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Reliability Analysis of Micro-Inverters considering PV Module Variations and Degradation Rates

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Keywords

«Reliability», «Mission profile», «Photovoltaic», «Power semiconductor device», «Thermal stress».

Abstract

This paper analyzes the impact of PV module variations on the micro-inverter reliability. The evaluation results show a significant deviation in the micro-inverter reliability for different PV modules. Moreover, the PV module degradation impacts are also taken into consideration in the reliability assessment. Such information can be used to reduce the cost of the final designed micro-inverter and better match the PV application.

Introduction

With the rapid growth of the photovoltaic (PV) technology and its applications in the last decade, research and development in fields of PV industry and the power converter industry are making a fast pace both in terms of cost and efficiency [1]. In the recent years, the concept of using a micro-inverter, where the inverter is integrated with the PV module, has gained a significant interest in the PV inverter market, especially for the residential grid-connected applications [2]. This is mainly due to its several advantages such as reduced installation cost, increased energy yield with module-level maximum power point tracking (MPPT) [3] and also the idea of having a plug and play installation, which is easily expandable. The deployment of micro-inverters also has a high potential to reduce the loss of energy yield introduced by the module mismatch and uncertain shading, especially in larger scale PV systems [4]. Nevertheless, the micro-inverters in general still have a relatively high initial cost and lower power conversion efficiency compared to string- and central-inverter technologies. Therefore, the high-reliablity operation is strongly demanded for micro-inverters in order to maximize the energy yield without having a maintenance cost (i.e., having low failure rates) during the entire lifespan of the PV systems and thereby minimize the cost of energy.

Due to the integrated system structure, the reliability of micro-inverters is inevitably dependent on the PV module in several aspects. From the lifetime expectation point of view, the micro-inverters are expected to have a comparable lifetime as that of the PV module, which is typically above 20 years with the recent technology [4]. Matching the lifetime target with the PV module is quite a challenging mission for the micro-inverters, which are exposed to outdoor operating condition (e.g., harsh environment) as well as low (or no) maintenance expectations during the entire operation [6]. Moreover, the variation in the mission profile also imposes a challenge in terms of design for reliability, which has been discussed [7]. For instance, the mission profile of the installation sites in desert-like climate conditions (e.g., Arizona) usually lead to a high loading of the inverter during the entire year. In contrast, some installation sites in the cold climate conditions (e.g., Denmark) usually lead to a lower average loading condition of the inverter, but with a stronger seasonal variation during the year. In addition, the PV module characteristics such as module size (i.e., power rating) also vary considerably for different manufacturers [8], as it is illustrated in Fig. 1(a). In general, most PV module manufacturers provide a wide-range of PV module size from 48 to 98 cells, which results in a broad power range of PV module, e.g., from 150 W to 350 W [7]. In that case, it is a challenging task to ensure the reliability of the designed micro-inverter for such a wide power range. Moreover, in the long-term perspective, the PV module also degrades during the operation, where the PV power production continuously will be reduced. This will inevitably affect the loading and thus the reliability

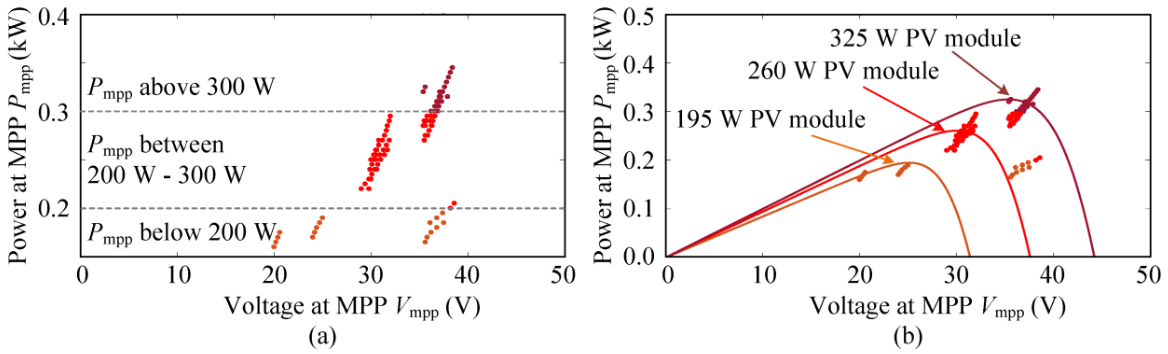

Fig. 1: Power and voltage at the maximum power point (MPP) of PV modules (under the standard test condition): (a) commercial available PV modules and (b) PV modules used in this paper.

