Design for Reliability in Renewable Energy Systems

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***Abstract* - Power electronics are widely used in renewable energy systems to achieve lower cost of energy, higher efficiency and high power density. At the same time, the high reliability of the power electronics products is demanded, in order to reduce the failure rates and ensure cost-effective operation of the renewable energy systems. This paper thus describes the basic concepts used in reliability engineering, and presents the status and future trends of Design for Reliability (DfR) in power electronics, which is currently undergoing a paradigm shift to a physics-of-failure approach. Two case studies of a 2 MW wind turbine system and a 6 kW photovoltaic system are presented to demonstrate the use of the DfR approach as a design tool to predict lifetime of components (e.g., power devices) as well as the overall systems (e.g., power converters) based on the required operating conditions (i.e., mission profile).**

I. INTRODUCTION

In the last decades, power electronics have been widely applied in emerging energy conversion applications, such as renewables, aircrafts, power transmission, etc. The fast growth on the installed capacity makes the failures of the power electronics system costly - not only due to the increased maintenance and repair, but also the adverse impacts on overall systems and loss of energy commitments [1]-[6]. Meanwhile, there has been continuous pressure for the power electronics manufacturers to reduce the cost, while maintaining the competitiveness of their products on the market. In order to satisfy the stringent reliability requirements with a limited the cost, development and testing time, there are strong demands for more accurate evaluation and design methods to ensure the reliability performances for power electronics converters.

The reliability is defined as the ability of a system or component to perform its required functions under stated conditions for a specified time [2]. Accordingly, a comprehensive reliability description includes five important aspects: definition of failure criteria, stress condition, reliability numbers (%), confidence level (%), and the time of interest. A reliability number can vary by adjusting any one of the other four aspects. Understanding the metrics used in reliability engineering is a fundamental step for the assessment of reliability performance and to be able to define the modelling targets. In the following, several important concepts and definitions are first to be clarified.

From a reliability engineering perspective, reliability $R(t)$ is a time-varying variable with the unit of percentage. It can be used to represent the percentage of a group of samples that can properly function at certain time t. Alternatively, if seeing from the individual sample point of view, reliability $R(t)$ can also represents the probability of one sample that can function at a certain time. On the other hand, the unreliability $F(t)$ can be defined as percentage of a group of samples (or probability of one sample) that fail at certain time t.

$F(t)$ can simply be calculated from $1\text{-}R(t)$, the plot of $F(t)$ against time t is also referred to Cumulative Distribution Function (CDF) curve. In most of the cases, it can be fitted by an analytical function with three parameters γ, β and η developed by Walloddi Weibull [4], as expressed in (1).

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

The widely used term "Mean Time To Failure (MTTF)", represents the average time that a group of samples fails. It is generally used in some reliability standards and handbooks for military and aerospace. The MTTF can be deduced from the reliability function $F(t)$ by (2). It is worth mentioning that the MTTF is an over-simplified term, which is independent of time and loses the whole picture of the reliability performance such as failure distribution and hazard rate. Therefore, benchmarking the systems or components by using MTTF is discouraged if the reliability function or CDF curve can be generated [1]-[3].

$$MTTF = \int_0^\infty R(t)dt \tag{2}$$

In order to better quantify the lifetime of the system or component, "percentile lifetime B_x" is more suitable and suggested to be utilized. It is the time when a group of samples has certain percentage of failure. For example, B_{10} lifetime is corresponding to the time by which 10% of the samples in a group are failed. From another perspective, this can also be viewed as a time by which a testing sample has 10 % probability of failure. The percentile lifetime can easily be solved from the reliability function or CDF curve, and the time-varying characteristic of failure is still kept.

The "failure rate $\lambda(t)$" (also called hazard rate $h(t)$) is another important reliability metrics widely used in reliability engineering. It describes the frequency with which a system or

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component fails. It can be expressed in failures per unit time as:

$$\lambda(\mathrm{t})=\frac{1}{R(t)}\frac{d\left[1-R(t)\right]}{dt} \qquad (3)$$

A typical failure rate curve against the time in the lifecycle of a power electronics product is plotted in Fig. 1, which is composed of three reliability functions and known as the "Bathtub curve" [2]. By examining the fitting parameters β in the reliability functions, three types of failures that are dominant at different stages of the lifecycle can be identified. The first part is dominant by early failures caused by "infant mortality" with a decreasing failure rate (where $\beta < 1$). The second part is dominant by random failures in the useful life of a product with a constant failure rate (where $\beta = 1$). The third part is dominant by wear-out failures in the end of life of product with an increasing failure rate (where $\beta > 1$).

