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System-Level Design for Reliability and Maintenance Scheduling in Modern Power Electronic-Based Power Systems

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ABSTRACT Power electronic converters will serve as the fundamental components of modern power systems. However, they may suffer from poorer reliability if not properly designed, consequently affecting the overall performance of power systems. Accordingly, the converter reliability should be taken into account in design and planning of Power Electronic-based Power Systems (PEPSs). Optimal decision-making in planning of PEPSs requires precise reliability modeling in converters from component up to system-level. This paper proposes model-based system-level design and maintenance strategies in PEPSs based on the reliability model of converters. This will yield a reliable and economic planning of PEPSs by proper sizing of converters, cost-effective design of converter components, identifying and strengthening the converter weakest links, as well as optimal maintenance scheduling of converters. Numerical case studies demonstrate the effectiveness of the proposed design and planning strategies for modern power systems.

INDEX TERMS Design, reliability, power converter, wear-out failure, maintenance, planning, power system.

I. INTRODUCTION

ELECTRIFYING the world is one of the pragmatic solutions for reducing carbon footprint [1]. Electric transportation, renewable energy generation, electric storage, smart and micro grid technologies, as well as digitalization are essential parts of sustainable electricity systems. These technologies are underpinned by power electronics as the core of their energy conversion process. For instance, the structure of future power electronics-based distribution systems is shown in Fig. 1, which includes AC/DC microgrids. However, power electronics has an Achilles heel: it might be a frequent source of failure and may cause downtime and costs in different applications [2]–[9]. For instance, power converters contribution on unplanned downtime in wind turbine systems [10], and unscheduled downtime costs in Photovoltaic (PV) systems [7] is remarkable. Therefore, power electronics reliability analysis is of paramount importance in the sustainable electric energy development.

Due to proliferation of power converters in future power systems, power electronics reliability engineering has gained an increasing interest in the recent decade. Conventional reliability prediction approaches in power electronics rely on historical data provided in Military Handbook 217 (MIL-HDBK-217) [11]–[14]. The main concerns of these approaches are outdated data for new technologies, vagueness of failure mechanisms, type of data, and exclusion of operation conditions. These data are still used for predicting the converter reliability in different applications in order to compare different converter topologies and control algorithms as well as system-level reliability assessment [15]–[21]. Besides inaccuracy of these methods, they are not able to predict aging failure characteristics as well. Therefore, the conventional

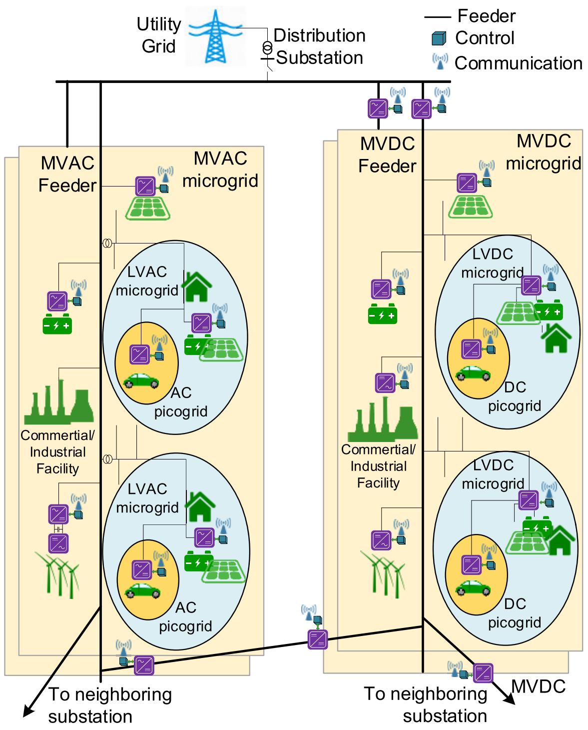

FIGURE 1. **Structure of future power electronic based power systems.**

approaches are not applicable for identifying and reinforcement of the weakest links of converters and systems from a reliability stand point.

In order to overcome the drawbacks of the conventional approaches, Model Based System Engineering (MBSE) approaches have been presented in power electronics reliability engineering. The MBSE approaches analyze, assess and enhance the converter reliability taking into account physics of failure mechanisms of its components. The state-of-the-art MBSE approaches can be hierarchically classified into three categories including component-, converter-, and system-level [22]. The component-level efforts are devoted to analyzing, modeling and enhancement of the failure modes and mechanisms in converter components such as power electronic switches and capacitors. The major efforts at the component-level are associated with identifying failure modes and mechanisms in components, developing lifetime model for different failure mechanisms by long-term operation and/or accelerated tests, and improving the weakest links of each component in the converter.

Furthermore, the converter-level activities are associated with reliability modeling and enhancement in power converters using the lifetime models of its components. The converter reliability is predicted based on a stress-strength analysis comparing applied stresses induced by a mission profile to its components lifetime [23]. Therefore, the converter reliability depends on its components lifetime, climate and operating conditions, converter topology [24]–[26], control algorithm [22], [27]–[31], and cooling system etc. Hence, design for reliability considering these factors can guarantee a desired long-term performance of converters. The system-level reliability studies are dedicated to the reliability analysis in multi-converter systems. So far, the system-level research is limited to incorporate the converter reliability into power system assessment and system reliability enhancement by appropriate control strategies [11], [22], [32].

All the approaches employed in the three levels from component up to system aim to improve the converter reliability by decreasing the failure rate and/or expanding its lifespan. They are reliant on the lifetime model of the fragile components of the converter such as power switches and capacitors. Thus, the converter design and control are performed by employing the MBSE concept in order to enhance its reliability as a long-term performance indicator. However, improving a converter reliability by itself may not be cost-effective at the system-level because of the following reasons:

1- Reliability of different converters with different applications does not have an identical impact on the system-level performance indicators. Thus, the design for reliability of converters must be performed with respect to their effect on the overall system reliability.
2- In most cases unless mission-based applications, the converters are maintainable components. Hence, instead of designing a converter for a long period of operation, replacing with a new converter may be a more economical solution to improve the system performance.

So far, system-level design for reliability and maintenance planning in Power Electronic-based Power Systems (PEPSs) have not been explored. However, they have considerable impact on the reliability worth in design and planning of PEPS. On the other hand, design and maintenance activities in conventional power systems are performed based on the historical data. However, these data may not guarantee optimal maintenance due to development of converter technologies and dependency of its reliability to operating conditions. Therefore, model-based system-level design for reliability and maintenance planning should be performed in order to enhance the PEPS performance.

This paper aims to introduce an MBSE approach for system-level design for reliability and maintenance planning in PEPSs employing lifetime model of converters in the three mentioned hierarchical levels. This will introduce a systematic method for design and planning of PEPSs in order to economically enhance the overall system performance. The main outcomes of this paper are as follows:

1- Employing the proposed MBSE approach will facilitate optimal design of PEPSs. Incorporating reliability model of converter components into the system-level design will result in economical and reliable decision-making during planning. Unlike the conventional methods, which relies on historical failure data, the proposed model-based design will yield more precise, and thus, cost-effective consequences.
2- The proposed system-level design for reliability will consider the functionality and impact of each converter

on the entire power system. Therefore, design and manufacturing of converters have been performed based on their impact on the overall system performance. However, the converter-level design for reliability approaches did not consider the interaction of converter functionality with the power system performance. Thus, the proposed approach will give appropriate insight to converter manufacturers and power system planners to design/select the converters based on power system reliability requirements.

3- The proposed approach facilitates identifying the weakest links of system from component up to system level. Thus, investment decisions for enhancing the overall system performance can economically be made by strengthening its critical components.

4- The proposed MBSE approach can be applied for maintenance planning in converters in order to cost-effectively replace their components. Notably, the conventional maintenance activities rely on historical data and average failure rate of units. These data can make erroneous results since the failure rate depends on usage and operational conditions. Moreover, the historical data may not accurately model the aging process of components. On the other hand, using average failure rates can decrease the accuracy of the system reliability model. However, the proposed approach relies on the reliability model of converter components which can appropriately incorporate the operational condition and accurately model the failure rate based on applied stress to the converters. As a result, optimal maintenance periods based on aging of converter components can be obtained.

