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ARTICLE

Electrical Power Improvement of Grid-tied Photovoltaic Solar System

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Abstract: The method that is used to improve performance and electrical power is to use optical reflectors. Optical reflectors improve performance and electrical power, because they increase solar irradiation. CIGS is an acronym for Copper Indium Gallium Selenide. CIGS PV solar module is a second-generation thin-film technology. The system with which optical reflectors are attached is 5kWp. CIGS PV solar system is situated at Al-Mansour factory, Baghdad-Iraq (longitude 44.4°E, latitude 33.3°N and 41m above the sea level). This study improves electrical power, current, performance ratio and array efficiency. All these improvements are done by increasing solar radiance *via* utilizing optical reflectors (fabricated from aluminum metal). The current system is divided into two parts: improved (PV modules with optical reflectors) and reference part (PV modules without optical reflectors). At 12:00 PM, the largest values of the solar irradiance, electrical power and current for improved and reference PV modules are 1346.1 W/m^2 and 981.5 W/m^2, 2.308 kW and 1.712 kW,6.01 A and 4.44 A, respectively. At 7.30 AM and 5:00 PM, the largest values of performance ratio and array efficiency of 98% and 14.8%, respectively, are recorded, while the minimum values are at 12:00 pm of 91% and 92.5% and 13.8% and 14.1%, respectively. The largest values of the improved and reference PV module temperatures are 56°C and 50°C, respectively, at the ambient temperature of 21°C. At 7:30 AM, the lowest values of the electrical power, current, solar irradiance and temperatures for the improved and reference PV modules are recorded to be 0.276 kW and 0.267 kW, 0.68 A and 0.65 A, 142.67 W/m^2 and 138.44 W/m^2, 33°C and 34°C, respectively, at an ambient temperature of 16°C. The maximum increment percentages (gains) for power, current, solar irradiance and module temperatures resulting from using optical reflectors are 34.4%, 35.3%, 37.1% and 6°C, respectively. The current work was achieved under clear sky conditions. The mean increment throughout a day is 24.4%, which is a very good indication of economic feasibility.

Keywords: PV solar system, Efficiency, Optical reflector, Grid-connected, CIGS.

Introduction

According to the low cost of the photovoltaic solar systems and the possibility of raising their efficiency, it is expected that PV solar systems will become one of the main future resources of energy production [1]. Traditional energy sources like oil and gasoline (fossil fuels) cause a lot of impacts on the environment, such as air contamination, ozone-layer depletion, acid rain, greenhouse effect, reduction of air quality and pollution of underground and surface waters. Increased carbon dioxide emitted into the air is the main cause of global warming, which is the main factor that harms the environment. So, clean-energy (renewable energy) resources are

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required to be alternative resources [2, 3]. The energy demand is increasing, whereas the fossil fuel resources which dominate most traditional energy systems are coming to be depleted because of great world demand [4]. The key source of carbon dioxide gas emission is fossil fuel combustion. Currently, the maximum electrical power consumption around the globe at any certain moment is 12.5TW and it is expected that by 2030, the globe will need 16.9TW [5]. Utilizing the PV solar systems decreases the amount of CO_2 released by more than a hundred Giga tonnes [6]. The applications of solar energy are basically divided into two types; solar thermal energy and photovoltaic solar (electric) energy. Thermal solar energy is the most commonly available source that can be utilized for cooking, water heating, crop drying, … and so on [7]. PV solar applications include cold storage, water pumps, traffic signals, street lighting, … etc. [8]. The concentrator PV solar (CPV) cell material contributes about 50% to 60% of the total cost of commercial PV solar modules [9]. Previous work studied the application of planar optical reflectors for PV solar and solar thermal applications. Many of the early studies on optical reflectors focus on the improvement of wintertime output for photovoltaic solar systems [10, 11]. A number of works used several sun-tracing models to estimate the increase in solar radiation from a given geometric reflector [12]. In 2018, Naseer, K.K. et al. used two reflectors (V-trough concentrators) to improve the performance of the PV solar modules in Baghdad-Iraq. They found that the maximum gain in electrical power is 48% and the daily average is 42.6% [13].

In 2000, Ronnelid et al. studied the performance of the PV modules with V-trough in adjustable tilt angles and lengths under the weather of Sweden. They discovered that the planar fixed optical reflector is able to increase the annual power output from 20 to 25% [14]. In 2007, experimental works in Mumbai, India were carried out by Sangani and Solanki. They have used a V-trough system with a geometric concentration ratio of (2-sun), which increased the power product to 44% compared with the planar concentration system [15]. In 2009, optical reflectors of several different materials were mounted to down and up edges of the PV solar modules to study the PV solar module performance of these materials. The best type of reflector's material can yield more electrical energy. Investigations were conducted on aluminum, stainless steel and chrome film reflectors to determine the most efficient type of optical reflector's material that harvests more electrical power and less surplus heat. It is found that the chrome optical reflectors produce 27.65% more electrical power product compared to aluminum-foil reflector and 34.05% more electrical power product compared to optical reflectors of stainless steel [16]. In 2013, K. Dewi et al. studied the planar reflector impact on the I-V characteristic curve of the PV modules. They found out that the aluminum-foil and stainless-steel planar reflectors are able to increase the electrical power product by 31.5% and 21.5%, respectively [17]. PV/T solar system with water mass flow rate of 0.042 kg/sec and optical reflectors reflect solar irradiance of 950 W/m^2, where the outcomes illustrate that combined thermal and electrical efficiencies are 71.40% with an electrical efficiency of 12.40% [18]. In 2015, Pavlov et al. showed that the utilization of fixed planar concentrators results in an increment in daily produced electrical power of up to 35% for amorphous silicon PV modules through clear-sky days at given times of the year. In 2016, W. Alshohani et al. conducted an experimental study to reduce the PV module heat [19].

