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Toward Reliable Power Electronics

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I. Introduction

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

In recent years, automotive and aerospatiale industries have brought stringent reliability constraints also on power electronic systems because of safety requirements. Also industrial and energy sector are following the same trend and more and more efforts are devoted to better 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. Better understanding on 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 to correct the deficiencies in the design phase is progressively increased as the product development proceeds. High failure rate during the field operation will also cause high maintenance cost.

Reliability of power electronics involves multiple disciplines. It is similar with power electronics itself, 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: analytical analysis to understand the nature of why and how power electronic products fail; design for reliability process to build in reliability and sufficient robustness in power electronic products during each development process; accelerated testing and condition monitoring to perform robustness validation and ensure reliable field operation. A university-industry collaborated center named of 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.

The aim 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. Challenges, design tools and opportunities for achieving more reliable power electronics are discussed in the following three sections, respectively.

II. Reliability Challenges in Power Electronics

Reliability is defined as the ability of an item to perform required function under stated conditions for a certain period of time, which is often measured by probability of failure, 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 Fig. 1, increasing electrical and electronic complexity, resource-consuming verification testing and so on. The authors here discuss 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 the wind power and photovoltaic systems have been discussed in [2].

Industries have advanced the development of reliability engineering from traditional testing for reliability to Design for Reliability (DFR) [3]. DFR is the process conducted during the design phase of a component or system that ensures them to be able to achieve the required level of reliability. It aims to understand and fix the reliability problems up-front in the design process. Accordingly, many efforts have been devoted to considerations into 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 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 and new opportunities in improving the reliability, which is worthwhile to be investigated. Moreover, design tools, except for the reliability prediction, are rarely applied in state-of-the-art research on reliability of power electronic systems.
- Over reliance 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 assumptions of MTTF or MTBF are constant failure rate and no wear out. Therefore, the calculated values may have high degree of inaccuracy if wear out occurs within the time. Moreover, MTTF represents the time when 63.2% of the items (under constant failure rate condition) would fail and varies with operation conditions and testing methods [12].

- Over reliance 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, 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 non-statistical factors (e.g. modification of designs, new components, etc.).

III. 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 have been 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 (MPPT) algorithms and implementations for photovoltaic (PV) inverters are discussed in [10].

It is not the intention of the authors to cover each block diagram shown in Figure 4 in this article, which has been presented in [2]. Important concepts and design tools are discussed as follows. A study case on a 2.3 MW wind power converter is also presented to demonstrate part of the DFR procedure.

A. Physics-of-Failure (PoF) 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. 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 caused by overstress and wear out, respectively. Overstress failure arises as a result of a single load (e.g. over voltage) while wear out failure arises because of cumulative damage related to the load (e.g. temperature cycling). Compared to 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.

B. 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 allocated within a certain interval which can be presented by a specific probability density function (e.g. normal distribution). Moreover, the strength of a material or device could be easily degraded 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 in-depth 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, worse case analysis, Six Sigma design, statistical Design of Experiments (DOE) and Taguchi design approach are the widely applied methods to deal with variations. It is worthwhile to mention 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. Detailed description and comparison of those methods are well discussed in [19].

C. Reliability Prediction Toolbox

Reliability prediction is an important tool to quantify the lifetime, failure rate and design robustness based on various source of data and prediction models. Figure 6 presents a generic prediction procedure based on the PoF approach. The toolbox includes statistical models and lifetime models and various sources of available data (e.g.

manufacturer testing data, simulation data and 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]-[21]. Temperature and its cycling are the major stressors that affect the reliability performance, which could be more significant with the trend for high power density and high temperature power electronic systems. In [2], two models presenting the impact of temperature and temperature cycling on lifetime are illustrated in detail.

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 mechanism. To map the component level reliability prediction to the system level, the system modeling method Reliability Block Diagram (RBD), Fault-Tree Analysis (FTA) or state-space analysis (e.g. Markov analysis) is applied as discussed in detail in [9].

