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Active methods to Improve Reliability in Power Electronics

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***Abstract*—Reliability of power electronics is a critical issue, as most of the electrical energy is processed by power electronics. Various stressors impact the safe operation of the systems, including harsh environments, temperature variations, humidity, vibration and radiation. Physics of failure analysis uses models that describe how failure mechanisms evolve over time and induce failures. Active methods help to increase the reliability during operation. These methods rely on intelligent control that help to avoid operation conditions that affect stress that lead to failures. This paper provides an overview on recent active methods to increase the reliability of power electronics and categorizes them according to their impact on reliability, invasiveness to system operation and open research opportunities. An industry perspective taken from a survey in the end of 2016 is included to rate how promising the different methods are considered.**

I. Introduction

Power electronics is increasingly used in a wide range of application fields such as variable speed drives, electric vehicles and renewable energy systems. It is becoming a crucial component for further development of emerging application fields like microgrids, lighting, more-electric aircrafts and medical systems [1]. The reliable operation of power electronics components and systems is consequently becoming a prerequisite for the safety of several key areas like energy, medical and transportation [2].

The reliability of a system indicates the probability that it will perform the required function without failure under stated conditions for a specified period of time [3]. It is an essential indicator for any power electronic system. Stressors like temperature, humidity, radiation and mechanical impacts quicken the aging of power electronics systems and increase the probability of failures [4].

This paper gives an overview on active methods to improve the reliability. These are software-based control structures that are applied during operation. The goal is changing system operation to release stress from its components while allowing none or only minor influence the overall performance. In collaboration with condition monitoring, which allows to obtain the health status of the system's components [5] and is used to predict reliability [6], an intelligent control can drive components with respect to their remaining lifetime [7].

The active methods distinguish from other methods that also increase the reliability of power electronics systems shown in Fig. 1: In the design process of the system's components the term Design for Reliability (DFR) is key [8], [9]. Its goal is to assure sufficient robustness of the system by proper engineering [10]. Load profiles for the components are computed regarding the stressors that occur during field operation [11]. Using the stress analysis, the necessary strength of the system is determined [12], which is usually a multi-parameter problem [13].

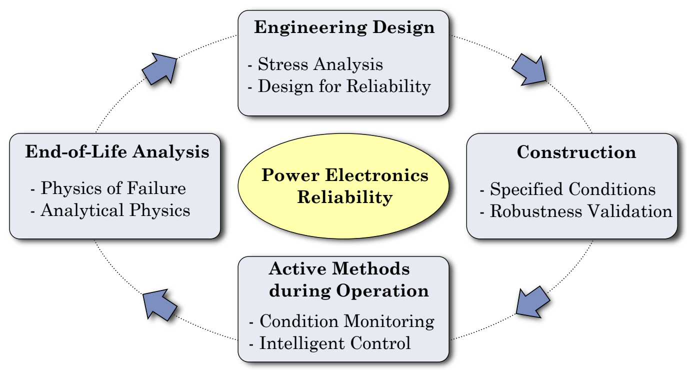

Fig. 1. Methods to improve the reliability of power electronics systems from design to end-of-life.

In the construction process of the system's components product testing routines are used to detect abnormal performance that may lead to early failures in the final product.

In the end-of-life analysis, the triggering failure mechanism is tracked down to its root cause in order to improve the weak point in the design stage of upcoming product versions. This procedure is a Physics of Failure (POF) approach. It is based on the understanding of the relationships between requirements and the physical characteristics of the product and the reaction of product elements to stressors and their influence on the degradation with respect to the use conditions and operating time [10].

In the following active methods to increase the reliability are studied in section II and experimentally demonstrated in section III. An assessment of these methods is given in section IV and an industry perspective on the usability is presented in section V. The paper is concluded in section VI.

II. Active methods to increase reliability

Active methods to increase reliability of power electronic systems act during the normal operation in an application. They distinguish from passive methods like over-rating and redundancy of components by reacting on harmful operation points in order to reduce the stress to the system. For power electronics, the most severe stressors are related to the temperature [14]. Active methods are well suited to react on

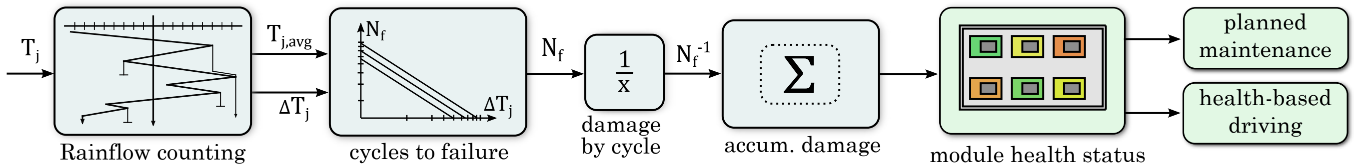

Fig. 2. Block scheme of model-based condition monitoring applied to a power semiconductor module.

temperature related stressors regarding semiconductors [15] and capacitors [16].

