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Reliability Assessment of PV Inverters with Battery Systems Considering PV Self-Consumption and Battery Sizing

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***Abstract*—To ensure the cost-competitiveness of Photovoltaic (PV) with integrated Battery Energy Storage Systems (PV-BESS), a highly reliable operation is demanded. The PV inverter has been reported as one of the reliability-critical components in the system, whose failures can lead to a severe negative impact on the cost of PV energy. Therefore, improving PV inverter reliability has high potential for the cost reduction of the PV-BESS. This paper thus investigates the impact of battery operation on the PV inverter reliability. A 6-kW residential PV-BESS in Germany is considered, where a self-consumption scheme is adopted. The evaluation results reveal that the reliability of the PV inverter is strongly affected by the battery operation. More specifically, the PV inverter loading is decreased significantly during the battery charging, which results in an improvement in the PV inverter reliability. In addition, the battery system parameters, such as battery capacity and battery converter power rating, also affect the PV inverter loading, whose impact on the PV inverter reliability has been analyzed.**

***Index Terms*—PV inverters, battery, lifetime, reliability, mission profile, self-consumption.**

I. Introduction

In recent years, the installation of Photovoltaic (PV) systems has been increasing continuously due to the declining cost of solar energy [1]. Since most of the PV systems are connected to the grid, a widespread of PV installation can bring several challenges to the electrical network due to the intermittent nature of solar energy [2], [3]. Accordingly, energy storage technology such as battery systems become a promising solution to improve the grid-integration of PV systems [4], [5]. There are several applications for PV systems with integrated battery energy storage systems (PV-BESS). For utility-scale PV systems, the battery systems can be employed to provide grid support (e.g., frequency regulation, power reserve) [6]–[8] and/or enable flexible active power control to fulfill grid requirements (e.g., limiting PV power ramp-rate, limiting maximum feed-in power) instead of using power curtailment [9]–[11]. For residential PV systems, the battery system was mainly used for back-up power application (e.g., uninterruptible power supply) and standalone systems (e.g., off-grid application) in the past [12].

Recently, the integration of battery systems in residential grid-connected PV systems has become more economically attractive in some countries with the PV self-consumption schemes [2]. This is mainly driven by several aspects such as: increasing electricity price, decreasing feed-in tariffs, and decreasing cost of PV panels and battery systems. For instance, since the beginning of 2012, the grid parity has been reached for PV systems below 10 kWp in Germany [13], where it is more profitable for the PV owner to supply the local load with the generated PV energy than to draw electricity from the utility grid. In that case, the generated PV power is consumed locally (within the household) as much as possible, and only the surplus PV power is being fed into the grid. However, the simultaneous use of the PV power for self-consumption (i.e., direct self-consumption) is usually limited due to the misalignment between the PV power generation period (e.g., during the day) and the high load demand period (e.g., during the night). Therefore, the battery system is employed to store the surplus PV energy during the day and supply the load demand during the night to maximize the self-consumption.

Due to the relatively long life-span expectation of PV systems (e.g., above 20 years), the reliability and lifetime of components in the system play a crucial role in the life-cycle cost assessment. Driven by the high initial cost of the battery system, the lifetime of batteries has been intensively investigated in previous studies. For instance, the lifetime modeling of batteries with PV self-consumption has been discussed in [14], where the impact of battery sizing has been analyzed. The influence of a self-consumption control strategy on the battery lifetime has also been addressed in [15]. Furthermore, an optimal battery sizing approach to minimize the cost of solar energy has been proposed in [16], [17]. In addition to the battery, the PV inverter is another reliability-critical component in the PV system, which has been witnessed with a high failure rate in field operation [18]. Notably, the PV inverter failure will not only lead to extra cost for replacement but also loss of revenue in the period of the inverter downtime. Therefore, ensuring a high-reliability operation is strongly demanded for the PV inverter, since it has a high potential for further cost reduction in PV systems [19].

In the prior-art study, several aspects related to PV inverter reliability and lifetime have been investigated. For instance, the influence of the PV inverter control strategy on the inverter reliability has been discussed [20]–[22]. In [23]–[25], the impacts of PV panel characteristics and installation locations on the inverter reliability have been addressed. A design for reliability approach has also been applied to grid-connected PV inverters in [26]. Nevertheless, the reliability of a PV inverter with a battery system has not yet been investigated. In fact, the battery system operation can affect the PV inverter loading and thereby its reliability (for the DC-coupled PV-BESS configuration), as it is illustrated in Fig. 1. More specifically, the loading of the PV inverter is affected by the charging/discharging power of the battery, in addition to the PV array output power. For instance, in the case of PV self-consumption, the PV inverter will experience less loading during the day, since part of the PV energy will be stored in the battery. On the other hand, the loading of the PV inverter during nights will be increased (compared to the case without battery system), as the battery system needs to supply the load through the inverter. Inevitably, the PV inverter reliability will be affected by the battery system operation, which needs to be analyzed to ensure a highly-reliable operation of PV inverters. In addition, the influence of battery system parameters (e.g., battery capacity and battery converter power rating) should also be considered in the analysis, which has not been yet been addressed in the literature.

