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# Photovoltaic Water Pumping System for a Desert Area in Egypt

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**ABSTRACT**

This paper illustrates a study of sizing and dynamic modelling of a large scale solar powered water pumping system for irrigation in Egypt. The system is expected to deliver 500 $m^3$ of water per day. Sizing such a system has been carried out by using some useful tool such as PVsyst. A 130 m water level in a deep well. System dynamic modelling is done using Matlab/Simulink which contains several models of such systems such as 58 kW solar arrays, DC-DC boost converter, 54 kW DC-AC converter (Inverter), 50 hp AC motor, and centrifugal pump. In order to improve the system efficiency, perturbation and observation (P&O) algorithm based maximum power point tracker (MPPT) was built in the system model for the converter. Matlab/Simulink simulation shows that this system can deliver the required energy with quite satisfactory controller dynamic performance.

**Key words:** Solar powered water pumping system, DC-DC boost converter, DC-AC converter (Inverter), MPPT, Renewable Energy, PVsyst

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## 1. INTRODUCTION

Solar powered water pumping system has been regarded as an appropriate choice for the grid-isolated countryside regions in developing and advanced countries, including Egypt, in which high amounts of solar radiation are available [1]. Solar powered water pumping systems have the ability to distribute drinking water without any type of additional power or the complicated upkeep, which, for example, require diesel pumps, as it was outlined in the report by the Department of Energy of the United States [2]. In addition, in spite of the fact that solar powered water pumping systems are not suitable for large-scale irrigation, they are able to efficiently operate in the areas with small-scale drip irrigation systems [3]. The solar powered water pumping systems could be regarded as being large-scale in a case when it serves more than two hundred and forty people. However, Photovoltaic solar panels are frequently utilized to perform various agricultural operations, in distant regions or in areas in which the utilization of an alternative energy sources is preferable [4]. To be precise, the solar powered water pumping systems have been established in the course of the last decade to consistently generate an adequate amount of electricity straight from the radiation of the sun in order to deliver water to cattles [5].

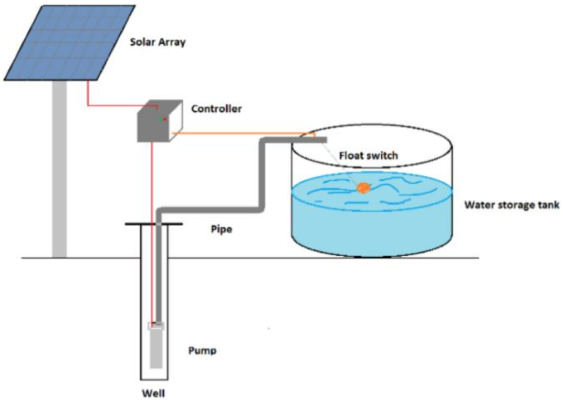


**Fig. 1** Constituents of solar powered water pumping systems.

The longstanding financial expenses and thecapability of solar powered water pumping system of being adjustable in accordance with the constantly altering demands has to be realized in the feasibility of this pumping system. This development is to some extent connected to the capability of the general population that utilizes the pumping system for irrigation of being able to adjust to constantly altering demands as well. According to [6], solar powered water pumping system is the one of best alternative solution for irrigation. The figure below shows the components of the solar powered water pumping system.

This paper is divided into several sections as follows: section 2 covers the description of PV water pumpingsystem. Optimization of system sizing using PVsyst software [11] is given in section 3,System modeling descriptionin section 4,The results will be discussed in section 5 followed by the conclusion.

## 2. PV WATER PUMPING SYSTEM (PVWPS) DESCRIPTION

PVWPS has been designated to be built in a shiny spotwhere there is noteworthy solar irradiation. This system issupplying to a farm located in Wadi El natron,Egypt which is blessed withhigh intensity of sun shine, as figure 2 depicts, where itreaches 7.049 kWh/$m^2$/day as the monthly average solarirradiation. We assumed off-grid and completelyindependent system and sizing using two softwares.

