Design for Reliability of Power Electronic Systems

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***Abstract* - Advances in power electronics enable efficient and flexible processing of electric power in the application of renewable energy sources, electric vehicles, adjustable-speed drives, etc. More and more efforts are devoted to better power electronic systems in terms of reliability to ensure high availability, long lifetime, sufficient robustness, low maintenance cost and low cost of energy. However, the reliability predictions are still dominantly according to outdated models and terms, such as MIL-HDBK-217H handbook models, Mean-Time-To-Failure (MTTF), and Mean-Time-Between-Failures (MTBF). A collection of methodologies based on Physics-of-Failure (PoF) approach and mission profile analysis are presented in this paper to perform reliability-oriented design of power electronic systems. The corresponding design procedures and reliability prediction models are provided. Further on, a case study on a 2.3 MW wind power converter is discussed with emphasis on the reliability critical components IGBTs. Different aspects of improving the reliability of the power converter are mapped. Finally, the challenges and opportunities to achieve more reliable power electronic systems are addressed.**

***Index Terms* – Design for reliability, power electronics, wind power converter, IGBT modules, physics-of-failure**

I. INTRODUCTION

Power electronics have enabled efficient conversion and more flexible control of electric energy in the last four decades. However, the reliability performance of power electronic systems imposes huge challenges in various emerging applications, especially for the grid integration of renewable energy with long operation hours under harsh environment. It has significant impact on the life cycle cost of the systems, levelized cost of energy and customer satisfaction, therefore, the penetration of renewable energy in our modern electrical grid is a challenge in the long run.

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 [1]-[2]. The penetration of wind power is expected to be 20% of the total electricity production by 2020 in Europe [3]. Meanwhile, the power capacity of a single wind turbine (WT) is increasing from tens of kW to 10 MW and the location of the wind farm is moving from onshore to offshore. Therefore, the reliability performance of the whole system is of primary concern due to increased time and cost for repairs after failures, having significant impact on the availability of the wind power generation. Unfortunately,

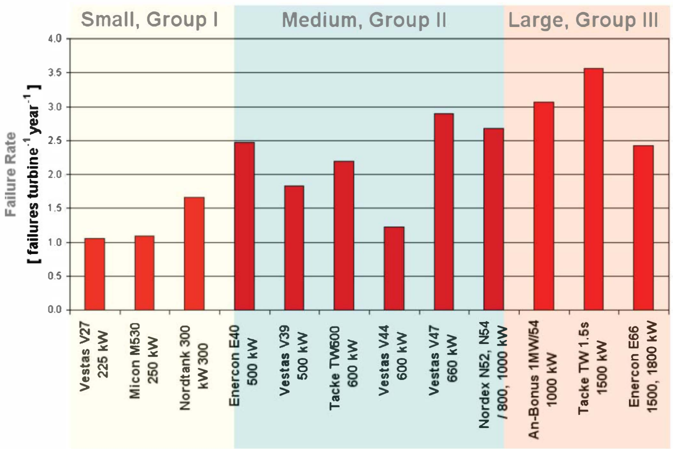


Fig. 1. Dependence of failure rate on power rating of wind turbines [4].

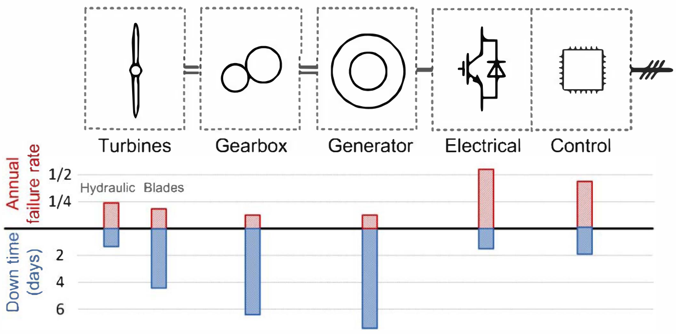


Fig. 2. Distribution of failure rate and downtime among various parts of the wind turbines in [5].

the larger WTs are prone to have higher failure rate as shown in Fig. 1 [4], which is according to the failure statistics on all of the WTs operating during 1993-2006 in Schleswig-Holstein, Germany. Regarding the failure rate distribution within a certain type of WT, an analysis is given in [5] and represented in Fig. 2. It can be noted that power converters dominant the failures, which is in line with the observations from other field surveys in [6]-[7].

In photovoltaic (PV) system, PV inverters are used for efficiently converting the dc voltage for ac applications or integration of the output energy into electrical grid [8]. With the progressive development of PV around the world, PV inverters are becoming the most critical subsystems in terms of failure rate, lifetime and maintenance cost. Leading manufacturers nowadays provide PV modules with over 20 years of warranty. However, the number is around 5 years for PV inverters on average in 2012 [9]. Therefore, even though inverters account only for 10%-20% of the initial system cost, they could need to be replaced 3-5 times over the life of a PV system, introducing additional investment [10]. According to the 5 years of field experience in a large utility-scale PV generation plant studied in [11], the PV inverters are responsible for 37% of the unscheduled maintenance and 59% of the associated cost.

Industries have advanced the development of reliability engineering from traditional testing for reliability to Design For Reliability (DFR) [12]. DFR is the process conducted during the design phase of a component or system that ensures them to be able to perform 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 [13]-[20], converters [21]-[29] and systems [30]-[35]. However, the reliability research in the power electronics area has the following limitations:

a) Lack of systematic DFR approach specific for design of power electronic systems. The DFR approach studied in reliability engineering is too broad in focus [12]. Power electronic systems have their own challenges and new opportunities in enhancing 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.

b) Over reliance on calculated value of Mean-Time-To-Failure (MTTF) or Mean-Time-Between-Failures (MTBF) and bathtub curve [36]. 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 [36] 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. For example, based on the assumptions, modern PV modules could have MTBF between 500 and 6000 years [37], however, lifetime and warranty time (e.g. 20 years) are much less than this due to wear out failures. 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 [38].

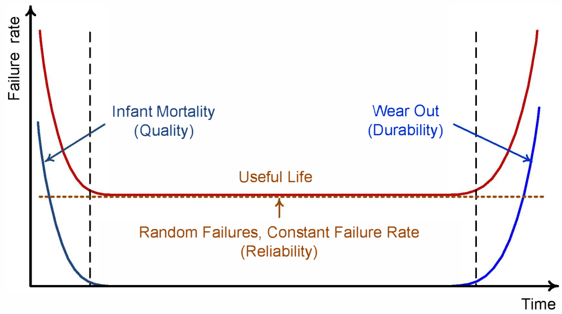


Fig. 3. Failure rates presented by bathtub curve during three distinct periods.

c) Over reliance on handbook-based models and statistics. Military handbook MIL-HDBK-217F [39] is widely used to predict the failure rate of power electronic components [22], [26]-[27] and [29]. 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 any insight into the root cause of a failure and the inspiration for reliability enhancement. Physically, a failure rate of a component is the sum of the failure rates of all failure modes, which have different reliability models corresponding to specific failure mechanisms. 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 conditions, statistics itself is not sufficient to interpret the reliability data without judgment of the assumptions and non-statistical factors (e.g. modification of design, new generation of components, etc.).

