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Peyghami, Saeed; Wang, Zhongxu; Blaabjerg, Frede

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A Guideline for Reliability Prediction in Power Electronic Converters

Saeed Peyghami, *Member, IEEE*, Zhongxu Wang, *Student Member, IEEE*, and Frede Blaabjerg, *Fellow, IEEE*

***Abstract*—Reliability prediction in power electronic converters is of paramount importance for converter manufacturers and operators. Conventional approaches employ generic data provided in handbooks for random chance failure probability prediction within useful lifetime. However, the wear-out failures affect the long-term performance of the converters. Therefore, this paper proposes a comprehensive approach for estimating the converter reliability within useful lifetime and wear-out period. Moreover, this paper proposes a wear-out failure prediction approach based on a structural reliability concept. The proposed approach can quickly predict the converter wear-out behavior unlike conventional Monte Carlo based techniques. Hence, it facilitates reliability modeling and evaluation in large-scale power electronic based power systems with huge number of components. The proposed comprehensive failure function over the useful lifetime and wear-out phase can be used for optimal design and manufacturing by identifying the failure prone components and end-of-life prediction. Moreover, the proposed reliability model can be used for optimal decision-making in design, planning, operation and maintenance of modern power electronic based power systems. The proposed methodology is exemplified for a photovoltaic inverter by predicting its failure characteristics.**

Keywords— converter reliability, failure rate, wear-out failure, constant failure rate, reliability modeling, systematic failure, catastrophic failure.

I. Introduction

Power electronics reliability has gained an increasing interest recently due to the role it plays in the modernization of the future power grids [1], [2]. Power converters are the main energy conversion system in a wide range of applications such as renewable energies, energy storages, high/medium voltage Direct Current (DC) transmission systems, medium/low voltage DC distribution systems and e-mobility [3], [4]. However, the converters seem to be the vulnerable components according to industrial experiences [1], [5], [6]. Therefore, high proliferation of the converters will pose new challenges in terms of optimal and reliable design, planning, operation, and maintenance of the future power grids.

An expected end-of-life of converters is of paramount importance for an optimal decision-making in planning of modern power electronic systems [7]. The optimal facility planning including cost-effective design and replacement scheduling depends on the converters lifetime. Moreover, the converter failure rate will affect its availability and optimal operational planning of power systems. The maintenance scheduling for repair and replacement of power converters requires appropriate reliability modeling. Moreover, reliability modeling is an important task for designers to do optimal and reliable converter manufacturing. As a result, the decision-making on investment during manufacturing, system-level planning, operation and maintenance of power electronic systems intensifies the importance of converter reliability prediction [2], [8]. Furthermore, evaluating new converter topologies/redundant operation [9]–[11], switching schemes, and control algorithms [8], [10], [12], [13] as well as analyzing the impact of control and operating conditions on the long-term performance of converters [2], [14] requires appropriate reliability models of the converter.

So far, different approaches have been used for converter reliability estimation [10], [12], [15]–[22]. The most common used method relies on the Military Handbook 217 (MIL-HDBK-217). The main concerns regarding MIL-HDBK-217 are out-of-date data for new technologies, vagueness of the failure mechanisms and data type, and exclusion of different operating conditions. Besides MIL-HDBK-217, some companies and organizations have updated this handbook data and methodology, such as Telcordia SR-322, Siemens SN29500, RDF-2000. All these approaches carry the MIL-HDBK-217 shortcomings even though they have some updates on this handbook. Later on, the International Electrotechnical Commission (IEC) released IEC TR-62380 [23], which considers the failure mechanisms for failure rate prediction throughout a mission profile. However, the provided data are not still updated and the failure mechanisms are not accurately modeled. Therefore, the IEC TR-62380 has been replaced by IEC 61709 [24], which provides a general guideline for mission profile based failure rate prediction.

In the aforementioned handbook methods, the failure mechanisms are not accurately modeled and physics of failures are not considered. Therefore, the predicted reliability may not be acceptable, and may not be suitable for reliable design of converter components. Moreover, identifying the weak points for reliability enhancement is not clear. Hence, another update on MIL-HDBK-217 has been provided by FIDES group where the physics of failures are considered in the failure rate prediction [25]. So far, the FIDES approach is the latest update on the failure rate prediction of electronic components.

All the handbooks provide a constant failure rate for components during their useful lifetime. It is assumed that the components are appropriately designed and they do not enter the wear-out phase during the mission life period [23], [25]. Moreover, the IEC TR-62380 has provided lifetime expectancy for the components prone to wear-out failure. In spite of considering the mission profile in the IEC TR-62380 for constant failure rate prediction, it is not taken into account for the end-of-life prediction. Therefore, the life expectancy limits may not be accurate enough for different operating conditions.

On the other hand, wear-out failure analysis in converter components based on physics of failures has been addressed recently in [17]–[21]. Particularly, the wear-out probability prediction in converter components has been explored in [17], [18]. A Monte Carlo Simulation (MCS) based technique is employed to model device aging. The employed method in [17], [18] relies on the MCS, where in practice the MCS suffers from computational burden. Specially, for large-scale power electronic based power systems, employing MCS for all the components in different converters with different mission profiles is almost infeasible. Moreover, on-line

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The authors are with the Department of Energy Technology, Aalborg University, Aalborg 9220 east, Denmark. (Email: sap@et.aau.dk, zhongxu2020@gmail.com, fbl@et.aau.dk)

reliability prediction for control purposes (e.g., in [8]) requires a fast reliability prediction approach. Meanwhile, the repeating MCS in design for reliability approaches is time consuming. Furthermore, system-level reliability prediction in a converter considering the wear-out failure of Semiconductor Devices (SDs) and Capacitors (Caps) is explored in [18]. Besides the aforementioned shortcomings of MCS used in this paper, the model uncertainties of the capacitor lifetime model are not appropriately conducted.

Also, the lifetime models provided in [17]–[21] are more applicable for wear-out modeling. The aging failure probability can be used for design for reliability and end-of-life prediction in power converters. However, the system-level design, planning, operation and maintenance of power electronic systems require the converter availability modeling. The converter availability depends not only on the wear-out failure rate, but also on the failure rate of useful lifetime. Therefore, a complete failure rate prediction within useful life and wear-out periods is required for converter design and operation.