A. Condition Monitoring of IGBT modules

The concept of Condition Monitoring (CM) is to assess the current health status of a system component [17]. This allows to make a prediction of the upcoming time of reliable operation and to detect incipient faults in order to take corrective actions before failures occur. Maintenance can be scheduled according to the system's needs instead of sticking to fixed intervals.

The CM can be applied to obtain the health status of power semiconductor modules. A possible concept that considers the stressors temperature swing and average temperature is shown in Fig. 2. The thermal swing can be extracted from the mission profile using the rainflow counting algorithm [18]. A model that links the taken stress to the consumed lifetime of a component is necessary. This can be obtained by accelerated lifetime tests in which the component is stressed with controlled dosage until its end-of-life. Miner's rule is applied to accumulate the damage [19]. Thus, the cumulative damage will rise the more stress occurs in the mission profiles. If the cumulative damage reaches 1, the component will fail according to the aging model [20]. The main advantage is the sheer software implementation, which can operate without additional hardware.

The data for the aging model can be obtained from the LESIT study, which includes a series of accelerated lifetime tests on IGBT modules [21]. The number of cycles to failure N_f is described in dependency of the amplitude of thermal cycles ΔT_j and the average temperature $T_{j,avg}$. Other coefficients consider the mechanical properties of the module and the electrical parameters of the operating point. Its analytical equation is:

$$N_f = A \cdot \Delta T_j^{\beta_1} \cdot exp\left(\frac{\beta_2}{T_{j,min}}\right) \cdot t_{on}^{\beta_3} \cdot i_B^{\beta_4} \cdot V_C^{\beta_5} \cdot d_b^{\beta_6} \quad (1)$$

The parameters of this model are the thermal cycle amplitude ΔT_j, the minimum chip temperature $T_{j,min}$, the pulse duration t_{on}, the current per bond foot i_B, voltage class V_C, bond wire diameter d_b and the empirically determined coefficients A and β_{1-6}. An overview on other lifetime models for IGBT modules are given in [22]. The accumulated damage is derived with Miner's rule and represents the current health status of the semiconductor.

Instead of a model-based estimation, the system's health status can be obtained by measurement of suitable parameters. The aging model shown in the previous paragraph is not essential for this approach. However, additional sensors and software evaluation is necessary.

Sensor-driven condition monitoring has been applied for detection of bond-wire lift off in power semiconductor modules. In [23] external dc currents are injected into the power unit to detect loosened bond wires. Another possibility is to use an electronic speckle pattern interferometry to measure optical displacement or strain of wire-bonds during operation [24]. The need for additional sensors is an additional invasiveness to the system.

B. Condition Monitoring of electrolytic capacitors

A well accepted lifetime model for electrolytic capacitors is given in [25]. The equation to describe the lifetime L_0 is:

$$L = L_0 \cdot 2^{\frac{T_{max}-T_h}{10K}} \cdot 2^{1-\left(\frac{I_a}{I_0}\right)^2 \cdot \frac{\Delta T_0}{A}} \cdot \left(\frac{V_a}{V_0}\right)^{-m} \quad (2)$$

In this equation T_{max} is the maximum permissible temperature, I_a is the applied capacitor current, I_0 is the rated capacitor current, ΔT_0 is the temperature increase when I_0 is applied, A is the temperature coefficient, V_a is the applied voltage, V_0 is the nominal voltage, and m is a manufacturer dependent voltage factor. The model consists of three parts, where each part is considering one of three major stressors: First the impact of the hotspot temperature T_h follows the Arrhenius rule, which constitutes a doubling in lifetime for each $10\,\text{K}$ temperature decrease. Second is the ripple current which is acting on the temperature rise. Third the applied voltage is taken into account, as an increasing voltage level causes degradation due to electrolyte evaporation effects [25].