D. Study Case on a Wind Power Converter

To demonstrate the DFR approach, a simplified study case on 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 (PWM) Voltage-Source-Converters (VSCs). 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. IGBT modules in the converter are focused 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 a half hour shown in Figure 7 is analyzed. The switching frequency of the converter is 1950 Hz and DC bus voltage is 1.1 kV. Two kinds of selections for the IGBT modules used in the grid side converter are analyzed. The selection I is two 1.6 kA / 1.7 kV 125ºC IGBT in parallel and the selection II is one 2.4 kA / 1.7 kV 150ºC 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 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

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

  where k and m are empirically-determined constants and N is the number of cycles to failure. ΔT is the temperature cycle range and ΔT_0 is the portion of ΔT that in the elastic strain range. If ΔT_0 is negligible compared to ΔT, it can be dropped out from the above equation and the equation turns to be 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$\varDelta T_0$)

which then has negligible impact on the lifetime.

- *Parameter estimation of lifetime models.* The parameters in the above 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 ΔT_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 ΔT_i accounts for a portion of damage. Failure occurs when the sum of the left hand side of the above equation reaches one.

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

IV. Opportunities Toward More Reliable Power Electronics

From the authors' point of view, the opportunities to achieve more reliable power electronics lie in the following aspects:

A. 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 in various kinds of power electronic systems. With multi-physics based simulation tools available in the market, the physics-of-failure of semiconductor devices and capacitors could be virtually simulated and analyzed. The joint efforts from power electronic engineers, reliability engineers and physics scientists will enable better understandings of both the components and the specific conditions they are exposed to.

B. 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 over engineering design or lack of robustness margin. Similar concept could be applied to the output power derating at the converter level or system level.
- *Fault tolerant design.* The design involves redundancy design, fault isolation, fault detection and on-line repair. In the event of a hardware failure, the redundant unit will be activated to replace the failed one during the repair interval. The repair of the failure is on-line 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 multi-level inverters and matrix converters could also have inherent fault tolerant capability without additional hardware circuitry [9].
- *Highly Accelerated Limit Testing (HALT).* It is a kind of qualitative testing method to find design deficiencies and extend design robustness margins with the minimum required number of testing units (typically 4 or 8) in minimum 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 which are under operation [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 monitoring the condition of batteries [26]. To implement EIS, it is necessary to use spread spectrum signals (e.g. Pseudo Random Binary Signals (PRBS) [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]-[29]. The power losses and therefore the thermal stresses on switching devices are reduced.

C. 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.

Concluding Remarks

More and more efforts have been devoted to alleviate the challenges in reliability

critical applications and in reduction of 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 of analytical physics, design for reliability and verification and monitoring. A state-of-the-art design procedure based on mission profile knowledge, physics-of-failure approach and design for reliability is presented. The major opportunities toward more reliable power electronics are addressed. Joint efforts from engineers and scientists in the multiple disciplines are required to fulfill the defined scope and promote the paradigm shift in reliability research.

Callout 1

Center of Reliable Power Electronics (CORPE)

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

The center addresses better understanding of how reliability of power electronic devices and systems is influenced by different stress factors such as temperature, overvoltage and current, 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 longer lifetime. The goals will be:

- Power electronic systems will be more reliable
- More efficient systems
- More competitive (price) by reducing maintenance and operation costs

Callout 2

Examples of Field Failures in Power Electronic Systems

One example is in the wind turbine application. In wind power generation system, power electronic converters are dominantly applied for regulating the fluctuating input power and maximizing 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-minute average SCADA (supervisory control and data acquisition) data, fault and alarm logs, work orders and service reports, and operation and maintenance (O&M) contractor reports. It shows that the power electronic frequency converters cause 13% of the failure rate and 18.4% of the downtime of the monitored wind turbines.

Another example is in the photovoltaic (PV) application. In PV system, PV inverters are used for efficiently converting the dc voltage for ac applications or integration of the output energy into electrical grids [S3]. Leading manufacturers nowadays could provide PV modules with over 20 years of warranty. However, the number is around 5 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 3-5 times over the life of a PV system, introducing additional investment [S5]. According to the field experiences during 2000 – 2005 in a large utility-scale PV generation plant studied in [S6], the PV inverters are responsible for 37% of the unscheduled maintenance and 59% of the associated cost as shown in Figure S1.

On the component level, semiconductor switching devices (e.g. Insulated Gate Bipolar Transistor, IGBT) 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, which is also 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 lifetime could be achieved with large design margin in terms of voltage, ripple current and temperature, such as the cases shown in [S9]-[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 of the stressors that directly or indirectly induce the failures of power electronic components. The US Air Force Avionics Integrity Program (AVIP) has conducted investigation into the failure sources of electronic equipment in 1980s and reached the conclusion shown in [S12] and represented in Figure S2 (b), indicating that temperature is the most dominant stressor.

