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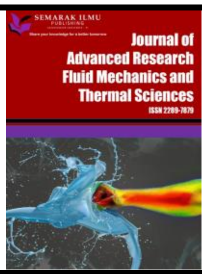

Controlling and Modelling a Grid Connected Photovoltaic System for Performance Investigation Purpose

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ABSTRACT

The world restriction of fossil power sources reserves and its side effect on the environmental pollution have impelled strongly using the photovoltaic technology as alternative renewable energy sources. The essential problem is the difficulty of importing and installing solar panels without having a fully knowledge about its effectiveness in the climatic conditions of the university site. Hence, the motivation of this study is to investigate the operational efficiency of the PV system in the Iraqi environmental conditions by modelling, controlling, and simulating the system using MATLAB/Simulink program. The proposed model has been driven based on the principle mathematical equations that depict the behaviour of the PV solar system. The proposed model is designed to affect with the sunlight irradiance, ambient temperature, AC loss, DC loss, the temperature of the panels' surfaces, and the efficiency of the used inverter. Preliminary results showed a strong correlation between sunlight irradiance and ambient temperature with the power generated by solar panels. Thus, these two parameters are chosen as the major inputs to the model. While, the electrical output power and the accumulative energy are set as the output of the simulated model. The study investigates the performance of the proposed model at the hottest day and coldest day throughout the year 2022. The results proved that the system generates more energy during the summer than in the winter due to the strength and a long period of the radiation falling on the ground during this season. Moreover, the investigation study evidenced that the system efficiency decreases as ambient temperatures increase. As the results, the cumulative energy during one day decreased by around 41.366% from the summer to winter. Finally, the authors recommend installing the suggested solar cell system in Iraq because its effectiveness was theoretically proved.

Keywords:
Control PV system; efficiency curve; modelling; output power; photovoltaic; renewable energy; sunlight irradiance; solar PV system; temperature effect

1. Introduction

The quest for energy is the primary contributors to global warming which is increasing the number of gases in the atmosphere. As a result, having a negative influence on the environment, upsetting ecosystems, and affecting human activities in terms of their way of life and economy [1-3]. Moreover, the need for energy, particularly electrical energy, is constantly increasing due to the modern way of human life [4]. In addition, Oil, gas, and carbon-based conventional energy sources

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are no longer adequate to meet the demands of the world economy [5,6]. In fact, experts caution that non-renewable resources may run out as soon as 2040 if energy consumption continues at its current rate [7,8]. For instance, in Iraq country, the overall annual consumption is 38.46 billion kWh of electric energy, while the total annual energy demand is 75.45 billion Kwh [9]. This indicates that more than 46% of the total power demand are affected by a deficit in the production of electric power. However, the widespread usage of private gasoline and diesel generators to make up for the lack of available electrical energy causes a rise in noise, visual fouling, and air pollution in public spaces [10,11].

The essential challenges in this field of study are environmental deterioration and climate change caused by traditional energy sources [12,13]. Numerous dangerous compounds are emitted into the atmosphere and water during the process of producing electrical power by using conventional resources. In addition, the environment is damaged by growing of the dust. As a result, several organizations have started putting policies into place to safeguard the environment and encourage non-conventional energy source alternatives. Environmental challenges on a global scale are becoming more generally recognized in modern society. As a result, there is a greater interest in energy produced from renewable resources, such as those derived from geothermal, wind, water, biomass, and solar radiation. Energy from renewable sources is always available, costs less than energy from conventional sources, and either emits no or very little gases into the atmosphere [13].

In fact, energy security is the ultimate objective for every national economy [14]. This phrase refers to the market economy's capacity to meet all present and foreseeable recipients' energy and fuel needs. Every nation must be able to provide its citizens with enough electricity at a cost they can afford while also upholding environmental conservation standards to be considered energy secure. Energy security is defined in a flexible way to encompass additional factors that emphasize environmental responsibility and energy efficiency [15,16].

In Iraq country, the production of the green energy is estimated about 4% of Hydroelectricity and approximately 0.08% of solar energy. While energy produce from the wind, geothermal, tide, wave, and waste energy generation is approached to zero [17]. As a result, awful lot study has been accomplished on renewable energy sources to compensate the traditional fossil fuel sources of energy. As anticipated, this significant stride toward the use of renewable energies will be crucial in meeting future energy demands for clean electricity. A plentiful source of familiar energy is solar energy. In fact, the quantity of solar energy that the earth's surface records in only one hour is greater than the planet's entire annual energy necessity [18]. For example, one city in Iraq, Baghdad, receives roughly 3000 hours of global radiation per year, with solar radiation ranging between $416\ W/m^2$ in Winter/January and $833\ W/m^2$ in Summer/June [9]. Iraq is one of the places with relatively lengthy sunshine hours. Another benefit is to Iraq's strategic placement in relation to facing the sun, which produces a small variation in the sun's irradiance across all of its cities. For instance, the amount of sunlight falling on a given square meter per day only varies from $4.5\ kWh/m^2/day$ in the north to $5.7\ kWh/m^2/day$ in the south [19,20]. In addition, because of Iraq's semi-uniform solar radiation dispersion, photovoltaic (PV) solar technology is a good fit for the nation's energy production. Recently, the Central Bank's proposal to finance solar energy systems for individuals and institutions was recently announced by the Iraqi government. As the Central Bank began its push to transition to clean energy within this framework, this move is consistent with the country's directives to follow the outcomes of the Paris Climate Conference.