In order to address the aforementioned shortcomings of the state-of-the-art methods, this paper proposes a comprehensive reliability prediction approach for power converters. The proposed approach predicts the failure characteristic of a converter within its useful and aging period according to an applied mission profile. In the proposed approach, the constant failure rate prediction based on the handbook estimation method is merged with the wear-out failure estimation approach. Furthermore, a Stress-Strength Analysis Method (SSAM) is proposed for the wear-out failure rate prediction employing a structural reliability concept [26]. Unlike MCS, the proposed SSAM can quickly predict the aging probability, which facilitates the reliability modeling, design for reliability and reliability evaluation in large-scale power electronic based power systems.

The proposed approach can facilitate reliable design and manufacturing of converters by identify its weakest links from reliability standpoint. Furthermore, it can be used for system-level decision-making within planning, operation and maintenance of power electronic systems in order to enhance the overall system reliability. This is due to the fact that the power electronic system reliability depends on different factors including converter topology and its application [9], [27], [28] control/switching schemes [2], [8], [27], [29], [30], operating conditions [8], [29]–[31], climate conditions [15], [16] and so on. Therefore, during planning phase, selecting suitable converter topologies for a desired application considering the climate conditions can enhance the system reliability. Furthermore, appropriate control/switching schemes can extend the converter lifetime and thus the overall system reliability during operation phase. Moreover, predicting the converter end-of-life will aid proper maintenance scheduling for different converters to retain the system availability.

In the following, the concept of reliability in power converters is discussed in Section II. Section III presents the reliability modeling within useful life. Moreover, the proposed SSAM is explained in Section IV. The proposed approach is exemplified by predicting the reliability of a Photovoltaic (PV) inverter under different operating conditions in Section V. Finally, the outcomes are summarized in Section VI.

II. Reliability of Power Converters

A typical hazard (failure rate) function of an item/a system within its life cycle is shown in Fig. 1 including infant mortality, useful life and wear-out periods. Usually the infant mortality failures are related to the manufacturing and debugging processes and they have been solved before operating the item/system. Therefore, the item will experience random chance failures within its useful lifetime. Moreover, due to the aging of materials, the item may enter wear-out phase depending on the materials strength and applied stresses within long-term operation.

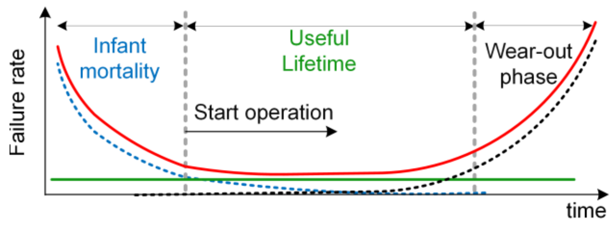

Fig. 1. Typical bathtub curve describing failure rate of an item.

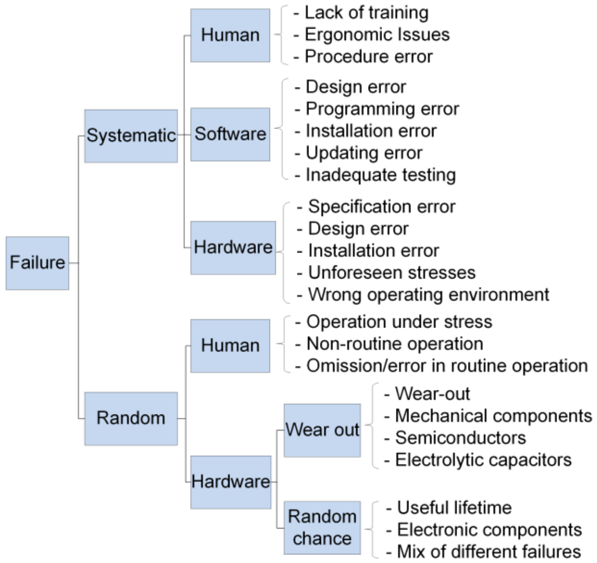

Fig. 2. Failures classification based on failure causes (sources) according to [33], [34].

Optimal and reliable design and operation of a converter depend on its hazard behavior in useful life and wear-out phase. This is due to the fact that the long-term performance of the converter remarkably depends on its useful lifetime and its availability. During the useful lifetime, failures occur by chance which yield a constant failure rate. The useful lifetime terminates once the item enters the wear-out phase where the failure rate rises. Therefore, wear-out failure probability prediction is of paramount significance since it can affect the overall system life cycle and operational/ maintenance costs. Therefore, the design for reliability concept has introduced to accurately design the components of a system to achieve a desired lifetime with a certain probability. Moreover, the limiting state unavailability U for an item is defined as [32]:

$$U = \frac{\lambda}{\lambda + \mu}, \tag{1}$$

where λ denotes the failure rate and μ is the repair/replace rate. In practice, the average operating time ($1/\lambda$) is much greater than the average down time ($1/\mu$) that means $\mu \gg \lambda$, and $U \approx \lambda/\mu$. Hence, higher failure rate causes higher unavailability and consequently higher system risk. Therefore, the system unavailability within useful lifetime should be acceptable. Moreover, entering wear-out phase, the failure rate will remarkably be increased, hence, the system unavailability and risk will be aggravated. In such a case, suitable maintenance strategies should be adopted to retain the overall system risks in an acceptable level. Therefore, unexpected operation and maintenance costs will be induced if the failure rate of system is not appropriately predicted. Consequently, power converter failures can affect the overall power system performance as well as the investment and operational costs. Hence, the failure rate prediction within useful life and wear-out phase is necessary for design and operation of converters.

General failure causes of an item can be classified into random and systematic failures as shown in Fig. 2 [33], [34]. The random failures occur at a random time resulting from one or more degradation mechanisms in the hardware. These failures may be caused by human error or associated with the hardware. The hardware (physical) failures are classified into random chance failure and wear-out (aging) failure [22]. The random chance failures, also called catastrophic failures [35], are caused by sudden overstress, such as overcurrent /overvoltage. These failures are modeled by the Exponential distribution function. Moreover, the aging failures, so-called gradual failures, are related to the wear-out phase of an item, which can be modeled, e.g., by a Weibull distribution. On the other hand, the systematic failures are associated in a deterministic way with a certain cause, which can solely be removed by a modification of the design and manufacturing processes, operational procedures or other relevant factors [33]. The systematic failures have non-physical causes, and will not re-appear if the causes are suitably corrected. Different root causes of random and systematic failures are summarized in Fig. 2 and more definition can be found in [33], [34]. In this paper, it is assumed that the converter is designed perfectly, that systematic failures will never appear and the expert staffs are employed for operation and maintenance in order to avoid the random human failures. Therefore, the only likely failures, which cannot be eliminated, include the random chance and wear-out failures.