The objective of this work is to increase the electrical power and consequently obtain good economic feasibility. The PV modules can be equipped with a cooling system to eliminate surplus heat generated in these PV modules. Cooling improves the PV modules' efficiency, because their resistance will reduce. This objective can be achieved by implementing the optical reflectors and cooling system. There are more techniques utilized to enhance the PV solar modules' performance by utilizing optical reflectors (planar concentrators) with cooling [20, 21].

Materials and Methods

(A) PV Solar System Specifications

The present PV solar system is situated in north Baghdad at Al-Mansour Factory at a coordinate location (latitude 33.3 ^{o}N and longitude 44.4 ^{o}E). Fig. 1 represents the current PV solar system.

FIG. 1. Gird-tied CIGS PV solar system.

TABLE 1. PV solar system and module specifications.

System Specifications	Value	Module Specifications	Value
Inverter model	SMA SB-5000T-21	Module model	TS-165C2 CIGS
Number of modules	30	Max. power (Pmax)	165 W
Inverter size	5.30 kWp	Open-circuit voltage (Voc)	88.7 V
Inverter efficiency	97%	Short-circuit current (I_{sc})	2.66 A
System size	5 kWp	Max. power voltage (V_{mpp})	68.5 V
Modules tilt angle	30°	Max. power current (I_{mpp})	2.41 A
Optical reflectors' tilt angle	30°	Max. reverse current (I_R)	6.5 A
PV array area	32.6 m^2	Operating temperature	-40°C to 85°C
		Module efficiency	15.2%

(B) PV Solar Modules and Optical Reflector

The current PV solar system comprises 30 PV solar modules that are separated into two parts; the first part consists of 12 PV solar modules that are assigned as improved modules and the second part consists of 18 PV solar modules that are assigned as reference modules. An inverter's data is exhibited in two sets (A and B), as shown in Fig. 4. An inverter in CIGS PV solar system comprises two inverters, each one is called a maximum-power point tracker (MPPT) [22]. The improved modules are exposed to a larger amount of solar radiation that comes from optical reflectors and from the sun compared to the reference modules. The optical reflectors are added in front of the improved part, while the reference part stays without optical reflectors, as displayed in Fig 3. An inverter in this PV solar system comprises two inputs; the first input (MPPT1) has 12 PV solar modules (1980 Wp) and the second input (MPPT2) has 18 PV solar modules (2970 Wp). The data is obtained by utilizing a speedwire that joins the laptop with an inverter, as shown in Fig. 5. Single-line diagram of CIGS grid-tied PV solar system is shown in Fig. 2.

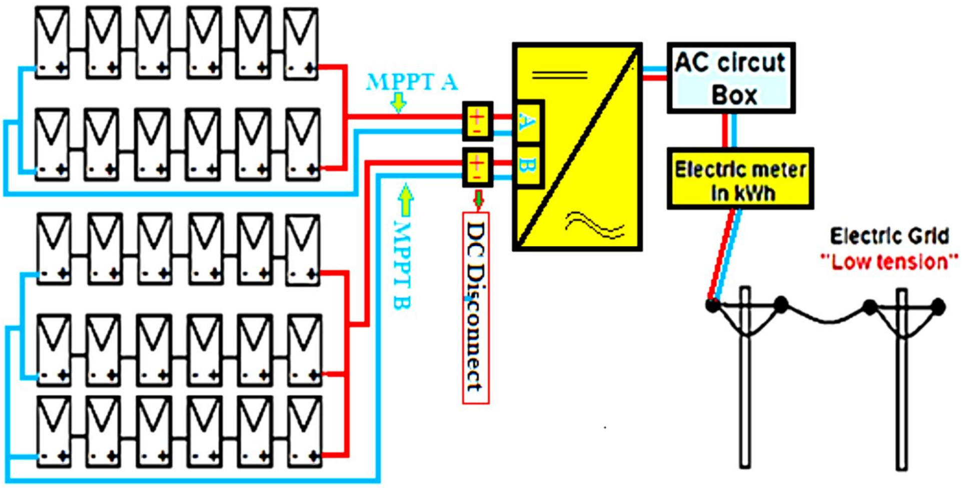

FIG. 2. Single-line diagram of CIGS grid-tied PV solar system.