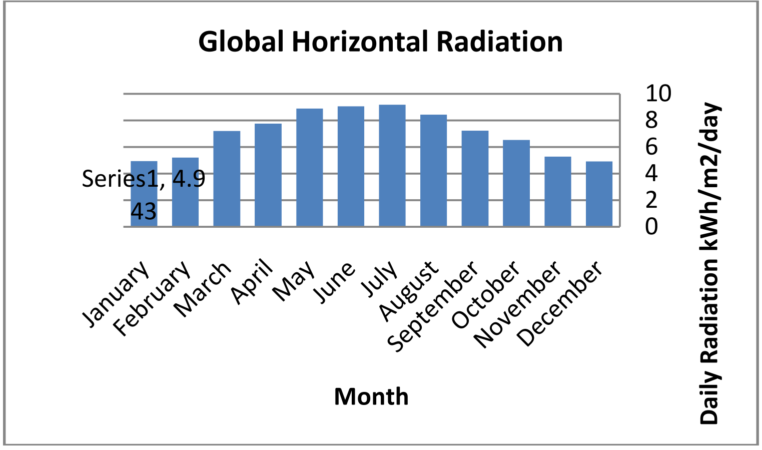


**Fig. 2** Monthly average solar irradiation in Wadi El Natron, Egypt.

## 3. SOLAR WATER PUMPING SYSTEM SIZING METHODOLGY

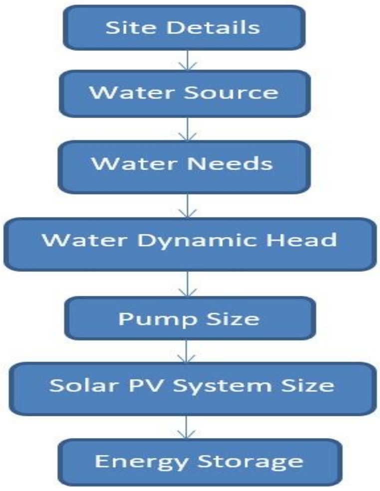


**Fig. 3** Flowchart of solar water pumping system sizing

-**Water Demand**: In this study, a large-scale solar powered water pumping system has been designed for an average farm located in Wadi El natron, Egypt. The required amount of water is estimated to be 500 $m^3$/day as an average daily demand. The layout of such system is shown below.

-**Water Dynamic Head:** The total head includes the distance from pump level tothe tank as well as the fraction of elbows. As shown below, the total head dynamic is :

THD = 155 m (vertical) + [(1.8 x 3 elbows) + 20 m] x 20% + 4 m (vertical) = 164.08 m

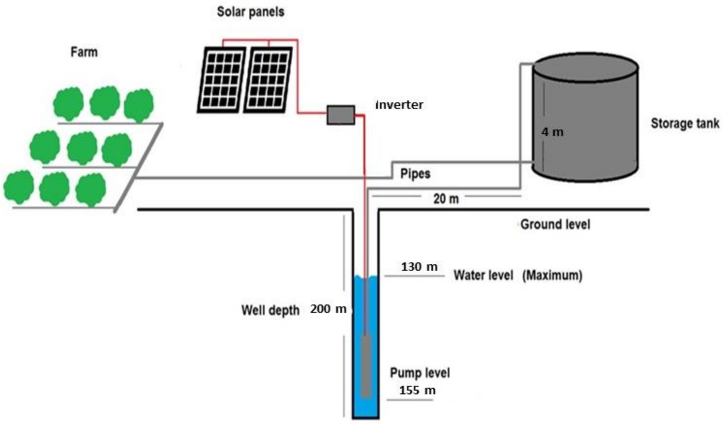


**Fig. 4** The layout of 500 $m^3$/day solar powered water pumping system

## 4. OPTIMIZATION OF SYSTEM SIZING USING PVsyst

To start sizing such a system, the pump size is an important aspect that needs to be assessed. As the total head and water demand are known for a farm, the pump size calculation is forthright, and can be completed using thefollowing expression.

