View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by MACAU: Open Access Repository of Kiel University

© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Digital Object Identifier (DOI): 10.1109/MIE.2018.2825481

IEEE Industrial Electronics Magazine (Volume: 12, Issue: 2, June. 2018)

Reliability of Power Electronic Systems: An Industry Perspective

Johannes Falck
Christian Felgemacher
Andreja Rojko
Marco Liserre
Peter Zacharias

Suggested Citation

J. Falck, C. Felgemacher, A. Rojko, M. Liserre and P. Zacharias, "Reliability of Power Electronic Systems: An Industry Perspective," in *IEEE Industrial Electronics Magazine*, vol. 12, no. 2, pp. 24-35, June 2018.

Reliability of power electronic systems: An industry perspective

Johannes Falck, Christian Felgemacher, Andreja Rojko, Marco Liserre, Peter Zacharias

I. Introduction

Power electronic systems are used increasingly in a wide range of application fields such as variable speed drives, electric vehicles and renewable energy systems. It has become a crucial component for the further development of emerging application fields such as lighting, more-electric aircrafts and medical systems [1]. The reliable operation over the designed lifetime is essential for any power electronic system [2], particularly because the reliability of power electronics is becoming a prerequisite for the system safety in several key areas like energy, medicine and transportation [3].

Demanding operation environments challenge the reliability aspects of power electronic systems [4]. Depending on the application of a specific system, several stressors like high temperatures, temperature cycling, humidity, dust, vibration, EMI and radiation can endanger the safe operation of its components. The large number of fragile components in power electronic systems includes semiconductors, capacitors, magnetics, controllers, sensors and auxiliary devices. Failures of a single component causes downtime and cost for maintenance.

The need for reliable systems forces both, academia and industry to address advances in the reliability research [5]. The aim of this paper is to identify the industrial challenges on which the future research and development (R&D) should focus in order to address the application specific reliability issues. The work is based on information obtained from a survey that included a large pool of power electronic systems reliability experts from the industry.

The structure of the paper is as follows: Relevant components of power electronic systems are identified first. For these components critical stressors and failure mechanisms are investigated for a broad range of power electronics applications. Next possible reliability measures are reviewed

and their utilization in industry is questioned. Finally, based on the findings, it is concluded: (1) on what the future reliability R&D should be focused and (2) how this R&D should be conducted in order to maximize the gain for industrial power electronic systems.

Until now only very few wider survey-based investigations of reliability aspects of power electronic systems as seen by the experts have been accomplished. Most surveys were conducted within the wind power industry and deal with the wind park availability, the comparison of different turbine concepts and the reliability of the subassemblies [6]. However, all these investigations only encompass the analysis of failure rates of the components of power electronic systems. The only industry-wide survey reported in literature was conducted in 2008 [7]. It also takes into account the analysis of stressors.

For this article, a comprehensive industry-wide survey was recently conducted with collaboration of the international organization European Center for Power Electronics (ECPE). The survey was circulated to the selected reliability experts from ECPE member companies resulting in 51 extensive responses.

The survey served to get an overview of the perceived reliability issues and the view on the current state of research in this field. It also helped to identify possible future approaches that may support further reliability improvements. In the initial section, the participants were asked to select for which application fields they would like to answer the application specific questions in the application specific sections. Each participant was able to perform the application specific part of the survey for multiple application fields. The distribution of the responses in the application specific part is given in Table I. The later sections of the survey are applicable to power electronic systems in general and are thus based on the results of the 51 participants, as this section was only completed once by each participant.

II. Components in power electronic systems

With increasing demands on power electronic systems in terms of its functions and performance, the complexity of these systems rises. The system level schematics of a wind power system, photovoltaic system and electric vehicle are shown. The system components are grouped in categories given in Fig. 1.

The block diagram of a generic wind power system is shown in Fig. 2. Mechanical components include the rotor, pitch and yaw system, gearbox and wind measurements. The generator side

TABLE I

DISTRIBUTION OF RESPONSES ACROSS THE DIFFERENT APPLICATION FIELDS.

Application	Responses
All	83
Wind Power	8
Photovoltaic	9
Electric Vehicles	21
Drive Systems	20
Traction	8
UPS & Power Supplies	7
Lighting	2
Air & Spacecraft	5
Energy Transmission	3

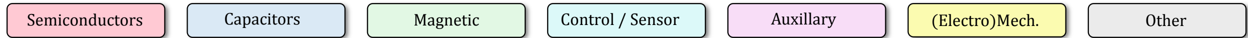

Fig. 1. Classification of power electronic system components.

converter is controlled using maximum power point tracking (MPPT). A grid side converter handles the grid feeding.

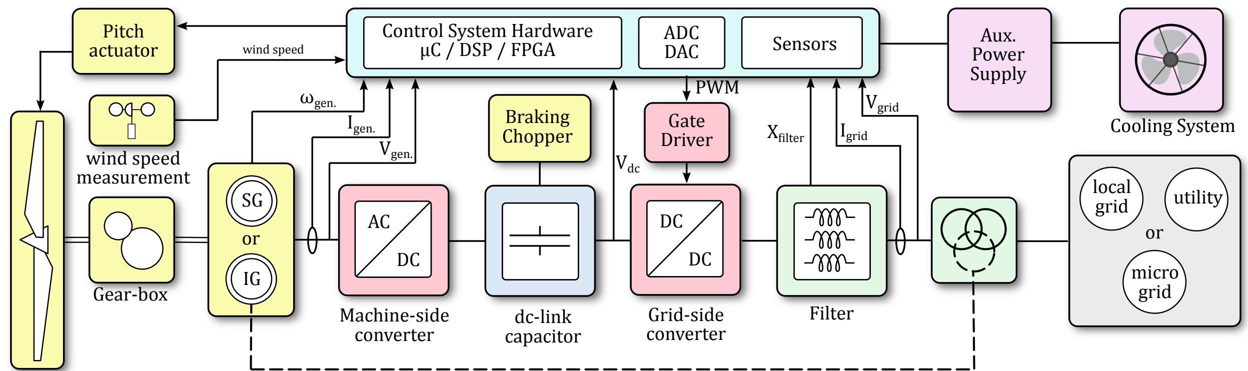

Fig. 2. Components of a wind power system.

The photovoltaic system shown in Fig. 3 gives a more detailed view of a power electronic system, as it also covers the relays to disconnect from the grid and relays for bypassing the boost converter to increase efficiency.