Therefore, the scope of this paper is first to give an introduction of failures in power electronic systems. Then a systematic DFR procedure based on physics-of-failure (PoF) [40] approach and mission profile analysis is proposed in section III. A case study on a 2.3 MW wind power converter is presented in section IV with emphasis on the reliability critical IGBT modules and the potential methods for reliability enhancement. The challenges and opportunities are addressed in the conclusions.

II. Failures in Power Electronic Systems

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. The essence of reliability engineering is to prevent the creation of failures. Deficiencies in the design phase have effect on all produced items and the cost to correct them is progressively increased as development proceeds. Therefore, this section introduces the following aspects of failure in power electronic systems.

A. Failure Criteria

In power electronic systems, the degradation of one component may affect the operation of another. For example, the reduction of capacitance will increase the associated voltage ripple, which may cause over voltage stress of switching devices even though the capacitor itself can still operate under a normal mode. Similarly, the deterioration of input and output performance of a specific power electronic converter may induce failures of other subsystems. Therefore, it could be more difficult to determine the failure criteria of a component or system in power electronics than in other domains. The selection of the parameter as the failure indicator and the corresponding criteria depends on specific design, operation condition and standard. For illustration, the failure criteria for electrolytic capacitors can be set as 100% increase of the equivalent-series-resistance (ESR) or 20% reduction of the capacitance. Different results could be obtained for different choices of the failure indicator.

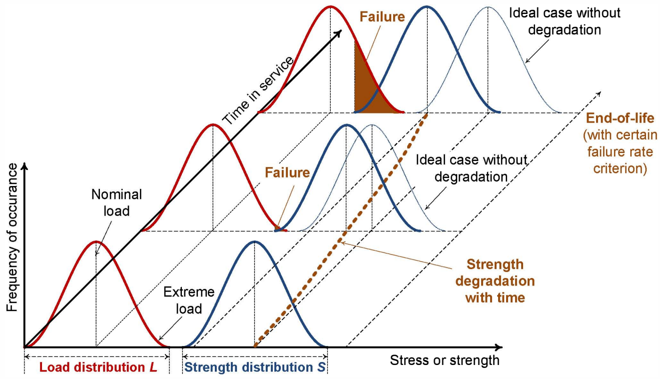


Fig. 4. Load-strength analysis to explain overstress failure and wear out failure.

B. Load and Strength Analysis

A component fails when the applied load L exceeds the design strength S. 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.) [12]. Fig. 4 presents a typical load-strength interference evolving with time. For most power electronic components, neither load nor strength are 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 degraded with time. Theoretically, the probability of failure can be obtained by analyzing the overlap area between the load distribution and the strength distribution. Practically, the exact distributions of load and strength are very often not available, Monte Carlo simulation as discussed in [12] can be applied to randomly select samples from each distribution and compare them and thus roughly estimate the probability of failure.

Although the load and strength analysis may not ensure an accurate prediction of probability of failure due to the uncertainty of their distributions, it provides insight into how to reduce failure. Proactive measures can be taken in design phase by setting a reasonable design margin (i.e. selection of S) or managing load (i.e. active control of L during operation). Therefore, degradation models and lifetime models are necessary to estimate the failures at the end-of-life in the initial design phase, which will be discussed later.

C. 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 the 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 [40]. Failure mechanisms can be generally classified into overstress and wear out. 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 load (e.g. temperature cycling). Compared to empirical failure analysis based on historical data, 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. Table I gives examples of wear out failure mechanisms for electronic components as presented in [41].

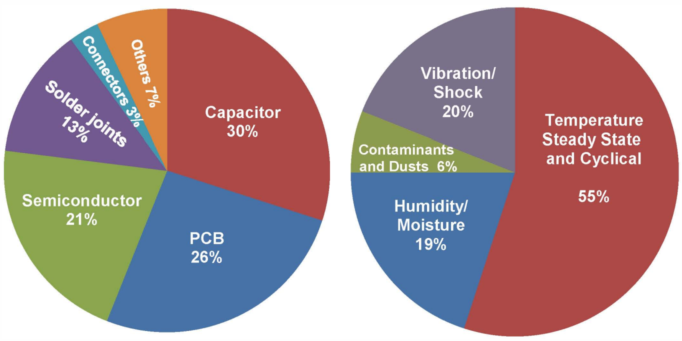
D. Typical Distribution of Failures and Source of Stresses in Power Electronic Systems

To perform reliability-oriented design, it is worthwhile to explore the major failure modes and failure mechanisms of all reliability-critical components. Fig. 5 (a) and Fig. 5 (b) show the failure distribution among power electronic components [42] and source of stresses that have significant impact on reliability [43]. It can be noted that capacitors and semiconductors are the most vulnerable power electronic components, which is also verified by the survey conducted in [21]. Temperature has the most significant impact on the reliability of power electronic components and systems. Therefore, electrical-thermal analysis and simulation are important and necessary to perform reliability-oriented design.

TABLE I. FAILURE MECHANISMS, RELEVANT LOADS, AND MODELS IN ELECTRONICS.

Failure mechanisms	**Failure sites**	**Relevant loads**	**Failure models**
Fatigue	Die attach, wire bond /TAB, solder leads, bond pads, interfaces	ΔT, T_{mean}, DT/dt, dwell time, ΔH, ΔV	Nonlinear Power law (Coffin-Manson)
Corrosion	Metallization	M, ΔV, T	Eyring (Howard)
Electromigration	Metallization	T, J	Eyring (black)
Conductive filament formation	Between Metallization	M, ΔV	Power law (Rudra)
Stress driven diffusion voiding	Metal traces	S, T	Eyring (Okabayashi)
Time dependent dielectric breakdown	Dielectric layers	V, T	Arrhenius (Fowler-Nordheim)

T: temperature; H: humidity; Δ: cyclic range; V: voltage; M: moisture; J: current density; ∇: gradient; S: stress.



(a) Failure root cause distribution. (b) Source of stresses distribution.

Fig. 5. Failure and stress distributions in power electronic systems (Data source: (a) from [42] and (b) from [43]).

