Toward Reliable Power Electronics: Challenges, Design Tools, and Opportunities

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A new era of power electronics was created with the invention of the thyristor in 1957. Since then, the evolution of modern power electronics has witnessed its full potential and is quickly expanding in the applications of generation, transmission, distribution, and end-user consumption of electrical power. The performance of power electronic systems, especially in terms of efficiency and power density, has been continuously improved by the intensive research and advancements in circuit topologies, control schemes, semiconductors, passive components, digital signal processors, and system integration technologies.

In recent years, the automotive and aerospace industries have brought stringent reliability constraints on power electronic systems because of safety requirements. The industrial and energy sectors are also following the same trend, and more and more efforts are being devoted to improving power electronic systems to account for reliability with cost-effective and sustainable solutions.
Figure 1 shows the product drivers and research trends for more cost-effective and reliable power electronic systems. A better understanding of the reliability of power electronic components, converters, and systems will alleviate the challenges posed in both reliability-critical applications and cost-sensitive applications. Figure 2 describes a general optimization curve to define the reliability specification of a product in terms of achieving minimum life cycle cost, in which the impact of reliability on customer satisfaction and brand value are not taken into account. The cost of correcting the deficiencies in the design phase is progressively increased as the product development proceeds. A high failure rate during field operations will also result in high maintenance costs.

Reliability of power electronics involves multiple disciplines. The same is true for power electronics, which also involves a combination of technologies. In 1974, William E. Newell defined the scope of power electronics based on three of the major disciplines of electrical engineering shown in Figure 3(a). Almost four decades later, from the authors’ perspective, the scope of reliability of power electronics is defined in Figure 3(b). It covers the following three major aspects:

1) analytical analysis to understand the nature of why and how power electronic products fail, 2) the design for reliability (DFR) process to build reliability and sufficient robustness into power electronic products during each development process, and 3) accelerated testing and condition monitoring to perform robustness validation and ensure reliable field operation. A center formed from university–industry collaboration, the Center of Reliable Power Electronics (CORPE) at Aalborg University, Denmark, is making efforts to promote the move toward reliable power electronics and extend the scope of power electronics that has been defined since 1974. For further details, see “CORPE.”

The purpose of this article is to give a brief description of the reliability of power electronics and review the state-of-the-art research on more reliable power electronics.

Reliability Challenges in Power Electronics

Reliability is defined as the ability of an item to perform a required function under stated conditions for a certain period of time, which is often measured by probability of failure, by frequency of failure, or in terms of availability [1]. The essence of reliability engineering is to prevent the creation of failures. The reliability challenges in power electronics could be considered from different perspectives, such as the trends for...
high-power-density products, emerging high-temperature applications, and reliability-critical applications (as illustrated in Figure 1), including increasing electrical and electronic complexity, resource-consuming verification testing, and so on. This article discusses the challenges from experiences in the field operations and shortcomings of the general practice applied in reliability research on power electronics.

Field experiences reveal that power electronic converters are usually one of the most critical parts in terms of failure rate, lifetime, and maintenance cost. Various examples in wind-power and photovoltaic (PV) systems have been discussed in [2]. See “Examples of Field Failures in Power Electronic Systems.”

Industries have advanced the development of reliability engineering from traditional testing for reliability to DFR [3]. DFR is the process conducted during the design phase of a component or system that ensures that the required level of reliability is achieved. The process aims to understand and fix the reliability problems in the design process up front. Accordingly, many efforts have been devoted to considering the reliability aspect performance of power electronic components [4], [5], converters [6]–[8], and systems [9], [10]. However, the reliability research in the area of power electronics has the following limitations.

- **Lack of a systematic DFR approach specific for design of power electronic systems:** the DFR approach studied in reliability engineering is too broad in focus [3]. Power electronic systems have their own challenges as well as new opportunities for improving reliability, which are worth investigating. Moreover, design tools are rarely applied, except for reliability prediction, in state-of-the-art research on reliability of power electronic systems.

- **Overreliance on calculated value of mean-time-to-failure (MTTF) or mean-time-between-failures (MTBF) and bathtub curve [11]:** bathtub curve divides the operation of a device or system into three distinct time periods. Although it is approximately consistent with some practical cases, the assumptions of random failure and constant failure rate during the useful life period are misleading [11], and the true root causes of different failure modes are not identified. The fundamental

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**CORPE**

CORPE is a strategic research center between industry and universities, led by Aalborg University, Denmark. The center aims to design more reliable and more efficient power electronic systems for use in power generation, distribution, and consumption.