A system overview of an electric vehicle and a charging station is given in Fig. 4. In addition

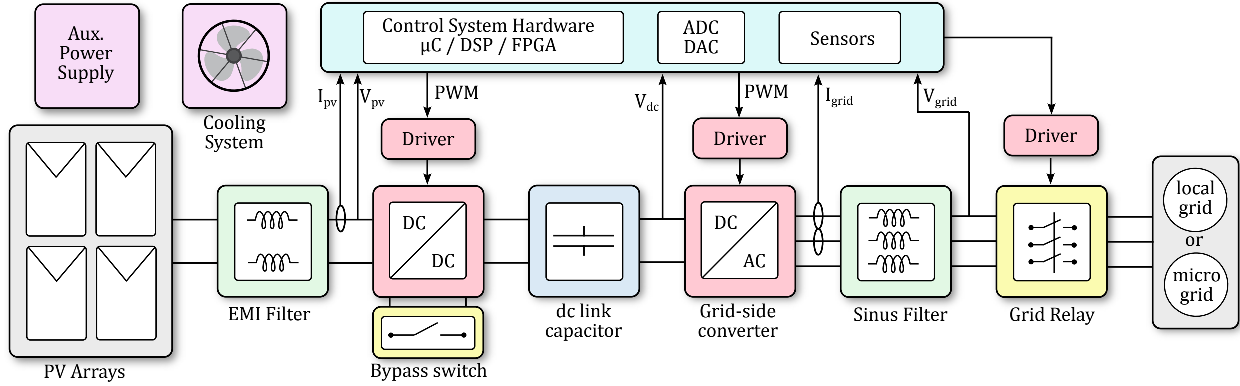

Fig. 3. Components of a photovoltaic system.

to the electric drive system (electric motor and inverter), various electromechanic auxiliary subsystems are additionally present. An on-board rectifier for AC-charging is installed and a much larger rectifier for fast DC-charging is present in the charging station.

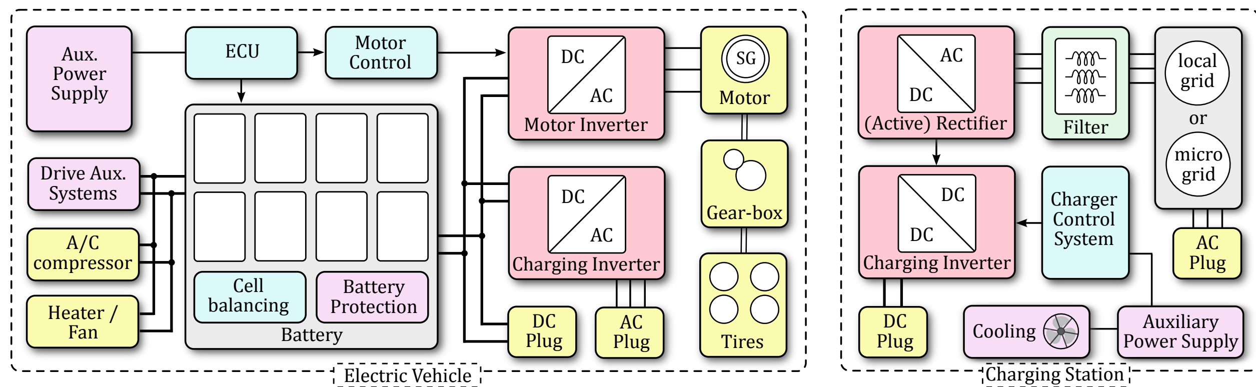

Fig. 4. Components of a electric vehicle system and charging station.

The system level schematics show only the major components and does not include components such as data-busses, communication-links as well as sensing and protection circuitry. The large number of system components increases the risk of malfunction and failures. Therefore, it is very important to address not only the main components like the power semiconductors, capacitors and drivers but also the complete set of system components.

III. Application specific reliability of components

Most critical are the components where the gap between the actual reliability and the required reliability is the highest. To identify such components the elements such as targeted lifetime,

typical stressors and failure mechanisms were analyzed.

From the engineering point of view, reliability is the probability that a system or component will perform a required function without failure under stated conditions for a specified period of time [8]. It is distinguished from robustness, which is the ability of a system to operate adequately over a specified range of parameter variations. Today, the industry is in a paradigm change toward more reliable power electronic systems. Especially the automotive and aerospace industry have raised the reliability requirements of their power electronic systems due to safety requirements [1]. The definition of reliability given above shows three developments that can lead to demands for an increased level of reliability: The required function may become more complex or difficult to fulfill, the stated conditions may become harsher and the specified period of time may increase. For most applications, the required function and the operating conditions are fixed. The required target lifetimes depend on the application, power scale and the target market [5].

A. *Requirements in lifetime*

To find out the expected lifetime of power electronic systems in the in predetermined applications the survey participants were asked on the target lifetime of power electronic systems manufactured by their company. Multiple selections were possible. The responses are given separated by application fields in Fig. 5. Very few respondents indicated that lifetimes shorter than 5 years are typical. Instead, for the most applications, the target lifetime between 5 and 20 years appears to be the norm. A longer target lifetime of 20 to 30 years is expected in wind power systems. These results agree with the investigations of Yang et al. in 2008 [7] and with identified target lifetimes in Wang et al. in 2014 [5]. Further this indicates that the expectancy on power electronic system lifetimes has not changed significantly in the last decade.

B. *Critical stressors*

The components in the power electronic systems are exposed to stressors that depend on the application and the operating conditions. Thus the knowledge of the application relevant stressors is extremely important.

Temperature related stressors affect the reliability of several components of power electronic systems, like the printed circuit boards (PCB), the semiconductors and the capacitors [9]. For

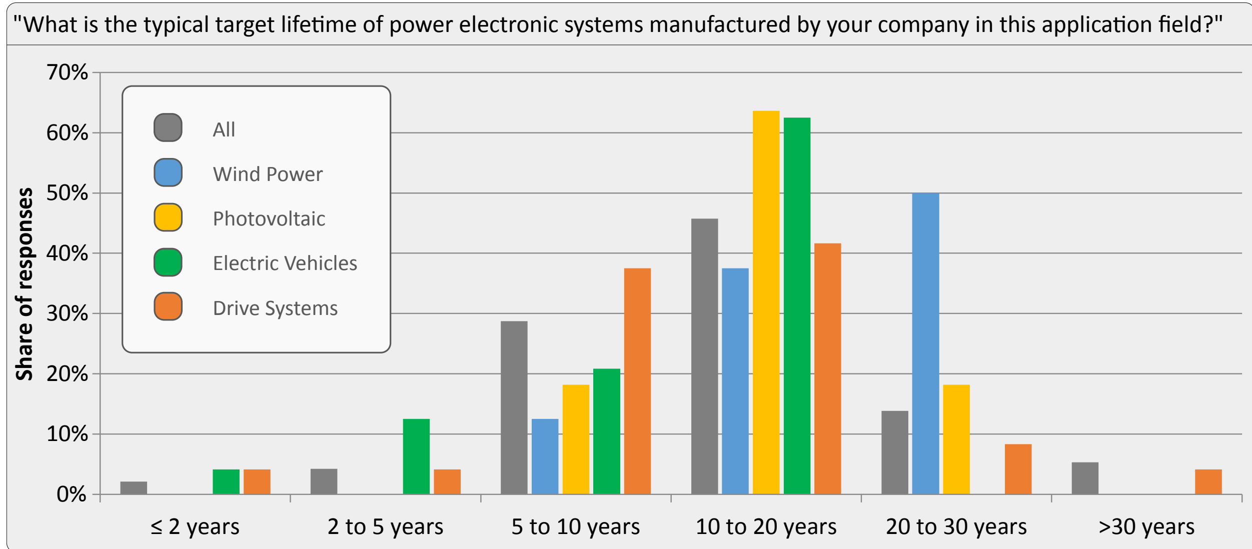

Fig. 5. Typical target lifetimes of power electronic systems by application.

semiconductors it is distinguished between the average and the cycling of the junction temperature. In addition, thermal cycling evoked by ambient temperature and temperature cycles evoked by self-heating of the components also known as power cycling are distinguished. The temperature related stressors are omnipresent stressors, which makes them more relevant. At the same time, thermal cycling due to internal losses is hard to avoid.