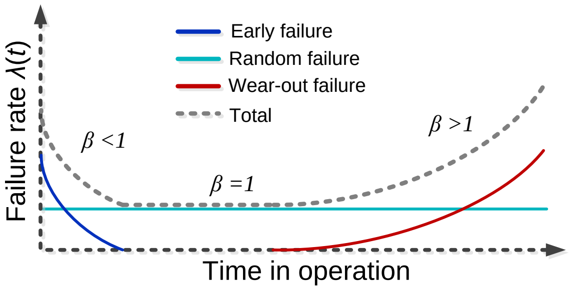


Fig. 1. "Bathtub curve" or failure rate in a life-cycle of a typical power electronics product.

The aforementioned reliability concepts are basically dedicated to the components. Seen from a system perspective, a collection of components and subsystems arranged according to a specific design in order to achieve desired function with acceptable performance and reliability. As it is shown in Fig. 2, the system reliability represents the time-to-failure of the entire system based on the lifetime distribution of the components and assemblies.

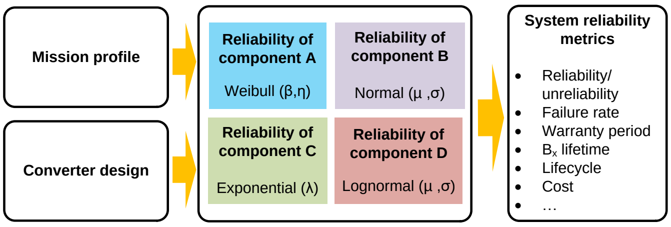


Fig. 2. Reliability metric calculations from components to system.

After the reliability curve of the individual power electronics components under the given mission profiles and converter design is generated, the overall reliability of the whole converter system can be decided depending on the connection logics of the components. Specifically, the system-level reliability can be derived by using the Reliability Block Diagram (RBD), and the Fault Tree Analysis (FTA) [7]. The most fundamental difference is that the success combination is focused in the RBD, while the failure combination is considered in the FTA. A reliability curve of the Polymer Electrolyte Membrane (PEM) Fuel Cell (FC) system [8], which consists of three subsystems (FC stack, Balance of Plant (BoP), and DC/DC converter), used in backup power application is shown in Fig. 3. It can be seen that the B_{10} lifetime (R=0.9) varies considerably from each subsystem to the whole system.

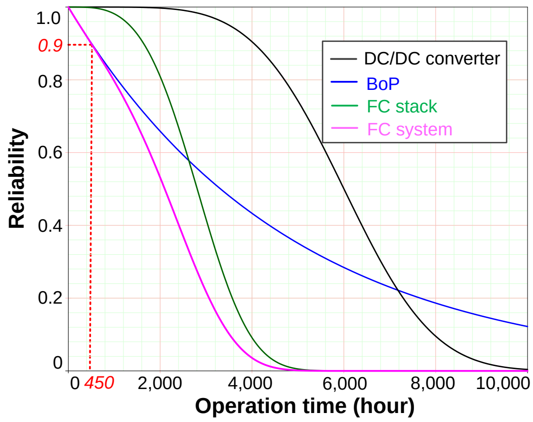


Fig. 3. Subsystem-level and system-level reliability of a 5 kW fuel cell system used in backup power application (FC: fuel cell, BoP: balance of plant).

Notably, this is based on an assumption that the failure of each individual component will have no impact on the loading and lifetime for the rest of the components in the system. However, this assumption may not always be valid in the power electronics systems. In such case, more complicated analysis for the system reliability need to be performed by taking into account the cross impact matrix and repairable system [2]. Moreover, the system design goal is to achieve the desired reliability, while performing all the intended functions at minimum cost. This involves a balancing act of determining how to allocate reliability to the components in the system, so the system is able to meet its reliability goal with all the other associated performance specifications [7].

II. DESIGN FOR RELIABILITY IN POWER ELECTRONICS

Industries have advanced the development of reliability engineering from traditional testing for reliability to Design for Reliability (DfR) [2]. DfR is the process conducted during the design phase of a component or system that ensures them to be able to perform the required level of reliability. It aims to understand and fix the reliability problems up-front in the design process.

