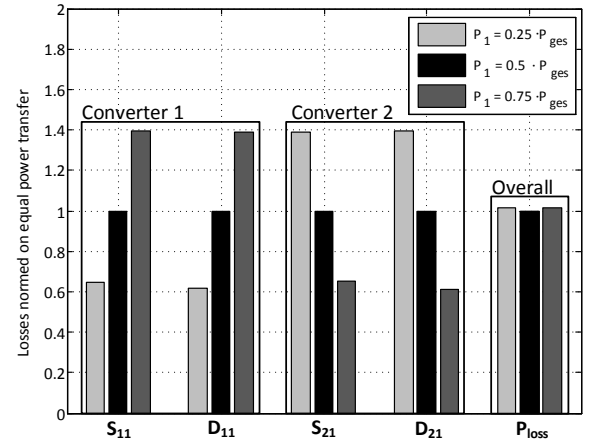


Fig. 13: Loss distribution of 2L-VSC inverter with different active power loadings.

#### D. Thermal control at system level

At the next level is the system control, normally suitable in the presence of parallel converters as shown in Fig. 12. The capability of controlling the active power among the parallel converters is shown in Fig. 13 for a difference in the active power distribution of the converters. As it can be seen, the overall losses reduction of the single converter is achieved by loading a converter less than the other one despite the disadvantage of higher losses in the overloaded converter and higher overall losses in the selected operation points. For the proposed case, the losses increase by 1.7%. Nevertheless, this demonstrates the feasibility to control the losses of one of the parallel converters, consequent its junction temperatures.

The reactive power delivered by a converter is a system control reference that is normally not fully utilized, and it is not restricted to the available mechanical/electrical power processed by the converter system, but it can significantly influence the loading of components, and thereby is suitable to achieve active thermal control for improved reliability performance of the converter [43]. A simple example can be seen in Fig. 14, where a 3L-NPC converter is operating under maximum Over-Excited (Q+) as well as Under-Excited (Q-) reactive power, respectively, with the rated active power output. The influence to the loss distribution of the same 3L-NPC converter by introducing different reactive power



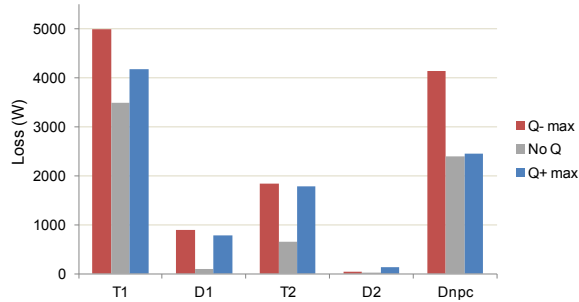


Fig. 14: Loss distribution of 3L-NPC inverter with different extreme reactive powers (Considering parallel converters).

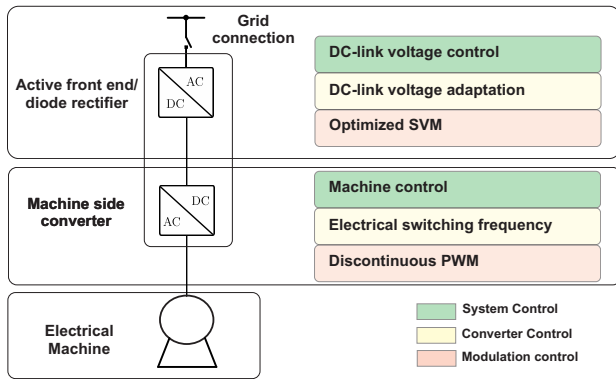


Fig. 15: Drive system and active thermal control possibilities.

can be seen. In addition the reactive power will not only modify the phase angle between the output voltage and current of converter, but also modify the current amplitude flowing in the power devices, which are all related to the power loss and thermal loading of power devices. This indicates a thermal control case by utilizing reactive power when the 3L-NPC grid-tied inverter is undergoing a power fluctuation. It can be seen that by introducing certain amount of under-excited reactive power to heat up the device during the low power period, the overall fluctuation of device temperature can be significantly reduced, with slightly increased mean temperature level. According to the lifetime models in Fig. 2, this is a more optimal loading condition with regard to lifetime extension.