Power electronic systems are exposed to a wide variety of ambients including the ones with high humidity. Humidity builds up within the enclosure of the system leads to water condensation, which can cause increased leakage currents and also corrosion [10]. The exposure to cycling ambient temperatures typical for night-day cycles causes significant increase of the water vapor concentration. The effect of humidity has also been studied for printed circuit board assembly.

Mechanic impacts such as vibration and shock primarily affect the robustness of mechanical components and interconnections of electric components [11]. Like most reliability concerns, processes of mechanical fatigue are multi-parameter problems. The combined effect of thermal cycling and mechanical vibration on solder connections is investigated in [12]. The results show that the solder crack propagation on PCBs is increased for the combined stressors compared to the individual stressors.

Sources of electromagnetic interference (EMI) can be found in the power electronic system itself, other electronics within range and the grid. They can endanger the undisturbed operation

of the system permanently. In contrast to EMI, terrestrial cosmic radiation can cause single-event-burnouts on power semiconductors, which has been experimentally shown in 1994 [13] and is still topic of active research. The harmfulness of EMI depends on the possible shielding and density in which the power electronic system is installed.

The participants of the industry survey were asked to rank the discussed stressors according to how critical they are considered to be for the selected application. This is given in Fig. 6. The results aggregated across all applications show that almost all of the considered stressors were judged critical as all received mean scores lie above 3.5. All thermal stressors were considered particularly critical with power cycling identified as the most critical stressor. It can also be observed that mechanical stress such as vibration is certainly application dependent. For many other stressors there is only little difference between the applications. The results were broken down into the different application fields to identify particularly critical stressors in the different applications.

C. Component failure mechanisms

To facilitate the target lifetimes of the whole system the reliability of all system components needs to be ensured. In this section, the failure mechanisms and the resulting failure modes are given for selected components of power electronic systems. They are evaluated regarding their effect on the reliability.

Failures of power semiconductors can be attributed either to failures occurring on chip level or to failures occurring in the package of the semiconductor. In literature, many reviews that describe the various relevant failure mechanisms can be found [14], [15].

Failures on the packaging level are often the consequence of continuously varying thermal stress applied on the interconnections between the semiconductor device and the external contacts of a power module [16]. The temperature variations lead to thermo-mechanical stress since the different components in the power module have varying coefficients of thermal expansion. Over a longer period of time this stress leads to the deterioration of the interconnects as wire-bonds and solder layers within power modules [17].

Device level failures of power semiconductors can occur due to various failure mechanisms. As long as devices are operated within datasheet parameters it may be safe to expect that issues such as parameter shifts and other degradations will not occur. However, overload stress applied to the devices can cause device failures. A specific failure mechanism that cannot be completely

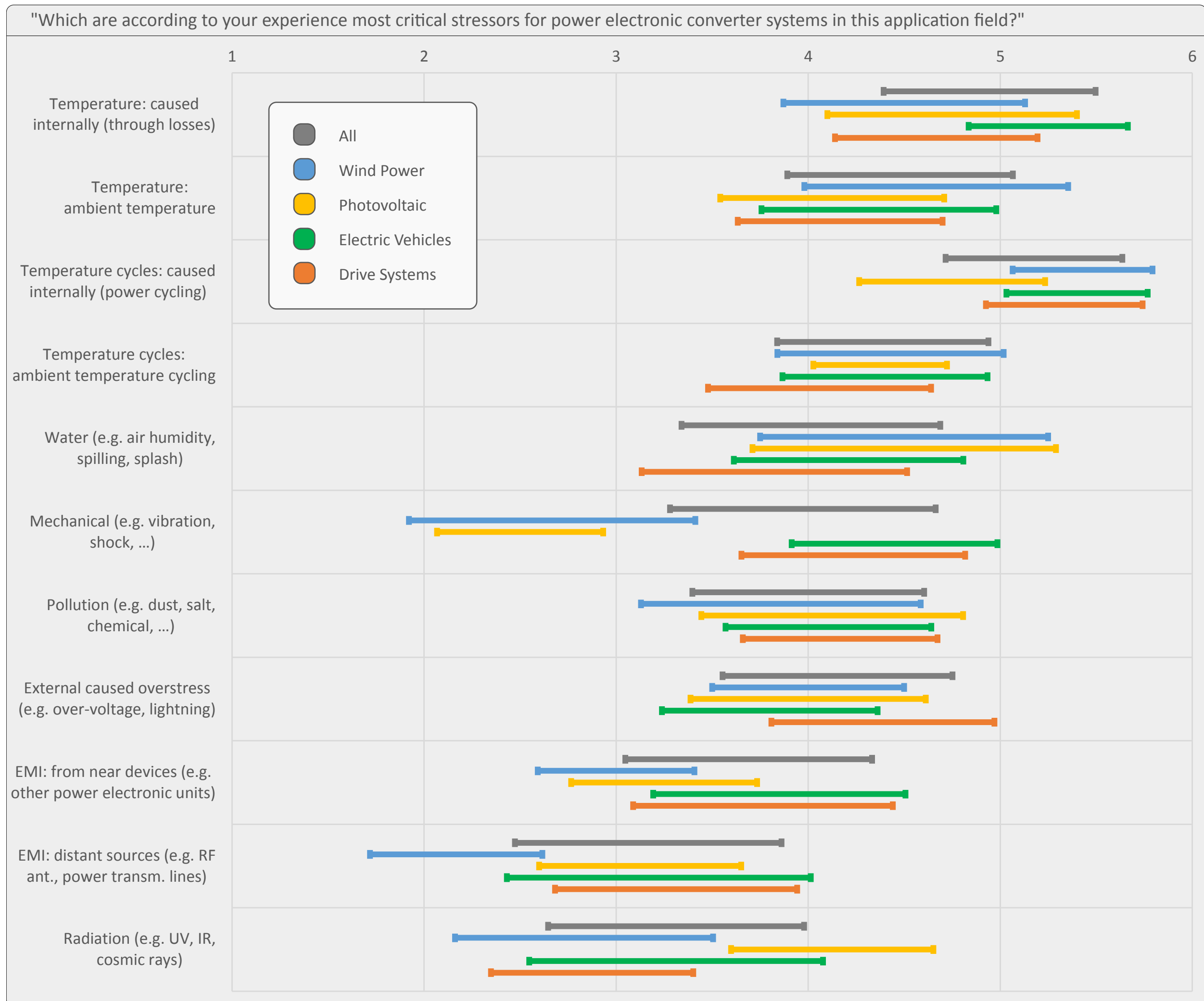

Fig. 6. Critical stressors for power electronic systems by application. The bars show the standard deviation around the mean value. The scale is from 1 (Not critical) to 6 (Very critical).

avoided is single-event-burnout induced by cosmic radiation. In the case of this specific failure mechanism, the robustness of the device and the applied voltage in the application can be analyzed to estimate whether the expected failure rate is acceptable for a given application.

