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Practical Design and Performance Investigation of a 3.7 MW Stand-alone Photovoltaic Power Plant Feeding Industrial Area in Egypt

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ABSTRACT : *This paper aims at designing and studying the performance of a large-scale (3.7 MW) stand-alone Photovoltaic (PV) system feeding actual loads in Egypt. This research gives the directions, detailed guidelines, considerations and technical procedures to implement the PV generation system. In this study, the site assessment and the sizing of solar PV system components as well as the storage system are considered to develop stable and highly efficient system works under different operating conditions. In addition, the appropriate control strategies are proposed in order improve the overall system performance. The location of the installed PV system is studied to identify the practical variation of the solar irradiation over the whole year. Moreover, the load profile of actual load is introduced to match its needs with the designed PV power plant. The proposed PV system, the storage system and the practical loads are also simulated using MATLAB software package to assess the designed system under different operating circumstances.*

KEYWORDS *stand-alone solar PV, large scale PV system, battery bank, load profile, PV MPPT*

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I. INTRODUCTION

Photovoltaic (PV) system are considered one of the most widespread renewable energy sources. Photovoltaic converts of sunlight to electricity directly. It has many advantages such as being clean energy, safe, no noise at all, supplied by nature and available almost anywhere where is sunlight. Operating and maintenance costs for PV panels are considered very low, also they are easy to be installed on the ground or on rooftops, easy be expanded by increasing solar panels and batteries as energy storage with. Moreover, their expected service life is more than 25 years. Also, The photoelectric system does not need private training to operate and it does not include mechanically moving parts [1].

The photovoltaic systems are classified into: grid-connected PV plants and stand-alone plants [2]. The stand-alone solar PV system is a convenient and useful system for people who do not want to deal with the national electric grid, and also for remote places that the national grid does not reach and provide electricity. Thus, large areas which requires energy can be reconstructed using this technology [3]. So, this work present technical guidance and an illustrative example of how to design a stand-alone large-scale PV system based on realistic loads in a systematic and structured way.

Due to the varying nature of the solar energy, it is essential to design a robust storage system to overcome any expected or unexpected changes. Also, the load should be fed by the proper amount of energy under different generation conditions. Therefore, this study is conducted to design the solar energy plant by studying the location of the solar power station and the amount of irradiation falling in this region, as well as by studying the actual loads that will be fed by this station. In this paper, The stand-alone PV system is designed to supply industrial load and residential load with total loads up to 3.7 MW. The proposed design of the PV is evaluated during feeding the load under different short-term changes such as solar irradiation changing or under long term changes over one day or from season to another.

II. SITE AND ELECTRICAL LOAD SPECIFICATIONS

Variations in solar radiation at a site can dramatically affect energy yields from solar generation facilities. Accurate assessments of solar power resources at a potential site can support planning and provide information that ensures optimum solar power yield which assist maximizing the return on investment in solar energy.

In this section, the site where the PV power plant is proposed to be installed is investigated to illustrate the nature of solar irradiation over the year in additional to the load profile variation.

a. Site location

As shown in Fig. 1, the proposed site is located at Elnahda area in Alexandria town Latitude 30.971504 and Longitude 29.827789. Besides this site, there is a promising industrial zone (Elnahda). Therefore, it is expected that the demand load in this area will be increased. So, it is required to find different energy sources to feed the loads.

Fig. 1. Solar power plant proposed location

b. Study the irradiation properties

The design of PV plant mainly depends on the amount of solar irradiation in the studied site. Fig. 2 illustrates the instantaneous irradiation of sample days in July and December (maximum and minimum expected irradiation). It is evident from the figure that the proposed site has high irradiation values in summer and winter (between 400 to 750 W/m^2) with a longer duration of daylight in the summer.