Notably, power electronic converters are used in different applications such as HVDC/MVDC transmission systems, electric vehicle chargers, renewable generations, interconnected ac/dc microgrids, energy storage units and many others [33]. The proposed approach for model-based design and maintenance in this paper is a general scheme for different types of PEPS with various applications of power converters. Therefore, without losing the generality, the effectiveness of the proposed approach is illustrated through a dc microgrid with different energy sources and converter topologies.

The remainder of this paper is organized as follows. Reliability modeling in power electronic converters is explained in Section II. Section III presents the proposed system-level design for reliability in PEPSs. Furthermore, the proposed model-based maintenance planning strategies are discussed in Section IV. Section V give some case studies illustrating the applicability of the proposed strategies. Finally, the outcomes are summarized in Section VI.

II. RELIABILITY OF POWER ELECTRONICS SYSTEMS

Power electronic converters like other engineering systems follow the bathtub shape failure behavior. It includes the three phases: infant mortality [34]–[36], useful lifetime and wear-out period. In practice, the infant mortality belongs to the debugging process which has been solved before operation. Therefore, the converter will experience random chance and aging-related failures within useful lifetime and wear-out phase respectively as shown in Fig. 2. The random chance failures are associated with overstressing of the components triggered by sudden single event such as overvoltage and overcurrent. Furthermore, the aging failures are associated with the wear-out of power modules, capacitors and Printed Circuit Boards (PCB) solder joints [3], [14], [23], [37], [38].

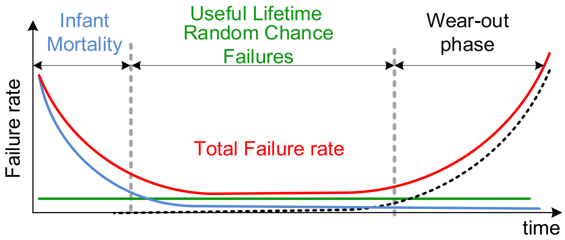

FIGURE 2. **Typical bathtub curve describing failure rate of an item.**

In order to predict the converter failure rate, its components failure modes and mechanisms must be realized. So far, the power switches and capacitors are known as the major source of failure in converters [2], [39]–[41]. Different failure sources and mechanisms of these components are summarized in [11]. They are prone to random chance failures, which are typically modeled by a negative exponential distribution function. Furthermore, they are exposed to aging failures, which can be represented by a Weibull distribution function with an increasing failure rate. In practice, the random chance failure rate prediction is a difficult task since the corresponding failure mechanisms are usually triggered by external sources. However, chance failure rate prediction is required to predict the long-term performance of the system for planning and economic analysis. There are several methods for chance failure rate prediction, which rely on (a) operational experiences in recent years or in similar cases, and (b) using generic data provided in handbooks [42].

There are several handbooks in the field of power electronics, which have provided failure rate data and correction factors in order to adjust the given data for different operation conditions and applications [12]–[14], [43]. The latest updated handbook in this regard is provided by FIDES Group [13]. The FIDES approach takes into account the impact of failure mechanisms and mission profiles on the chance failure rate of components.

According to the FIDES approach, the failure rate of a component (λ_c) is found by using (1) [13].

$$\lambda_c = \Pi_{PM}\Pi_{Prosess}\lambda_{Phy} \tag{1}$$

where, Π_{PM} is associated with the effect of quality and technical control within manufacturing, and $\Pi_{Process}$ is attributed to all processes from specification to field operation and maintenance. Moreover, λ_{phy} is a physical failure rate corresponds to operating conditions within a specific period of time given by a mission profile. Also, λ_{Phy} is obtained as [13]:

$$\lambda_{Phy} = \sum_{i=1}^{Phase} \left[\frac{t_{annual}}{8760}\right]_i \Pi_i \lambda_i \tag{2}$$

where, t_{annual} is the time period of i^{th} phase in the mission profile, and Π_i is the induced electrical, mechanical and thermal overstresses, which can be obtained using (3) [13].

$$\Pi_i = \left(\Pi_{Placement}\Pi_{App}\Pi_{Rugg}\right)^{0.511\cdot\ln(C_s)} \tag{3}$$

where, $\Pi_{placement}$ denotes the impact of the item placement in the system, Π_{App} denotes the impact of the usage environment for application of the product containing the item, Π_{Rugg} denotes the impact of the policy for considering overstresses in the product development, and C_s is associated with the sensitivity to overstress inherent to the item technology considered. Moreover, λ_i is the corresponding failure rate in each phase of the mission profile as given in (4) [13].

$$\lambda_i = \sum_k \lambda_{0k}\Pi_k \tag{4}$$

where λ_{0k} is the base failure rate and Π_k reflects the physical constraints that the component experiences during operation or in a dormant period. λ_i is attributed to case and solder joints related failures and thermal, humidity and mechanical stresses.

In this paper, the converter reliability is modeled based on the reliability of its fragile components, i.e., capacitors and power semiconductors. This assumption will result in more accurate modelling since these components have the dominant impact on the aging of converter. Inclusion of other components will enhance the accuracy of the converter reliability model. Therefore, in the following, the failure rate of semiconductor devices and capacitors based on FIDES approach is presented [13].

The failure rate in (4) for power semiconductor switches, λ_{Phy-SD} is obtained as [13]:

$$\begin{aligned}\lambda_{Phy-SD} &= \sum_{i=1}^{Phase}\left[\frac{t_{annual}}{8760}\right]_i \\ &\times \begin{pmatrix}\lambda_{0TH}\Pi_{Thermal} \\ +\lambda_{0TCyCase}\Pi_{TCyCase} \\ +\lambda_{0TCySolderjoionts}\Pi_{TCySolderjoionts} \\ +\lambda_{0RH}\Pi_{RH} \\ +\lambda_{0Mech}\Pi_{Mech}\end{pmatrix}_i (\Pi_{Induced})_i\end{aligned} \tag{5}$$

and for the capacitors, $\lambda_{Phy-Cap}$ is achieved by using (6) [13].

$$\lambda_{Phy-Cap} = \lambda_{0Cap}\sum_{i=1}^{Phase}\left[\frac{t_{annual}}{8760}\right]_i \begin{pmatrix}\Pi_{Thermo-electrical} \\ +\Pi_{TCy} \\ +\Pi_{Mechanical}\end{pmatrix}_i (\Pi_{Induced})_i \tag{6}$$

The base failure rates, λ_{0X} and Π_X for a failure factor of X has been given in the page of 120 for power switches and page of 138 for capacitors in [13]. However, these values can be provided by manufacturers or obtained based on operational experiences. In this paper, the converter reliability is modeled by the reliability of capacitors and power modules since they are the most fragile components according to the industrial experiences [2], [39]–[41]. Notably, more accurate models can be obtained by considering failure rates of other components provided in [13].

Moreover, the fragile components of the converter, i.e., capacitors and power switches are prone to aging failures [11], [14], [44]–[49]. This fact will limit the life expectancy of the converter. It will be of high importance knowing that their wear-out characteristics depends on operating conditions. Therefore, the wear-out failure rate should be predicted since it will affect any system-level decision making.

In order to predict the wear-out failure probability of these components, the concept of structural reliability has been adopted [11], [23], [50]. Based on this approach, the components resistances are compared to the applied stress and the corresponding lifetime consumption is obtained by using the linear Miner's rule as:

$$LC_D = \sum \frac{\sigma_{i,D}}{\rho_{i,D}}. \tag{7}$$

where, LC_D is the Lifetime Consumption (LC) of device D, $\sigma_{i,D}$ and $\rho_{i,D}$ are the applied stress and component resistance within the i^{th} phase of applied mission profile. According to (7), the aging process is modeled by linearly accumulating the components damage. Notably, the more accurate analysis can be obtained by components strength degradation modeling [37], which can enhance the accuracy of the reliability prediction. The term resistance, ρ in (7) is equal to the capacitor lifetime, L_r obtained by (8) [51] and the number of cycles to failures for power semiconductor switches, N_f is given by (9) [52].

$$L_o = L_r \cdot 2^{\frac{T_r - T_o}{n_1}}\left(\frac{V_o}{V_r}\right)^{-n_2} \tag{8}$$

$$N_f = A\cdot\Delta T_j^{\alpha}\cdot\exp\left(\frac{\beta}{T_{jm}+273}\right)\cdot\left(\frac{t_{on}}{1.5}\right)^{-0.3} \tag{9}$$

In (8), L_r is the rated lifetime under the rated voltage V_r and rated temperature T_r, and L_o is the capacitor lifetime under operating voltage V_o and temperature T_o. The constants of n_1 and n_2 are provided in [51]. In (9), ΔT and T denote the swing and mean values of junction temperature, and t_{on} is the rise time of temperature cycle. The constants A, α, and β can be obtained from aging tests [52].