Failures in the driver circuits can also be the reason for a malfunction of the system. An open circuit failure of the driver circuit disrupts the operation of the power electronic system. Delayed switching or short circuit failures can also harm the power semiconductor elements. Integration of driver circuits and sensors into power electronic modules can decrease the occurrence of parasitic elements due to lower paths of the current. However, amplifying circuits are sensitive to EMI, which can occur in direct closeness to the switching elements.

Capacitors are components that are most prone to failures in power electronic systems. The three main types of capacitors are aluminum electrolytic capacitors (Al-Caps), metallized polypropylene film capacitors, (MPPF-Caps) and multilayer ceramic capacitors (MLC-Caps). The wear out mechanisms depend on the type of capacitor. Al-Caps suffer from electrolyte vaporization that is accelerated at high temperatures and ripple currents. Electrochemical reactions are increased by voltage stress. The same stressors and humidity lead to dielectric loss in MPPF-Caps. MLC-Caps suffer from oxide vacancy migration and insulation degradation at the same stressors and vibration [5]. Wear out leads to a drift in the electrical parameters and can give rise to open circuit or closed circuit failure modes as shown in [18].

Printed circuit boards (PCBs) have to maintain their electrical and thermal capabilities in electrical lines and solder joints. Vibration is a main stressor for PCBs. Different resonance frequencies of soldered components and the PCB itself lead to mechanic strain and finally fatigue on the interconnections, which are the solder joints. The relation of vibration to other stressors like frequency, temperature and power cycling [12] were investigated. Humidity caused by both split water and condensation, can compromise board functionality. Deformation and tension during the assembly of the PCB in the case can lead to damaging of the soldered components.

The analysis of stressors, failure mechanisms and failure modes is used to conclude which components are prone to failures. Semiconductors and capacitors are used in the power stage of the system. As these components have a failure mode of short circuit, they are a potentially high risk regarding the safety of the system. For both components, omnipresent stressors like temperature cycles and voltage stress are crucial. Therefore, these components have most reasons to be prone to failures.

For mechanical and electromechanical components and subsystems, vibration and chemical exposure are relevant stressors in addition to temperature. The occurrence of these stressors depends on the application and their operating place. Especially for electric vehicles wide spread environmental conditions may occur which stresses these components.

These results are also reflected in the conducted industry survey. It was asked for components of power electronic systems that are perceived to be susceptible to failure. The participating industry experts were asked to assign scores between 1 (not susceptible) and 6 (very susceptible) to each of the given components. The results are shown in Fig. 7. The components evaluated to be most susceptible to failure across all applications are the semiconductors, both modules

and discrete devices as well as electrolytic capacitors. This result is in agreement with the results of a previous survey conducted in 2008 [7]. Film and ceramic capacitors are next, followed by semiconductor drivers, electro-mechanical components and protection devices and cooling systems. It was further analyzed how the evaluation of the components in terms of their susceptibility to failures varied for the different application fields. The results appear to show little difference between the applications. However, for the application of electric vehicles mechanic and electro-mechanic components are considered more susceptible to failure than in the other applications.

D. Components to focus in future research

Based on the previous analysis on stressors and components along with their possible failure mechanisms and failure modes a reasonable focus of future research is detected. Components that are prone to failures are more important to be addressed by future research. These are the switching devices, capacitors, electromechanical components and cooling systems.

The industry survey participants were asked to define components that are most important to be addressed by future research to improve the reliability of power electronic converter systems. For this question, free text answers were used. The responses were assigned to the previously used categories. This is shown in Fig. 8. It is apparent that the majority of participants wish to see more research to focus on power semiconductors and power semiconductor modules as well as capacitors. In the area of capacitors, electrolytic and film capacitors were named most often. In some of the free text responses, no specific components were named but it was claimed that in general components that are exposed to hash environments such as high temperature or humidity should be addressed.

IV. Potential of methods to improve the reliability

In this section, the potential of methods to improve reliability is identified. In general, two directions of research to increase the reliability of power electronic systems are performed: The first possibility is to detect and reinforce hardware materials and interconnections that are prone to failures. The second approach aims to change the utilization of the components to release the stress.

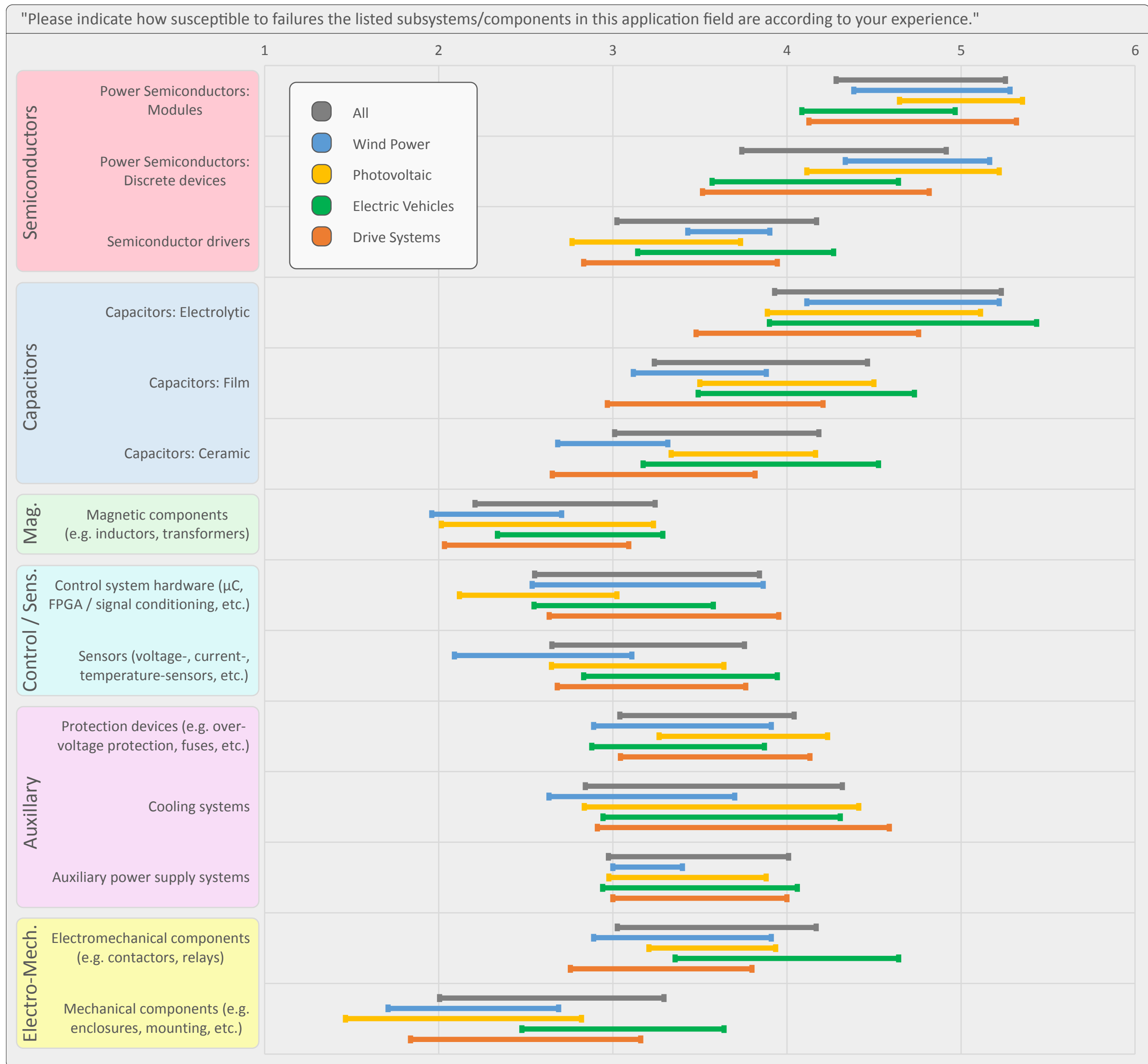

Fig. 7. Critical components of power electronic systems by application. The bars show the standard deviation around the mean. The scale is from 1 (Not critical) to 6 (Very critical).

