IMPACT OF MEASUREMENT DATA TIME RESOLUTION ON PREDICTED LIFETIME OF PV INVERTERS IN RESIDENTIAL SOLAR PANEL SYSTEMS

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ABSTRACT: The reliability of grid-tied PV inverters without integrated battery is compared with AC/DC-coupled PV-battery systems while varying the time resolution of the load and mission profiles (1 min – 60 min). Adding a battery increases self-consumption and can lower the needed grid power capacity in both DC- and AC-coupled configurations. A comparison between a battery-free PV system and a grid-tied PV-battery system shows that adding a battery to the system will not only improve the energy performance of the system but also increase the lifetime of the inverter (~15% in DC-coupled structure). The results have been extracted for two cases: (a) varying both mission profile and load profile resolutions, (b) varying the available load profile time resolution while keeping the mission profile time resolution constant at 1 min. The obtained results show that in our case, the influence of mission profile time resolution is greater than the input of load data. However, the expected PV inverter lifetime does not differ much for different time resolutions. This can highlight the importance of using measurement data with a resolution of even less than 1 minute because higher IGBT junction temperature swings can happen in a few seconds which cannot be seen in lower time resolutions.

Keywords: Lifetime estimation, Mission profile, Power devices, Time resolution, Battery.

1 INTRODUCTION

Due to the decline in PV panel prices over the recent decade, particular attention has been paid to the extensive use of solar energy. In an attempt to emerge this rising trend, researchers have made developments and improvements of PV systems a priority. However, the intermittent nature of PV power can induce major challenges on the grid when multiple residential units employ a grid-connected PV system [1]. Consequently, adding a battery to the PV systems seems to be a workable solution to ease the integration of these systems into the existing grid while PV self-consumption can be improved by using a storage system.

As the power electronic circuits are an integral part of these systems, enhancing their efficiency and reliability should be considered in the analysis. The semiconductor devices utilized in power electronics are the most failure-prone components in the system. Their lifetime is strongly influenced by environmental (mission profile) and operation (load profile) conditions [2]. Avoiding failures in the PV inverter is crucial to prevent energy losses and economic losses. On the other hand, the different system configurations will not only affect the compatibility of the entire system but also influence the efficiency, lifetime, and reliability. In Fig. 1, two different schemes have been adopted in order to link the PV panels to the battery and the grid. The first configuration is DC-coupled where the battery is connected to the DC-link directly. One and the same inverter is used as an interface between the battery and the electrical grid. Another configuration for the integration of the PV array to the battery and the grid is known as AC-coupled where the battery can be connected to the public grid at any point on the AC side. To realize this advantage, a dedicated inverter is used for the battery. However, this additional power conversion stage reduces the efficiency of the system [3].

The objective of this study is to assess the reliability of three PV system configurations: (1) without battery, (2) with a DC-coupled battery system, and (3) with an AC-coupled battery system. The reliability analysis is performed using four different mission and load profile resolutions (1 min – 60 min) which additionally provides an understanding of the sensitivity of lifetime estimations to the sampling rate. This study examines the performance of different system structures in terms of both reliability and energy waste (curtailed energy or fed from the grid). Also, in order to increase the accuracy, the power dependent efficiency of the converters is considered. The results will be compared with scenarios where an efficiency of 100% is assumed. The outcome of this study provides insights in the benefits of integrating a battery in a PV system.

2 METHODOLOGY

In this case study, a 4 kWp (SunPower SPR-200, 4 parallel – 5 series) solar array is considered. Additionally, a conventional three-phase grid-tied inverter is used for the power conversion of the PV panels and the battery. To control the charging and discharging of the battery, the approach is to maximize self-consumption [4]. Based on this control strategy, the storage system uses excess electricity when the PV production is greater than the electricity consumption. If the excess energy goes beyond the maximum battery power, the remaining energy must be injected into the grid or dissipated. On the other hand, the storage system will supply the demanded energy if the consumption exceeds the PV generation (e.g., during night). There is a limitation on the energy stored in the battery so that part of the demanded energy can be supplied by the grid. Nevertheless, the amount of energy that must be curtailed or absorbed from the grid can be specified in different scenarios.

The DC-coupled system, shown in Fig. 1(a), is comprised of three power converters: a solar DC-DC converter, a bi-directional DC-DC converter, and a three-phase inverter. Due to the internal resistance of the components inside each converter, their output power will be slightly lower than the input power, which is important to take into account in the analyses. The same procedure can also be applied on the AC-coupled system with four power converters. In both cases, the DC-link voltage is kept at a constant voltage (400 V) by using the control system. Additionally, the state-of-charge (SoC) of the battery is limited at 80 % to improve the cycle life of the battery [5]. In these cases, an LG Chem RESU3.3 battery (48 V, 63 Ah, 3 kW) is placed into the system. According to [6], the optimal battery size – combined with the PV panel with a capacity of 1 kWp/MWh – is chosen based on the optimal ratio of 0.75 kWh/MWh.

