Thermal management of grid-tied PV system: A novel active and passive cooling design-based approach

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Abstract
The photovoltaic (PV) cells are highly sensitive to temperature variations. The linear variation of PV cells with operating temperature could lead to the loss of conversion efficiency and permanent damage of PV material. To address this critical issue, while improving the performance of solar photovoltaic system (SPVS) during the operating period, the deployment of a proper cooling system is a prime requisite in the design process. Considering this, two new and cost-effective cooling techniques are proposed in this study, which can improve efficiency and increase the life of the PV panel. The first technique is the active cooling design with water. The proposed design enhances the access to PV cells to maximize cooling. The second one is an improved passive cooling technique that uses fins mounted on the backside of PV module. This further reduces the temperature by increasing the heat dissipation. Additionally, a third PV module without any cooling system is deployed as a reference margin. The techniques have been experimentally evaluated and a recommendation is made in order to reduce the temperature variation across the PV panel.

1 INTRODUCTION

Due to the fluctuation of oil prices in the international market, renewable energy systems have undergone rapid development around the world. While considering the sharp growth of CO2 and other harmful gases in the atmosphere [1], the trend is set towards securing electrical energy with minimum cost and low environmental impact. While eyeing for an economic energy resource, solar energy has become a popular and promising technology option [2]. Where solar energy could minimize the dependence on traditional energy sources, it could provide several other benefits of clean, inconsumable, abundant, low amount of carbon and harmful gases emissions energy source [3, 4]. To fully utilize these benefits, solar photovoltaic-based system (SPVS) is one of the prospective solutions [2]. However, high initial cost and low conversion efficiency are the chief complications of using SPVSs, which makes the solution more expensive than the traditional energy sources [5, 6]. Therefore, dropping the cost of energy (COE) from SPVS can reduce the COE, the operation is prone to high operating temperatures [8]. Different attempts are made to enhance the efficiency of the SPVS through various cooling technologies [9–27]. There are two distinguishable kinds of cooling techniques [10] reported to the date: (1) Active cooling that required electrical energy supply [9, 10], and (2) passive cooling that uses natural convection and conduction to remove excess heat [14]. The useful gain energy from active cooling system improves the electric efficiency and cultivates some useful thermal energy [2] thereby eventually enhance the performance of SPVS, which is the main aim and motivation of this work.

Different experimental works are reported in the literature to enhance PV performance with an effective cooling system. In [11], an experimental investigation was conducted to cool-down the PV module with a thermosiphon effect. Copper tubes are mounted in this work on the backside of module to enhance the efficiency by 19%. The study in [12] attempts to find a new method for cooling PV cells. This was achieved by using natural vapour as a coolant while studying different mass flow rates. Ref. [13] proposed a numerical approach to reduce PV panel
TABLE 1  Development of PV/T technology with air cooling—An overview

| References | Work formation | Air cooling characteristics | Performance improvement (%) |
|------------|----------------|----------------------------|-----------------------------|
| Current paper | Experimental and poly-crystalline-based PV Work | Aluminium fins heat sink | 7.0% |
| [19] | Experimental work | Air from the backside of PV | 4.5% |
| [14] | Experimental and poly-crystalline-based PV Work | Used super-thin absorber below the PV panels | 5.0% |
| [24] | Experimental and poly-crystalline-based PV Work | Air cooling effect involved | 8.9% |
| [25] | Experimental and poly-crystalline-based PV Work | Duct and fan air utilized | 0.6% |

