Power Electronics Tools Advanced Design for the Reliability

– Case Studies on a Photovoltaic (PV) System

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Abstract **– The most of the energy conversion devices,**

the power electronic converters are proven to have high failure rates. At the same time, the failures of the power electronics systems are becoming more and more unacceptable. capabilities and economy of power electronics system are determined by the active devices that are available. Their characteristics and limitations are a key element in the design of power electronics systems. Formerly, the mercury arc valve, the high-vacuum and gas-filled diode thermionic rectifiers, and triggered devices such as the thyratron and ignitron were widely used in power electronics. As the ratings of solid-state devices improved in both voltage and current-handling capacity, vacuum devices have been nearly entirely replaced by solid-state devices are used to improve the reliability assessment in power electronics. In this paper, an advanced design tool structures are used , which can acquire various reliability metrics of the power converters. The proposed reliability design tool is based on the failure mechanisms in the critical components of the power electronics system, and the mission profiles in the converter applications are also taken into account. Finally, the potential methodologies, challenges and technology trends involved in this tool structure are also discussed.

Keywords **– Power electronics, reliability, design for reliability, thermal analysis, mission profile, photovoltaic applications**

I. INTRODUCTION

The fast growth in the total installation and individual capacity makes the failures of the power electronics converters more critical, and they are also costly to repair because more and more power electronics are located in remote areas, which are hard to access [1]-[5]. In many important applications such as renewable energies, motor drives, power transmission, electric vehicles, etc., power electronics have particularly tough operating conditions: they have to withstand a large amount of power (even up to a few megawatts) with frequent fluctuations, perform a series of complicated functions, and be exposed to harsh environment like temperature swings, dust, vibration, humidity, etc. [1]-[5]. It has been found that in many of these applications the power electronics tend to be fragile and have become the "bottleneck" of the whole system, in respect to the reliability [6]-[18]. This problem will significantly increase the cost of energy conversion not only due to the increased maintenances or repairs, but also due to the reduced energy delivered to the customers.

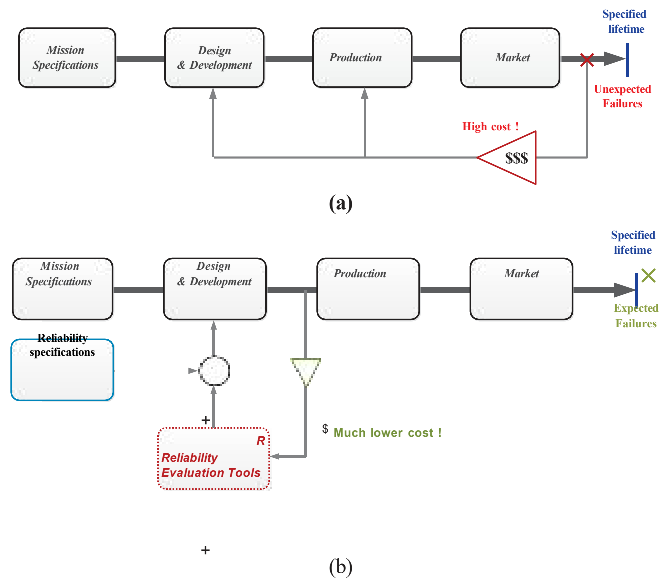


Fig. 1. Reliability improvement approaches for power electronics products: (a) typical flow in the past and (b) new flow in the future.

Unfortunately, the reliability improving approach for the power electronics is still expensive and time consuming. As shown in Fig. 1(a), a typical flow for improving the reliability of power converters is indicated from the point view of the whole life cycle of products. Due to the lack of reliability assessment in the design as well as the development phases, the design flaws/weakness has to be identified based on the failure information or statistics of the field products that have been massively produced and pushed into the market. It can be seen that in this approach the design feedbacks/iterations in order to improve the reliability are quite slow and expensive. As demonstrated in Fig. 1(b), by introducing the reliability assessment tool in the design and development phases, a more promising approach for improving reliability is enabled: the design flaws/weakness can be quickly identified and corrected before the projects are put into production and/or market. Moreover, some reliability targets are able to be integrated into the specifications of the products at the beginning of the design, contributing to significant cost reduction and shorter development cycle for the reliability improvement.