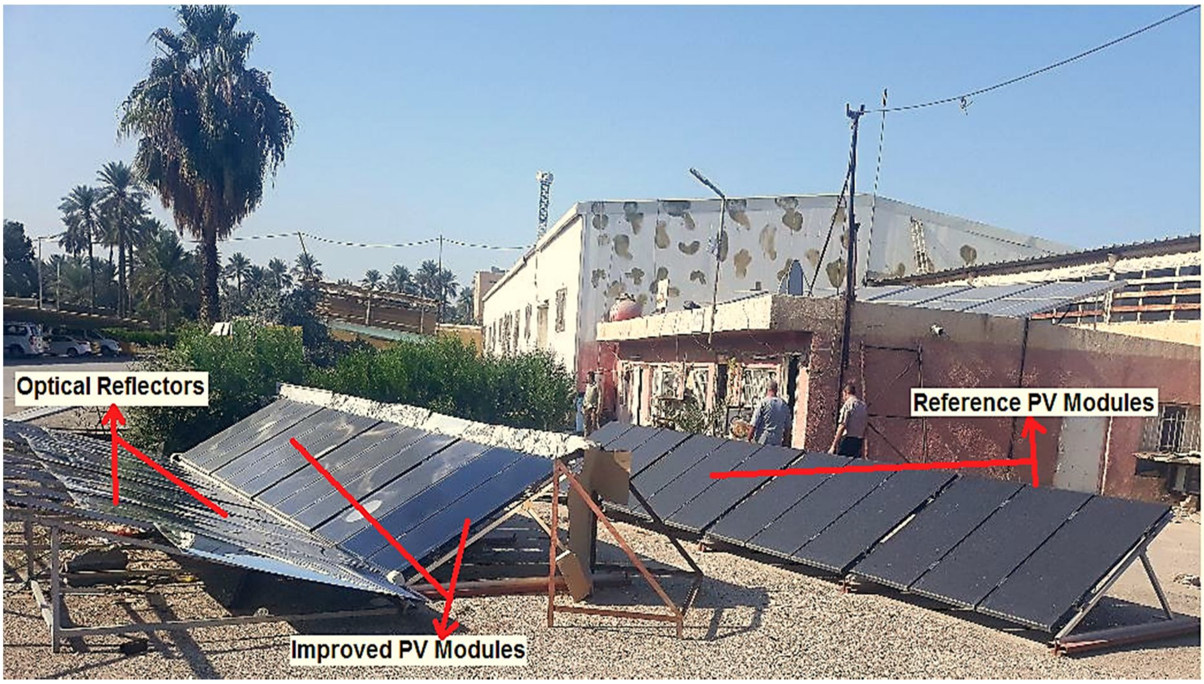

FIG. 3. PV solar system with optical reflectors.

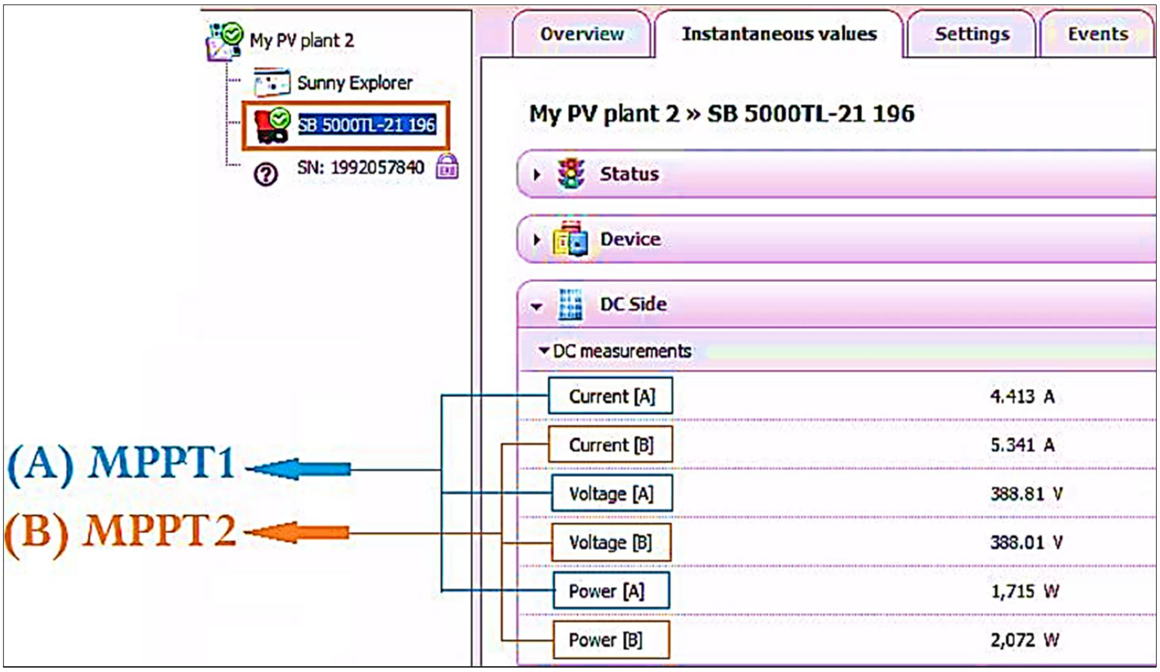

FIG. 4. Screenshot of inverter data display in PC.

