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Reliability of DC-link Capacitors in Two-Stage Micro-Inverters under different PV Module Sizes

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***Abstract*—The dc-link capacitor is one of the lifetime-limiting components in the photovoltaic (PV) micro-inverters, whose reliability should be evaluated carefully during the design. In micro-inverters, the PV module size (e.g., number of cells) is the parameter that determines the power rating of the PV module. The PV module size employed in the micro-inverter can vary for different manufacturers, and this variation can strongly affect the thermal stress and reliability of the dc-link capacitor in micro-inverters. To address this issue, an experimental-based reliability assessment is carried out in this paper using a two-stage micro-inverter where 60-cell and 72-cell PV modules are considered. Three different daily mission profiles are employed during the experimental test. The thermal stress and reliability of the dc-link capacitor under different operating conditions are evaluated together with the energy yield. The results indicate that employing a 60-cell PV module is more beneficial for the micro-inverter, especially during a clear day, where 19 % more energy can be captured during the entire lifespan of the micro-inverter. Thus, using the 60-cell PV module offers a better trade-off between the reliability and energy yield of the micro-inverter.**

***Index Terms*—Reliability, capacitors, mission profile, micro-inverters, PV modules.**

I. Introduction

In recent years, the concept of integrating the photovoltaic (PV) module with power electronic converters, referred to as PV micro-inverter, has gained more and more popularity due to its potential to increase the PV energy yield with a minimum installation cost [1]. This is mainly due to the advanced features of micro-inverters such as plug-and-play installation and module-level maximum power point tracking (MPPT) operation, which can increase the PV energy yield during non-uniform solar irradiance conditions [2].

Due to the integrated system configuration, the micro-inverters are expected to have a similar lifetime as the PV modules (e.g., $>$ 20 years) [3]. However, achieving high reliability with long operating lifetime is a challenging target for micro-inverters, which are exposed to outdoor installations with low maintenances. In many cases, this could lead to a harsh environmental operating condition of the micro-inverters, and thereby challenge their reliability [4]. According to some previous studies, the dc-link capacitor is considered to be one of the most fragile components in micro-inverters, which is usually subjected to high thermal stress during the operation [5]. Usually, a relatively high capacitance is required at the dc-link in order to suppress the double-line frequency ripple and maintain a high MPPT performance. This results in the use of aluminum electrolytic capacitor due to its merit of high energy density (e.g., compared to other capacitor technologies). However, the electrolytic capacitors are prone to failure especially under high thermal stress conditions. In several cases, they are considered to be the life-limiting component in micro-inverters [5]–[8]. Therefore, the reliability of the dc-link capacitor should be carefully evaluated.

In the previous works [9], [10], the design for reliability approach has been applied to the dc-link capacitor for single-phase PV inverters. By selecting a proper dc-link capacitor, a certain reliability target can be achieved. However, in real applications, there are uncertainties in the operating condition of micro-inverters, which may alter the reliability performance of the dc-link capacitors. For micro-inverters, one source of uncertainties is the variation of the PV module size (i.e., power rating). Depending on the manufacturer and technology, the power rating of commercial PV module can vary from 150 W to 350 W [11]. Clearly, employing a large PV module size (i.e., high power rating) will result in more energy yield (under the same solar irradiance and temperature conditions), which may be preferable from a PV energy production perspective. However, the loading of the micro-inverter will also inevitably increase with the large PV module size. This can increase the thermal stress of the dc-link capacitor considerably and thus potentially decrease its reliability. In that case, the cost associated with the inverter failure may counteract the increased energy yield when using the large PV module size [12]. In previous research [13], [14], the impact of PV module size on the reliability of the power devices in micro-inverters has been investigated. Nevertheless, its influence on the reliability of dc-link capacitor on micro-inverters has not yet been analyzed, although it can negatively affect the reliability of micro-inverters and eventually the overall system cost and energy yield. Moreover, an experimental-based reliability analysis from the real thermal stress of the dc-link capacitor is also required for the validation purpose.

