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Modelling and Simulation of Grid Connected Photovoltaic System using Matlab\Simulink Program

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ABSTRACT

Renewable energy such as solar energy became an important alternative sustainable energy source because it is inexhaustibly compared with fossil sources. Therefore, Al-Furat Al-Awsat Technical University (ATU) is interested in relying entirely on renewable energy. There is an idea to duplicate the photovoltaic (PV) system of the Australian University of Queensland (UQ) and install it in ATU formations. Thus, this work aims to study the effectiveness of installing the PV system of UQ by modelling, simulation, and verification of a MATLAB/Simulink program that simulates the performance of the actual installed PV system. The main goal of the MATLAB/Simulink program is to conduct a feasibility study by studying the performance of the PV system according to the Iraqi climatic conditions to avoid material losses resulting from the direct installation of the system. The suggested model has been driven based on the principle mathematical equations that describe the behaviour of the PV system. Accordingly, environmental conditions such as sunlight irradiance and ambient temperature as well as the hardware system information are set as the essential inputs to the model. Whilst, the electrical power and the accumulative energy are chosen as the main output. The output of the proposed model was compared with the actual set of data conveyed from the University of Queensland, Australia. The results proved the effectiveness of the suggested model by presenting an acceptable match between the simulated output and the real data. Consequently, the authors recommend applying the proposed model for the entire ATU formations based on their respective climatic conditions, individually.

1. Introduction

Nowadays, the lack of electrical energy has become an essential energy problem around the world because daily human activities are completely dependent on it [1]. In general, energy impacts our life like the environment and economy. Moreover, the modern style of life produces a continual rise in the demand for energy, especially electrical energy. For instance, in Iraq country, the entire daily requirement of energy is 45000 MW while the actual production of energy does not exceed 24000 MW. This means that the percentage of a shortage in electric power production exceeds 46% of total power requirements. However, private gasoline and diesel generators are widely used to

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compensate for the shortfall in the supplied electrical energy which, leads to increase noise, visual fouling, and air pollution in the public area [2,3]. Accordingly, massive research efforts were turned to renewable energies as a new compensation for energy sources to avoid using traditional fossil energy. As expected, this important step in using renewable energies will play an essential part as a clean electricity power source in future energy demands [4,5].

Solar energy is an abundant source of known energy. In fact, the amount of solar energy that records on the surface of the earth in only one hour is great than the planet's total energy requirements for a whole year [6]. Iraq is famed for its lengthy sunny hours. For instance, the Baghdad governorate, which is the capital of Iraq and has an area equal to 673 square kilometers, receives more than 3000 hours of solar radiation annually [7]. While the estimated annual solar radiation in Iraq is ranging from 2000 kWh/m2 to 2500 kWh/m2 [8,9]. Another advantage deals with the strategic location of Iraq regarding facing the sun that creates a miniature variety in the sun's irradiation between the entire Iraqi cities. For example, sun irradiation on the horizontal plane is only changing from 4.5 kWh/m2/day in the north to 5.7 kWh/m2/day in the south [7,10]. Thus, Iraq's semi-uniform distribution of solar radiation makes Photovoltaic (PV) solar technology suitable for the country's energy generation.

Recently, sustainable development has been growing in Iraq's society. While universities played an important role to enhance, develop, and maximize the output power of solar energy. Like most academic universities, Al-Furat Al-Awsat Technical University (ATU) aspires to be a part of sustainable development by directing efforts toward enhancing, developing, and studying renewable energies, particularly, solar energy systems. However, there is an idea to install solar cell systems comparable to the effective solar system that is installed in most buildings of the University at Queensland (UQ), Australia.

The idea aimed to install the solar system in whole colleges and institutes of the university. On one hand, general environmental conditions like the weather are definitely different between ATU and UQ locations, this may affect the efficiency of the cells. On the other hand, the ATU formations are not located in the same city. Table 1 shows all the locations of the colleges according to the head center of the university. The unique distribution of colleges at ATU University has to be considered.
Hence, a feasibility study must be done to show the extent of the benefit resulting from the implementation of this project, especially the energy supplied from it at each of the university sites, according to the environmental conditions of that site.