TABLE 2  Development of PV/T technology with water cooling—An overview

| References | Work formation | Water cooling characteristics | Performance improvement (%) |
|------------|----------------|-------------------------------|-----------------------------|
| Current Paper | Experimental and poly-crystalline-based PV Work | Flow of water with close casing | 10.2% |
| [20] | Experimental work | Front side of PV – Spilled water | 10.3% |
| [11] | Experimental work | Copper tube with serpentine material | 19.0% |
| [12] | Experimental work | Natural vapour | 22.9% |
| [15] | Experimental and theoretical work | Micro-heat pipe array technology-based PV system | 13.0% |
| [16] | Experimental work | Active water cooling | 6.5% |
| [26] | Experimental and mono-crystalline-based PV work | Technique built on submersion | 11.0% |
| [27] | Experimental work | Structure of heat pipes | 2.6% |

temperature, by using cooled heat sinks. These heat sinks are made of ribbed walls with different geometrical shapes. The maximum improved power produced by PV panel in this study ranged between 6.97–7.55%. Ref. [14] used a super-thin absorber-based experiment with PV panels for cooling. The proposed system enhanced the electrical output by 5% and thermal efficiency by 65% respectively. Ref. [15] developed a micro heat pipe array. A set of mathematical and experimental validations were obtained with the new heat pipe array to analyse the performance of a hybrid photovoltaic/thermal (PV/T) system. This resulted to have an electrical efficiency at around 13%. Ref. [16] proposed a PV/T system that operated under active water-cooling technique. This led to increase in the electrical efficiency by 7.8% at an optimum flow rate. Tables 1 and 2 show the summary of works for different PV/T air and water-cooling techniques, respectively. The active cooling method is very effective way for PV cooling. However, the flow rate and amount of heat dissipation are still very important issues. This requires new design of water channel and heat exchangers to be explored for thermal management of SPVS, which is the scope of this work.

To consider the parameters of flow rate and heat dissipation, it is significant to monitor the performance of PV module with real climatic conditions. Around 15–20% of the incident solar irradiance can be converted to electrical power. This pushes the output power to decrease at a rate of 0.25–0.5 % due to the rise of PV module temperature [17, 18]. The most critical period for the PV panel performance is the time of highest solar radiation with lowest speed of wind. During this period, the efficiency of PV panels reduces comprehensively leading to damage of PV module [19, 20]. Solar irradiance and temperature are the two focal parameters that effect the PV module performance [10]. Solar cell absorbs around 80% of solar irradiance. Only small portion of the absorbed irradiance can be converted to electrical power. The residue portion of solar radiance increases the cell temperature up to 40 °C above the atmospheric temperature [5]. This leads to decrease the performance of PV module. The open-circuit voltage of PV module is strongly affected by the temperature increase. This is due to the shrinkage of the band gap of the intrinsic semiconductor. A lower band gap permits more incident energy can be absorbed since a larger proportion of solar irradiance has enough energy for raising charge carriers from the valence band into the conduction band. Therefore, the photocurrent will be increase with increasing the temperature, though, the internal resistance of the material increases and hence the electrical conductivity decreases. The current increase for a certain temperature growth is proportionally lower than the voltage decrease. Hence, the cell efficiency is reduced [21]. A pattern of trends is also seen in [22–27].

The main contribution of this paper is to build an experimental rig to enhance the thermal management of grid-tied PV system. This is achieved by investigating the performance of two new designs of: (1) Improved passive, and (2) improved active cooling techniques, respectively. The water channel-based improved active cooling design allows water to touch the largest possible area of the cell and cool the largest part of the PV module. The passive cooling design uses fins with natural cooling air, which are designed to cover backside of the PV module to dissipate more amount of heat and reduce PV temperature. The improved designs have proposed a solution to address the PV temperature variations by optimizing the flow rate and heat
dissipation. The problem formulation is also enhanced by proposing the state representation of an SPVS system.

The formation of rest of paper is organized as follows: The problem formulation of SPVS system is represented in Section 2. The PV system setup and components are explained in Section 3, followed by results and evaluation in Section 4. Finally, conclusions are drawn in Section 5.