Sustainable development has recently become more prevalent in Iraqi society. Universities were crucial in enhancing, developing, and increasing solar energy's output power. Al-Furat Al-Awsat Technical University (ATU), like the majority of academic institutions, strives to contribute to sustainable development by focusing its efforts on researching and developing renewable energies, notably solar energy systems. The plan called for installing solar systems throughout the university's colleges and institutions, which are not situated in different locations within Middle Euphrates Region of Iraq [21].

Accordingly, the essential contribution of this project is to conduct a feasibility study about the advantage of installing solar cell systems in ATU University's buildings similar to the solar system that already installed in University of Queensland (UQ), Australia. The feasibility study in this research will be limited to covering the scientific aspects of installing the solar energy system and excluding the economic feasibility and cost. Firstly, a MATLAB/Simulink program was proposed to model, simulate, and verify the PV system of UQ under various environmental conditions. The MATLAB program that simulates the PV system was designed and proved in the previous work, as the first step of the entire study [21]. While, the second step of the research will present in this study. In this project, the possibility of installing a UQ solar system in Engineering Technical College-Najaf (ETCN) / Al-Furat Al-Awsat Technical University will be studied. The program will examined based on the environmental conditions of ETCN location, which represent the input data to the simulation program. The system will be examined under summer and winter conditions to investigate the effectiveness of the suggested PV system throughout the year.

The rest of this research is organized as follows: The major concept, mathematical model, and simulation process of the suggested PV system are explained in Section 2. While Section 3 presents the output results of the proposed simulation model. In addition, short discussions about the performance of the output results and the limitations of the work are debated in the same section. Finally, Section 4 concludes the paper and provides the suggested future work of the study.

2. Methodology

The essential concept of the suggested PV mathematical model will present in this section. Firstly, the model is divided into three main sub-systems to simplify the model and make it understandable. The three sub-systems are environmental sub-system, PV array sub-system, and inverter sub-system. The overall goal of the proposed mathematical model is to characterize the behavior of the PV system installed at the Prentice Building, UQ. Figure 1 illustrates the concepts of the proposed PV system paradigm. The three primary rectangles, which are shown with dashed red lines, stand in for the three main sub-systems. While the other black blocks represent the actions that take place within each sub-system.

