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Mission Profile based Power Converter Reliability Analysis in a DC Power Electronic based Power System

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Abstract: **This paper investigates the reliability of power electronic converters employed for different applications in a dc power system employing a mission profile based reliability approach. The power electronic converter reliability depends on its loading profile, which induces thermal stresses on the failure-prone components, hence, limiting the converter lifetime. The loading profile of different converters in a power system is relevant to the mission profiles (including environmental and operational conditions), which can be controlled by a power management strategy. Moreover, the battery converter sizing in a renewable based power system may affect the power flow through the converters, and hence, its loading profiles. Therefore, this paper studies the impact of mission profile, power management strategy, and battery converter capacity on the reliability of different converters. The obtained results are presented through numerical analysis.**

Keywords— reliability, mission profile, PV converter, dc power system, energy management.

I. Introduction

Moving towards high efficient, reliable and environmental-friendly energy resources has intensified the role of power electronic converters in future Power Electronics based Power Systems (PEPSs). In power converters, semiconductor switches and passive components are exposed to failure due to the short, medium and long term loadings which can be induced by climatic condition, load profile, and control system [1]. Hence, Design for Reliability (DfR) approach for power converters [2]–[6] as well as thermal management approaches for power converter reliability enhancement [3], [4], [7]–[12] have become main challenges for manufacturers and power system operators.

Active thermal control schemes have been presented in single or paralleled power converters in order to improve the lifetime and reliability of switching devices [3], [4], [7]–[13]. The prior-art methods include loss reduction by modulation strategies [4], [13], reactive power control [7], adaptive switching frequency control [9], junction temperature balance control [11], and even thermal related damage control [12].

Moreover, DfR approach gives an opportunity in designing converters for specific mission profile to properly size converter components by taking into account the reliability specifications. In this approach, the converter elements are designed based on a lifetime target [5]. It provides a suitable approach for sizing and selecting components of an individual converter to fulfill a target lifetime under given mission profile. However, in a multiple converter system, it remains a challenge to take into account the mission profile among different converters and the power management strategy in order to optimize the system performance, including reliability.

This paper analyzes the reliability of power converters operating in a dc power system to show the impact of mission profile, mutual loading effect among converters and battery converter capacity. This analysis can be employed by PEPS operators to identify the fragile converters of a system, size the storage system, and manage the system-level risk. Moreover, converter manufacturers can employ the proposed methodology to design power converters with desirable reliability in a specific PEPS.

II. Power Management Strategy

Fig. 1 shows the overall structure of the studied PEPS in this paper, which consists of one Photo-Voltaic (PV) unit and one Fuel Cell (FC) unit connected to a dc bus through a boost converter with one battery storage unit connected through a bi-directional dc/dc converter. Table I summarizes the specifications of the system.

Two kinds of load profiles are considered including a school-load and an apartment-load. Annual load profiles and PV output power is shown in Fig. 2. The load profiles with PV output power for January 15th to 21st are shown in Fig. 2(b) implying that the peak of the

