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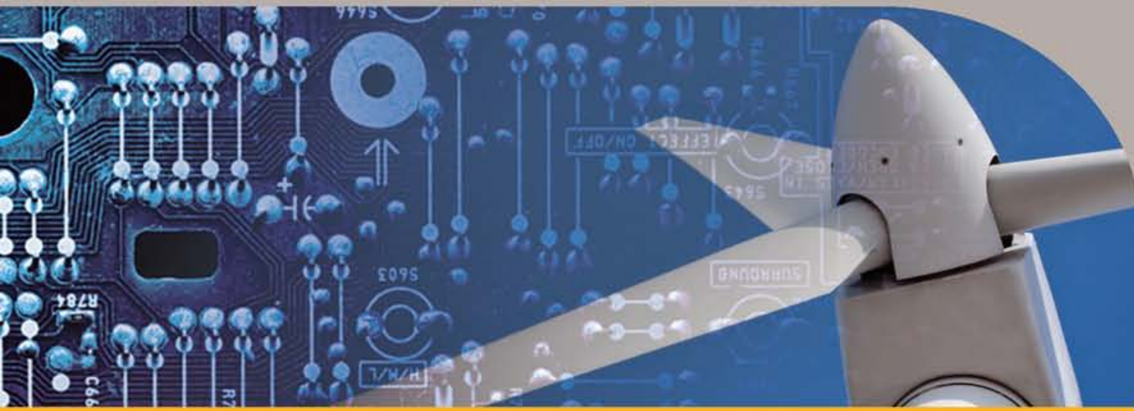

Reliability of Power Electronic Converter Systems

Edited by Henry Shu-hung Chung,
Huai Wang, Frede Blaabjerg
and Michael Pecht

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Contents

Chapter 1

Reliability engineering in power electronic converter systems

Huai Wang[1], Frede Blaabjerg[1], Henry Shu-hung Chung[2] and Michael Pecht[3]

1.1 Performance factors of power electronic systems

Power electronic systems aim to best serve the needs of highly efficient generation and conversion of electrical energy. This section discusses the basic architecture of a power electronic system and its design objectives and performance factors.

1.1.1 Power electronic converter systems

Electrical energy conversion by power electronic systems can be classified into the following four categories [1]:

1. Voltage conversion and power conversion for both direct current (DC) and alternate current (AC).
2. Frequency conversion.
3. Wave-shape conversion.
4. Poly-phase conversion.

The above four kinds of conversions are used to meet needs in many industry sectors, such as automotive, telecommunications, portable equipment, smart grids, high-voltage DC, flexible AC transmission systems, traction, renewable energy, mining, electrical aircraft, adjustable speed drives, and aerospace. The power-level ranges from sub-W to multi-MW and GW, processed by either a single power converter or multiple power converters.

Figure 1.1 shows the general architecture of a typical power electronic converter system. The electrical energy in the input and output is represented in the form of input voltage v_{in}, input current i_{in}, and input side frequency f_{in}, and output

[1]Center of Reliable Power Electronics (CORPE), Department of Energy Technology, Aalborg University, Aalborg, Denmark
[2]Centre for Smart Energy Conversion and Utilization Research, Department of Electronic Engineering, City University of Hong Kong, Kowloon Tong, Hong Kong
[3]Center for Advanced Life Cycle Engineering (CALCE), University of Maryland, College Park, MD, USA