To apply equation (2) the knowledge of the hotspot temperature within the capacitor is most challenging. In [26] a non-invasive capacitor hotspot temperature estimation is presented and validated experimentally. The method utilizes the linear relation between hotspot temperature and capacitance:

$$C(T_h) = p_1 \cdot T_h + C_0 \quad (3)$$

In this equation p_1 is the linear slope and C_0 is a constant. The values can be obtained in a series of experiments for each type of electrolytic capacitor. When applying the hotspot temperature to the lifetime model, a basic brick in the field of condition monitoring of electrolytic capacitors is given.

C. Health-based driving using CM

The health information given by the condition monitoring can be used for health-based driving of the monitored components. This is illustrated in the left of Fig. 2 for a power electronics IGBT module. When the first chip on the module fails, the system has to be shut down and the whole module must be replaced. The controller of the health-based driving can release the stress from the most damaged chips in the

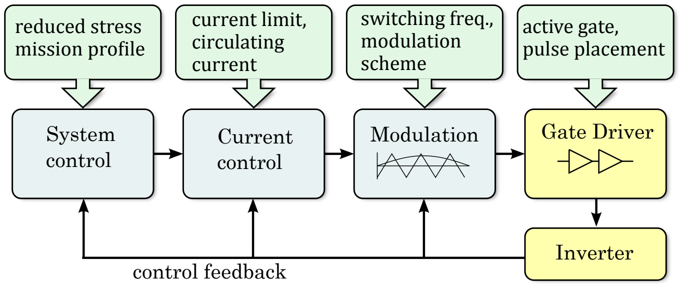

Fig. 3. Classification of parameters for Active thermal control by point of interaction with the power electronics control system.

module. As a consequence the time to failure can be increased and the module durability is consumed more efficient. To realize the health-based driving, the controller must be capable to influence the stress on specific semiconductors in the module. A possibility is to use direct control schemes like the Finite Control Set Model Predictive Control (FCS-MPC) as it is capable to control the conducting of each switch on a module individually [7].

The same concept can theoretically be employed for capacitor arrays. However, influencing the stress of single capacitors in a capacitor array implies additional active circuits.

D. Active thermal control by means of power routing

Power routing can be used to unevenly load building blocks in modular power converters and thereby control the stress for all devices in one building block [27]. It is proposed to equalize the useful remaining lifetime of the building blocks in a modular power converter. This was proposed for series connected building blocks [28], parallel connected building blocks [29] and building blocks connected by a multi-port transformer [30]. The advantage of the method is the low impact on the efficiency, whereas a disadvantage is increases stress for other building blocks in the system.

E. Active thermal control of IGBT modules

Active thermal control uses temperature related control parameters to influence the junction temperatures of power semiconductor modules online. The goal is to reduce the thermal stress in the module by smoothing the temperature variation. To influence the junction temperatures, the active thermal control increases or decreases the losses in the desired chips temporary. A classification of chosen control parameters by the hierarchic level of interaction with the system is done in Fig. 3. The levels reach from system control down to the gate driver. On the layer of the current control a variation of the current limit [31], circulating current among parallel connected converters [32] and circulating reactive power [33] have been applied to control the junction temperature. On the layer of the modulator a selection of the switching frequency [34] and the modulation method [35] have been applied. On hardware layer the gate voltage has been adjusted [36]. An electro-thermal model can be used to achieve online estimations of the junction temperatures on the basis of electrical measurements or Thermo-Sensitive Electrical Parameters (TSEP) [37].

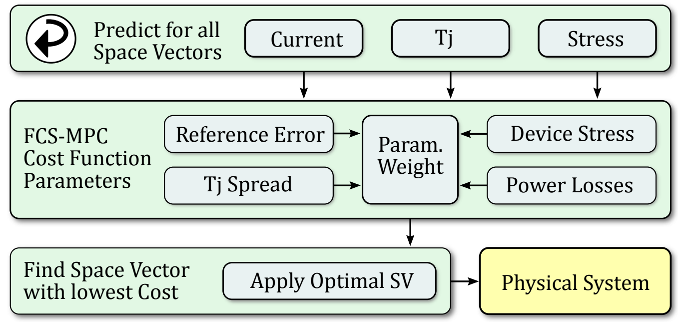

Fig. 4. Active thermal control structure using Finite Control Set Model Predictive Control (FCS-MPC).