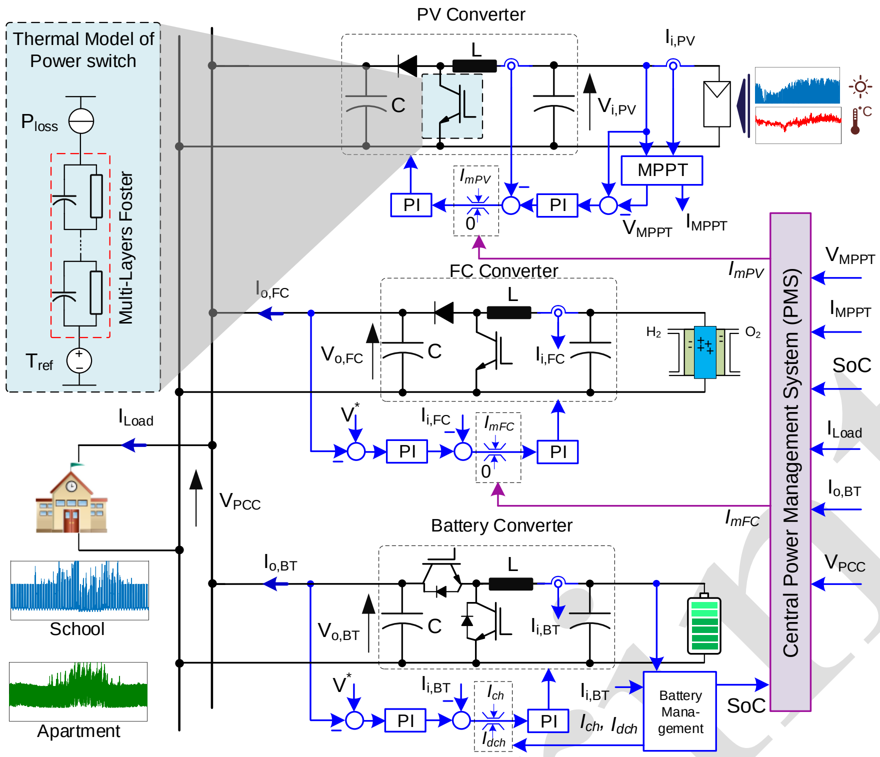

Fig. 1. Topology of the study dc power electronic based power system.

apartment-load occurs after sunset, while the peak of the school-load is during daylight. Mismatches between PV power and the peak load should be managed by the battery storage and the excessive demand needs to be supplied by another source like the FC. Notably, the mismatch between the peak power of the PV and load induces thermal stresses on the battery converter, while the mismatch among the PV, load and battery power induces thermal stresses on the FC converter. In the dc power system shown in Fig. 1, the sources of thermal stress on the converters include the variation of solar irradiance, ambient temperature, and load profile. Furthermore, the capacity of the battery converter as well as the power management system can intensify the induced stresses on the components.

In this paper, following the power management system, the PV converter operates in Maximum Power Point Tracking (MPPT) mode, and the mismatch power between PV and the load will charge/discharge the battery. Furthermore, the excessive load demand are supplied by the FC. Moreover, in order to extend the battery lifetime, 50% maximum depth of discharge is assumed. Six cases are studied, where in Case I & II the capacity of the battery converter is 5 kW and 2.5 kW for Case III & IV, and no battery storage unit for Case V & VI. Moreover, as already mentioned, two kinds of loads are considered as the school-load for Case I, III & V, and the apartment load for Case II, IV & VI. The annual energy generation and consumption in different cases with the employed power management strategy are given in Table II. According to Fig. 2, daily energy demands for both loads are almost equal. However, as

Table I. Specifications of power converters.

Parameter		Values
DC inductor		1 mH
DC output capacitor		500 µF
Switch	IGB10N60T	600V, 10A
	IKB06N60T	600V, 6A
Diode	IDV20E65D1	650V, 20A
	IDH10G65C5	650V, 10A
Switching Frequency		30 kHz
DC Link Voltage		400 V
FC converter rating		5 kW
Battery Converter Rating		2.5- 5kW
PV Converter Rating		5 kW
PV Array	Rated Power	260 W
	Open Circuit Voltage	64.4 V
	Short Circuit Current	5.58 A
	Voltage -Temp. coef.	-0.32%
	Current -Temp. coef.	0.04%
	No. of Series Panel	5
	No. of Parallel Panel	4
Battery Capacity		1000 Ah

the school is closed in the weekend, the annual energy consumptions are different.

In the Cases I & II, the maximum feasible PV energy is extracted since the battery converter capacity is as equal as the rated PV power. The influence of the battery converter capacity on the annual loss of PV energy is reported in Table II. As it can be seen, the loss of PV energy for school-load is higher than the apartment-load. This is because of the load profile behavior as shown in Fig. 2. For instance, the loading profile of the converters on the 320^{th} day of the year is shown in Fig. 3 illustrating the loss of PV energy by decreasing the battery converter capacity in Cases III to VI.