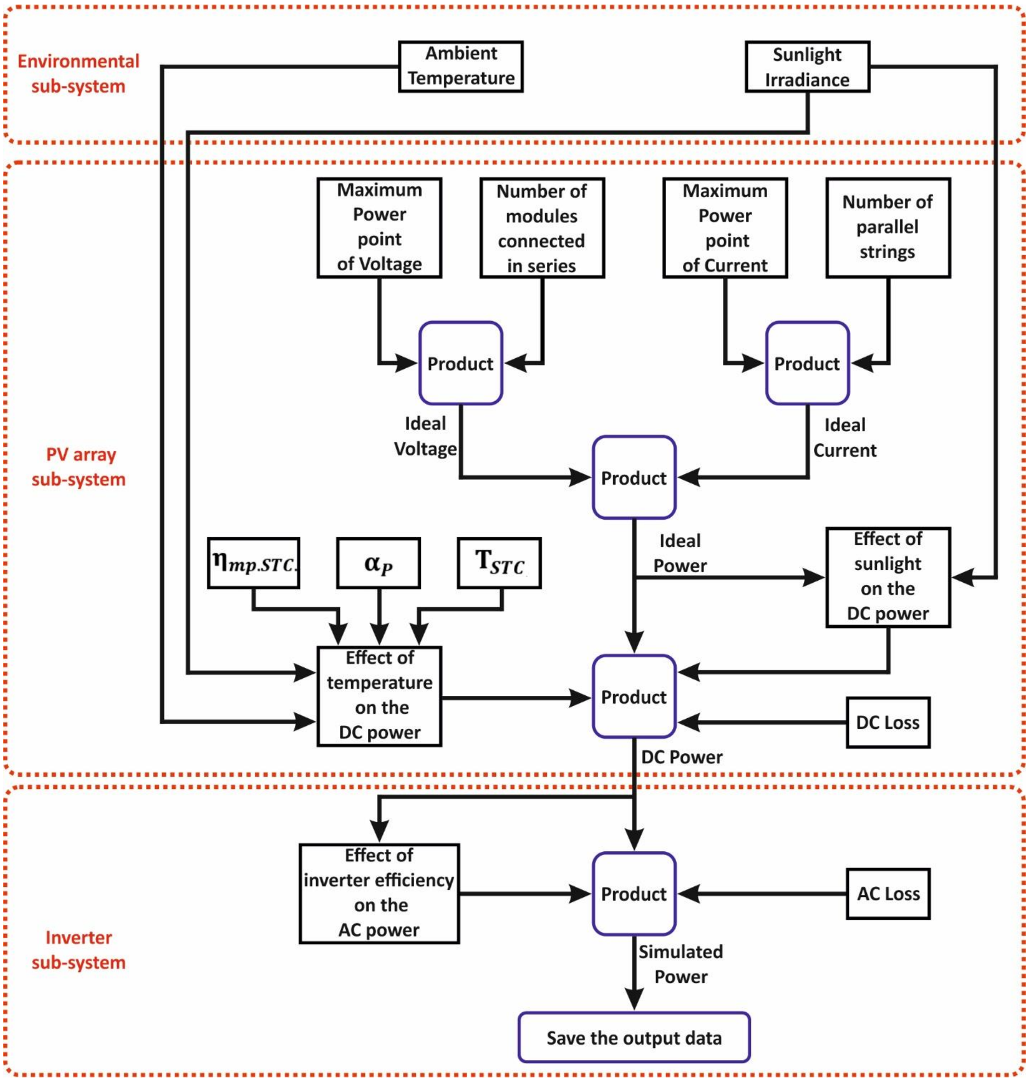


Fig. 1. The essential concepts of the suggested PV system model

2.1 Environmental Sub-System

The data supplied as input to Matlab/Simulink is represented by the environmental sub-system. The primary input data to the system are typically ambient temperature and sunshine irradiance. The environmental data is collected at the Engineering Technical College-Najaf (ETCN) / Al-Furat Al-Awsat Technical University, where the latitude and longitude of the location are 32.0300 and 44.150, respectively. The information of sunshine irradiance and ambient temperature are continuously recording by mean of using Davis Instruments Vantage Pro2 wireless measuring system [22].

The measuring instrument was positioned at a height of 10 m and was set to record data every 10 minutes. The Davis Instruments Vantage Pro2 wireless weather station consists of two parts: The Integrated Sensor Suite (ISS), as shown in Figure 2(a), which houses and manages the external sensor array, and the console, as presented in Figure 2(b), which provides the user interface, data display, A/D conversion, and calculations.

(a) (b)

Fig. 2. Vantage Pro2 wireless measuring system (a) outer ISS unite (b) indoor console unit

2.2 PV Array Sub-System

A PV array's essentially function is to convert solar radiation into direct current (DC) electrical power. The suggested Matlab/Simulink program was created using dimensions, requirements, and connection techniques that were similar to those of the actual PV array at the UQ site. The Trina Solar TSM-DC05 module, with a general size of 1650 x 992 mm, is used in a total of 56 panels at the UQ site. Two rows with two parallel strings each make up the entire arrangement of panels. While each string had a series connection with fourteen panels, as shown in Figure 3.

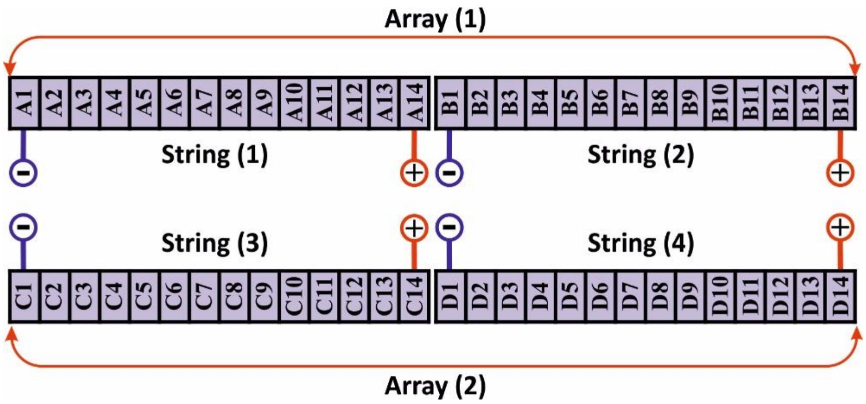


Fig. 3. The proposed PV modules connection

The datasheet for the Trina Solar TSM-DC05 module states that its maximum power point of voltage (V_{mpp}) and maximum power point of current (I_{mpp}) values are 30.40 V and 7.89 A, respectively. Nonetheless, the Maximum Power Temperature Coefficient is -0.45%/°C at 25 °C Cell stander temperature [21]. When these parameters are applied to Eq. (1), Eq. (2), and Eq. (3), the ideal DC electrical power (P_{Ideal}) of 56 panels is calculated, which is equal to 13.5 KW [23]. Where V_{Ideal} stands for V_{mpp} multiplied by the number of series-connected modules (N_{SM}), and $\mathrm{I}_{Ideal}$is the product of I_{mpp} multiplied by the number of parallel strings (N_{PS}).