A. Limitation of DfR in power electronics

Recent research has been devoted to study the reliability performance of power electronic components [9], [10], converters [11]-[13], and systems [14], [15]. However, the reliability research in the area of power electronics has the following limitations: DfR process discussed in [2] is too broad in focus, which could not reveal the specific challenges and new opportunities for reliability design of power electronic systems; over reliance on the value of Mean-Time-

Between-Failures (MTBF), which is found to be inappropriate to most practical cases as discussed in [16]; and over reliance on handbook-based models and statistics. For example, military handbook MIL-HDBK-217F [17] is widely used to predict the failure rate of power electronic components. However, temperature cycling, failure rate change with material, combined environments, supplier variations (e.g. technology and quality) are not considered in the prediction. Obviously, statistics are necessary when dealing with the 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.).

B. The state-of-the-art DfR in power electronics

A systematic DfR procedure specifically applicable to power electronic system design is proposed in [1], and it is illustrated in Fig. 4. It takes reliability into account during each development phase (i.e. concept, design, validation, production and release) of power electronic products, especially in the design phase. The design of power electronic converters is usually based on mission profile of the system (i.e. a representation of all of the relevant operation and environmental conditions throughout the full life cycle [5]). In that regards, parametric variation (e.g. temperature ranges, solar irradiance variations, wind speed fluctuations, load changes, manufacturing process) should also be considered. Main concepts and design tools shown in Fig. 4 are discussed in the following, which is also detailed discussed in [1].

A paradigm shift in reliability research on power electronics is still undergoing from traditional handbook based methods to more physics based approaches. The later approach could provide better understanding of failure causes and design deficiencies, and find solutions to improve the reliability rather than only obtaining analytical numbers. 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 [3]. Failures can generally be classified into two types caused by overstress and wear out, respectively. Overstress failure arises as a result of a single event (e.g. over voltage), while wear-out failure arises due to 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.

Reliability prediction is an important tool to quantify the lifetime, failure rate and design robustness based on various source of data and prediction models. The toolbox of the PoF approach includes statistical models and lifetime models and various sources of available data (e.g. manufacturer testing data, simulation data and field data, etc.). The statistical models are well presented in [1]. 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 [18]. For power electronics systems, temperature and its cycling are the major stressors that affect the reliability performance of some reliability-critical components in the system (e.g., power devices and capacitors). The degradation effect caused by the thermal stress on the reliable operation of the power devices are investigated in the following for wind and photovoltaic (PV) power application.

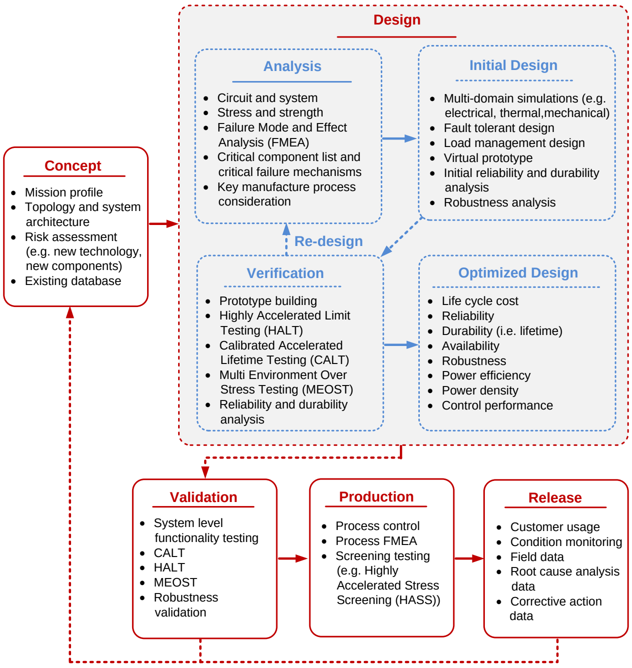


Fig. 4. State-of-the-art reliability design procedure for power electronics - Physics-of-Failure (PoF) approach.

III. CASE STUDY IN WIND TURBINE SYSTEM

This section gives an example of the DFR used in the wind turbine system. In accordance with the mission profile based reliability assessment, the influence of the grid code requirements and wind classes on the component-level lifetime estimation (single power device) will be evaluated.

