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Photovoltaic Module Characteristic Influence on Reliability of Micro-Inverters

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***Abstract*—Due to an integrated system structure between the Photovoltaic (PV) module and inverter, the characteristic of PV module can strongly influence the operating condition and loading of micro-inverters. The commercially available PV module has a certain variation in terms of power rating and voltage at the Maximum Power Point (MPP). Accordingly, the PV micro-inverter loading conditions, and thereby the reliability, will inevitably be affected by those variations. In this paper, the impact of PV module characteristic on the reliability of micro-inverters is investigated. Six commercial PV modules are used to demonstrate the variation in the PV module characteristic in real-field operation, and the mission profile of the installation site in Arizona is used as a case study. The evaluation results indicate that the voltage at the MPP of the PV module has a strong influence on the thermal loading and reliability of the micro-inverter. Employing a PV module with high voltage at the MPP can effectively reduce the loading of the micro-inverter, since the inverter efficiency is maintained at a high level during the operation. In that case, a high-reliable operation of the micro-inverters can be achieved.**

***Index Terms*—Micro-inverters, PV modules, power devices, lifetime, reliability, mission profile.**

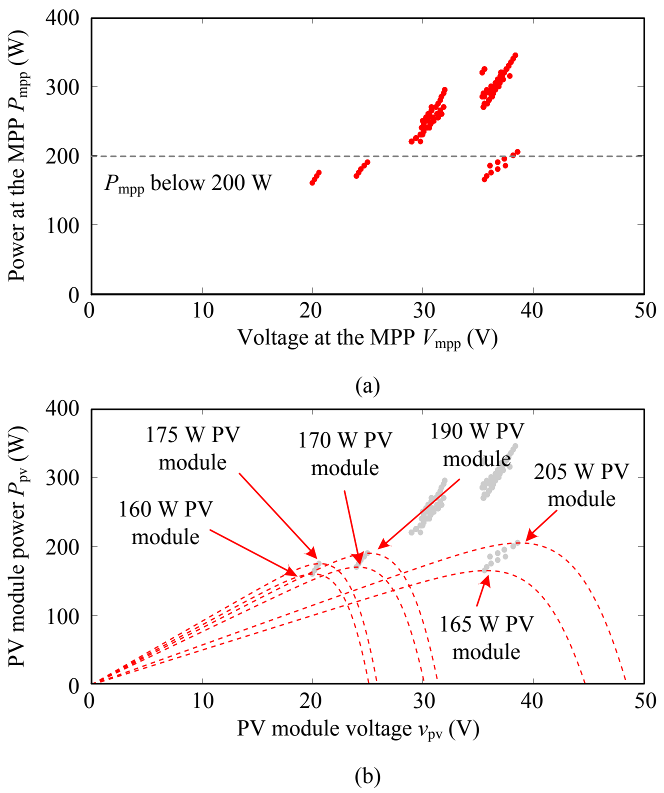
I. INTRODUCTION

With the aim to introduce more renewable energy into the energy mix, the Photovoltaic (PV) technology and its applications have been witnessed with a rapid growth during the last decade. Consequently, research and development of the PV technology are making a fast pace in several areas, especially, PV modules and inverters [1]. For the PV modules, reducing the module cost and increasing the conversion efficiency are the main research areas, which have high potential to reduce the cost of solar energy [2]. Moreover, enhancing the PV module lifespan by reducing the module degradation rate is also a major concern. For the PV inverters, increasing the inverter efficiency and improving the inverter reliability are the two aspects that have been in focus in recent years [3].