## V. APPLICATION FIELDS

Active Thermal Control can be applied to many power electronics areas. There are important differences between the algorithms and the applications. First, the application specific controller algorithms will be examined and then they will be categorized for their suitable applications.

### A. Electric Drives

Power semiconductors in power converters for electric drives do not only need to be sized to operate reliably for the rated current under the rated machine speed, but also for possible low speed operation with high torque. During low

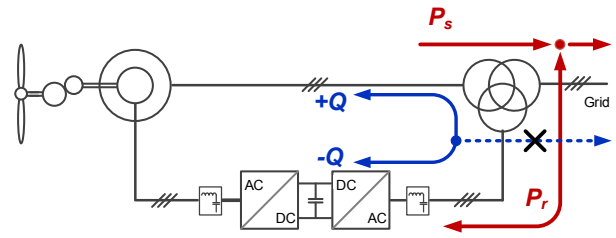


Fig. 16: Compensation scheme of the reactive power in the DFIG wind turbine system.

speed operation, the electrical fundamental frequency is very low and it results in severe thermal cycling for the power semiconductors, which can quickly lead to a failure. This was first found in [12] and addressed with an algorithm that reduced the switching frequency in order to limit the maximum temperature. Fig. 15 shows the drive system configuration and the thermal control possibilities, where the DC supply for the motor drive is given by a AC/DC rectifier. Usually, the rectifier is constituted of a three-phase diode bridge, so active thermal control is not normally possible. Some systems present an active front-end, and in this case the techniques explained in section IV are possible, especially related to the optimized PWM during LVRT conditions and DC link voltage adaptation for the control of the switching losses.

Regarding the machine side converter, in [12], [44], [45] a thermal controller is investigated, which applies the thermal controllers with a junction temperature limitation and an adjustment of the PWM (pulse width modulation) carrier frequency to reduce the losses in the device. This approach is extended in [13] with a fuzzy controller for the detection of power cycling and its reduction. In particular, a filter is employed to detect the magnitude of the thermal cycles, and this information constitutes the feedback signal for two regulators, that dynamically change the switching frequency and the current limit depending on the operating zone (normal, over temperature, power cycling high/low).

Changing the modulation strategy between continuous and 60° discontinuous PWM to achieve a loss reduction [18], [46], [47] is another approach. In [25] an active thermal control of an electric drive composed by an IPM motor and a three-phase, 2-level, back-to-back converter is realized by changing the switching frequency and the maximum current limit. Multiple thermal models, for the motor and the power module as well, were implemented and validated with actual measurements. Differently from other solutions presented in literature, the torque control is realized in a novel way, where the Maximum Torque Per Ampere (MTPA) control is substituted with the Maximum Efficiency Per Nm (MEPNm), where the losses of the devices/motor are taken into account in the computation of the optimum current values for the selected output torque. Basically, the MTPA and MEPNm loci differ because the reference for the direct current is optimized for the minimum iron losses.

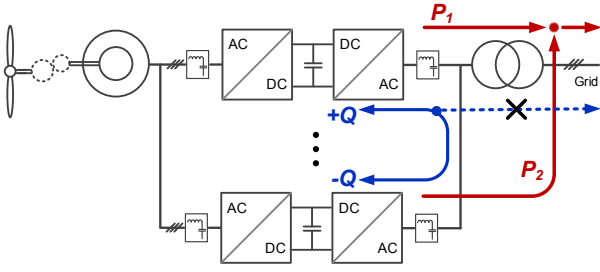


Fig. 17: Reactive power circulating among parallel converters in a wind turbine system.