In light of the above, this paper thus explores the impact of the battery system operation on the PV inverter reliability. The reliability assessment is carried out with a case study of PV self-consumption, as described in § II. The mission profile-based reliability assessment of the PV inverter is presented in § III, where the installation site in Germany is considered. The influence of the battery system parameters on the PV inverter reliability is also presented in § IV, where the battery capacity and battery converter power rating are considered. Finally, concluding remarks are given in § V.

II. Photovoltaic Self-Consumption

A. System Description

The system configuration of a residential single-phase PV-BESS is shown in Fig. 1, where the system parameters are given in Table I. In this configuration, the PV arrays and the battery systems are connected in parallel at the DC-link, referred to as the DC-coupled topology [16]. Regarding the power flow, the PV power is generated from the PV arrays, and it is delivered to the DC-link through the PV converter (i.e., uni-directional DC-DC converter). Here, a maximum power point tracking is implemented, in order to maximize PV energy yield. For the battery system, the power flow is bi-directional, where the battery can be charged or discharged through the control of the battery converter (i.e., bi-directional DC-DC converter). The total power delivered to the DC-link, which corresponds to the PV inverter loading, is determined by the difference between the generated PV power and the battery power. The PV inverter with full-bridge topology (i.e., DC-AC inverter) is employed as the interface between the DC-link and the point of common coupling. The main objective of the PV

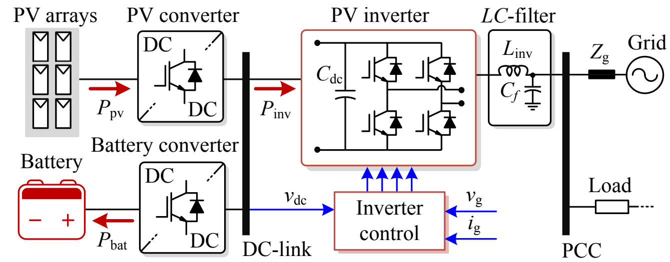

Fig. 1. System description of PV system with battery energy storage system (PV-BESS), where the battery system is connected at the DC-link ($P_{\rm pv}$: PV array output power, $P_{\rm bat}$: battery power, and $P_{\rm inv}$: PV inverter power.

TABLE I
Parameters of the Single-Phase PV-BESS (Fig. 1).

PV array rated power (at STC)	6 kW
Battery capacity	7.5 kWh
Battery converter rated power	3 kW
PV inverter rated power	6 kW
DC-link capacitor	$C_{\rm dc}$ = 1100 μF
LC-filter	$L_{\rm inv}$ = 4.8 mH, C_f = 4.3 μF
Switching frequency	Full-Bridge inverter: $f_{\rm inv}$ = 10 kHz
DC-link voltage	$v_{\rm dc}^*$ = 450 V
Grid nominal voltage (RMS)	V_g = 230 V
Grid nominal frequency	ω_0 = $2\pi\times 50$ rad/s

inverter is to deliver the power feed-in from the DC-link to the AC grid and/or supply the local load. This is achieved by regulating the DC-link voltage to be constant through control of the grid current [27]. In addition, a phase-locked loop is also implemented in the PV inverter to ensure proper grid synchronization.

The main focus of this paper is on the reliability of the PV inverter – in particular, the power devices. Regarding the power device selection, four Insulated-Gate Bipolar Transistor (IGBT) devices from [28] are used according to the system parameters in Table I. The cooling system (e.g., heat sink sizing) is designed to limit the junction temperature of the power device at 90 °C when the inverter operates at the rated power (i.e., 6 kW) and the ambient temperature of 50 °C.

B. Energy Management Control Strategy

In this paper, the energy management control strategy is based on a self-consumption scheme [16], which aims to maximize the local use of the generated PV power within the household. For the PV-BESS with self-consumption, the power difference between the PV generation and the load demand will be stored in (or taken from) the battery system, as it is demonstrated in Fig. 2. More specifically, the surplus PV power during the day will be used to charge the battery as long as the battery capacity is available. If the battery is fully charged, e.g., the maximum State of Charge (SOC) is reached, the surplus power is then fed into the grid. On the other hand, when the PV power generation is not available (e.g., during night) or lower than the load demand, the battery is discharged to supply the local load as long as the battery is available.