Moreover, the term of stress, σ_i for the capacitors is equal to the time period in the i^{th} phase of the mission profile with corresponding operating voltage of V_o and temperature of T_o. Also, σ_i is equal to the number of cycles in the i^{th} phase of mission profile with specific temperature, temperature swing and thermal rise time. These variables should be obtained by translating the given mission profile to the electro-thermal domain in order to obtain the lifetime consumption. This process faces various uncertainties associated with the manufacturing tolerance over the components thermal characteristics as well as model uncertainties in lifetime models given in (8) and (9). Therefore, the obtained *LC* in (7) is not deterministic. In order to identify the distribution function of *LC*, Monte Carlo simulations can be used for modeling the impact of uncertainties. This procedure has been explained in detail in [22], [23]. The wear-out failure probability of each device can be presented by a Weibull distribution as:

$$F(t) = 1 - e^{-\left(t/\alpha\right)^{\beta}} \sim Weibull(\alpha, \beta) \tag{10}$$

where, $F(t)$ is the failure Cumulative Distribution Function (CDF), with a scale and a shape factor of α and β. The corresponding wear-out failure rate can be calculated as:

$$\lambda_w(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \tag{11}$$

Finally, according to (1) and (11), the total failure rate of component x, λ_x(t) can be obtained as:

$$\lambda_x(t) = \lambda_c + \lambda_w(t). \tag{12}$$

The total converter failure rate can be modeled by series reliability block diagram of its individual components as their failure will cause converter shutdown. Thus, the converter failure rate is equal to the summation of the total failure rate of its components. Moreover, the converter reliability can be calculated as:

$$R(t) = \exp\left(-\int \lambda_{total}(t)\,dt\right). \tag{13}$$

where λ_{total}(t) is the total converter failure rate.

The predicted converter reliabiltiy is a useful index for design and maintenace of PEPS. In the following section, the propsed model-based design and maintenance scheduling in modern power systems are presented.

III. PROPOSED SYSTEM-LEVEL DESIGN FOR RELIABILITY

Design for reliability is a process to ensure that a product/system performs its function to meet desired performance under its use environment within a specified time period. The concept of design for reliability has been employed in power electronics engineering in order to design power converters with desired long-term performance [28], [41], [53]. According to this approach, the converter components, especially capacitors and power switches, are selected in such a way that the converter does not enter wear-out phase before its target lifetime [28], [41], [53]. So far, this approach has been applied for single unit converters [24], [28], [41], [53]–[55]. The main goal is to design an individual converter to achieve a desired B_x lifetime under a mission profile, which means the failure probability (wear-out related failures) of the converter after B_x (usually in years) will be lower than x%.

However, the converters are in most applications employed in a larger system, called power system. In the power systems, the concept of reliability is more general. The power system reliability is measured by its ability to supply its customers with power under different uncertainties [56], [57]. These uncertainties may be induced by planned outages, e.g., for maintenance, or unplanned outages such component failure, short circuits, and so on. Therefore, a power system should have enough capacity to supply the customers, and it should be able to respond to any sudden changes [58]. These abilities are measured by various indicators, which are generally categorized as power system adequacy and security [58]. The most popular index used for evaluating the reliability of power systems is Loss OF Load Expectation (LOLE) [59]–[61]. In a reliable power system, LOLE has a value of 4 to 8 hours per year depending on power grid regulations in each country [61]. Thereby, in order to have a reliable power system, its components should be properly designed to achieve an acceptable performance. Converters as vulnerable components in power systems may have significant impact on the overall system reliability [62]. Thus, they should be appropriately designed to meet power system reliability requirements especially in modern PEPSs. In order to achieve such an objective, a model-based design approach for reliability procedure is proposed in this paper as shown in Fig. 3.

According to the proposed approach, first, the converter components are selected with rated values of the converter. Annual loads and renewable-based generations are forecasted. Then, the system is simulated employing Power Flow (PF) analysis tools to find the mission profile of each unit under forecasted loads and generations. This is required to find the converter loading due to the fact that the converter reliability depends on its operating conditions. For instance, the impact of converter loading on the stress of semiconductor devices and capacitors are demonstrated by experiments in [22], [23], [31], [53], [63] [37]. Thus, the converter loading is determined by PF analysis and its functionality in the system with respect to the energy management strategy. Moreover, the system uncertainties such as the loss of generation units can also affect the converter loading. In order to take into account the impact of such kind of uncertainties and maintain the system security, *N-x* criterion will be considered during PF analysis. This means the system should be able to supply the load considering outage of x units. This will ensure preventing converters overloading within unplanned outage of any other units. After identifying the converters mission profiles, their failure rates and reliability will be predicted according to the reliability prediction procedure explained in Section II. If the converter B_x lifetime does not meet the designer requirements, the design process will be repeated with new components. This will continue until approaching the best component selection, which yields the desired converter lifetime.

If the converter B_x lifetime is acceptable, then, the system reliability will be evaluated to find out the system-level

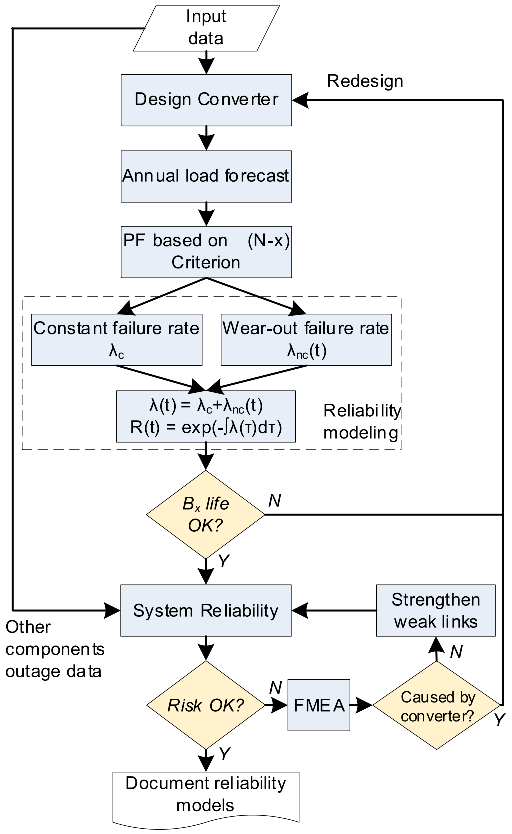

FIGURE 3. **System-level design for reliability in PEPS with N-x criteria – PF: power flow, FMEA: failure mode, and effect analysis.**

indices such as LOLE. The process of reliability evaluation in PEPSs considering wear-out failures are discussed in [62], and the same methodology is employed in this paper. Once the LOLE is calculated, if its value exceeds the acceptable level, it should be figured out if it is associated with any of the converters in the system. Thus, Failure Mode and Effect Analysis (FMEA) can be employed to find the weakest links of the system. If FMEA results show that any of converters affects the system reliability, then it should be redesigned to meet the system requirements. Once the system LOLE (or other system performance indicator used by designer) stays below a standard value, the design process is completed and the selected components and reliability information can be documented.

Notably, the main differences between system-level design for reliability and converter-level design for reliability are:

1- In the converter-level, the mutual impact of other units may not be considered. However, in the system-level approach, the mutual impacts are considered by PF analysis taking into account the power of loads and renewable generations.
2- In the system-level design, the system security will be ensured by applying N-x criterion during load flow analysis. This will prevent catastrophic failures in converters due to its overloading after other units outage.
3- The most important difference is that the converter design based on lifetime requirements may not guarantee power system requirements. Therefore, it is crucial to take into account the system-level indices during design and manufacturing of power converters. Otherwise, even though each converter is reliable by itself, but the overall system reliability is not achieved. Moreover, manufacturing a high reliable converter requires higher costs. However, a converter with lower reliability, consequently lower costs, may meet the system requirements. Thus, optimal and economical design and manufacturing of converters require analyzing their impacts on the system performance.
4- This process will give an insight to the planner of the power system to realize the behavior of the system according to the model of its components. Thus, the obtained reliability model can be used for model-based cost analysis, maintenance planning and optimal decision makings in the planning phase of PEPSs.