Table 1
The locations of the colleges according to the head centre of the ATU university

Building Name	Distance from ATU (KM)	Latitude (Degree)	Longitude (Degree)
The Technical Administrative College / Kufa	Same ATU campus	32.0300	44.400
College of Health and Medical Technologies / Kufa	Same ATU campus	32.0300	44.400
Al-Kufa Technical Institute	Same ATU campus	32.0300	44.400
College of engineering Technologies-Najaf	14	32.0290	44.3396
Al-Najaf Technical Institute	14	32.0290	44.3396
College of Engineering Technologies-Musayyib	101	32.7786	44.2900
Musayyib Technical Institute	101	32.7786	44.2900
Karbala Technical Institute	77	32.6167	44.0333
Al-Samawa Technical Institute	240	31.3167	45.2833
Babylon Technical Institute	84	32.4833	44.433
Al-Rumaitha Technical Institute	191	31.3167	45.2833
Diwaniyah Technical Institute	60	31.9892	44.9247

Thus, this study will cover the scientific part of the feasibility study in two steps. The first step is modeling, simulation, and verification of a MATLAB/Simulink program that simulates the real performance of the solar cell system of UQ in various conditions. The simulation has been divided into three main parts: the environment part, the solar cell part, and the inverter part. The simulation program was verified by comparing the output simulation results with the real recorded data of the UQ solar system. The second step will be applying the verified simulation program based on the environmental conditions data that recording in the entire ATU formations to decide whether this solar system is useful to install on each site or not. This paper covers the first step of the study, while the second step will be future work.

2. Methodology

The suggested mathematical model that describes the behavior of the PV system was divided into three main sub-systems to simplify and clarify the design. The three sub-systems are the environmental sub-system, the PV array sub-system, and the inverter sub-system. While the entire suggested mathematical model is typically designed to describe the behavior of the actual PV system that was installed at the Prentice Building, UQ. The essential concepts of the suggested PV system model are described in Figure 1. The three main rectangular, described with the dashed red lines, represent the three main sub-systems, while the other black blocks signified the process inside each sub-system.

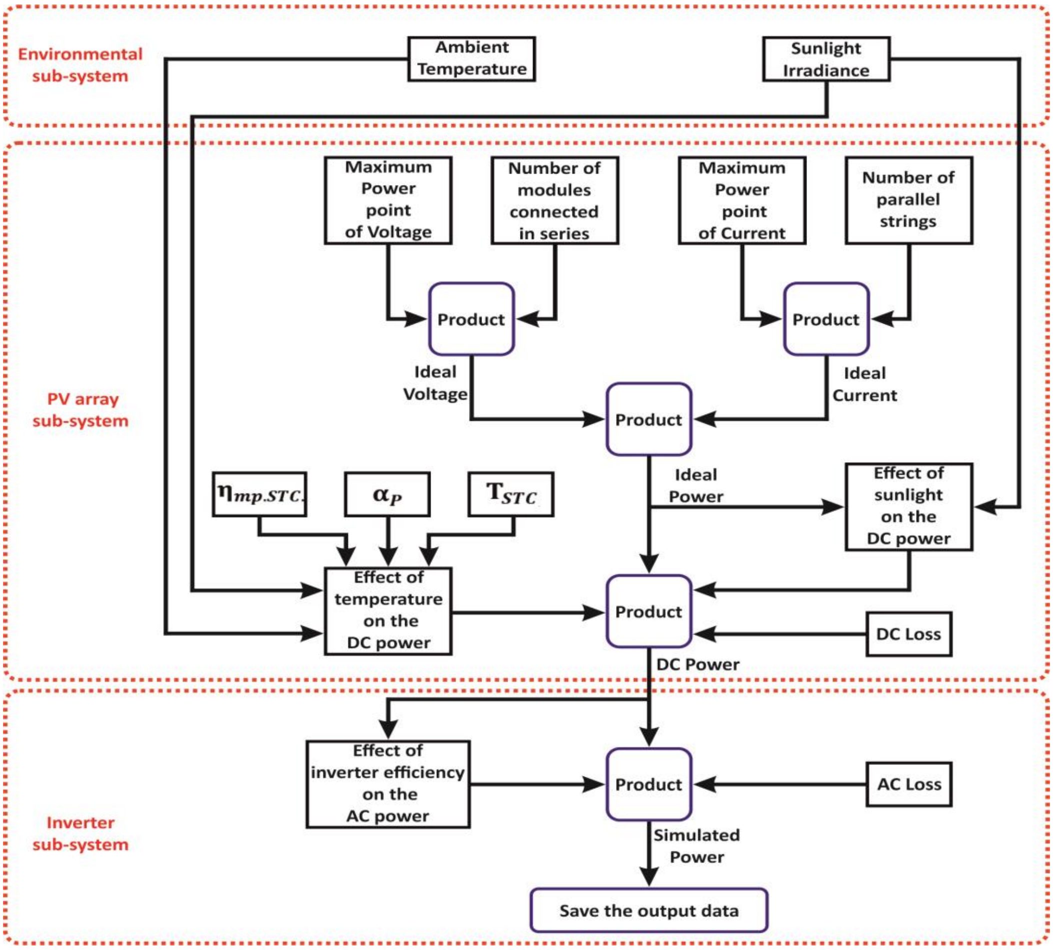

Fig. 1. The essential concepts of the suggested PV system model

2.1 Environmental Subsystem

The environmental sub-system represents the input data provided in Matlab/Simulink. In general, sunlight irradiance and ambient temperature are the main input data to the system. The environmental information is measured at the campus of UQ, which is located in Brisbane, Queensland, Australia, where the site latitude is 27°29′50″S and the site longitude is 153°0′47″E" [11]. The sunlight irradiance and ambient temperature data will be conveyed to the PV array sub-system to produce power.