$$P_{hyd} = \rho gHQ \quad (W) \tag{1}$$

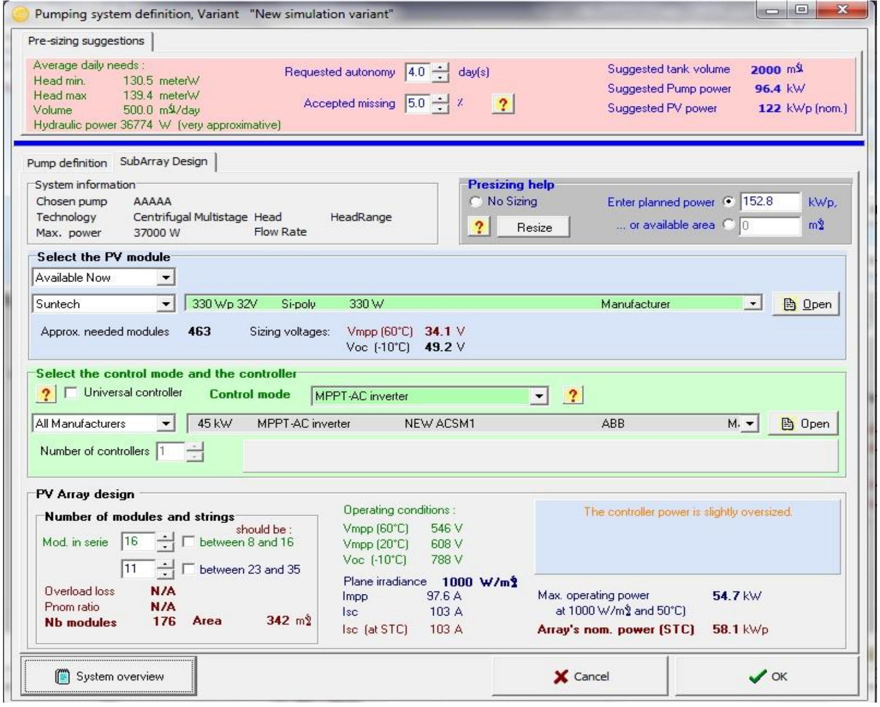
$$P = \frac{\rho gHQ}{\eta} \tag{2}$$

Where :

$\rho$ is the density of water (1000 kg/$m^3$), g is the gravitional acceleration (9.81 m/$s^2$), H is the total head (m) Q is the volumetric flow rate of water ($m^3$/s), and η pump efficiency(80%) .

Results from equations1, 2 show that the calculated pump size is 33.5 kW which can deliver the required amount of water.

Load has been inserted into PVsyst as shown in figure 5.It can be noticed that the pump runs for 8 hours per dayfrom 9 am to 5 pm. The aim is to utilize it as much aspossible, in daylight, particularly during the peak time from10 am to 6 pm.



Average daily needs :
Head min. 130.5 meterW
Head max 139.4 meterW
Volume 500.0 m³/day
Hydraulic power 36774 W (very approximative)

Requested autonomy 4.0 day(s)
Accepted missing 5.0 %

Suggested tank volume **2000** m³
Suggested Pump power **96.4** kW
Suggested PV power **122** kWp (nom.)

System information
Chosen pump AAAAA
Technology Centrifugal Multistage Head HeadRange
Max. power 37000 W Flow Rate

**Presizing help**
○ No Sizing
Enter planned power ● 152.8 kWp,
... or available area ○ 0 m²

**Select the PV module**
Available Now
Suntech
330 Wp 32V Si-poly 330 W Manufacturer
Approx. needed modules **463**
Sizing voltages: Vmpp (60°C) **34.1** V
Voc (-10°C) **49.2** V

**Select the control mode and the controller**
☐ Universal controller
**Control mode** MPPT-AC inverter
All Manufacturers
45 kW MPPT-AC inverter NEW ACSM1 ABB M.
Number of controllers 1

**PV Array design**
**Number of modules and strings**
should be :
Mod. in serie 16 ☐ between 8 and 16
11 ☐ between 23 and 35
Overload loss **N/A**
Pnom ratio **N/A**
**Nb modules** **176** **Area** **342** m²

Operating conditions :
Vmpp (60°C) 546 V
Vmpp (20°C) 608 V
Voc (-10°C) 788 V
Plane irradiance **1000 W/m²**
Impp 97.6 A
Isc 103 A
Isc (at STC) 103 A

The controller power is slightly oversized.