A. Improved Components

Analyzing of product returns allows detecting components that are prone to failures in a system. This led to several improvements to increase the strength. These improvements can be changes of the material properties as well as optimized utilization to relieve critical stress: Improvements in the connection technology and assembly of the modules have been done [14]. Sintering, also low temperature joining, instead of soldering of the chips is used to increase

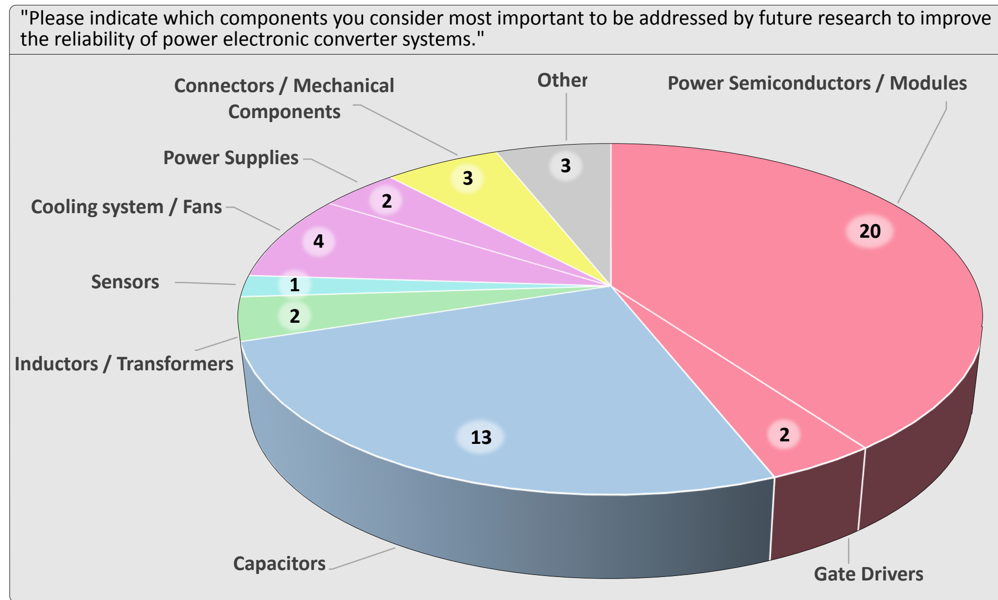

Fig. 8. Components of power electronic systems to be addressed by future research.

robustness of the connections and bonds are replaced by pressure contacts in high reliability product lines [16]. Delaminating of the substrate can be reduced by avoiding $90°$ angles on the pattern [19]. PCB layout and cooling flow can be optimized to enhance the capacitor cooling.

B. Physics of Failure Approach

Physics of Failure (PoF) is an approach that employs the knowledge of the root cause of failure mechanisms to improve product reliability. The concept 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 [5]. The influence of stressors to product components and materials is evaluated according to their influence on the fitness for use. Further variables are their variation in the manufacturing processes, use conditions and time of service [15]. This approach has been applied to increase lifetime and reliability of power electronic modules [9].

The PoF technique is closely connected to the term Design for Reliability [18]. Its goal is to assure sufficient robustness of the system in the design process [5]. Load profiles for the components are computed regarding the stressors that occur during field operation [20]. Using the stress analysis, the necessary strength of the system is determined, which is usually a multi-parameter problem. Fault tolerant topologies are discussed in [21].

C. Active methods

Active methods to improve the reliability 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 [22].

A first method is the Condition Monitoring (CM). The concept of CM is to assess the current health status of a system component and detect incipient faults in order to take corrective actions before failures occur [15]. This allows performing maintenance according to the system's needs instead of sticking to fixed intervals. Starting from a known system's condition, the CM allows predicting the onset of failures due to wear-out. When a critical state is diagnosed the device can be addressed for planned maintenance.

Active thermal control uses temperature related control parameters to influence the junction temperatures of power semiconductor modules online [23]. The goal is to reduce the thermal stress in the module by decreasing the temperature swings. To influence the junction temperatures, the thermal control increases or decreases the losses in the desired chips temporarily [24]. Only few active thermal control approaches have been proposed so far. A classification of chosen control parameters by the hierarchic level of interaction with the system is done in 9. The layers reach from system control down to the gate driver. On the layer of the control a variation of the current limit, the dc link voltage, circulating current among parallel connected converters, circulating reactive power have been applied to control the junction temperature [25], [26]. On the layer of the modulator a selection of the switching frequency and the modulation method has been applied. On the hardware layer the gate voltage has been adjusted. As an example, a short-term temperature drop can be prevented or reduced in amplitude when losses are increased temporary by increasing the switching frequency. An electro-thermal model can be used to obtain online estimations of the junction temperatures. Alternatively, temperature measurements via thermosensitive electrical parameters (TSEP) [4] can be applied. The active thermal control is a possibility to reduce the thermal stress, but commercial utilization has not been reported yet.

For capacitors, the temperature and the voltage ripple have been identified as the main stresses leading to failure [27]. 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 [28]. Usually the

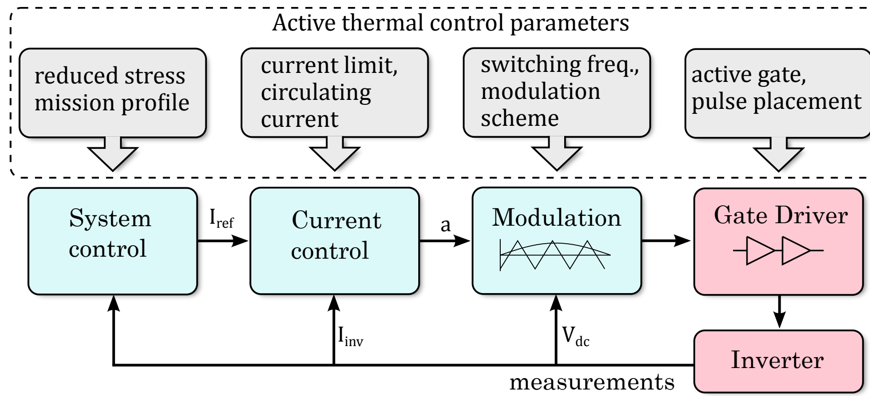

Fig. 9. Classification of parameters for active thermal control by point of interaction with the control system.

dc link capacitors reduce the voltage ripple. However, the voltage ripple is a critical stressor on Aluminum Electrolytic Capacitors (AL), Metallized Polypropylene Film Capacitors (MPPF) and high capacitance Multi-Layer Ceramic Capacitors (MLC) [18]. Thus, active ripple reduction circuit and voltage compensators have been implemented to reduce the capacitor size. This enables to replace AL capacitors with more reliable MPPF capacitors. However, the additional circuits and control schemes can be the source of new potential failures and increase the costs therefore they are rarely implemented in industrial products.