(C) Experimental Set-up

The current study is accomplished at Al-Mansour Factory, Iraq-Baghdad (latitude 33.3°N, longitude 44.4°E). The study parameters comprise: solar irradiance, power, current, efficiency and performance ratio, as well as ambient temperatures of PV modules (temperatures are measured for improved and reference modules). The electrical parameters mentioned above are documented for reference and improved modules. The data for each part is gotten from an inverter that shows this data separately in the form of (B) that regards reference modules which comprise 18 PV solar modules and (A) which regards improved modules that comprise 12 PV solar modules, as displayed in Fig. 4. The experiment extended from 7:30 AM till 5:00 PM on 19 March 2020, where the sky was clear and all PV solar modules (improved and reference PV solar modules) were cleaned.

Evaluation of the PV Solar System Parameters

The improved and reference modules are evaluated on the basis of the aforementioned electrical parameters. The array efficiency and performance ratio are obtained by utilizing the equations below. Temperatures of ambient atmosphere and PV solar modules are measured by utilizing a digital thermometer. Current and power are obtained from an inverter directly *via* utilizing a speedwire that joins an inverter with the PC, as displayed in Fig. 5.

Note: Before utilizing the formulae and equations aforementioned, the current and power of the reference modules are divided by 18 and multiplied by 12 to achieve an equalization in current and power (number of modules) between the reference and the improved parts, in order to make each part contain 12 PV modules, because the reference part contains 18 PV modules and not 12 PV modules.

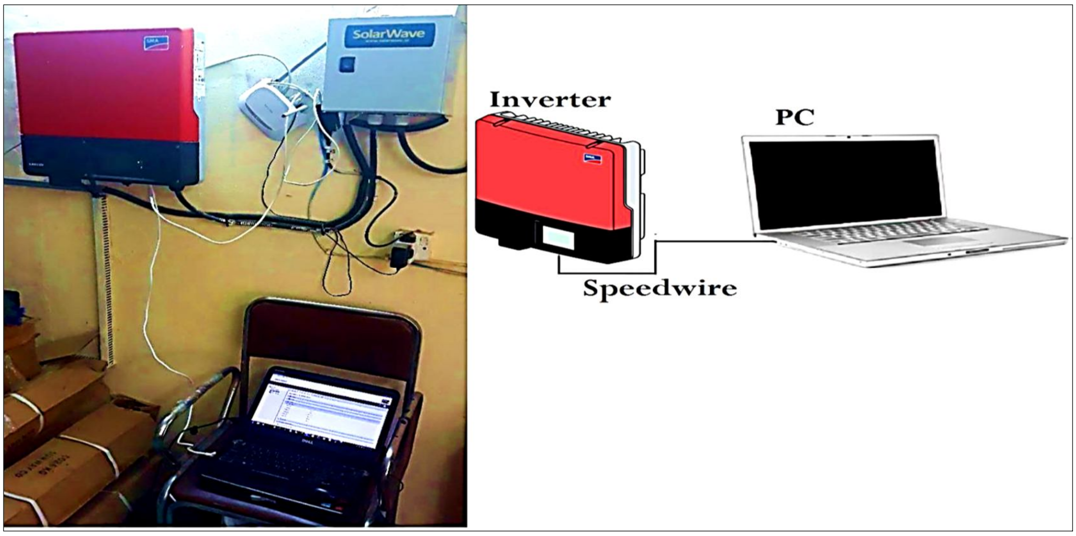

FIG. 5. Joining between an inverter and a laptop *via* a speedwire.

A. Efficiency

The efficiency can be estimated on a yearly, monthly, daily or hourly basis. The system efficiency (ηsys) is built on the AC energy product and the array efficiency (ηPV) is built on the DC energy product [23,24]. The array efficiency is the ratio of (yearly, monthly or daily) average of array energy output (DC) to the (yearly, monthly or daily) average of in-collimated plane solar irradiation multiplied by the area of the PV solar array [25]. The array efficiency is given as:

$$\eta_{PV} = \frac{100 * E_{DC}}{H_T * A_m} \% \quad (1)$$

where:- E_{DC}: DC energy, A_m : array area (m^2) and H_T : solar irradiation (in-collimated plane).

The system efficiency is calculated as:

$$\eta_{SYS} = \frac{100 * E_{AC}}{H_t * A_m} \% \quad (2)$$

where:- E_{AC}: AC energy, A_m : array area (m^2) and H_T : solar irradiation (in-collimated plane).

An inverter efficiency is calculated as:

$$\eta_{INV} = \frac{100 * E_{AC}}{E_{DC}} \%. \quad (3)$$

The inverter efficiency is (97% - 96.6%), because it is indoor [26].

B. Performance Ratio (PR)

The performance ratio is a very important parameter that illustrates all losses affecting the rated (nominal) power of the PV solar system. PR value displays how close it approaches perfect performance through real-work duration and permits comparison between different PV solar systems regardless of tilt angle, azimuth angle and nominal power [27]. PR can be calculated as the ratio of the (YF) over the (YR); it is given as [28, 29]:

$$PR = \frac{Y_F}{Y_R} \% \quad (4)$$

where: Y_F represents the final yield that is calculated by Eq. 5 and Y_R represents the reference yield that is calculated by Eq. 6.