Max. operating power **54.7** kW
at 1000 W/m² and 50°C)
**Array's nom. power (STC)** **58.1** kWp

**Fig. 5** Screenshot of PVsyst the simulation parameters and sizing suggestions

Figure 5 shows the parameters of the selected system in PVsyst which The PV size is 124 kW and pump size is 98.1 kW. As mentioned before, the pump size was 33.5 kW, which is not matching with suggested pump power. However, actually, we recommended the right pump to the honor, but he insisted on the small pump that he already had before.

## 5. SYSTEM MODELINGDESCRIPTION

A standalone 58 kW solar powered water pumping systemis designed .Such system is a DC coupled consists of 176 PV modules, maximum power point tracker (MPPT), DC-DC boost converter, DC-AC Inverter and AC water pump as shown in figure 6.

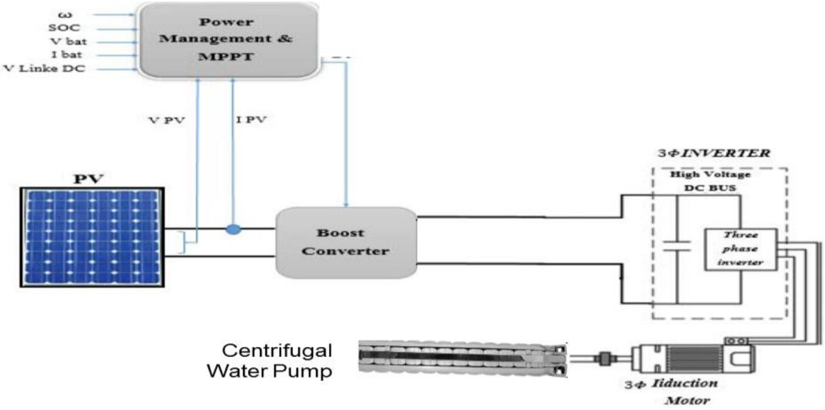


Fig. 6. The block diagram of the proposed system.

### 5.1. Modeling of PV Module

The specifications in table 1 for a 330W PV module havebeen used as well as the equations 3-6 to build such modulebased on the equivalent circuit of solar cell shown below infigure 7.

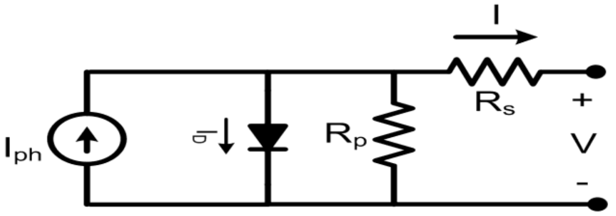


**Fig. 7** The equivalent circuit of solar cell

**Table -1 Solar PV Module Specifications**

| | **Electrical Characteristics** |
|---|---|
| 330 W | Rated Power |
| 37.5 V | Voltage at Maximum power (Vmp) |
| 8.81 A | Current at Maximum power ( Imp) |
| 46.2 V | Open circuit voltage ( VOC) |
| 9.38 A | Short circuit current ( ISCr) |
| 12 | Total number of cells in series (Ns) |
| 6 | Total number of strings in parallel (Np) |
| 45±2°C | Nominal Operating Cell Temperature (NOCT) |
| -0.41 %/°C | Temperature Coefficient of Pmax |
| -0.33 %/°C | Temperature Coefficient of Voc |
| 0.067 %/°C | Temperature Coefficient of Isc |

$$I = I_{ph} - I_{D1} - I_{D2} - \frac{V+IR_s}{R_p} \qquad (3)$$

$$I_{D1} = I_{o1}\left[exp\left(\frac{q(V+IR_s)}{akT}\right) - 1\right] \qquad (4)$$

$$I_{D1} = I_{o2}\left[exp\left(\frac{q(V+IR_s)}{akT}\right) - 1\right] \qquad (5)$$

$$I = I_{ph} - I_o\left[exp\left(\frac{q(V+IR_s)}{akT}\right) - 1\right] - \frac{V+IR_s}{R_p} \qquad (6)$$

### 5.2. Modeling of DC-DC Boost Converter

This part illustrates the design of DC-DC boost converter based on Matlab/Simulink. It helps regulating voltage of PV array to a fixed high level voltage which is going to meet the demand of 380V water pump.