2 PROBLEM FORMULATION: THERMAL MANAGEMENT FOR SPVS SYSTEMS

In this section, the problem formulation of thermal management setup is described. Figure 1 illustrates the block diagram of a considered system. It comprises of: (1) A set of PV panels, (2) micro inverter, (3) temperature sensors, (4) anemometer, (5) pyrometer, (6) water storage tank, (7) mechanical valves, (8) cold water supply, (9) hot water tank, and (10) data logger. Three identical polycrystalline PV panels are used to examine the cooling effect on the PV panel performance. Every PV module is connected separately with micro inverter. This combination is further coupled to a 220 V AC low grid with 50 Hz frequency. The operation of PV modules is described as follows: The first PV module operates with water-cooling system. In the second PV module, the cooling system using fins heat sink (natural cooling) has been utilized. The third PV module is considered as a reference module which operates without cooling. The setup is located in a dry desert condition in the Hashemite University, Jordan (32.05 N°, 36.06 E°). For achieving the best performance of PV modules, a tilt angle of 26 degrees is chosen facing the southern side.

2.1 State representation of SPVS system

A state representation of PV cell temperature $\Gamma_c$ for the SPVS system can be represented as:

$$\Gamma_{c,t+1}^f = F_{c,t+1} + \frac{1}{R_c(t)} (\alpha_{c,t} \Gamma_{r,t} + \beta_{c,t} \Gamma_{fc,t} + \gamma_{c,t} \Gamma_{wc,t})$$ (1)

where $\Gamma_{c,t+1}^f \in \mathbb{R}^r$ represents a fused temperature state for the system at time-instant $t$. The superscript $f$ can be expressed as $f=r+fc+wc$. Here $r$, $fc$, and $wc$ are the symbols representing the
reference, fins cooling and water cooling respectively. \( R_i \) \( \in \mathcal{R}^{r \times r} \) is a modal matrix of temperature state. \( \alpha_i, \beta_i, \gamma_i \in \mathcal{R}^{r \times r} \) are the transition matrices of reference PV module temperature \( \Gamma_{r,i} \), fins cooling PV module temperature \( \Gamma_{f,i} \), water-cooling PV module temperature \( \Gamma_{w,r} \) respectively, such that \( \Gamma_{r,i}, \Gamma_{f,i}, \Gamma_{w,i} \in \mathcal{R}^r \). \( \mathcal{R}^r \) is the total radiation on the PV module, such that \( \mathcal{R}^r = Q_{abs} / \rho_{abs} \sum_{i=1}^{3} \mathcal{A}_i \). Here \( Q_{abs} \) is the heat absorbed by the PV solar, \( \rho_{abs} \) is the heat absorption coefficient, \( \mathcal{A}_i \) represents the area of each PV module. \( Q_{abs} \) further expresses the heat production per unit as \( Q_{abs} = (1 - R) I_a \mathcal{S} \mathcal{R} \delta \), where \( R \) is the reflectivity, \( I_a \) is the intensity of solar radiation, \( \mathcal{S} \delta \) is the absorption coefficient, which is the function of temperature, such that \( \mathcal{S} \delta = f(\Gamma') \), and \( \mathcal{S} \) is the depth of solar light penetration.

### 2.2 Efficiency of the PV modules

The electrical efficiency (\( \eta \)) of the PV modules are determined using the relationship of input and output. The electrical efficiency (\( \eta \)) of the reference module can be represented as:

\[
\eta_{pv,r} = \frac{P_{out}}{P_{in}} = \frac{P_{pv,r}}{\mathcal{G} \mathcal{A}}
\]

(2)

where \( \eta_{pv,r} \) is the electrical efficiency of the reference module, \( P_{out} \) is the output module power in watts, \( \mathcal{G} \) is the incident solar radiation in (W/m²) and \( \mathcal{A} \) is module area in m². The electrical efficiency (\( \eta \)) of the fins cooling module can be represented as:

\[
\eta_{pv,fc} = \frac{P_{pv,fc}}{\mathcal{G} \mathcal{A}}
\]

(3)

where \( \eta_{pv,fc} \) is the electrical efficiency of the fins cooling module. Similarly, the electrical efficiency (\( \eta \)) of the water-cooling module is expressed as:

\[
\eta_{pv,wc} = \frac{P_{pv,wc}}{\mathcal{G} \mathcal{A}}
\]

(4)

where \( \eta_{pv,wc} \) is the electrical efficiency of the water-cooling module.