Fig. 4 shows a thermal control scheme using the Finite Control Set Model Predictive Control (FCS-MPC) to control the amplitude of thermal cycles [7]. The load current, junction temperature and the resulting thermal stress are predicted for all space vectors of the next sampling instant. These predictions are used to derive the FCS-MPC cost function parameters that include the error from the current reference, the thermal stress on the device, the temperature difference between the chips on a power module and the total power losses from switching and conduction the semiconductors. These parameters are weighted and the space vector with the lowest cost function is directly applied to the power converter.

F. Active capacitor voltage ripple reduction

A characteristic of single-phase ac line connected rectifiers is the pulsating power transfer that occurs to the dc bus, which generates a ripple on the dc bus voltage at twice the line frequency when the input voltage and current are sinusoidal [38]. The voltage ripple is usually reduced by usage of dc link capacitors. However, the voltage ripple is a critical stressor on aluminum electrolytic capacitors, metallized polypropylene film capacitors and high capacitance multi-layer ceramic capacitors [9]. Thus, active ripple reduction circuits and voltage compensators have been proposed [39]. The reliability of the capacitor part is improved, however, the additional circuits and control schemes will induce new potential failures.

III. Experimental demonstration

The experimental demonstration is divided in a part concerning reliability of an IGBT power module and an AL-capacitor. For experimental validation a three-phase two-level dc/ac inverter with an open IBGT module is used. A high speed infrared camera is used to measure the IGBT junction temperatures. For capacitor temperature sensing a fiber optic is integrated into an aluminum electrolytic capacitor. Photographs of the test setups are given in Fig. 5.

A. Thermal stress reduction for power modules

The active thermal control has been implemented to reduce the thermal stress in the IGBT module on the test setup. The mission profile of an industrial process shown in Fig. 6 is applied. For comparison the process is also run without the

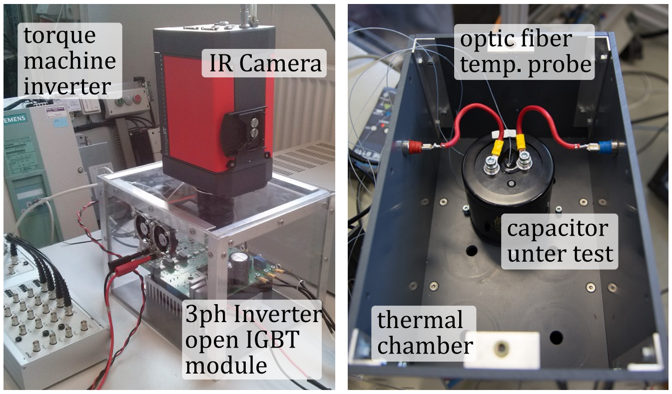

Fig. 5. Left: Three-phase inverter experimental setup. The infrared camera is used to measure the semiconductor temperature profile of an opened IGBT module during operation. Right: AL Capacitor in a thermal chamber. Optic fiber sensors are used to monitor the temperature inside and on the capacitor.

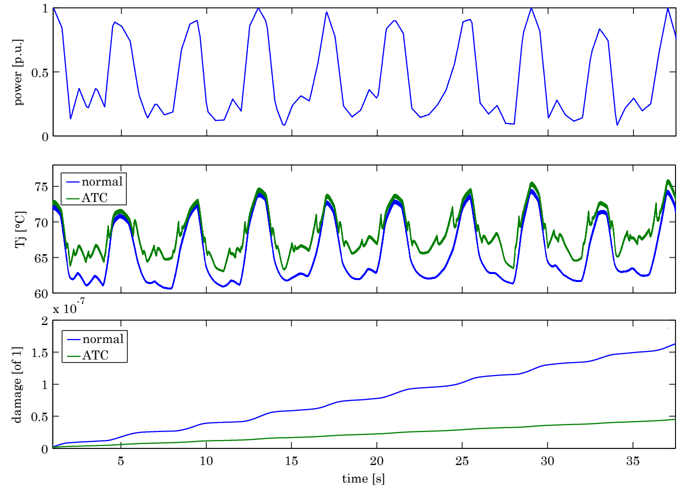

Fig. 6. Experimental demonstration of the active thermal control and model-based condition monitoring. A mission profile of an industrial process is driven on the machine-connected inverter.