Traditionally, central- and string-inverters are dominated in the PV inverter market due to their high power conversion efficiency [4]. However, the concept of integrating the PV module with the inverter, referred to as micro-inverters, are gaining more and more attention [5]–[7]. This is mainly due to several advantages of micro-inverters such as reduced installation time and cost, increased energy yield with module-level Maximum Power Point Tracking (MPPT) [8]. Nevertheless, the initial cost of micro-inverters are relatively high due to a large number of power converters in the system. Moreover, the efficiency of micro-inverters are usually lower than the central- and string-inverter technologies. Thus, the reliability of micro-inverters plays an important role in the overall cost assessment. More specifically, high-reliable operation is strongly demanded for micro-inverters in order to maximize the energy yield during the lifespan (without being replaced) and thus minimize the cost of solar energy.

Since the micro-inverters are integrated with the PV module, they are expected to have a comparable lifetime as that of the PV module. While having a lifespan above 20 years is becoming an industry standard for PV module technology [9], this is quite a challenging mission for power electronic systems, e.g., micro-inverters [10]. Additionally, the micro-inverters are being exposed to the outdoor operating conditions as well as low (or no) maintenance during the entire operation. In that case, the mission profile of the system (i.e., solar irradiance and ambient temperature conditions) will strongly affect the loading and reliability of micro-inverters, which have been addressed in [11]. However, the variation in the PV module characteristic is another challenge in terms of design for reliability of micro-inverters. Depending on the manufacturer, the PV module characteristic such as the power rating and the voltage at the Maximum Power Point (MPP) can vary in a certain range [12]. It can be seen from the characteristics of commercial PV modules in Fig. 1(a) that the module power rating can vary from 150 W to 350 W, while the voltage at the MPP of the module is in the range of 20 V to 40 V. Even under the same mission profile, the operating condition of the micro-inverters with different PV modules will be different. In that case, the loading of micro-inverters are affected by the variations in the PV module characteristic. Thus, it is a challenging task to ensure the reliability of the designed micro-inverters with a wide range of PV module characteristic, since the selection of PV module may affect the reliability performance of the micro-inverters.

To address the above issue, the impact of PV module characteristic on the micro-inverter reliability needs to be analyzed. In this paper, six PV modules are chosen to represent the variations of PV module characteristic in commercial products. The system description of the micro-inverter is discussed in § II. The variation in the operating condition of micro-inverters due to the PV module characteristic is addressed in § III, where the installation site at Arizona is considered. The reliability analysis is carried out in § IV, where the thermal loading and the damage of the power devices during one-year operation are investigated. Finally, concluding remarks are given in § V.



(a)

(b)

Fig. 1. Power and voltage characteristic of PV modules (at the standard test condition): (a) commercial PV modules and (b) the case study PV modules.

TABLE I
PARAMETERS OF THE PV MODULE USED IN THE CASE STUDY AT THE STANDARD TEST CONDITION [12].

Model	Power rating	Voltage at the MPP	No. of cells
TSM-160PEG40.07	160 W	20 V	72
TSM-165DA01	165 W	35.6 V	72
TSM-170PA03	170 W	24 V	48
TSM-175PEG40.07	175 W	20.6 V	72
TSM-190PA03	190 W	25 V	48
TSM-205DA01A.08	205 W	38.6 V	72

II. SYSTEM DESCRIPTION

A. PV Modules

Several PV module technologies are available commercially, where the silicon-based PV modules are the dominant in the market [13]. As shown in Fig. 1(a), the characteristic of PV module varies for different manufacturers (i.e., size of PV cell, efficiency, number of cells connected in series with a PV module). The power rating of the PV module, which is the main consideration for determining the energy yield, is in the range of 150 W to 350 W. Clearly, using a PV module with high power rating will increase the energy yield, but also the loading of micro-inverters (i.e., input power).

In addition to the power rating, the voltage at the MPP also varies in a wide range, especially for PV module with low power rating. In that case, the voltage at the MPP is in the range of 20 V to 40 V for the PV module with the power rating close to 200 W, as it is shown in Fig. 1(a). The voltage at the MPP plays an important role in terms of the operating efficiency of micro-inverters. Operating the micro-inverters at low input voltage (i.e., voltage at the MPP) will reduce the inverter efficiency due to high step-up ratio, and thereby increase the loss in the power device. In that case, the reliability of the micro-inverters will be affected.