of the micro-inverter in a positive direction [10], [11]. In that case, the impact of PV module degradation may be more pronounced for the micro-inverter with a large PV module size (under the same degradation rate and mission profile), and thus important for the design of micro-inverters.

Accordingly, the influence from PV module variations on the inverter reliability needs to be addressed in order to ensure the reliability of micro-inverters, which should be introduced for the market. In this paper, first, three representative PV modules are chosen to represent the variations of PV module power rating in commercial products based on a large number of module types. Then, their impact on the micro-inverter reliability, in particular, the power devices, will be analyzed using an interleaved-flyback topology and a mission profile from Denmark. Next, the impact of PV module degradation is also investigated for the different PV module sizes where a certain degradation rate is assumed. Finally, concluding remarks are given in the last section.

PV Module Characteristics and Variations

The PV technology has been under steady development for decades. In many cases, the PV systems can compete with conventional fueled power plants (e.g., coal-fired, gas turbine) in terms of cost of energy. The PV module technology is one of the areas that are making a very fast pace in terms of technology development. Emerging materials, better manufacturing techniques, and designs are the key aspects for pushing the boundaries of module efficiency. In that context, the scale factor in terms of production is important and it has pressed the price significantly down. The efficiency of PV module has also increased and it refers to the maximum amount of electricity a PV module can generate from sunlight at a given irradiation. Most PV modules have efficiencies in the range of 9%-25% [12]. The efficiency differs between different module designs and technologies, where the most highly efficient modules are usually the most expensive ones. However, they often have the best value for cost when considering the immediate and long-term investment of PV systems. Photovoltaic cells are mainly classified as polycrystalline, monocrystalline or thin-film. Monocrystalline solar cells have efficiencies of 18-22% (polycrystalline PV cell modules have an efficiency of 16%-18% and thin-layer PV cells modules have an efficiency between 9%-17%) and are the most efficient type of the three types of silicon PV modules [13]. Regarding the number of cells for the modules of the independent PV power system and grid-connected PV power system, the modules are generally 36 cells and 60 cells being the most common for residential and small commercial applications and while 72 cells are normally used for commercial solar installations [14].

Nevertheless, the characteristic of silicon-based PV module also varies for different manufacturers (i.e. size of the PV cell and its efficiency, number of cells connected in series within a PV module). From a reliability perspective, the PV module power rating is a parameter that strongly affects the loading of the micro-inverter and thereby its reliability. An example of the variation in the PV module characteristic in terms of power and voltage at the maximum power point (MPP) is illustrated in Fig. 1(a) based on data from 624 commercial PV modules [12]. It can be seen from the result that the power rating (e.g., nameplate power) of the PV module is in the range of 150 W to 350 W, while the

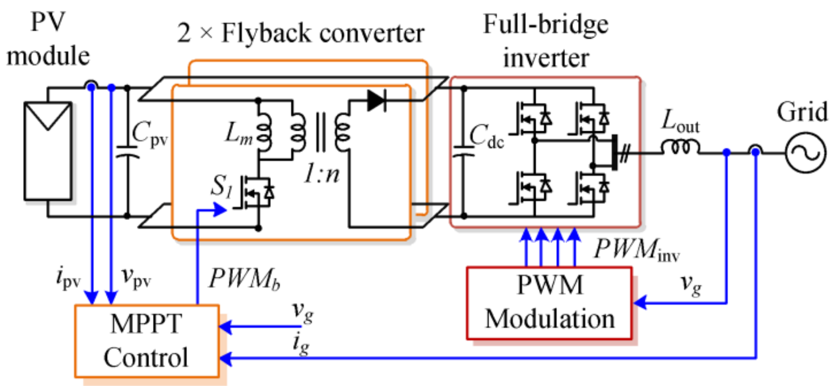

Fig. 2: System configuration of micro-inverter with interleaved-flyback and full-bridge topology.