In this paper, the impact of PV module size on the reliability of dc-link capacitor of micro-inverters is investigated experimentally. The thermal stress of the dc-link capacitor

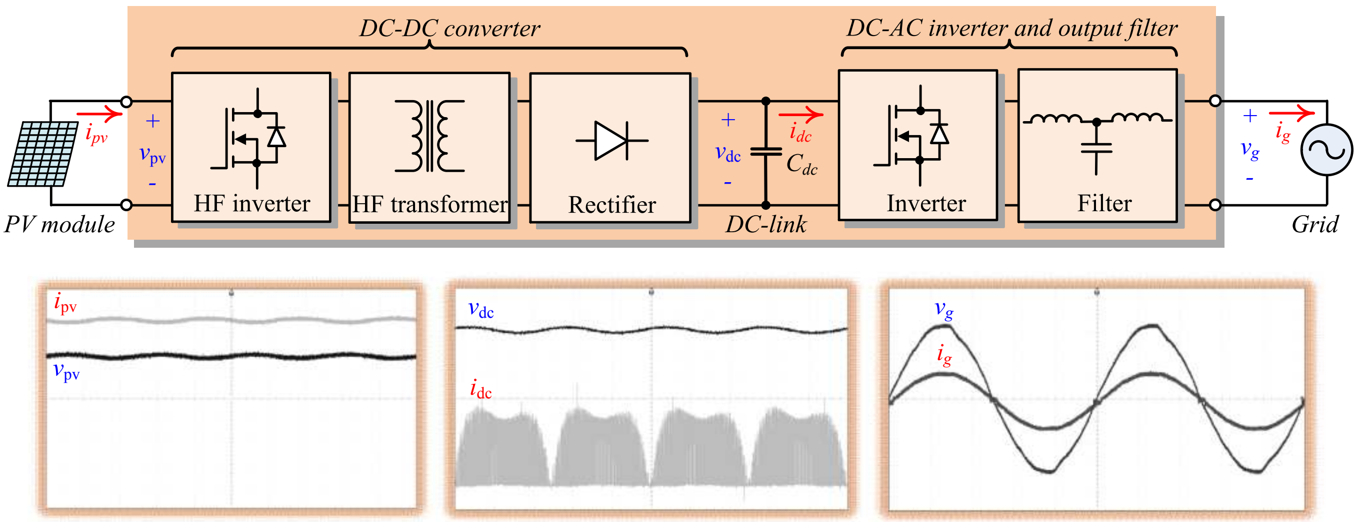

Fig. 1. System diagram of the two-stage micro-inverter and the typical operating waveforms in steady-state (e.g., constant power operation).

with different PV module sizes is investigated through a direct measurement of the capacitor hotspot temperature. This gives a more accurate result in real-operation of micro-inverters compared to the simulation studies. The obtained hotspot temperature profile is then used in the reliability analysis, and the performance metrics such as the accumulated damage of the capacitor and the energy yield are calculated and compared for different PV module sizes and mission profiles.

The rest of this paper is organized as follows: the system description of micro-inverters and PV modules are discussed in Section II. The reliability assessment method for dc-link capacitors is provided in Section III. In Section IV, three case studies of different operating conditions for the micro-inverters are considered in the reliability assessment. Finally, concluding remarks are provided in Section V.

II. Photovoltaic Micro-Inverters

A. System Description

In this paper, a micro-inverter with a two-stage configuration is considered, as it is illustrated in Fig. 1. In this configuration, the micro-inverter system consists of a dc-dc converter and an dc-ac inverter, where the system parameters are given in Table I. One important feature of the micro-inverter is the high step-up ratio between the input voltage v_{pv} (e.g., PV voltage in the range of 20-40 V) and the dc-link voltage (e.g., 330-450 V). This is normally required in order to be able to connect the micro-inverter to the ac grid (e.g., 230 V). In order to achieve this requirement, a high-frequency transformer is employed in the dc-dc conversion stage, which also inherently provide a galvanic isolation between the PV module and the grid. Then, the extracted dc power is delivered to the grid through the dc-ac conversion stage, which consists of a full-bridge inverter and the output filter. This power conversion stage is responsible for maintaining the power quality of the injected output current i_g as well as the grid synchronization using the phase-locked loop. An example of the operating waveform during steady state is shown in Fig. 1.