The standard sunlight irradiance, called "one sun" or a "peak sun" is equal to 1000 W/m^2 that measured on a clear day. However, the PV system should be installed at a location that has a sunlight irradiance equal to or greater than the irradiance threshold to obtain the possible electrical power [12]. On the other hand, the rise in ambient temperature negatively affects the overall performance of the photovoltaic system [13].

2.2 PV Array Subsystem

The essential function of a PV array is to convert the sunlight's irradiance into direct current (DC) electrical power. The suggested Matlab/Simulink program for the PV array was designed based on dimensions, specifications, and connection methods similar to the actual PV array at the UQ site. A total of 56 panels of the Trina Solar TSM-DC05 module with a 1650 x 992 mm general size are used in the UQ site The total number of panels is arranged in two rows, and each one has two parallel strings. While, each string contained fourteen panels in a series connection, as shown in Figure 2.

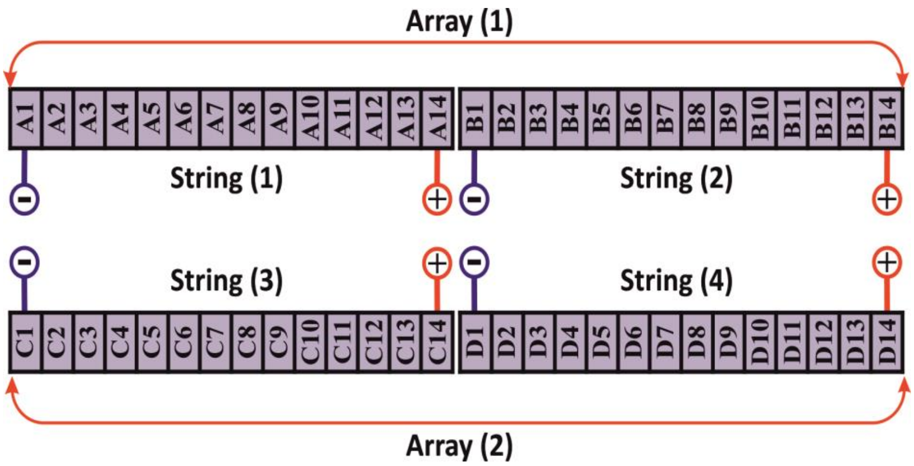

Fig. 2. Schematic drawing for PV modules connection

According to the Trina Solar TSM-DC05 module datasheet, the Maximum Power point of Voltage ($\mathrm{V_{mpp}}$) and the Maximum Power point of Current ($\mathrm{I_{mpp}}$) are equal to $30.40\ \mathrm{V}$ and $7.89\ \mathrm{A}$, respectively [14]. While the Temperature Coefficient of the Maximum Power is $-0.45\%/℃$ at $25\ ℃$ Cell stander temperature [14]. Based on these specifications, the total of 56 panels will produce $13.5\ \mathrm{KW}$ ideal DC electrical power ($\mathrm{P_{Ideal}}$) by applying Eq. (1), Eq. (2), and Eq. (3) [15]. Where $\mathrm{V_{Ideal}}$ represents the product of $\mathrm{V_{mpp}}$ and the number of modules connected in series ($\mathrm{N_{SM}}$) and $\mathrm{I_{Ideal}}$ is the product of $\mathrm{I_{mpp}}$ and the number of parallel strings ($\mathrm{N_{PS}}$).

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

$$\mathrm{I_{Ideal}} = \mathrm{I_{mpp}} \times \mathrm{N_{PS}} \tag{2}$$

$$\mathrm{P_{Ideal}} = \mathrm{V_{Ideal}} \times \mathrm{I_{Ideal}} \tag{3}$$

The Ideal DC electrical power ($\mathrm{P_{Ideal}}$) represents the ideal power of the total 56 panels of the Trina Solar TSM-DC05 module without taking the effect of the sunlight irradiance, temperature, and DC loss into count. Firstly, the effect of sunlight irradiance on the ideal power of the PV array ($\mathrm{P_{Irr.}}$) was calculated by the product of the Ideal DC electrical power ($\mathrm{P_{Ideal}}$) and the sunlight irradiance ($\mathrm{S_{Irr.}}$), as described in Eq. (4).

