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Peyghami, Saeed; Blaabjerg, Frede; Fotuhi-Firuzabad, Mahmud

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Model-based Reliability-Centered Design of Power Electronics Dominated Microgrids

Saeed Peyghami
Frede Blaabjerg
Department of Energy (AAU Energy)
Aalborg University
Aalborg, Denmark

Mahmoud Fotuhi-Firuzabad
Electrical Engineering Department
Sharif University of Technology
Tehran, Iran

***Abstract*- This paper proposes a model-based design approach for microgrids considering the aging of power electronic devices under different operating conditions. The proposed approach takes into account the physics of failure mechanisms in converter components as the failure prone devices in power systems. Furthermore, it considers the impacts of load profile on the aging of converter components and system performance. This approach facilitates accurate and optimized design of power electronic-based microgrids. According to this approach fragile links of power converters for a specified application can be identified. Moreover, the weakest converters based on their function in the microgrid can be recognized. As a result, economic decision making within design and planning of microgrids can be achieved.**

***Index*- aging, availability, design for reliability, microgrid, power converter.**

I. Introduction

Microgrids are building blocks of future energy systems. They reinforce power systems reliability and resilience against planned and unplanned events and uncertainties. Notably, power electronics play a key role in implementation and operation of microgrids. However, they are a frequent source of failure and downtime in many applications [1]–[5]. In order to guarantee the reliable and optimal operation of such systems, reliability-based design approaches need to be employed during planning of such systems.

Reliability of power electronics depends on various factors and conditions. Converter topology, switching scheme, cooling system, control strategy, operating and climate conditions all have a remarkable impact on converter reliability [6]. Imperfect design and consideration of these factors may cause aging of converter components. For instance, the impact of a switching scheme is explored in [7] where a suitable switching scheme can extend the life expectancy of a converter by up to 30%. Moreover, a suitable selection of converter topology for a specific application can introduce better life expectancy. As an example, the impact of converter topology on the end of life of photovoltaic (PV) converters is explored in [8].

In order to take the aforementioned factors into account, a design for reliability approach has been introduced for power electronic converters. This approach will guarantee desired function of a converter within a specified time period under a given mission profile [9]–[11]. This approach relies on the physics of failures in converter components. According to this approach, wear-out process of components, usually the most fragile ones, i.e., power modules and capacitors, are modeled using the applied mission profile. This approach is employed for different applications with single converters including PV and wind converters, and motor drives.

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The system level analyses, e.g., for microgrid applications or even larger power systems, are limited to approaches for analyzing the reliability of power electronic-based power systems. The physics of failure based reliability analysis in DC power systems is presented in [6]. This paper shows the impact of mission profile, converter topology, converter function, and energy management on the wear-out failure of converter components in a DC microgrid. Moreover, system level operation for reliability methods has been presented in [12], [13] in order to prevent the early aging of converter components.

So far, the dedicated research in power electronics systems has focused on reliable operation by proper control and maintenance approaches. However, proper design and planning of such systems will have a remarkable impact on the reliability, consequently planning and operation costs. Therefore, system-level design for reliability considering physics of failures is of high importance. This is due to the fact that design of a system, e.g., microgrid considering the physics of failures of its components can help identifying the weakest links at device, converter and system level. As a result, an accurate reliability model can be achieved, which in turn facilitates optimal design in a hierarchy from device up to system level. General concept of model-based design for reliability is introduced by the authors in [14] for modern power electronics-based power systems.

This paper further expands the concept of model-based design for microgrid applications considering impact of operating conditions. One of the main parameters affecting the reliability of power converters and consequently the reliability of the whole system is the load profile. This is due to the fact that a load profile will affect the thermal stress of the converter devices. Therefore, depending on the microgrid application, its loading will play an important role on the converter and system performance, and consequently on the planning costs. To address this concept, the proposed model-based reliability-oriented design approach for power electronics based microgrids is presented in Section II. Furthermore, Section III illustrates the numerical analysis. Finally, Section V summarizes the paper.

II. Proposed Model-Based Reliability Centered Design Approach

In this section, the concept of design for reliability at system level will be explained.