Once the efficiency modules are illustrated, there is a tool required to understand the percentage of improvement built on the two proposed designs of cooling.

### 2.3 Percentage improvement of the proposed cooling techniques

The improvement for each proposed cooling module can be calculated using a relationship. The improvement factor for water-cooling module can be expressed as:

\[
\xi_{pv,wc} = \frac{(P_{pv,wc} - P_{pv,r})}{P_{pv,r}}
\]

(5)

where \( \xi_{pv,wc} \) is the improvement factor of water-cooling, \( P_{pv,wc} \) and \( P_{pv,r} \) are the output module power with water-cooling and the reference (without cooling) in watts, respectively. Similarly, the improvement factor for fins cooling can be calculated using the following relationship:

\[
\xi_{pv,fc} = \frac{(P_{pv,fc} - P_{pv,r})}{P_{pv,r}}
\]

(6)

where \( \xi_{pv,fc} \) is the improvement factor of fins-cooling.

Once the improvement factors are defined, the performance ratio of the modules is represented.

### 2.4 Performance ratio of the proposed cooling techniques

The performance ratio of the proposed cooling techniques is calculated by comparing the actual and expected energy values. It can be represented as:

\[
PR = \frac{E_{actual}}{E_{expected}}
\]

(7)

where \( PR \) is the performance ratio, \( E_{actual} \) is the actual output module energy in kWh, and \( E_{expected} \) is the expected output module energy in kWh.

Once the problem is formulated, the SPVS system is described followed by experimental evaluations.

### 3 PV SYSTEM SETUP AND COMPONENTS

Figure 2 shows the PV system setup and different system components. The water-cooling panel is directly attached to the backside of the panel and a pair of equipped inlet and outlet valves. A set of thermocouples are placed 0.1 m apart from the pair of these inlet and outlet valves. A temperature sensor is located at the front of PV modules to measure cell temperature. The water flow remains constant at 4.2 L/min. The process starts with the cooling water, which flows through the panel, captures the waste heat from the panel and yield hot water that collected into insulated storage tank. The solar radiation
3.1 Hardware configuration and setup of water-cooling system

Figures 3 and 4 shows the water module and fins assembly structure respectively. A sheet of galvanized steel with 1.8 mm thickness attached to the back of the PV panel resembles shape of a box. 15 baffles are glued inside the box with thermal silicon to the backside surface of the panel. The main purpose of the baffles is to prevent the turbulent flow and to make the flow smooth. The baffles length is 90 cm. The diameter of the inlet and outlet valves is 3/4 in. The water-cooling system is an open loop system, where the water gets inside the panel does not make a cycle to cool the panel again, but it is used as a hot water for the domestic applications without any needs for water pumps.

3.2 Hardware configuration and setup of fins cooling system

A heat sink was fabricated of 100 aluminium rectangular fins with 1.5 mm thickness and 920 mm length. It has been designed as a U-shape tube with same cross sections and constant spacing of 10 mm. The heat sink is attached to the backside of the solar panel and glued by a thermal compound to acquire effective heat conductivity between the fins and the panel. The thermal compound is used to minimize the air gaps between the module and the fins which increase the heat conductivity and it has 25 mm height, 10 mm width and 920 mm in length along 1920 mm. The sectional view for a PV module with fins, fins assembly process and fins module construction are shown in Figure 5, respectively.