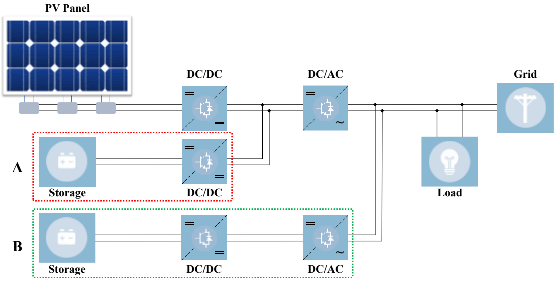


Figure 1: Typical diagram of a grid-connected PV system with (A) a DC-coupled backup battery and (B) an AC-coupled backup battery

The next step is to assess the reliability of the PV inverters. Figure 2 illustrates the used reliability assessment methodology starting from the given mission profile to the lifetime estimation of the switching devices.

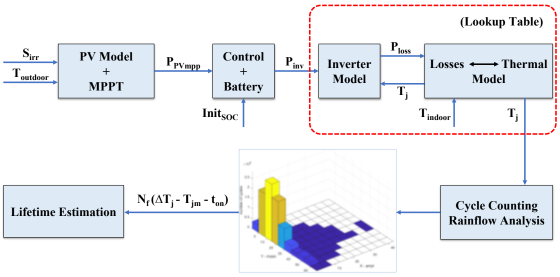


Figure 2: Lifetime and reliability assessment methodology of a PV inverter

The reliability approach used in this study has been adapted from [7]. In the inverter circuit, fast-switch insulated-gate bipolar transistors (IGBTs) rated at 600 V are used as the active switches. Based on the method displayed in Fig. 2, the one-year mission profile (solar irradiance and ambient temperature) is translated to a one-year PV generation profile. This profile is converted to the input power profile of the inverter which already includes the employed battery control strategy. In the next stage, a lookup table approach [8] has been adopted to translate the inverter input power to the power losses, then to the junction temperature of the IGBT. An important point to consider at this point is that the ambient temperature for the inverter must be assumed to be the indoor temperature T_{indoor}, since the inverter will be installed indoors in residential applications. By using the thermal model of the semiconductors and the heat sink, the input power can be translated into junction temperature profiles of the switches. The thermal model parameters are extracted from the datasheet provided by the manufacturer. Then, the rainflow cycle counting method has been used to determine the number of cycles with their corresponding amplitude (ΔT_j), average (T_{jm}), and period (t_{on}). The damage inflicted by every cycle can be calculated using the chosen lifetime model:

$$N_f = A \times \left(\Delta T_j\right)^{\alpha} \times (ar)^{\beta_1 \Delta T_j + \beta_0} \times \left[\frac{C+(t_{on})^{\gamma}}{C+1}\right] \times \exp\left(\frac{E_a}{k_b + T_{jm}}\right) \times f_d \qquad (1)$$

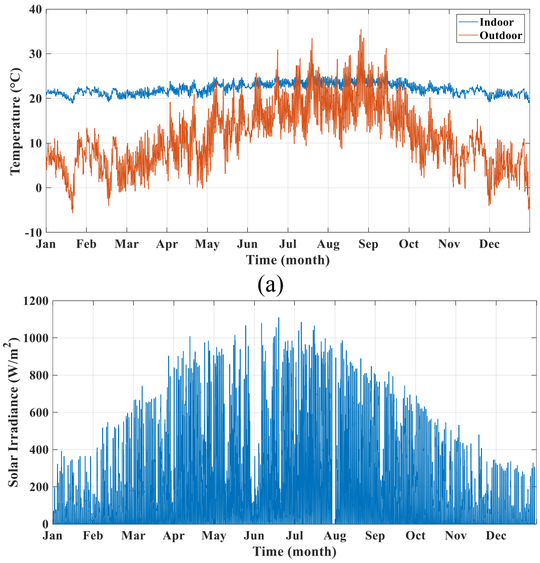
In this model, the output N_f is the number of thermal cycles to failure. The other model parameters are provided in [9]. This equation has been validated for a certain range of ΔT_j, T_{jm} and t_{on} which means that an extrapolation is required for several cycles laying outside of this range [10]. According to Miner's rule, displayed in Eq. (2), the damage inflicted by every cycle can be linearly accumulated to calculate the total lifetime consumption (LC) of the mission profile on the IGBT [10].

$$LC = \sum_i \left(\frac{n_i}{N_{fi}}\right) \qquad (2)$$

where n_i is the number of cycles obtained from the rainflow analysis with a certain combination of ΔT_j, T_{jm} and t_{on}.

