Hybrid Photovoltaic Battery (PVB) System for a Desalination Plant in Sinai Desert

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Abstract *–This paper presents a desalination system driven by a hybrid power supply system in Nikhil region, Sinai desert, Egypt. Reverse osmosis (RO) desalination plant with a capacity of 100 m^3/day is supplied by hybrid photovoltaic battery (PVB) system for brackish water. To overcome the intermittent nature of solar energy, PVB power source have been introduced. Also, Sizing PVB system to match the required load is discussed. Moreover, a control of battery current through dc-dc bi-directional converter is presented to maintain the dc link voltage at its reference value. The Simulation of PVB-RO system is accomplished using Matlab/Simulink. The results show that the outputs of PVB-RO system have a good response.*

Key words: *Photovoltaic, battery, Reverse Osmosis.*

1. Introduction

Energy demands around the world increased, for this reason the need for a renewable energy source that will not harm the environment has been increased. Some projections indicate that the global energy demand will almost triple by 2050 [1].

The rapid population growth all over the world has resulted in large escalation of demand for fresh water.

Brackish water is one of desalination sources to get pure water. Water desalination's techniques can be divided into two categories thermal processes and membrane processes [2].

Water desalination, through the technique of reverse osmosis, has proved to be the lowest energy consuming technique according to many studies. It consumes nearly around half of the energy needed for thermal processes, RO desalination plants are viable solution for small communities [3].

Dimitrios Mentis, 2016, [4], made study focused on developing a tool capable of designing and optimally sizing desalination and renewable energy units. The tool was applied on three islands in the South Aegean Sea, Patmos (large), Lipsoi (medium) and Thirasia (small)

Mariem Smaoui, 2015, [5], proposed a stand-alone hybrid system photovoltaic/wind/hydrogen which is designed to supply a seawater desalination unit where installed in the Kerkennah islands located in the south of Tunisia. Hydrogen is used as storage energy for this system.

Nasser Ahmed, 2014, [6], carried out a modeling and simulation to monitor the performance of a PV system in Dhahran city in Saudi Arabia as a case study. His numerical study was operated by fixed and tracking panels for feeding RO water desalination plant. The feed water pressure and the permeate flow rate for the whole year were estimated which gave him the ability to develop a complete model of RO membrane. He also showed that photovoltaic system should be orientated tilted.

Hazim Qiblawey, 2011, [7], made study of Water desalination by Reverse Osmosis and used Photovoltaic Technology with additional battery storage to generate electricity. And the system was applied to brackish water. Hartha Charitable

Society in northern part of Jordan was the case study where system has been designed, installed and tested

The study presented here is organized as follows, section 2 introduces the PVB-OR system and explains Nikhil desalination plant in more details, section 3 presents PVB system sizing, the control of PVB-RO is described in section 4, the simulation results are provided in section 5 and section 6 concludes the paper.

2. Nikhil Desalination plant description

PVB-RO system configuration, which was considered in our study, is illustrated in figure1.

Nikhil desalination plant basically consists of brackish water RO units. 100 m^3 of potable water, at 21 bar, is produced per day. The energy required will be supplied by hybrid PV battery (PVB) system. Step-up dc-dc converter is used to boost the output voltage of the PV array and extract maximum power of PV array under different environmental conditions. Step-up converter is continuously controlled to operate the PV array at its maximum power points. A Perturb and Observe (P&O) algorithm is used to adjust the duty cycle of step-up converter to achieve the maximum power extraction from PV array. KC200GT PV modules are used in this study [8].

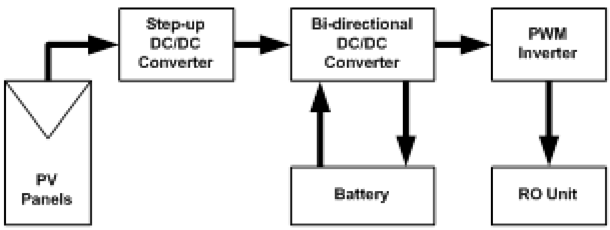


Fig.1. Structure of PVB-RO System.

Due to the change in environment conditions like cloudy days and radiation variation, the PV array will change. Battery can charge or discharge to keep balance between PV array energy and load energy. DC-DC bi-directional converter is used to manage the charging and discharging of the battery to compensate the unbalance PV energy and load energy and insure a constant voltage at the inverter's input.

