RELIABILITY ANALYSIS FRAMEWORK FOR A GRID-TIED PV-BATTERY SYSTEM: INFLUENCE OF PV AND BATTERY DEGRADATION ON RELIABILITY OF POWER ELECTRONIC SYSTEMS

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ABSTRACT: This paper presents a flexible framework to evaluate the reliability of power electronic systems used within a grid-connected PV-battery system. As a practical example to show the capability of this framework, the life consumption (LC) of power semiconductors (IGBTs and diodes) is determined considering both solar panel and lithium-ion battery degradation. Different panel degradation rates can be defined to the framework. The battery degradation is calculated by a closed-loop approach so that the battery degradation is adjusted based on the determined cycling and calendar aging. The outputs are obtained for three cases: (1) no degradation, (2) only PV degradation, and (3) both PV and battery degradation. The results showed that by considering the battery degradation, the battery DC-DC converter's switches will experience 14% lower LC compared to the case with both PV and battery degradation models, while the switches within the PV inverter have 2.3% higher LC when considering the battery degradation.
Keywords: Lifetime estimation, Mission profile, Power devices, Time resolution, Battery

1 INTRODUCTION

Power electronics converters are an integral part of photovoltaic (PV) systems. Lifetime (LT) of the power devices used within these converters is significantly influenced by the environmental and operating conditions of the system, also known as the mission profile. As the number of installed solar panels for household applications will increase dramatically in the coming years, special attention should be paid to the reliability of these systems. Hence, providing a flexible and comprehensive framework for reliability estimation of the PV-battery systems can be highly useful as it would be perfectly possible to modify the various parameters and inputs of the system and observe the effect of any change on the reliability.

In this paper, the proposed reliability analysis framework allows us to change all the inputs/parameters including mission profiles, PV-battery sizes, time resolution, battery characteristics/models, converters topologies, solar panel behavior, etc. Although several studies have shown the influence of different factors on the reliability of the photovoltaic systems (e.g., the mission profile [1], control methods [2], and functional modes [3]), the impact of both PV panel degradation and battery degradation on the lifetime of power converters has not been investigated. If the PV panel and battery degradation are not considered, the life consumption of subsequent years is the same as the first year which is not accurate. Here, the importance of this consideration is reflected as an example to demonstrate the capability of the adopted framework.

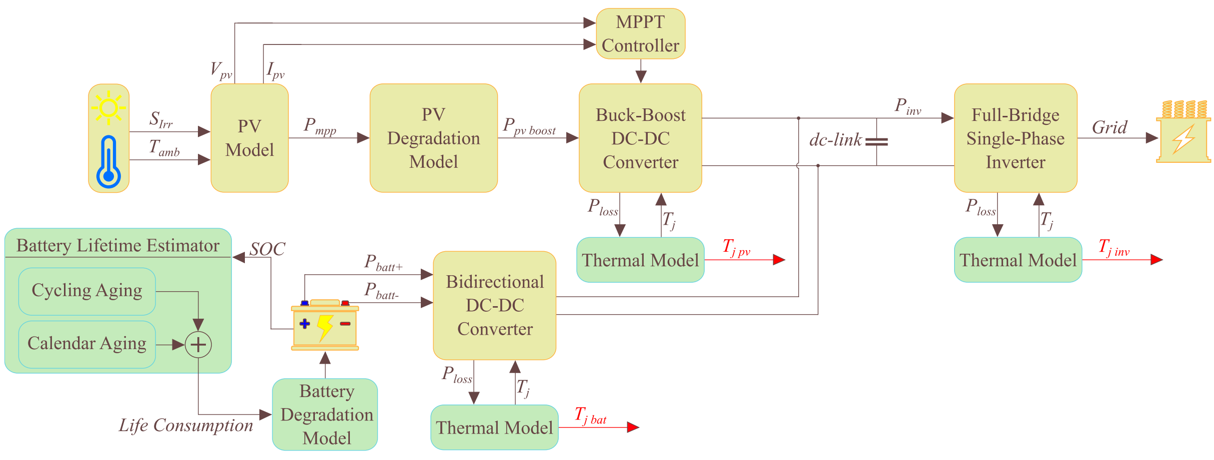
Ref. [4] assessed the influence of the PV panel degradation on the PV inverter lifetime. Their findings showed that considering the PV panel degradation leads to a higher estimated lifetime. A remarkable point is that many households will tend to integrate a battery storage system into their PV system in the future. As the expected lifetime of lithium-ion batteries is less than that off PV panels, the battery will be replaced multiple times over the useful life of the PV panels. Therefore, repeating the first year of damage of the power devices over the total inverter lifetime contradicts the fact that the system operation might change significantly by the battery degradation.