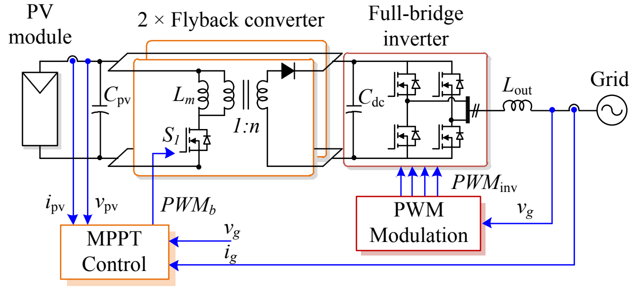


Fig. 2. System configuration of micro-inverter with interleaved-flyback and full-bridge topology and simplified control method.

In order to investigate the impact of variations in the PV module characteristic on the micro-inverter reliability, six commercial PV modules as shown in Fig. 1(b) are used as a case study, where the key parameters at the Standard Test Condition (STC) are given in Table I. Notably, the voltage at the MPP of some PV modules is not increased as the power rating increases (e.g., PV module with the power rating of 165 W and 175 W). This demonstrates a variation in the PV module characteristic in the real-field operation.

B. Micro-Inverters

A power electronic system (e.g., micro-inverter) is required as an interface between the PV module and the grid to enable power control of the PV system and to ensure proper grid-integration. In the case of micro-inverter, a high voltage step-up ratio is demanded, since the PV module voltage is in the range of 20-40 V while the AC grid voltage is around 220-230 V (in Europe). Typically, a two-stage power conversion system consisting of DC-DC and DC-AC conversion stages are required to achieve the above demand. At the same time, a Maximum Power Point Tracking (MPPT) operation is also implemented in the control of the DC-DC conversion stage.

A system configuration of the PV micro-inverter used in this study is shown in Fig. 2, where the system parameters are shown in Table II. The DC-DC conversion stage is realized by an interleaved-flyback topology in order to achieve a high step-up ratio [14]. Then, a full-bridge inverter is employed at 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 is subjected to high stresses thermally. Thus, the reliability of power device in the flyback stage (i.e., the power device S_1 in Fig. 2) is considered in this paper.

TABLE II
PARAMETERS OF THE SINGLE-PHASE MICRO-INVERTER WITH FLYBACK (DC-DC) AND FULL-BRIDGE (DC-AC) TOPOLOGY (FIG. 2).

Input voltage range	15-45 V
Maximum operating power	350 W
Switching frequency of flyback converter	f_s = 35 kHz
Switching frequency of full-bridge inverter	f_{inv} = 50 Hz
Magnetizing inductance	L_m = 10 μH
Output inductor	L_{out} = 7.2 mH
Turns ratio of transformer	n = 3
Capacitance of input capacitor	C_{pv} = 4700 μF
Capacitance of DC-link capacitor	C_{dc} = 1 μF
Grid nominal voltage (RMS)	V_g = 230 V
Grid nominal frequency	ω_0 = $2\pi\times 50$ rad/s

TABLE III
PARAMETERS OF THE LIFETIME MODEL OF THE POWER DEVICE S_1 [16].

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	

C. Power Devices

The power device in the flyback converter (i.e., S_1) is realized by the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) device from Infineon [15] following the system parameters given in Table II. The cooling system (i.e., the heat sink sizing) is designed to fulfill the requirement of 100 ^{o}C maximum junction temperature of power device when the inverter operates at the rated power (i.e., 350 W), the input power of 25 V, and the ambient temperature of 25 ^{o}C.

For the purpose of reliability assessment, the lifetime model of the power device is required. In this paper, the lifetime model related to the thermal cycling in [16] is employed, where the number of cycle to failure N_f under a certain thermal stress condition (e.g., ΔT_j cycle amplitude, T_{jm} mean value, and t_{on} cycle period) can be calculated as

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

where the lifetime model parameters are given in Table III.

