Thermal Performance of Finned Heat Sinks Embedded with Form-Stable Myristic Acid Phase Change Material in Photovoltaic Cooling for Green Energy Storage

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Abstract: Photovoltaic (PV) panels must be equipped with a cooling system to increase their electrical output generation. Despite numerous publications on the fabrication of form-stable phase change material (FSPCM) for thermal energy storage application, studies on the usage of FSPCM for PV cooling are incredibly limited. In this work, the cooling performance of myristic acid FSPCM encapsulated with cross-linked nitrile rubber (NBR) was investigated. A fin heat sink (FHS) was employed to hold the FSPCM. The thermal performance of the FHS embedded with FSPCM (FHS-FSPCM) was preliminarily tested in an indoor setup. Results show that the FHS-FSPCM has a lower temperature distribution curve than the bare FHS, highlighting the increase in cooling capability of fabricated FSPCM. Field-testing of PV panels integrated with an FHS-FSPCM displayed that FSPCM manages to reduce the operating temperature of the panel by 4 to 15 °C and increase power output generation by 38.61%.

Keywords: thermal energy; storage; FHS-FSPCM; performance; power increasing; innovative technology

1. Introduction

Typical photovoltaic (PV) panels convert 15% to 22.5% of solar power into electricity, whereas the remaining is turned into heat [1]. Unproductive heat energy contributes to an increase in the PV panels’ operating temperature and reduces its maximum power output production due to an increase in carrier concentration at the p-n junction. When the temperature of the PV module increases, the fill factor and open circuit voltage will reduce and cause a drop in electrical efficiency [2]. Therefore, PV panels must be equipped with a cooling system to maintain the low operating temperature [3]. Moreover, extreme heat exposure to PV silicone cells for a long period will result in long-term degradation that rapidly reduces its lifespan [4]. Reduction of PV panel temperature was found to increase the power generation in many studies, as shown in Figure 1. However, the amount of net power generation improvement could not to be directly correlated to the value of temperature reduction of the panel due to factors such as ability of the cooling system to continuously cool the surface of the panel for a period of time, the experimental time period (whole day time or peak time), the type of panel, wind speed and the amount of power used to operate the system (in the case of an active system). Thus, as can be observed in Figure 1, in studies conducted by Hassan et al. and Baqi et al. the temperature reduction of both systems using PCM is almost similar, but there is a large difference in terms of power generation [5–16].
PV cooling systems can be classified into active and passive cooling. Active cooling technologies include jet impingement via forced water circulation, water spraying systems, and microchannel systems via forced air or coolant circulation by a pump. Passive cooling technologies consist of phase change material (PCM), heat pipe, thermosiphon, and microchannel heat sink cooling systems [17,18]. Passive PV cooling systems offer more advantages than the active cooling methods, as they possess no additional energy consumption, high layout flexibility, and have minimum maintenance requirements [19].

Among passive cooling technologies, PCM has gained a great deal of interest for its high latent heat, chemical stability, and ability to store heat in a narrow temperature range [20]. When the PV panel temperature increases, the PCM absorbs and stores the heat as sensible heat until the PCM material reaches its melting temperature. Once the melting temperature is reached, the PCM changes phase from solid to liquid, and stores the heat as latent heat. Typical PCM has a 5 to 14 times larger heat storage capacity than the sensible heat storage materials [21]. Nevertheless, the practical usage of PCM in PV panel cooling is limited because PCM possesses high volume change during the phase transition from solid to liquid, which leads to a leakage issue. This issue needs to be solved to avoid corrosion on the PV panel’s surface, pressure build-up in the container, disturbance on PV wirings, and to avoid fire safety issues [22–24]. To prevent such consequences, form-stable phase change material (FSPCM) is preferable to be employed in PV cooling applications whereby PCM is encapsulated with a polymeric matrix.