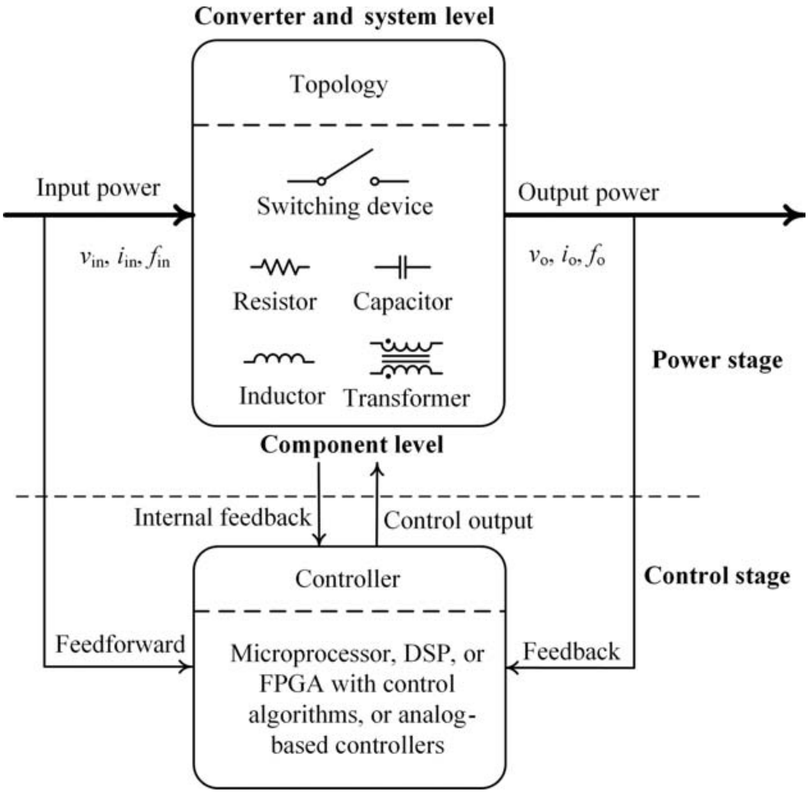

Figure 1.1 The basic architecture of a power electronic converter system. FPGA = field programmable gate arrays

voltage v_o, output current i_o, and output side frequency f_o. The upper and lower blocks in Figure 1.1 show the power stage and control stage, respectively. The power stage is composed of switching devices and one or more kinds of passive components, connected by a specific circuit topology. The switching devices are turned on and off at a frequency in the range of hundreds of Hz to hundreds of MHz, depending on the capability of the devices and the application requirements. The capacitors and inductors are used for energy storage and filtering purposes. The transformers are usually of the high-frequency type and are used for galvanic isolation and step-up/down of voltage. Resistors are in fact not desirable in power electronic systems since they introduce power loss. However, in practical systems, there are parasitic resistances in components and resistors used for circuit snubbers, balancing circuits, filter damping, and so on. The control stage receives conditioned low-voltage signals from the power stage and sends back driven signals to control the on/off of the switching devices, including protection signals at the presence of abnormal operation. It can be implemented either in analog circuits, digital processors, or a hybrid way of both analog and digital parts typically implemented on print circuit boards.

1.1.2 Design objectives for power electronic converters

With the advancements in power switching devices and passive components, circuit topologies, control strategies, sensors, digital signal processors (DSPs), and system integration technologies, there is a large variety of power electronic converter systems and they are still evolving. The converter- or system-level performance is determined by the component-level performance, the applied circuit topology and control strategy, and the practical implementation and usage conditions. Besides the required functionality under specified conditions, power electronic converter design mainly considers the following five performance factors:

1. Cost
   Cost is usually the foremost consideration in most consumer and industrial applications, such as lighting systems, photovoltaic plants, and wind turbines. For safety-critical applications, such as in aerospace, railway, and aircraft, other factors may weigh more than cost. A comprehensive cost analysis should include the design cost, manufacturing cost, operational cost, and recycle cost if applicable – that is, the life-cycle cost.

2. Efficiency
   One of the distinctive features of power electronic converters is that they can convert and control electrical energy with high efficiency. Therefore, improving the efficiency is always an important design objective to push close to the limit of zero power loss. The widely used efficiency definitions are peak efficiency, rated power efficiency, and weighted efficiency under multiple loading conditions (e.g., European weighted efficiency for PV inverters). For power converters used for renewable energy applications, such as PV and wind power, the long-term total energy production is more useful since the power level could fluctuate frequently with the weather conditions. Therefore, the energy efficiency defined by the annual output energy over the annual input energy of a power converter provides much more insight. It takes into account the long-term environmental and operational conditions, as well as the impact of component degradation.

3. Power density (kW/L or kW/kg)
   A general trend in power electronics is towards increased power density in terms of reduced volume or weight for a given power rating. This can be achieved mainly by reducing passive components with the aid of increasing switching frequency of the power devices, and better thermal management and integration solutions.

4. Reliability
   The usual engineering definition of reliability is the probability that an item will perform a required function without failure under the stated conditions for a stated period of time [2]. Accordingly, a comprehensive reliability description includes five important aspects: definition of failure criteria, stress condition, reliability numbers (%), confidence level (%), and the time after which the reliability number and confidence level apply. A reliability number will vary by adjusting any one of the other four aspects, indicating the importance

of understanding the background information behind a reliability number. As it is discussed in Section 1.1.3, more stringent reliability requirements and cost constraints are imposed on power electronic converters in both classical applications and emerging applications.