$$\mathrm{P_{Irr.}} = \mathrm{P_{Ideal}} \times \mathrm{S_{Irr.}} \tag{4}$$

Secondly, the effect of the panel's temperature on the efficiency of the PV array at its maximum power point ($\eta_{\mathrm{mp.Temp.}}$) is estimated utilizing Eq. (5) [16,17].

$$\eta_{\mathrm{mp.Temp.}} = \eta_{\mathrm{mp.STC.}} \times \left[1 + \alpha_{\mathrm{P}}\left[\mathrm{T_{panel}} - \mathrm{T_{STC}}\right]\right] \tag{5}$$

Where, $\eta_{\mathrm{mp.STC.}}$ represent the maximum power point efficiency under standard test conditions (%), α_{P} is the temperature coefficient of power (%/°C). $\mathrm{T_{panel}}$ and $\mathrm{T_{STC}}$ are the PV panel temperature (°C) and the panel temperature under standard test conditions ($25°\mathrm{C}$).

Finally, by assuming the DC loss is equivalent to 0.9, the DC electrical power output from the 56 panels of the PV system ($\mathrm{P_{DC}}$) can be calculated by applying Eq. (6). $\mathrm{P_{DC}}$ represents the output of the PV array sub-system and the input to the inverter sub-system.

$$\mathrm{P_{DC}} = \mathrm{P_{Ideal}} \times \mathrm{P_{Irr.}} \times \eta_{\mathrm{mp.Temp.}} \times \mathrm{DC\ Loss} \tag{6}$$

2.3 Inverter Subsystem

The general function of the inverter device is to convert the direct current (DC), which is the output of the PV array, into alternating current (AC). The PV system at the UQ site used a single inverter of type ABB PVI-12.5-TL-OUTD String Inverter [18]. The main specification of this inverter device is the ability to produce around $13.8\ \mathrm{KW}$ maximum AC output power compatible with the powerful ability of the entire used PV array that reaches $13.5\ \mathrm{KW}$. The DC input voltage and current of the inverter at its maximum power point reach $360 \sim 750\ \mathrm{V}$ and $36.0\ \mathrm{A}$, respectively. Due to the inverter sub-system being the last sub-system in the suggested Simulink model, the output AC power from the inverter will be called $\mathrm{P_{Sim.}}$. Thus, the output AC power of the system is described by Eq. (7). At which, the Simulink AC power is directly proportional to the input DC power from the PV array, the efficiency of the inverter ($\eta_{\mathrm{inv.}}$), and the AC loss that is assumed to be 0.9.

$$\mathrm{P_{Sim.}} = \mathrm{P_{DC}} \times \eta_{\mathrm{inv.}} \times \mathrm{AC\ Loss} \tag{7}$$

The Product manual of the used PVI-10.0/12.5-TL-OUTD inverter contains the power efficiency curve of the inverter, as shown in Figure 3(a). So, the power efficiency curve is a good way to describe the mathematical model of the inverter instead of the complicated math operations that should be used. Accordingly, the efficiency of the inverter ($\eta_{\mathrm{inv.}}$) was calculated in two main steps. The first step is plotting the efficiency curve with a Matlab coding program and creating a fitting curve that typically matches the actual curve with a 0.9979 root squared error (RSE). Considering the x-axis is the DC power of the PV array, as described in Figure 3(b), where the range from zero to 13.5 KW DC power in Figure 3(b) represents the range from zero to 100 % rated output power in Figure 3(a). The second step of calculating $\eta_{inv.}$ is generating a polynomial equation that describes the behavior of the fitting curve. Consequently, the generated polynomial equation represents the equation for determining the efficiency of the inverter, as described in Eq. (8).

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

Where: $n_1 = -7.02e-07$, $n_2 = 3.466e-05$, $n_3 = -0.0006886$, $n_4 = 0.007047$, $n_5 = -0.03952$, $n_6 = 0.1187$, and $n_7 = 0.8118$.