Final yield (Y_F) is the AC energy output for a specific time to the nominal power of the PV solar system [30]. It represents the number of hours that the PV array would need to operate at its rated power to provide the same energy. The units are hours or kWh/kW. It is calculated as:

$$Y_F = \frac{E_{AC}}{P_{rated}} (kWh/kW_P) \quad (5)$$

where: E_{AC} is the AC energy output in (kWh).

Reference Yield (Y_R) is the in-collimated plane global irradiation over the reference irradiance that equals 1kW/m^2. The reference yield is given as:

$$Y_R = \frac{H_T}{H_R} (kWh/kW_P) \quad (6)$$

where: H_R and H_T are the reference irradiance and in-collimated plane solar insolation (irradiation), respectively [26].

On the other hand, the performance ratio can be given by a simple formula as follows:

$$PR = \frac{\eta Actual}{\eta ref} \quad (7)$$

Eq. 7 is used to find the performance ratio.

The actual power and nominal (rated) power are given as:

$$\text{Actual Power } (P_{actual}) = H_R * \eta_{Actual} * A_m \quad (8)$$

$$\text{Rated Power } (P_{rated}) = H_R * \eta_{ref} * A_m \quad (9)$$

The actual efficiency (η_{Actual}) is given as:

$$\eta_{Actual} = \eta_{ref}[1-\beta(T_m-T_{ref})] \quad (10)$$

where: η_{ref} **:** rated efficiency (15.2% for CIGS module), A_m **:** area of improved and reference parts (13.04 m^2), β**:** temperature coefficient which equals 0.3%/$^{\circ}$C, T_{ref}: reference temperature = 25°C and T_m: module temperature.

When substituting Eq.10 into Eq. 8, Eq. 11 is obtained as follows:

$$H_R = \frac{P_{actual}}{A_m * \eta ref\,[1-\beta(T_m-\text{Tref})]} \quad (11)$$

Eqs. 11 and 7 are used to find solar irradiance (H_R) and performance ratio (PR), respectively.

The formulae utilized to calculate the increment percentage (gain) in electrical power and current are given as follows:

$$INCP_P = (P_{im}-P_{ref})/\ P_{ref} * 100\% \quad (12)$$

$$INCP_I = (I_{im}-I_{ref})/\ I_{ref} * 100\% \quad (13)$$

where: P_{im} and P_{ref}, are the improved and reference PV modules' power, respectively. I_{im} and I_{ref}, are the improved and reference PV modules' current, respectively. $INCP_I$ and $INCP_P$ are the increment percentages (INCP) in current and power, respectively.

Results and Discussion

Fig. 6 shows improved and reference PV modules' power. The figure demonstrates a clear difference between the two parts. The highest values of power for reference and improved PV modules are 1.712 kWp and 2.308 kWp, respectively, at 12:00 PM, while the INCP (the gain) is 34.4%, This value of gain has a significant influence on the economic feasibility of renewable energy. The lowest value of INCP is at 5:00 PM amounting to 4.9% and the average value through the day is 24.7%. Fig. 6 demonstrates the role of optical reflectors in increasing the electrical power from the PV solar system.

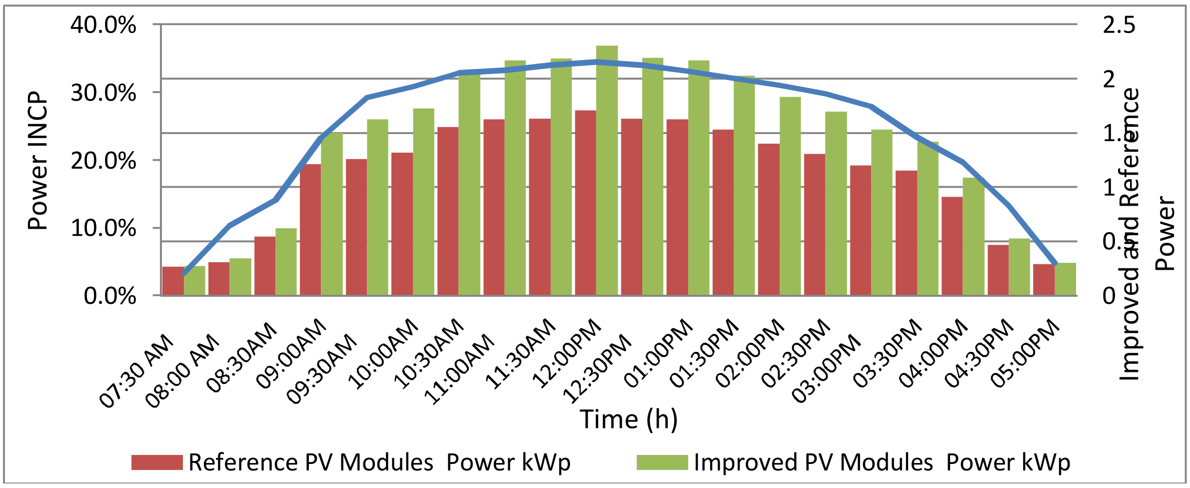

FIG. 6. Power INCP and improved and reference modules' power.