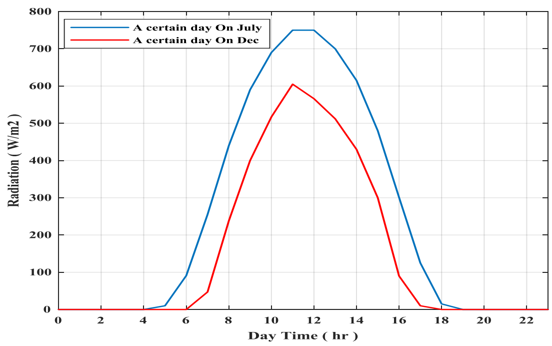


Fig. 2. Instantaneous irradiation of sample days in July and December

c. Load profiling

The load in any site may vary from day to day and season to season [4]. The total residential and industrial loads need the establishment of standalone photovoltaic power station with maximum capacity of 3.7 MW. Fig. 3 illustrates the variation of demand electrical load during a specified period. Initially a database was prepared, This information is used to plan how much power needed to be generated at any time.

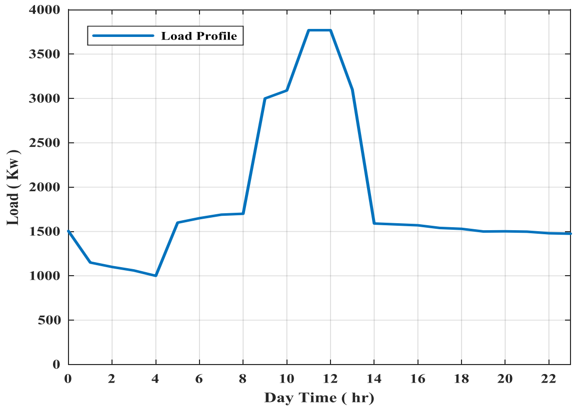


Fig. 3. Load profile of the load to be fed at a certain day at summer

Throughout the day, realistic loads were taken and included in the database to monitor the amount of power required during the whole day. By observing Fig. 2 and Fig. 3, it becomes clear that the highest irradiation is appears at the same time with the highest amount of load demand. This provides a good advantage related to the storage system design. The coincide of both maximum power demand and maximum generation decreases the maximum power required by the storage system.

III. SYSTEM DESCRIPTION OF STAND-ALONE SOLAR PV SYSTEM

The main components of stand-alone solar PV power system are shown in Fig. 4. A stand-alone system consists of PV array, DC/DC converter based on maximum power point tracking (MPPT) control system, a battery as a storage system and the inverter converts the DC electricity to AC to feed the AC loads [2]. A stand-alone system based upon solar panel and DC/DC converter with a controller for MPPT is connected with the DC bus [3].

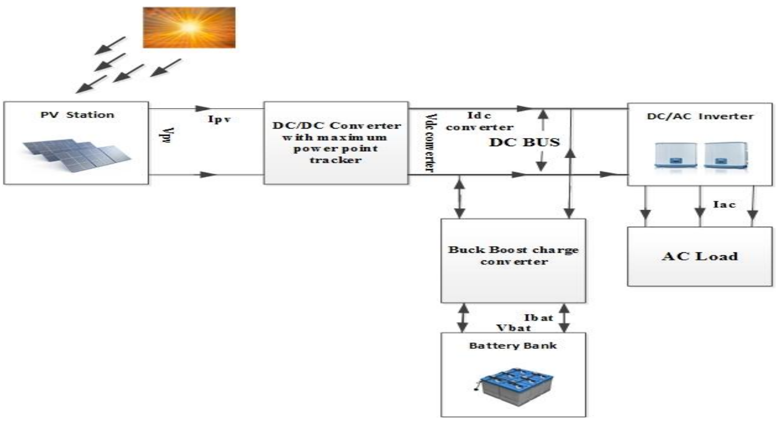


Fig. 4. Block diagram of Stand-alone photovoltaic System

In the block diagram, the out power from stand-alone PV system is given to DC/DC converter with controller. The MPPT algorithm is implemented in DC/DC converter to control the converter duty cycle.

The block of the battery bank is shown In Fig. 4, also has the charge controller using Bi-directional buck/boost DC/DC converter connected with the same DC bus [4]. Bi-directional buck/boost DC/DC converter is used for two modes charging and discharging batteries [5]. It is defined according to the voltage sense at the DC bus. The two modes are buck mode and boost mode. In the system, there are two power sources: PV panel and the battery. For discharging mode, the bidirectional converter works as a boost converter with the current control function. Thus, the power flow direction of the proposed bidirectional converter is from the battery bank to the DC bus to discharge the battery. While for charging mode, the bidirectional converter works as a buck converter. Thus, the power flow direction is from the DC bus to the battery bank to charge the battery [5]. The proposed inverter converts DC into AC. To track the maximum power point for PV, perturbation and observation-based (P&O) algorithm has been implemented. It has many advantages like its Simple ,responsive and It has no differentiation or integration like other algorithms [3].