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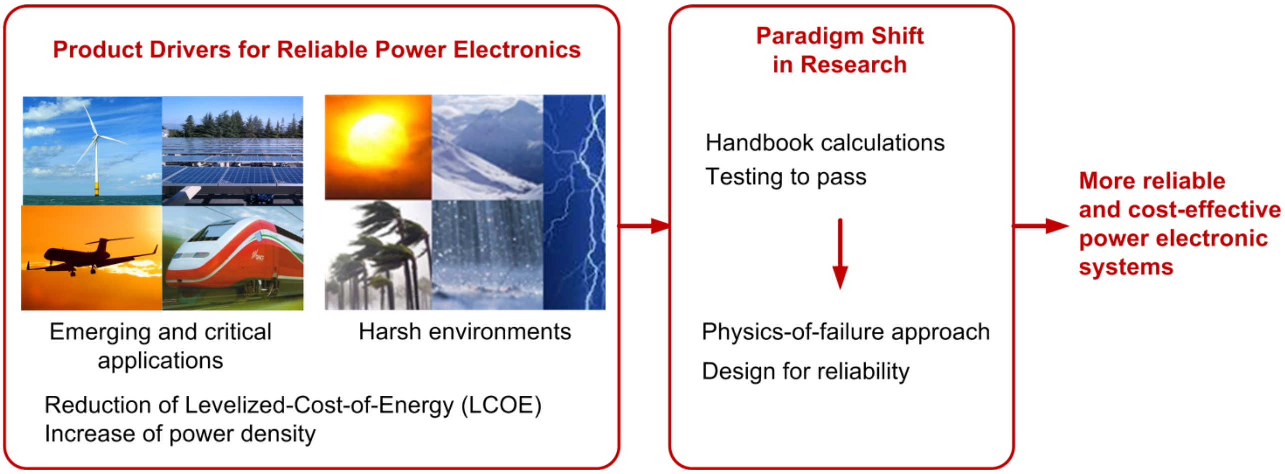

Product Drivers for Reliable Power Electronics
Emerging and critical applications
Harsh environments
Reduction of Levelized-Cost-of-Energy (LCOE)
Increase of power density
Paradigm Shift in Research
Handbook calculations
Testing to pass
Physics-of-failure approach
Design for reliability
More reliable and cost-effective power electronic systems

fig1

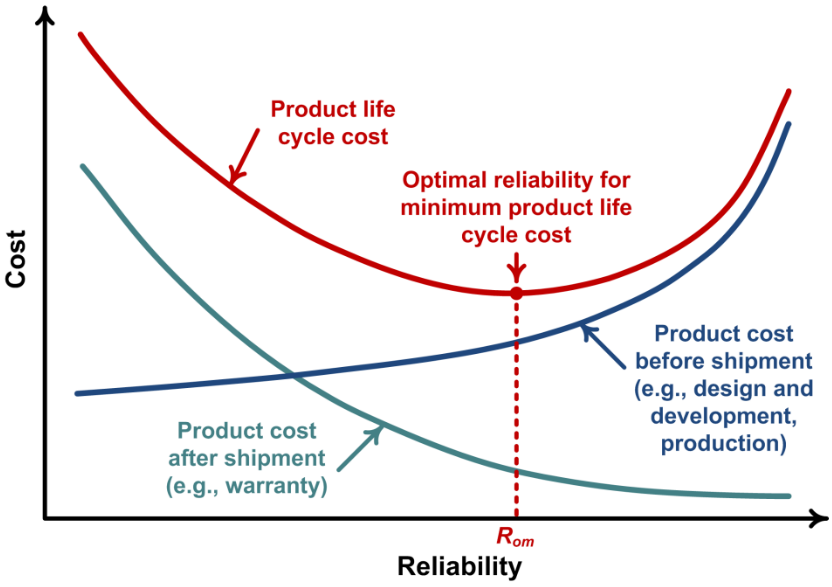

Product life cycle cost
Optimal reliability for minimum product life cycle cost
Cost
Product cost before shipment (e.g., design and development, production)
Product cost after shipment (e.g., warranty)
R_{om}
Reliability