4 RESULTS AND EVALUATION

The measurements were taken from the setup shown in Figure 1 and recorded to a PC using data acquisition modules. The recording of measurements lasted for 4 months. The following parameters are daily measured and calculated: (1) The
TABLE 3  Hourly set of daily results for each parameter for reference module without cooling

| TIME | 6:00 | 7:00 | 8:00 | 9:00 | 10:00 | 11:00 | 12:00 | 13:00 | 14:00 | 15:00 | 16:00 |
|------|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|
| Weather condition, $G$ (KW/m$^2$) | 0.021 | 0.285 | 0.365 | 0.621 | 0.706 | 0.815 | 0.910 | 0.933 | 0.886 | 0.775 | 0.606 |
| Weather condition, $T_{amb}$ ($^\circ$C) | 23.2 | 24.1 | 27.9 | 30.3 | 33.2 | 36.5 | 38.5 | 40.3 | 41.2 | 41.4 | 40.7 |
| Weather condition, $V_{air}$ (m/s) | 0.513 | 0.47 | 0.103 | 1.137 | 2.507 | 4.193 | 4.706 | 4.041 | 4.007 | 4.531 | 5.046 |
| Reference module (without cooling), $P_{mR}$ (W) | 19.9 | 76.0 | 129.0 | 174.0 | 213.0 | 220.0 | 217.0 | 207.0 | 176.0 | 139.0 | 83.0 |
| Reference module (without cooling), $T_{mR}$ ($^\circ$C) | 20.6 | 21.7 | 30.3 | 40.2 | 52.0 | 53.0 | 55.0 | 57.0 | 57.0 | 55.0 | 52.0 |

TABLE 4  Hourly set of daily results for each parameter for fins module

| TIME | 6:00 | 7:00 | 8:00 | 9:00 | 10:00 | 11:00 | 12:00 | 13:00 | 14:00 | 15:00 | 16:00 |
|------|------|------|------|------|-------|-------|-------|-------|-------|-------|-------|
| Weather condition, $G$ (KW/m$^2$) | 0.021 | 0.285 | 0.365 | 0.621 | 0.706 | 0.815 | 0.910 | 0.933 | 0.886 | 0.775 | 0.606 |
| Weather condition, $T_{amb}$ ($^\circ$C) | 23.2 | 24.1 | 27.9 | 30.3 | 33.2 | 36.5 | 38.5 | 40.3 | 41.2 | 41.4 | 40.7 |
| Weather condition, $V_{air}$ (m/s) | 0.513 | 0.47 | 0.103 | 1.137 | 2.507 | 4.193 | 4.706 | 4.041 | 4.007 | 4.531 | 5.046 |
| Fins module $P_{mF}$ (W) | 24.0 | 84.0 | 139.0 | 186.0 | 226.0 | 232.0 | 230.0 | 218.0 | 189.0 | 147.0 | 88.0 |
| Fins module $T_{mF}$ ($^\circ$C) | 19.8 | 20.8 | 28.1 | 38.1 | 50.3 | 51.2 | 52.4 | 55.1 | 53.6 | 50.2 | 45.0 |

AC electrical output energy (kWh/day) for each panel ($E$), (2) ambient temperature ($^\circ$C), (3) cell temperature for each module ($^\circ$C), (4) inlet water temperature ($^\circ$C), (5) global irradiation at inclination of (26$^\circ$) (kWh/m$^2$.day), (6) wind speed (m/s), (7) conversion efficiency ($\eta_{pv}$ %) for each systems, and (8) performance ratio (PR).

4.1 | Experimental data collection

In this work, the data was collected from June 01, 2019 to October 01, 2019, for which measurements were recorded every 1 h. The working hours at the Hashemite University, Zarqa – Jordan are 6am to 5pm at location 32.05$^\circ$N, and 36.06$^\circ$E. The weather condition in Zarqa, in general is hot and dry. The photovoltaic module was tilted facing south with an angle of inclination 26$^\circ$ for the three modules, at outdoor climate conditions, the water-cooling was set at constant flow of 4.2 L/min. A set of measurements reflecting measured parameters can be observed on the August 01, 2019 in Tables 3–5 for reference, fins and water-cooling modules, respectively.