TABLE I
Parameters of the Two-Stage PV Inverter (Fig. 1).

Input voltage range v_{pv}	8-60 V
Rated power	350 W
Compatibility	All 60- and 72-cell PV modules
Switching frequencies	DC-DC converter: 105 kHz, DC-AC inverter: 20 kHz
DC-link capacitor C_{dc}	150 μF, 500-V electrolytic capacitor
LCL-filter	L_{inv} = 2.6 mH, L_g = 1.8 mH C_f = 470 nF
Grid nominal voltage (RMS)	V_g = 230 V
Grid nominal frequency	ω_0 = $2\pi\times 50$ rad/s
Peak efficiency of power circuit	96.2 %
Peak MPPT efficiency	99.5 %

Between the two sides, the dc-link capacitor is used as an energy buffer, which is required to suppress the double-line frequency power oscillation between the dc power and the single-phase ac grid. The capacitor is designed based on the ripple voltage following:

$$\begin{aligned} C_{\text{dc}} &= \frac{P_{\text{pv}}}{\omega_0 \cdot \Delta v \cdot V_{\text{dc}}} \\ &= \frac{300}{(2\pi \cdot 50) \cdot (0.04 \cdot 400) \cdot 400} \approx 150\ \mu\text{F} \end{aligned} \quad (1)$$

where P_{pv} is the rated output power, ω_0 is the grid nominal frequency, and V_{dc} is the nominal dc-link voltage [15].

B. Photovoltaic Module Size

Nowadays, the PV modules are dominated by the silicon technology, where the number of PV cell per module is the main factor that determines the PV power rating (and voltage at the MPP). Although various PV module sizes are available in the market, the 60-cell and 72-cell technologies are the

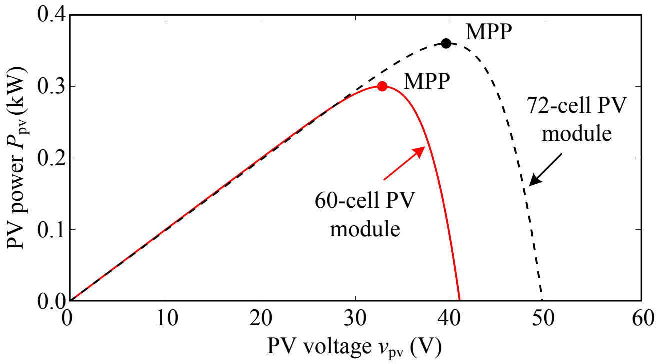

Fig. 2. Electrical characteristic of PV module with 60 and 72 cells under a standard test condition (MPP: Maximum Power Point) [16], [17].

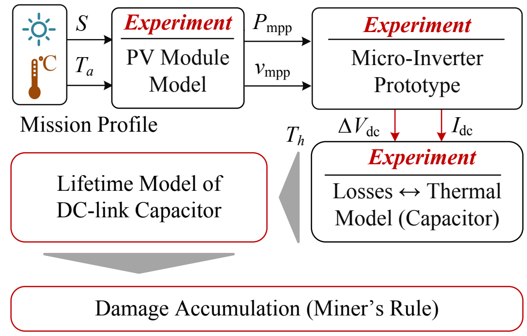

Fig. 3. Flow diagram of the reliability assessment of dc-link capacitor of micro-inverter, where the thermal stress T_h is measured.