Despite many research articles published on the fabrication of FSPCM, limited studies have been done on solar panels with FSPCM as a cooling system. Senthilkumar et al. successfully produced polyethylene glycol/expanded graphite FSPCM with a melting point of 34.7 °C and a phase change enthalpy of 125.97 J/g [25]. PV panels integrated with this FSPCM managed to keep the surface temperature lower than the reference panel by 4 to 6 °C throughout the experiment. Tangsiriratana et al. proposed the usage of FSPCMs made of sugarcane wax-Al₂O₃ composite encapsulated with gelatin-gum Arabic for PV cooling [26]. The average temperature of the module equipped with this FSPCM was lowered by 3.87 °C. Nevertheless, the PV cooling performance remains insignificant mainly because of the large heat storage density reduction during the fabrication of FSPCM [27]. Large weight fraction of coating or encapsulation material used reduces the weight percentage of the core material, which contributes to heat storage density. Thus, the selection of the coating or encapsulation material remains crucial for determining the cooling capability of FSPCM on the PV panel.
In the present study, the FSPCM employed was made of myristic acid (MA) as the core, and was encapsulated with cross-linked nitrile rubber via a dip-coating technique, as reported in our previous work [28]. MA was selected because of their high latent heat density and low-volume change during the phase transition [29]. Nitrile butadiene rubber (NBR) latex was chosen as the encapsulation material due to its excellent chemical and tensile properties and its mechanical properties can be further enhanced with sulfur vulcanization to form a thin and compact coating [30,31]. Therefore, the weight percentage of coating material on PCM can be reduced and consequently minimize the latent heat reduction.

In this research, the cooling capability of FSPCM prepared was evaluated in an indoor preliminary set up before field-testing on the PV panel occurred. The fin heat sink (FHS) acted as a “container” to hold the FSPCM, and the thermal performance of FHS filled with FSPCM (FHS-FSPCM) and without FSPCM was evaluated via heating with different power supplies of 10, 20, and 30 W. The cooling performance of FSPCM was analyzed and evaluated by comparing the temperature distribution of FHS and FHS-FSPCM. Then, the cooling performance of FHS-FSPCM on the solar module in field-testing was assessed and the maximum power output generation was determined.

2. Materials and Methods
2.1. Fin Heat Sink Configuration and Location of Thermocouples

In this study, two pieces of FHS made of aluminum with a dimension of 141 × 150 mm² base and a height of 46 mm were employed. These FHS consist of 39 fins with a length × width × height of 150 × 1.5 × 30.4 mm. The distance between the fins was 2.08 mm. Both FHS was machined with the dimension as illustrated in Figures 2 and 3 to enable positioning of thermocouples and its integration with FSPCM. Nine calibrated T-type thermocouples were fixed on each FHS using Araldite™ epoxy resin as shown in Figures 2 and 3. The locations of thermocouples were; three on the heated surface of FHS (labelled as T1 to T3), three on the base of FHS (labelled as T4 to T6), and three on the fin of FHS (labelled as T7 to T9).

Figure 2. The dimension of machined FHS and thermocouples positioning.
2.2. Experimental Setup for Preliminary Performance Assessment on FHS and FHS-FSPCM

The schematic experimental setup for this study was displayed in Figure 4. The setup consists of a FHS or FHS-FSPCM, insulated with polyurethane foam to prevent heat loss to its surroundings. Voltage regulator (TDGC2-2kVA) and a digital multimeter (GW Instek GDM-8034) were used to control the power supply. A heating pad with a thickness of 1.5 mm, type-T thermocouples, data logger (Graphtec data logger GL820) to record the temperature over time, and a multi-input terminal block (Graphtec B-564) that connects multiple thermocouples with the data logger were also used in the setup. Thermal paste was employed in between the heating pad and heated surface of the FHS to prevent contact resistance. FSPCM employed in present study was fabricated with MA as the core phase change material and encapsulated with cross-linked NBR latex via dip-coating technique as published in our previous work [28]. The produced FSPCM has a diameter of 108 mm and a thickness of 10 mm. The properties of materials utilized in this study are given in Table 1. Three different power supplies of 10, 20, and 30 W were studied to determine the temperature distribution of FHS and FHS-FSPCM. For the first 200 min, the voltage regulator was adjusted to obtain a power supply of 10 W and FHS was heated until it reaches a steady-state condition. The data logger recorded the temperature of thermocouples every 10 min. Then, the continuous power supply was increased to 20 and 30 W, respectively, after every 200 min of heating. The average temperature of thermocouples on three different parts of FHS was calculated as in Equations (1)–(3).