4.2 | Irradiation

Figure 6 shows how the irradiation changes with time. The time moves in daylong. This results in increasing the irradiation until it reaches its peak at solar noon. Note the irradiation changes during months of the year. Figure 7 displays the comparison of the maximum output power of each module during the chosen day (1st August 2019). The accumulated energy using water-cooling technique has the maximum output energy reached to 248 W. Simultaneously, the energy generated using fins cooling method is less than water method. This energy was reached to 230 W. While, the reference PV module without cooling has the minimum output energy reached to 217 W, it is noticed that the difference in energy accumulated between fins cooling and water-cooling start from 8 am to 1 pm and has the maximum difference at noon. An average increase in energy of 10% and 7% for water-cooling and fins cooling module, respectively was observed comparing to non-cooling module. In addition, it is clear that the PV module with different cooling techniques is more efficient especially during the middle of the day.

4.3 | Variation of module temperature

The variation of module temperature during the day (August 01, 2019) is shown in Figure 8. It is seen that the difference in temperature start from 9 am. It has been observed that there is a variation at energy generation too. Also, the module surface temperature is reduced due to the two cooling techniques.
TABLE 5  Hourly set of daily results for each parameter for water cooling module

| TIME       | 6:00  | 7:00  | 8:00  | 9:00  | 10:00 | 11:00 | 12:00 | 13:00 | 14:00 | 15:00 | 16:00 | 16:00 |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Weather condition, $G$ (KW/m²) | 0.021 | 0.285 | 0.365 | 0.621 | 0.706 | 0.815 | 0.910 | 0.933 | 0.886 | 0.775 | 0.606 | 0.397 |
| Weather condition, $T_{amb}$ (°C) | 23.2  | 24.1  | 27.9  | 30.3  | 33.2  | 36.5  | 38.5  | 40.3  | 41.2  | 41.4  | 40.7  | 39.0  |
| Weather condition, $V_{air}$ (m/s) | 0.513 | 0.47  | 0.103 | 1.137 | 2.507 | 4.193 | 4.706 | 4.041 | 4.007 | 4.531 | 5.046 | 5.389 |
| Water cooling module, $P_{mw}$ (W) | 20.0  | 83.0  | 147.0 | 201.0 | 243.0 | 245.0 | 248.0 | 220.0 | 184.0 | 140.0 | 86.0  | 24.0  |
| Water cooling module, $T_{mw}$ (°C) | 19.9  | 20.5  | 26.0  | 30.0  | 35.3  | 37.7  | 39.0  | 40.3  | 39.8  | 37.0  | 36.3  | 36.0  |
| Water cooling module, $T_{win}$ (°C) | 20.0  | 21.2  | 26.4  | 29.0  | 31.3  | 32.4  | 33.8  | 33.7  | 32.4  | 32.2  | 31.8  | 31.0  |
| Water cooling module, $T_{wout}$ (°C) | 21.1  | 22.0  | 27.3  | 33.2  | 33.6  | 35.0  | 35.0  | 36.6  | 36.0  | 36.4  | 34.0  | 33.2  |

FIGURE 7  Comparison of the maximum output energy of the different modules using day of August 01, 2019

FIGURE 8  Module temperature during the day—Variation analysis

compared to non-cooling module with maximum temperature difference of up to 40 °C for water-cooling and up to 55 °C for fins cooling, respectively. On the other hand, it reaches up to 57 °C for non-cooling module. As a result, the temperature difference between water-cooling modules compared to non-cooling module is 17 °C. Similarly, the difference temperature between fins module compared to non-cooling module is 2 °C. The percentage reduction observed in the back-surface temperature was 30% for water, and 3.5% for fins.