A. *Proposed Model-based Design Approach*

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

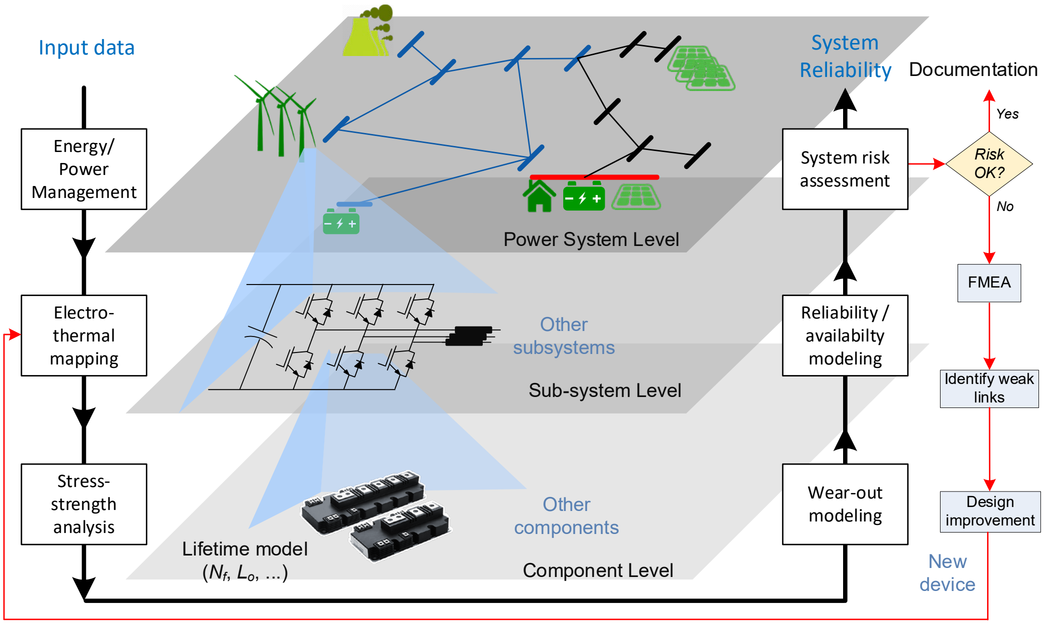

Fig. 1. Proposed reliability-centered design of power electronics dominated microgrids.

power converters with a desired long-term performance [15]. 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.

Since, the converters are operating in a system such as microgrids, motor drive systems, charging stations, the overall system performance must be guaranteed by proper design of converters. This requires an analysis of the impact of converters on the system performance. Then, the converter characteristics are designed with respect to the desired system level performance index. For this purpose, a reliability-centered V-shaped model-based approach is proposed as shown in Fig. 1.

In this approach, the system like a microgrid is analyzed from system-level to device-level and then the performance is evaluated from device-level up to system level. To do so, first, the energy and power flow analysis is performed in the system level to obtain the loading of each unit. Then, in the sub-system level, the converter loading is translated to the lifetime variables such as temperature. Next, in the device level, the thermal variables are translated into the reliability index using stress-strength analysis. In this stage, the physics of failure mechanisms are taken into account for each device. Considering potential failure mechanisms, the wear-out failure probability for that device will be obtained. Using the failure rate of components, the total reliability of converter can be predicted. Then, the converter availability will be calculated using the its failure rate and the required time for maintenance. Afterwards, the overall system reliability will be analyzed. The system reliability can be evaluated using risk indices like loss of load expectation (LOLE).

After evaluating the system reliability, if the system risk is acceptable, then our selected devices and designed converter are desirable. Otherwise, the weakest links, e.g., converters need to be identified either by using failure modes and effect analysis (FMEA) or sensitivity analysis. Next, the weakest devices in the weakest converters will be determined. Finally, the devices will be redesigned to ensure the acceptable performance in the system level. This procedure is shown in Fig. 1. Since, this paper focuses on the power converters, in the next subsection the reliability model of converters is presented.

B. *Reliability of Power Electronics Converters*

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 [16]. They are prone to random chance failures and aging failures. 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.

Moreover, the fragile components of the converter, i.e., capacitors and power switches are prone to aging failures. This fact will limit the life expectancy of the converter. Notably, their wear-out characteristics depends on operating conditions.