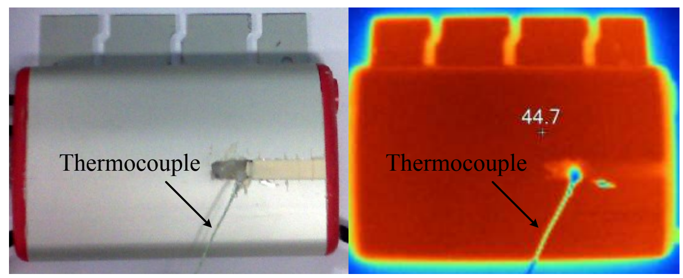

Fig. 4. Hardware prototype of the two-stage micro-inverter: (a) picture of the prototype with integrated thermal sensor for the dc-link capacitor and (b) the thermal image acquired at the rated power and ambient temperature of 28°C.

dominant PV module sizes currently [11]. In this paper, the 60-cell and 72-cell PV modules from commercial products [16], [17] are used as a case study. The power-voltage characteristic of the PV module under a standard test condition is shown in Fig. 2. Clearly, using a 72-cell PV module will result in a higher energy yield compared to using a 60-cell under the same operating conditions. However, the thermal loading of the micro-inverters may also increase considerably, and thereby affecting the reliability. It is also worth to mention that the operating voltage ranges of the two PV module sizes are also different. Due to the higher number of PV cells connected in series, the MPP voltage of the 72-cell PV module is higher than the 60-cell PV module. This aspect can also affect the efficiency of the micro-inverter during the operation. In order to quantify the impact of PV module size, the reliability and energy yield should be considered together.

III. Reliability Assessment of DC-link Capacitors

For the two-stage micro-inverter shown in Fig. 1, the dc-link capacitor is one of the weakest components in the system, which is highly stressed by the double-line frequency ripple during the operation. The internal hotspot temperature rise is one of the main stressors for the capacitor, which is induced by the power losses dissipation and also heated up by other components inside the micro-inverter enclosure and the environment. In this section, the reliability assessment of the dc-link capacitor in the micro-inverter will be discussed, following the flow diagram in Fig. 3.

A. Thermal Stress Evaluation

An aluminum electrolytic capacitor is normally used as a dc-link capacitor in micro-inverters, in order to fulfill a high capacitance requirement, as discussed in Section II. The increase of the hotspot temperature of the dc-link capacitor during the operation will lead to an electrolyte evaporation and contaminant, which are the dominant failure mechanisms of the aluminum electrolytic capacitors [18]. This will eventually lead to the wear-out failure of the dc-link capacitor due to the decrease in the capacitance and/or increase in the equivalent series resistance.

In order to accurately measure the hotspot temperature of the dc-link capacitor during the operation, a thermocouple is embedded in the capacitor. This is done during the manufacturing process of the capacitor, thanks to the support from the capacitor manufacturer. The dc-link capacitor is placed on the printed circuit board inside the enclosure, as it is shown in Fig. 4, and filled up with an encapsulation compound. By doing so, an accurate hotspot temperature profile can be directly measured during the operation including the thermal-coupling effect among different components, which can be a challenging task for an accurate modeling.

B. Lifetime Estimation

From the measured hotspot temperature, the wear-out failure of the capacitor can be projected by using the lifetime model. A widely used capacitor lifetime model can be calculated as

$$L_f = L_0 \times 2^{\frac{T_0 - T_h}{10}} \times \left(\frac{V}{V_0}\right)^{-5} \tag{2}$$

in which L_f is the lifetime under the thermal and electrical stresses T_h and V (e.g., real operating condition), L_0 is the lifetime under the reference temperature T_0 and the nominal voltage V_0 [19]–[21].