The given active methods to increase the reliability are not or only rarely used in power electronic systems. To evaluate the potential of these methods in improving the reliability, it was asked which trends would improve the system reliability of power electronic converters in the future. This is shown in Fig. 10 and Fig. 11. Active methods are marked with green color. The results show that all mentioned trends are evaluated as overall beneficial, as the mean values lie between 3.6 and 4.2. Most relevant is the use of components that proved to be reliable. Condition monitoring and control that avoids stressful operation conditions, like the active thermal control, achieved the second highest scores. Adding redundancy in the system and the increased utilization of wide-band-gap devices got the lowest scores. Wide-band-gap devices offer significant advantages, such as higher switching speed and higher operating temperature, which enables increased power density. However, this makes their temperature management critical, leading to new concerns for the PCB and components to which the device is connected.

Experimental verification of active methods to improve the reliability is complicated. The components have a rated lifetime in the scale of years which makes real-time lifetime tests time

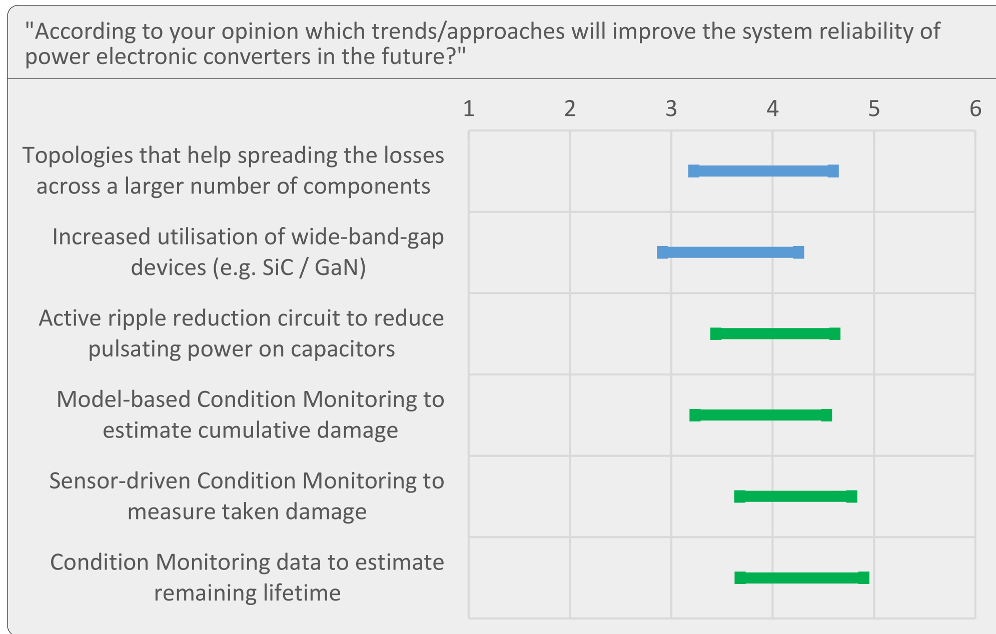

Fig. 10. Trends or approaches that will improve the system reliability of power electronic converters in the future. Scale: Not beneficial 1 to very beneficial 6. The bars show the standard deviation around the mean.

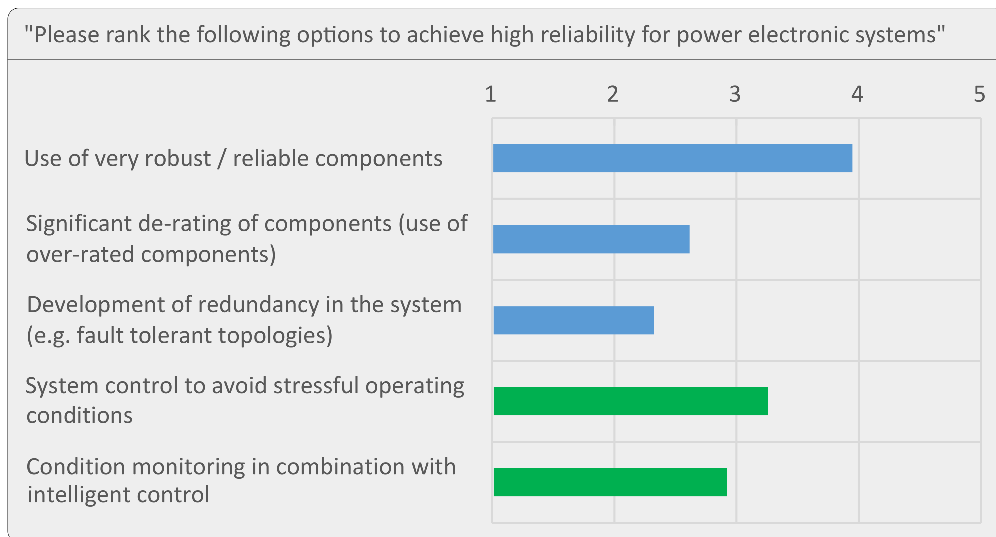

Fig. 11. Methods to achieve high reliability for power electronic systems. Highest priority 5 to lowest priority 1. The bars show the mean values of all answers.

consuming. Also constant test conditions like humidity or radiation have to be kept constant during the whole test. Therefore, accelerated life tests (ALT) are used to estimate the lifetime of the components. For the ALT, relevant stressors are identified first and then applied to the device

under test in quantifiable increased doses [29]. Multiple tests are necessary to generate sufficient statistical data. For thermal stressors, a common way to determine a life stress relationship is the Arrhenius lifetime model [16]. Even when only a few parameters are considered, the design of a lifetime model for a component is complex and relies on empirical data. Therefore, it is sensitive to errors. The lack of easy applicable verification methods is a general issue in reliability research [30].

D. Current state of reliability research

To investigate the general opinion in industry about the state of research concerning the reliability of power electronic converters, an evaluation on the current state of reliability research was performed. This is given in Fig. 12.