$$\mathrm{V}_{Ideal} = \mathrm{V}_{mpp} \times N_{SM} \tag{1}$$

$$\mathrm{I}_{Ideal} = \mathrm{I}_{mpp} \times N_{PS} \quad (2)$$

$$\mathrm{P}_{Ideal} = \mathrm{V}_{Ideal} \times \mathrm{I}_{Ideal} \quad (3)$$

Taking into consideration the impact of sunlight irradiance, the PV array's power that affected with the sunlight irradiance (P_{PV-Ir}) can be calculated by multiplying the Ideal DC Electrical Power (P_{Ideal}) with the sunlight irradiance ($\mathrm{S}_{Irr.}$), as shown in Eq. (4).

$$P_{PV-Ir} = P_{Ideal} \times S_{Irr.} \quad (4)$$

Moreover, Eq. (5) is used to figure out how the temperature of the panels effects the efficiency of the PV array at its maximum power point ($\eta_{mp.Temp.}$).

$$\eta_{mp.Temp.} = \eta_{mp.STC.} \times \left[1 + \alpha_P\left[T_{panel} - T_{STC}\right]\right] \quad (5)$$

where α_P represents the temperature coefficient of power (%/°C) and $\eta_{mp.STC.}$ illustrates the maximum power point efficiency under standard test conditions. T_{panel} is the temperature of the PV panel in degrees Celsius, and T_{STC} is the temperature of the panel under standard test conditions, which is $25C^{\circ}$. Lastly, by assuming the DC loss equals to 0.9, Eq. (6) can be applied to figure out the output of the PV array subsystem ($P_{PV-Ir-Temp.}$), which is represents the input to the inverter sub-system.

$$P_{PV-Ir-Temp.} = P_{Ideal} \times P_{PV-Ir} \times \eta_{mp.Temp.} \times DC_{Loss} \quad (6)$$

2.3 Inverter Sub-System

The inverter essential purpose is to change the direct current (DC) coming from the PV array into the alternating current (AC). One ABB PVI-12.5-TL-OUTD String Inverter was used for the entire PV system at the UQ location. This inverter has a maximum AC output power of roughly 13.8 KW, which is commensurate with the robust capability of the whole PV array. At the maximum operation power, the inverter's DC input voltage is $360 - 750\ V$ and its current is $36.0\ A$. The AC power supplied from the inverter will be denoted as $\mathrm{P}_{inverter}$ because it is the final sub-system in the proposed Simulink model. Hence, the AC power output is described by Eq. (7), by assuming the AC loss is 0.9. The AC power output from inverter is proportional to the inverter's efficiency ($\eta_{inv.}$) and the expected AC loss.

$$P_{inverter} = P_{PV-Ir-Temp.} \times \eta_{inv.} \times AC_{Loss} \quad (7)$$

The power efficiency curve for a selected PVI-10.0/12.5-TL-OUTD inverter, which can be found in the inverter's product handbook, illustrates in Figure 4(a). As a result, the power efficiency curve is a viable replacement for the extensive mathematical operations that are required to explain the inverter's mathematical model. Hence, the inverter efficiency ($\eta_{inv.}$) was determined in two stages. The first stage is to plot the efficiency curve using the Matlab coding tool, after which a fitting curve is generate with a Root Squared Error (RSE) equals to 0.9979. The DC power of the PV array is plotted against inverter efficiency in Figure 4(b). Overall, the power spectrum from zero to 13.5 KW, which corresponds to the power spectrum from zero to 100 percent of the rated output in Figure 4(a). The second stage is to create a polynomial equation that characterizes the fitting curve's behavior for calculating the inverter efficiency, as shown in Eq. (8).