### B. Renewable energy generation

In renewable energy generation systems such as wind power or photovoltaic, the converted power is normally weather-based and can impose adverse temperature fluctuations to the power devices, on the other hand the reliability requirements for these systems are normally high due to high cost of energy [48]. As a result, it is another important and promising application to incorporate various thermal controls methods to achieve more reliable power electronics.

It has been reported in [43], [49] that the active thermal control is applied in the wind power generation system by utilizing reactive power to smooth the thermal fluctuation of power device during wind speed variations, either in the Double Fed Induction Generation (DFIG) based system or full scale converter based system, as shown in Fig. 16. It is noted that in order to amplify the inference on the device temperatures but at the same time also to comply with the grid requirements/codes, the reactive power used for thermal control normally has to be circulated inside the converter system, either between generator and grid side converter in the DFIG system, or between paralleled converters in the full scale converter system, as illustrated in Fig. 17. In [50], a thermal control method controlling the active power of the PV system has been demonstrated. In this method the maximum power of PV panels is limited to a certain value by a specially modified MPPT control of the PV panels, thereby the fluctuation of the temperature caused by the randomly variation of solar irradiance/generated power is smoothed, as a result the lifetime of the PV converter is claimed to be extended. However, the drawbacks of reduced energy production and comprised converter efficiency still need to be justified in comparison with the benefits.

### C. Smart Transformer

The Smart Transformer interfaces the medium and low voltage grids, replacing the traditional passive transformer, with the aim of providing additional grid functionalities. From this point of view, a three-stage architecture seems to be the most promising for this application, due to the presence of the DC links, that allow an independent reactive power control in the MV and LV side [29]. Fig. 18 shows the ST in an example network and the different control layers with the control objective of each stage. Several of the techniques described in section IV can be used in the single converter, and

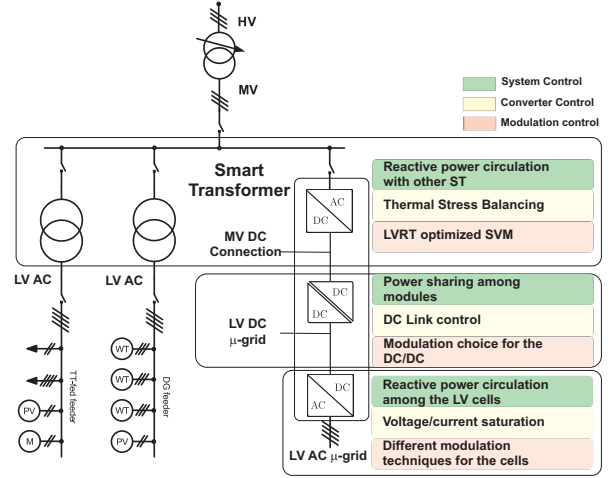


Fig. 18: Smart Transformer and active thermal control possibilities.

will be described in the following. It is important to highlight that the thermal stress is highly mission-profile dependent [51].

At the modulation level, optimized SVM can be used in the case of NPC converters, in the case of a modular structure like CHB or MMC, the modulation strategy can be used to equalize the thermal stress [27] among different modules, however, the results are very dependent on the number of modules and on the switching frequency. Temperature limitation at the control side can be performed by saturating the control variables of the LV side. As a matter of fact, a ST must provide the active power requested by the LV network, so a way to reduce the loading without affecting normal operation could be to modify the voltage reference in the LV side in order to reduce the power request. Different modulation techniques can be adopted among the LV cells in order to have different thermal stress.