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Table II. Annual converted Energy by the power converters in different Cases.

Case	Load Type	Battery Converter Capacity (kW)	Load Energy (MWh/yr)	FC Energy (MWh/yr)	PV Energy (MWh/yr)	Loss of PV Energy (%/yr)
I	School	5	24.3323	18.1072	6.0251	0
II	Apartment	5	29.4007	23.1844	6.0163	0
III	School	2.5	24.3323	18.3779	5.7545	4.5
IV	Apartment	2.5	29.4007	23.229	5.9717	0.75
V	School	0	24.3323	20.0891	4.2433	30
VI	Apartment	0	29.4007	24.3368	5.0639	16

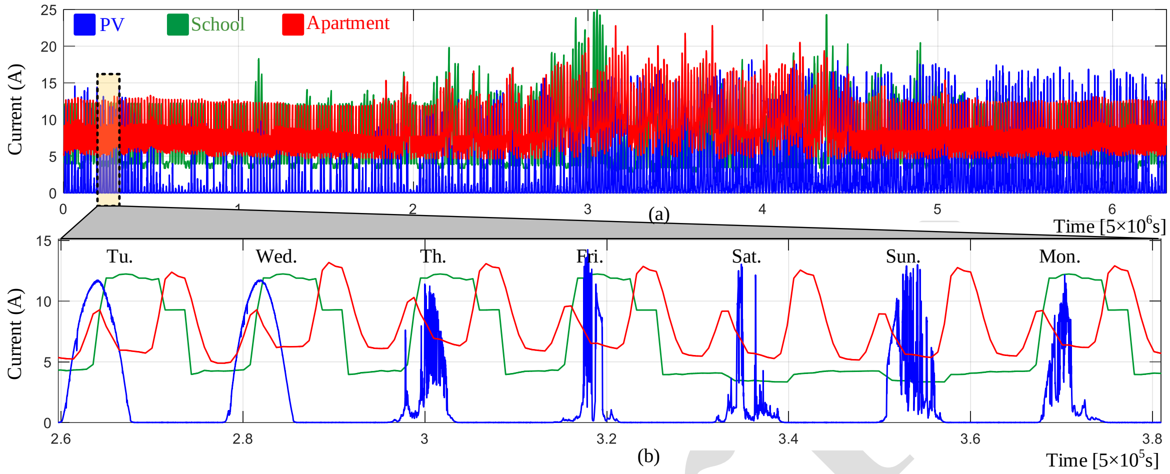

Fig. 2. Solar irradiance, annual school and apartment load profiles: (a) Annual profiles, and (b) profiles for January 15th to 21st.

III. Converter Reliability Prediction

In this section, the induced thermal stresses on the power switches of each converter under different scenarios are investigated. Two major failure mechanisms on the power switches are solder fatigue and bond wire wear out. Number of cycles to failure (N_{fs}) due to the baseplate solder fatigue is related to the case temperature variation ΔT_c which is:

$$N_{fs} = K \cdot \Delta T_c^{\gamma} \tag{1}$$

where K and γ being the curve fitting parameters. Furthermore, number of cycles to failure (N_{fb}) due to the bond wire wear out depends on the minimum junction temperature T_{jm}, junction temperature swing ΔT_j, and heating time t_{on}. N_{fb} as:

$$N_{fb} = A \cdot \Delta T_j^{\alpha} \cdot exp\left(\frac{\beta}{T_{jm}}\right) \cdot \left(\frac{t_{on}}{1.5}\right)^{-0.3} \qquad 0.1s \le t_{on} \le 60s \tag{2}$$

where A, α and β are the curve fitting coefficients [14].