III. OPERATING CONDITION OF MICRO-INVERTER CONSIDERING PV MODULE VARIATIONS

In order to determine the operating condition of the micro-inverter, a general procedure to translate the environmental condition of the system (e.g., mission profile) to the input parameter of the micro-inverters (e.g., input power and voltage) is required as it is illustrated in Fig. 3.

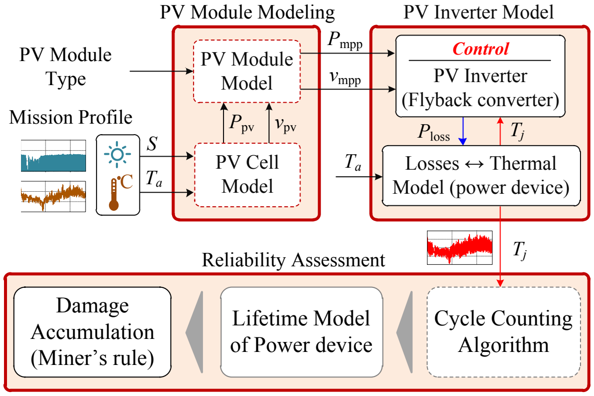


Fig. 3. Mission profile translation into loading and reliability metric of micro-inverter considering PV module characteristic [3].

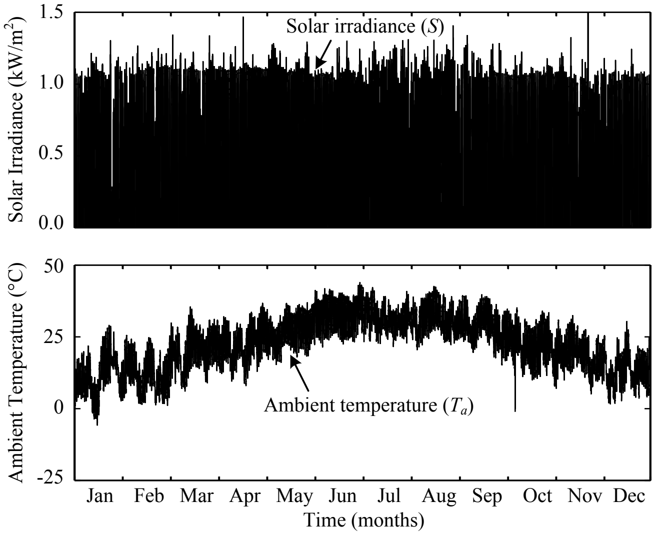


Fig. 4. One-year mission profile of the installation site in Arizona with a sampling rate of 5 mins per sample: (a) solar irradiance and (b) ambient temperature.

A. Mission Profile

The operating condition of the micro-inverter is strongly affected by the PV module power and voltage characteristic. During the operation, the power and voltage at the MPP of the PV module are mainly determined by the solar irradiance and ambient temperature conditions. Thus, both parameters are considered as a mission profile of the PV system. The one-year mission profiles recorded in Arizona, USA with a sampling rate of 5 minutes per sample are used in this study, as it is shown in Fig. 4. From the recorded mission profile in Arizona, the average solar irradiance level is high through the year, while the ambient temperature varies in a certain range due to seasonal variations (e.g., summer and winter periods).

B. Power at Maximum Power Point

The loading condition of the micro-inverter can be assessed from the power at the MPP of the PV module (i.e., input power of the inverter). From the mission profile in Fig. 4, the power