Table I: System parameters of Micro-Inverter.

Input voltage range	v_{pv} = 20-40 V
Nominal DC-link voltage	v_{dc} = 325 V
Nominal operating power	P = 350 W
Switching frequency	f_s = 35 kHz
Magnetizing inductance	L_m = 10 μH
Output inductance	L_{out} = 7.2 mH
Transformer turns ratio	n = 3
Capacitance of input capacitor	C_{pv} = 4.7 mF
Capacitance of DC-link capacitor	C_{dc} = 1 μF
Grid nominal voltage (RMS)	v_g = 230 V
Grid nominal frequency	f_g = 50 Hz

voltage at the MPP is in the range of 20 V to 40 V. This wide range of operating voltage and power will affect the micro-inverter loading and thereby its reliability.

In order to demonstrate the impact of PV module variations, the PV modules in Fig. 1(a) are classified into three groups based on their power rating: below 200 W, between 200 W and 300 W, above 300 W. Then, three PV modules are modeled in this paper with parameters corresponding to the average values (power rating of 195 W, 260 W, and 325 W) for PV module characteristics (power and voltage at the MPP) within each group, as it is shown in Fig. 1(b), and they will be employed in the reliability analysis in the following.

System Configuration of Micro-Inverter

The micro-inverter has two main tasks for operation – first it has to harvest the maximum energy available from the PV module and next it has to transfer the power to the grid efficiently and grid-friendly. A large number of micro-inverters have been proposed in the past – and no final and single solution exists [15]. Therefore, in this paper, the micro-inverter topology is kept at a minimum number of components in order to simplify the analysis. A system diagram of the selected micro-inverter used in this paper is shown in Fig. 2 and the system parameters are given in Table I. Here, an interleaved-flyback topology is used for the dc-dc conversion stage in order to achieve a high step-up voltage ratio [15]. Then, a full-bridge inverter is employed in the dc-ac conversion stage (i.e., unfolding stage), which operates at the grid fundamental frequency. In this topology, the flyback converter operates with high switching frequency and thus it will be subjected to high thermal stresses. Therefore, in this paper, the reliability of the power devices in the flyback stage is considered as a case study to assess the influence of PV module and mission profile characteristic.

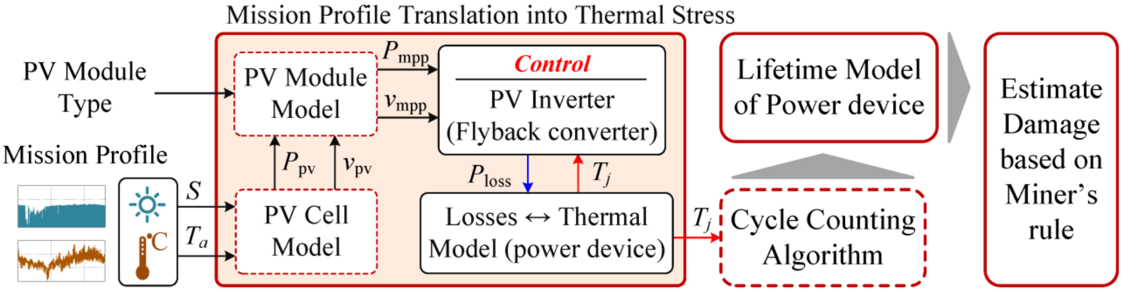

Fig. 3: Reliability assessment of PV micro-inverter considering PV module characteristic.