Figure 9 shows the variation of module temperature during the test months with enlarged of June and August month. A variation at power generation can be observed during the difference in temperature from 1st of August. Also, the resulted measured average module surface temperature is 31, 35, 40 and 42 °C for ambient, water module, fins module and without cooling module respectively. Moreover, it can be noticed that the average difference between water-cooling module and with no cooling module is 7 °C. Similarly, the average difference between fins cooling module and with no fin cooling module is 2 °C. In addition to that, the ambient temperature is the minimum temperature through all the period.

4.4  Energy generation analysis—daily and monthly

Figure 10 illustrates the monthly PV energy generated (kWh) for different cooling technique. The month of July has the minimum difference of power between with water-cooling module and with no cooling module. This could be due to the PV-module and the ambient temperature reaching the maximum value. Tables 6–8 illustrated all changes during this time-period of June, July, August and September, respectively.

Figure 11 illustrates the monthly average energy generated from fins module with wind speed variation. The wind speed is a positive factor for increasing the power generated from the panel with fins. The variation of total performance improvement with water inlet temperature is shown Figure 12. It is observed that the variation of the inlet water temperature is
inversely proportional with improvement of module efficiency. The temperature of water inlet decreases the improvement of module efficiency. When the temperature of water was at 29 °C, the improvement was 10%. Similarly, when the temperature of inlet water was as 31.5 °C, the improvement dropped to 6.2%.

### TABLE 7  Fins cooling module—Daily average results for each month

| Month | June | July | August | September |
|-------|------|------|--------|-----------|
| $T_{amb}$ (°C) | 30.40 | 33.00 | 31.00 | 29.30 |
| Fins cooling module, energy (kWh) | 55.00 | 54.20 | 56.00 | 48.70 |
| Fins cooling module, $T_{mF}$ (°C) | 39.00 | 42.20 | 40.00 | 38.60 |

### TABLE 8  Water cooling module—Daily average results for each month

| Month | June | July | August | September |
|-------|------|------|--------|-----------|
| $T_{amb}$ (°C) | 30.40 | 33.00 | 31.00 | 29.30 |
| Water cooling module, energy (kWh) | 57.22 | 56.10 | 57.00 | 50.30 |
| Water cooling module, $T_{mW}$ (°C) | 35.00 | 35.30 | 35.20 | 34.00 |

Figure 13 displays the comparison of electrical efficiency and performance improvement for three modules respectively. The maximum efficiency and minimum efficiency for water-cooled module occurred in September and July with 13% and 12.85%, respectively. This cumulates an average of 12.9%. For the fins-cooled module, they are occurred in July and June with percentages of 12.7% and 12.55%, respectively with an average of 12.6%. Whereas the maximum and minimum electrical efficiency for non-cooled module in July and in September reach...
up to 12.1% and 11.86%, respectively. The average is equal to 11.9%. These results confirm that the water-cooling technique is more efficient than the fins cooling technique. Figure 14 shows an analysis of performance improvement. The maximum improvement for water technique is achieved in September and equals 10.2% while the minimum improvement is achieved in July and equals 6.7%. The average efficiency equals 8.2%. Also, it is noticed that the maximum improvement for fins technique in September reach to 6.63%, while the minimum improvement is achieved in July which equal to 4.96%. The average is equal to 5.83%.

4.5 Performance ratio and efficiency comparison

Another important parameter that needs to be estimated is the performance ratio (PR). The ideal analysis period to estimate PR is one year. However, it is also possible to select shorter time periods. The PR for the present case study is calculated for month of June, July, August and September.