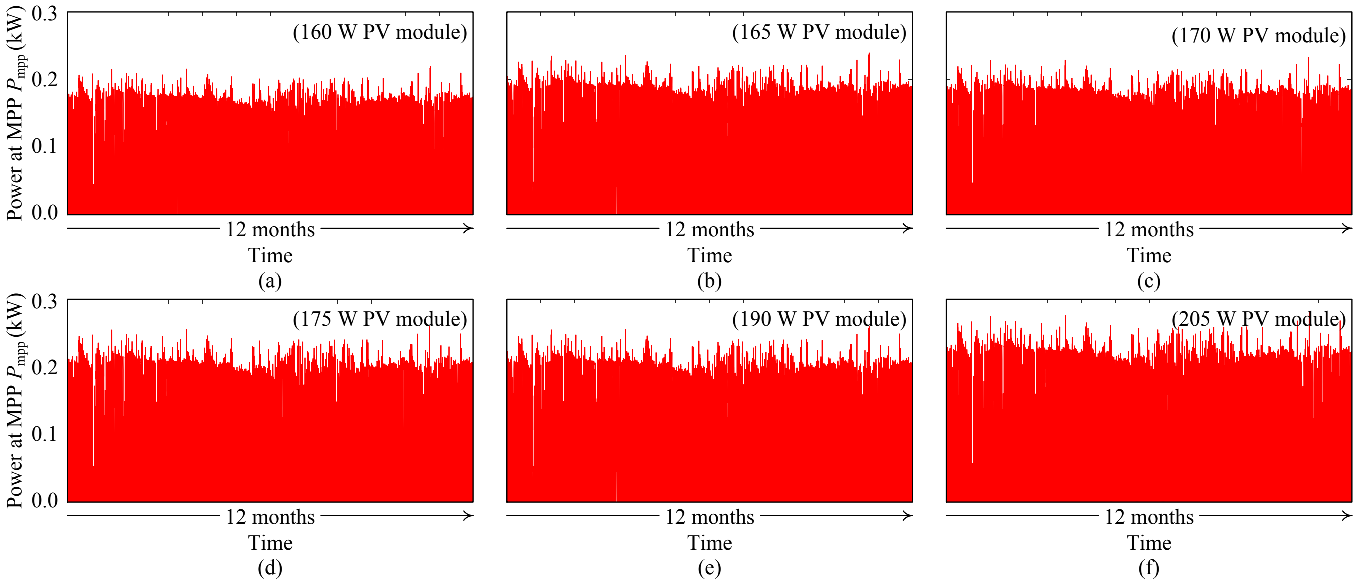


Fig. 5. Variation in the power at the MPP of the PV module with power rating of: (a) 160 W, (b) 165 W, (c) 170 W, (d) 175 W, (e) 190 W, and (f) 205 W.