In power electronic converters, following field data and industrial experiences, Capacitors (Caps) and Semiconductor Devices (SD) are the two most fragile components [5], [6], [36], [37]. They are exposed to random hardware failures which can be single-event catastrophic failures occurred within useful lifetime and long-term wear-out failures [22], [23], [35], [38]–[42]. The wear-out failures, namely intrinsic failures, are originated by internal degradation of component materials. Hence, they can be predicted by comparing the material mechanical strength with the applied stresses or accelerated life testing.

The random chance failures, which are usually extrinsic and caused by suddenly overstressing the components, are estimated based on field retuned data. The failure data can be collected and categorized following failure sources and mechanisms within a long-term operation. Thereafter, a complete reliability model for a specific operating condition can be derived. This procedure requires long-term operation data and proper classification of the failure causes and mechanisms under operating conditions. Using these data for the same item operating in another condition requires reasonable justifications [24] due to the impact of operating condition.

Meanwhile, during design and planning process, long-term field data do not exist. Hence, the failure data of similar cases can be employed by fair justifications. In practice, the field data of similar cases can be used for obtaining a reference (base) failure rate for a component under specific conditions. Notably, this can also be provided by the manufacturer. Moreover, test data can be used for modeling the impact of operating conditions on the failure rate by defining Acceleration Factors (AFs) in order to model the impact of operating conditions such as temperature, voltage and humidity.

This paper aims at predicting the reliability of power converters considering random chance and wear-out failures according to the accessible failure data and models for the converter components. Generally, a component/system failure occurs once one of the failure mechanisms due to either random chance failure or wear-out failure is triggered. Therefore, the total converter failure rate, λ_C is equal to:

$$\lambda_C = \lambda_{C-useful} + \lambda_{C-wear} \tag{2}$$

where, $\lambda_{C\text{-}useful}$ is the useful life failure rate and $\lambda_{C\text{-}wear}$ is the wear-out failure rate. The useful life and wear-out failure rates are obtained by adding the failure rate of individual components, i.e., Caps and SDs as:

$$\lambda_{C-useful} = \sum \lambda_{Caps-useful} + \sum \lambda_{SD-useful} \tag{3}$$

$$\lambda_{C-wear} = \sum \lambda_{Caps-wear} + \sum \lambda_{SD-wear} \tag{4}$$

In (3) and (4), it is assumed that the converter will fail if one of the components fails, hence a series reliability network is employed to model its reliability. In the case of stand-by systems and redundant configurations, suitable reliability modeling techniques such as Markov Process can be adopted [32]. The converter reliability is obtained by using:

$$R(t) = \exp\left(-\int_0^t \lambda_C(\tau)\, d\tau\right), \tag{5}$$

where *R(t)* is the converter reliability at instant *t*. In the following, the prediction of random chance and wear-out failure rates of converters are presented.

III. Constant Failure Rate Prediction

The failure rate during useful lifetime can be predicted considering the historical failure data within last operation of the converter. The more accurate data come from the long-term operation under identical operating conditions. These type of data, so-called user-provided data [24], may be obtained based on maintenance database and shutdown reports. Moreover, in the case the reliability data are not available, some generic data provided in handbooks can be employed [24]. Another data source for reliability estimation is the data prepared by the manufacturers [24]. Moreover, in most cases, especially during the design phase of new technologies, these data are not available, hence, expert judgment elicitation [24] could be the only option in which the data of similar cases may be employed by reasonable justifications. This approach is a difficult process.

As already mentioned, the MIL-HDBK-217, Telcordia SR-322, Siemens SN29500, RDF-2000, IEC-TR-62380, IEC-61709 and FIDES [23]–[25] prepared methods and base failure data for components where the failure rates can be modified according to the operating conditions. It is also possible to use the manufacturer or user-provided data as the base failure rate in order to predict the failure rate under desired operating conditions. Moreover, the IEC-TR-62380, IEC-61709 and FIDES provides a general mission profile-based approach for electronic components operating at different conditions. According to [23]–[25], the failure rate of a component can be obtained as a weighted average of failure rate in different operating phases. The failure rate of each phase can be predicted based on the reference failure rate provided by manufacturer/field data/handbooks, which are modified according to the operating condition considering AFs. Moreover, the FIDES approach provides a detailed method for estimating the constant failure rate of electronic components due to the fact that it considers the statistics of possible failure causes according to the physics of failure analysis [25].

Following the FIDES approach, the failure rate of an item (λ) is predicted by using (6) [25].

$$\lambda = \Pi_{PM} \Pi_{Prosess} \lambda_{Phy}\ , \tag{6}$$

where,

$$\lambda_{Phy} = \sum_{i=1}^{Phase} \left[\frac{t_{annual}}{8760}\right]_i \Pi_i \lambda_i\ , \tag{7}$$

$$\Pi_i = \left(\Pi_{Placement}\Pi_{App}\Pi_{Rugg}\right)^{0.511\cdot\ln(C_s)}, \text{ and} \tag{8}$$

$$\lambda_i = \sum_k \lambda_{0k}\Pi_k\ , \tag{9}$$

in which, Π_{PM} is the impact of quality and technical control over manufacturing, and $\Pi_{Process}$ models the effect of all processes, from specification to field operation and maintenance. The physical contribution is modeled by λ_{Phy}, which is given in (7) considering the mission profile., where, t_{annual} is the duration of i^{th} phase within one year. The term Π_i in (8), is the induced electrical, mechanical and thermal overstresses. The parameters in (8) is defined in [25]. The term λ_i in (9) is the corresponding failure rate in each phase of the mission profile, in which, λ_{0k} is the base failure rate of the item, which can be found in the handbooks or provided by the manufacturer. The AFs of Π_k reflects the physical constraints the item experiences within operation or dormant phases. The failure rate of λ_i is divided into thermal, case and solder joints related, as well as humidity, and mechanical stresses. In particular, the failure rate in (7) for SDs, $\lambda_{Phy\text{-}SD}$ is defined as:

$$\lambda_{Phy-SD} = \sum_{i=1}^{Phase}\left[\frac{t_{annual}}{8760}\right]_i \begin{pmatrix} \lambda_{0TH}\Pi_{Thermal} \\ +\lambda_{0TCyCase}\Pi_{TCyCase} \\ +\lambda_{0TCySolderjoionts}\Pi_{TCySolderjoionts} \\ +\lambda_{0RH}\Pi_{RH} \\ +\lambda_{0Mech}\Pi_{Mech} \end{pmatrix}_i \left(\Pi_{Induced}\right)_i \ . \tag{10}$$