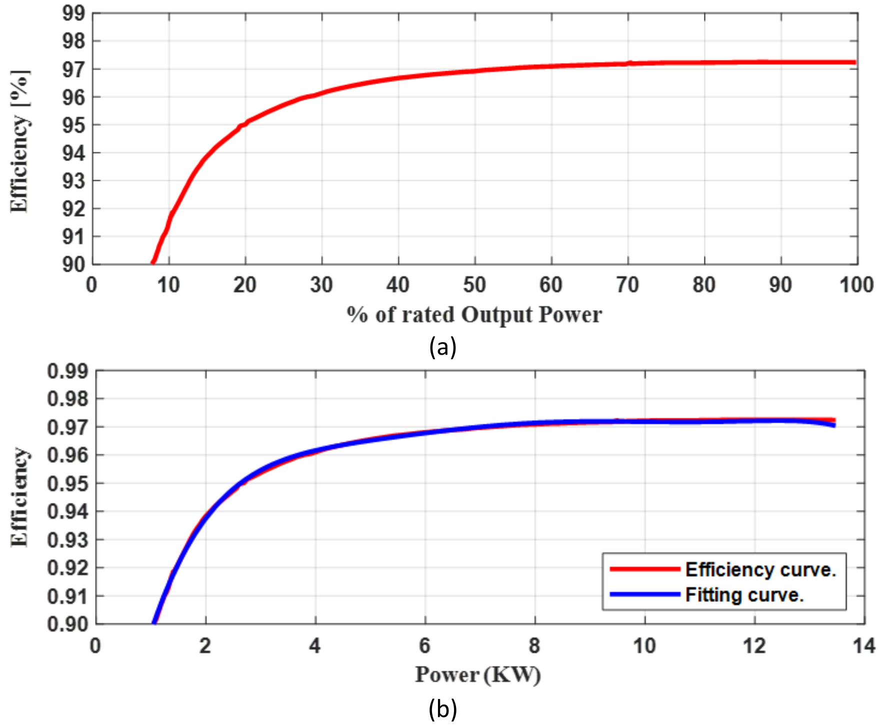


Fig. 4. The efficiency pattern of the PVI-10.0/12.5-TL-OUTD inverter

$$\eta_{inv.} = n_1 \times P_{DC}^6 + n_2 \times P_{DC}^5 + n_3 \times P_{DC}^4 + n_4 \times P_{DC}^3 + n_5 \times P_{DC}^2 + n_6 \times P_{DC}^6 + n_7 \quad (8)$$

where the symbols n_{1-7} represents the coefficients of the fitting equation, which are placed in front of formulas to balance the equation as follow: $n_1 = -7.02e-07$, $n_2 = 3.466e-05$, $n_3 = -0.0006886$, $n_4 = 0.007047$, $n_5 = -0.03952$, $n_6 = 0.1187$, and $n_7 = 0.8118$.

2.4 Verification Process

The verification process has been achieved by comparing the simulated output response of the AC inverter power with the DC power of PV arrays due to the effect of the (i) sun irradiance and (ii) sun irradiance and ambient temperature. The comparison allows the deviations between the two data to be identified. However, the root squared error (RSE) and the root mean squared error (RMSE) are used for error computation presses. The RSE and the RMSE forms used to figure out deviations are described in Eq. (9) to Eq. (12). The abbreviation $PV-Ir$ refers to the PV array that effected with the sun irradiance. While, the sample $PV-Ir-Temp$ mentions to the effecting of the sun irradiance and ambient temperature on the efficiency of the PV array.

$$RSE_{PV-Ir} = \sqrt{(\sum P_{PV-Ir} - \sum P_{inverter})^2} \quad (9)$$

$$RSE_{PV-Ir-Temp} = \sqrt{(\sum P_{PV-Ir-Temp} - \sum P_{inverter})^2} \quad (10)$$

$$RMSE_{PV-Ir} = \sqrt{\frac{(\sum P_{PV-Ir} - \sum P_{inverter})^2}{Total\ Data}} \quad (11)$$

$$RMSE_{PV-Ir-Temp} = \sqrt{\frac{(\sum P_{PV-Ir-Temp.} - \sum P_{inverter})^2}{Total\ Data}} \quad (12)$$

3. Results

Overall, the sunlight irradiance and the ambient temperature are fixed as the main input variables to the suggested simulation program. Therefore, these environment parameters should be recorded and analyzed to examine the seasonal variations at the ETCN location. Thus, the monthly mean values of sunlight irradiance and the ambient temperature throughout the year 2022 are depicted in Figure 5. The left green y-axes represents the sunlight irradiance in Wh/m^2 unit, and the right red y-axes outlines the ambient temperature in C° unit. The figure shows that the seasonal pattern of sunlight irradiance varying during the year. Moreover, there is a direct proportion between the average values of the irradiance and temperature. In addition, the bar chart clarifies that the longer durations of sunlight are achieved in summertime compared to wintertime. Higher amounts of irradiance are noted in summer months and lower values in winter months. A maximum average sunlight irradiance value of $282.635\ W/m^2$ is found in the month of June while the minimum of $111.587\ W/m^2$ in January.