Fig.5 illustrates a flowchart which describes the Perturb and Observe technique. Perturb and Observe technique introduces an initial perturbation to the voltage by changing the duty cycle D of DC-DC converter by a factor ΔD and then observations are made using sensors [6]. The P&O algorithm is based on knowing the photoelectric voltage and current then deducing and controlling the output power of the PV systems. The Perturb and Observe technique works continuously by knowing the present value of the power output and preceding value to find out the change on the solar array voltage or current. The algorithm technique measures the value of current and voltage at the output of the solar PV system. At n^{th} instant, the magnitude of voltage and power are stored. Then at $(n+1)^{th}$ instant the magnitude of power and voltage are measured again and power is calculated from the measured values. The perturbation will continue in the same direction in the next cycle when the magnitude of power increases, , otherwise the perturbation direction is reversed [7]. When the system reaches the maximum power point (MPP), the system fluctuates around it. To reduce the expected fluctuation, the perturbation step size should be reduced. when the operating point is far from the MPP, the step size change in duty cycle should be larger, then when it closes to MPP, the change of step should be reduced.

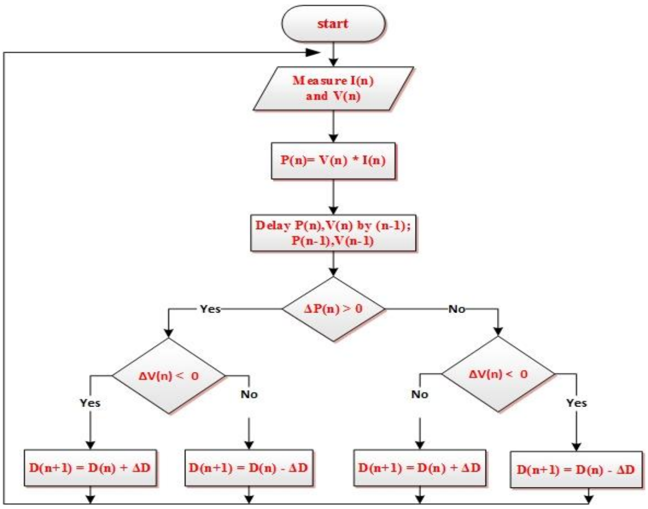


Fig. 5. Flowchart of the Perturb and Observe method

IV. SIZING OF THE PV SOLAR ARRAY

The amount of power produced from solar panels varies according to the size and number of the panels, as well as, the weather conditions for the proposed site has significant effect as illustrated in Fig. 2. The sizing of PV power plants depends on knowing the worst cases of solar irradiation and required loads [1]. Therefore, in order to know the size and number of PV modules needed to operate the target loads, the rated peak-watts produced by the chosen panel is needed to be determined. So, before sizing the array, the worst total daily maximum power during the year in Watt-hours (E), the average sun hour per day Tmin , and the DC-voltage of the system (Vdc) must be specified. Once these elements provide, the sizing process can be achieved. D.C load for input to inverter is obtained from equation (1).

$$E_{inv} = \frac{E}{\eta_{inv}} \quad (1)$$

where E_{inv} represents daily DC input energy to inverter (Wh/day). E represents daily energy of AC load (Wh/day) η_{inv} represents inverter efficiency (value ~ 0.85). The ampere-hours (Ah) needed at the converter is obtained from equation (2) [8].

$$I_{dc} = \frac{E_{inv}}{V_{dc} * T_{min}} \quad (2)$$

where I_{dc} represents the current output from boost converter. The relation between the converter input voltage Vpv (output PV voltage "voltage of series connected modules") and Vdc is as the following:

$$V_{pv} = (1 - D) * V_{dc} \quad (3)$$

where D represents a certain duty cycle at certain irradiation assuming the used converter is from boost converter type.

$$I_{pv} = \frac{V_{dc} * I_{dc}}{V_{pv} * \eta_d} \quad (4)$$

where I_{pv} represents whole module current from PV station η_d represents derating which is about 90% (10% losses due to dirt and temperature effect).