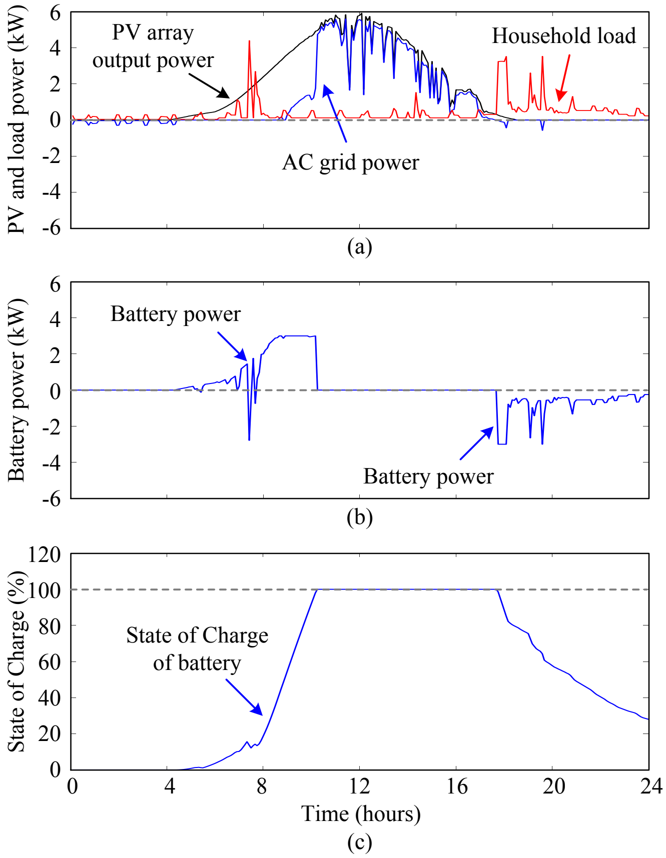

Fig. 2. Daily operation of a PV-BESS with self-consumption: (a) PV array output power P_{pv}, household load demand P_{load}, and grid power exchange P_{grid}, (b) battery power P_{bat}, and (c) state of charge of the battery.

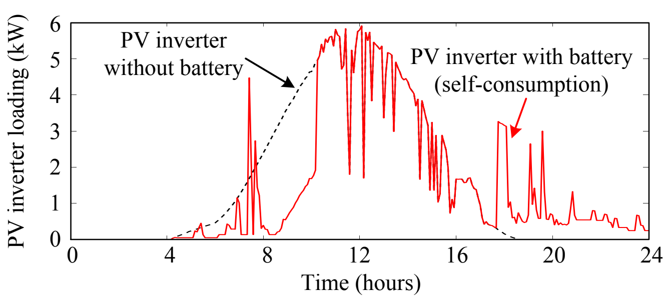

Fig. 3. Daily loading of a PV inverter with battery system (red solid line) and without battery system (black dotted line).

When the battery is fully discharged, the load is then supplied by the utility grid. The battery power P_{bat} during the self-consumption scheme can be summarized as:

$$P_{\mathrm{bat}} = \begin{cases} P_{\mathrm{pv}} - P_{\mathrm{load}}, & \text{when} \quad 0 \le \mathrm{SOC} < 100 \\ 0, & \text{when} \quad \text{otherwise} \end{cases} \tag{1}$$

where P_{pv} is the PV output power from the PV arrays, P_{load} is the load power demand, and SOC is the state of charge of the battery. The positive and negative value of the battery power P_{bat} corresponds to the charging and discharging operation, respectively. Notably, the maximum charging or discharging power of the battery system is limited by the battery converter power rating $P_{\mathrm{bat,max}}$ (i.e., $|P_{\mathrm{bat}}| \le P_{\mathrm{bat,max}}$).

Following the power flow diagram in Fig. 1, the PV inverter loading (e.g., input power) is determined by

$$P_{\mathrm{inv}} = P_{\mathrm{pv}} - P_{\mathrm{bat}} \tag{2}$$

An example of the PV inverter loading with PV-BESS self-consumption is shown in Fig. 3, where the battery operation in Fig. 2 is applied. It can be seen from the result in Fig. 3 that the loading of the PV inverter is reduced significantly during the day due to the battery charging (i.e., $P_{\mathrm{bat}} > 0$). In general, this will result in a positive impact on the PV inverter reliability due to the reduced thermal loading. On the other hand, the loading of the PV inverter will be increased during the battery discharging (i.e., $P_{\mathrm{bat}} < 0$). In that case, it may introduce negative impact of the PV inverter reliability. In order to quantify the battery operation impact, the reliability analysis will be carried out in the following.

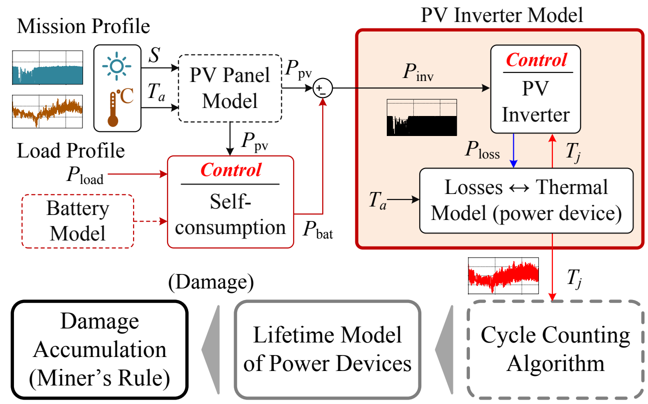

Fig. 4. Reliability assessment of PV inverters with battery storage system based on mission profile and PV self-consumption.