In this paper, an advanced design tool (Design For Reliability - DFR), which can acquire the reliability metrics of power converter, is thus proposed. It is based on the failure mechanisms in the critical components of the entire power electronics, and the mission profiles for the whole converter system are also taken into account. The tools are demonstrated on a single-phase transformerless PV power converter. Some important metrics for the converter design can be quickly identified and evaluated according to the proposed design tool. It is concluded that with the proposed design tool structure, more detailed information related to reliability performances in power converters can be obtained before the converters actually fail in the real-field, and many potential research topics can be also enabled.

II. General Structure and Flow to Access Reliability Performances

The reliability research in power electronics has been carried out for decades. As the state-of-the-art trend, the reliability engineering in power electronics is now moving from a solely statistical approach that has been proven to be unsatisfactory in the automotive industry, to a more physics-based approach which involves not only the statistics but also the analysis of root causes behind the failures [10]-[15]. In this physics-of-failure based approach, the correct mapping of loading profile which can trigger the failures of components (the stress analysis), as well as the strength modeling which reflects how much loading the components can withstand (the strength tests), are two of the most important activities for reliability assessment.

A promising tool structure is thereby depicted in Fig. 2, which can be generally categorized as four groups of activities or approaches. In this structure, the critical components as well as the major failure mechanisms in the power converter system are first identified. Then, based on the interested failure mechanisms in the critical devices/components, the corresponding stresses and the ability of components to withstand the stresses (also referred as strength) are tested and modeled separately. Finally, a series of algorithms and statistical distributions are introduced to map the stress and strength information of the components to the reliability metrics of the entire power converter. The reliability metrics may include either direct reliability performances like lifetime, robustness, probability of failures changing with time, etc., or indirect reliability-related performances like the maximum stress level, stress margin, optimal component rating, etc.

III. Demonstrations of the DFR Tool on a Single-Phase Transformerless PV Converter

A. *Basic Efficiency and Reliability Analysis*

As it is shown in Fig. 2, the DFR tool enables a basic analysis of the power converter candidates in terms of efficiency and reliability. It can directly translate the mission profile specified by the users into power losses and thermal loading on the power electronics devices/components (e.g., IGBTs and MOSFETs). Taking a single-phase transformerless PV inverter shown in Fig. 3 as an example, real-field mission profiles can be easily translated into the corresponding power losses and thermal loading on the power switching devices. The system parameters are listed in Table I. Fig. 4 shows two considered real-field mission profiles of different PV sites (Aalborg-Denmark and Arizona-USA). In accordance to the DFR tool shown in Fig. 2, the mission profiles are translated, and the resultant loading profiles as well as the efficiency curves are presented in Fig. 5. When applying the mission profile to different transformerless PV inverters, the thermal

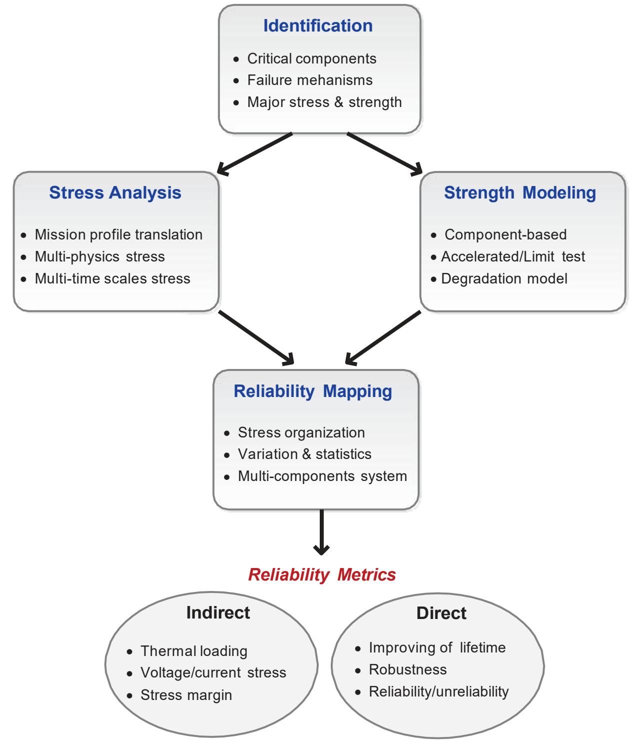


Fig. 2. Proposed Design For Reliability (DFR) tool structure and research activities for evaluating and designing the reliability metrics of power electronics.