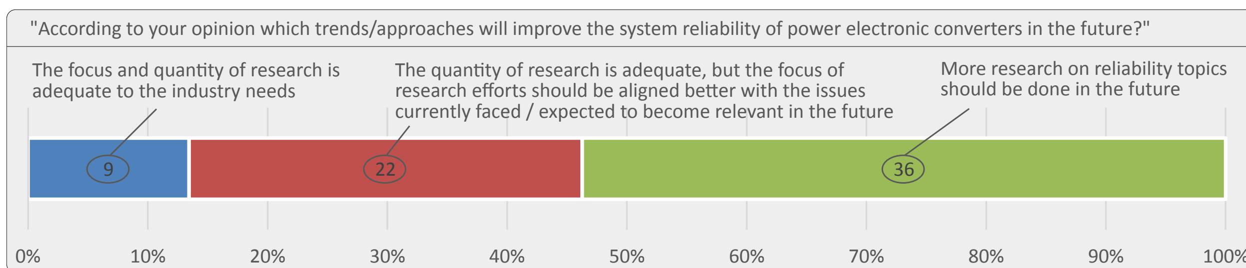

Fig. 12. Current state of reliability research in power electronic converters.

The three possible answers stand for very different opinions in the evaluation of the current state of research in reliability. Only 13% of respondents believe that the current quantity and focus of research is adequate to the industry needs. A total of 54% of respondents indicated that the amount of research should be increased and the remaining respondents are of the opinion that the research quantity is adequate but the focus needs to be better aligned with the industry needs. Overall, the results can be interpreted as a call for action. They suggest that more research in the area of reliability should be conducted and that the research efforts should be better aligned with the needs of the industry.

E. Promising ways to improve reliability

As a majority of the responses suppose that focus and quantity of reliability research are not adequate to the industry needs, the following question aims to identify which approach for

organizing reliability research is considered the most promising way to improve reliability in the future. This is given in Fig. 13.

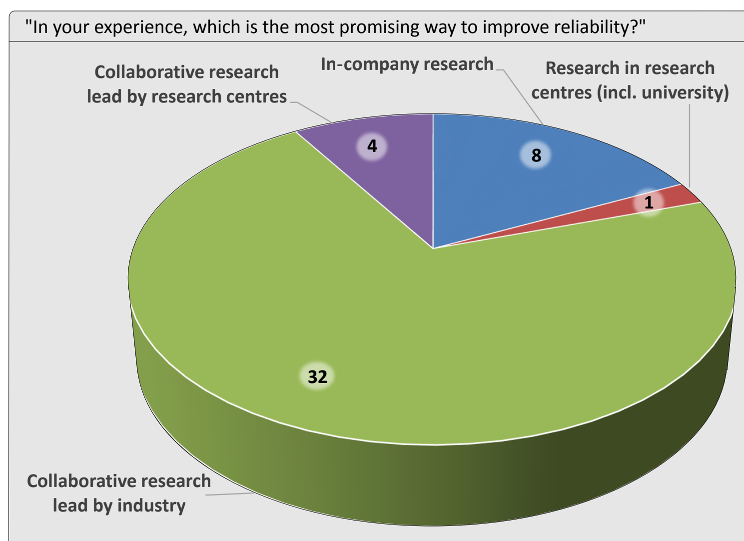

Fig. 13. Promising ways to improve reliability in power electronic systems.

The responses clearly show that collaborative research lead by industry is considered the most promising approach to improve reliability, followed by in-company research. A major advantage of research lead by industry is that it can be optimally aligned to industry-needs. The used methods and focus components can be chosen in best fit to the demand. Additionally, in-company research can have the benefit of obtaining a competitive advantage and avoiding external associates in sensitive topics. The low approval with research conducted in research centers indicates a disagreement between the needs of the industry and the research that is actually conducted. A possible explanation is that the conducted research may be considered application-unrelated or not relevant.

F. Reliability improvement pays off

Higher reliability reduces costs for outages and maintenance. Thus, better reliability may result in a higher willingness of customers to pay for a product under certain circumstances like power electronic systems with high outage costs and rather cost sensitive applications. Therefore, especially customers for wind power, energy transmission and aircraft systems may pay extra for systems that are more reliable. Lighting systems are often still considered a commodity that is expected to wear out and then be replaced. Thus, less benefit for this application is expected.

The participants were asked how big they expect the willingness of customers to pay premium for reliable products in various applications areas. This is shown in Fig. 14. As expected, in aircraft and energy transmission applications a high willingness to pay for reliability can be found. Third highest score is achieved for the wind power application. The remaining application areas received similar results. Only the lighting application stands out with lower scores. For consumer goods, low costs seem to be more important than improvement in reliability. Overall, the results of this part of the survey confirm that aircraft, energy transmission and wind power applications have a high focus on reliability and may be more willing to pay to ensure higher reliability.

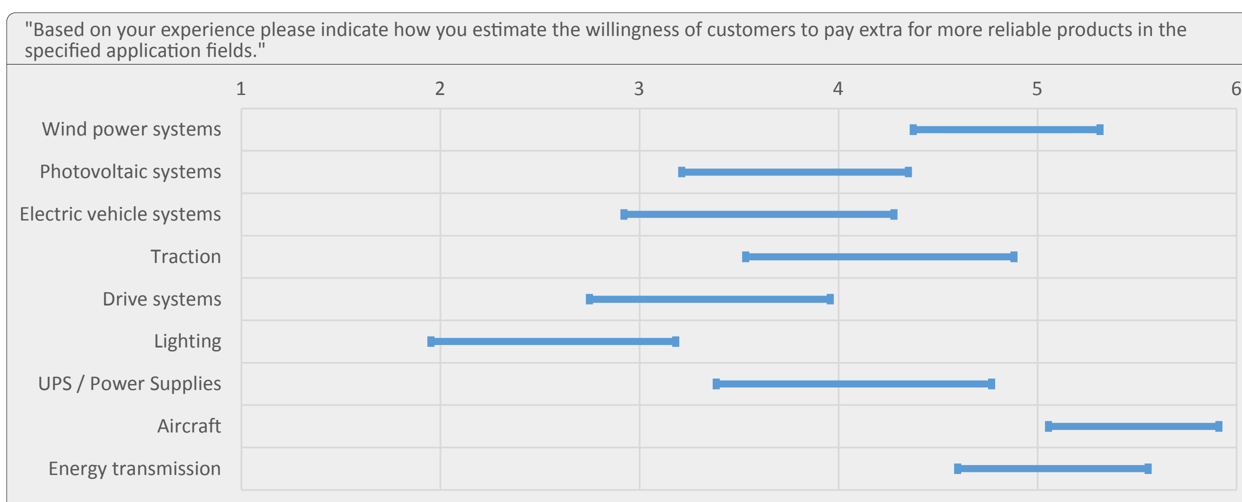

Fig. 14. Willingness of customers to pay extra for more reliable products in different applications. The bars show the standard deviation around the mean.

V. Conclusion

A comprehensive industry-wide survey has been conducted to analyze which topics future R&D should concentrate on and how to perform this research. Firstly, typical target lifetimes of 5 to 30 years with a strong dependency on the application field were identified. The investigation on stressors that limit these requirements showed that all thermal stressors were considered particularly critical with power cycling identified as the most critical stressor. Along the same lines, semiconductor devices were identified the most critical components closely followed by capacitors. Also the cooling system, protection devices and electromechanical components were identified critical. This corresponds with the components that should be addressed in future

research. Active methods that help to increase the reliability during operation like condition monitoring and avoiding stressful operating conditions were indicated only slightly positive. However, there is potential in these methods as the majority wish to see more research on these topics. Especially in applications like aircraft, energy transmission and wind power a high willingness to pay for more reliable systems was identified.