From the point of view of active thermal control, the system control seems to be the most promising, especially when modularity is considered. Due to high current demand in the LV side, multiple converters will be mandatory, so reactive power circulation [43] can be easily implemented in the modular structure. From the DC/DC side point of view, power can be shared among multiple power converters during partial load conditions, reducing the thermal cycling with respect to an on/off activation system [29]. This idea was expanded to all three stages of the ST [52]–[54], where also a quantification of the stress for a highly fluctuating mission profile was done and it was shown, that the stress for one of the cells was reduced to 23% of the stress in the balanced case, whereby the stress for the two other cells was six times higher. As a conclusion, the system controls seem to be the most promising techniques to implement active thermal control in a ST application, since the high voltage and current level demand for a highly modular system. Losses can be modified by circulating the power among the cells or by unbalancing the power sharing to preserve the most damaged cells.

#### D. Potential of the active thermal control approaches for the different applications

The potential of the various approaches is highly dependent on the mission profile of the application. For this reason, it is impossible to give a generally valid quantification of the potential.

The basic difference between electric drives and renewable/grid application is the variable speed operation. In fact, in addition to the mission profile variation, the low fundamental frequency operation can already induce very high thermal stress. Instead, for the other two applications the mission profile is inducing the dominant thermal cycles. The thermal cycles affecting the power semiconductors of renewable energy systems are dependent on the fluctuations induced by the weather conditions. These cycles are expected to occur in more and shorter time periods compared to the power variations of the Smart Transformer.

As a consequence, for the application in electric drives, the approaches having an immediate effect are promising. This are the gate driver and the switching frequency control in this application. The modulation is a limited instrument also acting on the losses of the single device, which is limited in its application. The control of the DC-link is only feasible if the DC-link is fed by a converter, which is also limiting the applicability of the approach. The mission profile shaping in this application does not seem to be feasible.

In the application of renewable energy systems, the duration of the power cycles is longer than in the electric drives, which is why the gate driver based junction temperature control, the switching frequency control and the variation of the modulation are counteracted by the costs for the additional losses for potentially long periods. Due to the limitation in the potential DC-link voltage variation, this approach is also not promising. Instead, the control of the active and reactive power in the parallel stacked converters does have a high potential and the shaping of the mission profile is possible as discussed.

For the ST, the promising approaches are similar to the renewable energy systems, because of the very long time periods of the cycles. The mission profile shaping by the saturation of the control variables in the grid instead does not increase costs, but only reduces the stress. This makes it promising to be applied for the shaping of thermal cycles with long time periods.

## VI. CONCLUSION

Active thermal control is a technique to reduce the thermal stress of power semiconductors for achieving higher reliability of the system. The active actions can happen at several levels, from the very low-level of the gate driver, to the system level, where the presence of multiple power converters is exploited. With the possible benefits of avoiding the components de-rating or of increasing their lifetime, the thermal limits of the power semiconductors are exploited.

Depending on the application and its mission profile, the severe thermal cycles can have different duration. The controller design needs to consider the redundancies in the system as well as the potential costs for higher losses or less energy

production in renewable energy sources. For the three applications of electric drives, renewable energy generation and smart transformer potential active thermal control algorithms have been reviewed and evaluated. While thermal cycling in short time periods, like it is occurring in electric drives, may justify a short time increase of costs, the compensation of long term cycles needs to be addressed with other algorithms. For these long time periods, profile shaping algorithms or algorithms, which utilize potential redundancies seem to be more suitable.

Based on the reviewed material, several techniques showed potential in reducing the thermal stress of the power semiconductors. Linking this stress reduction to an actual lifetime extension is still a missing point, that could be addressed with accelerated tests or with the implementation of pilot projects in cooperation with Industry. This would also allow improved tuning procedures to reach the desired efficiency/lifetime trade-off.

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TABLE I: Potential of the existent active thermal control algorithms in the three considered applications.