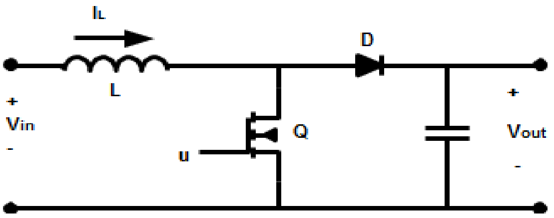


**Fig. 8** The block diagram of DC-DC boost converter.

$$\frac{V_{out}}{V_{in}} = \frac{t_{on}+t_{off}}{t_{off}} = \frac{1}{1-d} \quad ;Where\ d = duty\ cycle \tag{7}$$

the inductor ripple current

$$\Delta IL = 1.75\% \text{ X } Iout(max) \text{ X} \frac{V_{out}}{V_{in}} \tag{8}$$

$$L = \frac{V_{in}\ X\ (V_{out} - V_{in})}{\Delta IL\ X\ FsX\, V_{out}} \tag{9}$$

MPPT is commonly used to increase the efficiency of PVsystems. It operates in very high frequency, usually from 20 to80 kHz. The reason behind that is it converts DC to DC tooperate PV at MPPT. High frequency circuit works as a largetransformer that allows boosting voltage and current to thedesirable values, thus, meeting the voltage demand of waterpump and a controller.

PV voltage and current regulated to MPP by P&O algorithmas shown in figure 10 and the flow chart in figure 9.