A. Focused wind turbine system

Due to the recently required Low Voltage Ride-Through (LVRT) capability of renewable energy system, a Permanent Magnet Synchronous Generator (PMSG) based wind turbine system with full-scale power converter is more widely employed with the advantage of full power controllability [19]. The back-to-back power converter consists of the generator-side converter and the grid-side converter as shown in Fig. 5. At the generator-side converter, the rotor speed of the PMSG is regulated to ensure the Maximum Power Point Tracking (MPPT) operation, and transfer the active power from the wind to power grid. For the grid-side converter, the active power is controlled by regulating the dc-link voltage to be constant, while the reactive power can also be provided in demanded. Since the grid-side converter is responsible to fulfill the grid code requirements, it is the main focus in the case study. A widely adopted low-voltage 2 MW PMSG system is selected as a case study, and the parameters of the system are listed in [20].

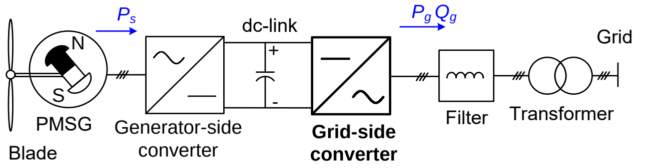


Fig. 5. Configuration of the full-scale power converter based permanent-magnet synchronous generator wind turbine system.

B. Mission profile based reliability evaluation

Since the PMSG system may not require the gearbox, which is commonly considered as a fragile part of the wind turbine system, the reliability of power electronics components becomes the main life-limiting factor in the system. The flowchart to assess the reliability metrics of the power electronics components in the wind turbine system is shown in Fig. 6.

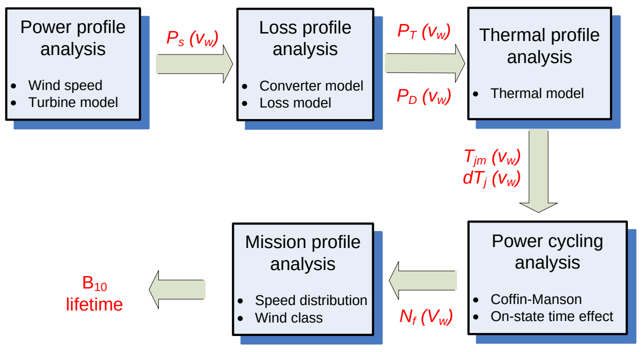
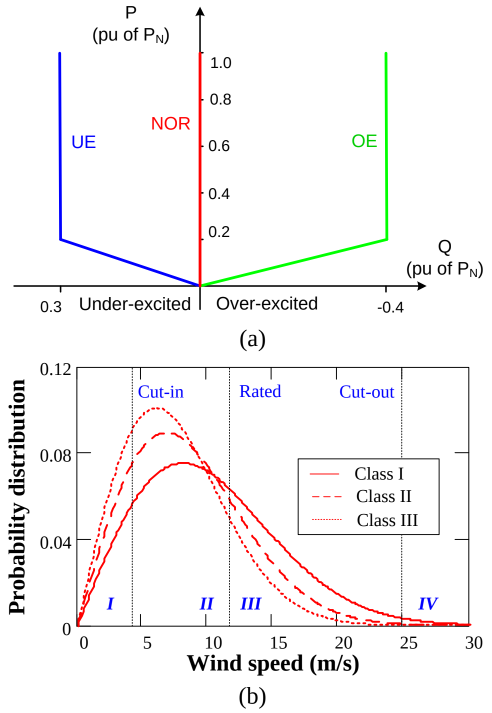


Fig. 6. Mission profile based approach to assess the reliability of a wind power converter.

The procedure starts with the analysis of the power profile in order to establish the relationship between the wind speed v_w and the output power P_s, which determines the loading of the grid-side converter. Together with the power converter model and the loss model for the power devices, the loss dissipation of the IGBT P_T and the diode P_D can be calculated according to the loading profile of the power converter. Based on the thermal model of the power module, the thermal profile of the power semiconductors can be calculated in terms of the mean junction temperature T_{jm} and the junction temperature fluctuation dT_j. Afterwards, the power cycles of the power semiconductor N_f can be obtained taking into account the Coffin-Manson model as well as the on-state time effect (i.e. thermal cycling period). Finally, considering the mission profile (such as the wind speed distribution and wind class), the B_{10} lifetime of the power converter can be estimated.