Accordingly, the performance of the PV system on two varying days in different seasons will be simulated to find out the effectiveness of the system. Two sets of data dated July 20 and January 20, 2022, were chosen to be used in the simulation model. The investigation process will inspect the hottest day and coldest day during the year 2022. Subsequently, the output power and cumulative energy of the PV system will be analyzed to highlight the deviations among the seasons of the year.

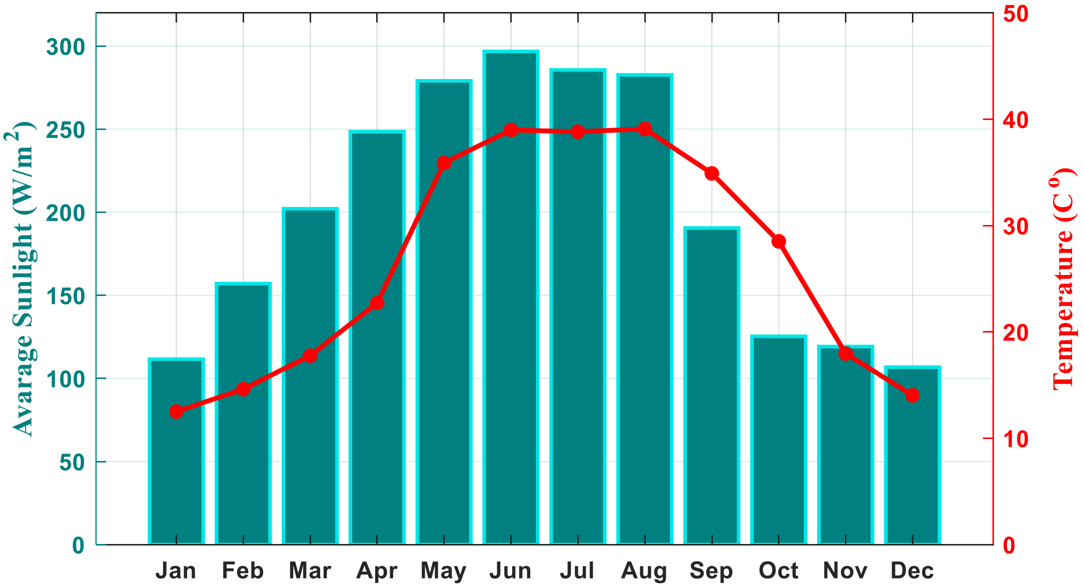
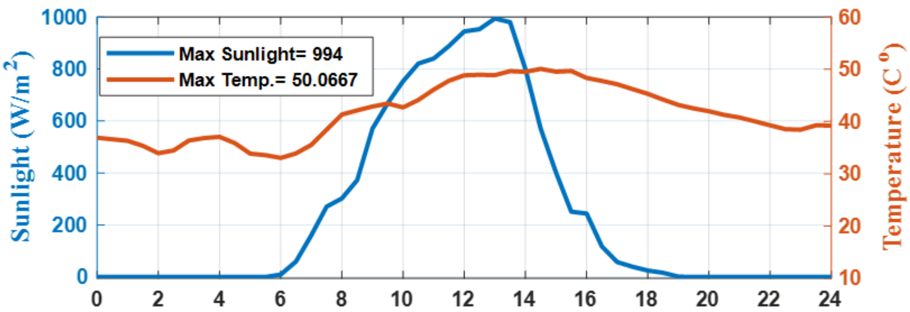


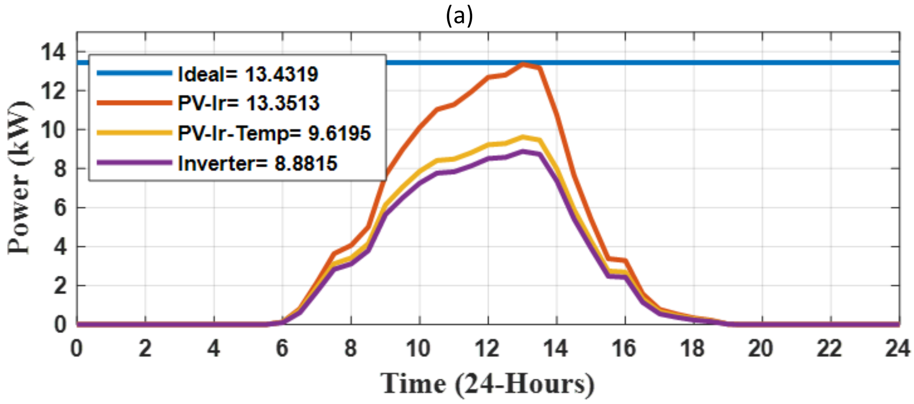
Fig. 5. The monthly average data of environmental performance throughout the year 2022

The performance of the suggested simulation model during a hot day, July 20, 2022, is highlighted in Figure 6. Firstly, the recorded sunlight irradiance and ambient temperature throughout the day are presented in Figure 6(a). It is noted that the sunlight rises after 05:30 AM and sets at 07:00 PM. In addition, the maximum sunlight irradiance recorded during the noon period. The measuring device recorded that the irradiance rose to $994\ W/m^2$ at 01:00 PM, while the temperature achieved its maximum value at 02:30PM equal to $50\ C^{\circ}$. Thus, the noon period is expected to accomplish the maximum output power throughout the hot day.