In order to apply the lifetime model in (2) with the real operating condition (e.g., mission profile), where the hotspot temperature T_h and operating voltage V are dynamically changing during the operation, the Miner's rule is applied to estimate the damage accumulation [22]. According to the

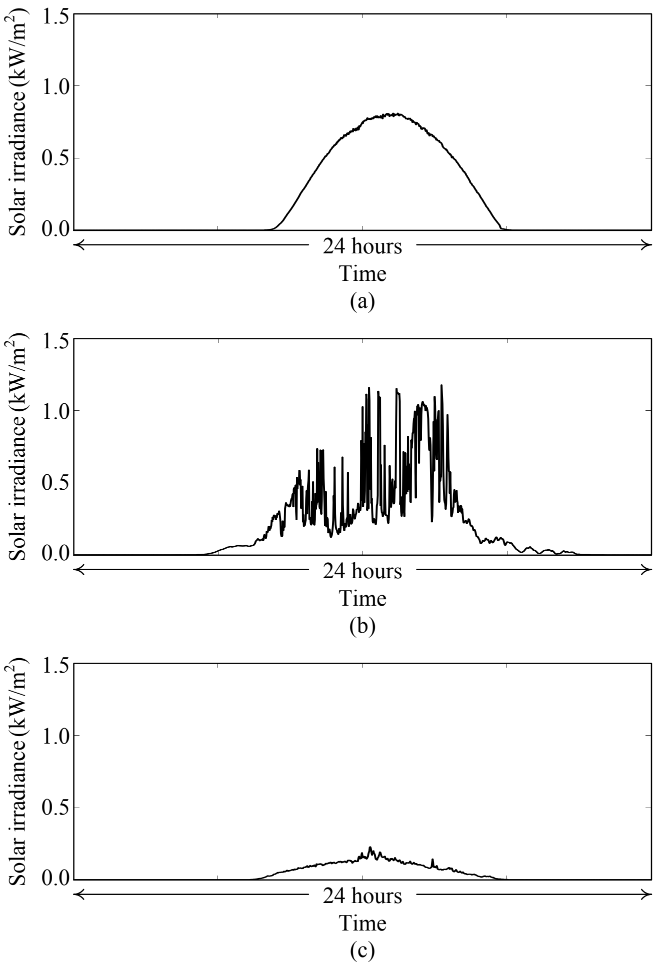

Fig. 5. One-day mission profile (i.e., solar irradiance profile) used in the case study: (a) Clear day, (b) Cloudy day, and (c) Low-irradiance day.

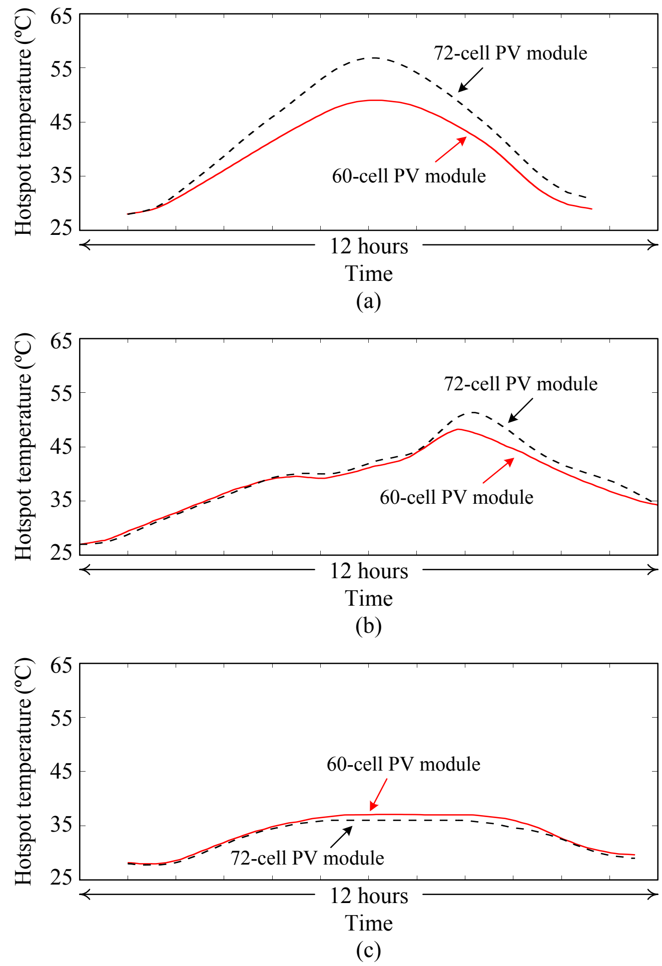

Fig. 6. Measured thermal stress of dc-link capacitor with different PV module sizes during: (a) Clear day, (b) Cloudy day, and (c) Low-irradiance day.