Fig. 7 illustrates the electrical current of the improved and reference PV modules. The maximum values of current INCP (the gain) and improved and reference PV modules current are at 12:00 PM amounting to 35.3%, 6.01A and 4.44 A, respectively and the minimum values are at 5:00 PM being 3.9%, 0.99A and 0.955A. The daily average of current INCP is 25%. In the time duration from 10:00 AM to 3:30 PM, the supremacy is to the current upon the power, because the optical reflectors raise the value of PV modules' temperature and solar irradiance and these two parameters raise the value of current, since the optical reflectors and temperature increase electrons. PV modules' temperature decreases the voltage; so the power reduces. On the contrary, in the time duration from 4:00 PM to 5:00 PM, the supremacy is to the power upon the current, because the PV modules' temperature decreases and the solar irradiation reflected from optical reflectors to PV modules deflects away from some of these PV modules.

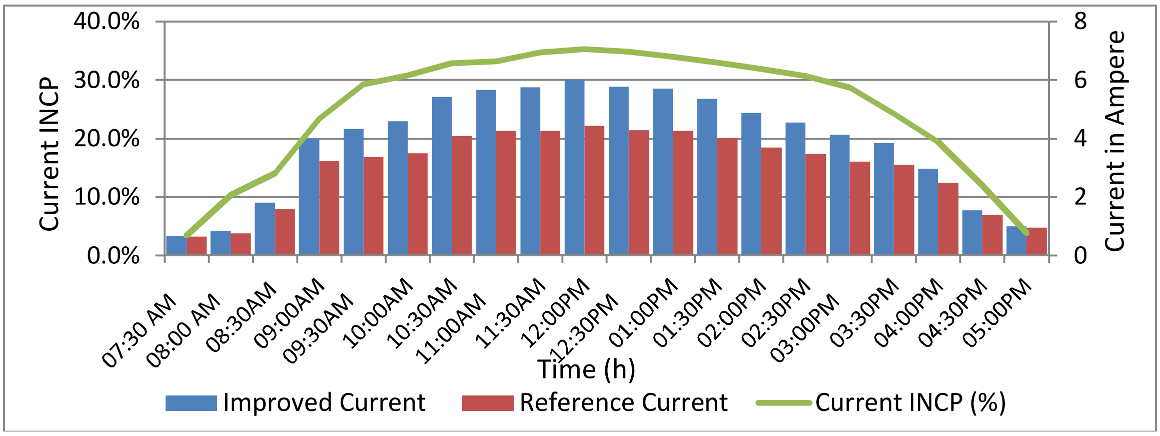

FIG. 7. Current INCP and reference and improved PV modules' current.

Fig. 8 shows the performance ratio (PR) of the improved and reference PV modules. At 7:30 AM and 5:00 PM, where the maximum values of the performance ratio of the improved and reference PV modules were recorded to be 97.5% and 97.3%, respectively, while the losses caused by the optical reflectors are zero, whereas the minimum values are 91% and 92.5%, respectively at 12:00 PM. At midday, the PR of the improved and reference PV modules is at the lowest value, because the PV modules get hotter. The PR of the improved PV modules becomes less than the PR of the reference PV modules, because the optical reflectors attached to the improved PV modules' raise the PV modules temperature, but the difference in the PR between the improved and reference PV modules is very small. As shown in Fig. 8, the losses do not exceed 2% and decrease toward sunrise and sunset to zero due to a decrease in the PV modules' temperature. PR is a measurement indicator of how close a PV solar system approaches perfect performance through actual work and permits comparison of PV solar systems, regardless of azimuth angle, tilt angle and nominal power.

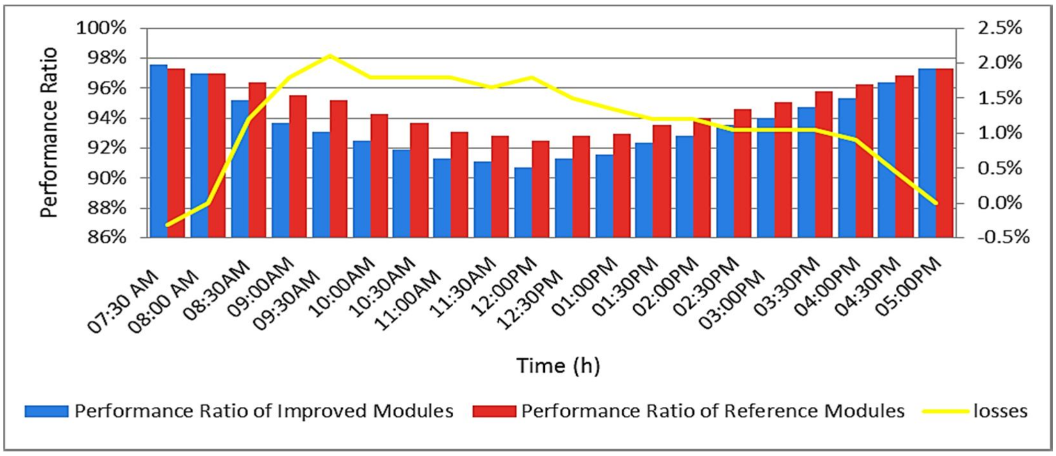

FIG. 8. Improved and reference PV modules' performance ratio.