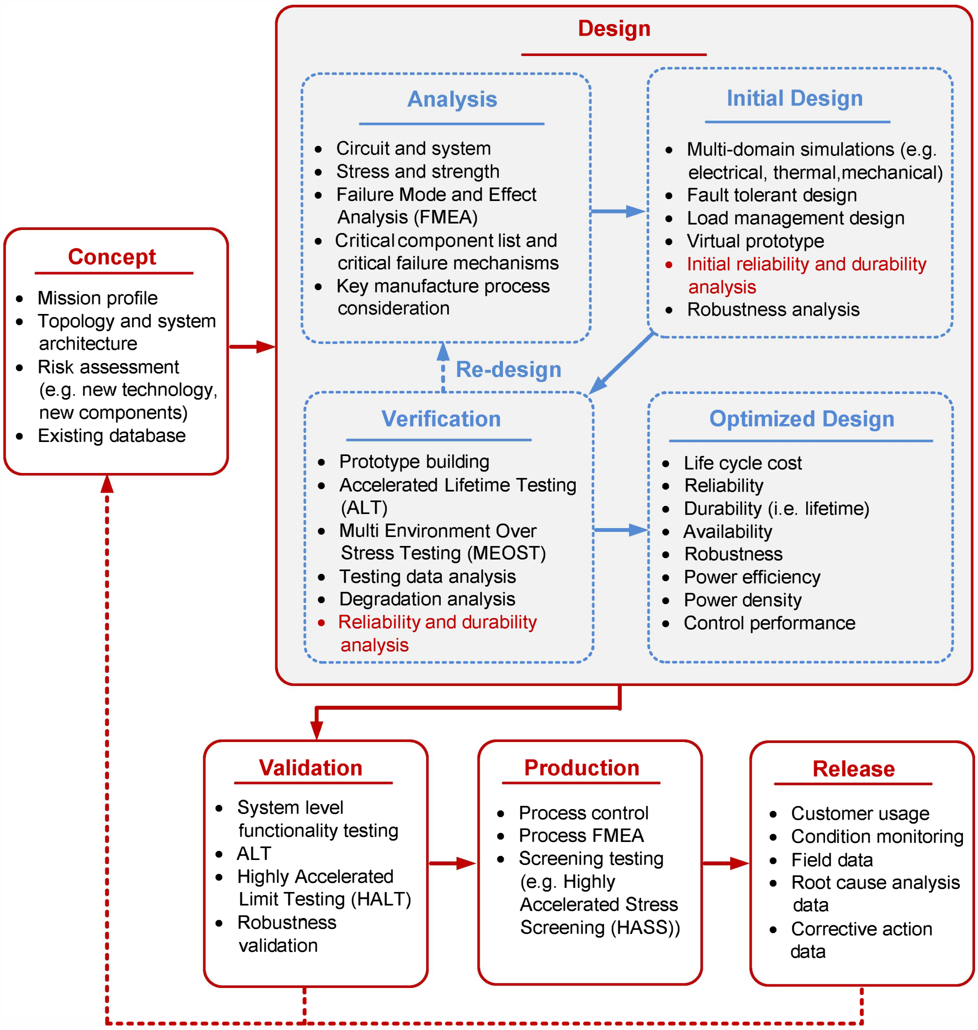


Fig. 6. Proposed design for reliability procedure for power electronic systems.

III. Proposed DFR Procedure for Power Electronic Systems and Associated Design Tools

A systematic DFR procedure specifically applicable to power electronic system design is proposed as given in Fig. 6. It can be noted that the procedure designs reliability into each development process (i.e. concept, design, validation, production and release) of power electronic products, especially in the design phase. Therefore, attention is given to the detailed procedures and various design tools applied in the design phase according to the initial design concept.

A. Concept Phase

In the initial concept phase, the relevant conditions to which the power electronic systems are expected to be exposed (i.e. mission profile) are identified. Benchmarking of system architecture and circuit topology is conducted. Then, the potential new risks brought into the design are analyzed based on past experience and applied new type of devices and topologies. In the wind power application, the mission profile mainly depends on the wind speed profile. Therefore, it is necessary to analyze the feature of the wind profile based on record data of a specific location and time period. Fig. 7 gives an example of the wind speed distribution at the Lee Ranch facility in Colorado during the year of 2002 [44].

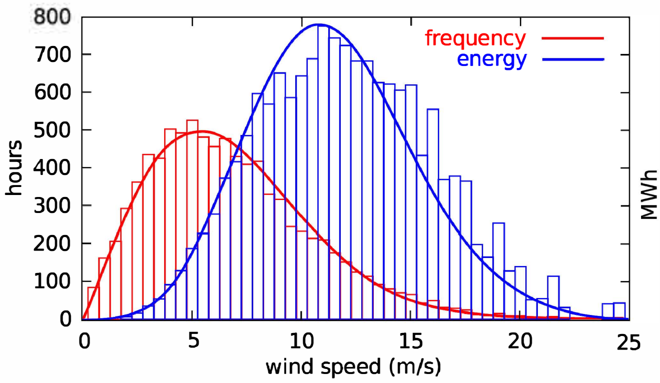


Fig. 7. Distribution of wind speed (red) and energy generated (blue) for all of 2002 at the Lee Ranch facility in Colorado. The histogram shows measured data, while the curve is the Raleigh model distribution for the same average wind speed (source: Wikipedia adapted from [44]).

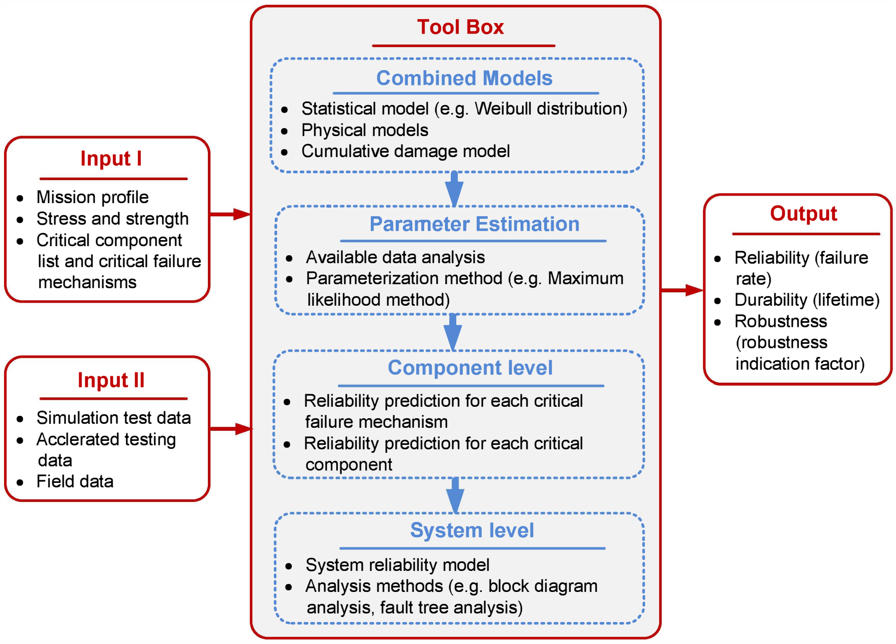


Fig. 8. Proposed reliability prediction procedure for power electronic systems.