fig2

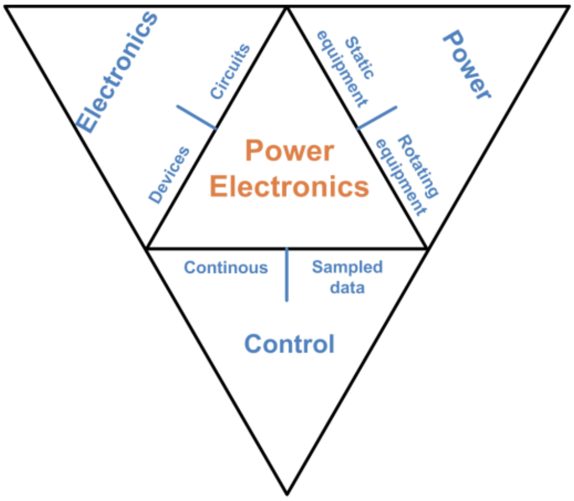

Electronics
Circuits
Devices
Static equipment
Power
Rotating equipment
Power Electronics
Continous
Sampled data
Control

fig3a

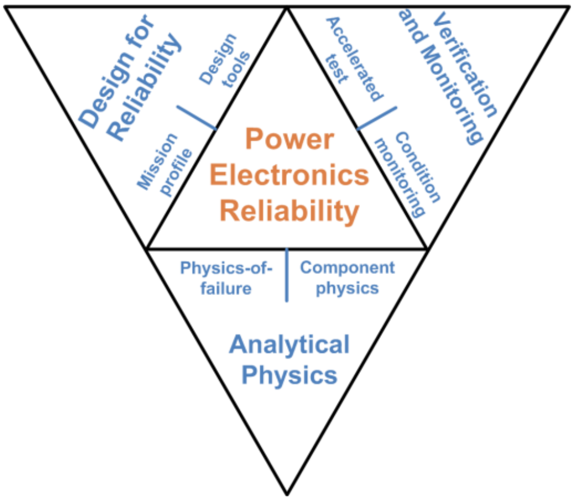

Design for Reliability
Design tools
Mission profile
Verification and Monitoring
Accelerated test
Condition monitoring
Power Electronics Reliability
Physics-of-failure
Component physics
Analytical Physics

fig3b

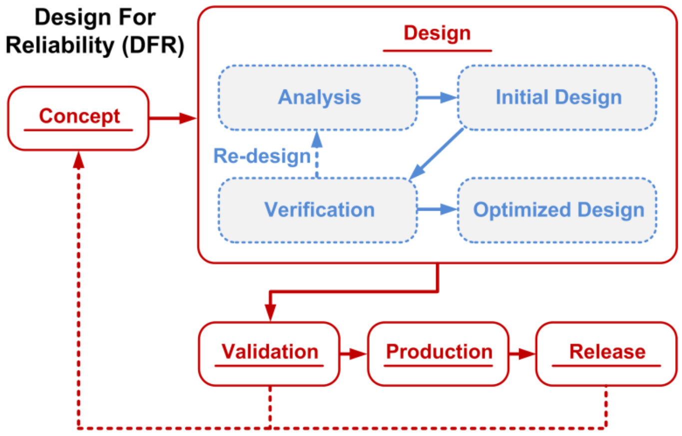

Design For Reliability (DFR)
Concept
Design
Analysis
Initial Design
Re-design
Verification
Optimized Design
Validation
Production
Release