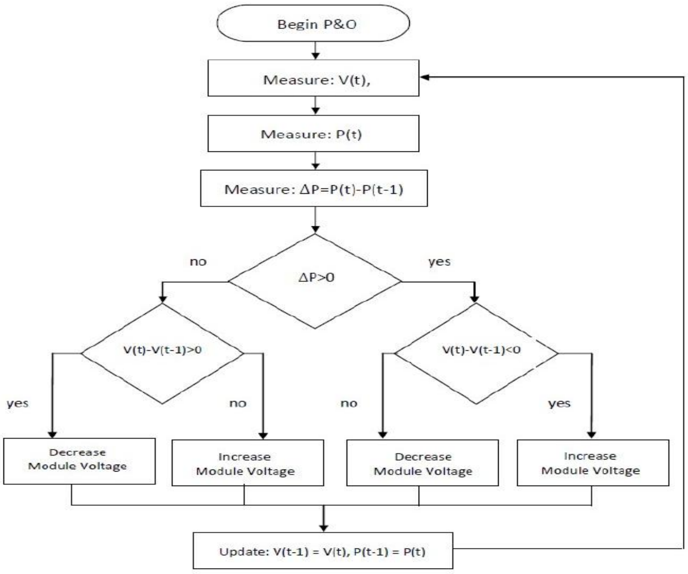


**Fig. 9** Perturbation and observation method algorithm.

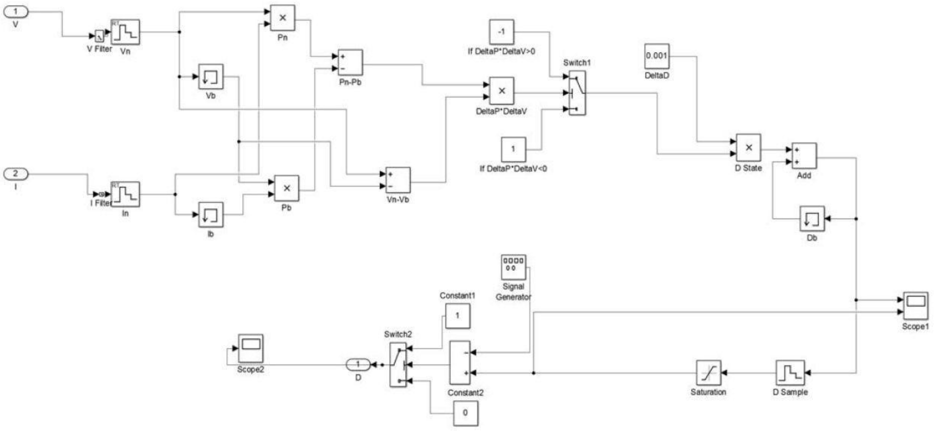


**Fig. 10** P&O algorithm implementation

### 5.3. Modeling of DC-AC Inverter

Voltage source inverters (VSI) are mainly used to convert a constant DC voltage into 3-phase AC voltages with variable magnitude and frequency. The inverter is composed of six switches S1 through S6 with each phase output connected to the middle of each “inverter leg”. Two switches in each phase are used to construct one leg. The AC output voltage from the inverter is obtained by controlling the semiconductor switches ON and OFF to generate the desired output. Pulse width modulation (PWM) techniques are widely used to perform this task. In the simplest form, three reference signals are compared to a high frequency carrier waveform. The result of that comparison in each leg is used to turn the switches ON or OFF. This technique is referred to as sinusoidal pulse width modulation (SPWM). It should be noted that the switches in each leg should be operated interchangeably, in order not to cause a short circuit of the DC supply.

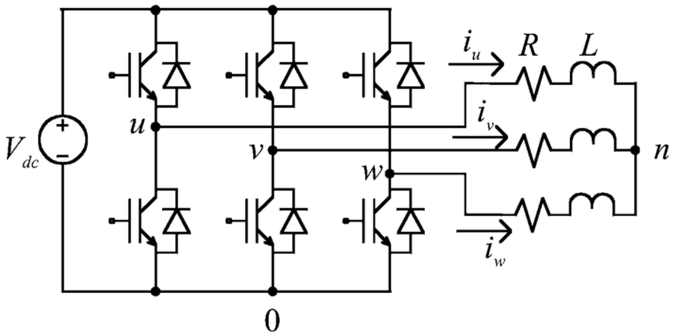


**Fig. 11** The block diagram of DC-AC Inverter

### 5.4. Modeling AC Motor and Centrifugal Pump

A 37 kW AC motor connected to a centrifugal pump hasbeen designed by Simulink to deliver 500 $m^3$ of water per day.

The AC motor and pump specifications are shown in table 2.

**Table- 2 Motor and Pump Specifications**

| AC Pump Specifications | | | | | |
|---|---|---|---|---|---|
| **TYPE** | **Impeller** | **Voltage (V)** | **Pump Power (W)** | **Max Flow ($m^3$/H)** | **Max Head (m)** |
| GRUNDFOS - SP | Centrifugal | 400 | 37000 | 60 | 300 |
| **AC Motor Specifications** | | | | | |
| **TYPE** | **Nominal Power (HP)** | **Voltage (V)** | **Frequency (Hz)** | **Nominal Speed (RPM)** | **Pole Pairs** |
| Three Phase Induction Motor | 50 | 400 | 50 | 2860 | 2 |

The equivalent circuit of the AC motor has been modeled in Simulink as shown in figure 12. (simscape blocks)