B. Design Phase - Analysis

The analysis covers the following four aspects: a) basic operation of the power electronic circuit and system; b) electrical and thermal stress analysis based on the system specifications and mission profile for preliminary selection of components to meet the stress-strength requirement; c) Failure Mode Effect and Analysis (FMEA) [12] to identify the failure mechanisms as shown in Table I, failure mode (e.g. open circuit, short circuit, etc.), occurrence and severity level of the failure and likelihood of prior detection for each cause of failure and d) list of reliability critical components in the system and their associated failure mechanisms.

C. Design Phase – Initial Design

Multi-domain simulation, especially the electrical-thermal simulation is a very useful tool to virtually investigate the static and dynamic properties of the system to be designed as discussed in [45]-[46]. The link between the electrical domain and thermal domain is the power loss and thermal model of individual component. Finite Element Analysis (FEA) can be used to study the thermal distributions.

Fault tolerant design is a way to reduce the system level failures for some critical applications (e.g. data center) requiring high level of reliability. Due to the redundancy design as summarized in [30], a fault in a component or subsystem does not induce the failure of the whole system, therefore, preventing the system from significant loss or unexpected interruptions.

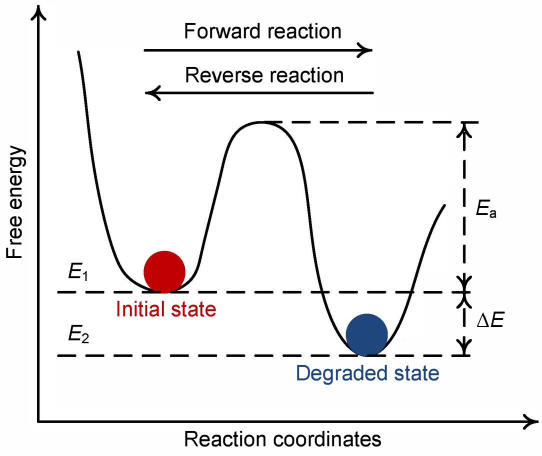
At this stage, an initial reliability prediction can be performed. Fig. 8 proposes a generic prediction procedure based on the PoF approach. The toolbox includes combined models and various sources of available data (e.g. manufacturer testing data, simulation data and field data, etc.) for the reliability prediction of individual components and then the whole system. Statistical models are well presented in [12] and will not be discussed here. Temperature and temperature cycling are the major stressors that affect the reliability performance as shown in Fig. 5, which will be more significant with the trend for high power density and high temperature power electronic systems. Therefore, two models are presented here to study their effects.

a) Degradation model on the temperature effect

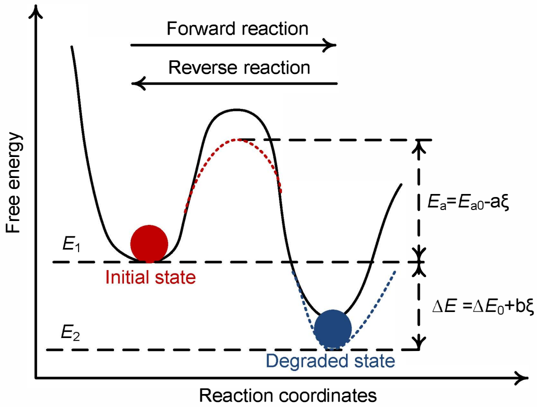
Fig. 9(a) illustrates the degradation of a material or device from initial stable state with free energy of E_1 to a degraded state with free energy of E_2. The driving force for this degradation is the free energy difference between E_1 and E_2, defined as ΔE. The heat induced by power losses in power electronic components provides the energy for the transformation from one state to another. The rate of the degradation is limited by the activation energy E_a. Define k_{foward}, $k_{reverse}$ and k_{net} as the degradation rate, recovery rate and net reaction rate, respectively. It can be derived that

$$k_{net} = k_{forward} - k_{reverse} = k_0 e^{-\left(\frac{E_a}{K_B T}\right)}\left[1 - e^{-\left(\frac{\Delta E}{K_B T}\right)}\right] \approx k_0 e^{-\left(\frac{E_a}{K_B T}\right)} \quad (1)$$

where $E_a = -K_B\left[\partial \ln\left(k_{net}\right)/\partial\left(1/T\right)\right]$, K_B is the Boltzmann's constant (8.62×10^{-5}eV/K), T is the temperature in Kelvin and k_0 is a material/device specific constant. It should be noted that the simplified result in (1) is the same as Arrhenius equation that is widely used for reliability prediction. The value of the activation energy is dependent on the type of material and device.



(a) Free energy description of material/device degradation.



(b) The impact of additional stress on material/device degradation.

Fig. 9. Material/device degradation from free energy perspective (adapted from [48]).

When combined stresses are applied, the activation energy ΔE is dependent on additional applied stress ξ (e.g. electrical stress, mechanical stress, and chemical stress) as shown in Fig. 9(b). The parameters a and b are determined from stress-induced degradation testing data. a is temperature dependent and defined as $a = a_0 + a_1 K_B T$. It can be obtained that $k_{net} = k_0 \left(\frac{b}{K_B T}\right) \xi e^{-\left(\frac{E_{a0}}{K_B T}\right)}$ and $k_{net} = k_0 e^{a_1 \xi} e^{-\left(\frac{E_{a0} - a_0 \xi}{K_B T}\right)}$ under low ξ and high ξ, respectively. Therefore, a power law dependence for stress ξ is used to bridge the gap between low stress (k_{net} is linear with ξ) and high stress (k_{net} is exponential with ξ). That is

$$k_{net} = k_0 \xi^n e^{-\left(\frac{E_a}{K_B T}\right)} \tag{2}$$

b) Lifetime model on the temperature cycling effect

The thermal cycling is a response to the converter line and loading variations as well as periodically commutation of power switching devices. It will induce cyclic temperature stress on different layers of materials used for fabrication of power electronic components. For example, Fig. 10 shows the typical structure details of IGBT modules.