Fig. 9 shows the efficiency of improved and reference PV modules. At 7:30 AM and 5:00 PM, the maximum values of efficiency for improved and reference PV modules were recorded at 14.8% and 14.8%, respectively. The minimum values for improved and reference PV modules' efficiencies are 13.8% and 14.1%, respectively at 12:00 PM (midday). The maximum values of efficiency synchronize with the lowest PV module temperature and *vice versa*. So, the maximum efficiency occurs at sunrise and sunset. It is noticed in this study that the efficiency of reference PV modules is slightly larger than the efficiency of the improved modules; namely, the losses are very small. The optical reflectors associated with the improved modules raise the temperature of the modules and consequently, the efficiency decreases. There is a tight correlation between the PV solar modules' efficiency and temperature, as shown in Fig. 9.

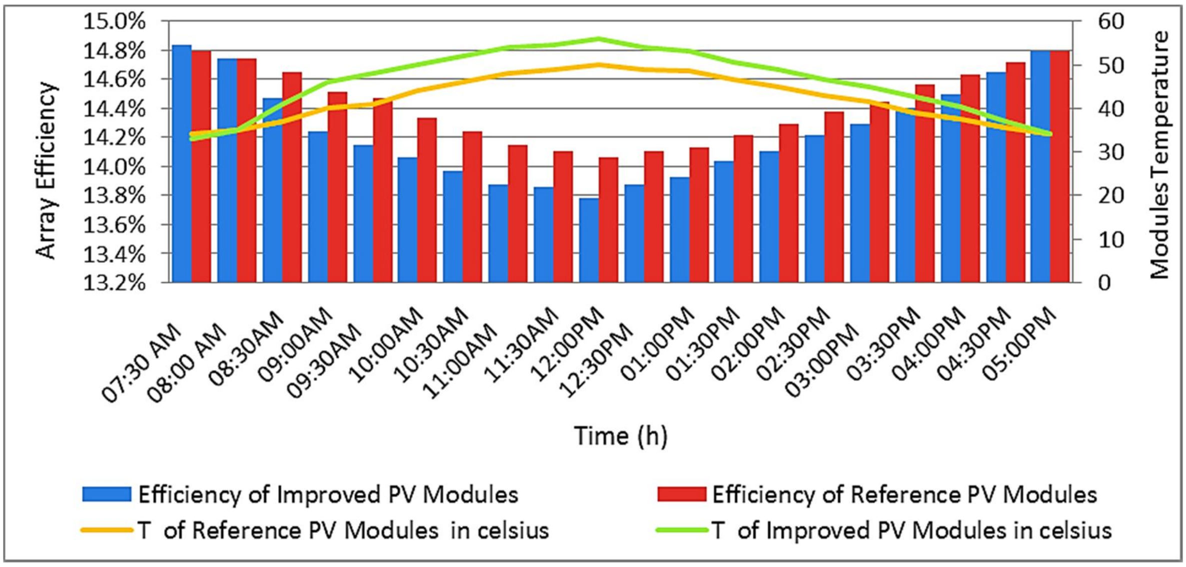

FIG. 9. Improved and reference PV modules' efficiency.

Fig. 10 demonstrates the increment percentages (INCP) and improved and reference PV modules' solar irradiance (S.R.). At 12:00 PM, the maximum values for increment percentage (the gain) and solar irradiance of the improved and reference PV modules were 37.1%, 1346.1W/m^2 and 981.8W/m^2, respectively, where the solar irradiance INCP (37.1%) is equivalent to 364.4 W/m^2. At 7:30 AM, the minimum values were recorded at 3.1%, 142.7 W/m^2 and 138.44 W/m^2, respectively. During the time duration specified from 7.30 AM to 8:30 AM and from 4:30 PM to 5:00 PM, there is a convergence between the solar irradiance values of the reference and improved PV modules, because the solar radiation that reflects from optical reflectors to PV modules deflects away from these modules. On the contrary, at midday, no deflection occurs to solar radiation, but it directly reflects on the PV modules. This means that the improved PV modules obtain a bigger amount of solar radiation compared to the reference PV modules; so there is a divergence between the reference and improved PV modules' solar radiation.

Fig. 11 illustrates ambient temperature, temperature of improved PV modules (T of improved modules) and temperature of reference PV modules (T of reference modules). At 12:00 PM, the maximum values of ambient temperature, improved and reference PV modules' temperature were recorded at 21°C, 56°C and 50°C, respectively. whereas at 7:30 AM, the minimum values were recorded at 16.2°C, 34°C and 33.8°C, respectively. At 12:00 PM, the rise in the PV modules' temperature caused by utilizing optical reflectors is 6°C solely. This means that the optical reflectors do not add large heat to the PV modules; so this addition in temperature has a very small impact on the voltage. This increment (6°C) does not continue longer than 25 sec to 30 sec. On the contrary to the maximum ambient temperature that occurs at 3:00 PM, the maximum temperature of the PV modules occurs at 12:00 PM.