In this paper, Insulated Gate Bipolar Transistor (IGBT) and Silicon diode are selected as the power semiconductor components (see Table I). Furthermore, the converters are assumed to put in a cabinet and the PEPS is an indoor system. Hence, the temperature variation on heatsink, and thereby, on the case, ΔT_c has small values. Thereby, the bond wire fatigue is the dominant failure mechanism of the switches. In order to calculate the stress on the bond wires, the loading profile should be translated to junction temperature by employing an electro-thermal model [15]. Then, a rain-flow counting algorithm calculates the number of cycles, minimum junction temperature, and junction temperature variation. The annual Accumulate Damage (AD) on the IGBT and diode of the converters then can be calculated as:

$$AD = \sum_{h=1}^{H} \frac{n_{cycle,h}}{N_{fb,h}} \tag{3}$$

where, $n_{cycle,h}$ is the number of power cycles obtained from rain-flow counting, $N_{fb,h}$ is the number of cycles to failure for the h^{th} power cycle, which is obtained by (2) . Also, H is the total number of power cycles due to the converter loading profile. The annual accumulated damage for the switch and diode of converters in different loading scenarios (i.e., Case I – VI as shown in Table II) is shown in Fig. 4. As it can be seen, under all considered loading scenarios, the IGBT has higher level of damage for the PV converter, while it is the diode for the FC converter. For the battery converter the stresses of both IGBTs are almost equal. Furthermore, the converters with the same rated power pose to unequal damages under different applications. As it is shown in Case I and Case II in Fig. 4, even though the rated power of all converters are 5 kW, the damage on the PV converter is significantly higher than that of the FC and battery converters. Meanwhile, as given in Table II, the converted energy by the FC converter is 3~4 times higher than the PV converter.