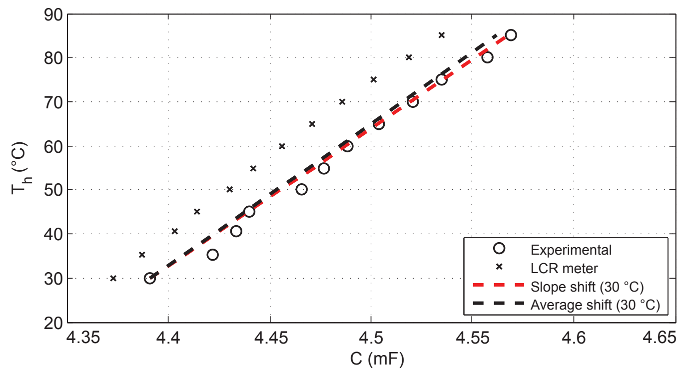

Fig. 7. Experimental demonstration of capacitor hotspot temperature estimation on basis of electrical capacitance measurement [16].

thermal control. A reduction of the thermal cycling amplitude of about 10 % to 30 % can be observed. The model-based condition monitoring according to Fig. 2 has been applied to show the accumulated damage in both cases. The slope of the accumulated damage over time is reduced to a third of its initial value. The reduction in the damage affects an increase of the remaining useful lifetime.

B. Capacitor hotspot temperature estimation

This experiment demonstrated the online monitoring of the hotspot temperature based on the linear dependence between capacitance and temperature of electrolytic capacitors presented in section II-B. For this, a set of nine samples of the same aluminum capacitor type is characterized by means of capacitance measurements at different hotspot temperatures. The obtained linear correlation is used to calibrate hotspot temperature estimation for the investigated electrolytic capacitor type. The experimental results in Fig. 7 validate that the temperature estimation error of the proposed method is well below 5 K. Thus, the proposed procedure can be used as a basis for future research on improving condition monitoring of electrolytic capacitors.

IV. Assessment of the Methods

The active methods to increase the reliability are assessed according their potential to improve the reliability, their invasiveness to the system and their effort for integration to a system. The results are shown in Fig. 8 and explained in the following.

The potential to improve reliability in condition monitoring methods is to detect failures prior to the end of life. The degradation of affected components can be observed and actions like operating in safe mode or planed maintenance can be conducted. The accuracy for sensor-driven condition monitoring is evaluated higher than model-based condition monitoring as the design of the model is more prone to errors. However, additional sensors are necessary in contrast to the model-based version which is an additional feasibility for failures. The condition monitoring is not an active method to increase the reliability according to the definition given in the introduction. However, the health-based driving is a promising application of the condition monitoring. Active thermal control reduces the thermal stress in the components without adding additional hardware. Active voltage ripple reduction can improve the capacitor lifetime. However, the additional circuit adds additional feasibility for failures.

The invasiveness to the operation includes both, additional hardware components and changing of the system's operating point. The condition monitoring has either none or only minor affect the the system operation as short test currents may be injected. For the active thermal control it depends on the control parameter. Current limits, circulating currents between parallel components or varying switching frequency can influence the system's operation. However, the parameters are chosen for minimal impact on the intended mission profile. The active voltage ripple reduction can be designed to have no influence in the system's operation.

V. Industry Perspective

To obtain an overview of the reliability related issues relevant for power electronic systems an industry-wide survey was conducted with collaboration of the network of European Companies in Power Electronics (ECPE) [40].

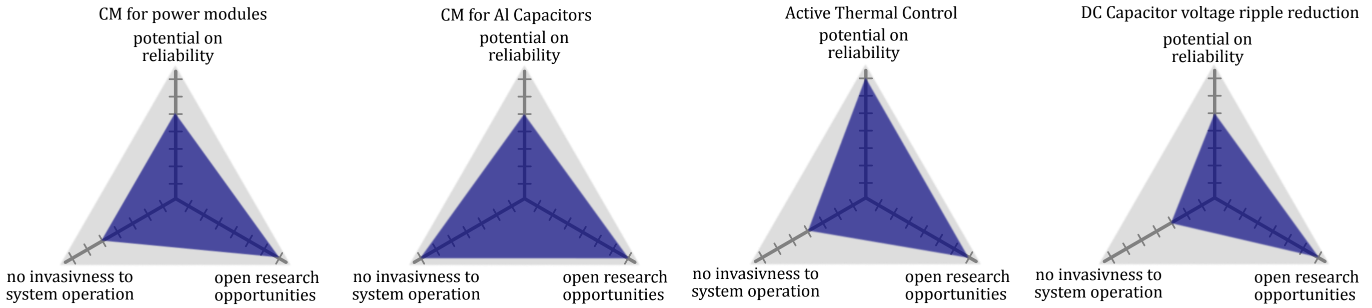

Fig. 8. Assessment of active methods to increase the reliability according impact on reliability, invasiveness to system operation and open research opportunities.