The failure rate of Caps is also obtained by using (11).

$$\lambda_{Phy-Cap} = \lambda_{0Cap}\sum_{i=1}^{Phase}\left[\frac{t_{annual}}{8760}\right]_i \begin{pmatrix} \Pi_{Thermo-electrical} \\ +\Pi_{TCy} \\ +\Pi_{Mechanical} \end{pmatrix}_i \left(\Pi_{Induced}\right)_i \tag{11}$$

The base failure rates, λ_{0X} and the corresponding AFs, Π_X for a failure factor X has been provided in page 120 for SDs and page 138 for Caps in [25]. However, these values can be provided by the manufacturer or predicted based on operator/user experiences. Following the accuracy of the data, one of the handbooks methods [23]–[25] can be employed.

The total converter failure rate during its useful lifetime can be modeled considering the series reliability block diagram as any individual component failure cause converter failure. Therefore, the converter constant failure rate, $\lambda_{C\text{-}useful}$ is the sum of failure rate of individual components of Caps, $\lambda_{Caps\text{-}useful}$ and SDs, $\lambda_{SD\text{-}useful}$ as (3).

This paper considers the impact of two fragile components. Notably, for more detailed analysis, the failure rate of other components provided in [25] can also be included. Moreover, the software reliability can also be predicted according to IEEE Std 1633 [43].

IV. Wear-out Failure Rate Prediction

The components wear-out failure distribution can be estimated by Stress-Strength Analysis (SSA). In this approach, which is adopted from structural reliability [26], the component strength (Resistance, R) is compared to the applied load (Stress, S), and hence, the performance function Z is expressed as:

$$Z = R - S\ . \tag{12}$$

Therefore, failure probability P_f is obtained by using (13).

$$P_f = Pr\left(Z<0\right), \tag{13}$$

where $Pr(\cdot)$ denotes the probability of $(\cdot)$. As shown in Fig. 3, both stress and strength may have uncertainties in practice. Uncertainty can be defined as knowledge incompleteness due to the inherent deficiencies with acquired knowledge [26]. It could be associated with the ambiguity and vagueness in defining paraments and variables of components. They may

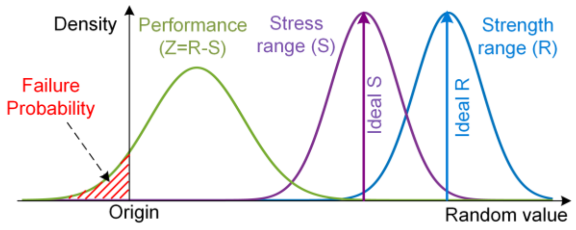

Fig. 3. Failure probability estimation concept based on mismatch of stress and strength.

have cognitive and noncognitive sources including physical randomness, parameters and variable uncertainties, model uncertainties, definition of quality and performance of failure, deterioration, and so on [26]. These uncertainty sources can generally be classified into two categories including aleatory and epistemic uncertainties [26], [44]. The aleatory sources are inherently random and non-deterministic in nature. This type of uncertainty is related to the physical world and cannot be reduced by obtaining more information and knowledge. Moreover, the epistemic uncertainties are due to the incomplete knowledge, which can be reduced by enhancing the knowledge base [26], [44].

In SDs, the wear-out failure mechanisms include bond-wire lift-off/cracking, chip solder joints cracking and baseplate solder joints cracking [22]. A device will fail due to the deformation of its structure caused by one or more failure mechanisms. The source of uncertainties in this case can be the strength model of device materials, characteristics of the materials and applied load on the device. There are different models provided in the literature for predicting the strength of bond-wires and solder joints [45]. In this paper, an empirical lifetime model is employed for predicting the reliability of the SDs as [46]:

$$N_f = A\cdot \Delta T_j^{\alpha}\cdot exp\left(\frac{\beta}{T_{jm}}\right)\cdot\left(\frac{t_{on}}{1.5}\right)^{\gamma}\ , \tag{14}$$

where, N_f is the number of cycles to failure, ΔT_j and T_j are the junction temperature swing and mean values, and t_{on} is the rise time of temperature cycle. A, α, β and γ are lifetime model constants, which can be obtained from aging tests [46]. In this model, A, α, β and γ are the epistemic sources of uncertainty in the lifetime model where their accuracy can be enhanced by repeating lifetime tests. Moreover, ΔT_j and T_j depend on the component electro-thermal characteristics which vary from sample to sample due to the manufacturing uncertainties. Therefore, these variables cause aleatory uncertainties in the lifetime prediction, which cannot be reduced by collecting more data.

Furthermore, the wear-out failure mechanisms of an electrolytic Caps include electrolyte vaporization and electro-chemical reaction [22]. Its lifetime can be modeled as [47]:

$$L_o = L_n\cdot 2^{\frac{T_n-T_o}{n_1}}\left(\frac{V_o}{V_n}\right)^{-n_2}\ , \tag{15}$$

in which, L_n denotes the nominal lifetime under nominal voltage V_n and nominal temperature T_n, and L_o is the capacitor lifetime under operating voltage V_o and temperature T_o. The constants n_1 and n_2 are provided in [47]. In this model, n_1, n_2 and L_n are the epistemic uncertainty sources, whereas T_o and V_o are the aleatory uncertainty sources.

In the provided lifetime model for SDs and Caps, the epistemic uncertainties such as model constants must be determined by lifetime tests. The accurate reliability model requires more tests with an acceptable confidence level. Moreover, the aleatory uncertainties such as temperature come from manufacturing variations and applied mission profile.

These uncertainties must be accurately defined based on the provided data by manufacturers and precisely electro-thermal mapping of mission profile. After recognizing uncertainties, the density function of stress and resistance can be identified and consequently the component reliability can be obtained by using (13).

The failure probability described by (13) can be obtained by MCS [17], [18]. In practice, for large-scale power electronic based power systems, MCS is not feasible due to the calculation burden. Hence, a First Order Reliability Method (FORM) [26] is adopted in order to find the components failure probability.