The number of parallel strings can be specified by the following equation [9].

$$N_p = \frac{I_{pv}}{I_r} \quad (5)$$

where N_p represents the number of parallel strings. I_r represents the rated current of one photovoltaic module.
The number of series modules can be deduced which equals the output PV voltage "voltage of series connected modules" divided by the rated voltage of each module [8], [9]:

$$N_S = \frac{V_{pv}}{V_{pv\ module}} \quad (6)$$

where N_S refers to the number of series modules. $V_{PV\ modules}$ refers to photovoltaic module voltage.

V. SIZING OF THE BATTERY BANK

The role of battery in the stand-alone PV system is to store electric energy for night time supply or when there is insufficient sunlight during the day. The capacity of the storage batteries (B_C) can be calculated according to the battery efficiency and the number of continuous cloudy days (N_C) to cover the total energy required.
The storage capacity in Wh can be obtained from equation (7) [8].

$$B_C = \frac{E_{inv} * N_C}{\eta_{coulomp}} \quad (7)$$

where B_C represents the battery storage capacity (Wh) and N_C represents the number of no sun days $\eta_{Coulomp}$ represents coulomb efficiency (value ~ 0.8).
This battery storage capacity is then divided by the nominal voltage output of converter to get the battery size C in ampere-hours (Ah) [8], [9].

$$C = \frac{B_C}{V_{dc}} \quad (8)$$

The number of parallel paths N_{Pbat} is obtained by dividing the capacity C of the battery bank in ampere-hours by the capacity of one of the battery C_b selected in ampere-hours [8], [9]:

$$N_{Pbat} = \frac{C}{C_b} \quad (9)$$

The connection of the battery bank can be then easily figured out. The number of batteries in series N_{Sbat} equals the DC voltage of the system divided by the voltage rating of one of the batteries selected V_b[8]:

$$N_{Sbat} = \frac{V_{dc}}{V_b} \quad (10)$$

VI. NUMERICAL SIZING OF THE PV POWER PLANT ACCORDING TO THE NATURE OF PRACTICAL LOADS

Electrical load consumption varies with time, type of consumer and consumer location. Thus, it should be taken into account the variation of loads with time and the variation of irradiation when calculating the loads throughout the day. TABLE I shows the actual loads during a certain day in July. It is the maximum daily load during the year. It was chosen for the design as a worst condition. This table will be used to design the standalone photovoltaic power station [12]. This design was done at system voltage of 600 V, duty cycle 0.534, irradiation 400 W/m2 as minimum expected irradiation and modulation index 0.75 for inverter.

TABLE I. THE LOAD VARIATION DURING A DAY IN JULY AND THE ESTIMATED TOTAL ENERGY

Load MW	TIME (hr)	Load MW	TIME (hr)	Load MW	TIME (hr)
1.505	00:00	1.7	08:00	1.57	16:00
1.15	01:00	3	09:00	1.54	17:00
1.1	02:00	3.09	10:00	1.53	18:00
1.06	03:00	3.77	11:00	1.5	19:00
1	04:00	3.77	12:00	1.502	20:00
1.6	05:00	3.1	13:00	1.49	21:00
1.65	06:00	1.59	14:00	1.48	22:00
1.69	07:00	1.58	15:00	1.47	23:00
Total Energy	**E = 44.437 MWh**				

SolarWorld PV-SW(255W) polycrystalline silicon solar panel is proposed for the construction of 3.7 MW PV power plant and also used for simulation study. The datasheet specifications of Solar World SW255 are [9]:

- Model name: SolarWorld SW255 Poly.
- Cell type: Poly-crystalline Silicon.