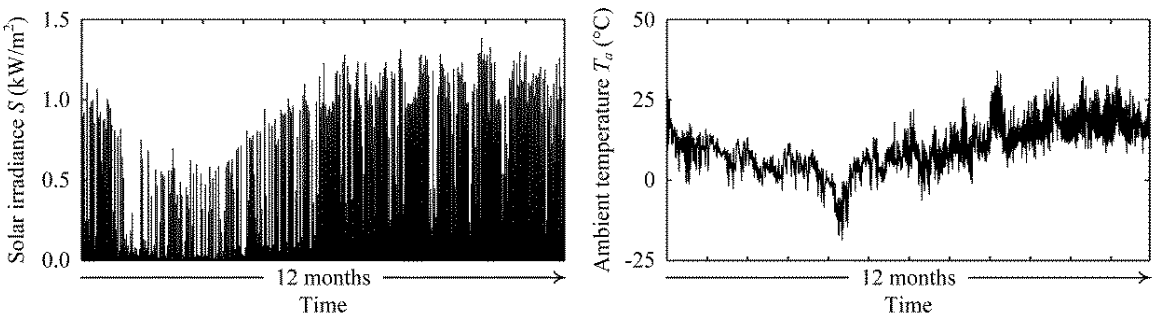

Fig. 4: One-year mission profile of PV system installed in Denmark with the resolution of 5 minutes/sampling: (a) solar irradiance and (b) ambient temperature.

Reliability Analysis of Micro-Inverter considering PV Module Variations

A general procedure to analyze the reliability of micro-inverter is illustrated in Fig. 3, where the PV module model is taken into account. There are three main steps involved: 1) Mission translation into PV power and voltage, 2) Thermal loading determination, and 3) Reliability assessment, which will be demonstrated in the following.

In this study, a mission profile from an installation site in Denmark is considered. A one-year mission profile, consisting of the solar irradiance and ambient temperature, recorded with 5 minutes/sample resolution is shown in Fig. 4. When applying the mission profile to the PV module model, the power and voltage at the MPP of the PV module can be obtained. The variations in power and voltage at the MPP during one-year of different PV modules are shown in Figs. 5-7. It can be seen from the result that the power at the MPP increases considerably with the increased PV module power rating. Moreover, the voltage at the MPP also varies in the wide range for the 325 W PV module (i.e., between 29 V and 40 V), compared to the case with 195 W PV module (i.e., between 21 V and 28 V). On one hand, the high operating voltage usually increases the efficiency of the flyback converter due to the lower step-up ratio requirement. However, it is also quite a challenge for the micro-inverter design in terms of maintaining high-efficiency over a wide voltage range.

From the PV power and voltage profiles in Figs. 5-7, the power losses dissipated in the power device can be calculated based on the loss model and applied to the thermal model of the power device, in order to evaluate the thermal stress. In this case, the thermal cycle amplitude ΔT_j and the mean junction temperature T_{jm} are considered, as they are the main life-limiting factors of power devices, which causes bond-wire lift off after a number of cycles [16]. The thermal stress of the power device in the micro-inverter with the PV module of 195 W, 260 W, and 325 W are shown in Figs. 8-10, respectively. It can be seen from the thermal loading of the power device that the thermal stress increases as the PV module power rating increases. This is due to the higher loading (i.e., input power) of the micro-inverter during the operation.

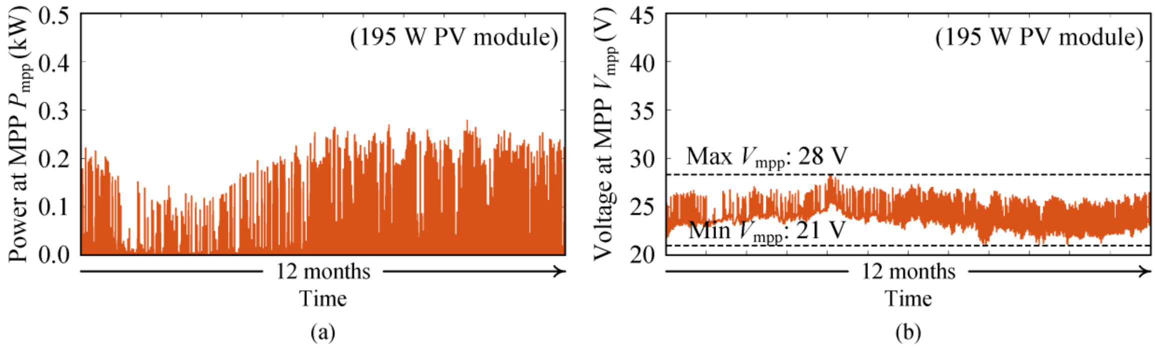

Fig. 5: Variation in the operating condition of the micro-inverter with 195 W PV module during one-year operation: (a) power at the MPP and (b) voltage at the MPP.