fig4

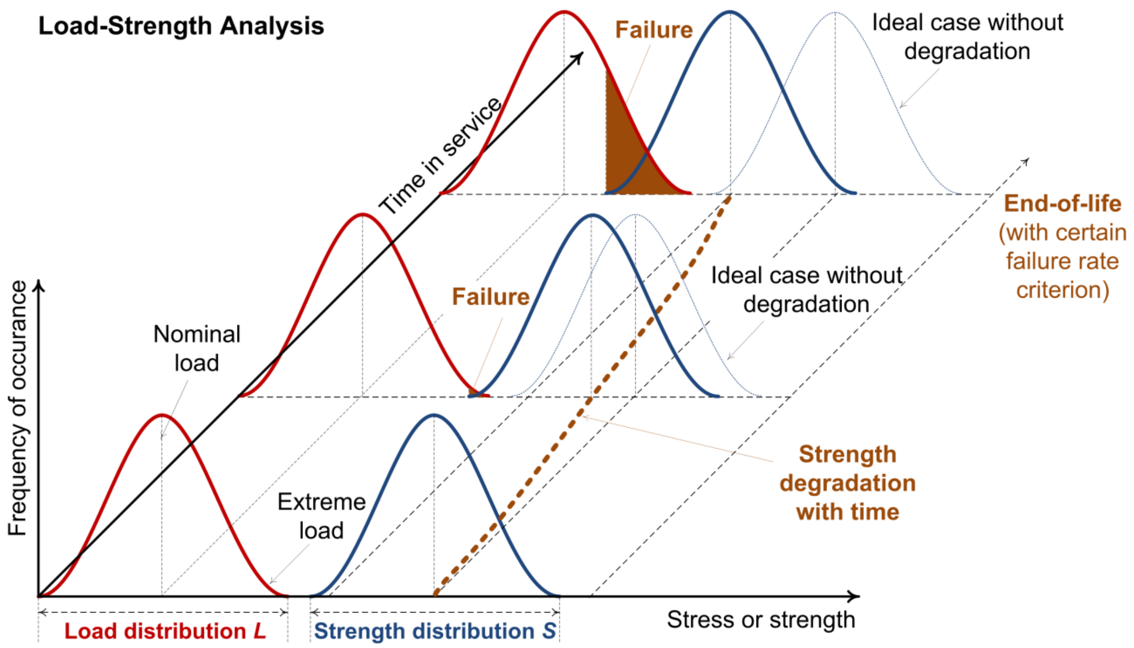

Load-Strength Analysis
Failure
Ideal case without degradation
Time in service
End-of-life
(with certain failure rate criterion)
Failure
Ideal case without degradation
Nominal load
Frequency of occurance
Extreme load
Strength degradation with time
Load distribution L
Strength distribution S
Stress or strength

fig5

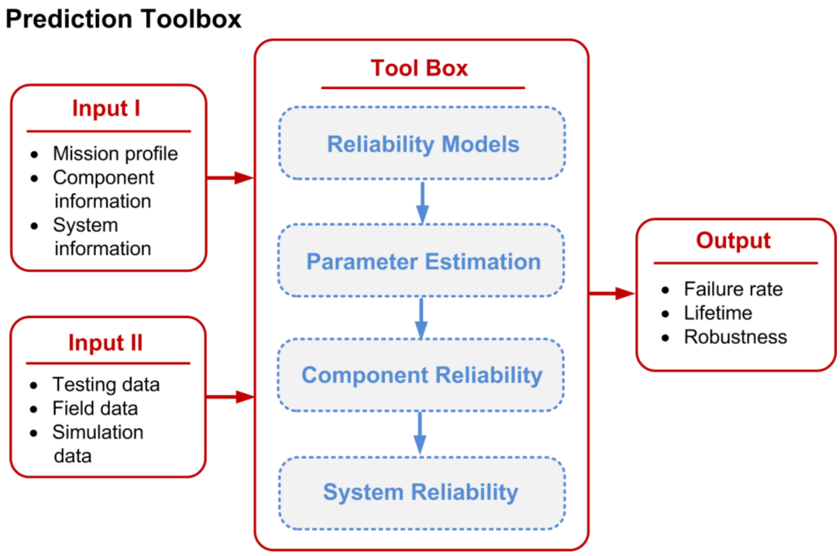

Prediction Toolbox
Input I
Mission profile
Component information
System information
Input II
Testing data
Field data
Simulation data
Tool Box
Reliability Models
Parameter Estimation
Component Reliability
System Reliability
Output
Failure rate
Lifetime
Robustness