III. Reliability Assessment of PV Inverters

A general procedure for reliability assessment for PV inverters with battery system is illustrated in Fig. 4. In this case, the power device (i.e., IGBT) is considered as an example, since it has been reported as one of the reliability-critical components in the PV inverters [29]. Nevertheless, the same procedure can also be further applied to other components.

Following the approach in Fig. 4, at the first step, the PV array output power P_{pv} is determined from the mission profile (i.e., solar irradiance and ambient temperature). The PV inverter loading P_{inv} (i.e., inverter input power) is then calculated following (2), where the battery power P_{bat} is obtained from the self-consumption control strategy for a given load profile. From the PV inverter loading profile (i.e., inverter input power), the power losses dissipated in power devices can be calculated and applied to the thermal model, in order to obtain the thermal loading of the power device. Due to mission profile dynamics, a cycle-counting algorithm is normally required to extract the thermal cycle information from the obtained

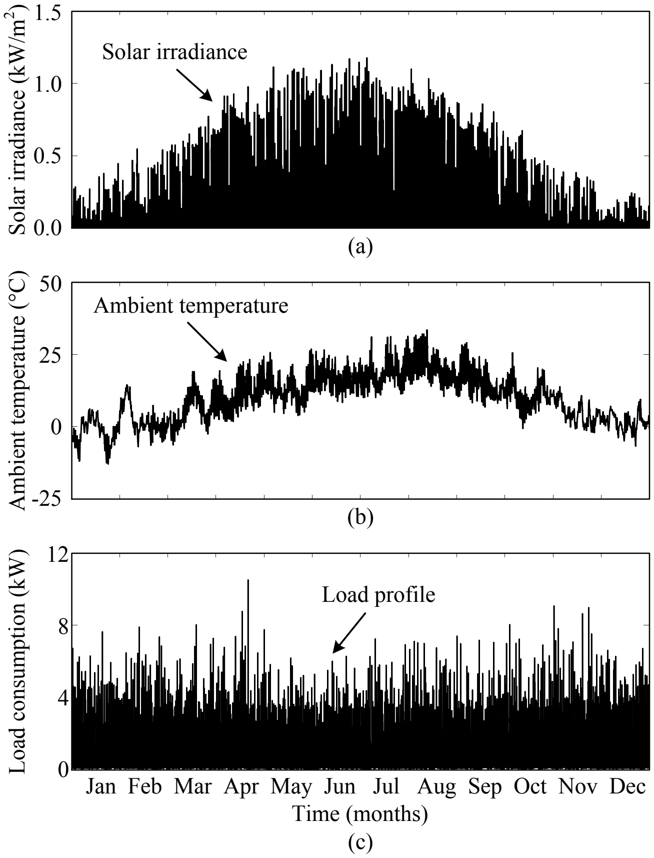

Fig. 5. One-year mission profile of the PV-BESS in Lindenberg, Germany with a sampling rate of 1 minute per sample: (a) solar irradiance, (b) ambient temperature, and (c) household load profile.

thermal loading profile [26]. Afterwards, the obtained thermal cycle information can be applied to the lifetime model of the power device and the corresponding damage can be calculated as a reliability metric. In the following, a case study of the PV-BESS installed in Lindenberg, Germany will be demonstrated.

A. Mission Profiles

A mission profile plays an important role in the reliability assessment [30], as affects the loading of the PV inverter during the operation. Typically, the solar irradiance and ambient temperature are considered as mission profiles, since they determine the PV output power. A one-year solar irradiance and ambient temperature profiles recorded in Lindenberg, Germany with the sampling rate of 1 minute per sample are shown in Fig. 5. It can be seen from the mission profile that there is a strong seasonal variation in both the solar irradiance and ambient temperature between summer and winter seasons. In this case, it can be expected that the PV inverter loading during summer will be much higher than that during winter due to the relatively high solar irradiance level in summer (e.g., during May-July).

From the solar irradiance and ambient temperature profiles, the PV array output power can be determined using the PV panel model. However, in the case of a PV-BESS, the load profile of the household also needs to be considered, as it determines the battery operation for the self-consumption scheme. A household load profile used in the case study is shown in Fig. 5(c). This load profile is based on the measurement data from 32 residential households, which has been stochastically modified to represent a typical 4-persons household load profile with the annual energy consumption of approximately 4800 kWh/year [13]. Together with the PV array output power profile, the battery power profile with the self-consumption strategy can be obtained. Afterwards, the PV inverter loading profile can be calculated following (2).

TABLE II
PARAMETERS OF THE LIFETIME MODEL OF AN IGBT MODULE [31].