\[ T_{hs} = \frac{T_1 + T_2 + T_3}{3} \]  
\[ T_{bs} = \frac{T_4 + T_5 + T_6}{3} \]  
\[ T_{fin} = \frac{T_7 + T_8 + T_9}{3} \]

where \( T_{hs} \) represents average temperature on heated surface of FHS, \( T_{bs} \) represents average temperature on base of FHS, and \( T_{fin} \) represents average temperature on fin of FHS.
2.3. Experimental Setup for Application of FHS-FSPCM on Photovoltaic (PV) Panel

As the FHS-FSPCM has better cooling capability than the FHS, it was selected to be further investigated on the PV panel. Figure 5 outlines the setup of PV panels for FHS-FSPCM and the location of the thermocouples. Eight pieces of modified FHS-FSPCM were prepared with one thermocouple each installed on the heated surface, top of the FHS surface, and fin of the FHS. In addition, eight thermocouples were attached on the surface and rear part of PV panel, respectively. FHS-FSPCM were attached to the rear part of the PV panel. Figure 6 shows the outdoor experimental setup to study the performance of PV cooling. Two pieces of 39.25 W monocrystalline PV modules were employed; one was used as a reference and the other was attached with 8 pieces of FHS-FSPCM on its rear surface. The specific electrical properties of the PV panels are displayed in Table 2. Two panels with similar electrical properties were chosen for the field-testing. One thermocouple was used to measure the ambient temperature. The solar irradiance was measured by a pyranometer. A multimeter was utilized to obtain the current produced by the panel. Multi-input terminal block serves as a terminal to connect thermocouples, voltage cables, and pyranometer with the data logger so that the voltage generated by the PV module, temperature, and solar irradiance can be recorded concurrently. This experiment was conducted from 10 am. to 3 pm. for 30 sunny days on October and November 2020. PV panels system were tilted to an inclination angle of 15° and the modules were facing towards south. The experiment was performed on the rooftop of Block E, Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, Malaysia. Maximum power output was calculated as in Equation (4) with short circuit current and open circuit potential [32]. The relative humidity was recorded to be between 80 and 82% on these days and the wind speed was recorded to be between 3 and 5 km/h.

\[
P_{out} = V_{oc} \times I_{sc} \times FF
\]  

(4)

Table 1. Properties of materials employed in the present study.

| Material                   | Specific Heat (kJ/kgK) | Latent Heat of Melting (J/g) | Melting Point (°C) | Latent Heat of Freezing (J/g) | Freezing Point (°C) |
|----------------------------|------------------------|-----------------------------|-------------------|-----------------------------|-------------------|
| FSPCM                      | 3.01                   | 130.30 ± 1.29               | 54.60 ± 0.08      | 129.95 ± 1.21               | 50.51 ± 0.08      |
| Aluminum                   | 0.88                   | 399.90                      |                    | 660.3                       |                   |
| Polyurethane foam insulator| 1.50                   | -                           |                    | -                           |                   |
where $P_{out}$ represents maximum power output, $V_{oc}$ represents open circuit voltage, $I_{sc}$ represents short circuit current, and FF represents fill factor.

**Figure 5.** The schematic diagram of experimental setup for application of FHS-FSPCM on PV panel.

**Figure 6.** Outdoor PV panel setup for cooling performance study.
Table 2. Properties of PV Panel.

| Parameter          | Value   |
|--------------------|---------|
| Maximum power      | 39.25 W |
| Maximum current    | 2.05 A  |
| Maximum voltage    | 19.15 V |
| Short circuit current | 2.18 A |
| Open circuit voltage | 22.89 V |
| Fill factor        | 0.79    |