- Number of cells: 60 cells.
- Maximum power rating STC (Pmax): 255.02 W.
- Open circuit voltage (Voc): 37.8V.
- Short circuit current (Isc): 8.73A.
- Maximum power current (Imp): 8.2A
- Maximum power voltage (Vmp): 31.1V.

a. Sizing PV array

From the derived equations in the previous section, the numerical values of the design are summarized as the following. The daily energy required from the solar array can be determined as the following:

$$E_{inv} = \frac{E}{\eta_{inv}} = \frac{44.437}{0.85} = 52.3 \text{ MWh}$$

The current output from boost converter can be determined assuming the number of sun appearance T_{min} equals 6 hours.

$$I_{dc} = \frac{E_{inv}}{V_{dc} * T_{min}} = \frac{52300000}{600*6} = 14528 \text{ A}$$

At a certain duty cycle of 0.534 at 400 W/m^2 and system voltage 600 V so

$$V_{pv} = (1 - D) * V_{dc} = 0.466*600=279.6 \sim 280V$$

consider the derating of PV is 90% (10% losses due to dirt and temperature).

$$I_{pv} = \frac{V_{dc} * I_{dc}}{V_{pv} * \eta_d} = \frac{600 * 14528}{280 * 0.9} = 34590 \text{ A}$$

First, the number of parallel strings:

$$N_p = \frac{I_{pv}}{I_r} = \frac{34590}{8.2} = 4218.2 \sim 4218$$

Second, the number of series modules which equals to:

$$N_S = \frac{V_{pv}}{V_{PV\ modue}} = \frac{280}{31.1} = 9$$

Finally, the total number of modules N_t = 4218 ∗ 9 = 37962 modules.

b. Sizing of the battery bank

Days of autonomy or the no-sun days assumed to be 3 days to ensure continue feeding at night and in times of low irradiation or the increased need for energy.

According to the selected battery (250 AH, 48V-DC).

The amount of battery storage capacity is:

$$B_C = \frac{E_{inv} * N_C}{\eta_{Coulomb}} = \frac{52300000*3}{0.8} = 196125000 \text{ Wh}$$

The output voltage of converter equals 600 V so the capacity of the battery bank in ampere-hours is:

$$C = \frac{B_C}{V_{dc}} = \frac{196125000}{600} = 326875 \text{ Ah}$$

The number of parallel paths N_{Pbat} is obtained by:

$$N_{Pbat} = \frac{C}{C_b} = \frac{326875}{250} = 1307.5 \sim 1308$$

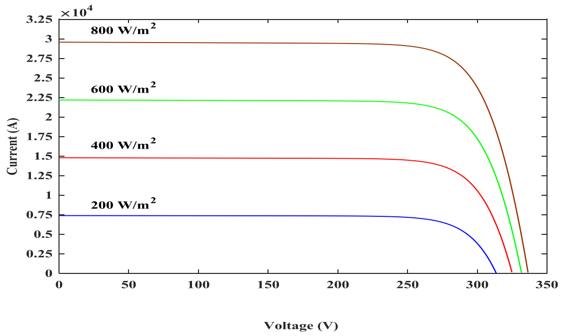
Then number of batteries in series equals to:

$$N_{Sbat} = \frac{V_{dc}}{V_b} = \frac{600}{48} = 12.5 \sim 13$$

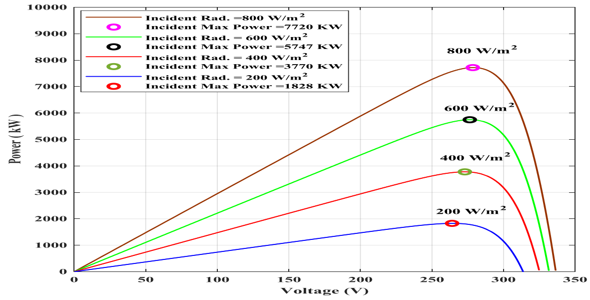
Altogether there are 13 batteries in series with 1308 parallel strings = 17004 batteries in total.

VII. PERFORMANCE OF THE DESIGNED PV SYSTEM DURING SHORT PERIOD CHANGES

The standalone solar power station is designed to supply loads of up to 3.7 MW. As mentioned in the previous section, the PV plant is consisted of 37962 modules, each with a capacity of 255.02W, 4218 modules connected in parallel and 9 modules connected in series. Fig. 6(a) and (b) illustrate the characteristics of the designed station; Fig. 6(a) shows the voltage/current characteristics of the overall station at different irradiation; while (b) illustrates the variation of power with the voltage under different irradiation levels. The values of maximum powers are illustrated under different irradiation. It can be noticed that the maximum power produced by the station may exceed the rated load at certain irradiation (600W/m^2 and 800W/m^2). On the other hand, the maximum developed power may coincide the required load or may less than it. Therefore, the need for storage system is essential to store the excessive generated power or to feed the remaining power required by the load.