fig6

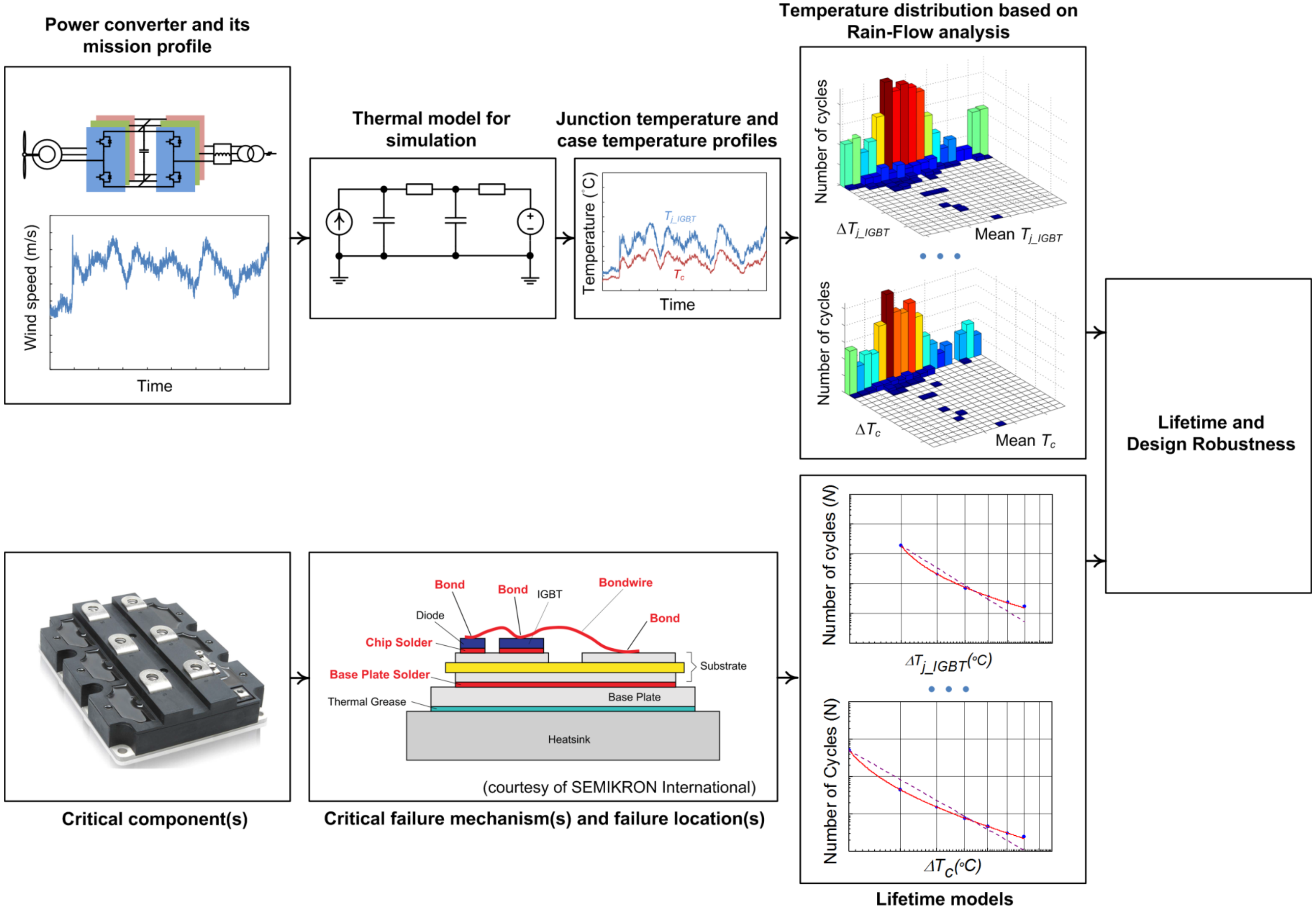

Power converter and its mission profile
Wind speed (m/s)
Time
Thermal model for simulation
Junction temperature and case temperature profiles
Temperature (°C)
T_{j_IGBT}
T_c
Time
Temperature distribution based on Rain-Flow analysis
Number of cycles
ΔT_{j_IGBT}
Mean T_{j_IGBT}
Number of cycles
ΔT_c
Mean T_c
Lifetime and Design Robustness
Number of cycles (N)
ΔT_{j_IGBT}(°C)
Number of Cycles (N)
ΔT_C(°C)
Lifetime models
Critical component(s)
Bond
Bond
IGBT
Bondwire
Diode
Bond
Chip Solder
Substrate
Base Plate Solder
Thermal Grease
Base Plate
Heatsink
(courtesy of SEMIKRON International)
Critical failure mechanism(s) and failure location(s)

fig7

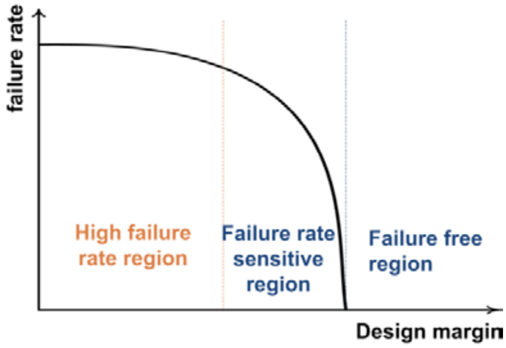

failure rate
High failure rate region
Failure rate sensitive region
Failure free region
Design margin