Acknowledgment

This project has been supported in the frame of the ECPE Joint Research Programme and the EKSH doctoral studies grant.

References

[1] H. Wang, M. Liserre, and F. Blaabjerg, "Toward reliable power electronics: Challenges, design tools, and opportunities," *IEEE Industrial Electronics Magazine*, vol. 7, no. 2, pp. 17–26, June 2013.

[2] F. Blaabjerg and K. Ma, "Future on power electronics for wind turbine systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 139–152, Sept 2013.

[3] J. G. Kassakian and T. M. Jahns, "Evolving and emerging applications of power electronics in systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 2, pp. 47–58, June 2013.

[4] N. Baker, M. Liserre, L. Dupont, and Y. Avenas, "Improved reliability of power modules: A review of online junction temperature measurement methods," *IEEE Industrial Electronics Magazine*, vol. 8, no. 3, pp. 17–27, Sept 2014.

[5] H. Wang, M. Liserre, F. Blaabjerg, P. de Place Rimmen, J. Jacobsen, T. Kvisgaard, and J. Landkildehus, "Transitioning to physics-of-failure as a reliability driver in power electronics," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 1, pp. 97–114, March 2014.

[6] K. Fischer and J. Wenske, "Towards reliable power converters for wind turbines: Field-data based identification of weak points and cost drivers," *in Scientific Proceedings of EWEA*, 2015.

[7] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1441–1451, May 2011.

[8] P. D. O'Connor, P. O'Connor, and A. Kleyner, *Practical reliability engineering*. John Wiley & Sons, 2012.

[9] P. Ghimire, S. Beczkowski, S. Munk-Nielsen, B. Rannestad, and P. B. Thogersen, "A review on real time physical measurement techniques and their attempt to predict wear-out status of igbt," in *Proc. of 2013 15th European Conference on Power Electronics and Applications (EPE)*, Sept 2013, pp. 1–10.

[10] H. Conseil-Gudla, Z. Staliulionis, M. S. Jellesen, M. Jabbari, J. H. Hattel, and R. Ambat, "Humidity buildup in electronic enclosures exposed to constant conditions," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 7, no. 3, pp. 412–423, March 2017.

[11] S. J. Watson, B. J. Xiang, W. Yang, P. J. Tavner, and C. J. Crabtree, "Condition monitoring of the power output of wind turbine generators using wavelets," *IEEE Transactions on Energy Conversion*, vol. 25, no. 3, pp. 715–721, Sept 2010.

[12] J. S. Karppinen, J. Li, and M. Paulasto-Krockel, "The effects of concurrent power and vibration loads on the reliability of board-level interconnections in power electronic assemblies," *IEEE Transactions on Device and Materials Reliability*, vol. 13, no. 1, pp. 167–176, March 2013.

[13] H. Kabza, H. J. Schulze, Y. Gerstenmaier, P. Voss, J. W. W. Schmid, F. Pfirsch, and K. Platzoder, “Cosmic radiation as a cause for power device failure and possible countermeasures,” in *Proceedings of the 6th International Symposium on Power Semiconductor Devices and Ics*, May 1994, pp. 9–12.

[14] M. Ciappa, “Selected failure mechanisms of modern power modules,” *Microelectronics reliability*, vol. 42, no. 4, pp. 653–667, 2002.

[15] H. Oh, B. Han, P. McCluskey, C. Han, and B. D. Youn, “Physics-of-failure, condition monitoring, and prognostics of insulated gate bipolar transistor modules: A review,” *IEEE Transactions on Power Electronics*, vol. 30, no. 5, pp. 2413–2426, May 2015.

[16] A. Wintrich, U. Nicolai, W. Tursky, and T. Reimann, *Application Manual Power Semiconductors*, 2nd ed., ISLE, Ed. Semikron, 2015.

[17] V. Smet, F. Forest, J.-J. Huselstein, F. Richardeau, Z. Khatir, S. Lefebvre, and M. Berkani, “Ageing and failure modes of igbt modules in high-temperature power cycling,” *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4931–4941, Oct 2011.

[18] H. Wang and F. Blaabjerg, “Reliability of capacitors for dc-link applications in power electronic converters - an overview,” *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3569–3578, 2014.

[19] A. Volke and M. Hornkamp, *IGBT modules: technologies, driver and application*, 2nd ed. Infineon Technologies AG, 2012.

[20] M. Musallam, C. Yin, C. Bailey, and M. Johnson, “Mission profile-based reliability design and real-time life consumption estimation in power electronics,” *IEEE Transactions on Power Electronics*, vol. 30, no. 5, pp. 2601–2613, May 2015.

[21] W. Zhang, D. Xu, P. N. Enjeti, H. Li, J. T. Hawke, and H. S. Krishnamoorthy, “Survey on fault-tolerant techniques for power electronic converters,” *IEEE Transactions on Power Electronics*, vol. 29, no. 12, pp. 6319–6331, Dec 2014.

[22] J. Falck, M. Andresen, and M. Liserre, “Active methods to improve reliability in power electronics,” in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Oct 2017, pp. 7923–7928.

[23] D. Murdock, J. Torres, J. Connors, and R. Lorenz, “Active thermal control of power electronic modules,” *IEEE Transactions on Industry Applications*, vol. 42, no. 2, pp. 552–558, March 2006.

[24] J. Falck, G. Buticchi, and M. Liserre, “Thermal stress based model predictive control of electric drives,” *IEEE Transactions on Industry Applications*, vol. 54, no. 2, pp. 1513–1522, March 2018.

[25] M. Andresen, K. Ma, G. Buticchi, J. Falck, F. Blaabjerg, and M. Liserre, “Junction temperature control for more reliable power electronics,” *IEEE Transactions on Power Electronics*, vol. 33, no. 1, pp. 765–776, Jan 2018.

[26] K. Ma, M. Liserre, and F. Blaabjerg, “Reactive power influence on the thermal cycling of multi-mw wind power inverter,” *IEEE Transactions on Industry Applications*, vol. 49, no. 2, pp. 922–930, March 2013.

[27] H. Wen, W. Xiao, X. Wen, and P. Armstrong, “Analysis and evaluation of dc-link capacitors for high-power-density electric vehicle drive systems,” *IEEE Transactions on Vehicular Technology*, vol. 61, no. 7, pp. 2950–2964, Sept 2012.

[28] R. Wang, F. Wang, D. Boroyevich, R. Burgos, R. Lai, P. Ning, and K. Rajashekara, “A high power density single-phase pwm rectifier with active ripple energy storage,” *IEEE Transactions on Power Electronics*, vol. 26, no. 5, pp. 1430–1443, May 2011.

[29] J. M. Thebaud, E. Woirgard, C. Zardini, S. Azzopardi, O. Briat, and J. M. Vinassa, “Strategy for designing accelerated aging tests to evaluate igbt power modules lifetime in real operation mode,” *IEEE Transactions on Components and Packaging Technologies*, vol. 26, no. 2, pp. 429–438, June 2003.

[30] Y. Song and B. Wang, “Survey on reliability of power electronic systems,” *IEEE Transactions on Power Electronics*, vol. 28, no. 1, pp. 591–604, Jan 2013.