(a). Current vs. Voltage for the designed standalone solar station



(b). Power vs. Voltage for the designed standalone solar station

Fig. 6. Characteristics of the designed PV plant

Using MATLAB/SIMULINK package, the designed PV power station is tested during short period study to assess the its performance to supply the rated load of 3.7MW at different levels of irradiation.

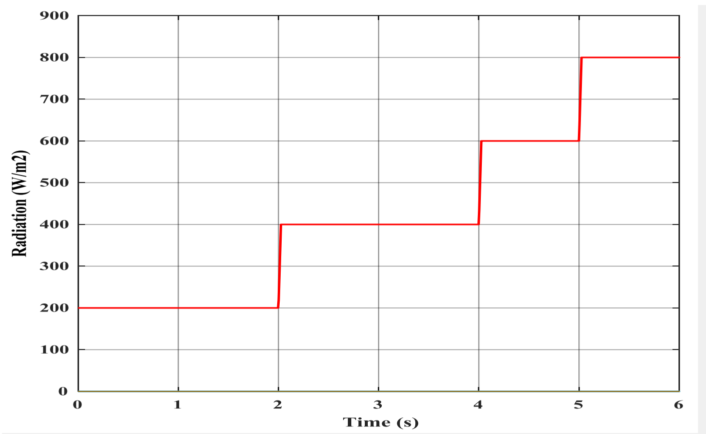


Fig. 7. Irradiation diversity with time

As shown in Fig.7, the irradiation is assumed to be changed with levels (200-400-600-800) W/m^2. Whereas, these irradiation values express the average irradiation in the studied region where a solar power station is to be built, as shown in Fig. 2. According to the PV plant characteristics and the continuous activation of the MPPT mode, the output power of the PV plant is changed as shown in Fig. 8.

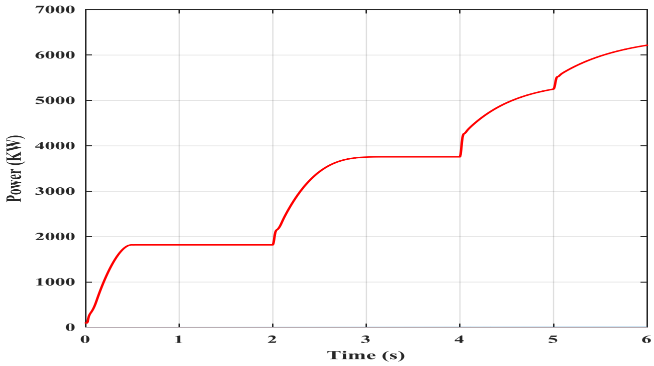


Fig. 8. Variation of PV power station due to variation of irradiation with time

As shown in Fig. 8, in the case of irradiation 200W/m^2, the maximum generated power is about 1828 kW and in the case of irradiation 400W/m^2, the maximum power is about 3770 kW and it is confirmed by the Fig. 6(b) where it shows the characteristics of the station in terms of the relationship between the irradiation and the maximum produced power.

Because of using (MPPT), some power may be available to be stored in the storage system "battery bank ". This energy is stored to be used in periods when the solar power plant is insufficient to feed the load required power.

The difference between the required power 3.7MW and the maximum PV generated power at 200W/m^2 of 1.8MW equals 1.9MW. The battery bank supplies this power difference in this period as shown in Fig. 9. The transition from certain level of power to the other depends on the MPPT control algorithm and converter circuit.

At 400W/m^2 during the period from 3 to 4s, the maximum generated power approximately equals 3.7MW. Thus, the storage system doesn't have any power contribution during this period.

As shown in Fig. 8, when the irradiation equals or more 600W/m^2, the maximum generated power is more than the required load power. Then, the additional power will be used to charge the battery bank. This different is represented as a negative value as shown in 9 after 4s.