The center addresses a better understanding of how the reliability of power electronic devices and systems is influenced by different stress factors such as temperature, overvoltage and current, and overload and environment. Further, the center will develop device and system models that will enable simulation and design of power electronic systems very close to the limits of the devices and enable designed reliability. The knowledge will also be used online during operation to predict lifetime and enable smart derating of the equipment still in operation and ensure a longer lifetime. The goals will be as follows:

- more reliable power electronic systems
- more efficient systems
- more competitive (price) by reducing maintenance and operation costs.

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**FIGURE 3** – The defined scope in (a) power electronics by William E. Newell in 1970s and (b) power electronics reliability by CORPE in 2010.
EXAMPLES OF FIELD FAILURES IN POWER ELECTRONIC SYSTEMS

One example of field failure is in the wind-turbine application. In wind-power generation systems, power electronic converters are dominantly applied to regulate the fluctuating input power and maximize the electrical energy harvested from the wind [S1]. In [S2], the operation of around 350 onshore wind turbines associated with 35,000 downtime events has been recorded from 10-min average supervisory control and data acquisition data, fault and alarm logs, work orders and service reports; and operation and maintenance contractor reports. It shows that the power electronic frequency converters cause 13% of the failures and 18.4% of the downtime of the monitored wind turbines.

Another example of field failure is in the PV application. In PV systems, PV inverters are used to efficiently convert the dc voltage for ac applications or to integrate the output energy into electrical grids [S3]. Leading manufacturers can currently provide PV modules with over 20 years of warranty. However, the number was around five years for PV inverters on average in 2012 [S4]. Therefore, even though inverters account only for 10–20% of the initial system cost, they may need to be replaced three to five times over the life of a PV system, introducing additional investment [S5]. According to field experiences between 2001 and 2006 in a large utility-scale PV generation plant studied in [S6], the PV inverters were responsible for 37% of the unscheduled maintenance and 59% of the associated cost, as shown in Figure S1.

At the component level, semiconductor switching devices (e.g., insulated gate bipolar transistors [IGBTs]) and capacitors are the two types of reliability-critical components. Figure S2(a) represents a survey in [S7], showing the failure distribution among power electronic components. It can be noted that capacitors and semiconductors are the most vulnerable power electronic components; this is verified by another survey conducted in [S8]. It should be noted that the lifetime of electrolytic capacitors depends on both the rated lifetime at nominal conditions and the actual experienced stresses in the field operation. Long life could be achieved with a large design margin in terms of voltage, ripple current, and temperature, such as the cases shown in [S9] and [S10]. Therefore, there may be controversial views on the application of electrolytic capacitors in PV inverters as discussed in [S11]. Temperature, vibration, and humidity are the three major stressors that directly or indirectly induce failure in power electronic components. The U.S. Air Force Avionics Integrity Program conducted an investigation into the failure sources of electronic equipment in 1980s and reached the conclusion shown in [14] and represented in Figure S2(b), indicating that temperature is the most dominant stressor.

REFERENCES


FIGURE S1 – Field experiences of a 3.5-MW PV plant [S6]. (a) Unscheduled maintenance events by subsystem. (b) Unscheduled maintenance costs by subsystem.

FIGURE S2 – Surveys on failures in power electronic systems. (a) Failure distribution among major components [S7]. (b) Source of stress distribution for failures [S12].
Overreliance on handbook-based models and statistics: military handbook MIL-HDBK-217F [13] is widely used to predict the failure rate of power electronic components [7], [8]. However, temperature cycling, failure rate change with material, combined environments, and supplier variations (e.g., technology and quality) are not considered. Moreover, as failure details are not collected and addressed, the handbook method could not give designers insight into the root cause of a failure and the inspiration for reliability enhancement. Statistics is a necessary basis to deal with the effects of uncertainty and variability on reliability. However, as the variation is often a function of time and operating condition, statistics itself is not sufficient to interpret the reliability data without judgment of the assumptions and nonstatistical factors (e.g., modification of designs, new components, etc.).

Reliability Design Tools for Power Electronics

Figure 4 presents a DFR procedure applicable to power electronics design. The procedure integrates multiple state-of-the-art design tools and designs reliability into each development process (i.e., concept, design, validation, production, and release) of power electronic products, especially in the design phase. The design of power electronic converters are mission profile (i.e., a representation of all of the relevant operation and environmental conditions throughout the full life cycle [14]) based by taking into account large parametric variations (e.g., temperature ranges, solar irradiance variations, wind-speed fluctuations, load changes, manufacturing process, etc.).