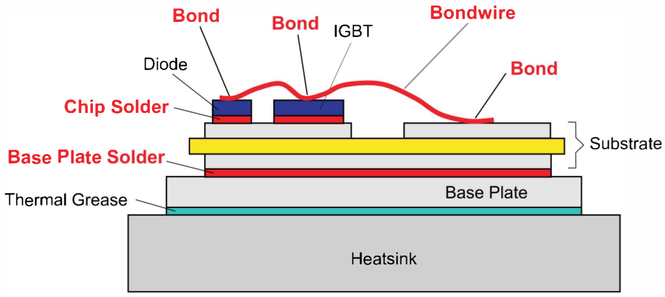


Fig. 10. Structural details of an IGBT module (connections that are relevant to module lifetime are marked red) [47].

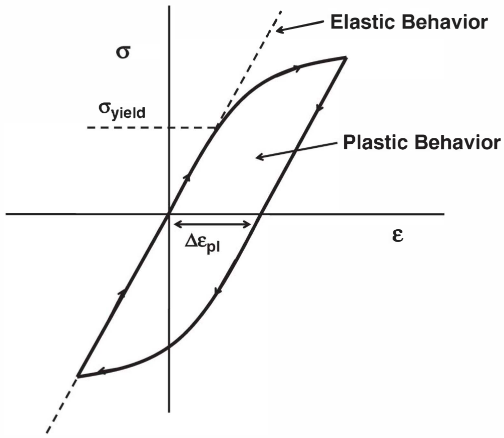


Fig. 11. A typical stress-strain (σ-ε) curve for a material [48].

Thermal cycling is found to be one of the main drivers for failure of IGBT modules. The effect of the temperature cycling can be explained by the typical stress-strain curve in Fig. 11. σ is defined as the cyclic stress (e.g. temperature cycling) and ε is defined as the deformation. With a low cyclic stress below σ_{yield}, no damage occurs and the material is in the elastic region. When the stress is increased above σ_{yield}, an irreversible deformation is induced and the material enters into the plastic region. The coefficients of thermal expansion for different materials in the IGBT modules are different, leading to stress formation in the packaging. The degradation will continue with each cycle until the material fails. The number of cycle to failure for temperature cycling can be obtained as

$$N = k\left(\Delta T - \Delta T_0\right)^{-m} \tag{3}$$

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 [15].

Constant parameters in the combined models can be estimated according to the available 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 [30].

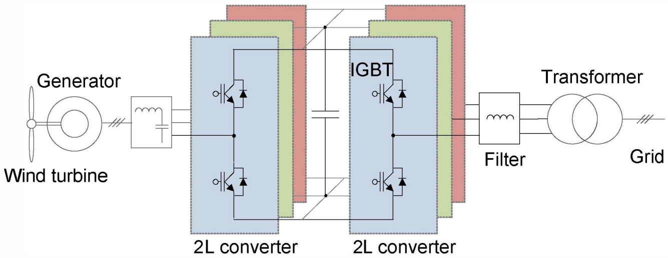
IV. CASE STUDY ON A 2.3 MW WIND POWER CONVERTER

A. Topologies for Wind Power Converter

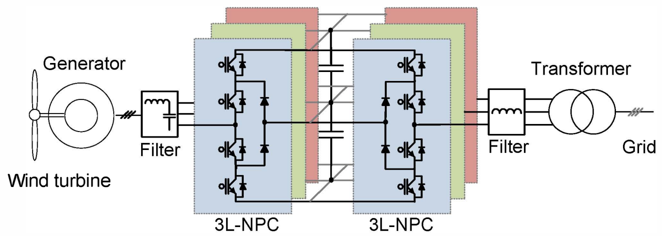
As the state-of-the-art and most adopted solution for wind power generation, single-cell partial-scale power converter is used in conjunction with the Doubly-Fed Induction Generator (DFIG) [2]. Another configuration that is becoming popular in the wind power application is a single-cell full-scale power converter with asynchronous generator, electrically excited synchronous generator (WRSG) or permanent magnet excited type (PMSG) [2].

Three-phase converters are dominant for wind power application to handle high power and reduce the energy of cost compared to single phase ones. Pulse width modulation-voltage source converter with two-level output voltage (2L-PWM-VSC) is the most frequently used three-phase power converter topology in wind power systems. As the interface between the generator and power grid, two 2L-PWM-VSCs are usually configured as a back-to-back structure (2L-BTB) with a transformer on the grid side, as shown in Fig. 12 (a). 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.

Three-level neutral point clamped back-to-back converter (3L-NPC-BTB) topology is one of the most commercialized multi-level converter topologies on the market, which is shown in Fig. 12 (b). It achieves smaller size of filters and higher voltage handling capability. However, it is found that the loss distribution is unequal between the outer and inner switching devices in a switching arm, which might lead to uneven lifetime of power switching devices [49]-[51].



(a) Two-level back-to-back converter (2L-BTB).



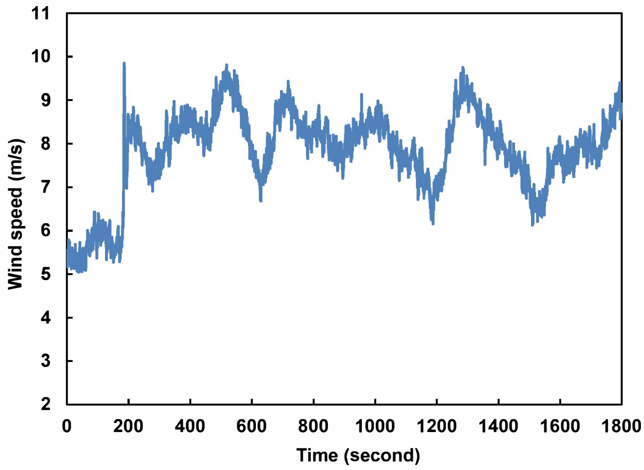
(b) Three-level neutral point clamped back-to-back converter (3L -BTB).

Fig. 12. State-of-the-art circuit topologies for wind power converters [2].

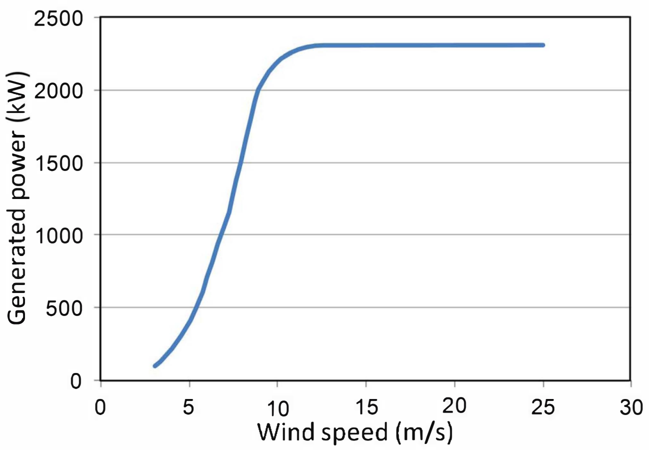
TABLE II. CONVERTER PARAMETERS FOR CASE STUDY.