The components resistance R in (14) and (15) can generally be represented as:

$$R = g(x_1,...,x_n)\ , \tag{16}$$

where x_1, …, x_n are random variables describing the component strength by a function of g(·). Time variant performance function Z can be expressed as:

$$Z(t) = R - tS; t = 1,2,...\ , \tag{17}$$

where, t is the multiple of period of applied stress S. In practice, S is not a stationary stress over the mission profile, and it comprises of different levels of {S_1, …, S_h} according to the applied mission profile [2]. Therefore, the performance function can be modified as:

$$Z(t) = \sum_{i=1}^{h}(R_i - tS_i); t = 1,2,...\ , \tag{18}$$

where h is the total number of stress levels within a period of time, e.g., one year, and $R_i = g(x_{1,i}, \ldots, x_{n,i})$ is the component strength due to the applied stress of S_i. The failure probability at time t can be calculated by substituting (18) in (13). In practice, h is a quite large number if an annual mission profile is considered. Thereby, the random variables Z may follow the Normal Distribution following the central limit theorem [26].

Solving (13) requires multiple integration to obtain the failure probability, which can be a difficult task. To avoid computational difficulties, the non-stationary stress should be transformed into a stationary one. First, the impact of different stress levels of the component can be defined as a Damage (D), which is defined as:

$$D = \sum_{i=1}^{h}\frac{S_i}{R_i}\ . \tag{19}$$

Next, the stationary stress and equivalent resistance should be defined in such a way that the resultant damage to be identical to the non-stationary one obtained by (19) [48]. The total stress S_T over a mission profile is:

$$S_T = \sum_{i=1}^{h} S_i\ , \tag{20}$$

and, the resultant strength R_T due to the applied stresses is:

$$R_T = \frac{S_T}{D}\ , \tag{21}$$

Furthermore, the equivalent random variables {$x_{1,eq}$, …, $x_{n,eq}$} can be determined to obtain the same damage as for the set of random variables {$x_{1,i}$, …, $x_{n,i}$} i = 1, …, h. Therefore, the equivalent of the i^{th} random variable, except the k^{th} one, is defined as its average value using (22).

$$\forall_{\substack{i=1:h\\ i\neq k}} x_{i,eq} \triangleq \frac{1}{h}\sum_{j=1}^{h} x_{i,h} \tag{22}$$

The equivalent of the k^{th} random variable is obtained by (23).

$$x_{k,eq} \triangleq g^{-1}(R_T)\big|_{x_{i,eq}^{(h)},\, h\neq k} \tag{23}$$

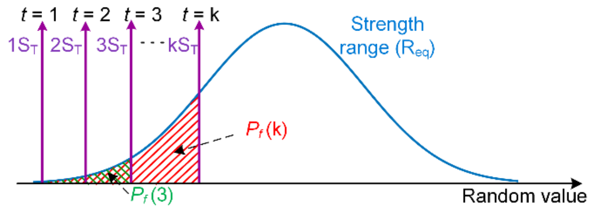

Fig. 4. Failure probability estimation concept based on proposed SSAM.

According to (22) and (23), the converted random variables will yield an equivalent strength and damage with the stationary values which is identical to the stationary one. Finally, the performance function in (18) is re-defined as:

$$Z(t) = R_{eq} - tS_T = g\left(x_{1,eq},...,x_{n,eq}\right) - tS_T \tag{24}$$

The failure probability can be calculated by integrating the stress function at its left-hand tail limited by the stress level as shown in Fig. 4. This integration can be predicted by the FORM [26]. In this method, the mean μ and variance σ of random variable Z are estimated by the first order Taylor approximation as:

$$\mu_Z \approx g\left(\mu_{x_{1,eq}},...,\mu_{x_{n,eq}}\right) - tS_T\ \text{, and} \tag{25}$$

$$\sigma_Z^2 \approx \sum_{i=1}^{n}\left(\frac{\partial g\left(x_{1,eq},...,x_{n,eq}\right)}{\partial x_{i,eq}}\right)^2 \sigma_{x_{i,eq}}^2\ , \tag{26}$$

where ∂ denotes a partial differential operator, and μ_θ and σ_θ are the mean and variance of random variable θ. As already mentioned, Z may follow the normal distribution in practice. Therefore, the failure probability is obtained as:

$$P_f(t) \approx \Phi\left(-\frac{\mu_Z}{\sigma_Z}\right) \tag{27}$$

where Φ(·) is the standard normal distribution function. The component reliability $R(t) = 1 - P_f(t)$. Finally, the wear-out failure rate of component X is calculated by:

$$\lambda_{X-wear}(t) = -\frac{1}{R(t)}\frac{dR(t)}{dt}\ , \tag{28}$$

where, d is a differential operator.

V. Case Study on a PV Inverter

The reliability prediction procedure in power converters has been discussed in previous conventional sections. The It is highlighted that the converter reliability depends on both random chance failure and wear-out failure. Furthermore, both failure types can be affected by the operating and climate conditions, converter topology, control/switching scheme and so on. In this section, the proposed method is exemplified for a PV inverter in order to show the impact of operating conditions (which is associated to the solar irradiance) and climate conditions (here the ambient temperature). The inverter reliability is predicted considering both random chance and wear-out failures under two mission profiles. Furthermore, the effectiveness of the proposed SSAM for predicting the aging failure rate is evaluated and compered to the conventual Monte Cardo simulation-based approach. Moreover, it identifies the weakest links of the converter operating under different mission profiles, that is useful to enhance the converter reliability during design process. The inverter reliability function is beneficial for proper decision-making in planning of the power systems for cost analysis and maintenance scheduling based on the predicted failure rate and end-of-life of inverter.

This case study shows the detailed analysis of the proposed reliability prediction approach in a PV converter, that can be applied for different converters with different applications. The structure of the double-stage PV inverter is shown in Fig.

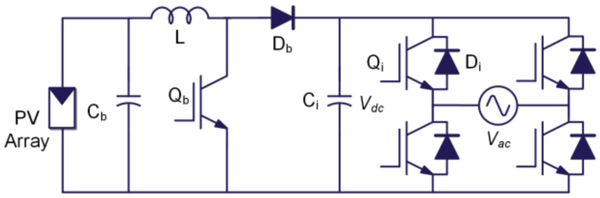

Fig. 5. Structure of the single-phase double-stage PV inverter.

TABLE I. INVERTER COMPONENTS PARAMETERS AND LIFETIME MODEL.