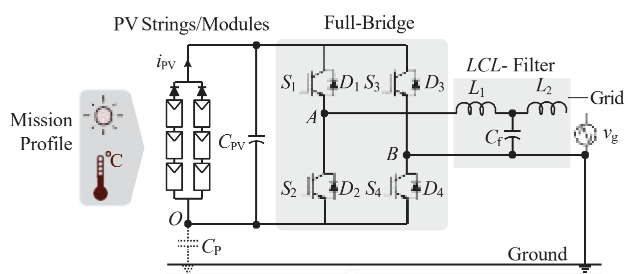


Fig. 3. A single-phase grid-connected transformerless PV system with an *LCL* filter.

TABLE I.
PARAMETERS OF THE SINGLE-PHASE PV SYSTEM.

Parameter	Symbol	Value
Grid voltage amplitude	v_{gn}	325 V
Grid frequency	c_0	2n×50 rad/s
DC-link capacitor	C_{pv}	2200 μF
LCL filter	L_1	3.6 mH
	C_f	
	L_2	
Switching frequency	f_{sw}	

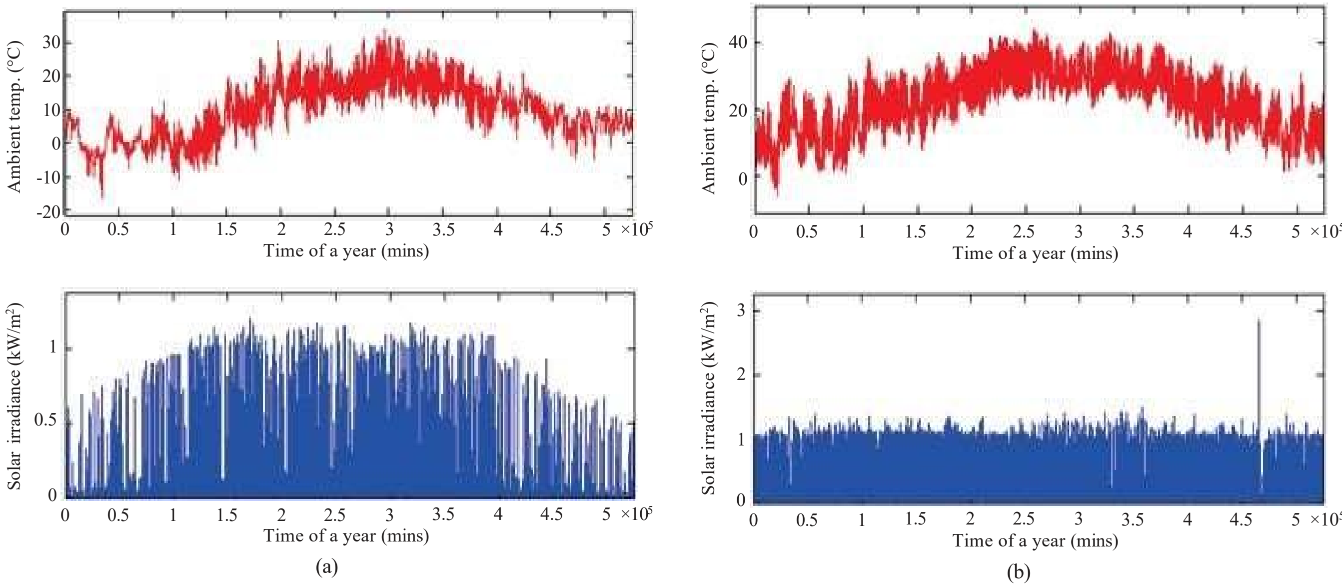


Fig. 4. Two considered mission profiles from different locations (top: ambient temperature; bottom: solar irradiance): (a) Aalborg and (b) Arizona.