C. Impacts of mission profile on lifetime estimation

It is well-known that reactive power is preferred for LVRT in order to support the grid voltage for modern renewable energy system. Nevertheless, many countries with high penetration level of wind energy (e.g., Germany, Denmark, UK) have issued grid codes that also require the reactive power capacity during normal operation. An example of grid requirement in Germany is shown in Fig. 7(a) [21], in which up to 40% Over-Excited (OE) and 30% Under-Excited (UE) reactive power is delivered if the produced active power is above 20% of the nominal power.



(a)

(b)

Fig. 7. Typical mission profile in wind turbine system. (a) Reactive power range stated in German grid codes; (b) Annual wind distribution with different wind classes defined by IEC standard.

For the wind speed, there are two common used density distributions – Weibull and Rayleigh function [22]. Various IEC wind classes I, II and III using Weibull distribution with average wind speeds of 10 m/s, 8.5 m/s and 7.5 m/s, respectively, are shown in Fig. 7(b) [22]. With the specified cut-in, rated and cut-out wind speed, four regions of wind distribution can be categorized.

According to the aforementioned procedure of the reliability evaluation, the impacts of the different operating power factors on the lifetime estimation can be evaluated. By using the base value of lifetime span under the circumstance of wind Class I without reactive power injection (NOR), the annual damage with OE, NOR, and UE reactive power requirement is compared, as it is shown in Fig. 8. It is noted that both OE and UE reactive power requirement has higher annual damage compared to the NOR operation due to their higher current stress. Moreover, a one year operation with the OE reactive power requirement can reduce the lifetime by almost a factor of two. In addition, the impacts of the wind class can also be investigated, where it can be seen that the lifespan increases more than 2 times if the wind turbine is located at the wind condition of Class III.

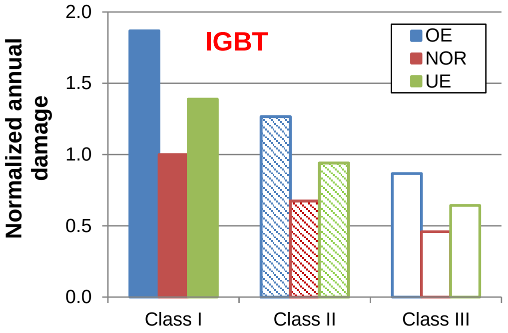


Fig. 8. Normalized annual damage of the power device with various reactive power types and wind classes.

IV. CASE STUDY IN PHOTOVOLTAIC SYSTEM

In this section, the DfR approach discussed previously will be applied with the PV application. A single-phase 6 kW PV system is considered as a case study, where the reliability target of the PV inverter is specified as B_1 lifetime for more than 25 years.

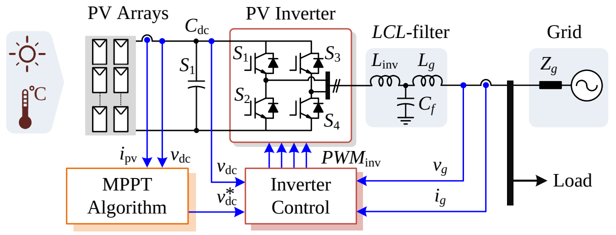


Fig. 9. System configuration of single-phase single-stage grid-connected PV system with full-bridge inverter topology.

A. Single-phase grid-connected PV inverters

A single-phase single-stage PV inverter with a full-bridge topology as shown in Fig. 9 is used in this study [23]. With this configuration, the power stage consists of four power devices (S_1-S_4), operating as a switch to convert the dc power from the PV arrays to the ac power. From the reliability perspective, the system-level assessment (e.g., PV inverter) can be determined from the component-level assessment using a reliability block diagram. In this case, the unreliability of the system can be determined following

$$F_{sys}(t) = 1 - \prod_{n=1}^{4}(1 - F_n(t)) \tag{4}$$

where $F_{sys}(t)$ and $F_n(t)$ denote the unreliability function of the power converter and each IGBT, respectively.

Therefore, the unreliability of the individual component in the system is first needed to be determined from the lifetime evaluation process, which will be discussed in the following.