Parameter	Value	Experimental condition
A	3.4368×10^{14}	
α	-4.923	64 K $\leq \Delta T_j \leq 113$ K
β_1	-9.012×10^{-3}	
β_0	1.942	$0.19 \leq ar \leq 0.42$
C	1.434	
γ	-1.208	0.07 s $\leq t_{on} \leq 63$ s
f_d	0.6204	
E_a	0.06606 eV	32.5 °C $\leq T_j \leq 122$ °C
k_B	8.6173324×10^{-5} eV/K	

B. Damage Calculation

From the PV inverter loading profile obtained in the previous step, the thermal loading of the power device (i.e., junction temperature) can be calculated by using the loss and thermal models of the power device. Then, by applying the cycle counting algorithm, the thermal stress metric such as the number of cycles n_i at a certain cycle amplitude ΔT_j, mean junction temperature T_{jm}, and cycle period t_{on} can be obtained. The thermal stress metric can be applied to the lifetime model of the power device in order to calculate the damage for a given thermal stress condition as

$$D = \frac{1}{N_f} \tag{3}$$

where D is the damage occurring in the power device and N_f is the number of cycles to failure at a certain stress condition: T_{jm}, ΔT_j, and t_{on}, which is calculated as

$$\begin{aligned} N_f = \; & A \cdot (\Delta T_j)^{\alpha} \cdot (ar)^{\beta_1 \Delta T_j + \beta_0} \cdot \left[\frac{C+(t_{on})^{\gamma}}{C+1}\right] \\ & \cdot \exp\left(\frac{E_a}{k_b \cdot T_{jm}}\right) \cdot f_d \end{aligned} \tag{4}$$

where the lifetime model parameters are given in Table II.

The total damage occurred during operation (e.g., mission profile) can be accumulated by using the Miner's rule [32] as

$$AD = \sum_i D_i = \sum_i \frac{n_i}{N_{fi}} \tag{5}$$

where AD is the accumulated damage of the power device, n_i is the number of cycles for a certain T_{jm}, ΔT_j, and t_{on}, and N_{fi} is calculated from (4) at that stress condition.

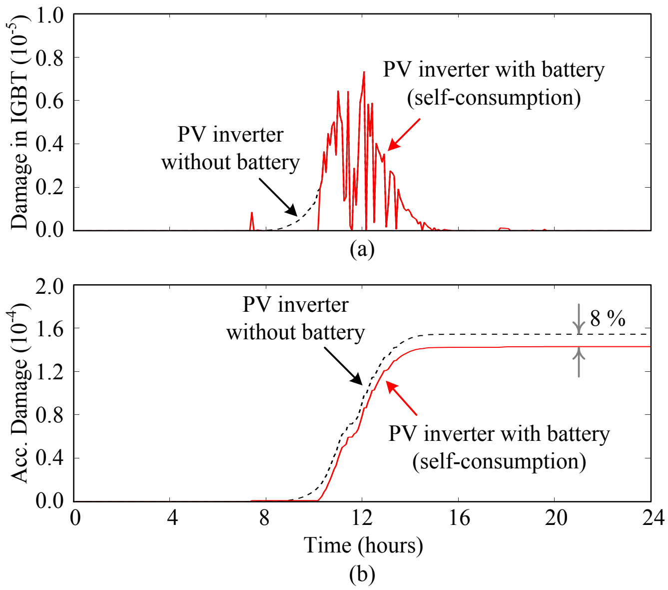

Fig. 6. Short-term (one-day) reliability assessment of the PV inverter: (a) the damage and (b) the accumulated damage of the power device.

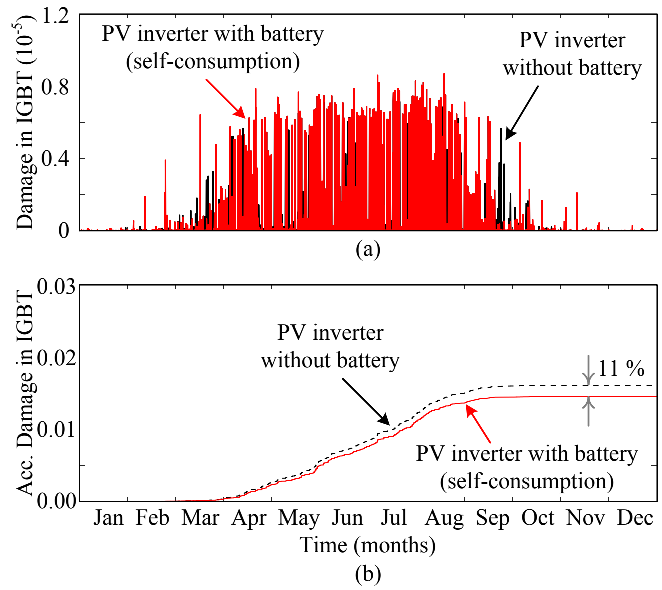

Fig. 7. Long-term (one-year) reliability assessment of the PV inverter: (a) the damage and (b) the accumulated damage of the power device.

The damage calculated from (5) can be used as a reliability metric to quantify the impact of the operating condition (e.g., mission profile and battery operation) on the PV inverter reliability. For instance, the operation with high damage indicates a low reliability and short lifetime expectation of the power device. When the damage is accumulated to unity (i.e., AD = 1), the power device is considered to reach its end of life.