3 RESULTS & DISCUSSION

The studied one-year mission and load profiles are depicted in Fig. 3. The household electric power consumption with a one-minute sampling rate has been extracted from [11]. The solar irradiance and ambient temperatures have been captured from Belgium. In this analysis, the PV panel-to-load ratio is assumed to be 100%. As the PV inverter can be installed indoors, the indoor temperature is assumed to be controlled by the heating/cooling system which can keep the inside temperature in a limited range. The approach presented in [12] has been used to produce the indoor temperature profile from the outdoor temperature. The results of this study showed that for two temperature ranges (below and above 15°C), the indoor temperature can be estimated by a linear fit.



(a)

(b)

Figure 3: A one-year mission profile from Belgium with (a) the outdoor/indoor temperature and (b) the solar irradiance

The implemented control approach enables us to determine the amount of curtailed energy as well as the amount of absorbed energy fed to the load from the grid. To increase the accuracy of computations, the efficiency of converters used in the PV system is considered to be less than 100% because the input and output powers of these converters are not the equal and this should be taken into account in the calculations. Thus, as a part of analysis, three values of 95%, 97.5%, and 100% are considered as the converters' efficiency. The obtained results reveal that considering the converter's efficiency in the calculations has a great impact. As a general trend, increasing efficiency leads to a decreased thermal stress. On the other hand, the results imply that PV curtailment increases by boosting the efficiency. For instance, if the efficiency is changed from 95% to 100%, the curtailed energy value will vary from 32% to 43% of the total energy, while the absorbed energy from the grid only drops 4% from 735 to 704 kWh. The effect of the variable efficiency on the system performance has also been investigated and, since there is less than 2% difference compared with the case with a constant efficiency (95%), its use has been neglected in other stages.

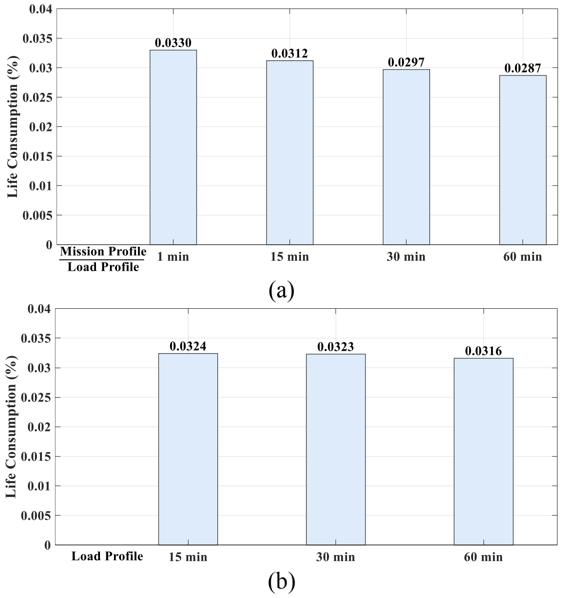
In the next step, the aforesaid procedure has been applied on the given mission profile with a time resolution of 1 min. Then, the 1-minute mission profile has been converted to lower resolution data (15 min – 60 min) in order to investigate the effect of reducing time resolution on the system's reliability as well as the performance. This resolution reduction is accomplished by averaging the 1-min dataset over the chosen time resolution. This time resolution reduction has been achieved in two ways: (1) the resolution of the mission and load profiles are both reduced, (2) it is only assumed that the number of load samples is reduced, but the mission profile resolution remains the same (1 min).

For a better comparison between systems, the aforesaid approach is firstly applied on a PV system without battery storage. The results of this configuration are illustrated in Table I.

Table I: The obtained results of the PV system without battery storage

Load Profile Resolution	1 min	15 min	30 min	60 min	15 min	30 min	60 min
Mission Profile Resolution	1 min	15 min	30 min	60 min	1 min	1 min	1 min
Life Consumption *LC* (%)	0.0330	0.0312	0.0297	0.0287	0.0324	0.0323	0.0316
Energy Curtailment *EC* (kWh/y)	3112.30	3106.50	3100.70	3087.70	3102.40	3096.70	3089.20
Energy from Grid *EG* (kWh/y)	1284.10	1294.70	1316.70	1334.80	1291.90	1294.40	1298.50

The results can be divided into two categories: (1) both the resolutions of meteorological sensors and the meter change simultaneously, and (2) only the sampling rate of the electricity meter changes. To show the calculated lifetime sensitivity to the sampling rate, the results of these two groups are shown in Fig. 4.