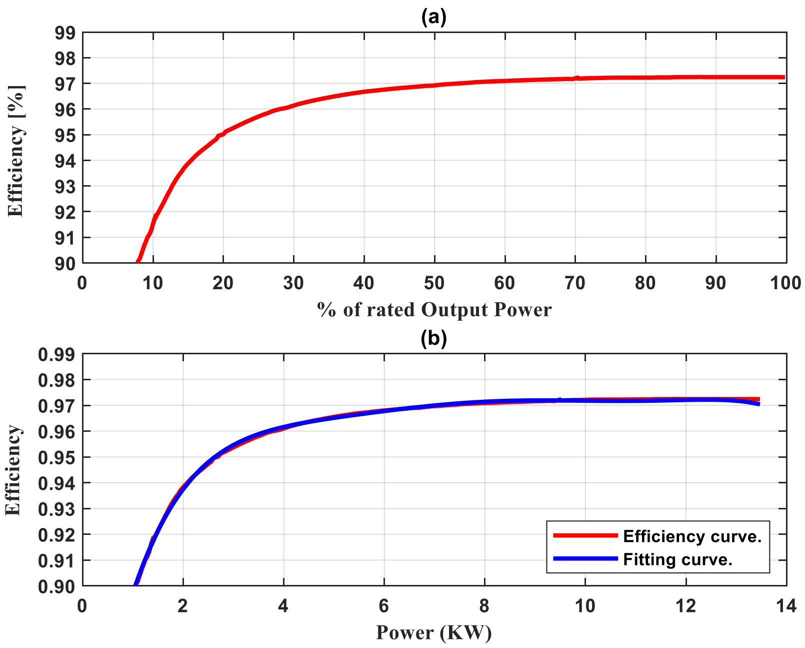

Fig. 3. The power efficiency curve of the PVI-10.0/12.5-TL-OUTD inverter

2.4 Performance Verification Process

The performance verification process has been performed by comparing the response of the simulated AC output power of the suggested model with the real AC output power of the UQ PV system. Therefore, the simulated model will be examined under the same environmental conditions such as sunlight irradiance and temperature. Then, the deviation between the simulated and real output power will be determined by utilizing Eq. (9) to evaluate the performance of the suggested Matlab\Simulink model.

$$\text{Error} = P_{Sim.} - P_{Real} \tag{9}$$

3. Results and Discussions

The overall behavior, response, and deviation of the proposed PV system Matlab\ Simulink model compared to the real installed system at the UQ site are briefly presented in this section. The model response of output power during one day, cumulative energy during one day, and the average of the output power during one month are displayed to offer an overall view of the system's performance. Moreover, the simulated model was examined for two different days in varying months during the year to be sure that the model's performance closely resembles the pattern of the real PV system at the UQ site. The results offer the operation hours of the PV system during the day and exclude the night hours.

The response of the proposed PV system model to the real input data recorded in 31.July.2022 is illustrated in Figure 4. Firstly, the sunlight and the ambient temperature distribution curves from the sunshine at 5.15 am to sunset at 6.15 pm are displayed in Figure 4(a). Where the blue left axis refers to the sunlight irradiance, the pinky right axis is the temperature. It's clear to note that the value of the sunlight irradiance is zero at the sunshine and sunset times. In addition, the sunlight irradiance reaches its peak value at 12:10pm with a mount of 1339 W/m^2. The sunlight curve has several drops due to the cloudy or unclear sky. On the other side, the ambient temperature ranged from 21.6°C to 34.1°C.

Figure 4(b) represents the comparison between the AC output electrical power of the simulated model and the actual system in 31.July.2022. The figure shows an acceptable match between the two output power curves. The two responses rose and fell approximately at the same time. Furthermore, the peak values of the simulated and actual responses, 10 KW and 9.866 KW, respectively, were achieved around 12.10 pm at a moment of the peak sunlight. Figure 4(c) proved that the output power of the suggested model and the actual system have a miniature deviation over the whole time. Except at the sunlight drop points, it rises to reach 8.34KW.

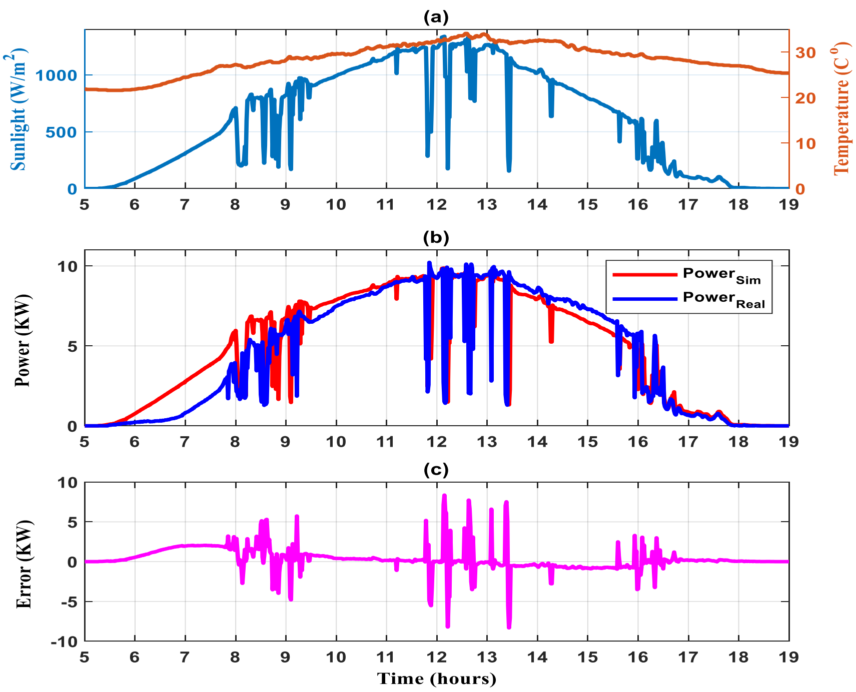

Fig. 4. The response of the PV model in 31.Jule.2022 (a) Sunlight irradiance and temperature (b) Comparison between real and simulation power (c) The error of power