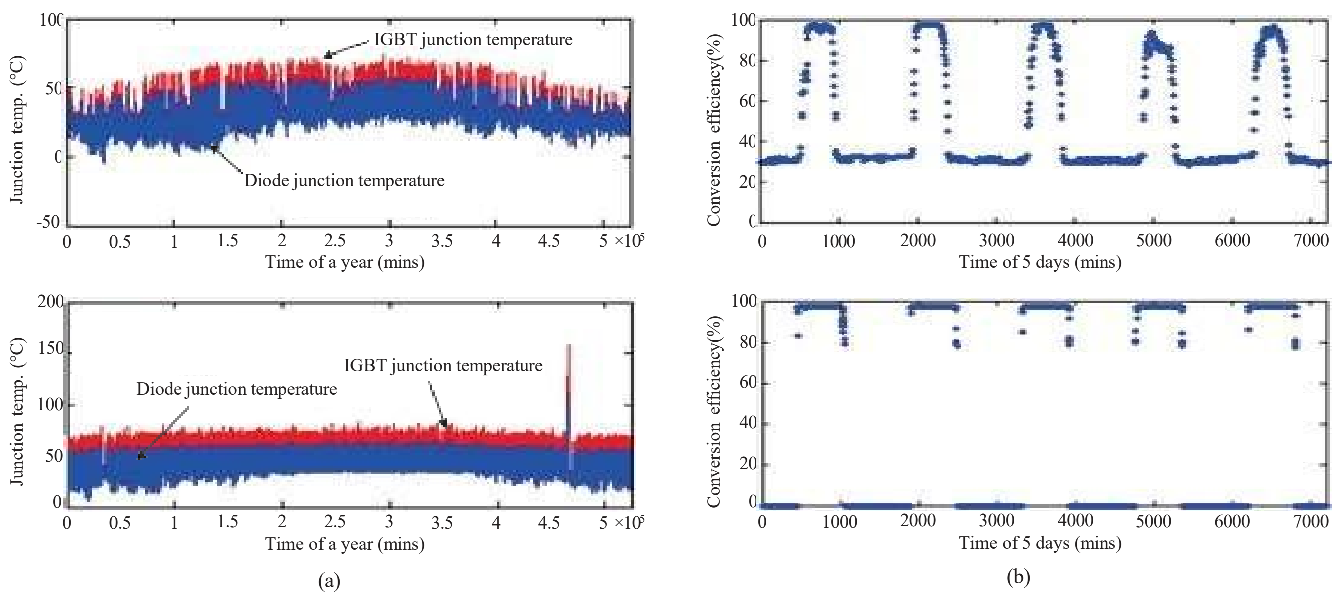


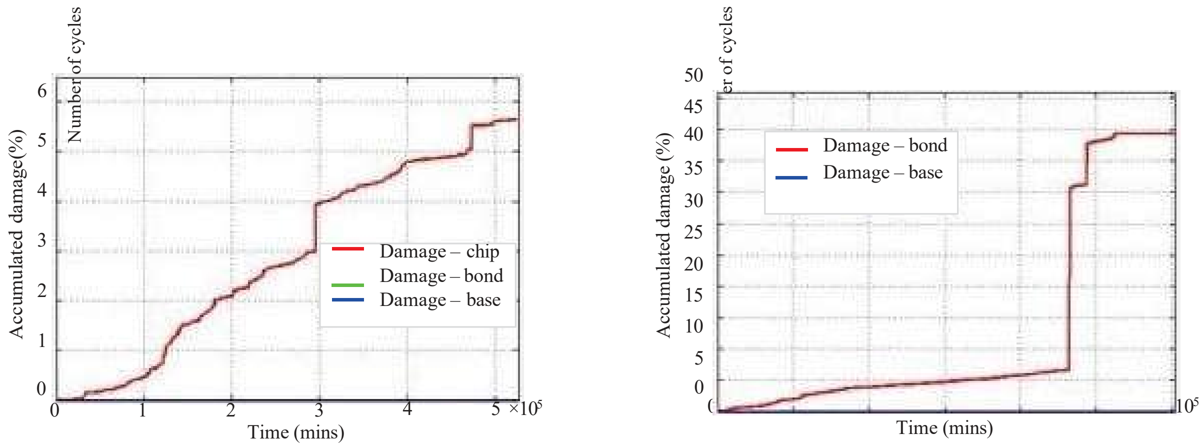
Fig. 5. Thermal loading profile and the conversion efficiency of 5 days translated from the mission profiles shown in Fig. 4 (top: Aalborg, bottom: Arizona): (a) device thermal loading and (b) instantaneous conversion efficiency in the case of a five-dayoperation.

loading and/or power loss profiles can readily be obtained using the DFR tool. Thus, a basic comparison between those candidates can be done in terms of efficiency and reliability, as exemplified in [1], [4].