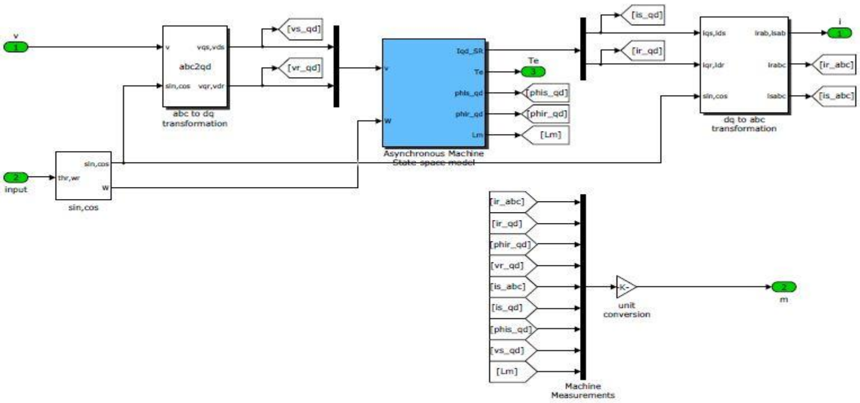
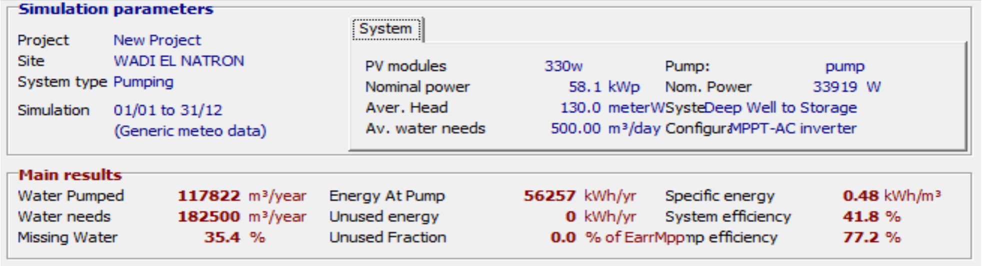


**Fig. 12** AC motor simulation in Simulink.

## 6. SIMULATION RESULTS AND DISCUSSIONS

### 6.1 Results of PVsyst Software


**Simulation parameters**

Project New Project
Site WADI EL NATRON
System type Pumping
Simulation 01/01 to 31/12
(Generic meteo data)

System

| | | | |
|---|---|---|---|
| PV modules | 330w | Pump: | pump |
| Nominal power | 58.1 kWp | Nom. Power | 33919 W |
| Aver. Head | 130.0 meter | WSyste | Deep Well to Storage |
| Av. water needs | 500.00 m³/day | Configura | MPPT-AC inverter |

**Main results**

| | | | | | |
|---|---|---|---|---|---|
| Water Pumped | **117822** m³/year | Energy At Pump | **56257** kWh/yr | Specific energy | **0.48** kWh/m³ |
| Water needs | **182500** m³/year | Unused energy | **0** kWh/yr | System efficiency | **41.8** % |
| Missing Water | **35.4** % | Unused Fraction | **0.0** % of Earr | Mpp mp efficiency | **77.2** % |

**Fig. 13** Screenshot of PVsyst the main results and the simulation parameters

The pumps' sizes were somewhat different due to the limitations in PVsyst software, which only offers fixed sizes, however, the sizes were not too different. The selected pumps were Grundfos with 700 V nominal voltage and 86A nominal current.

PV power outputs and energy were changing every month. As shown in figure 14, the peak of power output happened in June, July, and August, while the least happened in January and December.

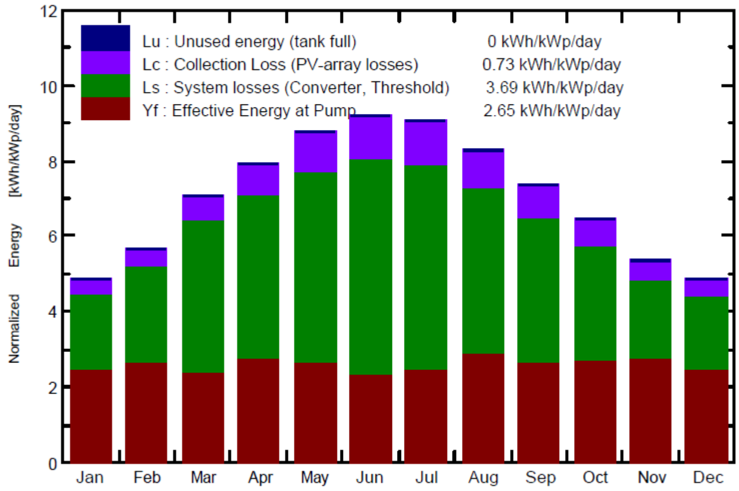


**Fig. 14** Normalized productions (per installed kWp)

The possibility of having cloudy days are taken into account. For example, in January and July presented in Figs. 15 and 16 the results of the Algorithm for July clear that is the most critical month forthe crops irrigation and the amount all the stored energy is consumed.