C. Short-term Reliability Analysis (One day)

As discussed in the previous section, with the self-consumption operation, the PV inverter loading will be decreased during the day (e.g., when the battery is being charged) and increased during the night (e.g., when the battery is being discharged). In order to analyze this operation impact, a short-term reliability assessment during one day is first carried out.

The PV inverter loading during one-day operation shown in Fig. 3 is considered for a short-term reliability analysis. The corresponding damage occurred in the power device is demonstrated in Fig. 6(a), where the two cases of the PV inverter with and without battery system are compared. It can be seen from the results in Fig. 6(a) that the damage in the power device of the PV inverter with battery system is reduced significantly during the battery charging period (i.e., 8:00-10:00). However, there is a small increase in the damage occurred before 8:00, which is the time when the battery is discharged to supply the load demand in the morning.

In the afternoon, the PV power generation is relatively low after 16:00. Therefore, the damage in the PV inverter without battery system is almost not noticeable. In the case of the PV inverter with battery system, a small increase in the loading has been observed around 18:00, corresponding to the discharging period of the battery in Fig. 2. However, the increased PV inverter loading at night is relatively low (compared to that during the day) during most of the period, as it can be seen in Fig. 3. Thus, the increased thermal stress (i.e., ΔT_j) due to the battery discharge is relatively small and its contribution to the damage is not significant, following (4). Accordingly, when accumulating the damage during the entire day, the operation of the battery system can reduce the accumulated damage of the power device in the PV inverter by 8 % (compared to the case without battery system), as it is shown in Fig. 6(b).

D. Long-term Reliability Analysis (One year)

Due to the seasonal variation in the mission profile (e.g., during summer and winter), the long-term reliability assessment is necessary to explore the battery operation impact on the reliability of the PV inverter. Here, a one-year mission profile in Fig. 5 is applied to the reliability assessment process in Fig. 4. The corresponding damage in the power device for the case of PV inverter without battery and with battery are shown in Fig. 7(a) and the accumulated damage of the two cases are also shown in Fig. 7(b).

In general, the damage in the power device of the PV inverter with battery is lower than the case without battery. There are only a few occasions where the damage of the power device is increased with the battery operation, which occurs during the day with a high load demand during nights. In that case, the increased loading of the PV inverter during the battery discharge is significant (compared with the load reduction during the day). Nevertheless, when considering the operation during the entire year, the accumulated damage in the power device of the PV inverter with battery system is 11 % lower than the case without battery system. Thus, the reliability of the PV inverter can be improved with the integration of the battery system (i.e., PV self-consumption).

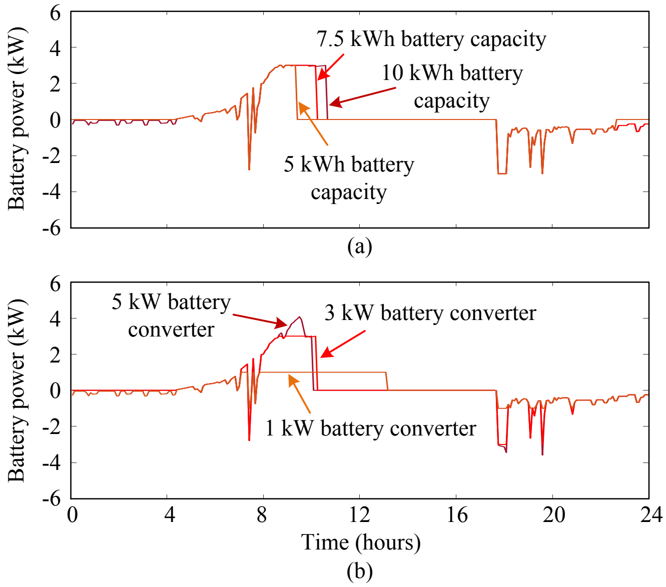

Fig. 8. Battery charging/discharging power profile during one-day operation of PV self-consumption with different: (a) battery capacities (3 kW battery converter power rating) and (b) battery converter power ratings (7.5 kWh battery capacity).

IV. Battery System Parameters Impact on PV Inverter Reliability

The previous analysis indicates that the battery system operation can improve the reliability of the PV inverter due to the significant load reduction during the day. However, the battery capacity and the battery converter power rating are the two main parameters that affect the battery system operation, as it is demonstrated in Fig. 8. In this section, the impact of the battery system parameters on the PV inverter reliability will be analyzed.

A. Impact of Battery Capacity

The battery capacity is one of the design parameters which needs to be selected properly (e.g., battery sizing), in order to ensure the economical benefit of the system. In the previous case, the battery capacity of 7.5 kWh was considered for the 6-kW PV system, following the design recommendation in [16]. In fact, this design parameter is in close agreement with the real-field data in [33].