Active thermal control approach	Electric drives	Renewable energy systems	Smart Transformer
Gate driver $T_j$ control	High	Medium	Medium
Switching frequency control	High	Medium	Medium
Modulation	Medium	Medium	Medium
DC-link voltage control	Medium	Low	Low
Q control	Low	High	Low
P control	No	High	High
Profile shaping	No	High	High

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**Markus Andresen** (S'15) received his B.Sc and M.Sc in electrical engineering and business administration from Christian-Albrechts-University of Kiel, Kiel, Germany. Since 2013 he is working towards his Ph.D degree from the chair of power electronics at Christian-Albrechts-University of Kiel, Germany. In 2010, he was an intern in the Delta Shanghai Design Center at Delta Electronics (Shanghai) Co., Ltd., China. He is a student member of the IEEE Industrial Electronics Society. His current research interests include control of power converters and

reliability in power electronics.



**Ke Ma** (S'09-M'11) received the B.Sc. and M.Sc. degrees in electrical engineering from the Zhejiang University, China in 2007 and 2010 respectively. He received the Ph.D. degree from the Aalborg University, Denmark in 2013, where he was a Postdoc in 2013 and became an Assistant Professor in 2014. In 2016 he joined the faculty of Shanghai Jiao Tong University, China as a tenure-track Assistant Professor. His current research interests include the design and enhancement of power electronics reliability in the application of renewable energy and motor

drive systems. He is now serving as Associate Editor for *IEEE Transactions on Industry Applications*, and Guest Associate Editor for *IEEE Journal of Emerging and Selected Topics in Power Electronics*. In 2016 He was recruited by the "Thousand Talents Plan Program for Young Professionals" of China. He was the receiver of "Excellent Young Wind Doctor Award 2014" by European Academy of Wind Energy, and a few prized paper awards by IEEE.



**Giampaolo Buticchi** (S'10-M'13) was born in Parma, Italy, in 1985. He received the Masters degree in Electronic Engineering in 2009 and the Ph.D degree in Information Technologies in 2013 from the University of Parma, Italy. He is now working as a postdoctoral research associate at the University of Kiel, Germany. His research area is focused on power electronics for renewable energy systems, smart transformer fed micro-grids and reliability in power electronics.



**Johannes Falck** received the M.Sc. degree in Electrical & Information Engineering from Kiel University, Germany, in 2015. Afterwards he began a PhD at Kiel University in junction temperature control of power semiconductor devices connected to electric drives to improve lifetime. His research interests include reliability in power electronics, active thermal control, finite control set model predictive control, induction motor control, model-based junction temperature estimation and accelerated lifetime tests.



**Frede Blaabjerg** (S'86-M'88-SM'97-F'03) was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. From 1988 to 1992, he was a Ph.D. Student with Aalborg University, Aalborg, Denmark. He became an Assistant Professor in 1992, Associate Professor in 1996, and Full Professor of power electronics and drives in 1998. His current research interests include power electronics and its applications such as in wind turbines, PV systems, reliability, harmonics and adjustable speed drives. He has received 17 IEEE Prize Paper Awards, the

IEEE PELS Distinguished Service Award in 2009, the EPE-PEMC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014 and the Villum Kann Rasmussen Research Award 2014. He was an Editor-in-Chief of the *IEEE TRANSACTIONS ON POWER ELECTRONICS* from 2006 to 2012. He is nominated in 2014 and 2015 by Thomson Reuters to be between the most 250 cited researchers in Engineering in the world.



**Marco Liserre** (S'00-M'02-SM'07-F'13) is Full Professor and Head of the Chair of Power Electronics at the University of Kiel (Germany). He has published over 200 technical papers (1/3 in international peer-reviewed journals) and a book at second reprint and also translated in Chinese. These works have received more than 15000 citations, for this reason he is listed in ISI Thomson report "The world's most influential scientific minds" from 2014. He has been awarded with an European ERC Consolidator Grant, one of the most prestigious in

Europe. He is member of IAS, PELS, PES and IES. He did serve all these societies in various capacities such as reviewer, associate editor, editor, conference chairman or track chairman. He has been founding Editor-in-Chief of the *IEEE Industrial Electronics Magazine*, founding Chairman of the Technical Committee on Renewable Energy Systems, and IES Vice-President responsible of the publications. He has received several IEEE Awards.