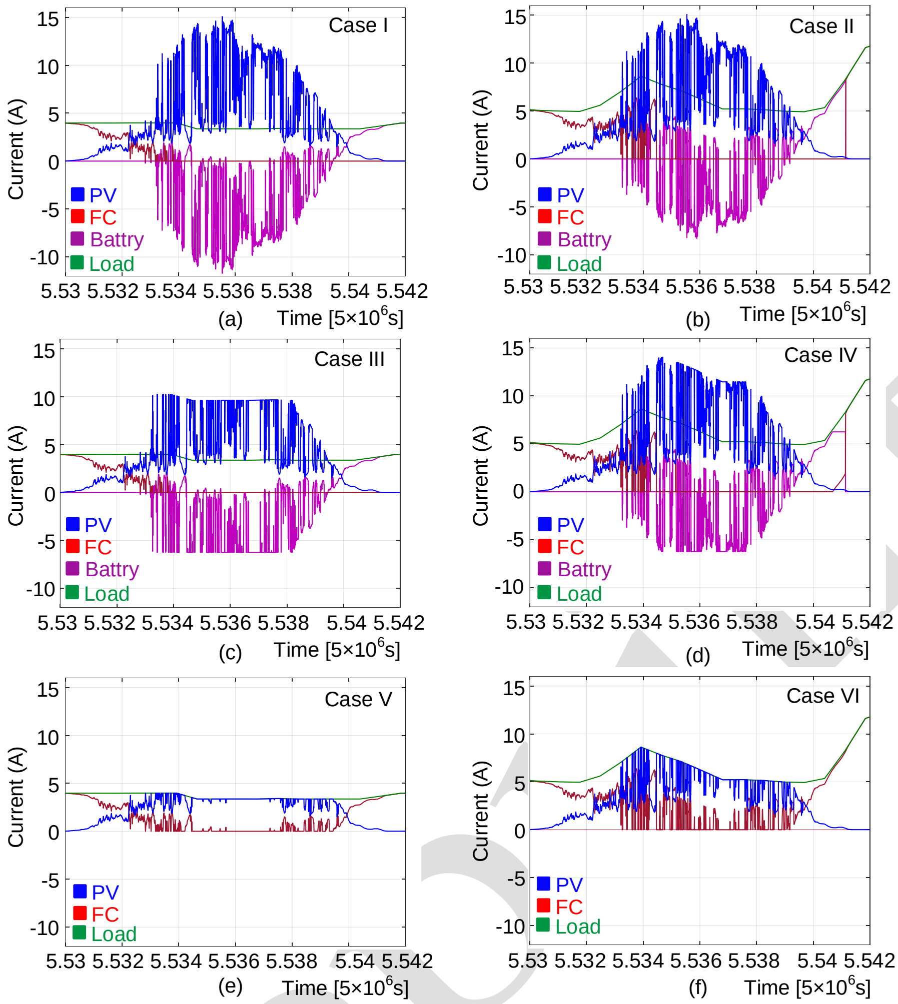

Fig. 3. Loading profile of converters and load in different cases (see Table II) in 320th day of year; (a) Case I: School-load with 5 kW battery converter; (b) Case II: Apartment-load with 5 kW battery converter, (c) Case III: School-load with 2.5 kW battery converter, (d) Case IV: Apartment-load with 2.5 kW battery converter, (e) Case V: School-load without battery, and (f) Case VI: Apartment-load without battery.

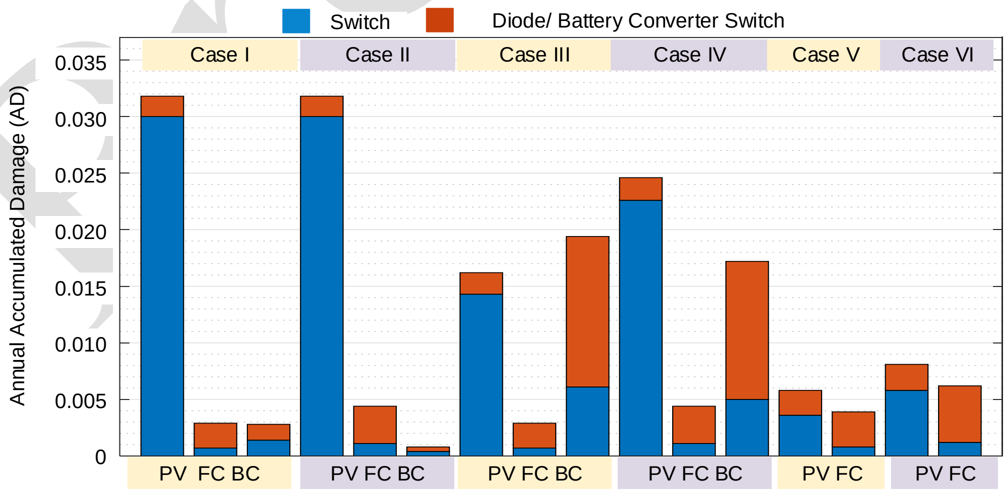

Fig. 4. Annual accumulated damage on the semiconductor components (IGBT switch and Diode) of the converters due to the bond wire fatigue in different cases (see Table II) –BC: Battery Converter.

The accumulated damage calculated following (2) and (3) can be used to predict the lifetime and reliability function of the devices [15]. However, the prediction is based on an ideal case (under predefined mission profile and constant parameters in lifetime model given in (2)). The lifetime parameters and stresses have a stochastic behavior and the uncertainty on these parameters should be considered. In this study, a population of 10,000 power switching devices (IGBT and diode) are considered. Monte-Carlo simulation is employed to obtain the reliability function of each components in converters for different cases. Since failure of any component causes the system failure, the converter-level reliability can be found by series reliability block diagram model, i.e., by multiplying the reliability of diode and IGBT [15].

IV. Results and Discussions

Fig. 5 depicts the estimated unreliability of PV, battery, and FC converters for all studied cases. Comparing Cases I, II, III & IV implies that the unreliability of PV converter is significantly higher than the FC converter, while both has the same capacity and the converted energy by FC converter is 3~4 times higher than PV converter. Therefore, PEPS operators should take into consideration the reliability of converters when similar commercial converters are employed for different applications. Due to the fact that it may affect the system operation and maintenance cost.