Topology	2L-BTB as shown in Fig. 12 (a)
Rated output active power P_o	2.3 MW
DC bus voltage V_{dc}	1.1 kV DC
*Rated primary side voltage V_p	690V rms
Rated load current I_{load}	1.93 kA rms
Switching frequency f_c	1950 Hz
Filter inductance L_f	132 μH
IGBT *Selection I* (grid side)	1.6 kA/1.1kV/125ºC, 2 in parallel
IGBT *Selection II* (grid side)	2.4 kA /1.1kV/ 150ºC, single switch

* Line-to-line voltage in the primary windings of transformer



(a) Wind speed profile for the case study.



(b) Power curve against wind speed of the chosen 2.3 MW wind turbine.

Fig. 13. Wind speed profile and power curve of the wind turbine.

B. Case Study

a) Wind speed profile and converter specifications

Table II shows the parameters of a 2.3 MW wind power converter for the case study. For illustration purpose, the half hour wind speed profile shown in Fig. 13(a) is analyzed. It should be noted that for a specific practical application, wind speed patterns are obtained by collecting wind speed profile during a much longer time period. Fig. 13(b) shows the power curve against wind speed for the chosen wind turbine. IGBT modules as the reliability-critical components will be focused in the case study.

b) Lifetime prediction models

The reliability of the IGBT modules in the grid side converter is investigated. There are three dominant failure mechanisms for IGBT modules when temperature cycling is applied: baseplate solder joints cracking, chip solder joint cracking and the wire bonds lift-off [52]. Based on the PoF approach, the specific lifetime model is required for each failure mechanism. Therefore, three models are to be calibrated from (3), which considers both the plastic and elastic behavior of the associated materials.

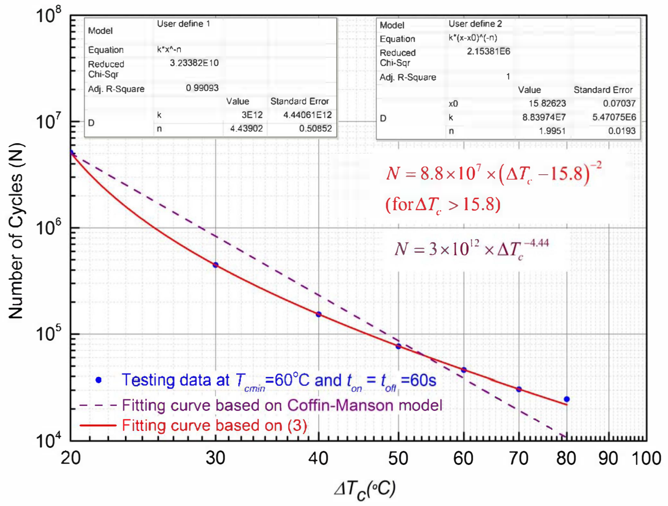
Moreover, as the amplitude and average temperature level of the thermal cycling are different when the wind speed is fluctuating, the Palmgren - Miner linear cumulative damage model [53] is applied in the form of

$$\sum_i \frac{n_i}{N_i} = 1 \tag{4}$$

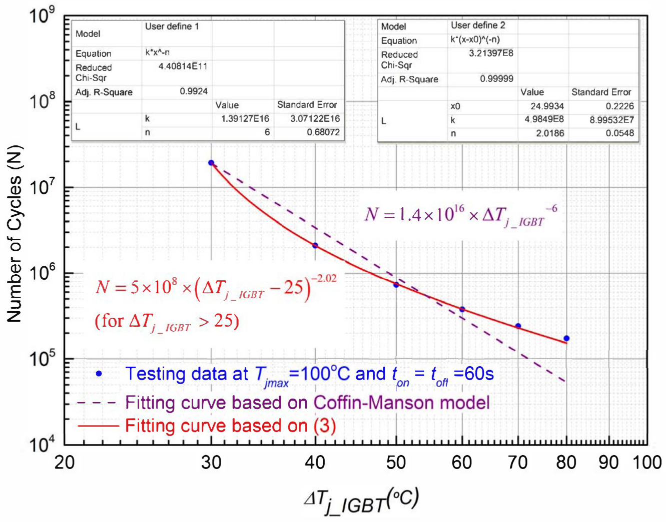
where n_i is the number of applied temperature cycles at stress ΔT_i and N_i is the number of cycles to failure at the same stress and for the same cycle type. Therefore, each type of ΔT_i accounts for a portion of damage. Failure occurs when the sum of the left hand side of (4) reaches 1.

c) Parameter estimation of lifetime models

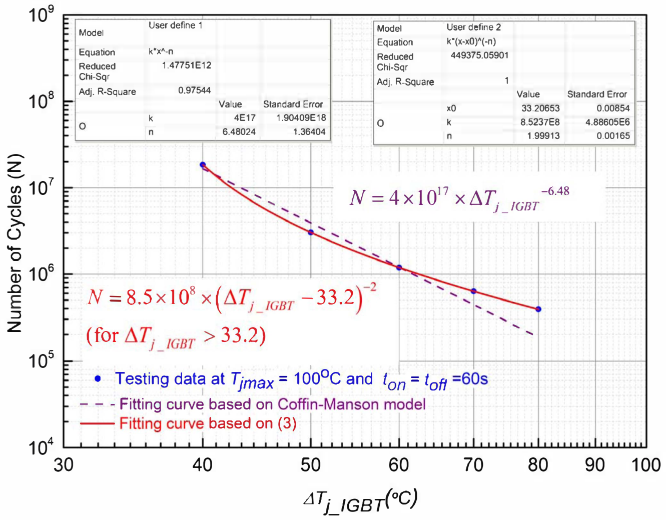
The manufacturer of the IGBT modules has performed a series of power cycling experiments as described in [52]. Based on the B_{10} lifetime testing data (which is the number of cycles during which 10% of the total number of modules fail), the parameters of the derived model in (3) can be estimated as shown in Fig. 14.



(a) Cycle to failure models for thermal cycling on baseplate solder joints for t_{cycle} = 120s and T_{cmin} = 60°C.



(b) Cycle to failure models for thermal cycling on chip solder joints for t_{cycle} = 120s and T_{jmax} = 100°C.



(c) Cycle to failure models for thermal cycling on wire bonds T_{jmax} = 100°C.

Fig. 14. Parameter estimation based on the model derived in (3) and the Coffin-Mansion model (lifetime testing data source: [52]).