Parameter	Value	Parameter	Value
L	2 mH	A	9.34E14 ± 5%
C_b	120 μF	α	-4.416 ± 5%
C_i	3×390 μF	β	1285 ± 5%
Q_b	IGB10N60T	γ	0.3 ± 5%
Q_i	GB15N60T	n_1	10 ± 5%
D_b	IDV20E65D1	n_2	3 ± 5%
D_i	IDV20E65D1	T_n	105°C
f_{sw}	20 kHz	V_n	450 V
V_{dc}	400 V	V_{ac}	230 V, 50 Hz

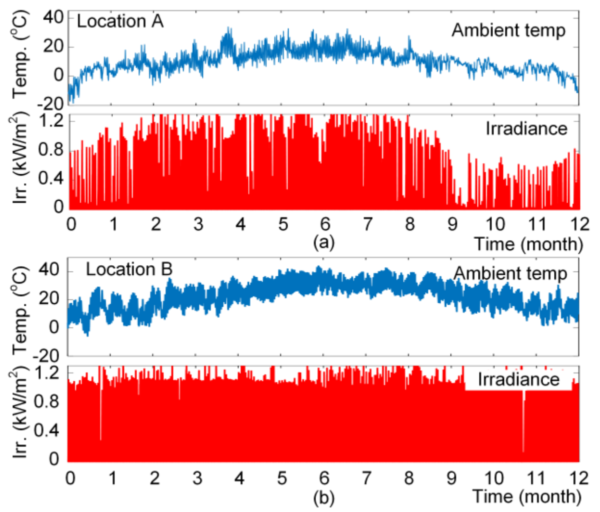

Fig. 6. Annual solar irradiance and ambient temperature for (a) Location A, (b) Location B.

5. The inverter includes a boost stage as a maximum power point tracker and a single-phase inverter for connecting a 2.5 kW PV array to the grid. The measured mission profiles of the solar irradiance and ambient temperature of two different locations are used for the analysis as shown in Fig. 6. The converter parameters and specifications are provided in TABLE I.

This section includes three sub-sections. The first sub-section presents the effectiveness of the proposed SSAM for wear-out failure probability prediction. Moreover, the inverter reliability is estimated in the second sub-section employing the proposed reliability prediction method. Finally, the last sub-section demonstrates the operating conditions impacts on the inverter reliability by the help of experimental tests.

A. *Effectiveness of the proposed SSAM*

The performance of the proposed SSAM is examined by predicting the wear-out failure probability of the inverter switch and capacitor operating under mission profile of Location B shown in Fig. 6. The lifetime model parameters and corresponding uncertainties are summarized in TABLE I. Moreover, the MCS is run for 10,000 samples of uncertain parameters. The switch wear-out failure probability density function (pdf) and cumulative distribution function (cdf) estimated by both approaches are shown in Fig. 7. As it can be seen in Fig. 7(a), the predicted failure pdf both approaches are almost the same. The predicted B_{10} lifetime has a negligible error (0.12/22 = 0.6%) as shown in Fig. 7(b), while the simulation burden is reduced by 1.85/0.02 = 60 times by employing the proposed approach. Notably, the simulations have been run in MATLAB environment on a personal computer with Intel (R) Core (TM) i7-7600U CPU @ 2.8 GHz and 8 GB memory.

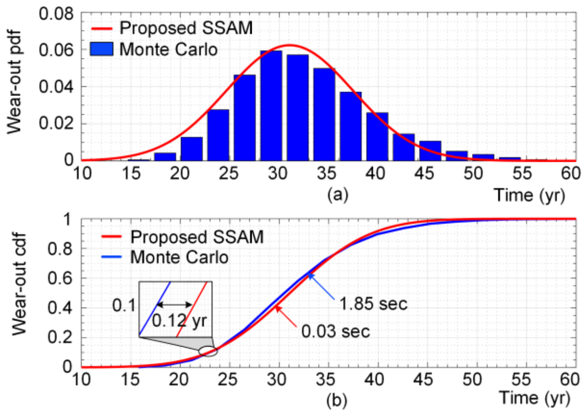

Fig. 7. Inverter switch wear-out (a) pdf, (b) cdf, using Monte Carlo analysis and the proposed SSAM under the mission profile of Location B.

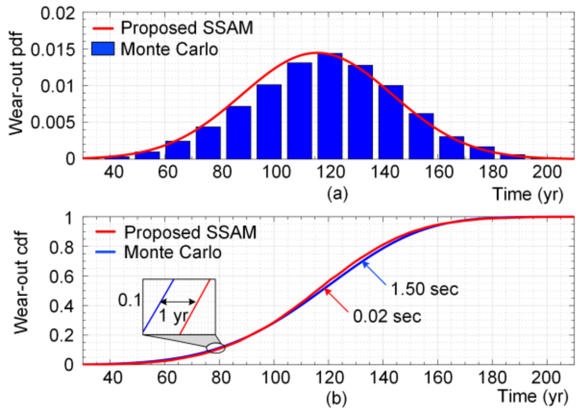

Fig. 8. Inverter capacitor wear-out (a) pdf, (b) cdf, using Monte Carlo analysis and the proposed SSAM under the mission profile of Location B.

The performance of the proposed approach is further evaluated by predicting the inverter capacitor and the results are compared to the MCS based approach. As shown in Fig. 8(a), the failure pdf of the proposed approach is asymptotically following the MCS results. Moreover, the predicted B_{10} lifetime has 1/80 = 1.2% error as shown in Fig. 8(b), while the computational effort is reduced by 1.50/0.02 = 75. The induced error is due to the fact that the proposed approach relies on a first order estimation of strength function in (25) and (26). For accurate results, the higher order approximations can be employed.

The presented cases evaluate the performance of the proposed SSAM compared to the conventional MCS-based method from accuracy and performance standpoints. Following the obtained results, the proposed SSAM can remarkably reduce the calculation efforts for large-scale power electronic based power systems with a huge number of converters. Moreover, in design for reliability applications, running MCS for each iteration of design procedure is time consuming, while the proposed approach can facilitate this process as well.