Several design examples are discussed in [15]–[17]. It should be noted that the reliability design of power electronic systems should consider both hardware and control algorithms. The reliability issues of different maximum power point tracking algorithms and implementations for PV inverters are discussed in [10].

We do not intend to cover each block diagram shown in Figure 4 in this article, as they have already been discussed in [2]. Important concepts and design tools are discussed in the following sections. A case study of a 2.3-MW wind-power converter is also presented to demonstrate part of the DFR procedure.

Physics-of-Failure Approach

A paradigm shift in reliability research on power electronics is going on from today’s handbook-based methods to more physics-based approaches, which could provide better understanding of failure causes and design deficiencies, so as to find solutions to improve the reliability rather than obtaining analytical numbers only. The physics-of-failure (PoF) approach is a methodology based on root-cause failure mechanism analysis and the impact of materials, defects, and stresses on product reliability [18]. Failures can be generally classified into two types: those caused by overstress and those caused by wearout. Overstress failure arises as a result of a single load (e.g., overvoltage), while wearout failure arises because of cumulative damage related to the load (e.g., temperature cycling). Compared with empirical failure analysis based on historical data, the PoF approach requires the knowledge of deterministic science (i.e., materials, physics, and chemistry) and probabilistic variation theory (i.e., statistics). The analysis involves the mission profile of the component, type of failure mechanism, and the associated physical statistical model.

Load-Strength Analysis

The root cause of failures is load-strength interference. A component fails when the applied load \( L \) (application stress demand) exceeds the design strength \( S \) (component stress capability). The load \( L \) here refers to a kind of stress (e.g., voltage, cyclic load, temperature, etc.), and strength \( S \) refers to any resisting physical property (e.g., harness, melting point, adhesion, etc.) [3]. Figure 5 presents a typical load-strength interference evolving with time. For most power electronic components, neither load nor strength is fixed, but instead they are allocated within a certain interval that can be presented by a specific probability density function.
Moreover, the strength of a material or device could easily degrade with time. The probability of failure can be obtained by analyzing the overlap area between the distributions of load and strength, which is based on well-defined and indepth understanding of mission profile and component physics.

Since the variations of load and strength cannot be avoided, it is important to perform robust design and analysis to minimize the effects of variations and uncontrollable factors. Safety factors/derating, worst-case analysis, Six Sigma design, statistical design of experiments, and Taguchi design approach are the widely applied methods to deal with variations. It is worth mentioning that the Taguchi design approach tests the effect of variability of both control factors and noise factors (i.e., uncontrollable ones) and uses signal-to-noise ratios to determine the best combination of parameters, which is different from the worst-case analysis and other methods. A detailed description and comparison of those methods are well discussed in [19].

**Reliability Prediction Toolbox**

Reliability prediction is an important tool to quantify the lifetime, failure rate, and design robustness based on various sources of data and prediction models. Figure 6 presents a generic prediction procedure based on the PoF approach. The toolbox includes statistical and lifetime models and various sources of available data (e.g., manufacturer testing data, simulation data, field data, etc.) for the reliability prediction of individual components and the whole system. The statistical models are well presented in [3]. The lifetime models for failure mechanisms induced by various types of single or combined stressors (e.g., voltage, current, temperature, temperature cycling, and humidity) are discussed in [20] and [21]. Temperature and its cycling are the major stressors that affect reliability performance, which could be more significant with the trend for high-power-density and high-temperature power electronic systems. Two models presenting the impact of temperature and temperature cycling on lifetime are illustrated in detail in [2].

Constant parameters in the lifetime models can be estimated according to the available testing data. Therefore, the reliability of each critical individual component is predicted by considering each of its associated critical failure mechanisms. To map the component-level reliability prediction to the system level, the system modeling method reliability block diagram, fault-tree analysis, or state-space analysis (e.g., Markov analysis) is applied as discussed in detail in [9].

**Case Study of a Wind-Power Converter**

To demonstrate the DFR approach, a simplified case study of a 2.3-MW wind-power converter is discussed here. The selected circuit topology is a two-level back-to-back (2L-BTB) configuration composed of two pulse-width-modulated voltage-source-converters. A technical advantage of the 2L-BTB solution is the relatively simple structure and few components, which contributes to a well-proven robust and reliable performance. The focus is on insulated gate bipolar transistor (IGBT) modules in

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FIGURE 5 – The load-strength analysis to explain overstress failure and wearout failure in components and systems.
the converter in this case study as an example. Other components that could also be reliability-critical are not covered here. Figure 7 presents the procedure to predict the lifetime of the IGBT modules for a given wind-speed profile application. The main steps are illustrated as follows:

- **Wind-speed profile and converter specifications**: for illustration purpose, a wind-speed profile during one-half hour, shown in Figure 7, is analyzed. The switching frequency of the converter is 1,950 Hz and the dc bus voltage is 1.1 kV. Two kinds of selections for the IGBT modules used in the grid side converter are analyzed. Selection I is two 1.6 kA/1.7 kV 125 ºC IGBT in parallel, and selection II is one 2.4 kA/1.7 kV 150 ºC IGBT.