3. Results and Discussion

3.1. Preliminary Thermal Performance Assessment of FHS and FHS-FSPCM with Different Power Supply

The temperature distribution of the FHS and FHS-FSPCM was analyzed with the continuous power supplies of 10, 20, and 30 W (an increment of 10 W every 200 min). Figure 7 shows the average temperature collected from three parts of the FHS (heated surface $T_{hs}$; base of FHS $T_{bs}$; fin of FHS $T_{fin}$). The temperature of thermocouples at steady-state conditions is outlined in Table 3. In general, the temperature recorded by the thermocouples in the system with only FHS is higher compared to the system with FHS-FSPCM. The difference between the temperature of the thermocouples in both systems is wider at higher power value. The melting temperature of FSPCM could not be reached at the power supply of 10 and 20 W. In the first 200 min and power supply of 10 W, the temperature distribution curve of FHS-FSPCM is only slightly lower than the FHS because FSPCM provides cooling by absorbing heat from its surrounding in the form of sensible heat [33]. In between 200 and 400 min and heating power of 20 W, the temperature difference between the FHS and FHS-FSPCM became more prominent due to the larger sensible heat energy storage by the FSPCM as temperature of the FHS rises [34]. During this time period, the absorbed heat is stored by the change in temperature of storage medium. The amount of stored heat is proportional to the temperature rise [35]. The temperature distribution curve of FHS-FSPCM grows closer towards the FHS’s curve when approaching steady-state conditions, indicating that the FSPCM’s sensible heat storage capability had reduced.

Figure 7. Temperature distribution curve of FHS and FHS-FSPCM with different power supply.
Table 3. Temperature of Thermocouples when Reaching a Steady-State Condition.

| Heat Sink | Power (W) | Temperature of Thermocouples (°C) |
|-----------|-----------|-----------------------------------|
|           |           | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 | T9 | Tfin |
| FHS       | 10        | 38.7 | 38.6 | 38.3 | 38.5 | 38.3 | 38.2 | 38.2 | 38.2 | 38.1 | 38.1 |
|           | 20        | 53.6 | 53.4 | 53.5 | 53.5 | 53.0 | 52.9 | 53.0 | 53.0 | 52.9 | 52.9 |
|           | 30        | 69.0 | 68.5 | 68.7 | 68.7 | 67.9 | 68.0 | 67.9 | 67.9 | 67.7 | 67.7 |
| FHS-FSPCM | 10        | 34.2 | 34.4 | 33.8 | 34.1 | 29.8 | 29.7 | 29.7 | 29.7 | 29.7 | 29.6 |
|           | 20        | 49.5 | 49.2 | 49.0 | 49.2 | 44.4 | 44.4 | 44.3 | 44.4 | 44.2 | 44.2 |
|           | 30        | 61.3 | 61.0 | 60.8 | 61.0 | 56.4 | 56.4 | 56.3 | 56.4 | 56.2 | 56.2 |

When heating power was increased to 30 W from 400 to 600 min, the temperature distribution curve for FHS-FSPCM slightly flattened from 408 to 420 min, which differs from the curve obtained by the FHS as it increases rapidly. FSPCM was heated beyond its melting point and absorbed thermal energy in the form of latent heat during the phase transformation from solid into a liquid state. The difference between the FHS and FHS-FSPCM’s curves remained consistent until the steady-state condition, due to the larger latent heat storage capacity of FSPCM as shown in Table 1 [36,37]. Thus, FSPCM could absorb more waste heat energy from PV panel.

Throughout the experiment, FHS-FSPCM successfully maintained its surface temperature to be much lower compared to the FHS. This finding affirms the capability of FSPCM to store thermal energy in the form of sensible and latent heat. Thus, FHS-FSPCM provides better cooling performance than the FHS system.

Table 4 summarizes the average temperature recorded by thermocouples at the heated surface, top of FHS surface, and fin of the FHS and their temperature difference for the FHS and FHS-FSPCM at a steady state. The FHS-FSPCM managed to reduce the temperature by 11.43% at the heated surface and 22% at the top of FHS surface and fin of the FHS when the power supplied was 10 W. Temperature reduction at the heated surface of the FHS was smaller compared to top of the FHS surface and fin of the FHS because they were nearest to the heating source. Thermal energy at the top of the FHS surface and fin of the FHS can be easily dissipated into the environment. When continuous power supply increased to 20 W, FSPCM reduces $T_{hs}$ by 8% while $T_f$ and $T_{fin}$ by 16%. Meanwhile, when power supply increased to 30 W, $T_{hs}$ reduced by 11% while $T_f$ and $T_{fin}$ by 17%.