Nevertheless, to explore the battery capacity impact on the PV inverter reliability, two other cases with a battery capacity of 5 kWh and 10 kWh are compared. According to the battery power profile in Fig. 8(a), it can be seen that the charging (and also discharging) time duration is strongly affected by the battery capacity. A large battery capacity (e.g., 10 kWh battery) will prolong the charging process, while the battery with 5-kWh capacity is fully charged much earlier. From the PV inverter loading perspective, the large battery capacity will ensure that more PV inverter loading during the day will be shifted to the night. For instance, this impact is reflected in the damage of the power device, as it is shown

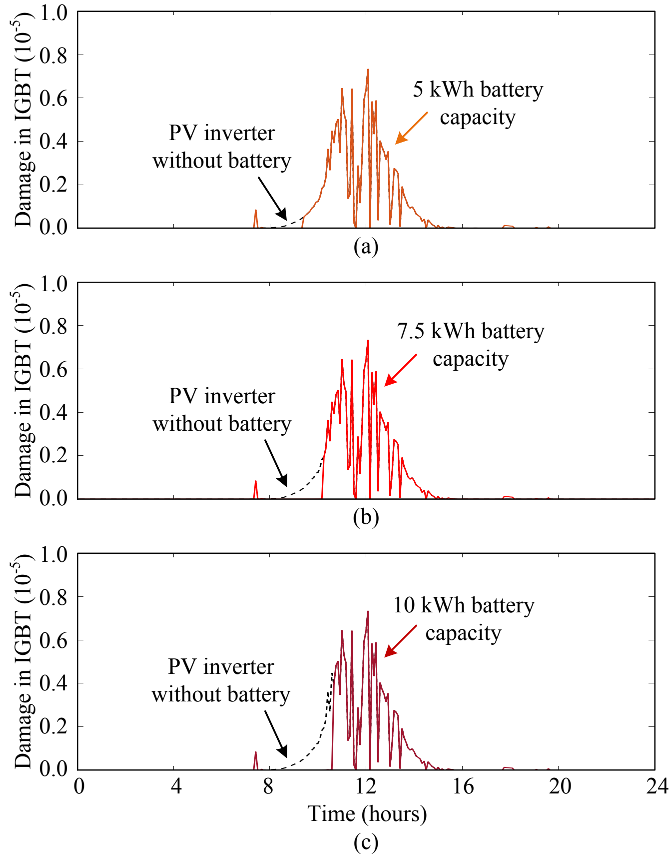

Fig. 9. Damage of the power device during one-day operation of the PV-BESS with a 3-kW battery converter power rating and the battery capacity of: (a) 5 kWh, (b) 7.5 kWh, and (c) 10 kWh.

in Fig. 9. With a small battery capacity (e.g., 5 kWh battery), the damage of the power device in PV inverter with battery system is comparable to the case without battery system. On the other hand, the difference in the damage increases with increased battery capacity, where a significant damage reduction is observed when the 10 kWh battery is employed. Therefore, increasing the battery capacity will improve the overall PV inverter reliability.

B. Impact of Battery Converter

The selection of the battery converter (i.e., power rating) can highly affect the charging/discharging power of the battery system. Typically, the battery converter can be selected smaller than the PV array rated power, since most of the time the battery system will not be charged at the peak power of the PV array. However, the battery converter power rating should be higher than the average load demand, in order to ensure the self-consumption operation. Here, three different battery converters with a power rating of 1 kW, 3 kW, and 5 kW are considered to demonstrate the impact of battery converter selection on the PV inverter reliability.

With the same battery capacity, the charging/discharging time duration will be increased with the smaller battery converter (e.g., 1 kW battery converter). In that case, more peak-

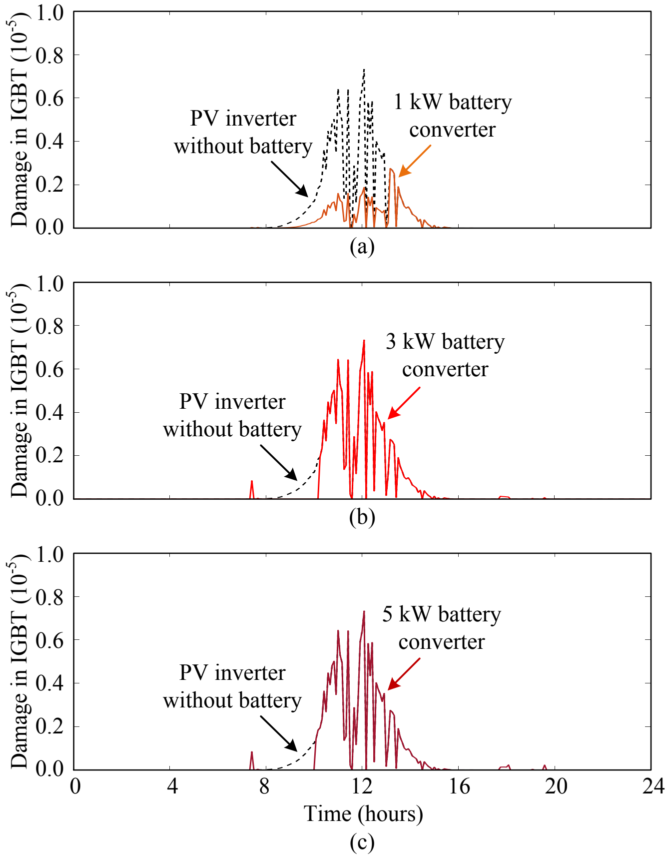

Fig. 10. Damage of the power device during one-day operation of the PV-BESS with 7.5 kWh battery capacity and the battery converter power rating of: (a) 1 kW, (b) 3 kW, and (c) 5 kW.