It can be observed in Fig. 5(a) that the PV inverter located in Arizona experienced a relatively "flat" junction temperature loading on the power devices compared to that of the PV system in Aalborg, which thus contributes to less temperature cycles. However, the mean junction temperature of the power devices in Arizona is higher than that of the PV inverter installed in Aalborg, which may accelerate the inverter degradation. In addition, using the DFR tool, the instantaneous conversion efficiency under different mission profiles can also be obtained as shown in Fig. 5, where it can be seen that the system conversion efficiency is higher in Arizona, leading to more energy production through the year.

B. *Reliability Assessment using the DFR Tool*

The translated power losses and the thermal loading of the power electronics devices (e.g., Fig. 5(a)) can be used to estimate the total energy yield through the period of this mission profile, and also the reliability of the power devices, respectively. However, the thermal loading profiles have to be properly interpreted by means of a counting algorithm (e.g., rain-flow counting) [10], [17], [18] or Monte-Carlo analysis [19], [20], which are able to extract necessary information from the thermal loading profile according to certain lifetime models, e.g., the Coffin-Mason model [5], [9]. According to Fig. 5(a), the rain-flow counting of the thermal loading for the



(a) (a)

Fig. 7. Accumulated chip, bond (wire), and base damage of the power devices of the PV inverter: (a) in Aalborg and (b) in Arizona.

power devices in the PV inverter has been done, and the results are shown in Fig. 6. It can be identified that the thermal loading of the PV inverter in Arizona has a larger number of high mean junction temperatures (i.e., T_{jm}) and a smaller number of junction temperature variations (i.e., OT_j/2). This is in a close agreement with the analysis presented in § III.A. However, the higher mean junction temperature may pose a bigger challenge to the lifetime of the power devices. In other words, the PV inverter in Arizona may have a shorter lifetime, if operating under the mission profile shown in Fig. 4(b). By applying the obtained counting results to suitable lifetime models, a quantitative lifetime prediction can be achieved. In the proposed design tool, different lifetime (damage) models can be integrated. To demonstrate, in this paper, the LESIT model [21], [22] has been adopted and applied to the thermal loading profile (c.f., Fig. 6), and thus the reliability can be predicted in terms of damage. The lifetime model is given as,

$$N_f = A \bullet \mathrm{O}T_j^{\alpha} \bullet \exp\left(\frac{E_a}{k_b \bullet T_{jm}}\right) \quad (1)$$

where N_f is the number of cycles to fail, and the parameters are explained in Table II.

TABLE II.
PARAMETERS OF THE LIFETIME MODEL USED IN THIS PAPER.

Parameter	Symbol	Value
Curve fitting factor	A	3.025×10^5 K^{-a}
Curve fitting factor	a	-5.039
Activation energy	E_a	9.891×10^{-20} J
Boltzmann constant	k_b	1.381×10^{-23} J/K

The accumulative damage of the power devices of the PV inverter in the two cases is shown in Fig. 7, and accordingly the lifetime can be estimated as,

$$LF = \frac{t_{mp}}{D} = \frac{t_{mp}}{\sum N_{fi}} \quad (2)$$

in which LF is the predicted lifetime, t_{mp} is the mission profile duration, D is the accumulated damage, and N_{fi} is the number of cycles to fail at the i^{th} stress of T_{jm} and OT_j according to (1). It can be seen from Fig. 7 that the damage of the power electronics devices/components of the PV inverter in Arizona accumulates at a faster rate compared to that of the PV inverter in Aalborg. Consequently, the PV inverter installed in Arizona will go into the end of life much faster as well, according to (2). This is also in a close agreement with the above discussion. The results shown in Fig. 7 indicate that, the power devices of higher reliability have to be chosen in the design and planning phases for the PV inverters in Arizona, leading to higher cost and more investments, although a higher total annual energy yield is possible to achieve (Fig. 5(b)). Fig. 8 further summarizes the reliability prediction procedure in details, which is integrated in the design tool – DFR tool.