Table 4. Temperature comparison between a system with an FHS and FHS-FSPCM when reaching a steady-state condition.

| Power | Temperature of Thermocouples (°C) | Difference | Percentage (%) |
|-------|-----------------------------------|------------|----------------|
|       | $T_{average}$ | Without FSPCM | With FSPCM | Difference |       |
| 10 W  | $T_{hs}$       | 38.5        | 34.1        | 4.4        | 11.43 |
|       | $T_f$          | 38.2        | 29.7        | 8.5        | 22.25 |
|       | $T_{fin}$      | 38.1        | 29.7        | 8.4        | 22.05 |
| 20 W  | $T_{hs}$       | 53.5        | 49.2        | 4.3        | 8.04  |
|       | $T_f$          | 53.0        | 44.4        | 8.6        | 16.23 |
|       | $T_{fin}$      | 52.9        | 44.2        | 8.5        | 16.07 |
| 30 W  | $T_{hs}$       | 68.7        | 61.0        | 7.7        | 11.21 |
|       | $T_f$          | 68.0        | 56.4        | 11.6       | 17.06 |
|       | $T_{fin}$      | 67.8        | 56.3        | 11.5       | 16.96 |

3.2. Application of FHS-FSPCM on Photovoltaic Panel

Two monocrystalline PV panels, integrated with and without a cooling system, were employed to determine their maximum output power generated. The first panel was utilized as a reference (bare panel) and another panel was integrated with FHS-FSPCM. Figure 8 shows the details of solar irradiance and ambient temperature over time. The
average solar irradiance and ambient temperatures were reported as 686.7505 W/m² and 33.6 °C, respectively. Solar irradiance and the ambient temperature reached its peak at 12.40 pm. with 1043.75 W/m² and 41.2 °C, respectively. Ambient temperature registered an increasing trend with increasing solar irradiance.

Figure 8. Solar irradiance and ambient temperature.

Figure 9 displays the surface temperature and voltage against time for reference and FHS-FSPCM integrated PV panel. FSPCM managed to keep the temperature of the PV panel lower than the reference panel by minimum temperature difference of 4 °C and maximum temperature difference of 15 °C, as shown in Figure 10a. Furthermore, the temperature distribution curve for FHS-FSPCM was flattened from 12.30 to 12.40 p.m., indicating the storage of thermal energy in the form of latent heat by the FSPCM. The heat from PV panel was transferred to the FSPCM by conduction and regulated by the FHS [24]. The temperature of PV panel is one of the most important factors that influences the energy conversion efficiency of PV panel, and the efficiency of PV panel is a decreasing function of temperature [38,39].

Average voltage output by the bare PV panel and FHS-FSPCM were recorded as 19.61 and 20.28 V, respectively. The average voltage output of the solar panel with FHS-FSPCM was increased by 3.41%. Maximum voltage output by bare solar module was 20.1 V and the minimum voltage output was 19.10 V. Meanwhile, for the solar module with FHS-FSPCM, the maximum voltage output recorded was 20.86 V and the minimum voltage output was 20.10 V. FSPCM exhibited a lower melting temperature than the PV panel surface temperature at peak solar irradiance time which leads to melting of FSPCMs and latent heat absorption. More heat is continuously absorbed into the FSPCM from the PV panel surface, which then causes a continuous cooling effect on the PV panel. The heat absorbed by FSPCM could be released through convention to the air surrounding the system. Due to this phenomenon, a higher voltage output between 11.20 a.m. to 12.30 p.m. is observed in this work.

When the temperature of PV panel increases, the bandgap in PV cell will reduce, thus the energy of electrons in the material will increase, and the increase in temperature of PV cell will influence the open circuit voltage. The open circuit voltage is dependent on an intrinsic carrier concentration for silicon, which then depends on the bandgap energy. Higher temperatures, reduce bandgap, cause higher intrinsic carrier concentrations and lower voltage output by panels. The differences in voltage values are shown in Figure 10b.
Current generated by PV modules against time was plotted in Figure 11; the average current output by reference solar panel was 0.98 A and panel with FHS-FSPCM was 1.29 A.
The average current generated by the solar module integrated with FHS-FSPCM increased by 31.635%. The bare module has a maximum and minimum current output of 1.80 and 0.38 A, respectively. For the module with FHS-FSPCM, it recorded maximum and minimum current of 2.10 and 0.52 A, respectively. The current generation pattern is very much similar to solar irradiance pattern as shown in Figure 8, indicating that solar irradiance has a direct influence on the current generation. Theoretically, the short circuit current generated in PV cell should increase slightly when temperature increases since the bandgap energy decreases and more photons have enough energy to create e-h pair. However, in this work, the voltage and current was measured concurrently during the field-testing and both value increases with incorporation of FHS-FSPCM. This finding needs further investigation and might be associated with heat being stored in FSPCM at the rear part of the PV module instead of being extracted completely from the system. Further, it is noteworthy that, in most of the reported PV cooling work, current values are not being presented [38]. The difference in current outputs between the reference PV panel and PV panel with FHS-PCM are shown in Figure 10c.