The proposed approach can be used for any power electronic-based systems including more electric aircrafts, more electric ships, ac and dc microgrids, etc. It will result in reliable design based on the converter lifetime models. This approach can be generalized by considering the lifetime model of other components especially the battery storage as their penetration is increasing in power systems.

IV. PROPOSED MAINTENANCE SCHEDULING

As already mentioned, the converter- and system-level reliability studies are mostly dedicated to reliability enhancement by decreasing the failure rate of components and extending the useful lifespan. This approach can be an effective solution for mission-based systems like space stations. However, for maintainable applications such as in power systems, this solution may not be an economically feasible approach. This is due to the fact that in this application availability is the measure of system performance [56]. Availability is defined as the probability of being in the operating state at instant t given that the system starts operation at $t = 0$ regardless of any failure occurrence in this period [64]. Therefore, it is important to repair or replace the system whenever it fails. Thus, the frequency of failure and repair/replacement time matter to the converter performance. These two factors are related to the maintenance activities in any engineering systems. This section will discuss different maintenance strategies and proposes a model-based maintenance planning for power electronic converters in the following.

A. MAINTENANCE STRATEGIES

Different maintenance strategies are employed in order to reduce the failure frequency and/or repair/replacement time, consequently enhancing the system availability. Generally, the maintenance strategies are categorized into two major policies including corrective and preventive strategies as shown in Fig. 4. The corrective maintenance tasks, also known as breakdown maintenance, is performed once a

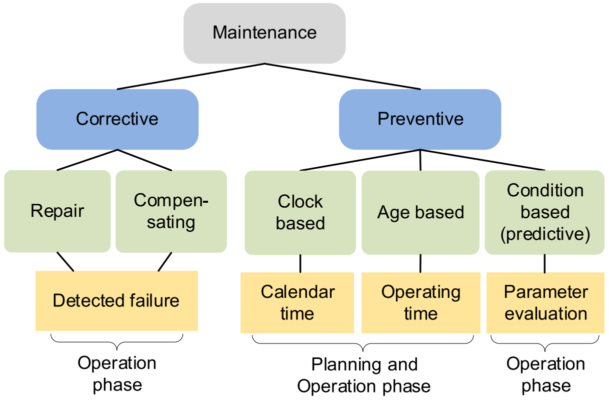

FIGURE 4. **Classification of maintenance types in a power system.**

system breaks down. Thus, after failure occurrence, the system will be repaired, replaced by another one, or compensated by a stand-by system.

Since the system failure will increase its unavailability and consequently the overall system risk, in practice, the failure occurrence is prohibited by an appropriate preventive maintenance policy. The preventive maintenance policies can be performed periodically at predefined clock-based times or age-based times or condition-based times. The clock-based maintenance task is applied at specified calendar times; hence, it can easily be planned especially for large-scale systems. For instance, in wind farms, a possible clock-based maintenance would be replacement of all converters every 10 years.

The age-based maintenance strategies are carried out at specified age of the system, for instance, the number of cycles to failure for a power module. Moreover, the condition-based maintenance task is applied based on measurements of systems deteriorating variables such as on-state voltage of a power switch, or capacitance of a capacitor. The maintenance will be performed once the measured variable approaches or passes a certain threshold value. If the condition variable is associated with the consumed lifetime of the system, the term "predictive" is usually used instead of "condition-based" in maintenance classification [65]. In this case the system will be replaced once the consumed lifetime approaches one.

In power systems, the maintenance strategies can play different roles in planning and operation phases. During operation, the goal of maintenance tasks is to retain the system at the operating mode. Thus, all maintenance policies in Fig. 4 can be applied during operation time depending on the type and size of system, data availability, failure characteristics and so on. However, in the planning phase, the aim of maintenance scheduling is to make economic decisions and cost analysis. Therefore, corrective and condition-based preventive maintenance are not applicable. During design and planning of a system, the replacement times can be predicted employing clock-based and age-based preventive maintenance strategies.

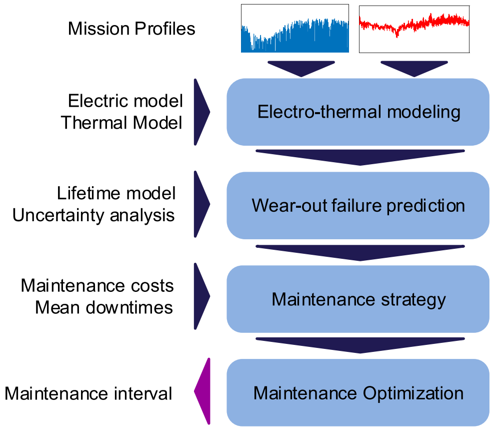

FIGURE 5. **Proposed age-based maintenance scheduling process in power electronic converters.**

It is obvious that in the clock-based maintenance, the system will be replaced at prespecified time periods regardless of its wear-out. This strategy can easily be applied for large-scale systems like wind farms. However, in most cases, new items must be replaced at the planned times. Thus, this approach is not an economic efficient maintenance strategy. On the other hand, the condition-based strategy requires monitoring a deteriorating variable, which in large-scale systems may introduce higher costs. This strategy is, hence, applicable for systems with higher downtime costs, production loss or personal damage.

Moreover, it is not applicable for systematic design and planning since it relies on real time monitoring within operation. On the other hand, the age-based replacement policy can be used to predict proper maintenance times based on wear-out characteristics of the system. Thus, it requires estimating the wear-out failure probability of the system.

B. PROPOSED MODEL-BASED MAINTENANCE PLANNING

Power electronic converters penetration level is increasing steadily in power systems. They may pose higher downtime and maintenance costs, production loss and personal injury at system-level such as in on-shore/off-shore wind farms and more electric ships/aircrafts. Therefore, predictive maintenance is more applicable for these cases. Furthermore, in some applications like PV plants, predictive maintenance may introduce higher maintenance costs, while other preventive maintenance can be applied in order to enhance the overall system performance. In the following the proposed model-based age replacement policy and predictive approach for power converters are presented.

The proposed age-based maintenance planning approach is shown in Fig. 5. According to this approach, the wear-out failure probability is predicted based on the reliability model of converter components, which is discussed on Section II. First, the converter mission profile is translated into the electro-thermal variables, which are used in the components lifetime following (8) and (9). Afterwards, the wear-out failure probability will be predicted. The failure probability is used to estimate the maintenance times, which can be obtained by optimizing the system availability or maintenance costs.

According to the age-replacement policy, the converter will be replaced upon failure or at a pre-specified age t_0, whichever comes first. Thus, the mean time between replacements can be achieved using (14),

$$\begin{aligned} T_R(t_0) &= \int_0^{t_0} tf(t)\,dt + t_0 \cdot \Pr(T \geq t_0) \\ &= \int_0^{t_0} (1 - F(t))\,dt \end{aligned} \tag{14}$$

where $T_R(t_0)$ is the mean time between replacements and $f(t)$ denotes the aging failure Probability Density Function (PDF). If a failure does not occur within the replacement interval of t_0, the scheduled replacement cost will be ε. Furthermore, an unplanned failure occurrence before t_0 will introduce extra maintenance/production loss costs of κ. Therefore, the total mean replacement Costs per Time unit $CT(t_0)$ can be calculated as:

$$CT(t_0) = \frac{\varepsilon + \kappa F(t_0)}{T_R(t_0)} \tag{15}$$

In the case of very large replacement interval, the mean replacement costs will be:

$$CT(\infty) = \frac{\varepsilon + \kappa}{MTTF} \tag{16}$$

where, $MTTF$ is the Mean Time To Failure of failure CDF, which is equal to $MTTF = T_R(\infty)$. A Cost Efficiency measure $CE(t_0)$ can hence be defined as [65]:

$$CE(t_0) = \frac{CE(t_0)}{CE(\infty)} = \frac{1 + r \cdot F(t_0)}{1 + r} \frac{MTTF}{\int_0^{t_0} (1 - F(t))\,dt} \tag{17}$$

where $r = \kappa/\varepsilon$. $CE(t_0)$ shows the ratio of mean costs of preventive maintenance to the means costs of corrective maintenance. Therefore, the preventive maintenance is applicable if $CE(t_0) < 1$, implying lower maintenance costs in the case of employing preventive maintenance. The best maintenance time is the argument of the minimum of $CE(t_0)$.