In order to predict the wear-out failure probability of these components, the concept of structural reliability has been adopted [17]. 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 presented in (1):

$$LC_D = \sum \frac{\sigma_{i,D}}{\rho_{i,D}}. \qquad (1)$$

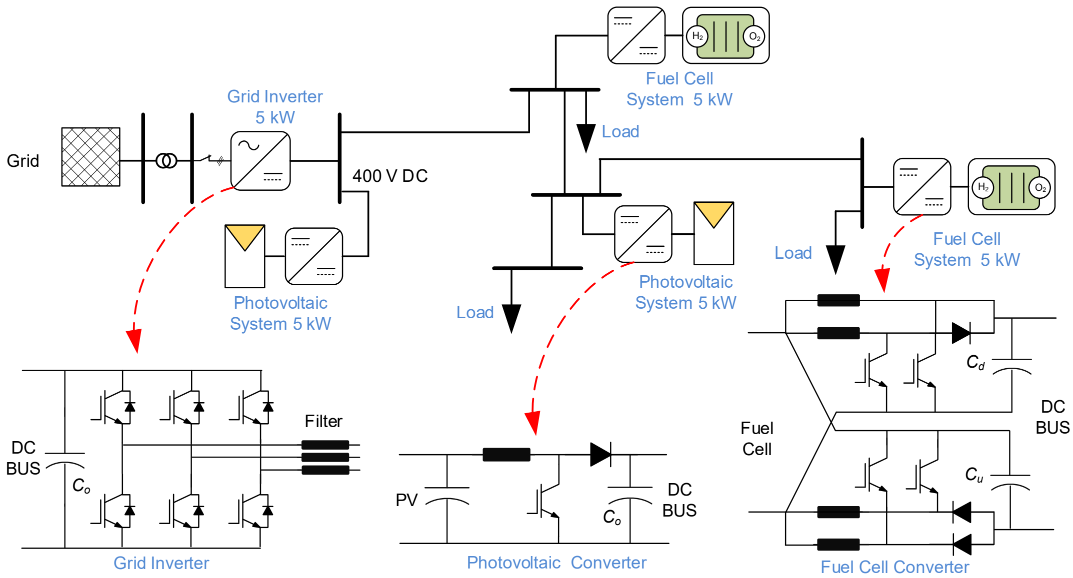

Fig. 2. Single line diagram of a DC microgrid with Fuel Cell, photovoltaic system and interlink converter connected to the main grid.

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. The term resistance, ρ in (1) is equal to the capacitor lifetime, L_o obtained by (2) [18].

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

Where, 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 [18]. 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.

Furthermore, the term $\rho_{i,D}$ for semiconductor devices is equal to the number of cycles to failures, N_f which can be obtained by (3) [19].

$$N_f = A \cdot \Delta T_j^{\alpha} \cdot exp\left(\frac{\beta}{T_{jm} + 273} \right) \cdot \left(\frac{t_{on}}{1.5} \right)^{-0.3} \quad (3)$$

where, 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 [19]. 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 (2) and (3). Therefore, the obtained LC in (1) 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 [17].

According to (2) and (3), the lifetime and hence the reliability of capacitors and power devices depends on the operating conditions. Therefore, applied operating conditions will impact the overall system performance. Therefore, this needs to be taken into account during design and planning of power electronics systems. This fact will be illustrated with numerical analysis in the next section.

III. Numerical Analysis

This section presents numerical analysis to illustrate the effectiveness of the proposed design for reliability approach in power electronics systems. A DC microgrid shown in Fig. 2 is considered two Fuel Cell (FC) stacks and two PV units which is connected to the main grid though an interlinking inverter. The PV system parameters is given TABLE I. the FC voltage-current characteristics is given in Fig. 3. Furthermore, the simulated converter structures are shown in Fig. 2 with the parameters and specifications that are summarized in TABLE II. The mission profile for solar irradiance and ambient temperature is shown in Fig. 4. Also, two load profiles for a small clinic (load 1) and an apartment (load 2) are shown in Fig. 5.

It is assumed that the PV is operated in MPPT mode, the FC will support the load if PV power is not sufficient, and finally the grid will support the load if the power of FC and PV are not adequate. On the other hand, the excess power of PV will be injected into the grid. Considering this operating principal, the converters reliability and the system risk is analyzed in the following for both given loads in the DC microgrid in Fig. 2.