B. Mission profile based reliability evaluation

A mission profile plays a crucial role in the lifetime prediction of power converters. Thus, it is usually taken into consideration during the lifetime evaluation process, which mainly involves three procedures as

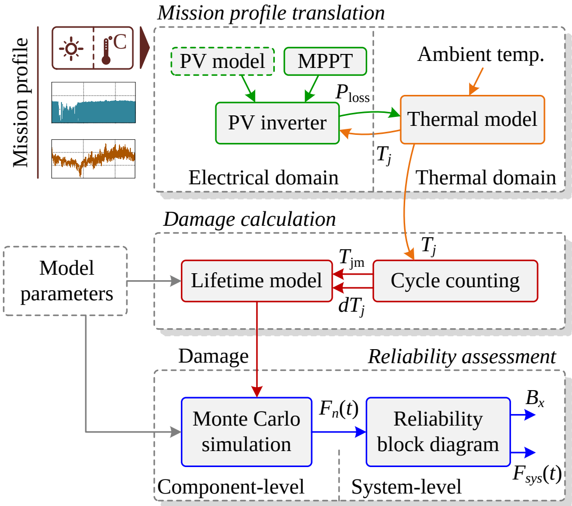
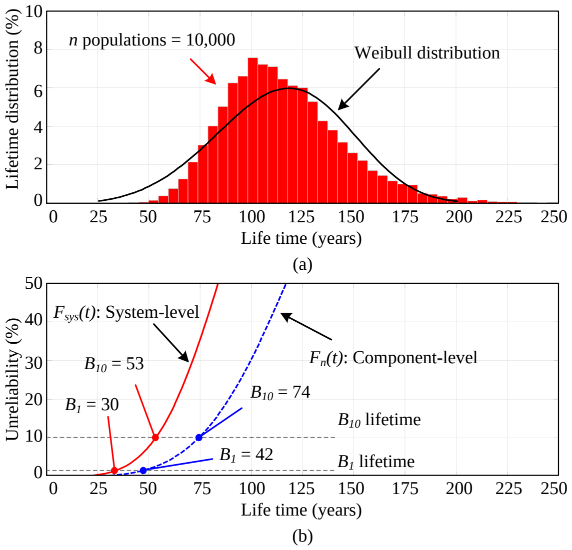


Fig. 10. Mission profile based reliability evaluation of PV inverter, where the Monte Carlo simulation is employed for reliability assessment.

- Mission profile translation: For the PV systems, the solar irradiance and ambient temperature, which are considered as mission profile of the system, need to be translated into the input power of the PV inverter. Afterward, the thermal loading profile (e.g., junction temperature) can be obtained by applying the power losses dissipated in the power device together with the thermal model of the device.
- Damage calculation: Due to the mission profile dynamic, the cycle counting algorithm is usually essential for quantifying the number of thermal cycle according to the mean junction temperature T_{jm} and junction temperature fluctuation dT_j. Then, the damage of the power device can be predicted by using the lifetime model (e.g., based on the accelerated test).



(a)

(b)

Fig. 11. Results from the Monte Carlo simulation. (a) Lifetime distribution of the power device; (b) Unreliability function of the power device (component-level) and the PV inverter (system-level).

- Reliability assessment: The reliability assessment can be achieved by using Monte Carlo simulation, where parameter variations are taken into account. By doing so, the unreliability functions of the power device (component-level) and the inverter (system-level) can be obtained.

C. Results and Discussion

The lifetime evaluation process in Fig. 10 is applied to the case study of the PV inverter in Fig. 9. The lifetime distribution of the power device is shown in Fig. 11(a), while the unreliability function is presented in Fig. 11(b). From the system-level unreliability function (e.g., red plot), it can be seen that the B_1 lifetime of the PV inverter is 30 years, which meets the reliability target of more than 25 years. Thus, the designed PV inverter can fulfill the reliability specification following the DfR approach.

V. CONCLUSION

Reliability is becoming an important performance metric of power electronic converters in renewable energy systems. Reliability engineering research on power electronics is currently undergoing a paradigm shift from traditional handbook based calculations to the physics-of-failure approach. The status and future trends of design for reliability in power electronics are presented in this paper. The case studies on a 2 MW wind and 6 kW photovoltaic power applications demonstrate the lifetime prediction of component-level power device and further to system-level power converter. It is based on analysis of the mission profile, failure mechanism, thermal profile and the parameter estimation of associated lifetime models. Joint efforts from the multiple disciplines are required to fulfill the research needs and promote this paradigm shift in reliability research.

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