C. LCOE Analysis with the DFR Tool

As both the reliability/lifetime (i.e., the downtime during operation) and the energy yield are the key indicators of the Levelized Cost Of Energy (LCOE) [7], [8], [23], [24], the DFR tool also enables an access to the LCOE of the power converter candidates using the obtained energy yield as well

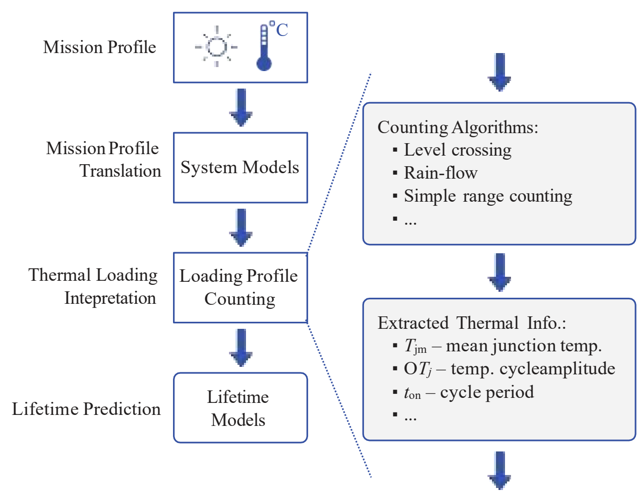


Fig. 8. Flow-chart of the mission profile based reliability analysis approach for PV inverters, which has been integrated in the proposed design tool.

as the lifetime data. As a consequence, means to reduce the LCOE can be initiated, e.g., using highly efficient power converters and/or applying advanced control strategies to lower the thermal loading. In addition, the resultant LCOE from the DFR tool is also of significant usefulness for renewable energy system planning in the consideration of the mission profiles. Here, the LCOE calculation procedure based on the DFR results is demonstrated. As known, the PV inverter LCOE (€/Wh) is a function of the inverter power rating (denoted as P_r), and it can be expressed as [7], [8],

$$LCOE(P_r) = \frac{C_{inv}(P_r)}{E_y(P_r)} \tag{3}$$

where $C_{inv}(\cdot)$ (€) is the present total cost of the PV inverter during its lifetime and $E_y(\cdot)$ (Wh) is the total energy injected into the grid by the PV inverter during its lifetime. Since the PV inverter is required to operate in the Maximum Power Point Tracking (MPPT) mode [25], [26], it holds that $P_r = P_n$, with P_n being the inverter nominal power.

The present total cost of the PV inverter depends on the corresponding manufacturing and maintenance costs [8]:

$$C_{inv}(P_r) = C_m(P_r) + M_c(P_r) \tag{4}$$

in which $C_m(P_r)$ (€) is the PV inverter manufacturing cost and $M_c(P_r)$ (€) is the present total maintenance cost of the PV inverter during its lifetime. The PV inverter manufacturing cost is proportional to the inverter power rating:

$$C_m(P_r) = c_m \bullet P_r + C_0 \tag{5}$$

where c_m is the proportionality factor (€/kW) and C_0 is the initial cost. C_0 can be considered as zero since it is much lower than the total cost of the PV inverter.

Therefore, in the MPPT operation mode, the PV inverter cost is proportional to P_n. The total maintenance cost, M_c, depends on the PV inverter reliability features, which in turn depend on the power rating of the PV inverter. Based on the DFR tool, the lifetime (in years) of the PV inverter power devices is initially calculated. It is assumed that each time when the end-of-life of the PV inverter power devices is reached, the maintenance of the PV inverter will be performed, imposing the corresponding maintenance cost. Thus, the present total maintenance cost of the PV inverter, $M_c(P_r)$, is calculated by reducing the (future) expenses occurring at the end of the power devices lifetime for repairing the PV inverter to the corresponding present value, as follows:

$$M_c(P_r) = \sum_{j=1}^{n} LF_j(P_r) \bullet R_c \bullet P_r \bullet \frac{(1+g)^j}{(1+d)^j} \tag{6}$$

in which n is the PV inverter system operational lifetime (e.g., 30 years), R_c (€/kW) is the present value of the PV inverter repair cost per kW of the power rating, g (%) is the annual inflation rate, d (%) is the annual discount rate, and $LF_j(\cdot)$ is defined as:

$$LF_j(P_n) = \begin{cases} 1 & \text{if lifetime expires at the } j^{\text{th}} \text{ operation year} \\ 0 & \text{else} \end{cases} \tag{7}$$

with $1 \le j \le n$. Notably, the repair cost R_c in (4) consists of both the purchase cost of the failed power devices, as well as the potential labor and transportation costs for repairing the PV inverter. Therefore, the LCOE can be calculated using the DFR tool.