2.1 RO Desalination Plant

Reverse osmosis is one of the desalination systems; it has three processes to get pure water from brackish water. These processes are: pre-treatment, RO processes, and the post- treatment. In this case study no need for post-treatment; as the salinity of the water is good enough to drink after RO process. Pre-treatment process is to prepare brackish water that will be desalinated. Brackish water is filtered by using a pump coupling with three phase induction motor rated at 7.64 kW.

The RO unit consists of membrane and high pressure pump that supplies the pressure needed to enable the water to pass through the membrane and have salts rejected. In Nikhil desalination plant there are two modules each one has three membranes. It is obtaining an average of 16 operating hours per day in the summer and 14 hours in the winter.

FILMTEC- BW30-400 membrane is used (spiral module) for its rejection capacity. The spiral membrane is characterized by Pressure = 21 bar, Flow = 100 m³/d, Recovery = 65 % and Feed water salinity less than 2000 ppm [9]. Brackish water has a much lower osmotic pressure than seawater and therefore its desalination requires less energy.

The pump shaft power in kilowatts is given by the following equation (1) [10]:

$$P = \frac{Q_F \times P_a}{36.7 \times \eta} \quad (1)$$

Where Q_F is the feed flow (m^3/s), P_a is the pump pressure (bar) and η is the pump efficiency (%). The motor shaft power must be more than pump shaft power by 20% at least for more reliability and safety for induction motors [10]. The two motors for RO unit in Nikhil are rated at 11.19 kW for each one.

There are two motors coupling with two high pressure pumps as shown in figure 2.

Fig.2.Two high pressure pump motors for (RO system).

3. Sizing PVB system

The main goal of system sizing is to achieve the right balance between daily needs of electrical energy consumed by the loads and daily produced electrical energy by the PV array. Sizing of the PVB-RO desalination system depends on many factors: climate of site location, the rated output watt-peak of the PV module, total power and energy consumption of all loads.

3.1 Location of the desalination plant

RO plant is in Nikhil region located in middle of Sinai desert, Egypt (see figure 3). The geographical data of Nikhil region are reported in Table 1.

Table 1
The Geographical Data of Nikhil Region

Latitude	29.94˚N
Longitude	34.17˚E
Hemisphere	North

To design any power system based on solar energy, the availability of solar radiation must be analyzed. All the solar data used in this study is from NASA surface meteorology and solar energy data [11]. As shown in table 2, the available solar radiation data consists of horizontal data only. Since solar panels should be installed with slope and oriented toward south direction so the radiation data for titled surface should be estimated from horizontal data.

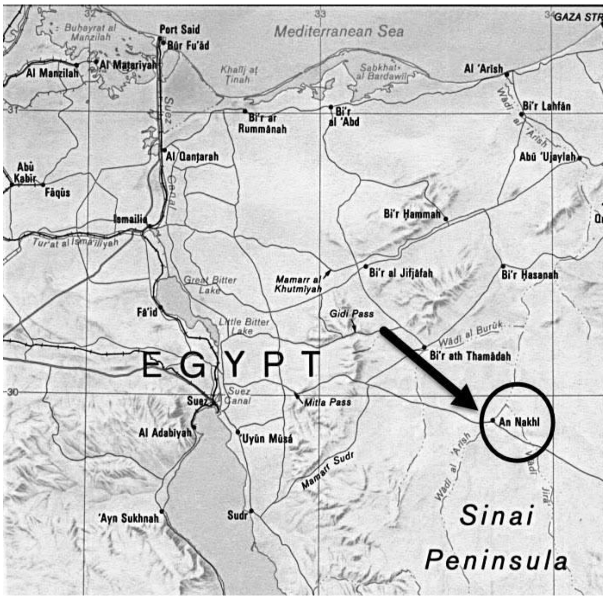


Fig. 3. Location: Nikhil, North Sinai (Egypt)

Table 2
Climatic characteristics of Nikhil Region

Month	***Air Temperature (^0C)***	***Horizontal***
January	10.7	3.21
February	11.7	4.16
March	15.0	5.49
April	19.9	6.6
May	23.5	7.37
June	25.3	8.16
July	26.8	7.98
August	26.8	7.42
September	25.4	6.32
October	21.9	4.72
November	17.1	3.5
December	12.3	2.9