- **Critical failure mechanisms and lifetime model of IGBT modules**: fatigue is the dominant failure mechanism for IGBT modules due to temperature cycling, occurring at three failure sites: baseplate solder joints, chip solder joints, and the wire bonds [22]. The coefficients of thermal expansion for different materials in the IGBT modules are different, leading to stress formation.

![Figure 6](image-url) **FIGURE 6** – The reliability prediction toolbox for power electronic systems.

![Figure 7](image-url) **FIGURE 7** – The case study on lifetime prediction of IGBT modules in a 2.3-MW wind-power converter.
in the packaging and continuous degradation with each cycle until the material fails. A specific lifetime model is required for each failure mechanism. According to the derivation in [2], the applied model is

$$N = k(\Delta T - \Delta T_0)^{-m},$$

where \( k \) and \( m \) are empirically determined constants and \( N \) is the number of cycles to failure. \( \Delta T \) is the temperature cycle range, and \( \Delta T_0 \) is the portion of \( \Delta T \) in the elastic strain range. If \( \Delta T_0 \) is negligible compared with \( \Delta T \), it can be dropped out from the aforementioned equation, which then turns into the Coffin–Manson model, as discussed in [4].

- **Distribution of temperature profile:** electrical–thermal simulation is conducted to analyze the case temperature and junction temperature of the IGBT modules based on their thermal models. To perform the lifetime prediction, the analysis of the temperature cycling distribution is necessary. The rainflow counting method [23] is applied to extract the temperature information as shown in Figure 7. It can be noted that the majority of the temperature cycling is of low amplitude (i.e., less than \( \Delta T_0 \)), which has negligible impact on the lifetime.

- **Parameter estimation of lifetime models:** the parameters in the aforementioned applied lifetime model are estimated respectively for baseplate solder joints, chip solder joints, and the wire bonds based on the lifetime testing data described in [22].

- **Lifetime prediction:** as the amplitude and average temperature level of the thermal cycling are different when the wind is fluctuating, the Palmgren–Miner linear cumulative damage model [24] is applied in the form of

$$\sum_{i} \frac{n_i}{N_i} = 1,$$

where \( n_i \) is the number of applied temperature cycles at stress \( \Delta T_i \), and \( N_i \) is the number of cycles to failure at the same stress and for the same cycle type. Therefore, each type of \( \Delta T_i \) accounts for a portion of damage. Failure occurs when the sum of the left-hand side of the above equation reaches 1.

By following the above steps, the lifetime of the two kinds of selected IGBT modules is predicted for the wind-power converter application. Further analysis on the robustness (i.e., design margins) could also be done, as discussed in [14].

**Opportunities Toward More Reliable Power Electronics**

From our point of view, the opportunities to achieve more reliable power electronics lie in the following aspects.

- **Better Understanding of Mission Profile and Component Physics**

  With accumulated field experience and the introduction of more and more real-time monitoring systems, better mission profile data are expected to be available for various kinds of power electronic systems. With multiphysics-based simulation tools available in the market, the PoF of semiconductor devices and capacitors could be virtually simulated and analyzed. The joint efforts from power electronics engineers, reliability engineers, and physics scientists will enable better understanding of both the components and the specific conditions to which they are exposed.

- **Better Design, Testing, and Monitoring Methods**

  The following methods could be applied to improve the reliability during design, testing, and operation of power electronic systems.

  - **Smart derating of power electronic components and load management:** investigation into the relationship between failure rate and design margin could provide a smart derating guideline of power electronic components in terms of the compromise between cost and reliability, as shown in Figure 8(a). It avoids either overengineering design or lack of robustness margin.

  - **Fault-tolerant design:** the design involves redundancy design, fault isolation, fault detection, and online repair. In the event of a hardware failure, the redundant unit would be activated to replace the failed one during the repair interval. The repair of the failure would be online, and the system operation could be maintained. Fault-tolerant design is widely applied in reliability-critical applications to improve system-level reliability, as shown in Figure 8(b). Certain types of multilevel inverters and matrix converters could also have inherent fault-tolerant capabilities without additional hardware circuitry [9].