From Fig. 5, comparing Case I with Case III for school-load (or Case II with Case IV for apartment-load) shows that decreasing the battery converter capacity will improve the reliability of the PV converter while reducing the reliability of the battery converter. According to the power management system, decreasing the battery converter capacity reduces the energy production from the PV converter. Therefore, there is a compromise between increasing the reliability and loss of PV energy. As given in Table II, loss of PV energy is 4.5% and 0.75% of annual PV produced energy for school and apartment-load, respectively. Hence, the battery converter capacity can be optimized following the converter reliability and yield loss of PV energy.

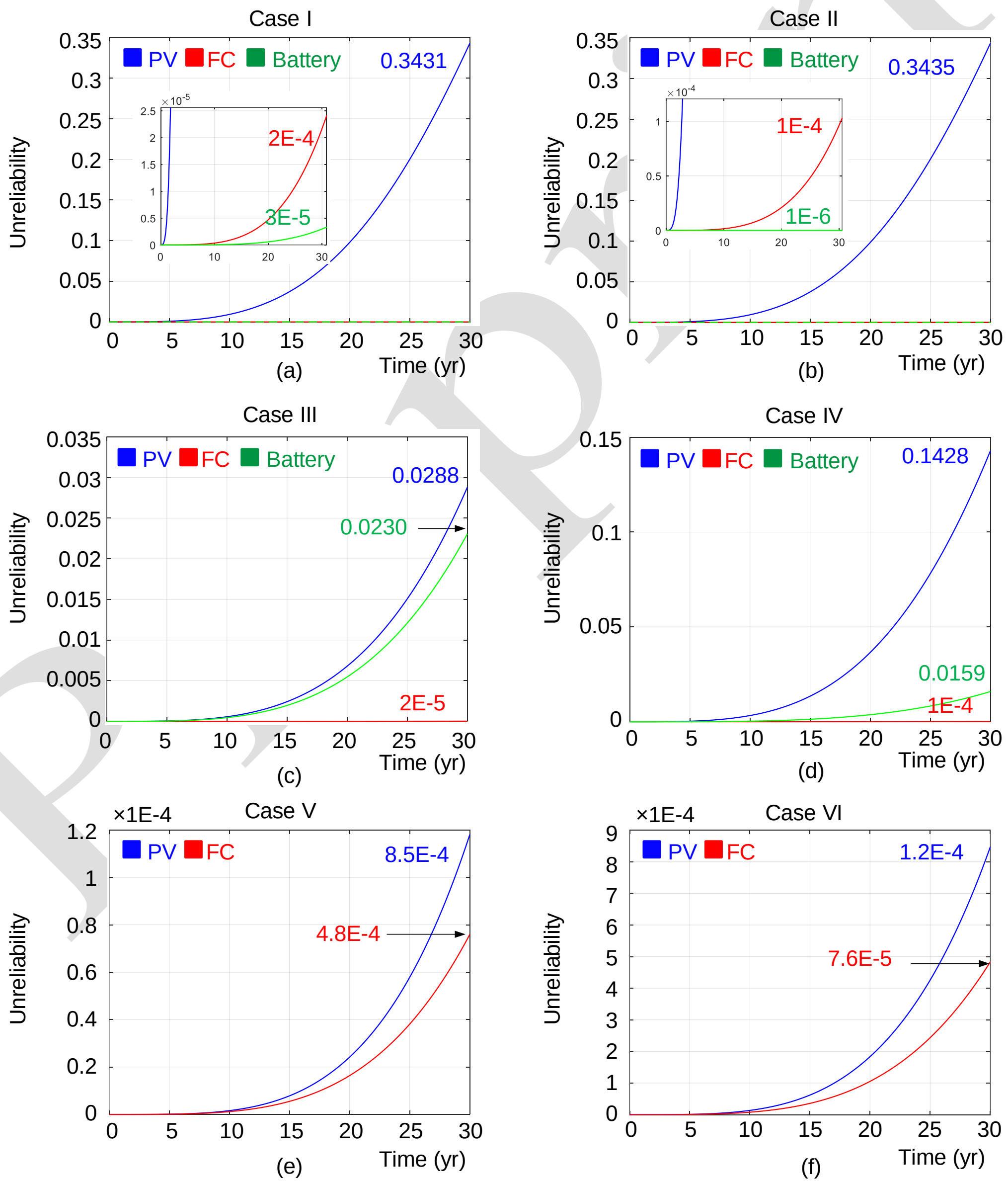

Fig. 5. Unreliability function of converters during their useful lifetime due to the bond wire failure of switches in different cases (see Table II); (a) Case I: School load with 5 kW battery converter, (b) Case II: Apartment load with 5 kW battery converter, (c) Case III: School load with 2.5 kW battery converter, (d) Case IV: Apartment load with 2.5 kW battery converter, (e) Case V: School load without battery, (f) Case VI: Apartment load without battery.

Considering Case I & II as shown in Fig. 5(a) and (b), the unreliability of PV converter is almost the same despite of load type. This is due to the fact that the battery converter capacity is equal to the rated power of the PV plant, hence it makes the power management system to extract the maximum feasible PV power. Therefore, the loading profile of the PV converter is almost the same for both cases, leading to a same unreliability level.

However, Cases III & IV clearly illustrate the impact of the load type on the unreliability of converters. As it is shown in Fig. 5(c) and (d), it can be seen that unreliability of the PV converter is 0.0288 and 0.1428 for school-load and apartment-load, respectively. Since the battery converter capacity is 2.5 kW, the power management controller cannot extract the PV power in some time intervals, e.g., Fig. 3(c & d). Therefore, the load type (peak power and its time and duration) can affect the PV output power, consequently affecting the thermal damage and reliability of the PV converter.