The solar panels should be installed with a slope and oriented toward sun direction. Thus, it is necessary to correct the solar radiation from horizontal [11] to tilted surface using the following equation (2) [10]:

$$E' = E \, . \, k_1 . \frac{\cos(\theta-\beta-\partial)}{\cos(\theta-\partial)} \quad (2)$$

Where E is the daily solar radiation on horizontal surface, k_1 is the radiation correction factor fixed to 0.95, θ is the latitude, β is the tilt angel of the module measured from the horizontal, ∂ is the solar declination angel which can be calculated by equation (3):

$$\partial = 23.45 \sin(360 \frac{(284+N)}{365}) \quad (3)$$

Where, N is the Number of the day related to the year which is here the 15th of each month.

To find the appropriate tilt angle for PV array, the available solar radiation will be estimated for three different tilt angles ($\theta - 15, \theta, \theta + 15$), the plot of the average solar radiation for every month on the three tilted surfaces is shown in Figure 4.

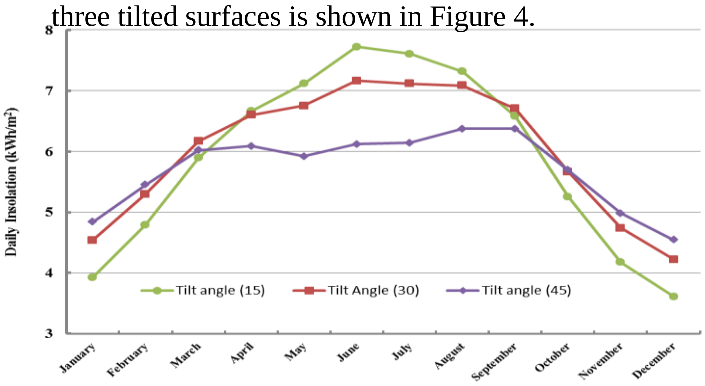


Fig. 4. Solar radiation for three different tilt angles

By investigating the radiation incident on tilted surface, it is observed that the monthly average solar radiation on surface with 30 tilt angle (approximately equal to local latitude) varies from 4.22 to 7.17 $kWh/m^2/day$ with the annually average value is 6.00 $kWh/m^2/day$ and total radiation 2192 kWh/m^2-yr and the monthly average solar radiation on surface with 15 tilt angle varies from 3.61 to 7.72 $kWh/m^2/day$ with the annually average value is 5.89 $kWh/m^2/day$ and total radiation 2149 kWh/m^2-yr while the monthly average solar radiation on surface with 45 tilt angle varies from 4.54 to 6.37 $kWh/m^2/day$ with the annually average value is 5.71 $kWh/m^2/day$ and total radiation 2086 kWh/m^2-yr. For annual performance, the appropriate angle is 30 with average radiation 6 $kWh/m^2/day$.

3.2 Daily Load Energy

The system will operate during the daytime and, also, in night. The energy required to produce 100 m^3/day using RO units is the total daily energy required for the RO units, filter's pump, pure water pump and lighting. The total energy has been calculated as follows:

Power of Filter pump is 7.64 kW with operating hours 16hours/ day, power of two high pressure pumps is 22.38 kW with operating hours 16 hours/day, power of fresh water pump is 3 kW with operating hours 5 hours/ day, and lighting loads of 5.65kW for 6hours/day. The daily energy required E_1; including the lighting loads will be 529.22kWh/day.

3.3 PV Array sizing

The energy requirements of the RO unit will be 529.22kWh/day, but the inverter losses, the battery losses, and the PV array thermal losses have to be taken into consideration. Assuming the inverter losses to be about 10%, the battery losses about 10%, the PV array thermal losses in the Egyptian environment about 15% and the motor losses are 16 % [3], the peak power of the PV array can be determined as following equation (4):

$$P_{peak} = \frac{E_l}{PSSH \times F_{TH} \times \eta_{BA} \times \eta_{INV} \times \eta_{Mot}} \quad (4)$$

For the given case, P_{peak} will be 152.51 kW, as the average peak sunshine hours in Nikhil, PSSH, is 6 hrs, the PV array thermal factor in Nikhil,F_{TH}, is 0.85, the battery efficiency, η_{BA}, is 90% and the inverter efficiency, η_{INV}, is 90% and the motor efficiency is 84%. And for any forecasting loads, it will be assumed 156 kW.