Figure 6(b) shows the pattern of the PV power output during different model's stages, which are the ideal power, the PV array power affected by irradiance, the PV array power affected by irradiance and temperature, and the final AC power output from inverter. It is clearly seen that the pattern of the AC output power of the final stage, which is the power output from the inverter, strongly matches the sunlight irradiance. The sunlight irradiance reaches its maximum value at 01:00 PM to record 8.88KW which represents the peak irradiance during the day. In addition, the output power of the PV system is absent during the absence of daylight at the night.



(a)



(b)

Fig. 6. The performance of the suggested simulation model during a hot day (a) irradiance and temperature (b) the output powers during different model's stages

On the one hand, the results show that the AC output power is strongly impacted by the sunlight irradiance, temperature, AC loss, DC loss, and inverter's efficiency. The correlation between the inverter power and the PV array power affected with the irradiance recorded a high deviation, RMSE equal to 1.772. While, the deviation between the inverter power and the PV array power affected with the irradiance and temperature documented RMSE equal to 1.3379. On the other hand, the outputs present that the efficiency of the PV system is influenced with the exaggerated rise in ambient temperature. In fact, many previous studies have proven that solar systems are negatively affected by temperatures above their normal operating limits [24].

The performance of the suggested simulation PV model during a very cold day at the winter, January 20, 2022 are illustrated in Figure 7. The distribution of the sunlight irradiance and the ambient temperature per the selected day are presented in Figure 7(a). While, the output simulated powers during different model's stages are shown in Figure 7(b). During the cold day, the sun rose at 7:30 in the morning and set at 7:30 in the evening. The maximum irradiance achieved at the 03:00 PM, which is reached to 337 W/m^2. On the other side, the ambient temperature varied from 0 C°at the morning to 12.87 C° at the noon.

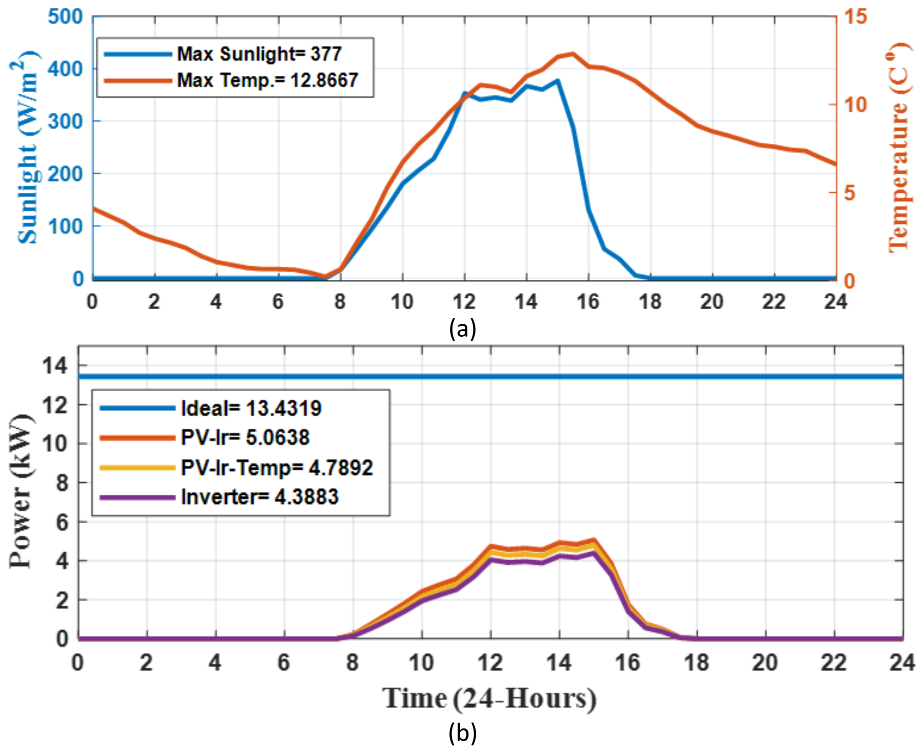


Fig. 7. The performance of the suggested simulation model during a cold day (a) irradiance and temperature (b) the output powers during different model's stages

It can be clearly noted that the simulated results of the output powers exceedingly resemble the pattern of the sunlight irradiance, and there is no direct effect of the temperature on the pattern of the generation power. In addition, the results show the inverter AC output power reached its maximum value, which equals to $4.388\ KW$ during the peak time irradiance period.