In the case, the converter availability is more important than the maintenance costs, such as in traction applications, the unavailability-based age replacement strategy can be performed. The mean downtime of the converter $T_D(t_0)$ with age replacement policy at an age of t_0 can be obtained as:

$$\begin{aligned} T_D(t_0) &= T_U \cdot F(t_0) + T_P \cdot (1 - F(t_0)) \\ &= T_P \cdot (1 + (k - 1) F(t_0)) \end{aligned} \tag{18}$$

where, T_P denotes a mean planned downtime, T_U is a mean unplanned downtime due to a failure occurrence during t_0, and $k = T_U/T_P$. Therefore, the converter unavailability $U(t_0)$ with an age replacement policy is defined as [65]:

$$\begin{aligned} U(t_0) &= \frac{T_D(t_0)}{T_R(t_0) + T_D(t_0)} \\ &= \frac{T_P \cdot (1 + (k - 1) F(t_0))}{T_R(t_0) + T_P \cdot (1 + (k - 1) F(t_0))} \end{aligned} \tag{19}$$

A low value of unavailability implies a high performance of the converter. The minimum of $U(t_0)$ can be achieved by solving V, where ∂ denotes the derivative operator. Following V, the optimum replacement time is dependent on the failure probability function and k factor, while it is independent from the mean planned downtime T_P.

$$\begin{aligned} \frac{\partial U(t_0)}{\partial t_0} = {} & \frac{T_P}{(T_R(t_0) + T_D(t_0))^2} \\ & \times \left(T_R(t_0)(k - 1) \frac{\partial F(t_0)}{\partial t_0} \right. \\ & \left. - (1 + (k - 1) F(t_0)) \frac{\partial T_R(t_0)}{\partial t_0} \right) = 0 \end{aligned} \tag{20}$$

Notably, the age-replacement policy can be used during planning based on the reliability model of converters. Moreover, it can be used during operation by employing the experienced mission profile in order to accurately predict the maintenance times. This is due to the fact, for planning, a historical mission profile is usually employed, but within operation, the real experienced mission profile is available. To make it more precise, predictive maintenance can be applied. In this strategy, the lifetime consumption, LC of components (see (7)) is calculated based on the real-time variables during operation. According to (7), the component will fail once the LC approaches one. This approach is more accurate and deterministic but requires monitoring of different variables, which will introduce higher costs in large-scale systems.

V. CASE STUDIES

In this section, two case studies are presented to illustrate the effectiveness of the proposed design for reliability and maintenance scheduling in PEPSs. The first case presents numerical analysis of design for reliability concept in a dc-based PEPS. The second case shows the impact of model-based maintenance strategies on a PV inverter.

A. CASE A: SYSTEM-LEVEL DESIGN FOR RELIABILITY IN A DC PEPS

In this case, a dc microgrid as a dc PEPS is considered and the concept of system-level design for reliability is investigated. The structure of the dc microgrid is shown in Fig. 6. It contains of two PV units, two Fuel Cell (FC) stacks, and a grid connected inverter. The power sharing strategy is based on local priority that the microgrid local load has the higher priority and only the excess power of PV units will be injected into the utility grid. Moreover, the FC units will just supply the local load. The grid considered is also a backup if the local sources cannot adequately supply the load.

The whole system has been simulated in the switching domain using the PLECS software environment. The specifications of the PV system are given in TABLE 1. The PV array is made up of 3 parallel-connected strings where there are 5 series-connected PV panels in each string. Furthermore, the output power of the FC is modeled based on the voltage-current characteristics shown in Fig. 7. The topologies of the

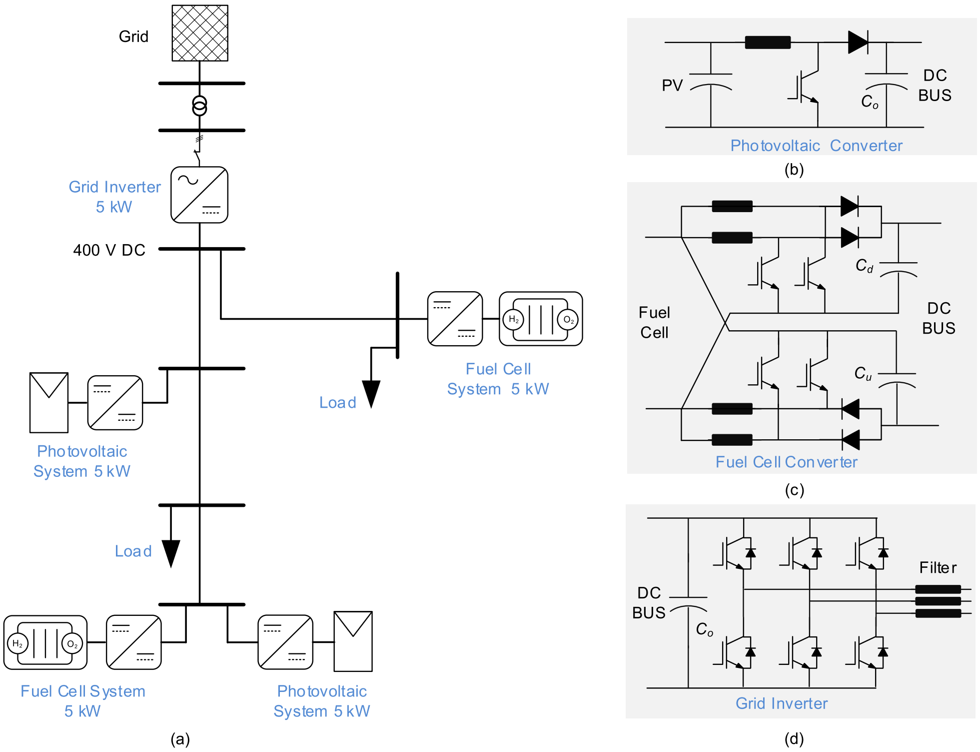

FIGURE 6. Structure of dc Power Electronic-based Power System (PEPS); (a) single line diagram of the dc grid, (b) Photovoltaic (PV) converter, (c) Fuel Cell (FC) converter, (d) Grid inverter. (Case A).

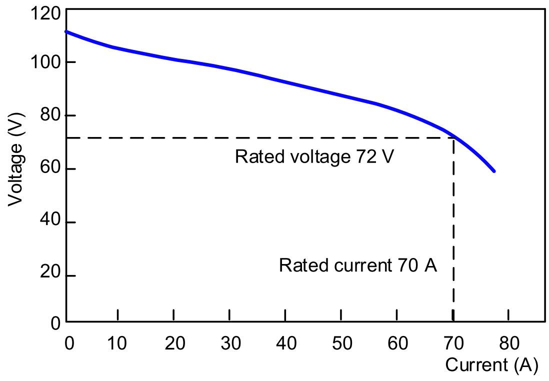

FIGURE 7. Voltage-current characteristics of the Fuel Cell stack.

TABLE 1. PV system parameters used for Case A.

Parameter	Value
Panel Rated Power	345 *W*
Number of Series panels in string	5
Number of Parallel strings	3
Open Circuit Voltage	64.8 *V*
Short Circuit Current	7.04 *A*
MPPT Voltage	54.7 *V*
MPPT Current	6.26 *A*
Voltage temp. Coeff.	-0.27 *%/K*
Current temp. Coeff.	0.05 *%/K*

interface converters for FC, PV and grid are shown in Fig. 6. Moreover, the detailed electro-thermal parameters employed for analysis are summarized in TABLE 2.

In this study, a load profile of a small clinic is considered as shown in Fig. 8(a), which is based on the hourly peak load during one year. The load profile for one week from the day of 203rd to 210th is also shown in Fig. 8(b). The load duration curve based on hourly peak load is further shown in Fig. 8(c). Furthermore, measured solar irradiance and ambient temperature are shown in Fig. 9(a) and (b) respectively. The time resolution of solar irradiance is one minute. The detail solar irradiance for a few days of January is shown in Fig. 9(a). The solar irradiance was measured in Arizona on a tilted surface with an angle equal to the latitude of measured location. Therefore, the PV system output power is calculated considering the fixed-mount PV panels. Furthermore, the probability of output power of each PV unit based on annual solar irradiance and ambient temperature are shown in Fig. 9(c). In the following, the obtained results are explained.