(a)

(b)

Figure 4: The obtained life consumptions based on different resolutions: (a) both mission and load profile resolutions change simultaneously, and (b) the load profile resolution changes while the mission profile resolution remains constant at 1 min

According to Fig. 4(b), by enlarging the resolution of the load profile, the calculated lifetime only experiences a slight change so that even if the time resolution is increased to 1 hour, the error is not more than 4%. On the other hand, Fig. 4(a) also shows that the sensitivity of the results to the mission profile resolution is significant as by increasing the resolution of both profiles, the error rate rises to 13%. Nevertheless, to draw a comparison between different configurations, the 1-min profiles have been selected as the reference.

Table II lists the obtained results by applying the approach on both DC and AC-coupled systems compared to the case without battery (WOBatt).

Table II: The obtained results with a 3.3 kWh battery

	WOBatt	DC	AC
Life Consumption (%)	0.0330	0.0280	0.0348
Energy Curtailment (kWh/y)	3112.3	2471.4	2398.6
Energy from Grid (kWh/y)	1284.1	735.7	701.3

As expected, by removing the battery, the amount of energy that must be curtailed as well as the absorbed energy from the grid will increase. A comparison of the battery-free system and the DC-coupled system shows that adding a battery improves the PV inverter reliability and enhances the overall system performance. The results indicate that by inserting a suitable battery into the grid-tied PV system and choosing a proper configuration, it would be feasible to increase the PV inverter reliability by 15.15%. An earlier study also confirms the improvement of the inverter lifetime by connecting a battery as a DC-coupled structure [13].

The outcome from the AC-coupled system analysis is provided in Table II. The PV inverter loading depends on the PV generation and battery operation. Hence, the main difference between the DC and AC-coupled configurations is that the excess solar generation should be exported to the battery or the grid through the PV inverter. But, in the DC-coupled design, the power of the PV inverter reduces because the battery will be charged/discharged on the DC side; thus, the PV inverter suffers less from thermal stress. Thus, the AC-coupled configuration reduces the lifespan of the PV inverter (5.45% less than the battery-free system). This is explained because of the curtailment that happens at the DC link level in the system without battery which is higher than in the case of a system with battery, so the PV inverter has to convert more energy in the system with AC coupled battery compared to a system without battery. The results indicate that the reliability of the PV inverter is 24.3% higher in a DC-coupled system than in an AC coupled system. Our findings are in line with a previous research by Sandelic et al., who found that installing PV inverters in an AC-coupled configuration leads to a shorter lifetime compared to the DC system (26.6% less) [14]. Although adding a battery in an AC-coupled configuration reduces the PV inverter reliability, this configuration effectively improves the total systems energy use, 25% less energy is curtailed compared to the battery-free system. Therefore, it can be concluded that the added battery in both AC and DC configurations has benefit to the overall performance. It is worth mentioning that a battery can also work as a filter to support the PV inverter by stabilizing its input voltage. Using a multi-port/input converter can be a suitable solution to lower the number of total components in the PV-battery system.

The effect of time resolution on the estimated lifespan is not very significant, perhaps because the highest possible resolution is considered 1 min, while within a few seconds the junction temperature can fluctuate sharply. This can lead to a severe reduction in life expectancy, especially on cloudy days. As the thermal time constant between the junction-to-heatsink ($\tau_{J\text{-}H}$) is around a few minutes, but the thermal time constant for junction-to-case layers is much lower, a further investigation on finding a marginal/optimal measurement time resolution needs to be conducted.

4 CONCLUSIONS

In this paper, a reliability assessment of the PV inverter has been performed concerning different configurations of grid-connected photovoltaic systems. Three different configurations have been chosen: a grid-tied PV system without battery, a grid-tied PV system integrated with a DC-coupled battery storage system, and a grid-tied PV system integrated with an AC-coupled battery storage system. The effect of load/mission profiles with various sampling rates (1 min – 60 min) has been determined on a PV system configuration. The results showed that changing the load and mission profile resolutions from 1 min to 60 min leads to an error of 13% in the lifetime estimation. By integrating a DC-coupled battery system into the PV system, the lifetime of the PV inverter can be increased by 15%. Although adding a battery to the system improves the overall performance in terms of energy efficiency, the AC-coupled configuration will reduce the lifetime of the PV inverter by 5% compared to the battery-free structure. For further studies, a reliability assessment of the DC-DC converters utilized in the PV battery system, and the effect of different control strategies on the lifetime estimation are suggested.

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