Miner's rule, the damage in the component can be accumulated linearly and independently during the operation as

$$D = \sum_i \frac{l_i}{L_{\text{fi}}} \tag{3}$$

where l_i is the time duration when the capacitor is subjected to the hotspot temperature of T_h and operating voltage of V, and L_{fi} is the corresponding time-to-failure at that specific stress condition calculated from (2). The end-of-life of the capacitor is determined when the damage of the capacitor is accumulated to unity, i.e., D = 1.

IV. Case Studies

In order to investigate the impact of PV module size on the reliability of dc-link capacitor under various operating conditions, three mission profile are used as case studies. For each case study, the performance of the micro-inverter with 60-cell and 72-cell PV modules are measured and compared in terms of thermal stress, reliability, and energy yield.

A. Mission Profiles

The mission profiles used in this paper are shown in Fig. 5, which are recorded during different environmental conditions of the micro-inverters. For instance, the mission profile in Fig. 5(a) represents the operating condition during the clear day, where the solar irradiance changes smoothly and slowly during the day. This is a typical operating condition of the micro-inverter during the clear-sky condition. On the other hand, the cloudy-day condition is also considered during the test, as it is demonstrated by the mission profile in Fig. 5(b). In this case, the solar irradiance, and thereby the output power of the micro-inverters, fluctuates considerably during the entire day. Another operating condition considered in the test is shown in Fig. 5(c), where the mission profile during the low-irradiance day is considered. This mission profile represents the operating condition during winter periods, where the solar resources are relatively low during the entire day.

B. Thermal Stress of DC-link Capacitors

The thermal stress profiles of the dc-link capacitor during the operation are shown in Fig. 6, which are obtained by applying the mission profiles in Fig. 5. For each mission profile, the hotspot temperature of the dc-link capacitor during the operation with 60-cell and 72-cell PV modules are measured and compared experimentally. In general, the thermal stress of the capacitor is the highest during the clear-day condition due to the high power production of the PV module and high power losses generated by the micro-inverter. This is applied to both the micro-inverter with 60-cell and 72-cell PV modules where the maximum hotspot temperature of the capacitor reaches 50°C and 57°C, respectively. A considerable amount of thermal stress increase (e.g., 7°C) when applying the 72-cell PV module is mainly due to the increase of loading of the micro-inverter due to higher PV power production. During the cloudy-day operating condition, a small increase in the thermal stress is observed when applying the 72-cell PV module, as it can be seen from Fig. 6(b).

Interestingly, the thermal stress of the dc-link capacitor with 60-cell PV module is slightly higher than in the case of the 72-cell PV module during the low-irradiance day shown in Fig. 6(c). This can be explained by the fact that the MPP voltage of the 60-cell PV module is relatively low during the low-irradiance condition. Consequently, during this operating condition, the micro-inverter efficiency will be lower with the 60-cell PV module, resulting in more power dissipation inside the enclosure. This will increase the temperature of the dc-link capacitor due to the thermal-coupling effect. Nevertheless, the impact of PV module size on the thermal stress of the capacitor under the cloudy day and low-irradiance day is relatively small compared to the case during a clear day.