According to the proposed design for reliability approach shown in Fig. 3, the dc microgrid is simulated based on the forecasted load and generation profiles shown in Fig. 8(a) and Fig. 9(a). Afterwards, the wear-out failure rate and reliability of converters are predicted based on the procedure explained in Section II considering the components given in TABLE 2. The predicted wear out failure rate and reliability of converter

TABLE 2. **Power converter parameters in Case A.**

Parameters	PV Converter #1, 2	Inverter	FC Converter #1, 2
Rated power	5 *kW*	5 *kW*	5 *kW*
Switching frequency	20 *kHz*	20 *kHz*	20 *kHz*
Output capacitor	2×220 μF	2×220 μF (C_o)	5×220 μF
ESR per capacitor @ 100 Hz	0.35 Ω	0.41 Ω	0.24 Ω
Capacitor thermal resistance	19.5 *K/W*	19.5 *K/W*	28 *K/W*
Capacitor thermal time constant	10 *min*	10 *min*	10 *min*
Inductor	1 *mH*	3 *mH*	1 *mH*
Switch	IGB10N60T	IGB20N60H3	IGB15N60T
Diode	IDV20E65D1	IDV15E65D2	IDV20E65D1
DC Bus voltage	400 *V*	400 *V*	400 *V*
Input voltage	220 – 320 *Vdc*	150 *Vac,rms* (@50 *Hz*)	72-110 *Vdc*

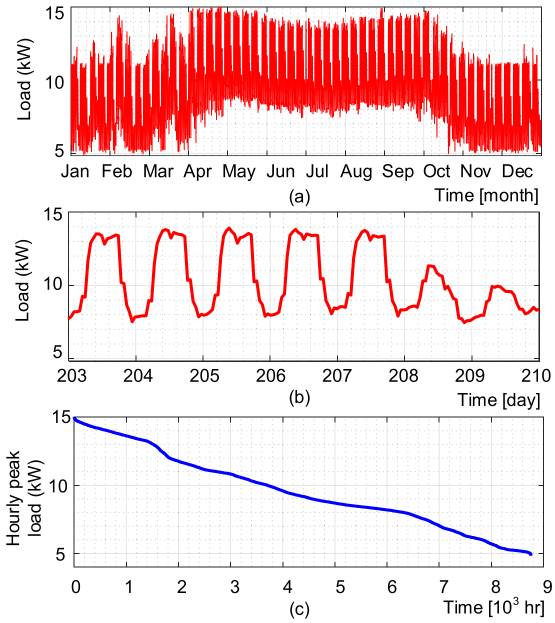

FIGURE 8. **Load profile for a small clinic; (a) annual load profile, (b) daily load profile for one week, and (c) load duration curve based on hourly peak load.**

components for PV, FC and inverter are shown in Fig. 10 to Fig. 12 respectively. According to Fig. 10 and Fig. 11 the capacitor bank is the dominant component affecting the converter lifetime. Furthermore, the diode is the fragile component of inverter according to Fig. 12. This is due to the fact that the grid converter is operating in the rectification mode at most of the time according to the employed energy management strategy. In the rectification mode, the diodes are dominant components affecting the converter reliability [27]. These results are of importance for reliability enhancement if the designed converter does not meet the reliability requirements.

In this study, it is assumed to have B_{10} lifetime of 10 years for each converter. As shown in Fig. 10(b) to Fig. 12(b), the corresponding B_{10} lifetime of converters are higher than 10 years. Thus, the selected components, which are reported in TABLE 2 are acceptable from a converter lifetime measure point of view.

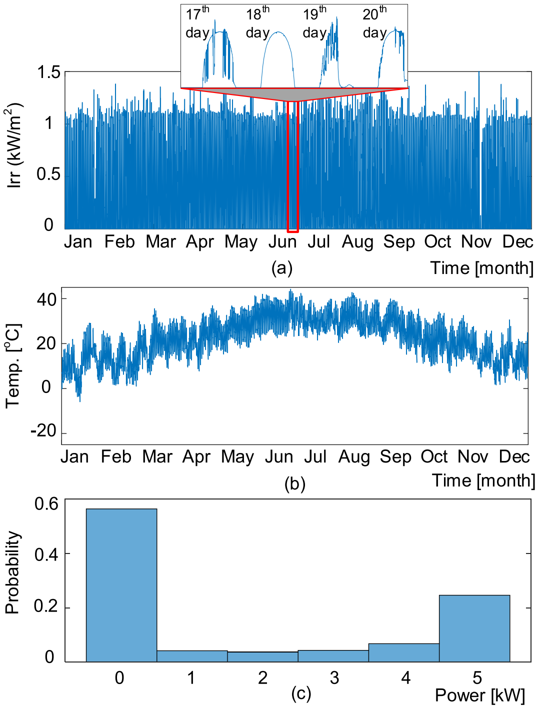

FIGURE 9. **Annual mission profiles: (a) solar irradiance, (b) ambient temperature, and (c) probability of PV system output power.**

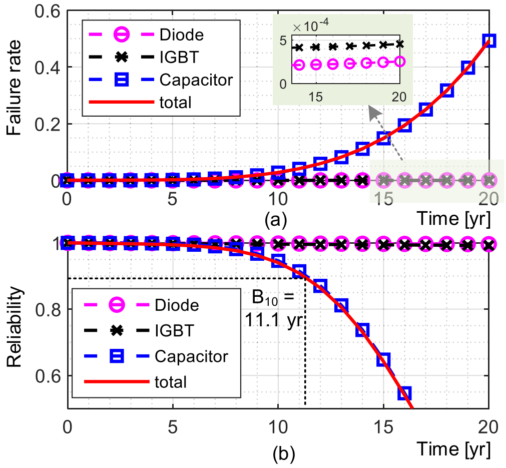

FIGURE 10. **PV converter wear out failure rate (a) and reliability (b).**

In order to check the system-level requirement, the LOLE of the microgrid is calculated for 20 years of operation. The failure rate and average repair time of units are given in TABLE 3. In order to predict the LOLE, the unavailability of units should be calculated. Since the failure function of converters are time varying, the unavailability is predicted using the method of device of stages [62]. Furthermore, since

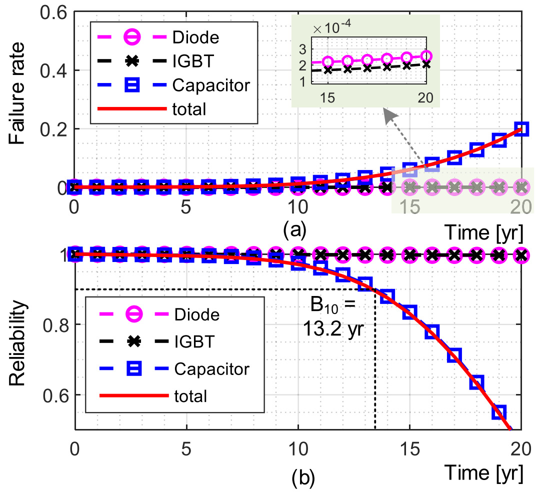

FIGURE 11. FC converter wear out failure rate (a) and reliability (b).

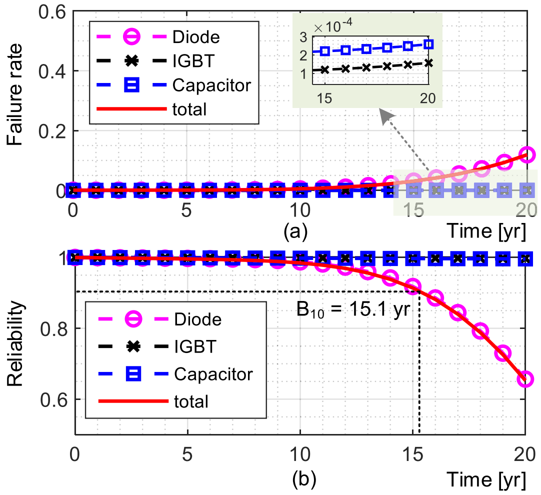

FIGURE 12. Inverter wear out failure rate (a) and reliability (b).