The lifetime testing data are also used to fit the widely used Coffin-Mansion model, in which the yield amplitude of temperature cycle, thus, the elastic behavior is neglected. However, with high number of cycling (> 10^4), thus, with low cyclic temperature stress, the absence of the elastic behavior may induce high level of inaccuracy. As shown in Fig. 14, there is a considerable discrepancy between the two models, of which the model in (3) can fit the testing data well. The estimated value of ΔT_0 in (3) implies that it has negligible impact on the lifetime for temperature cycling with amplitude less than ΔT_0.

Moreover, the number of cycles to failure is also dependent on the average junction temperature T_j and average case temperature of T_c. A scaling factor is provided by the manufacturer in [54] as

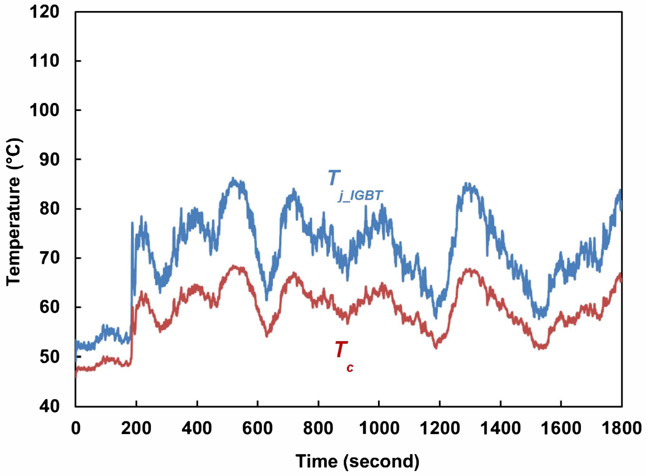
$$\text{Scaling factor} = 1.017^{\left(\Delta T_{level}^{1.16}\right)} \tag{5}$$

where ΔT_{level} is the difference between two maximum junction temperature levels or two minimum case temperature levels.

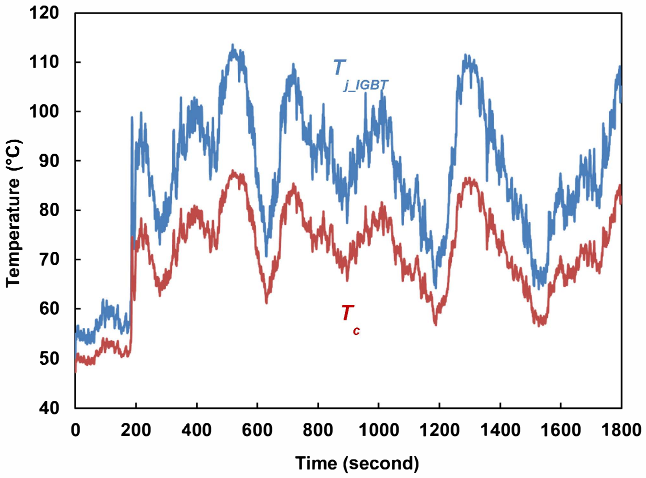
d) Distribution of Temperature profile and temperature cycling

Fig. 15 (a) and (b) show the case temperature and junction temperature for IGBT modules of *Selection I* and *Selection II*, respectively. It can be noted that IGBT modules with a lower current rating have higher amplitudes of ΔT_j and ΔT_c, thus, lower number of cycles to failure.

To perform the lifetime prediction, the analysis of the temperature cycling distribution is necessary. The Rainflow counting method [55] is applied to extract the temperature information as shown in Fig. 16. Fig. 16(a) and (b) show the case temperature and junction temperature cycling with the IGBT modules of *Selection I*. Fig.16(c) and (d) give those of the IGBT modules of *Section II*. It can be noted that most of the temperature cycling is of very low amplitude which has negligible impact on the lifetime.

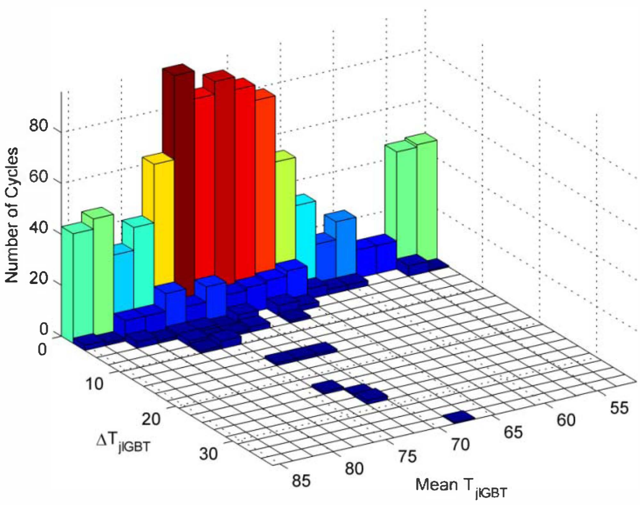


(a) The IGBT junction temperature and case temperature with *Selection I* of two 1.6 kA/1.1kV IGBTs in parallel.

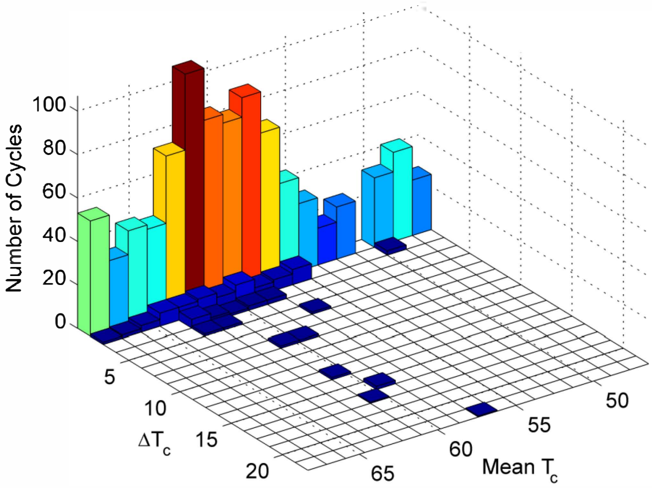


(b) The IGBT junction temperature and case temperature with *Selection II* of single 2.4 kA /1.1kV IGBT.

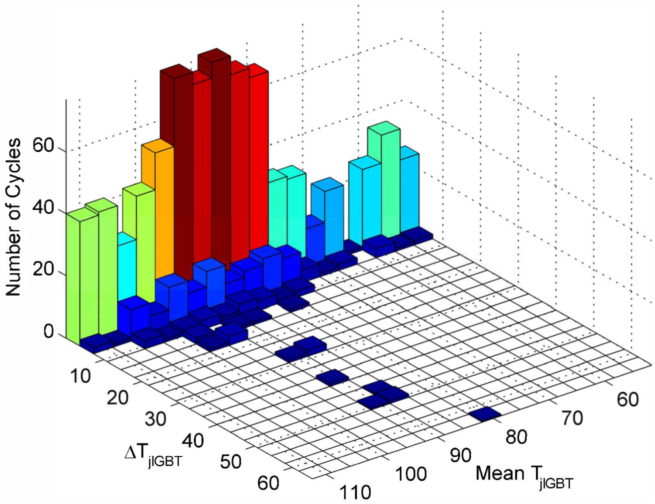
Fig. 15. Temperature profile of the two selected IGBT modules.