In Cases V & VI, the FC supports the load. In most real-world applications, operating an off-grid PV plant without a storage is not economical since the loss of PV energy is high as mentioned in Table II. However, this case is considered here to show the effect of loading profile on the converter reliability. As shown in Fig. 3(e) and (f), the PV power fluctuations induce power fluctuations on the FC converter. Hence, the unreliability of FC converter is higher than the other cases as shown in Fig. 5 (e), (f) compared to the Fig. 5(a)-(d). Notably, the main factor affecting the reliability of a power converter is the power fluctuations rather than the total converted energy.

As a result, the loading profile of one converter can be affected by the loading of the other converters, which is controlled by a power management system. Furthermore, the capacity of other converters, e.g., battery converter can affect the reliability of other converters. Moreover, the converter application type has more influence on the reliability considering the unreliability results obtained for PV and FC in this study.

V. Conclusion

This paper presents a system-level Design for Reliability (DfR) of different converters operating in a dc Power Electronic Based Power Systems (PEPS). The analysis showed that a converter reliability can be affected by the renewable source mission profile as well as loading profile of other converters in a PEPS. Furthermore, it is revealed that depending on the application and mission profile different active components may play the major role on the converter lifetime.

The obtained results based on empirical lifetime model of active switches showed the dependency of the converter reliability on the mission profiles, power management strategy, converter sizing, and converter application. In the studied dc PEPS, the stresses and damages of the Photo-Voltaic (PV) converter are much higher than those of the Fuel Cell (FC) and battery converters due to the solar irradiance and ambient temperature fluctuations, even though all of the converters have the same capacity. Moreover, suitable battery converter sizing can remarkably improve the reliability of the PV converter. The load profile can also affect the different converter reliability due to the mismatch between the PEPS peak load and PV system peak power, which can change the other converters loading controlled by the power management system.

The proposed methodology can provide a solution for power converter manufacturers to implement a model-based design approach considering the operating conditions. PEPS operators can also employ the methodology for planning and risk management by identifying the most fragile converters in the system.

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