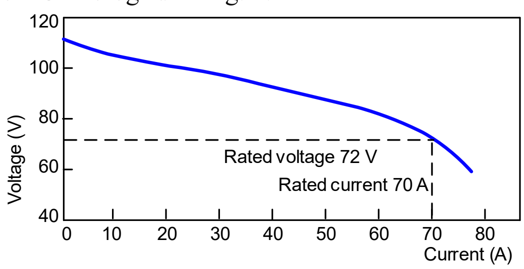

Fig. 3. Voltage-current characteristics of the Fuel Cell stack.

TABLE I. 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/current	54.7 *V* / 6.26 *A*
Voltage temp. Coeff.	-0.27 *%/K*
Current temp. Coeff.	0.05 *%/K*

TABLE II. Power converter parameters.

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*

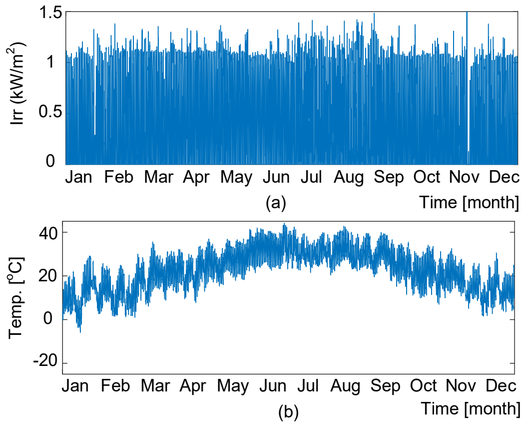

Fig. 4. PV system profiles: (a) irradiance (Irr), (b) ambient temperature.

The reliability of PV converter and its components is shown in Fig. 6. It is obvious that the capacitor has the dominant impact on the PV converter reliability. Moreover, the B_{10} lifetime of PV converter is 11.1 years according to Fig. 6. The reliability of FC converter under load 1 and 2 is shown in Fig. 7 and Fig. 8 respectively.

For the FC converter, the capacitor is the most failure prone components as well. Furthermore, the B_{10} lifetime of FC under load 1 is higher than that of load 2. This is due to the fact that the PC converter in load 1 is less loaded compared to load 2. As it can be seen from Fig. 9, the load 1 is concurrent with the solar irradiance. Therefore, the majority of load 1 power will be supplied by PV. As a result, The FC loading is less in this case, and aging of its components are slow. Thus, its reliability is better.

Moreover, the reliability of grid inverter and its components under load 1 and load 2 is shown in Fig. 10 and Fig. 11. It can be seen from these figures that diodes are the failure prone components in the inverter. Furthermore, the inverter lifetime in load 2 is less than that of load 1. The reason for the inverter reliability is similar to the FC and it is due to higher loading of converter under load 2.

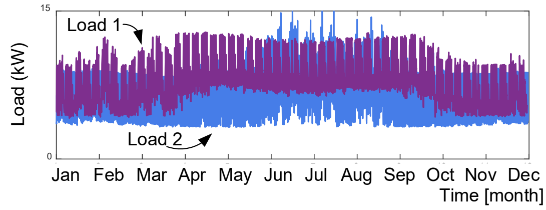

Fig. 5. Two different load profiles.

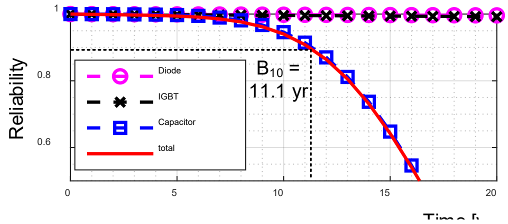

Fig. 6. PV converter and its components reliability.

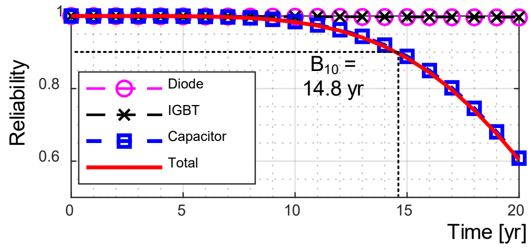

Fig. 7. FC converter and its components reliability under load 1.