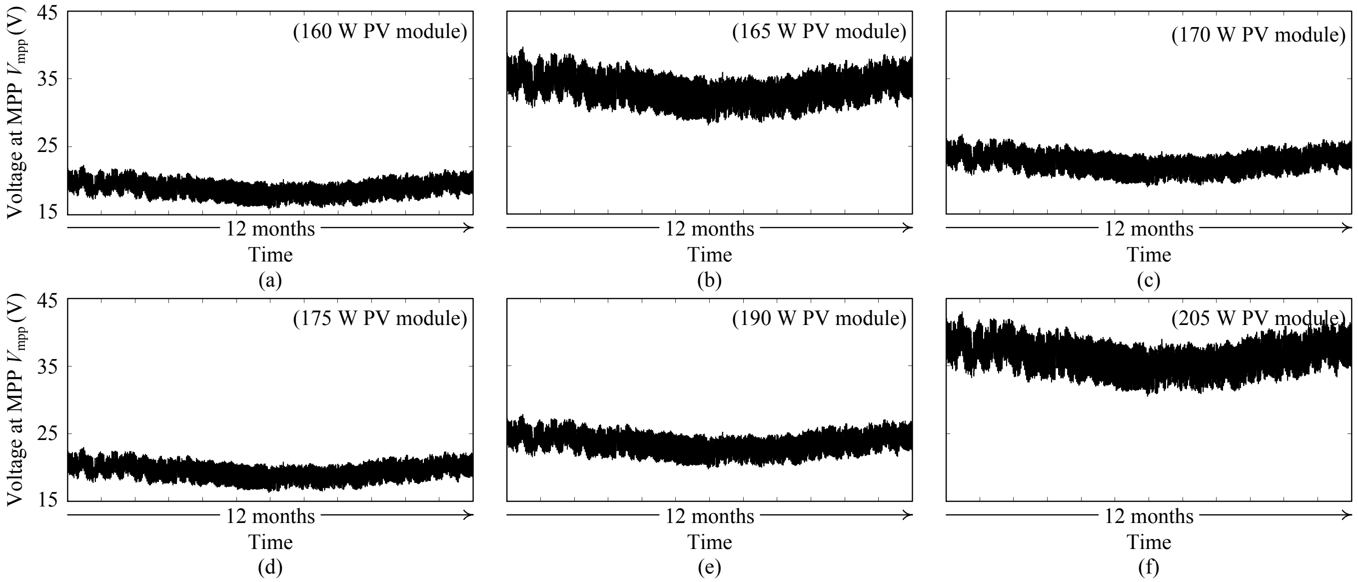


Fig. 6. Variation in the voltage at the MPP of the PV module with power rating of: (a) 160 W, (b) 165 W, (c) 170 W, (d) 175 W, (e) 190 W, and (f) 205 W.

at the MPP of each PV modules can be determined from the PV module model, as it is shown in Fig. 5. It can be seen from the results in Fig. 5 that the power at the MPP has a similar tendency as the solar irradiance profile, which is constantly high over the entire year. When comparing the power at the MPP of different PV modules, it can be seen that the maximum power of the PV module increases as the PV module power rating increases (e.g., from Fig. 5(a) to Fig. 5(f)). Since the power at the MPP of the PV module is corresponding to the input power of the micro-inverter, employing a PV module with high power rating (e.g., 205 W PV module) will increase the loading of the micro-inverter during the operation.

C. Voltage at Maximum Power Point

In addition to the power at the MPP, the voltage at the MPP of the PV module is another parameter that strongly affects the operating efficiency of the micro-inverter, especially, the DC-DC conversion stage. In general, the efficiency of the DC-DC converter (e.g., flyback converter) decreases as the step-up ratio increases (e.g., at a low input voltage condition). In that case, operating the micro-inverter with low input voltage will decrease the inverter efficiency, resulting in more power losses dissipated in the power device.

The voltage at the MPP during one-year operation of different PV modules is shown in Fig. 6. It can be seen from