TABLE 3. Reliability data of generation units [7], [62], [66], [67].

Unit	Prime Mover		Converter	
	failure rate [f/yr]	Repair time [hr]	Constant failure rate [f/yr]	Repair time [hr]
PV	0.15	80	9E-4	100
FC	0.10	150	8.5E-4	100
Inverter	1.00	5	7E-4	100

the output power of PV units is variable, the probability of its output power is obtained from the given mission profile as shown in Fig. 9(c). The LOLE is predicted based on a method presented in [62], and therefore details are not provided in this paper.

The microgrid units unavailability is shown in Fig. 13 (a). It is obvious that the units unavailability is increased due to the aging of converters. According to Fig. 10(a), the PV converter has higher failure rate compared to the other units, and hence, it has higher unavailability (considering that the converters has the same repair rime following TABLE 3).

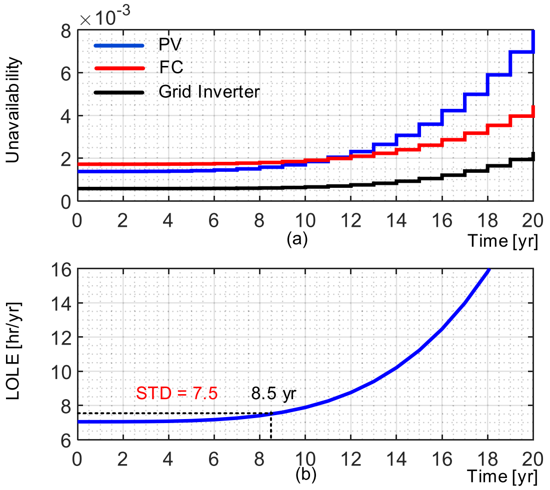

FIGURE 13. Obtained system-level results: (a) individual generation unit unavailability and (b) LOLE – STD: standard level.

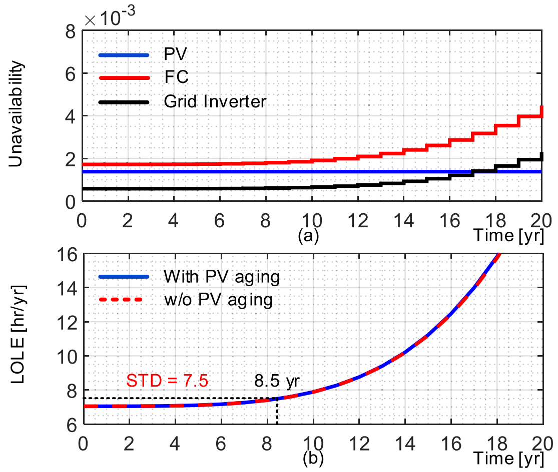

FIGURE 14. Obtained system-level results without PV converters aging: (a) individual generation unit unavailability and (b) LOLE– STD: standard level.

Moreover, the microgrid LOLE is shown in Fig. 13(b). If the standard LOLE is considered to be 7.5 *hr/yr*, after 8.5 years, the system LOLE raises beyond the standard level. As a result, if the system lifetime is considered to be 10 years, therefore, after 8.6 years, it will become unreliable. In order to find out the affective component on the system unavailability, FMEA should be employed. In this case, since the size of system is small, the impact of converters is manually explored.

At first, the system LOLE is calculated without considering aging failure of PV converters. The generation units unavailability and the microgrid LOLE are shown in Fig. 14(a) and (b) respectively. As shown in Fig. 14(b), the PV converters aging has a negligible impact on the system LOLE. This is due to the lower probability of PV output at different power levels as shown in Fig. 9(c). For instance, considering the failure rate of 0.2 for PV converter, the PV unit unavailability – with output power of zero kW – will

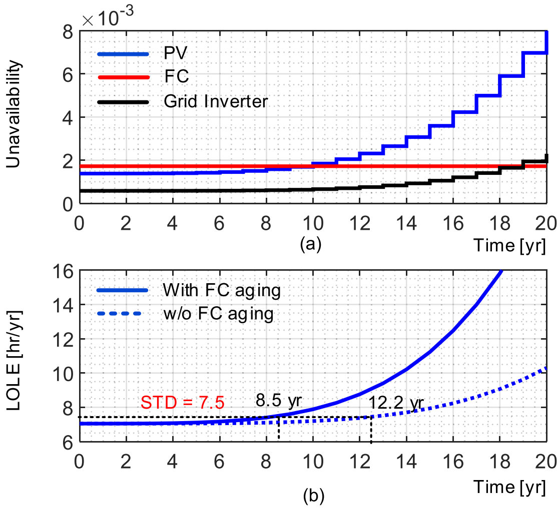

FIGURE 15. Obtained system-level results showing the impact of FC converters aging: (a) individual generation unit unavailability and (b) LOLE– STD: standard level.

be 0.56579. This value is calculated considering the states of resulting zero PV power, which is the sum of (1) the probability of having zero solar power, and (2) the probability of having non-zero solar power multiplied by the unavailability of conversion system (converter and PV arrays given in TABLE 3). Increasing the PV converter to 0.4 failure per year, the PV unit unavailability with zero output power will be 0.56678. Thus, by doubling the failure rate, due to aging, the PV unavailability change is negligible.

In the next step, the generations unavailability and microgrid LOLE are calculated without considering the aging of FC converters. The results are shown in Fig. 15 implying that the FC converters have remarkable impact on the system LOLE. As it is seen from Fig. 15(b), by removing the aging failure of FC converters, the system will approach the standard LOLE after 12 years of operation. As a result, the system with 10 years of operational lifetime will be reliable by a proper design of FC converters.

According to the system-level analysis, the FC converters cannot guarantee system reliability requirements. Therefore, they must be redesigned to fulfill the overall system reliability. In order to improve the FC converter reliability, the capacitor bank must be redesigned according to Fig. 11. As a result, the model-based system design brings an opportunity to model, analyze, design and enhance the system reliability from component up to system level. It is obvious that the obtained results depend on the standard level of LOLE as the system performance indicator, and the operational lifetime of the microgrid.

The proposed approach will bring an extra opportunity to the system designer to decide among different strategies based on reliability worth-cost analysis. For instance, the designer may decide between two options of (1) redesigning FC converter with new components, or (b) replacing the FC converter after 5 years. The cost analysis will help to make an optimal decision among different alternatives. Moreover, the inverter has almost negligible impact on the system reliability, even if it has higher B_{10} lifetime as shown in Fig. 12. Therefore, it can be redesigned with a lower reliability, but at a lower cost. Thus, the proposed system-level design approach is a suitable tool for optimal and economical design of converters.

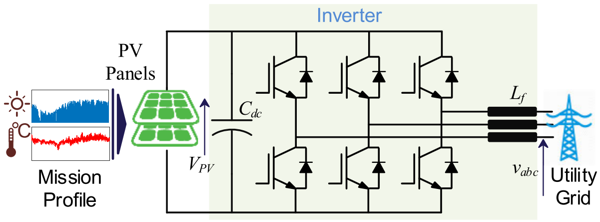

FIGURE 16. Structure of a 100-kW central PV inverter for Case B.

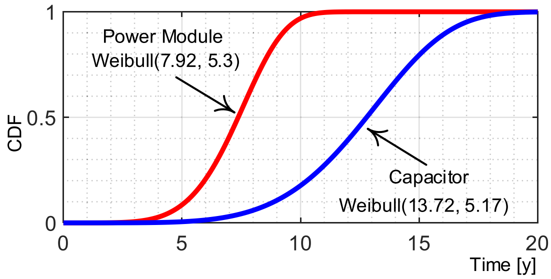

FIGURE 17. Wear-out Cumulative Distribution Function (CDF) of power modules and capacitor bank for Case B.

TABLE 4. Specifications of the 100-kW central PV Inverter used for Case B.