5. Manufacturability
   With the ever increasing cost of labour involved in the manufacturing process, it is desirable to have power electronic design solutions that can be easily and economically implemented into final products. The manufacturability is largely dependent on the decisions made during the design phase [3]. When it comes to the power electronic converters, the modular design and integration at the component level, power module level, and system level can be accomplished to improve the manufacturability [4]. The emerging additive manufacturing technologies, including 3D printing, will provide new opportunities for power electronic converter design in order to have better manufacturability and thereby to lower the cost [5].

The performance requirements of power electronic products are increasingly demanding in terms of the above five performance factors. Of these, the reliability performance influences the safety, service quality, lifetime, availability, and life-cycle cost of the specific applications.

1.1.3 Reliability requirements in typical power electronic applications

While targets concerning the efficiency of power electronic systems are within reach, the increasing reliability requirements create new challenges as discussed in Reference 6:

1. Mission profiles for critical applications (e.g., aerospace, military, avionics, railway traction, automotives, data centres, and medical electronics).
2. Emerging applications under harsh environments and long operation hours (e.g., onshore and offshore wind turbines, photovoltaic systems, air conditioners, and pump systems).
3. More stringent cost constraints, reliability requirements, and safety compliance requirements (e.g., demand for parts per million (ppm) level failure rates in future products).
4. Continuous need for higher power density in power converters and higher level integration of power electronic systems, which may invoke new failure mechanisms and thermal issues.
5. Uncertainty of reliability performance for new materials and packaging technologies (e.g., SiC and GaN devices).
6. Increasing complexity of electronic systems and software architectures in terms of functions, number of components, and control algorithms.
7. Resource constraints (e.g., time, cost) for reliability testing and robustness validation due to time-to-market pressure and financial pressure.

Table 1.1 The reliability challenges in industry: past, present, and future [6]

	Past	**Present**	**Future**
Customer expectations	– Replacement if failure – Years of warranty	– Low risk of failure – Request for maintenance	– Peace of mind – Predictive maintenance
Reliability target	– Affordable market returns (%)	– Low market return rates	– ppm market return rates
R&D approach	– Reliability test – Avoid catastrophes	– Robustness tests – Improving weakest components	– DFR – Balance with field load/mission profile
Main R&D tools	– Product operating and function tests	– Testing at the limits	– Understanding failure mechanisms, field load, root cause – Multi-domain simulation – . . .

Table 1.2 Typical lifetime target in different power electronics applications

Applications	**Typical design target of lifetime**
Aircraft	24 years (100,000 hours flight operation)
Automotive	15 years (10,000 operating hours, 300,000 km)
Industry motor drives	5–20 years (60,000 hours in at full load)
Railway	20–30 years (73,000–110,000 hours)
Wind turbines	20 years (120,000 hours)
Photovoltaic plants	30 years (90,000–130,000 hours)

Table 1.1 illustrates the industrial challenges from a reliability perspective of past, present, and future. To meet the future application trends and customer expectations for ppm level failure rate per year, it is essential to have a better understanding of failure mechanisms of power electronic components and to explore innovative R&D approaches to build reliability in power electronic converter systems.

Table 1.2 summarizes the typical design target of lifetime in different applications. To meet those requirements, a paradigm shift is going on in the area of automotive electronics, avionics, and railway traction by introducing new reliability design tools and robustness validation methods [7–9].

In the applications listed in Table 1.2, the reality is that power electronic converters are usually one of the weakest links to limit the lifetime of the system. For example, with the increasing penetration of renewable energy sources and the increasing adoption of more efficient variable-speed motor drives [10,11], the failure of power electronic converters in wind turbines, photovoltaic systems, and motor drives is becoming an issue. Field experiences in renewables reveal that power electronic converters are usually one of the most critical assemblies in terms of failure level, lifetime, and maintenance cost [12]. For example, it shows that frequency converters caused 13% of the failures and 18.4% of the downtime of 350 onshore wind turbines in a recent study associated with 35,000 downtime events [13]. Another representative survey in Reference 14 concludes that PV inverters are responsible for 37% of the unscheduled maintenance and 59% of the associated cost during 5 years of operation of a 3.5-MW PV plant. It should be noted that such statistics always look backwards, as those designs are more than 10 years old. The present technology will have different figures.