This paper considers a 30-year timeframe for the damage to provide more accurate results. The yearly mission profile is extracted for a location in Belgium and is duplicated for the entire timeframe. The overview of the proposed approach is illustrated in Fig. 1. Each converter is controlled by a control system, e.g., maximum power point tracking is responsible to control the buck-boost converter. The charge/discharge of the battery is determined based on maximizing the self-consumption. It should be noted that in all simulations, the converters' efficiency is variable and is considered as a function of the converter's input power.

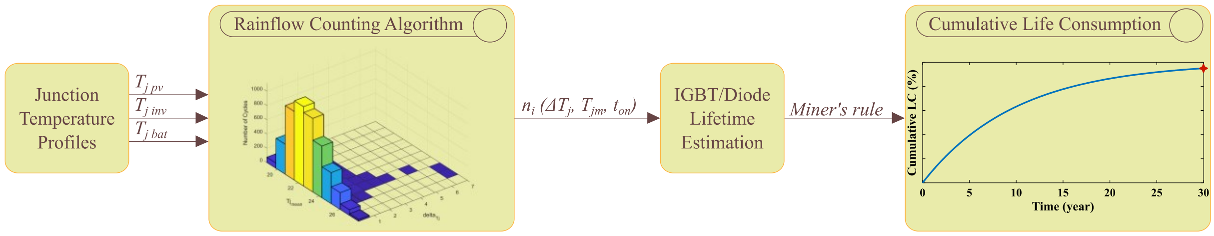
2 BATTERY LIFETIME ESTIMATION APPROACH

As the batteries play an important role in PV applications, estimating a reliable battery lifetime is important. In general, the reduction in the battery capacity depends on the number of battery charge/discharge cycles as well as the amplitude of these cycles. Thus, the state-of-charge (SOC) of the battery over a year can be translated to cycles with different depths by a rainflow counting algorithm. Then, from the battery's cycles-to-failure (N_f) versus depth-of-discharge diagram, the number of cycles-to-failure for each cycle can be determined. Finally, Miner's rule is used to accumulate the yearly damage of the battery. There is also another aging factor reducing the battery lifetime called the calendar aging, while the battery SOC idles at a constant level. A simplified formula has been used to calculate the calendar aging based on the SOC level and the idling time. A similar procedure has been adopted in [5].

The battery lifetime depends on both the mission profile as well as the decreased PV power generation as a result of degradation. In other words, a closed-loop calculation is needed to determine the battery lifetime so that the written program detects daily data and determines the battery life consumption over that data set.



(a)



(b)

Figure 1: (a) General scheme of the proposed approach, (b) employed lifetime estimation procedure.

3 METHODOLOGY

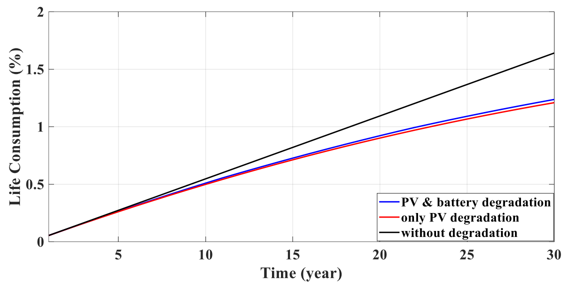
The reliability approach used in this study has been adapted from [6]. A lookup table approach has been adopted to translate the converters' input power to the power losses, then to the junction temperature of the IGBTs/diodes. An important detail to consider at this point is that the ambient temperature of the inverter must be equal to the indoor temperature, since the inverter will be installed indoors in residential applications. Then, the rainflow counting method has been used to determine the number of thermal cycles with their corresponding amplitude (ΔT_j), average (T_{jm}), and period (t_{on}). The damage inflicted by every cycle on the bond wires can be calculated using the chosen lifetime model. This model has been explained in [7]. Finally, according to Miner's rule, the damage inflicted by every cycle can be accumulated to calculate the total life consumption (LC) of the mission profile on the IGBT/diode:

$$LC = \sum (n_i / N_{fi}) \quad (1)$$

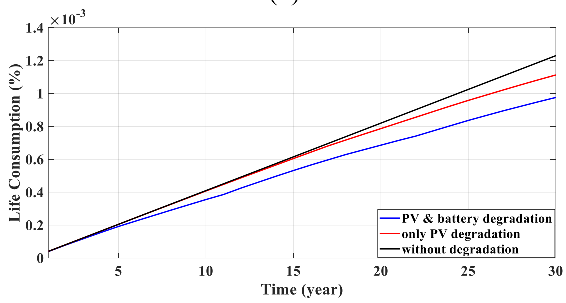
where n_i is the number of cycles obtained from the rainflow analysis with a certain combination of ΔT_j, T_{jm} and t_{on}.

4 RESULTS AND DISCUSSION

Here, a linear degradation based on a 30-year PV lifespan is chosen as the reference case, and the analysis is performed over this timeframe. The lifetime calculations are performed for every semiconductor device used within the power converters. A part of the obtained results is shown in Fig. 2(a-b).



(a)



(b)

Figure 1: The estimated life consumption of the chosen IGBTs: (a) Single-phase inverter, and (b) Bidirectional DC-DC converter.

Fig. 2(a) depicts the life consumption related to the first-leg upper IGBT of the single-phase inverter. As is obvious, the estimated life consumption is much higher in the case without considering the degradation. This is expected because adding the degradation rates into the calculations decreases the input power of the converters; and as a result, this reduction relieves some of the thermal stresses in the semiconductors. By considering both the PV and battery degradation rates, the life consumption of this switch is reduced by 24.6%. Interestingly, the battery degradation has not had much impact on the inverter lifetime as it only causes approximately 2.3% difference with the case considering only PV degradation.

Fig. 2(b) illustrates the life consumption of the lower IGBT within the battery converter. The results of this converter are different from the previous case. Between the case without degradation and the case with all degradation rates included, there is an error of 26%. Considering the fading battery capacity will result in a lower life consumption as the input power of the battery converter declines. Additionally, avoiding the battery degradation into the simulations will lead to almost 14% difference compared to the case with both degradations.

The main problem with the aforesaid IGBT/diode lifetime estimation method is that the estimated life expectancy is not realistic, and the predicted life consumption can be only used to compare different scenarios. The employed lifetime model for semiconductor devices is obtained in such a way that the components are tested by a power cycling lab setup under different thermal conditions (e.g., different average temperatures T_{jm} and temperature fluctuations ΔT_j) and at the same time, different lifetime indicators such as collector-emitter voltage and junction-to-case thermal resistance are measured/monitored. When these indicators exceed their allowable value, it is assumed that the IGBT/diode is failed. These longevity tests can only be performed for high temperature fluctuations over a limited time. Due to the limitations of the empirical data on the number of cycles to failure (N_f) for low thermal fluctuations (ΔT_j), the model parameters for these small temperature swings must be extrapolated, which will lead to a non-realistic estimated lifetime.

5 CONCLUSIONS

This paper presents a flexible/comprehensive reliability analysis framework for power electronics circuits used in PV systems. The inputs and parameters of this framework can be easily modified in accordance with difference cases/scenarios. Here, an example of this framework was investigated to show the effect of PV panel degradation and battery degradation on the predicted lifetime of power electronics converters. Both calendar and cycling aging of the battery has been considered into the calculations. A linear degradation has been also added to the PV panel model.

The initial results have been provided for both the PV inverter and the DC-DC battery converter. To conclude, the primary results indicate that although the influence of the battery degradation on the inverter lifetime is negligible, it should be included for the battery converter.

The present lifetime model will lead to a non-realistic estimated lifetime more than expected lifetime, but this method can be used for comparison purposes. To overcome this lifetime prediction issue, an improved method consisting of real experimental output data on several components as well as accurate finite element method (FEM) simulations should be provided. In addition to the lifetime model related to semiconductor devices, the degradation model of the solar panel and energy storage conversion system can be replaced with a more accurate model to have a meaningful comparison not only in terms of component-level reliability but also in terms of system-level reliability.

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