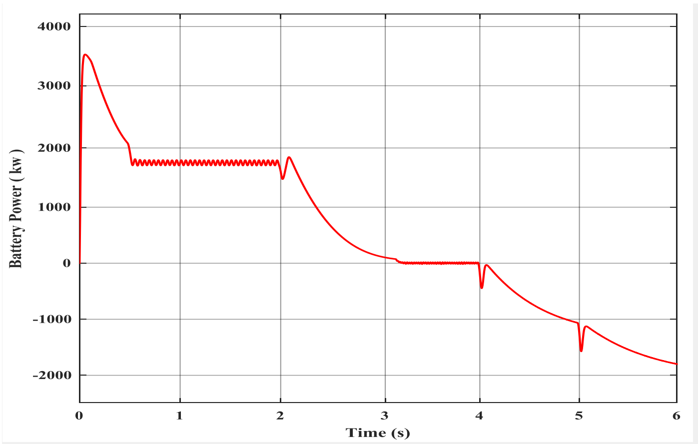


Fig. 9. A mount of power produced by the battery bank.

The maximum power point tracker is activated until the batteries charge state reaches 100 percent, then the maximum power point tracker feature is deactivated.

Fig. 10 shows the status of the battery bank. It is assumed that the battery bank starts with initial state of charge of 90%. From this figure, the changing of charge depends on the amount of power produced or absorbed. Low solar irradiation results in the decreasing of charge and vice versa.

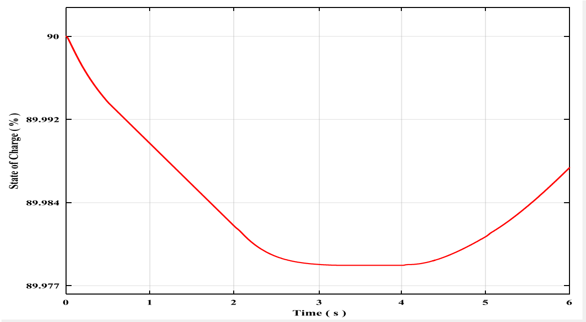


Fig. 10. The state of charge of battery at various irradiation

VIII. ANALYSIS OF THE DESIGNED PV DURING SUPPLYING EXPECTED PRACTICAL LOADS

In this study the designed PV plant is studied during supplying actual practical load estimated by Egyptian ministry of electricity and renewable energy for the studied location. Here, the performance of the system is evaluated during whole day operation. In this study, the load profile for one day in summer and winter season is studied to be fed by the suggested PV power station. Here, the system is tested under the worst scenario; one day when the load is maximum (in summer) and one day when the generation is minimum (in winter).

In Fig. 11, the actual loads during full day hours in December and July. According to the load profile, the station capacity is determined, and the station is designed as explained in the previous paper sections. It is also clear from the figure that the loads in July are greater than the December loads. So, the design is achieved depending on the July load.

Fig. 12 demonstrates the relationship between the power produced from the PV power plant during whole day hours in December and during a whole day hour in July, taking into account the irradiation during the day periods according to Fig. 2. It can be noticed that the maximum load happens approximately in the middle of the day when the PV system produces the maximum amount of power. This leads to the lower stress on the battery bank system and therefore increase its time life. During daytime, as the battery bank is not fully charged, the MPPT technique is activated. Consequently, the PV plant makes use of the maximum available power in daytime to be used in nighttime. Fig. 13 shows the amount of power that charges and discharges the batteries over a whole day. Fig. 14 illustrates the status of the batteries during the whole day hours under the different loads assuming the batteries starts with initial charging percentage of 90%.

The results indicate that the amount of energy consumed is almost equal to the amount of energy charged to the batteries on a certain day in December or a certain day in July, and this ensures continuous operation and an appropriate design of the quantity of both batteries and solar panels.

IX. CONCLUSION

The use of solar energy has become a pressing issue in the world and in Egypt in particular, because it is rich in high solar radiation. The geographical position of Elnahda site makes it a region comparatively rich in the sun with annual solar radiation more than 2000 kWh/m2.

This paper describes technical guidance and an illustrative practical example of how to design a stand-alone large-scale PV system based on realistic loads in a systematic and structured manner to feeding energy for large scale area.

By using MATLAB/SIMULINK package, the performance of the proposed design has been estimated using proper simulation model.