The entire energy that cumulated during 31.Jule.2022 for the simulated and actual data, is offered in Figure 5(a). The red and blue curves represent the daily accumulated energy of the simulated model and actual PV system, respectively. The results show the two curves have the same behaviors. In other words, the curves started from zero at sunrise time and reached their maximum value at sunset time. At the end of the day, it's clear to note that the maximum cumulative energy of the simulated model (67.93 KWh) is more than the maximum cumulative energy of the real system (63.66 KWh) because the power generated by the simulated model is greater than actual power at the most times of the day. The deviation between the two cumulative energies is clarified in Figure 5(b), where the height deviation occurs at 01.20 pm and reaches 6KWh

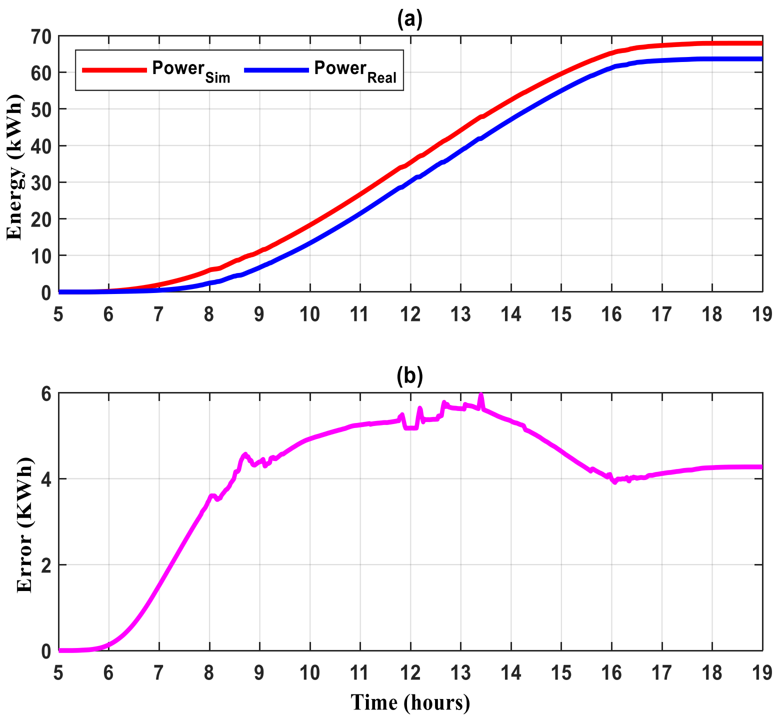

Fig. 5. The response of the PV model in 31.July.2022 (a) Comparison between real and simulation accumulative power (b) The error of accumulative power

To be sure that the performance of the suggested model is approximately comparable to the performance of the real PV system, the study examined the performance of the simulated model over a long period of time. Thus, the average of the simulated AC power was compared with the average actual AC power for 31 days in July.2022, as shown in the bar chart of Figure 6(a). The red chart represents the average of the actual daily power, while the blue chart is the average simulated daily power. The results proved that the simulated power is mostly greater than the actual power. In addition, the results show that the output powers are varying for each day based on the weather conditions. The variation between the average simulated and actual power for each day during the month is displayed in Figure 6(b).