Figure 11. Current generation against time for PV panel with an FHS and FHS-FSPCM.

Figure 12 shows the maximum power output generated by the PV panels against time. The average power output produced by bare and FHS-FSPCM modules was 14.79 and 20.50 W, respectively. The power output produced by the solar module with FHS-FSPCM has increased by 38.61%. The bare module has a maximum and minimum power of 25.13 and 6.25 W, respectively, while the module with FHS-FSPCM has maximum and minimum power of 33.23 and 8.44 W. The power differences between reference panel and PV panel with FHS-PCM are shown in Figure 10d. The power output increases because FHS-FSPCM can maintain PV panel at constant temperature for a long time and delays panel temperature rise. The latent heat absorbed by the FSPCM will be released to environment through convention completely during nighttime and cause solidification of FSPCM again.

Many other methods are also being employed to contain PCM and resolve problems such as leakage, which leads to corrosions of the PV module. An attempt was made to fill commercial PCMs into copper tubes in order to contain the PCM and increase the area of exposed surface for heat dissipation. This approach results in a PV panel temperature reduction of between 6.4 °C and 7.5 °C, but only increases electrical power output by 4.19% [40–42].
High solar irradiance causes an increase in the surface temperature of the PV panel, but FSPCM managed to keep the average temperature of the PV panel lower by 4 to 15 °C as compared to the panel without a cooling system. Moreover, higher solar irradiance causes the PV panel to generate a lower voltage output, but obtains a higher current output. The maximum power output generated by the PV panel is higher when the surface temperature of the PV panel is low.

Table 5 shows comparison between current work and other researchers’ work in terms of FSPCM properties and their cooling performance on the PV panel. FSPCM utilized in the present study has a larger heat storage capacity than the FSPCM used in other works of literature due to the formation of thin and compact coating. Thus, the average operating temperature of the panel was effectively reduced between 4 to 15 °C, while other research works reported less than a 5 °C reduction. Furthermore, the maximum power output recorded by the current study is higher than the others due to the lower operating temperature of PV panel. Besides, the FHS container plays a crucial role in increasing the heat absorption rate of FSPCM because of their high thermal conductivity. Indeed, the FHS also helps FSPCM to dissipate heat more efficiently.

Table 5. Comparison Between Current Work and Other Researchers’ Work on PV Cooling Using FSPCM.

| No. | FSPCM (PCM/Supporting Material) | FSPCM Properties | PV Cooling |
|-----|---------------------------------|------------------|------------|
|     |                                 | Melting Point (°C) | Latent Heat of Melting (J/g) | Freezing Point (°C) | Latent Heat of Freezing (J/g) | Reduction of PV Panel’s Temperature (°C) | Increment of Maximum Power Output Generation (%) | Reference |
| 1.  | Myristic acid/cross-linked nitrile rubber Polyethylene | 54.60 ± 0.08 | 130.30 ± 1.29 | 50.51 ± 0.08 | 129.95 ± 1.21 | 7.2 | 39.45 | Current study |
| 2.  | Polyethylene glycol/expanded graphite | 34.7 | 125.97 | - | - | 4-6 | - | 25 |
| 3.  | Sugarcane wax-Al2O3 composite/gelatin-gum Arabic | 62 | 68.09 | 60.83 | 53.77 | 3.87 | 7 | 26 |
4. Conclusions

In this work, the cooling capability of FSPCM was determined via preliminary indoor setup, whereby the temperature distribution curve of FHS-FSPCM was consistently kept below the FHS’s curve. The test also confirms that FSPCM absorbs and stores heat in the form of sensible and latent heat. Field-testing demonstrates that the temperature of the PV panel increases with increasing solar irradiation. FSPCM successfully cooled the PV panel by showing a temperature reduction of between 4 to 15 °C during the testing period. The maximum power output produced by the PV panel fixed with FHS-FSPCM increases by 38.61 % as compared to the reference panel. However, the increment of current measured directly from the PV panel needs to be further investigated.

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