The size of the PV array will be 156 kW. If PV modules are selected, each of 200 W, as peak power (I_{mp}= 7.61 A, V_{mp}= 26.3 V at standard test condition (STC), then 780 modules will be needed.

Considering that the DC voltage required for the inverter is 775 V DC according to the equation (5) [12]:

$$V_{AC} = \frac{\sqrt{3}}{2\sqrt{2}} \times m \times V_{DC} \quad (5)$$

Where modulation index (m = 0.8) to feed 380 V AC then the PV array will consist of 52 parallel strings, each of 15 series PV modules in Nikhil region to get 156 kW to feed the desalination plant.

3.4 Battery Sizing

The change in environment conditions like cloudy days and radiation variation will affect directly the PV output power so battery energy storage is used to keep balance the power between PV generation and loads. Battery can discharge to compensate that decrease in both voltage and power and insure a constant voltage at the input of the inverter as the mechanical parts of the osmosis modules suffer the dynamic strains of the Pressure changes.

Assuming a battery maximum depth of discharge (DOD) of 50%, the required maximum battery capacity will be calculated as follow (6) [3]:

$$\text{Battery capacity (kWh)} = \frac{E_1}{DOD \times \eta_{BA} \times \eta_{INV}} \quad (6)$$

The battery capacity will be 1306.7kWh. As the voltage output required from the battery bank is 400 V, so the required battery bank capacity in AH = 1306.7×1000 / 400 =3266.75 AH.

A battery bank consisting of 120 batteries each one has 110 AH100V DC connected in 4 series and 30 parallel. The suitable battery charge controller for this system is expected to be able to handle the current and voltage.

4. System Performance

PVB-RO system to produce 100 m^3 of potable water in Nikhil region is shown in Figure 5. The power circuit consists of a PV array, dc-dc boost converter, batteries with charger controller, three phase PWM inverter, LC filter and loads consist of induction motors as inductive loads and lamps as resistive loads. The system consists of two power sources and power electronics interface to drive the three phase induction motors coupled to RO unit pumps. PV array is connected to dc link thought dc-dc boost converter. The duty cycle of the converter is continuously adjusted to operate the PV array at its maximum power points. The adjusting of the duty cycle is achieved by a Perturb and Observe (P&O) algorithm. The maximum power extraction algorithm (P&O) algorithm basically depends on the measuring of the PV array voltage and current. The battery is connected to the dc link through a dc-dc bi-directional buck-boost converter. The buck-boost converter allows using battery with voltage lower than the dc link voltage. The dc-dc converter controller used to regulate the charging/ discharging current of the battery to maintain the dc bus. The battery should discharge (charge) when there is decreasing (increasing) in solar isolation. The control action is carried out by comparing the dc bus reference value with the present value then the battery will provides the power instantaneously to maintain the bus voltage when the irradiation or the temperature is changing according to the climate in Nikhil region to insure a constant voltage at the inverter's input.