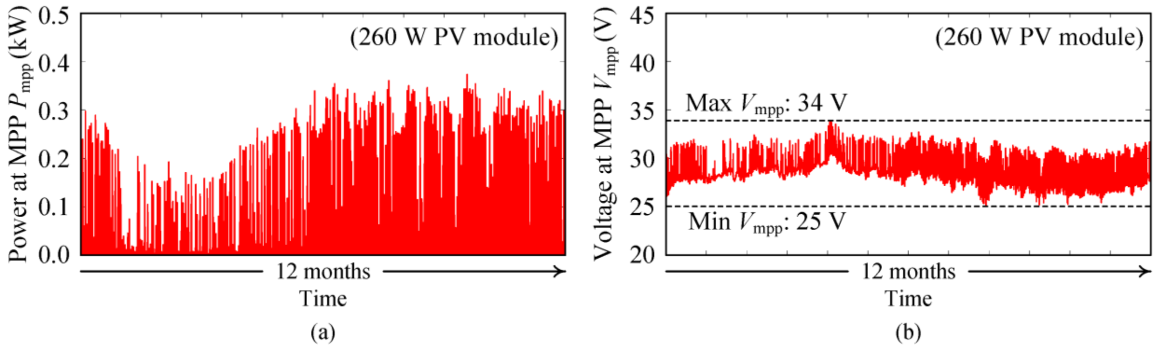

Fig. 6: Variation in the operating condition of the micro-inverter with 260 W PV module during one-year operation: (a) power at the MPP and (b) voltage at the MPP.

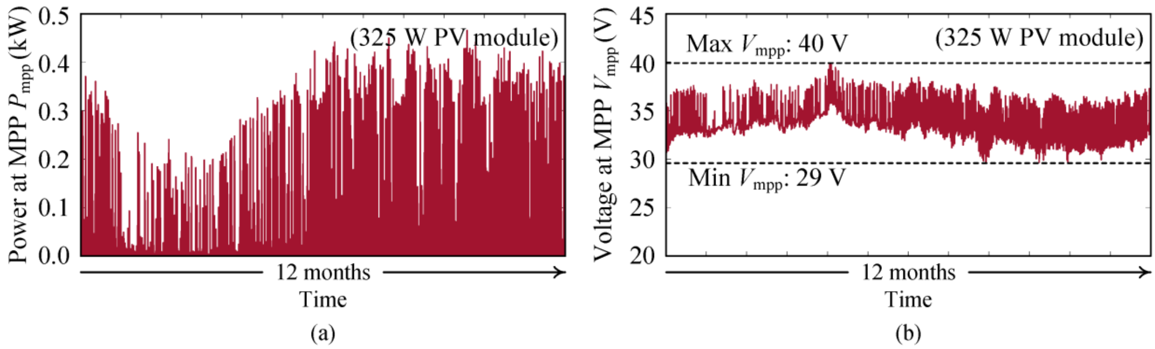

Fig. 7: Variation in the operating condition of the micro-inverter with 325 W PV module during one-year operation: (a) power at the MPP and (b) voltage at the MPP.

From the thermal loading of the power device, the damage occurred during the operation can be evaluated by using the lifetime model of the power device [16]. The damage can be used as a reliability metric for comparing the reliability performance of the micro-inverter with different PV modules. A high damage indicates the low reliability of the power device, where the end-of-life is determined when the damage is accumulated to 1. The damage accumulation in the power device during one-year operation of micro-inverter is summarized in Fig. 11. Clearly, using a large PV module leads to a high accumulated damage during the operation, due to high loading of the micro-inverter. In the case of 325 W PV module, the accumulated damage during one-year is 0.029, which corresponds to the expected lifetime of 34 years. On the other hand, the accumulated damage of the power device in the micro-inverter with 195 W PV module is 0.004 per year (resulting in the expected lifetime of 250 years). This indicates a significant impact of the PV module characteristic on the reliability and lifetime prediction of the micro-inverters. From another perspective, a certain design