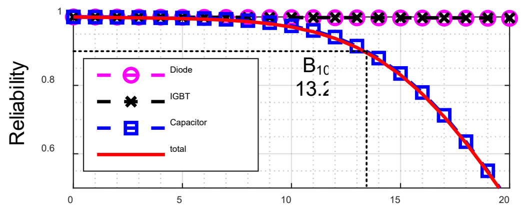

Fig. 8. FC converter and its components reliability under load 2.

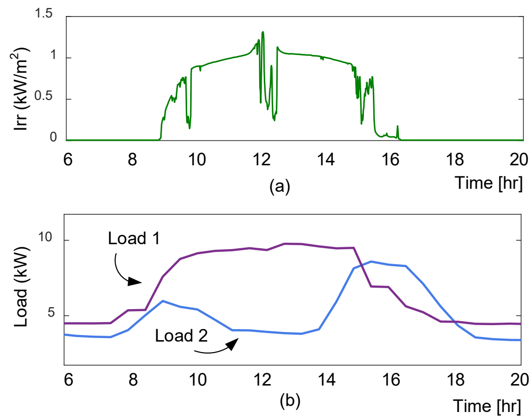

Fig. 9. Daily profile for (a) solar irradiance in Fig. 4(a) and load 1 and 2 in Fig. 5.

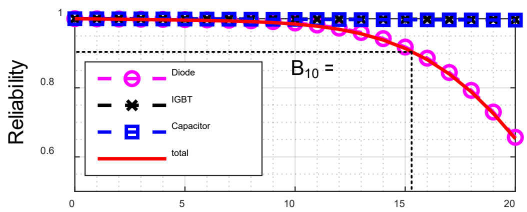

Fig. 10. Inverter and its components reliability under load 1.

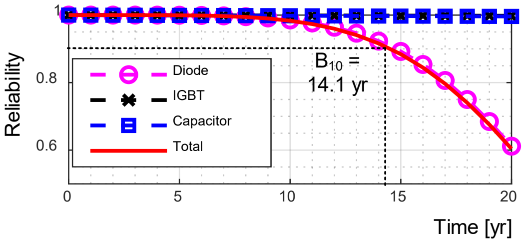

Fig. 11. Inverter and its components reliability under load 2.

In the next step, the system reliability is analyzed using LOLE measure. The reliability data for the system components are summarized in TABLE III. Notably, beside aging failure, the converters are facing random chance failures [17]. The unavailability of the units and the system LOLE under load 1 and load 2 are presented in Fig. 12 and Fig. 13 respectively. If the standard level (STD) for LOLE is considered to be 8 hrs/yr, the system becomes unreliable after 10 years under load 1 and 12 years under load 2. These results show that the load profile can not only affect the reliability of converters, but also affecting the overall reliability of the system. The same system with the rated powers and load, may have different reliability performance due to the different loading characteristics.

From design and planning perspective, the system reaches its limit after 10 /12 years for load 1 / load 2. If the system is intended to operate for longer time, there is two options to guarantee its reliability. first option is to reinforce the weakest links, and the second one is to plan for maintenance of weakest links. In both cases the most failure prone converter and its components must be identified. To do so, sensitivity analysis is performed here. The analysis is given for load 1 but it is the same for load 2. In the sensitivity analysis two marginal conditions are assumed. First, the converters are considered to face aging failures. Seconds, it is assumed that the converters are not facing aging failures. This analysis shows that the PV and grid converters has negligible impact on the system LOLE, while FC converters has dominant impact. The impact of FC is, thus, illustrated here in Fig. 14. It is clear that without aging of FC converter, the system life span under standard LOLE level is 15 years, that is 50% higher than the case that FC converter aging is considered.

If reinforcement is the option to extend the system life span, thus the FC converter needs to be improved from reliability perspective. According to Fig. 7 and Fig. 8, the DC link capacitor is the weakest link of FC converter. Therefore, to obtain desired performance at the system level, the capacitor bank of FC converter needs to be redesigned. Moreover, if the maintenance, i.e., replacement is the solution to expand the system life span, the FC converter and its capacitor bank needs to be replaced. Furthermore, the proposed model-based approach provides the replacement times for a weakest component in the system. This replacement time, depends on the loading profile where it is 10 years and 12 years for load 1 and load 2 according to Fig. 12 and Fig. 13.