A. Survey methodology

The survey was circulated to approximately 360 selected experts in industry inside the ECPE network. Over a period of two months a total of 51 responses were received in the end of 2016. The survey was laid out to get an overview of the perceived reliability issues and the view on the current state of research and to identify possible future approaches that may support further reliability improvements. For this paper, two questions of the survey have been selected to support the assessment of the active methods to improve reliability.

The questions were asked to evaluate the potential of these methods in improving the reliability of power electronic systems. Both, active and passive methods are analyzed to obtain a comparison. The questions and results are given in Fig. 9 and Fig. 10. Passive methods are marked in blue color and active methods are marked in green color.

B. Survey results

The results of Fig. 9 show that all mentioned methods are evaluated as overall beneficial, as all mean values lie in the upper half. The standard deviation is moderate for all bars. The active methods better than the passive methods. Especially the usage of condition monitoring is evaluated to be promising.

In Fig. 10 the five methods to increase reliability had to be ranked. To analyze the results 5 points were assigned to each option if it was selected as the highest ranking option, 4 points for second and so on. As a result, the usage of components that proved reliability have the highest priority, followed by the two selectable active methods. The other passive methods are given less points.

VI. Conclusion

A critical survey on active methods to increase the reliability of power electronics converters has been given with some possible examples. The methods have been assessed according their potential to improve the reliability, their invasiveness to the system and their effort for integration to a system.

Active methods are part of the overall concept to increase the reliability of power electronics systems. Condition monitoring has none or only minor impact on the operation of the system and can provide useful information on the systems fitness in use, which allows to anticipate the time of reliable operation. Active thermal control can be implemented as a pure software approach. This makes it a low-cost solution

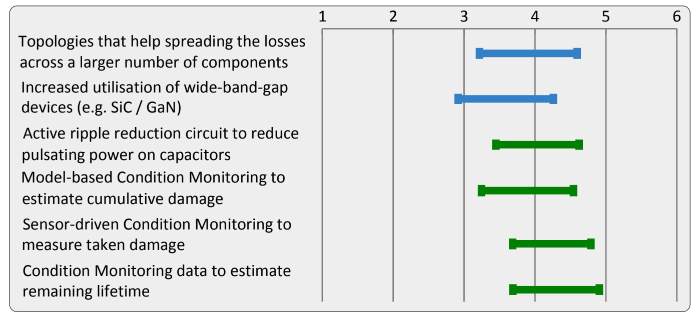

Fig. 9. Industry survey results on question: Which trends or approaches will improve the system reliability of power electronic converters in the future? Scale: Not beneficial 1 to very beneficial 6. The bars show the standard deviation around the mean value.

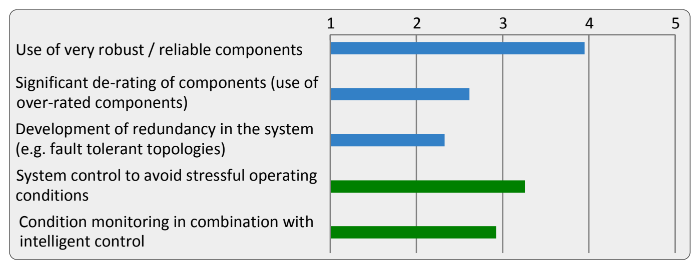

Fig. 10. Industry survey results on task: Please rank the following options to achieve high reliability for power electronic systems. Highest priority 5 points to lowest priority 1 point. The bars show the mean values of all answers.

to reduce the thermal stress during operation. The capacitor voltage ripple reduction is applicable for dc-link capacitors, which has a great potential because of their frequent use.

Experimental demonstration of an controller to reduce the thermal stress of an power module and the sensorless capacitor hotspot temperature estimation show the applicability of active methods during operation.

The industry survey substantiates the beneficial deployment of the methods as they were evaluated more promising to help increasing the systems reliability than design-based methods.

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