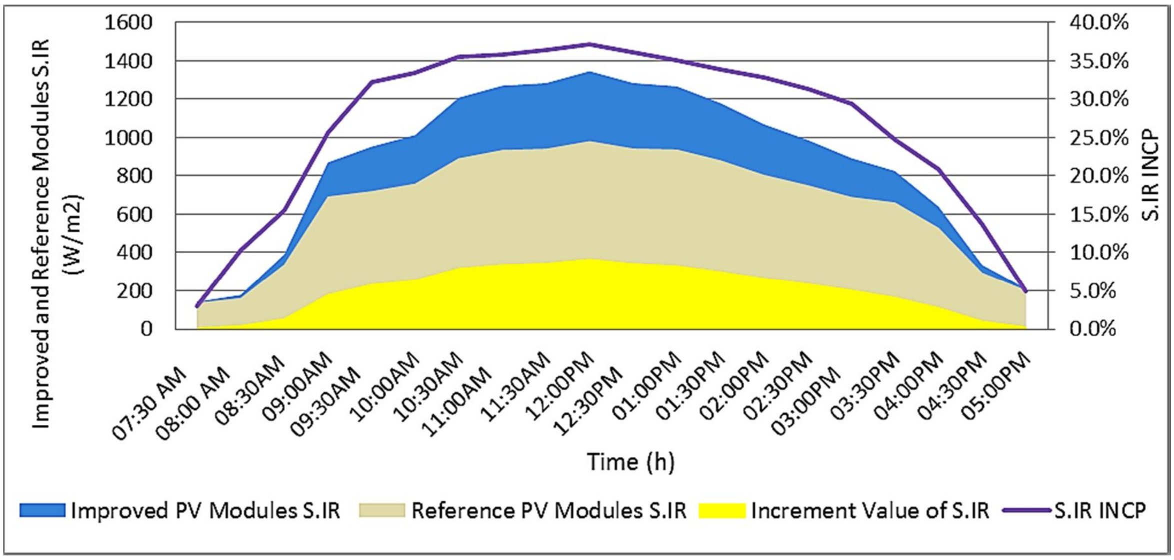

FIG. 10. S.IR INCP and improved and reference PV modules' solar irradiance (S.IR).

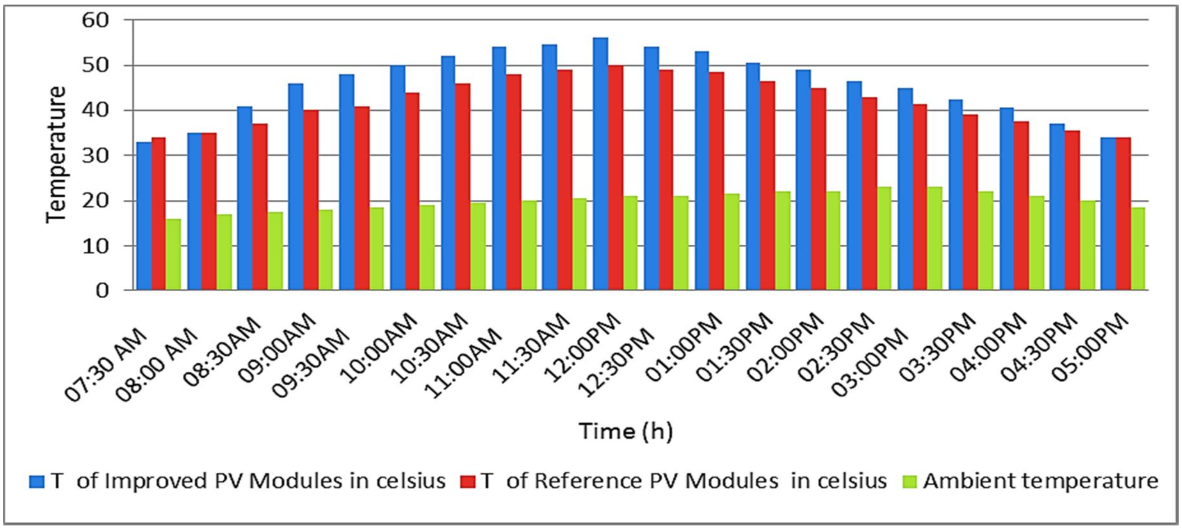

FIG. 11. Temperatures of ambient atmosphere, improved and reference PV modules.

Conclusions

- The results presented that optical reflectors have a significant impact on the INCP obtained from solar radiation, power and current.
- The power was improved by a percentage of 25% daily, which means that the power saved is 1250Wp of the rated power of the CIGS system (5kWp) which equals 7kWh per day, because the total energy produced is 28kWh per day.
- As an average value during March, the energy saved is 217kWh.
- Approximately, the maximum gain (INCP) of all electrical parameters is 34.5%.
- Performance ratio and efficiency for improved and reference PV modules increase at sunrise and sunset, while they decrease at midday.
- The expectations indicate that the PR and efficiency of the improved and reference PV modules decrease in summer and increase in winter, spring and fall seasons.
- Increasing the PV modules' temperature as a result of utilizing the optical reflectors does not have a large influence on the PV modules' lifetime, because this increase is only 3.9°C as a daily average; so the optical reflectors can be attached to two sides of the PV modules' string in this month and in winter, spring and fall seasons.
- In view of the points aforementioned, it can be said that there is good economic feasibility that can be obtained when utilizing optical reflectors.

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Author Contribution Statement

A.N.A. designed the work. N.K.K. and A.N.A. conducted the experiments. H.H.H. and N.K.K. edited the manuscript. All authors have read and approved the final version submitted to the journal.

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