C. Reliability and Energy Yield of Micro-Inverter

In order to quantify the impact of the PV module size on the dc-link capacitor reliability, the experimental measurements of the hotspot temperature were used to calculate the accumulated damage in the dc-link capacitor following (2) and (3). At the same time, the PV energy captured during the operation is also measured for each case study (e.g., mission profile and PV module size) as another performance metric. The evaluation results are shown in Fig. 7 where the accumulated damage and the corresponding energy yield are shown for each operating condition (e.g., mission profile and PV module size). In general, applying the 72-cell PV module result in a higher energy yield for all mission profiles. The difference is more significant during the clear day compared to the other cases (e.g., low-irradiance day). However, the accumulated damage in the capacitor is also increased accordingly due to the high loading of the micro-inverter. From the results in Fig. 7, the accumulated damage in the capacitor with 60-cell PV module increase linearly with the energy yield, while this relationship becomes more exponentially in the case of 72-cell PV module. In both cases, there are always a trade-off between the energy yield and accumulated damage of the micro-inverters.

The trade-off between the energy yield and reliability (e.g., accumulated damage) can be quantified by dividing the energy yield with the accumulated damage during the operation. This performance ratio (e.g., the energy yield per damage)

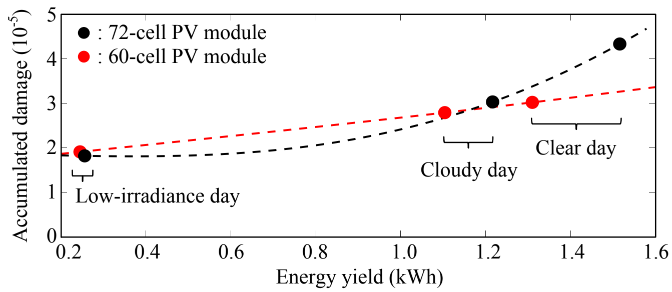

Fig. 7. Accumulated damage and PV energy yield under different mission profiles (i.e., one-day operation) and PV module sizes.

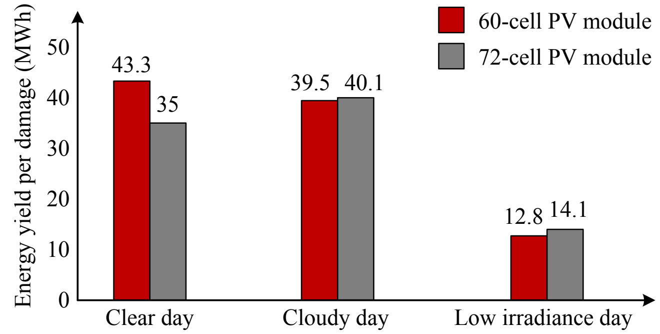

Fig. 8. Energy yield during the lifespan of micro-inverter with different mission profiles and PV module sizes.

can be used to compare the total PV energy yield given the same lifespan of the micro-inverter. The energy yield per damage of the micro-inverter with different PV module size are summarized in Fig. 8. It can be seen in Fig. 8 that employing either the 60-cell or 72-cell PV module will result in a similar energy yield per damage during the cloudy and low-irradiance days. However, under the clear-day condition, the energy yield during the entire lifespan of the micro-inverter with the 60-cell PV module is 19 % higher than the case of the 72-cell PV module. Thus, employing a 60-cell PV module, in general, offers a better trade-off between the reliability and energy yield of the micro-inverter.

V. Conclusions

In this paper, the impact of PV module size on the reliability of dc-link capacitor of micro-inverter is evaluated experimentally. The hotspot temperature during the operation with different mission profiles and PV module sizes are measured and used for the reliability assessment. The reliability performances of the micro-inverter and the PV energy yield for the case of 60-cell and 72-cell PV modules have been evaluated. The results indicate that employing a 60-cell PV module is more beneficial for the studied micro-inverter, especially during the clear-day conditions, where 19 % more energy can be captured during the entire lifespan of the micro-inverter. Thus, in this case, employing the 60-cell PV module offers a better trade-off between the reliability and energy yield of the micro-inverter compared to the case with 72-cell PV module.

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