load during midday will be stored in the battery. Moreover, the smaller battery converter will also limit the peak-power during night when the battery is discharged to supply the load. This operational impact is reflected in the damage of the PV inverter shown in Fig. 10, where a significant damage reduction of the PV inverter with 1 kW battery converter occurs during midday. In contrast, most of the damage reduction in the PV inverter occurs in the early morning (e.g., from 8:00) for the larger battery converter (e.g., 5 kW battery converter). When comparing the impact of PV inverter load reduction, reducing the peak-load during midday has more benefit in terms of PV inverter reliability. Thus, using a small battery converter will improve the PV inverter reliability.

C. Discussion

The influence of the battery system parameters is further analyzed with the one-year mission profile in Fig. 5. The difference in the power device damage compared with the case of PV inverter without battery system is calculated and shown in Fig. 11, where various values for battery capacity and battery converter power rating are considered. Similar to the one-day reliability assessment discussed previously, the accumulated damage decreases with large battery capacity and small battery converter (i.e., low power rating). However, when

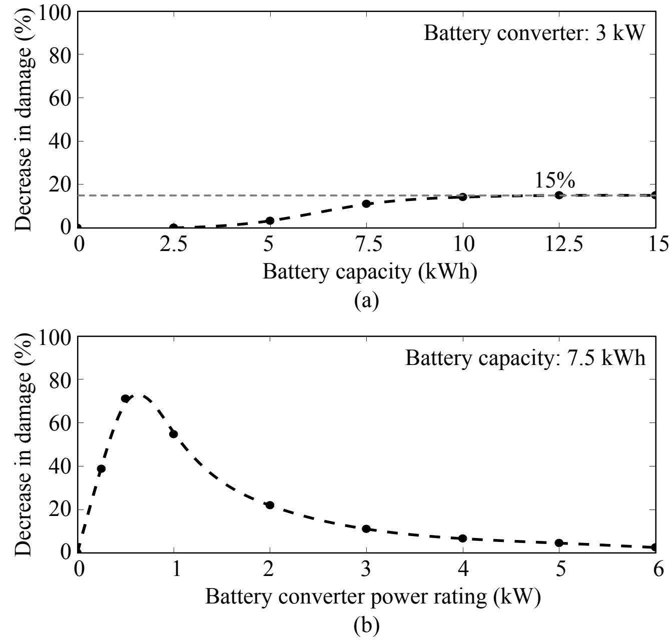

Fig. 11. Impacts of the battery system parameters on the long-term (one-year) accumulated damage of the PV inverter with different: (a) battery capacity and (b) battery converter power ratings.

the battery capacity is further increased higher than 10 kWh, the damage is not further decreased, but the damage difference is saturated around 15 % of the initial value. In that case, the battery is highly over-dimensioned and its capacity is not fully utilized during the operation. In other words, the battery is not being fully charged during the day and discharged during the night, and thereby the battery power profile will not be further affected by increasing the battery capacity. However, the high battery capacity means a higher cost.

As discussed previously, a smaller battery converter (e.g., low power rating) will improve the PV inverter reliability. In general, this argument can also be applied to the long-term reliability assessment, where the damage of the power device in the PV inverter decreases as the battery converter power rating decreases, as it is shown in Fig. 11(b). However, when the power rating becomes too small (e.g., below 0.6 kW), the charging or discharging power is not enough to fully charge the battery during the day and supply the load demand during the night. In other words, the battery system is not fully utilized and its influence on the PV inverter reliability is limited. In that case, the damage of the power device in PV inverter becomes comparable to the case without battery system.

Notably, the above analysis only considers the impact of battery system design regarding the reliability of PV inverters. In practice, other design aspects (e.g., cost of energy, self-consumption rate, and lifetime of batteries) should also be taken into account together with the PV inverter reliability in order to maximize the overall benefit of the battery system in PV applications. In that case, the above analysis can be used as part of a multi-dimensional design tool.

V. Conclusion

In this paper, the reliability assessment of a PV inverter with integrated battery system was carried out. The impact of battery operation under the self-consumption scheme on the PV inverter reliability was investigated with a case study of a 6-kW PV-BESS installed in Germany. The reliability analysis has shown a considerable decrease in the PV inverter loading during the day due to the battery operation. In that case, the integration of PV and battery system will result in an overall improvement in the PV inverter reliability, where the accumulated damage over one year of operation can be reduced by 11 %. In addition, the PV inverter reliability can be further improved by increasing the battery capacity and/or reducing the battery converter power rating, which should be considered together with other design aspects (e.g., cost, battery lifetime) to maximize the benefit of the battery system in PV applications.

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