TABLE III. Reliability data of generation units [20]–[22].

Unit	Prime Mover: failure rate [f/yr]	Prime Mover: Repair time [hr]	Converter: Constant failure rate [f/yr]	Converter: 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

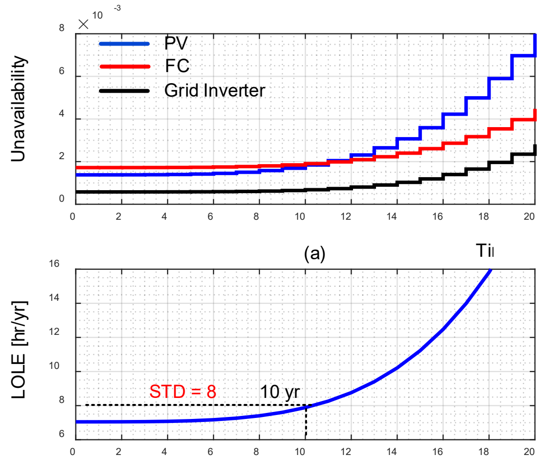

Fig. 12. Obtained system-level results for load 1: (a) individual generation unit unavailability and (b) LOLE – STD: standard level.

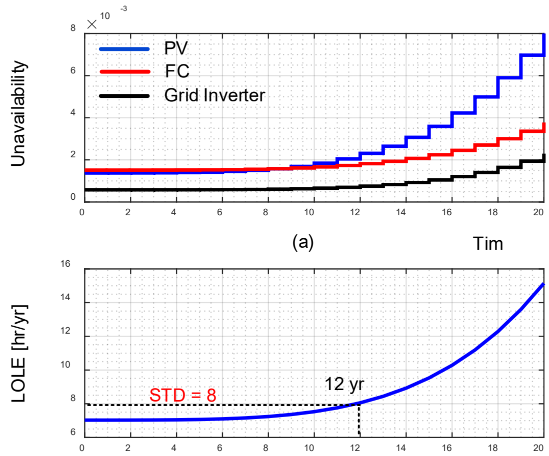

Fig. 13. Obtained system-level results for load 2: (a) individual generation unit unavailability and (b) LOLE – STD: standard level.

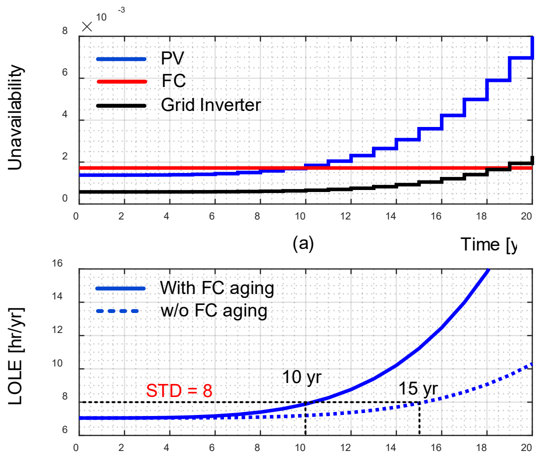

Fig. 14. Obtained system-level results for load 1 showing the impact of FC converters aging: (a) individual generation unit unavailability and (b) LOLE– STD: standard level.

IV. Conclusion

This paper proposed a model-based design approach for power electronics dominated microgrids in a hierarchical procedure from device up to system level. It takes into account the reliability model of converter devices to identify the weakest links under operating conditions that can facilitate optimal and cost-effective design of microgrids. Numerical analysis under two different loading conditions in a DC microgrid is provided. The analysis showed that the load profile can remarkably impact the device, converter and system level performance. For instance, the reliable life span of the studied DC microgrid supporting an apartment load was 10 years while for clinic load, it was 12 years. Furthermore, the proposed approach facilitates identifying the weakest components in the system and subsystems. This will facilitate optimal and cost-effective reinforcement and/or maintenance of the system components. For instance, numerical analysis showed that the fuel cell converter was the dominant component affecting the system reliability where its capacitor bank limits the converter reliability. Thus, according to the proposed model-based approach, reinforcement and/or maintenance planning actions could be applied to fuel cell converter and its capacitor bank.

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