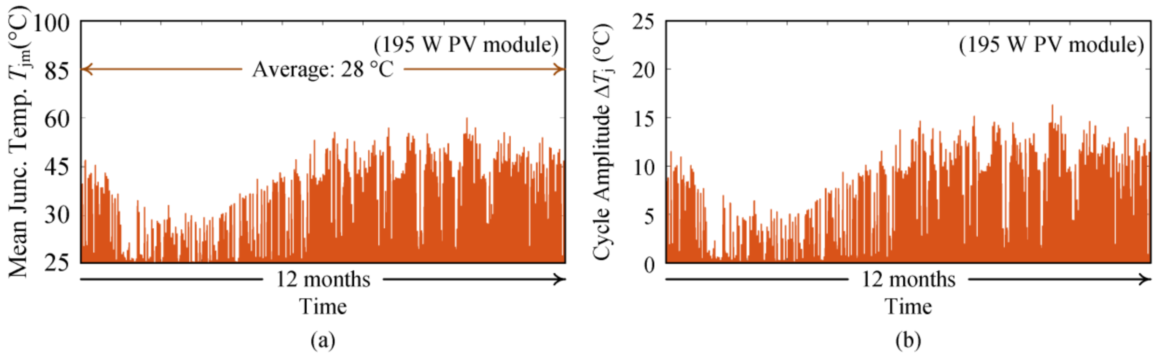

Fig. 8: Thermal loading of the micro-inverter with 195 W PV module during one-year operation: (a) Mean junction temperature and (b) cycle amplitude.

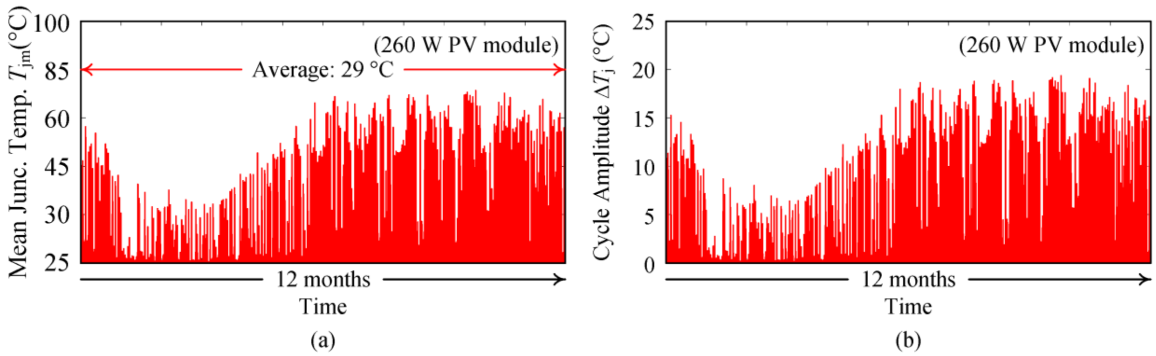

Fig. 9: Thermal loading of the micro-inverter with 260 W PV module during one-year operation: (a) Mean junction temperature and (b) cycle amplitude.