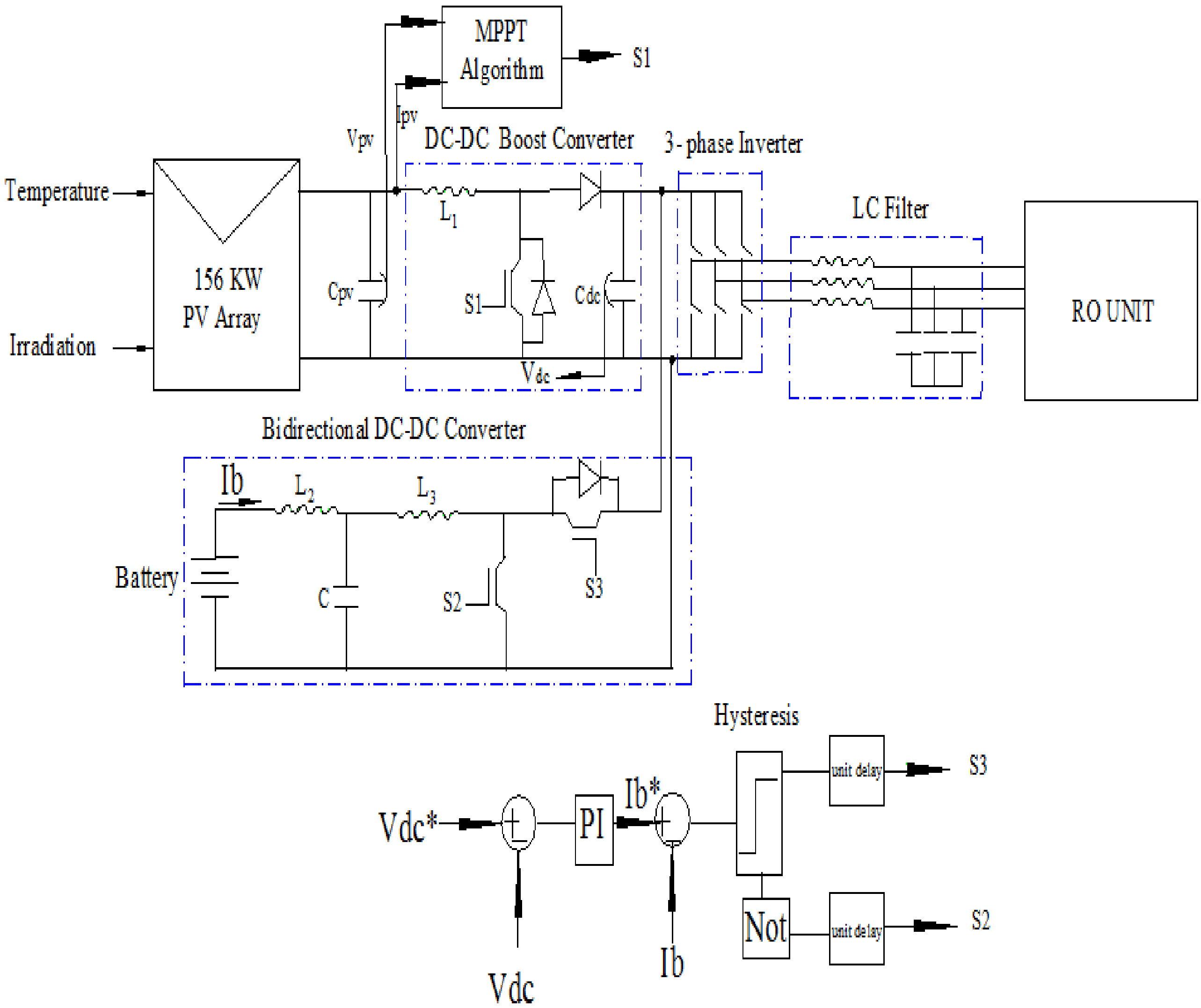
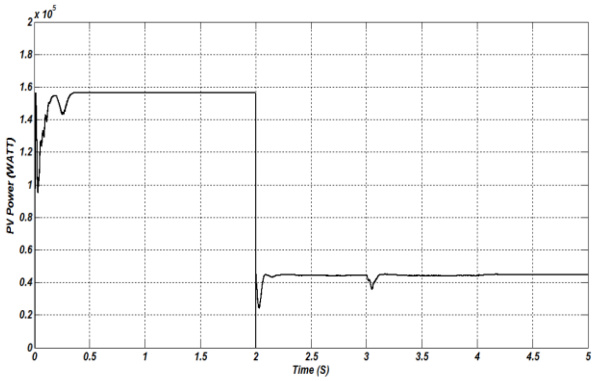


Fig.5. the Control Blocks of PVB system.

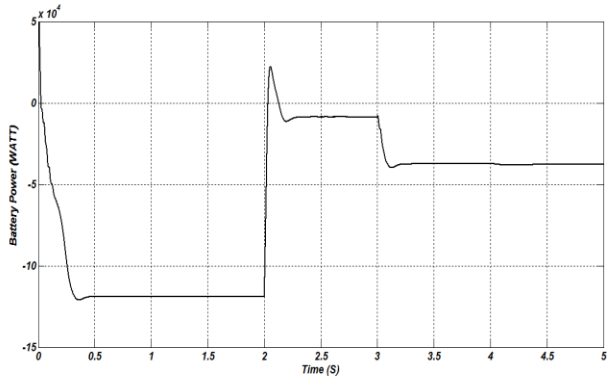
The load side PWM inverter will generate high frequency harmonics in the output ac voltage which supplies the three phase induction motors with ac power. The load side PWM inverter will generate high frequency harmonics in the output ac voltage which supplies the three phase induction motors with ac power. The switching frequency of PWM inverter is 5 kHz. LC filter is designed to improve the quality of ac voltage, the values of LC filter are obtained as L= 86 mH and C= 3(100) μF.