B. *Comprehensive reliability prediction*

In this sub-section, the inverter reliability is predicted under both mission profiles shown in Fig. 6. First, the failure rate of converter components within their useful lifetime is estimated based on FIDES approach and the results are shown in Fig. 9. The components failure rate under mission profile B is much higher than mission profile of Location A as shown in Fig. 9. Thereby, the components constant failure rate significantly depends on the operating conditions. Moreover, according to Fig. 9, the boost capacitor (C_b) and diode (D_b) with inverter capacitor (C_i) are the weakest components under mission profile A and the corresponding failure rates are almost identical. However, the failure rate of the boost diode (D_b) is the most stressed component followed by boost switch (Q_b) and inverter switch (Q_i) under mission profile B as shown in Fig. 9. Therefore, not only the failure rate of components, but also the weakest links of converter significantly depend on the operating conditions. This is due to the fact that the induced thermal cycles and the average temperature are not identical for both mission profiles. Therefore, following (10) and (11), the resultant failure rate on different components will be different.

In the next step, the wear-out failure rate of converter components is estimated and shown in Fig. 10(a) and (b) respectively for mission profiles of Locations A and B. Following the obtained results shown in Fig. 10(a), the inverter switch (Q_i) and capacitor (C_i) are the most fragile components under mission profile A from wear-out point of view. However, the inverter switch (Q_i) is the only fragile component under mission profile B as shown in Fig. 10(b). Moreover, the components operating in Location B is more prone to wear-out failures compared to the operating condition in Location A as shown in Fig. 10. These results show that the wear-out failure also depends on the mission profiles. Furthermore, the inverter switch (Q_i) is the vulnerable component in both cases, while the inverter capacitor (C_i) is also a weak link in Location A. As a result, inverter switch and capacitor limit the converter useful life expectancy under mission profile A, and in the case of mission profile B, the inverter switch is the only player.

The analysis shows that the stress on the components within useful lifetime is different from that of within wear-out phase as shown in Fig. 9 and Fig. 10. This outcome could be beneficial for appropriate maintenance planning during useful lifetime depending on the operating conditions. Moreover, the converter availability can be improved by re-designing the weakest components during useful life. Furthermore, the converter can be properly designed to achieve a desired lifetime by predicting its components end-of-life and wear-out behavior. The wear-out analysis is also beneficial for system level preventive maintenance, where the converter unavailability rises over an undesired value.

In the following, the total constant failure rate of the converter is calculated by summing the failure rate of all components. The total constant failure rate is shown with green-dashed line in Fig. 11(a) for Location A and in Fig. 12(a) for Location B. The total wear-out failure rate under both mission profiles are also shown in Fig. 11(a) and Fig. 12(a) with a blue line. The total failure rate of the converter is shown by red line in Fig. 11(a) and Fig. 12(a), which is in fact the sum of constant and wear-out failure rates.

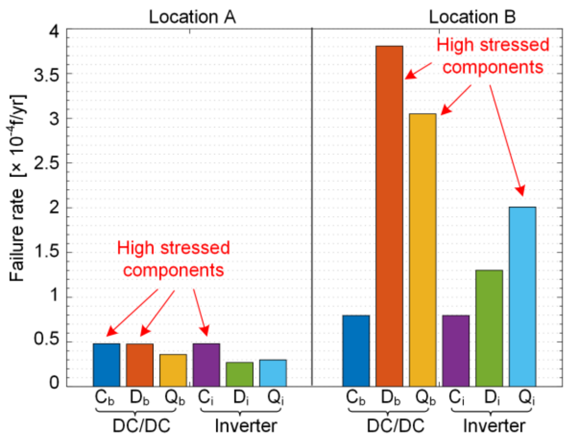

Fig. 9. Constant failure rate of individual components of converter under the two mission profiles according to FIDES.

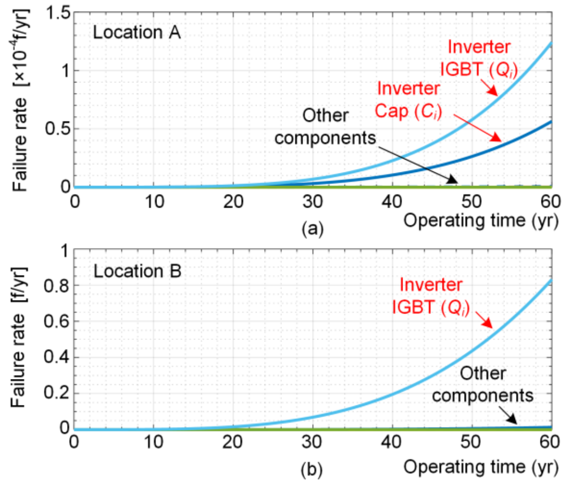

Fig. 10. Wear-out failure rate of individual components of converter under the mission profile of (a) Location A and (b) Location B.

The converter reliability due to components aging under both mission profiles is shown in Fig. 11(b) and Fig. 12(b) with blue graph. The B_1 lifetime of the converter due to the wear-out failures in Location A is 60 years, while it is 9 years for location B. This fact is because of the different stress levels induced by the mission profiles. The total reliability of the converter is shown in Fig. 11(b) and Fig. 12(b) with a red graph. The total B_1 lifetime of converter under mission profile A is 18 years and under mission profile B, it is 4 years. These results show that the converter design based on the wear-out failure may introduce an undesired consequence, hence the constant failure rate should also be considered in the design procedure. Moreover, the obtained results show that unlike IET TR-62380, the life expectancy remarkably depends on the mission profiles.

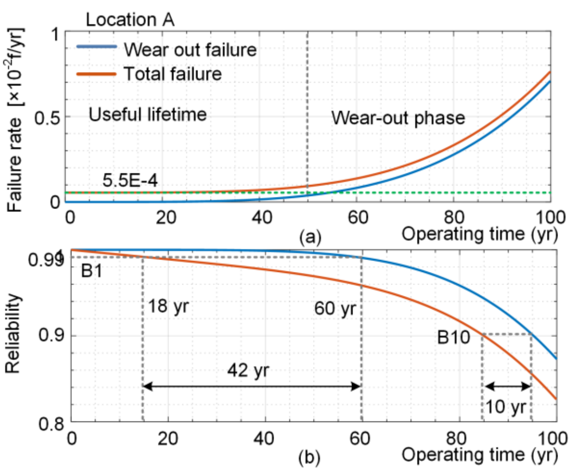

Fig. 11. Failure rate and reliability of PV inverter under mission profile of location A.