Moreover, the results display that there was little effect of the efficiency of the PV array at its maximum power point ($\eta_{mp.Temp.}$) on the system's performance. Thus, there is a noticeable convergence between the curves of the simulated PV array affected by the irradiance, the PV array power affected by the irradiance and temperature, and the AC inverter's power. The correlation between the inverter power and the PV array power affected by the irradiance recorded a high deviation, RMSE equal to 0.326. While, the deviation between the inverter power and the PV array power affected by the irradiance and temperature documented RMSE equal to 0.176.

The cumulative energy simulation results of the modelling system through each hot and cold day during the year 2022 are presented in Figure 8. The blue line represents the cumulative energy produced during the hot day, while the red line refers the cold day. The results show that the simulation results of total energy generated throughout the hot day are greater than those of the cold day. At the end of the day, cumulative energy reached to $57.0239\ KWh$ and $23.5883\ KWh$ in the hot and cold days, respectively. In other words, the cumulative energy produced from the PV model on a hot day is much higher than the energy produced on a cold day because, during the summer in Iraq, solar radiation is very strong and continues to reach the surface of the Earth for long periods during one day.

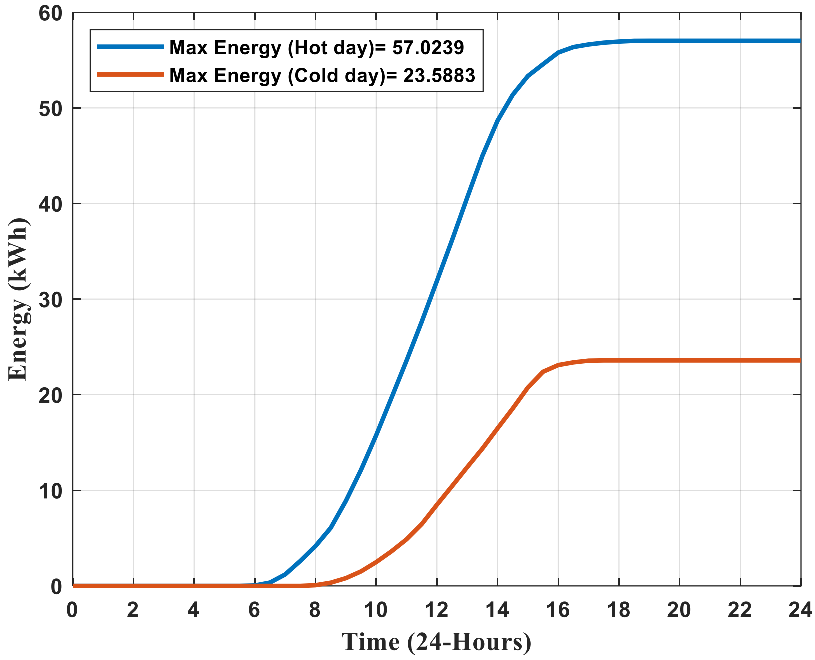


Fig. 8. The cumulative energy of the PV system in a hot and cold day

In general, the results proved that the performance of the PV panels become more effectible at the low ambient temperature. This finding is also proved in the previous studies [25-27]. Furthermore, the study was carried out based on irradiance measured on a horizontal surface and not an inclined surface as in solar panels, which is a weakness of this study.

4. Conclusions

A theoretical investigation was conducted in this study to determine the possibility of installing a PV solar energy plant in Najaf, Iraq, with an acceptable efficiency and high productivity. However, the researchers simulated the PV system, which was installed at the University of Queensland (UQ), Australia, and ran the simulation model using the data from the measuring system at the ETCN location in AL Najaf, Iraq. The simulated model is designed to affect with the sunlight irradiance, ambient temperature, AC loss, DC loss, the temperature of the panels' surfaces, and the efficiency of the used inverter. The model has been examined based on the data from two different days among the year 2022. The results proved the hard relationship between sunlight irradiance and the output PV power. Thus, sunlight irradiance is an essential input variable when developing and examining the PV system. On the other side, it has been proven that the efficiency of a PV system is affected by ambient temperature. Low ambient temperature can enhance the performance of the PV panels. In fact. The output results proved that the cumulative energy during one day decreased by around 41.366% from the summer to winter. In general, the study proved that there is a high degree of economic feasibility in installing a solar energy unit at the ETCN site, AL Najaf Governorate, Iraq. The researchers will continue to install the PV system and examine it practically in future work.

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