4.5.1 Calculation of performance ratio

The analysis period for this calculation was for 4 months (June, July, August, and September). The measured average solar irradiation intensity in 4 months is 219 kWh/m². The generator area of the PV plant is 5.85m². The efficiency factor of the PV modules is 15.4%. Electrical energy exported by plant to grid is 637.52 kWh. The irradiation values measured on location yields an average solar irradiation for the entire analysis period of 219 kWh/m². This irradiation value is extrapolated to the module area of the PV plant as follows: Irradiation value in kWh/m² × plant area in m² = 219 kWh/m² × 5.85 m² × 4 = 5125 kWh. To subsequently calculate the nominal plant output, the irradiation value for the PV plant is multiplied by the module efficiency as: 5125 kWh × 15.4% = 789.2 kWh. An anticipated nominal plant output of 789.2 kWh is therefore obtained for the selected analysis period. This anticipated nominal plant output corresponds to a performance ratio of 100%.

\[ \text{PR} = \frac{637.52 \text{ kWh}}{789.2 \text{ kWh}} = 81\% \]

However, the actual value for electrical energy exported by the PV plant to the grid is only 637.52 kWh. If this value and the calculated nominal plant output are fed into the formula for calculating the performance ratio, the following result is obtained: The PR value is approx. 81%. This means that approx. 19% of the incident solar energy in the analysis period is not converted into usable energy due to circumstances such as conduction loss, thermal loss or, for example, Defects in components. Here the performance ratio acts as an indicator and can prompt more detailed inspection of the PV plant so that, for example, soiling of the PV modules is removed, or defective components can be repaired or replaced. The actual annual final yield is \( = 3 \times 300 = 900 \text{ W} \). This employs that 900 W \( \times 6 \text{h} = 5.4 \text{ kWh/day} \) where the sun peak hour at Hashemite University are 6. Also, the irradiation value is:\n
\[ \text{kWh/m}^2 \times \text{plant area} = 219 \text{ kWh/m}^2 \times 1.95 \text{m}^2 \times 4 \text{month} \times 0.154 = 263 \text{ kWh}. \]

After doing all the calculations, it was noticed that the output cumulative energy of the water-cooling system is more efficient than both system outputs by 9% and 3.7% for modules without cooling and fins cooling respectively. However, a comparison between both systems based on their conversion efficiencies is required.

The performance ratio for water-cooling module and fins module has improved. The water-cooling technique and fins technique can improve the performance ratio to the maximum value of 84% and 81%, respectively. Finally, it should be stated that the total efficiency of the system could be enhanced by recovering the hot water at the outlet, since the use of the extracted heat in any domestic application will be considered a benefit to the entire system.

A comparison of the present study and the previous studies is illustrated in Figures 15 and 16. Here PS represents the acronym of the proposed scheme in the figure. The efficiency improvement is measured in the comparison. The present study has superseded the efficiency from [16, 19] in heat fins cooling comparison and is nearly touching the efficiency of [13]. Similarly, in the water-cooling technique comparison, the proposed scheme stands tall in comparison to [11, 20, 24, 25].
water-cooling technique shows improvement by increasing heat dissipation due to an access to the maximum possible area of PV panels, it is the recommendation of this work. Moreover, a fusion of the improved design with existing performance-based design can enhance the effectiveness and efficiency towards temperature variations.

5 | CONCLUSION

The performance of SPVS system is improved through two different proposed cooling techniques while addressing the parameters of flow rate and amount of heat dissipation. Three identical PV modules are used. Every PV module is connected separately with micro-inverter and further connected to a 220 V AC 50 Hz grid. The experimental results proved the performance of the water-cooling technique. It has substantially lowered the PV panel temperature. Moreover, it performed better than the heat sink (fins) cooling technique. In performance conditions, both cooling techniques performed better than the reference PV panel at wind speeds greater than zero. This has further confirmed the advantages to maintain the temperature of the PV panel does not exceed to 65 °C. The average improvement using water and fins as heat sink as coolants are 8.17% and 5.8%, respectively in comparison with no cooling. The performance ratio for water-cooling, fins and no cooling techniques are 84%, 81% and 77% respectively. The performance evaluation using thermal image showed the temperature distribution for the cooling module, which is as low as 25 °C and in comparison with the reference module which had different temperature distribution from 37 to 54 °C where the ambient temperature was 32 °C.

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