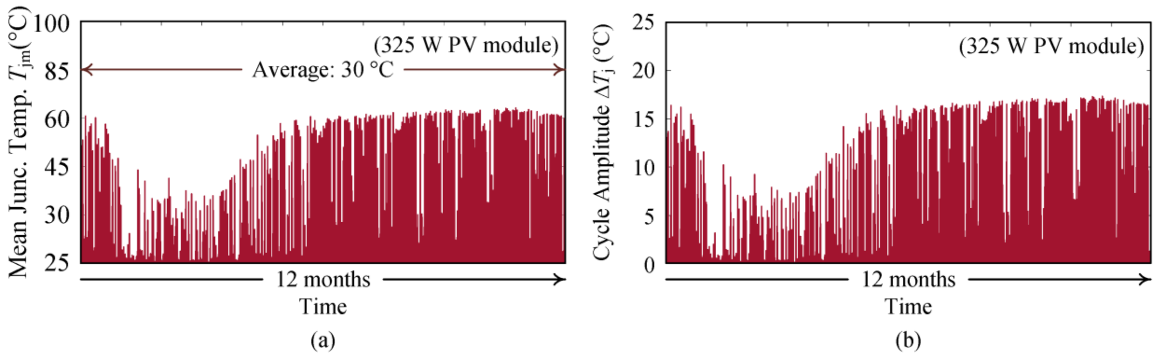

Fig. 10: Thermal loading of the micro-inverter with 325 W PV module during one-year operation: (a) Mean junction temperature and (b) cycle amplitude.

margin in terms of reliability is required when the micro-inverters need to cope with a large variation in the PV module characteristics (e.g., power rating).

Impacts of PV Module Degradation on Reliability

Further, the degradation of PV module is another aspect that should be taken into consideration in the reliability assessment. The aging of PV module usually leads to a continuous reduction in the PV output power which may have a certain impact on the micro-inverter reliability. Specifically, the output power of the PV module and thereby the loading of micro-inverter will decrease over time due to the degradation. The PV output power of different PV modules for the 1st and after the 20th years of operation are shown in Figs. 12(a)-14(a). In that case, the thermal stress of the power device after several years of operation will be reduced significantly following the loading condition of the micro-inverter. Typically, a linear degradation is considered for determining the long-term PV module output

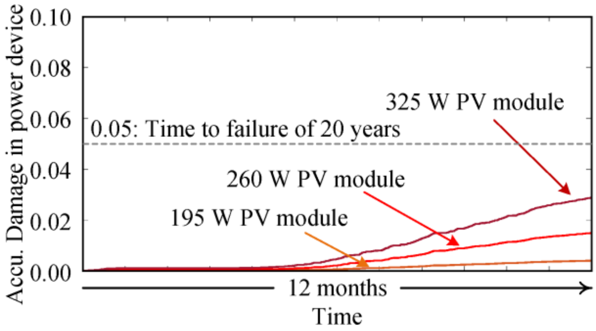

Fig. 11: Damage accumulation of power device in micro-inverter with different PV modules.

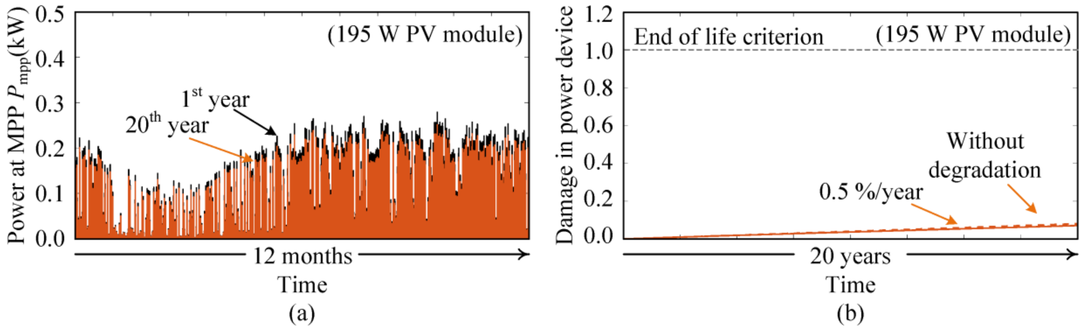

Fig. 12: Impact of PV module degradation on the reliability of micro-inverter with 195 W PV module: (a) power at the MPP and (b) the damage accumulation.