To fulfil future reliability requirements, multidisciplinary efforts devoted to both power electronics and reliability engineering are needed. Traditional academic research on power electronics focuses on improving the efficiency and power density, while reliability performance is usually not considered in the design phase. It is therefore necessary to better bridge the gap between the power electronics research in universities and the needs of industry.

1.2 Reliability engineering in power electronics

This section will start with the key terms and metrics that are widely used in reliability engineering. Then the historical development of both power electronics and reliability engineering will be discussed. After that, a brief presentation on the topics that are correlated to Chapter 2 to Chapter 16 in this book will be given. It covers the reliability of power electronic components, design for reliability (DFR) in power electronics, accelerated testing, and strategies to improve the reliability of power electronic converter systems.

1.2.1 Key terms and metrics in reliability engineering

1.2.1.1 Failure distribution

A failure distribution shows the frequency histogram of the failure occurrence, modelled as a kind of probability density function (pdf) $f(x)$. The variable x could be time, distance, cycles, or something else depending on the parameter of importance. Figure 1.2 shows an example of the failure distribution of a group of capacitors for power electronic applications. By defining $F(x)$ as the cumulative distribution function, reliability is shown as

$$R(x) = 1 - F(x) = 1 - \int_0^x f(x)dx \tag{1.1}$$

where the hazard rate $h(x)$ is defined as the conditional probability of failure in the interval x to $(x + \Delta x)$ [2], that is

$$h(x) = \frac{f(x)}{R(x)} \tag{1.2}$$

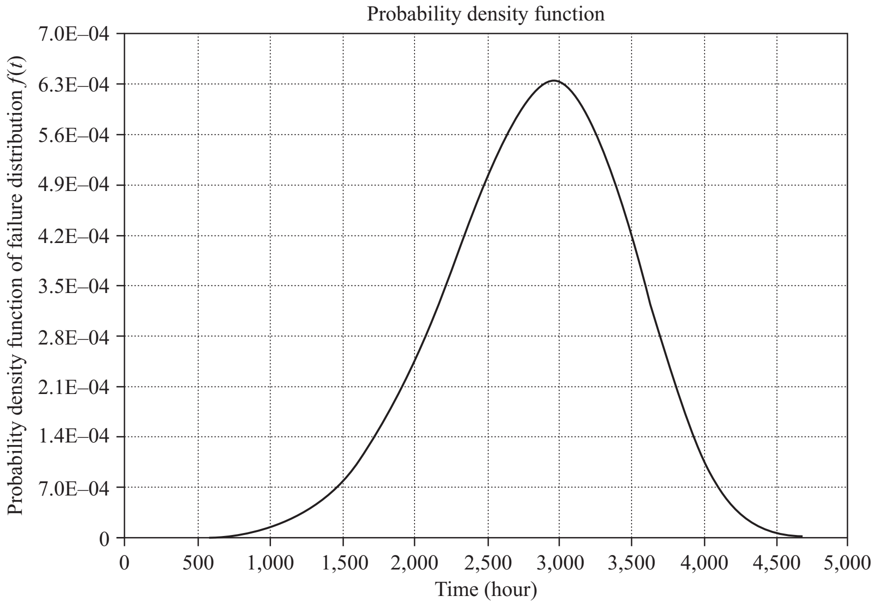

Figure 1.2 An example of a failure distribution of power electronics capacitors

There exists a bunch of failure distribution functions as discussed in Reference 2. In this chapter, the exponential distribution and Weibull distribution are discussed. The pdf of the exponential distribution is as follows

$$f(x) = \lambda \exp(-\lambda x) \tag{1.3}$$

According to (1.1)–(1.3), the hazard rate

$$h(x) = \lambda \tag{1.4}$$

It can be noted from (1.4) that the exponential distribution describes a scenario of constant hazard rate, also called the constant failure rate, λ.

The Weibull distribution was introduced by Weibull [15]. Its pdf function, reliability function, and hazard rate are defined as

$$f(x) = \frac{\beta}{\eta^\beta} x^{\beta-1} \exp\left[-\left(\frac{x-\gamma}{\eta}\right)^\beta\right] \tag{1.5}$$

$$R(x) = \exp\left[-\left(\frac{x-\gamma}{\eta}\right)^\beta\right] \tag{1.6}$$

$$h(x) = \frac{\beta}{\eta^\beta} x^{\beta-1} \tag{1.7}$$

where β is the shape parameter and η is the scale parameter, or characteristic life, which is the life at which 63.2% of the population will have failed. γ is the location