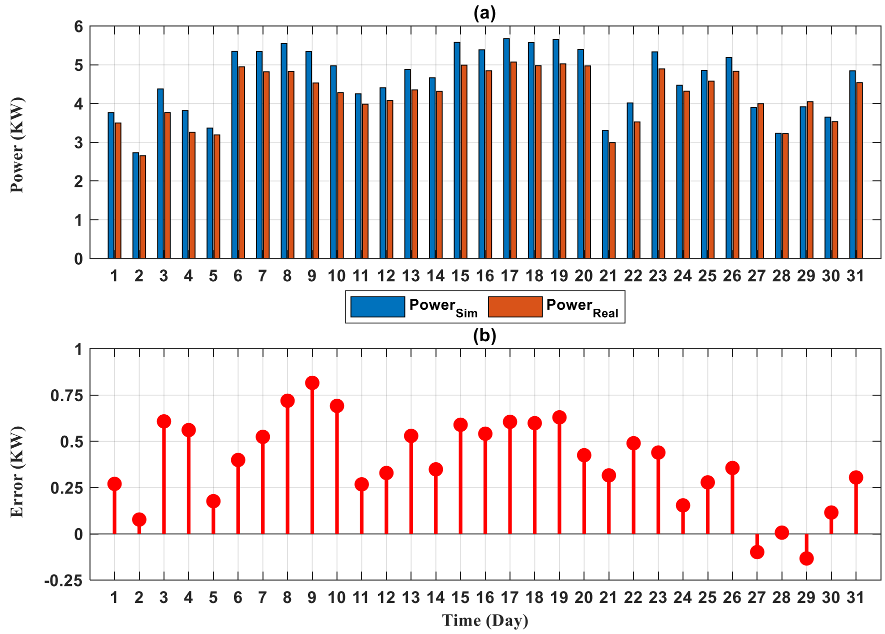

Fig. 6. The performance of the PV model in one month \ July.2022 (a) Comparison between the average real and simulation power (b) The deviation of the average power

The evaluation test for the proposed Matlab \ Simulink model of the PV system presented in Figures 4 to Figure 6 was repeated for another date, to be sure that the suggested model is functional under any operating conditions. Figure 7 and Figure 8 are displayed the comparison between the simulated power and energy with the actual power and energy in 31.Oct.2022. The results show that the simulated and actual output power and energy have approximately the same pattern. Also, the results proved that the output of the simulated model is usually greater than the real data, as demonstrated in Figure 9 for Oct.2022. Moreover, the responses' oscillation also appears in the new set of data because the sunlight irradiance that impacts the solar cell is affected by changes in weather conditions, such as sunny or cloudy days, clear sky, mild rain, gloomy, or heavy rain.

In general, the difference between the output power of the proposed model and the actual data of the PV system refers to several reasons. The first is the sunlight recording method. In fact, the sunlight irradiance at the UQ site records on a horizontal surface, while the panels of the actual system are installed at a certain angle to increase its efficiency.

The second reason regards using the maximum power point efficiency under standard test conditions. The simulation model is programmed with the optimum value of the photovoltaic efficiency, which is set as 15%. On the other side, the efficiency of the actual model has not exceeded 7% under real operation environmental conditions [19]. In addition, the efficiency of the actual system is highly effective over time, especially with the dust accumulation over the PV cells [20].

Another reason is related to the sunlight reflecting from the photovoltaic cells. The loss of irradiance due to the sunlight reflecting wasn't taken into account during the programming of the simulated model. Actually, more than 30% of the sunlight is usually reflected from the solar cell due to the high refractivity of its silicon material [21].

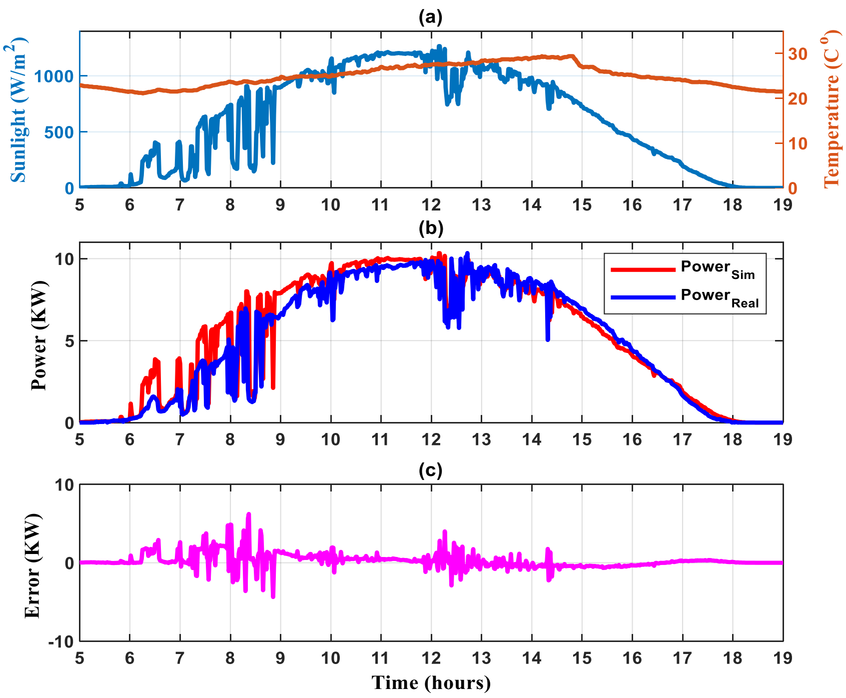

Fig. 7. The response of the PV model in one day \ 31.Oct.2022 (a) Real sunlight and temperature (b) Comparison between real and simulation power (c) The error of power