fig8a

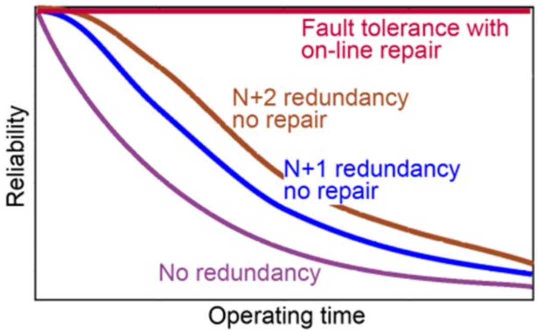

Fault tolerance with
on-line repair
N+2 redundancy
no repair
N+1 redundancy
no repair
No redundancy
Reliability
Operating time

fig8b

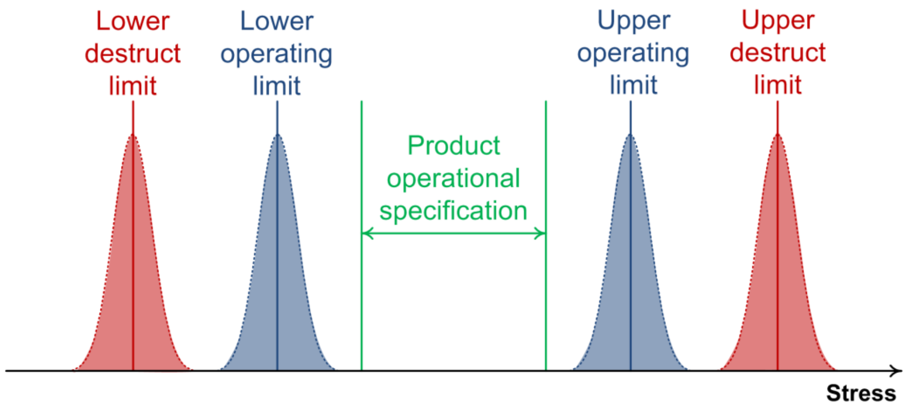

Lower destruct limit
Lower operating limit
Product operational specification
Upper operating limit
Upper destruct limit
Stress