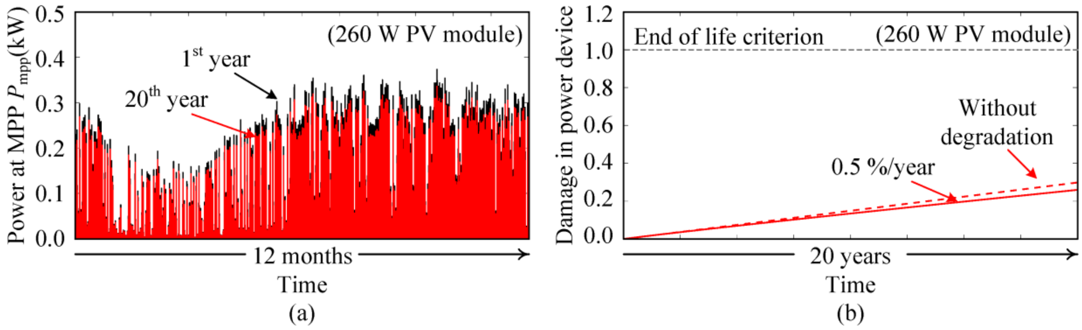

Fig. 13: Impact of PV module degradation on the reliability of micro-inverter with 260 W PV module: (a) power at the MPP and (b) the damage accumulation.

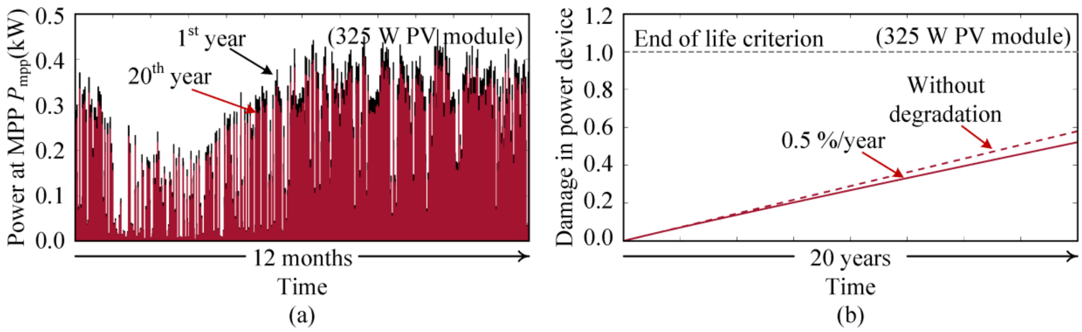

Fig. 14: Impact of PV module degradation on the reliability of micro-inverter with 325 W PV module: (a) power at the MPP and (b) the damage accumulation.

power, where the degradation rate of 0.5%/year is used in this paper, according to the field experience [17]. For the same degradation rate, the PV module with high power rating will experience a more significant decrease in the PV power over time. From the micro-inverter reliability perspective, this will be reflected in the long-term accumulated damage, where the damage per year will decrease significantly for the micro-inverter with large module size (e.g., 325 W). The impact of PV module degradation on the micro-inverter reliability is demonstrated in Fig. 12(b), where the accumulated damage over 20 years for 195 W PV module is demonstrated. In this case, the difference in the damage is relatively small, as the degradation rate has a less effect on the PV module with a low power rating. In contrast, the impact of PV module degradation is more pronounced for the PV module with a higher power rating. This is demonstrated in Figs. 13(b) and 14(b), where the accumulated damage in the power device considering the PV module degradation is shown. In the case of 325W PV module, the difference in the accumulated damage between the case with and without considering PV module degradation is about 10 %, indicating a significant impact of the PV module degradation on the reliability prediction. Thus, in that case, the degradation rate of the PV module should also be taken into consideration during the reliability assessment, in order to represent a more realistic loading condition of the micro-inverters under a long-term operation (e.g., 20 years).

Conclusion

The reliability of micro-inverter has been analyzed in this paper, where the impact of PV module variations is taken into consideration. Three PV modules with different power ratings are used as a case study to represent the variation in the PV module characteristic from different manufacturers. The analysis is carried out with a mission profile from Denmark, where the reliability of the power device in the flyback converter is considered. The evaluation results show a significant deviation in micro-inverter reliability for different PV module power ratings. Employing a PV module with high power rating results in high accumulated damage of the micro-inverter, which decreases the lifetime. Moreover, the impact of PV module degradation is also pronounced with the case of large PV module, where the damage in the micro-inverter decreases significantly over time, and such information can be used to decrease the cost of the micro-inverter.

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