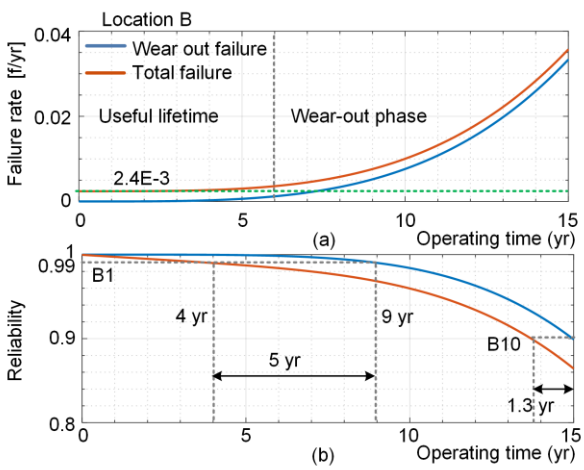

Fig. 12. Failure rate and reliability of PV inverter under mission profile of location B.

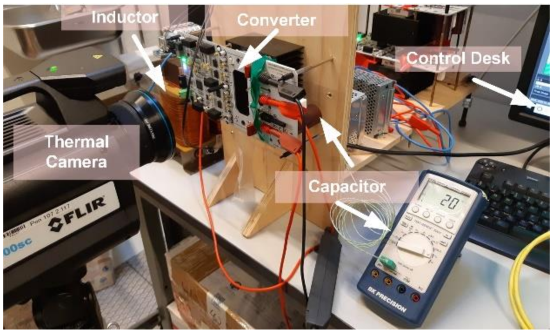

Fig. 13. Photograph of the implemented dc-dc boost converter.

C. Operation impact on device temperature

The temperature of the device is the main factor limiting its lifetime. It depends on the operating condition and mission profiles and this fact was the motivation to include the mission profile analysis in the reliability studies. Therefore, the impact of operating conditions on the temperature of different components in the converter is demonstrated in this sub-section. A photograph of the test prototype is shown in Fig. 13, where the junction temperature of power module and the hotspot temperature of the capacitor are measured under different loading conditions.

The converter is tested under 0.8 *kW*, 1.8 *kW*, and 3.2 *kW*, load power and the components temperatures are measured as shown in Fig. 14(a). As shown in Fig. 14(a), the components temperature depends on the operating conditions. Moreover, the temperature variation in terms of converter loading is not linear. As shown in Fig. 14(a), the temperature rises at high loads, e.g., 2-3.2 kW is greater than lower loads, i.e., 0.8-1.8 kW. This shows that, for example, the Q_i failure rate operating at low powers will be less than operating at high load powers. This is shown in Fig. 10, where the failure rate of Q_i in location B is higher than location A. This is due to the different load variations in location A and B as shown Fig. 6, where within months from 8 to 12 in location A, the loading is low and hence the failure rate will be low. Moreover, comparing the temperature difference of D_b with D_i (and Q_b with D_i) shows that at low powers the Di has the greater temperature, while at high power D_b (and Q_b) has the greater temperature. This shows that different components may limit the converter reliability depending on the operating condition. Furthermore, according to Fig. 14(a), the temperature level of Q_i is higher than other components, which may make it dominant component limiting the converter lifetime.

In general, the temperature rise, temperature difference and temperature level will affect the components reliability and consequently limiting the converter lifetime. As a result, the reliability prediction approaches, such as MIL-HDBK-217, which rely on the rated power, cannot accurately estimate the converter lifetime. Moreover, it cannot be used to identify the weakest links of the converter, and hence, improve its reliability during design and manufacturing. Hence, the mission profile analysis is required for reliability modeling in converters. The thermal stress distribution over the semiconductor devices for both boost and inverter is further illustrated in Fig. 14(b & c) operating under 1.8 *kW*. According to these results, the inverter switch, Q_i has the highest temperature. This obtained result is identical with the SSAM results provided in Fig. 10.

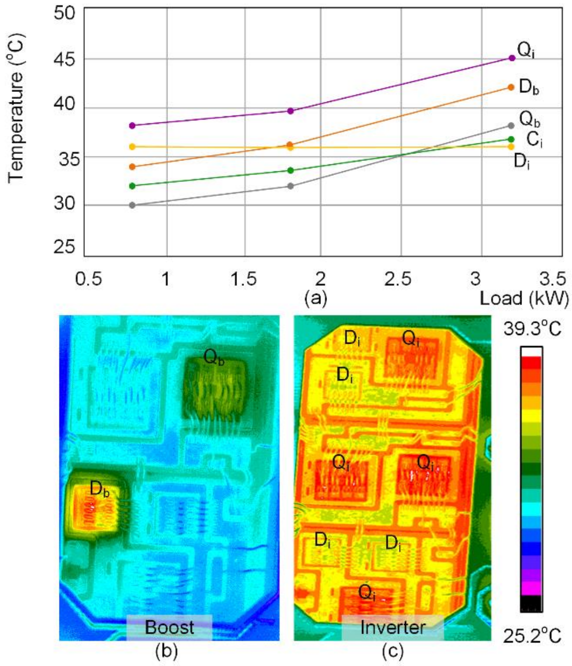

Fig. 14. Obtained experimental results. (a) The converter components temperature at different loading condition. Thermal image of (b) Q_b & D_b temperature at 1.8 *kW*, and (c) Q_i & D_i temperature at 1.8 *kW*.

VI. Conclusion

This paper has proposed a guideline for reliability prediction in power electronic converters. The failure characteristics within useful life is estimated based on generic handbook-provided data. Moreover, the wear-out failure rate is predicted based on the proposed Stress-Strength Analysis Method (SSAM) employing the concept of structural reliability, where the physics of failures are taken into account. The proposed reliability model can be used for optimal design and manufacturing of the converters as well as for system-level planning, operation and maintenance of power electronic systems.

The proposed method is exemplified for a photovoltaic inverter under two climate conditions. The obtained results show that the proposed SSAM for aging failure prediction introduces 60~70 times lower calculation burden compared to the conventional Monte Carlo Simulation based approaches. This can facilitate the power electronic-based power systems reliability modeling and evaluation with a large number of aging-prone components. Furthermore, the analysis shows that the individual components failure rate and the weakest links within useful life and aging period remarkably depend on the applied mission profile. Moreover, the converter weakest link in useful life may be different from the wear-out phase according to the employed reliability models provided in the literature. Therefore, strengthening the converter in both phases requires accurate reliability modeling according to the applied mission profile. Finally, the design for reliability based on the wear-out failure probability introduces higher difference with the case the total failure probability is considered. For instance, the B_1 lifetime of inverter under mission profile A changed form 60 years to 18 years when both failures are modeled. This fact may cause an unreliable design of a converter, hence, a complete reliability model within useful and wear-out phases is required for reliable design of a converter.

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