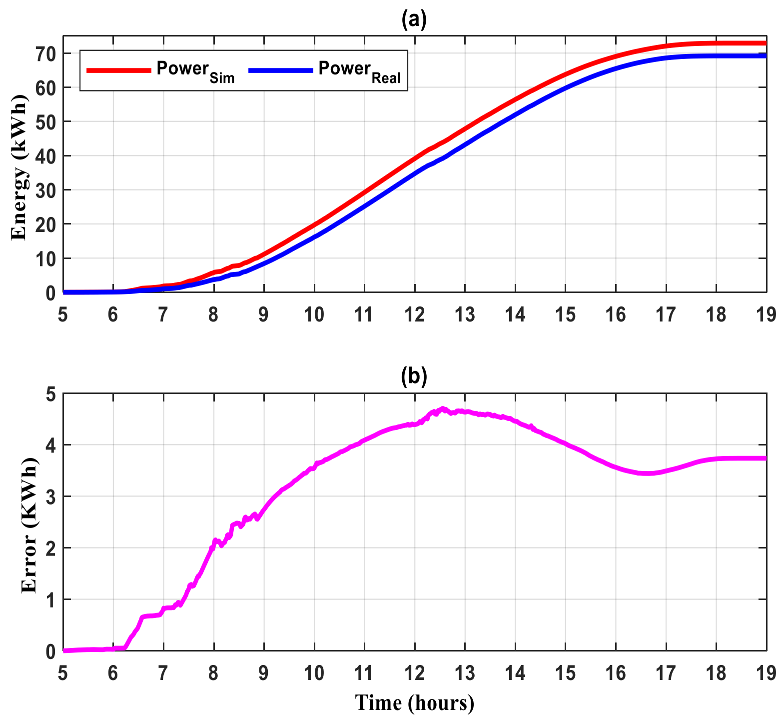

Fig. 8. The response of the PV model in one day \ 31.Oct.2022 (a) Comparison between real and simulation accumulative power (b) The error of accumulative power

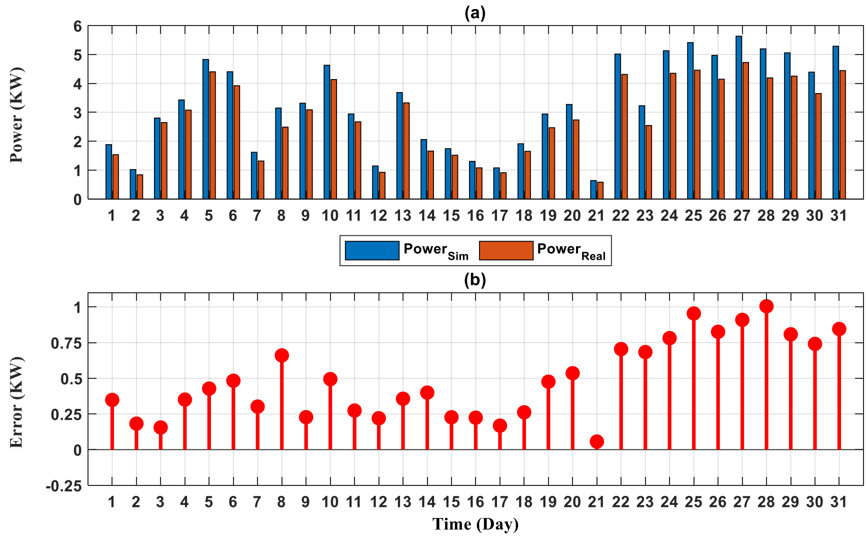

Fig. 9. The performance of the PV model in one mouth \ Oct.2022 (a) Comparison between the average real and simulation power (b) The deviation of the average power

4. Conclusions

Because chemical industrial fuels like oil, gas, and others are running out, scientists are always trying to find new ways to get energy. Therefore, this paper presents an easy and effective Matlab/SIMULINK model that can describe the behavior of the solar PV cell. The proposed model is derived based on the fundamental equations that describe the behavior of PV system components. In addition, the effects of physical and environmental parameters such as sunlight irradiance and ambient temperature are taken into account during driving the model. The simulated model was validated by comparing its output electrical power, average power, and accumulative energy with the real set of PV system data installed at the UQ site.

The results verified that the proposed model is effective enough to describe the performance of the actual PV system because its outputs are significantly close to the pattern of the real data. Accordingly, such a model is highly recommended to use as a tool to prognosticate the performance of any solar PV system under different climate conditions. Moreover, the proposed model can be regarded as a smart program to figure out the internal parameters of any photovoltaic system, such as the ideal factor, series of cells, and shunt resistance. Some of these parameters are not continually delivered by the manufacturers. As well as the proposed model, it can be utilized to study the optimum operation conditions, cell connections, site selection, power production, and others. Hence, applying the proposed model to the entire ATU formations to examine whether using the PV system is useful in each formation or not is proposed as future work.

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