The LCOE calculation is demonstrated on a 3-kW single-phase PV inverter system installed in Aalborg (c.f., Fig. 3) under the mission profile shown in Fig. 4(a). Accordingly, the nominal power P_n = 3 kW, the following parameters are chosen for the case study: n = 30 years, c_m = 200 €/kW, R_c = 200 €/kW, g = 2 %, and d = 5 %. Based on the design tool – DFR tool shown in Fig. 2 and the detailed lifetime prediction approach illustrated in Fig. 8, the thermal loading, the power losses, as well as the annual energy yield can be calculated through the year. The calculated lifetime is around 38 years, which is higher than the designed lifetime (i.e., 30 years), thus guaranteeing no failures of the power devices will occur during that period, leading to no maintenance cost during operation. According to (4) and (5), the total cost of the PV inverter is only the inerter construction cost: $C_{inv}(P_r) = C_m(P_r) = c_m \cdot P_r$ = 200 €/kW × 3 kW = 600 €, and thus the LCOE can be approximated as 0.17 €/kWh.

It should be pointed out that, in this demonstration, the following assumptions are made for simplicity:

1) In the reliability (lifetime) calculation, only the thermal cycles induced by the mission profile are considered, where the grid fundamental-frequency thermal loading cycles are ignored;
2) The energy production is calculated without considering the power losses on the passive components;
3) The LCOE presented above is only for the PV inverters, while the PV panel cost also accounts for a major share of the total cost of the entire PV system, also including circuit boards and capacitors, etc.

Nevertheless, it is still possible to use the proposed DFR tool for the LCOE analysis as long as more detailed thermal, electrical, and loss models are incorporated in the tool.

D. *Expanded Use of the DFR Tool*

Beyond the above analysis enabled the DFR tool and with the development of advanced monitoring technologies, it is possible to acquire mission profiles with different sampling rate, e.g., from micro-seconds to minutes, and thus the DFR tool can extensively be used. However, for the electrical systems and the junction temperature of the switching devices, it may take up to seconds to come into steady-state. Moreover, the cycle period, t_{on}, is taken into account in some lifetime models [9], [10]. Therefore, the available mission profile with a certain resolution may have some impacts on the reliability analysis. It is also of interest to investigate what the appropriate resolution is for lifetime estimation in power converter applications. The introduced DFR tool can also be employed to analyze how the resolution of the mission profiles will affect the lifetime prediction.

Furthermore, the power electronics as well as the power converter technologies have been experiencing a very fast growth [27], [28]. In the future, more power electronics devices will come into the market, and this will also advance the power converters technology and its applications, e.g., in the renewable energy systems. When such advanced power electronics systems come into reality, the DFR tool can also be adopted for reliability-oriented analysis and design, where minor changes may be required. For instance, the database including the thermal data of the power devices and the topology data should be updated accordingly.

IV. Conclusions

In this paper, an advanced design tool for reliability of the power electronics converters has been presented. The proposed Design For Reliability (DFR) tool is based on the physics-of-failure mechanisms, and it takes the costumer-specified mission profiles as the input. As the outcomes of the DFR tool, the thermal loading, the power losses, the efficiency of the critical components and also the power converters can be obtained through the DFR tool. The application of the DFR tool is demonstrated on a single-phase transformerless PV inverter in this paper when considering two real-field mission profiles from different PV locations, where the efficiency, the thermal loading, and thus the lifetime (in terms of accumulated damage) of the power devices are analyzed. A basic comparison has also been done. In addition, the DFR tool also enables the LCOE analysis, which is also exemplified on the PV inverter system in this paper. Further applications of the proposed DFR tool are highlighted as well, which can be future research perspectives.

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