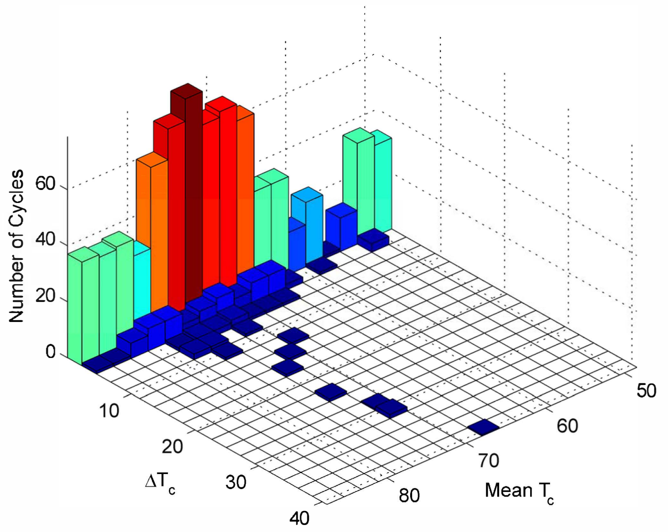
(a) Distribution of junction temperature cycling with *Selection I* of two 1.6 kA/1.1kV IGBTs in parallel (Temperature unit: °C).



(b) Distribution of case temperature cycling with *Selection I* of two 1.6 kA/1.1kV IGBTs in parallel (Temperature unit: °C).



(c) Distribution of junction temperature cycling with *Selection II* of single 2.4 kA /1.1kV IGBT (Temperature unit: °C).



(d) Distribution of case temperature cycling with *Selection II* of single 2.4 kA /1.1kV IGBT (Temperature unit: °C).

Fig. 16. Rainflow counting of the temperature profiles for IGBT modules.

e) Lifetime prediction results

According to the calibrated models shown in Fig. 14, only the temperature cycling with ΔT_c > 15.8°C, ΔT_{j_IGBT} > 25°C and ΔT_{j_IGBT} > 33.2°C are considered for the lifetime prediction for baseplate solder joints, IGBT chip solder joints and wire bonds, respectively. The impact of the ones with lower amplitude is sufficiently to be neglected. For illustration purpose, the wind profile is assumed to repeat as that in the studied 30 minutes and the wind turbine operates 24 hours per day and 365 days per year. According to the models estimated in Fig. 14 and the ones shown in (4) and (5), the lifetime of the two selected IGBT modules is given in Table III.

It should be noted that the purpose of the study case on the IGBT modules is to demonstrate the procedure to perform reliability prediction based on mission profile and PoF approach with differentiation of various failure mechanisms. For practical considerations, wind speed profile during long time period at specific location should be analyzed. Therefore, wind profile as shown in Fig. 7 could be useful for future research. Moreover, other failure mechanisms in IGBT modules may induce additional failures and should also be considered in the lifetime estimation.

TABLE III. LIFETIME PREDICTION RESULTS.

Failure mechanisms	B_{10} lifetime (year)	
	Selection I	***Section II***
Baseplate solder joints (due to ΔT_c)	358	24
IGBT chip solder joints (due to ΔT_{j_IGBT})	438	22
Wire bonds (due to ΔT_{j_IGBT})	2633	74
Overall (determined by the shortest one)	**358**	**22**

C. Methods to Improve Reliability

a) Selection of proper devices

The results shown in Table III imply that the selection of IGBT modules has significant impact on the lifetime. Comprehensive analysis on the device selection based on both cost and performance is needed to avoid either over engineering design or fail to meet the specifications.

b) Low Voltage Ride Through (LVRT) thermal optimized modulation

Thermal loading of the power device can be improved by the modulation schemes. Some modulation methods for thermal optimization of 3L-NPC-BTB wind power converters during extreme LVRT are proposed in [56]. The basic idea of these modulations is to select the proper vector sequences which can reduce the dwelling time or commutations involving zero voltage level. The loss and thermal in the most stressed devices can thereby be reduced.

c) Reactive power control during wind gust

The amplitudes of ΔT_c and ΔT_j have significant impact on the lifetime of IGBT modules. To limit the increase of the thermal cycling stress during wind gust, the possible ways to control the reactive power and reduce the thermal loading is discussed in [57]. The normal operation mode and reactive power control mode of the converter is switched according to the grid condition.

d) On-line condition monitoring

Condition monitoring is an effective way to enhance reliability when the power converters are in operation [58]. It provides the real-time operating characteristics and health conditions of the systems by monitoring specific parameters of power electronic components (e.g. saturation voltage of IGBTs). Therefore, proactive maintenance work could be planned to avoid failures that would occur.

CONCLUSIONS

More and more efforts have been devoted to better power electronic systems in terms of reliability to ensure higher availability, more power generation and low maintenance cost. A paradigm shift in reliability research on power electronics is going on from simple handbook based calculations to the physics-of-failure approach and design for reliability process. A systematic design procedure consisting of various design tools is presented in this paper to give an outline on how to design reliability into the power electronic products from the early concept phase. The case study on a 2.3 MW wind power converter demonstrates some aspect of the design procedure with emphasis on the lifetime prediction of the two kinds of IGBT modules. It is based on analysis on mission profile, failure mechanism, thermal profile and estimation of the associated lifetime models.

The major challenges and opportunities in the research on reliability of power electronic systems are addressed.

A. Challenges

a) Outdated paradigms and lack of understanding in design for reliability approach.

b) Uncertainties in mission profile and strength of components.
c) Increasing electrical/electronic content and complexity.
d) Lacking of understanding of failure mechanisms and failure modes of reliability critical components.
e) Resource-consuming testing for reliability prediction and robustness validation.

B. Opportunities

a) Better mission profile and on-line monitoring data from the field.
b) Physics-of-failure approach provides insight into how to avoid failures in power electronic systems.
c) Control of heat flow and thermal distribution by controlling the power in power electronic circuits.
d) Component level and system level smart de-rating operation.
e) Condition monitoring and fault tolerant design allow extended lifetime.
f) Emerging semiconductor and capacitor technologies ensure more reliable power electronic components.
g) Computer-aided automated design software to save time and cost.

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