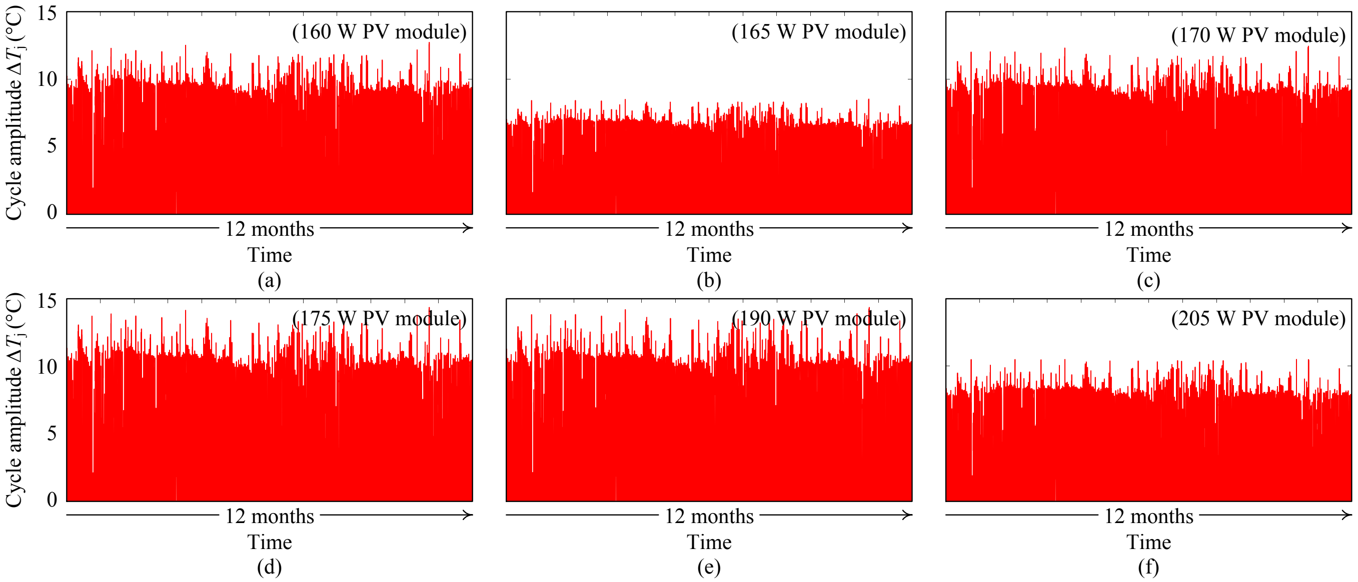


Fig. 7. Thermal loading of the power device (cycle amplitude) in the micro-inverter with the PV module with power rating of: (a) 160 W, (b) 165 W, (c) 170 W, (d) 175 W, (e) 190 W, and (f) 205 W.

the results in Fig. 6 that the variation in the voltage at the MPP correlates with the PV module characteristic in Table I. For instance, the voltage at the MPP of the PV module with the power rating of 160 W and 175 W are in the range of 16-22 V, which is close to the voltage at the MPP at the STC of the PV module, i.e., 20 V. The highest average voltage is observed in the PV module with the power rating of 165 W and 205 W, where the average voltage at the MPP during one-year operation is 33 V and 36 V, respectively. In those cases, the voltage at the MPP of the PV module also varies in a wider range during the day compared to the other cases.

IV. RELIABILITY ANALYSIS

From the power and voltage at the MPP of the PV module, the loading of the micro-inverter can be determined. Then, the power losses dissipated in the power devices can be obtained by using the losses and thermal model of the power devices, following the procedure in Fig. 3. Afterwards, the thermal loading of the power device can be estimated and applied to the lifetime model to obtain the damage during the operation, which then can be used as a reliability metric.

A. Thermal Loading fo Power Devices

The input power and voltage of the micro-inverter (i.e., power and voltage at the MPP of the PV module) can be translated into the thermal stress of the power device. In this case, the thermal cycle amplitude ΔT_j is considered, as it is one of the main life-limiting factors of power device, which causes bond-wire fatigue after a number of cycles [17].

The thermal cycle amplitude of the power device during one-year operation of the micro-inverter is shown in Fig. 7. From the results in Fig. 7, it can be seen that the PV module characteristic has a strong influence on the thermal stress of the power device. More specifically, the cycle amplitude of the power device decreases significantly for the micro-inverter with the PV module with high voltage at the MPP, as it can be seen in Fig. 7(b) and 7(f). Notably, the thermal stress in the case of 205 W PV module is even lower than that of the 160 W PV module in Fig. 7(a) even the power rating is significantly higher. That is to say, the operating voltage of the micro-inverter has a strong influence on the inverter efficiency and thereby thermal loading of the power devices, in addition to the power rating of the module.

B. Damage of Power Devices

For the wear-out failure mechanism related to the thermal cycling of the power devices, it is normally assumed that the contribution of each thermal cycle to the failure, referred to as damage, is accumulated linearly and independently during operation (i.e., using the Miner's rule) [18]. For instance, the accumulated damage in the power device during the operation can be calculated as

$$AD = \sum_i \frac{n_i}{N_{fi}} \tag{2}$$

where AD is the accumulated damage of the power device, n_i is the number of cycles for a certain thermal stress condition (e.g., ΔT_j, T_{jm}, and t_{on}). Notably, the operation with high accumulated damage indicates low reliability of the micro-inverters (e.g., power device), where the end-of-life of the power device is determined when the damage is accumulated to unity (i.e., AD = 1).