5. Simulation Results

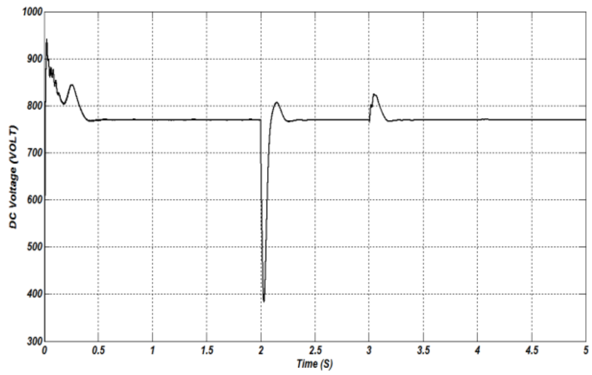
Finally, simulation results on MATLAB/Simulink software are carried out to validate the performance of the proposed system. In order to investigate the effectiveness of the control algorithms of the PV system, dynamic simulation is done with solar irradiance is dropped from $1000\,\mathrm{w/m^2}$ to $300\,\mathrm{w/m^2}$ at 2 sec as well as PV power decreased too from $156\,\mathrm{kW}$ to $42\,\mathrm{kW}$ nearly at 2 sec too (See Figure6(a,b))



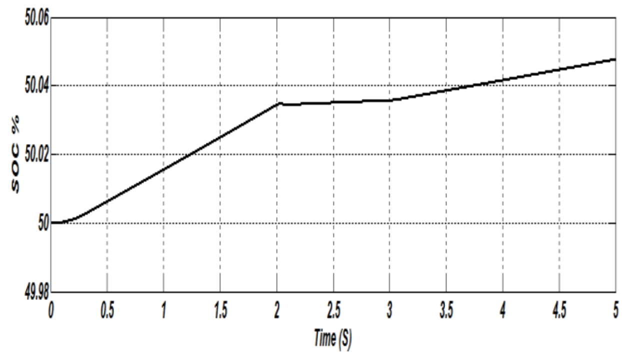
(a)The Power of PV Array.



(b) The Power of the Battery.

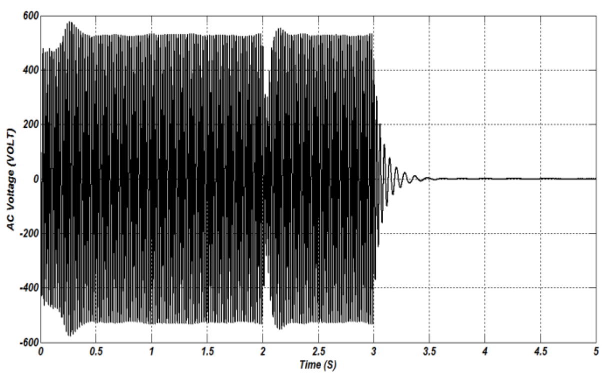


(c) The DC voltage.

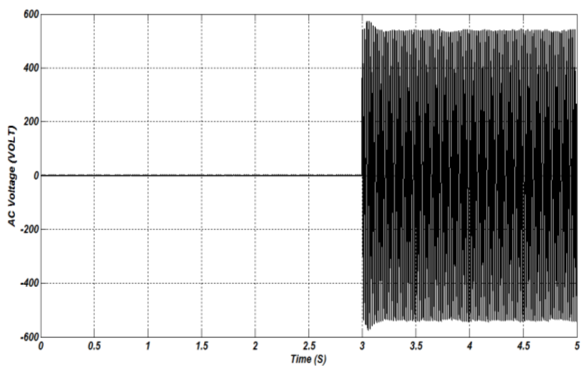


(d) SOC % of the Battery .