  - **Highly accelerated limit testing (HALT):** a kind of qualitative testing method to find design deficiencies and extend design robustness margins with the minimum required number of testing units (typically four or eight) in the minimum amount of time (typically a week) [3]. The basic concept of HALT is illustrated in Figure 8(c). The stresses applied to the testing units are well beyond normal mission profile to find the weak links in the product design.

  - **Diagnosis, prognosis, and condition monitoring:** these are effective ways for fault detection or health monitoring to enhance the reliability of power converters that are operational [25]. The condition monitoring provides the real-time operating characteristics of the systems by monitoring specific parameters (e.g., voltage, current, impedance, etc.) of power electronic components. For example, impedance characteristics analysis based on electrochemical impedance spectroscopy (EIS) has been used to monitor the condition of batteries [26]. To implement EIS, it is necessary to use spread spectrum signals (e.g., pseudorandom binary signals (PRBSs) [26], [27]) to excite the system and observe the corresponding response. By applying prognosis or condition monitoring
to power electronic systems, proactive maintenance work could be planned to avoid failures that would occur. Figure 8(d) shows an example of a condition monitoring system for wind-turbine power converters.

Reactive power control and thermal optimized modulation: thermal loading of switching devices in power electronic converters can be improved by reactive power control and modified modulation schemes as discussed in [28] and [29]. The power losses and therefore the thermal stresses on switching devices are reduced.

**Better Power Electronic Components**

Application of more reliable and cost-effective active components and passive components is another key aspect to improve the reliability of power electronic converters and systems. With the advances in semiconductor materials, packaging technologies, and film capacitor technologies, the reliability of active switching devices and passive components is expected to be improved.

**Conclusions**

More effort has been devoted to alleviate the challenges in reliability-critical applications and to reduce the life cycle cost of power electronic systems. A new paradigm shift is going on from handbook-based calculations to more physics-based approaches. This article defines the scope of reliability of power electronics from three aspects, i.e., analytical physics, DFR, and verification and monitoring. A state-of-the-art design procedure based on mission profile knowledge, PoF approach, and DFR is presented. The major opportunities toward more reliable power electronics are addressed. Joint efforts from engineers and scientists in multiple disciplines are required to fulfill the defined scope.
and promote the paradigm shift in reliability research.

**Biographies**

**Huai Wang** (hw@et.aau.dk) earned his Ph.D. degree in electronic engineering from City University of Hong Kong in 2012. He is currently an assistant professor at CORPE, Aalborg University, Denmark. In 2009, he worked as an intern at ABB Corporate Research Center, Dättwil, Switzerland. He has been conducting research on reliable electronic systems since 2010. He is the recipient of an individual postdoctoral grant on reliability of capacitors in electronic systems from the Danish Council for Independent Research. He has published 25 papers and filed three patents. He is a Member of the IEEE and a member of IEEE Power Electronics Society (PELS), Industrial Electronics Society (IES), Industry Applications Society (IAS), and Reliability Society (RS).

**Marco Liserre** earned his M.Sc. and Ph.D. degrees in electrical engineering from Bari Polytechnic University, Italy, in 1998 and 2002, respectively. In 2004, he became an assistant professor at Bari Polytechnic University, where he was an associate professor in 2012. He is currently a professor of reliable electronics at Aalborg University, Denmark. He has worked in the field of reliability of power electronic systems since 2011 cooperating with CORPE, Aalborg University, where he is currently a manager. He is an editor or associate editor of several IEEE journals. He was a founder and editor-in-chief of *IEEE Industrial Electronics Magazine*, cochair of ISIE 2010, and IES vice-president of publications. He has received several IEEE awards. He is a Fellow of the IEEE, a member of IAS, PELS, IEEE Power and Energy Society (PES) and IES; and a senior member of the IES AdCom.

**Frede Blaabjerg** earned his Ph.D. degree from the Institute of Energy Technology, Aalborg University, Denmark, in 1992, where he became a full professor in power electronics in 1998. Since 2011, he has been the director of CORPE at Aalborg University, researching reliability of power electronic components, converters, and systems. He was editor-in-chief of *IEEE Transactions on Power Electronics* from 2006 to 2012 and a Distinguished Lecturer for the IEEE Power Electronics Society from 2005 to 2007 and for the IEEE Industry Applications Society from 2010 to 2011. He was the chairman of EPE in 2007 and of PEDG in 2012, Aalborg. He has published over 800 scientific papers, received numerous national and international awards, and held visiting professor positions in several universities. He is a Fellow of the IEEE and a member of IEEE IES.

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