Based on the daily load profile, location, and daily irradiation. The capacity sizing of PV array and battery storage are developed in this work. The results have illustrated the response speed of the storage system in order to continue feeding at night and in times of low radiation, by monitoring the charging and discharging state of the batteries. Moreover, the long-term performance (during one day) of the proposed design has been investigated to illustrate its robustness and dependability. So, this paper will be useful for assessing design and installing stand-alone large-scale photovoltaic power plants to feed large scale isolated load.

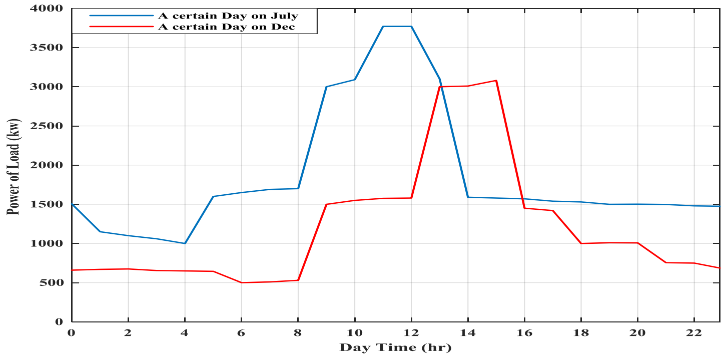


Fig. 11. Load power variation during one day

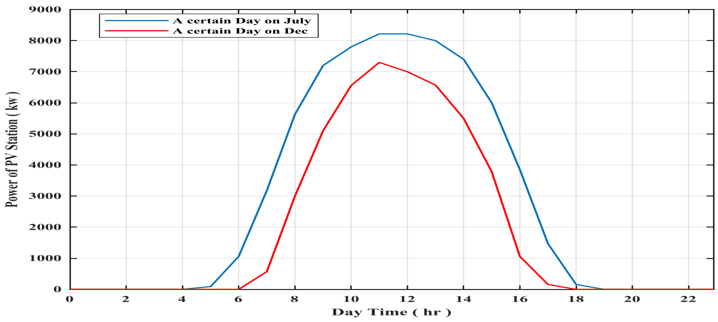


Fig. 12. Power produced from photovoltaic power plant during one day

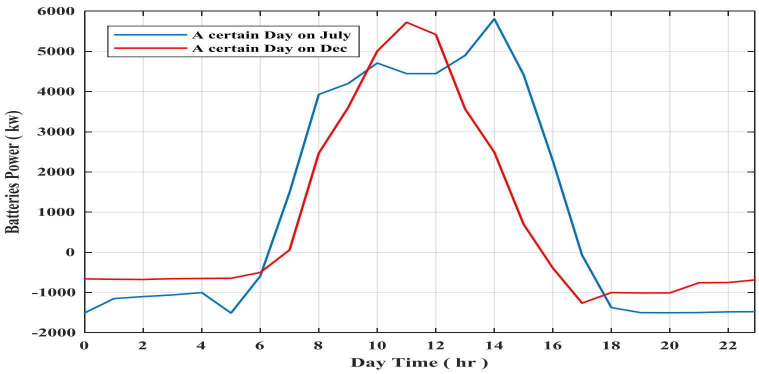


Fig. 13. Transferred power from or to the batteries during the day

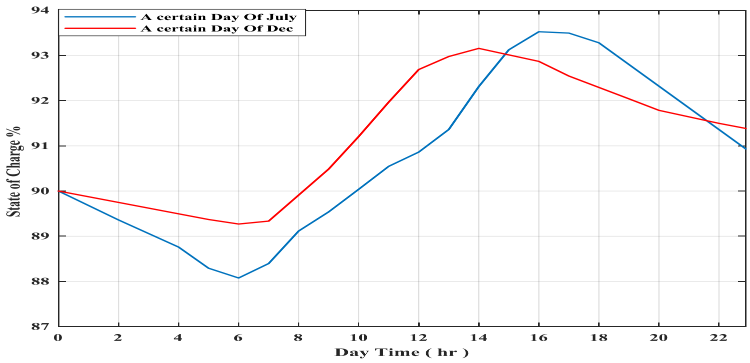


Fig. 14. State of charge during feeding the actual loads

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