Parameter	Value	Parameter	Value
Inverter Rated Power	100 *kW*	**Panel Rated Power**	280 *W*
Switching Frequency	5 *kHz*	**Open Circuit Voltage**	47.2 *V*
DC Bus Voltage	400-950 *V*	**Short Circuit Current**	8.21 *A*
AC Voltage	480 *V*	**MPPT Voltage**	38.5 *V*
AC Frequency	50 *Hz*	**MPPT Current**	7.53 *A*
Inverter filter	4.5 *mH*	**Voltage temp. Coeff.**	-0.1230 *V/K*
Power module	*FF225R12ME4_B11*	**Current temp. Coeff.**	0.0032 *A/K*
DC Bus Capacitor (EPCOS)	*2×(6×390) μF, 500 V, 5.23 A*	**Number of Series panels**	22
MPPT Algorithm	*Perturb & Observation*	**Number of Parallel panels**	16

B. CASE B: MAINTENANCE SCHEDULING IN A PV INVERTER

In this section, the preventive maintenance planning for a 100-kW PV inverter is explored. The structure of the PV inverter is shown in Fig. 16. The PV system parameters are summarized in TABLE 4. Furthermore, the solar irradiance (*Irr*) and ambient temperature profiles employed for reliability prediction are shown in Fig. 9.

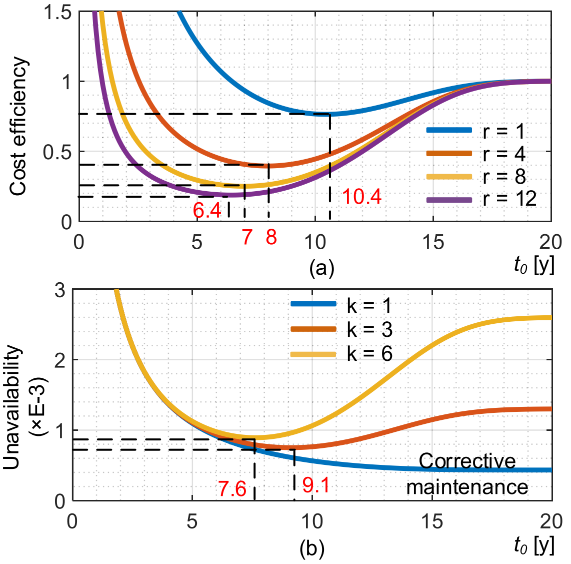

FIGURE 18. Cost efficiency (a) and unavailability (b) of the capacitor bank in terms of planned replacement time t_0.

The wear-out probability of converter is predicted and the CDF for the power module and capacitor bank are shown in Fig. 17. They are represented by the Weibull distribution function. It is clear that under a given mission profile, the power module is exposed to wear-out faster than the capacitor bank.

In order to obtain an optimal replacement time for the power module and the capacitor bank, the cost efficiency and unavailability functions are plotted in terms of replacement time of t_0. Fig. 18(a) shows the cost efficiency of capacitor bank replacement for different $r = \kappa/\varepsilon$ values. It is obvious that the optimal replacement time depends on the r value, where by increasing the r value, the optimal replacement time will be decreased. For instance, if $r = 4$, the optimal preventive replacement time for capacitor bank under the given mission profile is every 8 years. Furthermore, the optimal replacement time based on the unavailability of the capacitor bank is shown in Fig. 18(b) for different values of $k = T_U/T_P$. Following Fig. 18(b), for $k = 1$, which denotes the same downtime of planned and unplanned failures, the optimal replacement policy is corrective maintenance. However, for the downtime of unplanned failures higher than the downtime of planned failure, preventive replacement is required to minimize the system unavailability. For instance, if $k = 3$, the optimal preventive maintenance time is every 9.1 years.

The cost efficiency and unavailability of the power module are shown in Fig. 19(a) and (b). Like the capacitor bank, the optimal replacement time depends on the maintenance policy and r or k ratios. For instance, the optimal replacement time according to the cost efficiency measure is every 4.6 years for $r = 4$ as shown in Fig. 19(a). Furthermore, following the unavailability-based replacement policy, the suitable replacement time is every 5.2 years for $k = 3$ as shown in Fig. 19(b).

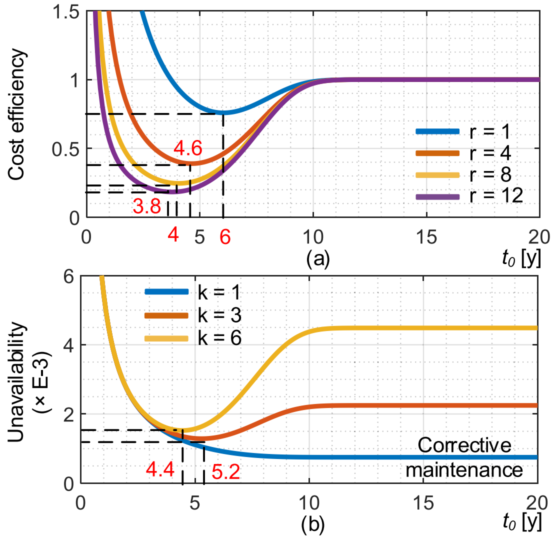

FIGURE 19. Cost efficiency (a) and unavailability (b) of the power module in terms of planned replacement time t_0.

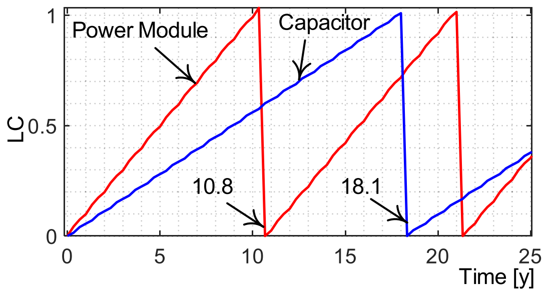

FIGURE 20. Predictive maintenance based on LC: lifetime consumption.

The obtained results in Fig. 18 and Fig. 19 show that the preventive replacement time depends on the replacement policy such as cost efficiency measure and unavailability. Moreover, the ratio of planned and unplanned replacement costs as well as the ratio of planned and unplanned downtime will affect the preventive maintenance scheduling. Moreover, the replacement time of devices depends on the failure probability function under a given mission profile. For instance, the cost efficiency-based replacement time considering $r = 1$, for capacitor bank is 10.4 years following Fig. 18(a) and for power module is 6 years according to Fig. 19(a). As a result, proper maintenance scheduling in power converters requires a model-based analysis in order to predict the failure probability of devices, and consequently, schedule for the optimal preventive replacement.

Moreover, the impact of condition-based (predictive) maintenance on converter performance is further illustrated in Fig. 20. The power module and capacitor variables are measured during long-term simulation. Then, the LC of both components is calculated every four months, and the accumulated LC is shown in Fig. 20. Notably, the degradation of components is not considered in the simulations. However, in a real case operation, it is inherently taken into consideration for LC calculation.

According to Fig. 20, the power modules should be replaced before 10.8 years of operation and the capacitor bank should be replaced before 18.1 years. These results are deterministic and valid for the specific power module and capacitor bank given in TABLE 4. This is because the thermal characteristics of the components are not identical for other modules due to the manufacturing uncertainties. In this approach the components can be replaced whenever they have approached to the end of their life, and hence more utilization will be achieved. However, it requires real time monitoring, which introduces extra maintenance costs.

VI. CONCLUSION

Power electronic converters are becoming an underpinning technology for modernizing electric power systems while they might be a source of failure and shutdown in such applications. Therefore, reliability enhancement in Power Electronic-based Power Systems (PEPSs) is of paramount importance. This paper has explored system-level reliability improvement in PEPSs by model-based design and maintenance within planning of these systems. Thus, a model-based design approach and model-based maintenance strategies have been proposed.

According to the proposed approach, converter design and its components sizing will be based on their impact on power system performance. This will help converter manufacturers to design their converters based on reliability worth measures at higher level, hence more cost-effective products can be expected. Meanwhile, the impact of operational conditions on the weakest links of converters will be identified and high reliable system can thus be implemented. Moreover, the proposed model-based maintenance strategies will yield appropriate maintenance time prediction based on failure characteristics of converter components. It can be useful during planning to optimally replace the converters in order to minimize the impact of unplanned outages on the overall system performance.

Due to the grid modernization and economization, model-based design and operation of future power systems are growing. This is because of the fact that model-based approaches guarantee having more reliable and resilient energy delivery in presence of uncertain and intermittent energy resources. Hence, more efforts should be done by incorporating model of affective components to enhance the performance of future electric networks.

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