When applying the thermal loading in Fig. 7 to the lifetime model in (1), the accumulated damage during one-year operation can be determined following (2). The accumulated damage of the power device in the micro-inverter with different PV modules are given in Table IV and the comparison

TABLE IV

ACCUMULATED DAMAGE IN THE POWER DEVICE OF MICRO-INVERTER WITH DIFFERENT PV MODULES.

Power rating	Voltage at the MPP	Accumulated Damage (per year)
160 W	20 V	22.54×10^{-3}
165 W	35.6 V	4.47×10^{-3}
170 W	24 V	20.83×10^{-3}
175 W	20.6 V	37.56×10^{-3}
190 W	25 V	37.76×10^{-3}
205 W	38.6 V	11.02×10^{-3}

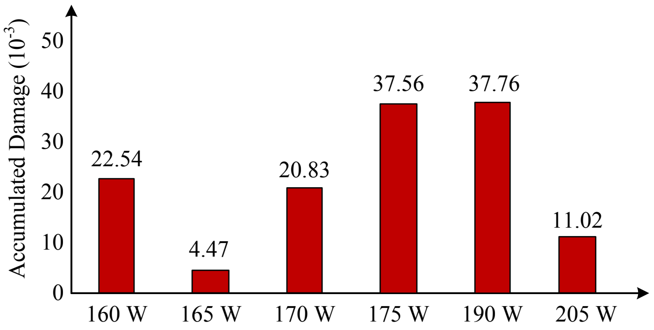


Fig. 8. Comparison of the accumulated damage of power device in the micro-inverter (i.e., flyback converter) over one year for different PV modules.

is summarized in Fig. 8. The highest accumulated damage occurs in the case of micro-inverter with the 175 W and 190 W PV modules. In both cases, the accumulated damage is almost equal although the PV module power rating is different. This implies that the operating voltage of the micro-inverter has a strong influence on the loading of the micro-inverter, in addition to the PV module power rating. Here, the voltage at the MPP of the 190 W PV module is higher than that of the 175 W PV module, as it is shown in Fig. 6(d) and 6(e). Thus, the micro-inverter with the 190 W PV module operates with higher efficiency, and thereby the power losses and thermal loading of the power devices are comparable with the case of micro-inverter with 175 W PV module (which operates at lower efficiency due to a lower input voltage).

On the other hand, the operation with the lowest accumulated damage occurs in the case of micro-inverter with the PV module power rating of 165 W. In that case, the power rating of the PV module is low and, at the same time, the voltage at the MPP of the PV module is relatively high. Therefore, the micro-inverter operates with high efficiency during most of the time, resulting in low power losses. Surprisingly, the second lowest accumulated damage occurs in the case of the micro-inverter with the 205 W PV module. In this case, it is mainly due to the operating voltage of the micro-inverter, which is relatively high through out the year (sees Fig. 6). In that case, the energy yield during the operation is high due to the high power rating of the PV module and the reliability of the micro-inverter is also maintained high (compared to the other cases) because of a high efficiency operation.

V. CONCLUSION

The reliability of micro-inverter has been analyzed in this paper, where the impact of PV module variations in terms of power and voltage at the MPP are taken into consideration. Six PV modules with different characteristic (e.g, power and voltage at the MPP) are used to demonstrate the variation in the commercial PV module. The reliability assessment is carried out with a case study of the installation site in Arizona, where the reliability of the power device in the flyback converter is considered. The results indicate that the voltage at the MPP of the PV module has a strong influence on the loading of the micro-inverter, in addition to the PV module power rating. Employing a PV module with high voltage at the MPP can maintain the high-efficiency operation of the micro-inverter due to the low step-up ratio requirement, and thereby minimizing the power losses in the power device.

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