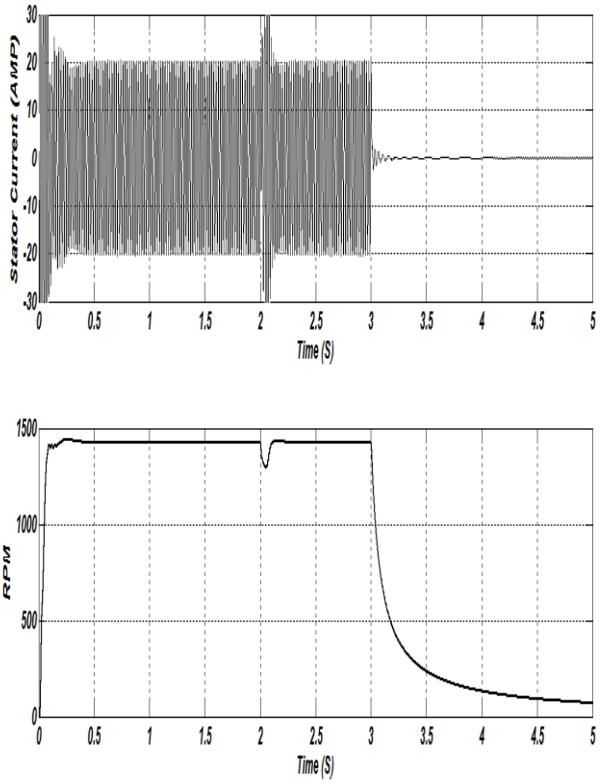
Fig.6. Simulation Results for PV Array and the Battery to Maintenance the Dc Voltage.



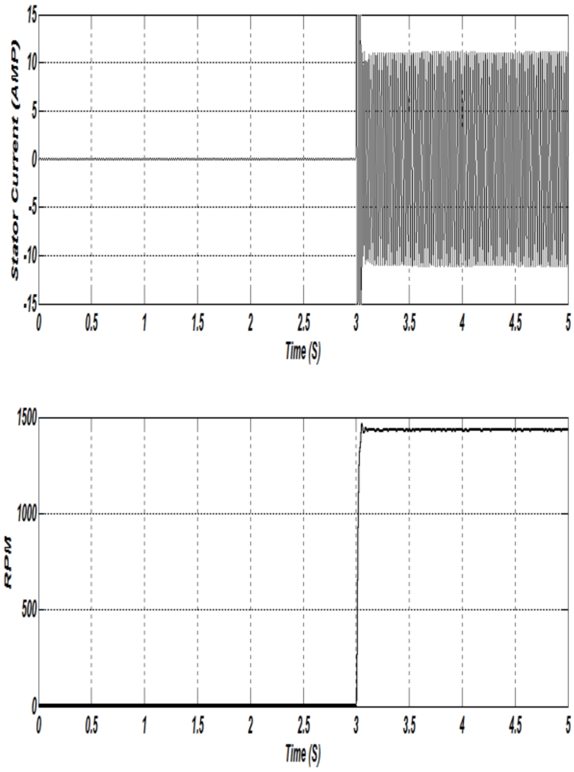
(a) voltage waveforms at one of two first induction motors.



(b) voltage waveforms at second induction motor.



(c) The Current and Speed Waveforms at (one of First Induction Motors).



(d) The Current and Speed Waveforms at fourth Induction motor.

Fig.7. Simulation Results of Voltage, Current and Speed for two induction motors in different starting time.

The DC link voltage maintained constant at 775V by battery controller is shown at Figure 6(c). State of battery charging is in figure 6(d). This operation has four motors working as three of these motors (filter and RO) are working till 2 sec, one of them is shown at Figure 6(a, c) then stopped and the fourth motor (pure water) will work from 3 sec till 5 sec is shown at Figure 7(b, d).

Table 3
Parameters for Simulation

PV array type ***No. of Series modules*** ***No. of Parallel strings***	KC200GT 15 Modules 52 Strings
DC-DC converter ***Output voltage at MPP***	Boost converter 775V
Switching frequency ***PWM inverter out put***	5kHz 380 AC volt R.M.S
Battery depth of discharge (DOD) ***Battery capacity (kWh)***	50% 1306.7 kWh
Load voltage ***Load frequency***	380V 50 Hz

Conclusion

In summary, hybrid photovoltaic battery (PVB) system supplies RO desalination system to produce $100m^3$/day in Nikhil region of Sinai desert, Egypt has been presented. Also, sizing PVB system depending on climatic conditions is analyzed. PVB-RO system has been simulated using MATLAB/Simulink software. The simulated system has included the maximum power extraction algorithm, dc-dc converter controller, and battery current controller. The results obtained from the simulation of the system illustrated that the system has the ability to supply the RO plant under different climatic condition

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