fig8c

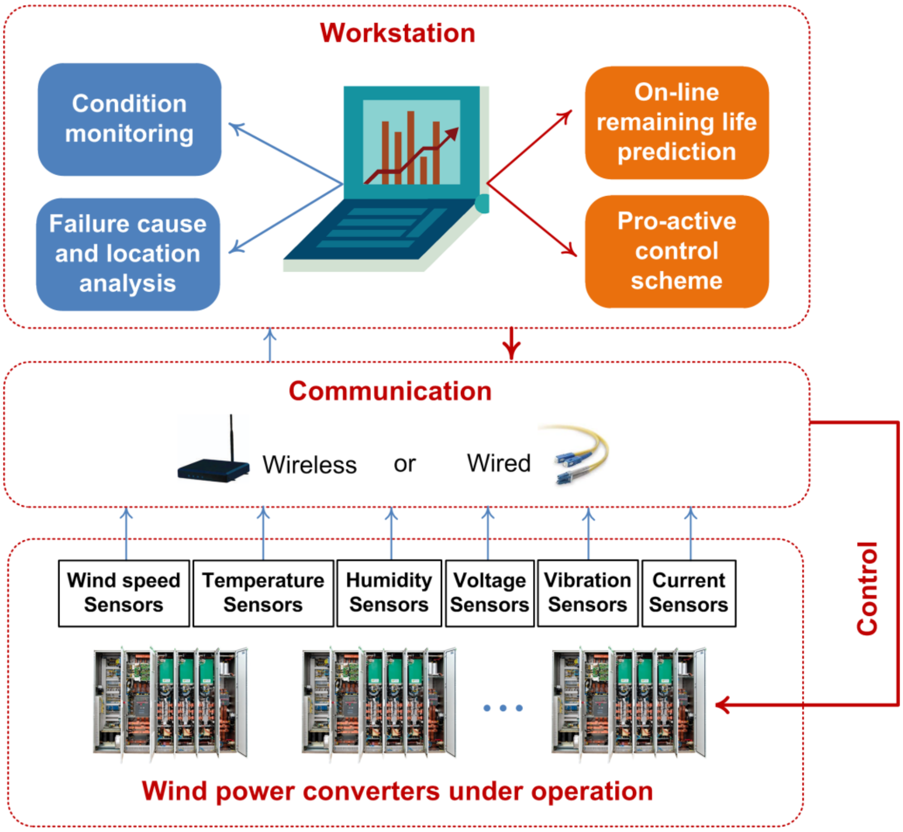
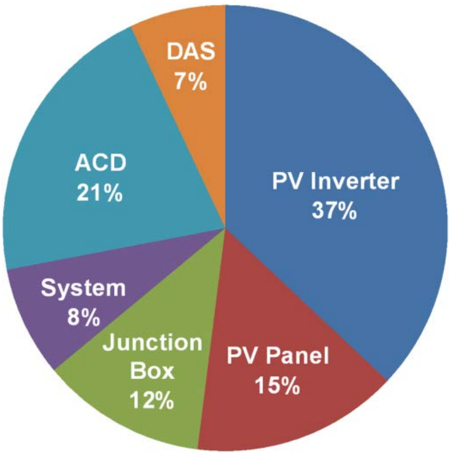
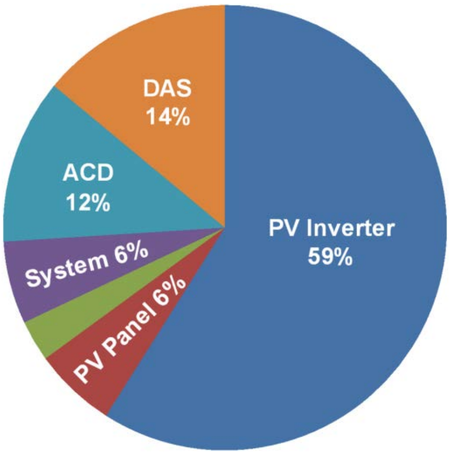

Workstation
Condition monitoring
Failure cause and location analysis
On-line remaining life prediction
Pro-active control scheme
Communication
Wireless
or
Wired
Control
Wind speed Sensors
Temperature Sensors
Humidity Sensors
Voltage Sensors
Vibration Sensors
Current Sensors
Wind power converters under operation

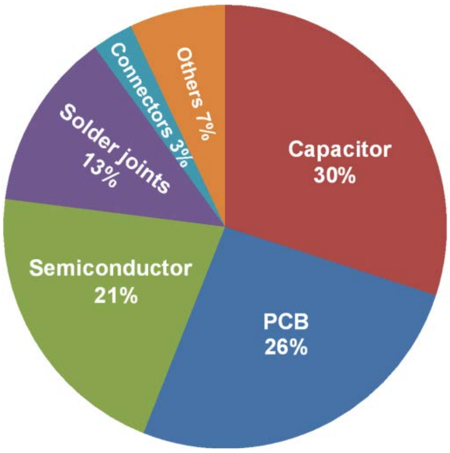
fig8d


DAS
7%
PV Inverter
37%
ACD
21%
System
8%
Junction
Box
12%
PV Panel
15%

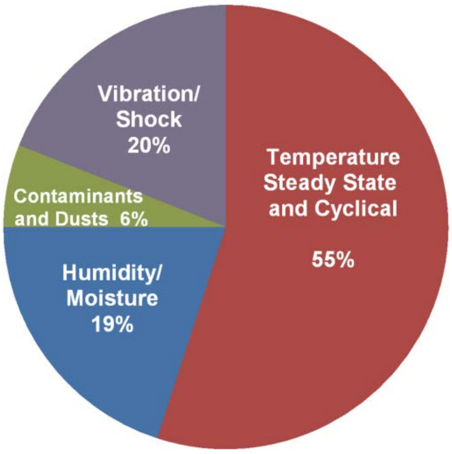
figS1a



figS1b


Others 7%
Connectors 3%
Solder joints 13%
Capacitor 30%
Semiconductor 21%
PCB 26%

figS2a


Vibration/
Shock
20%
Temperature
Steady State
and Cyclical
55%
Contaminants
and Dusts 6%
Humidity/
Moisture
19%

figS2b