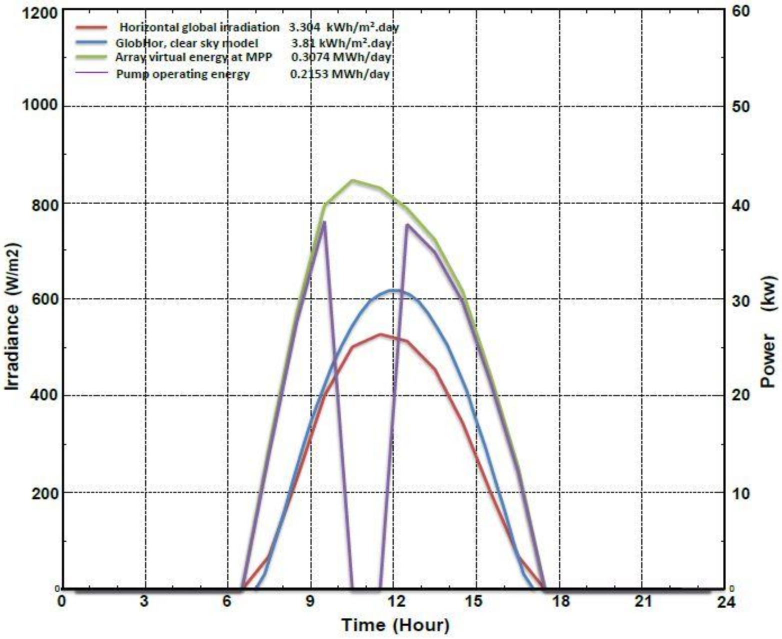


**Fig. 15** Irradiation, array and pump energy over one day in January

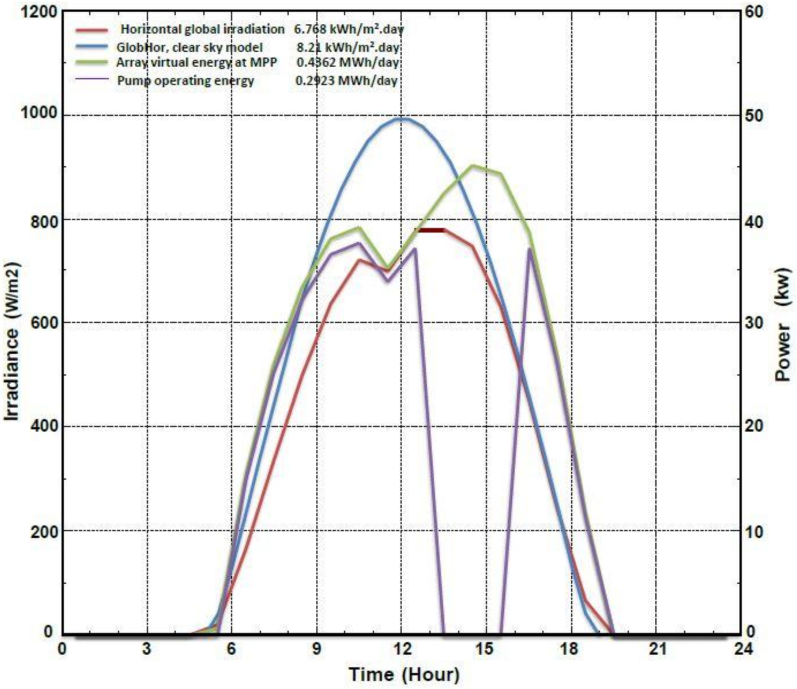


**Fig. 16** Irradiation , array and pump energy over one day in July

### 6.2. Results of Simulation

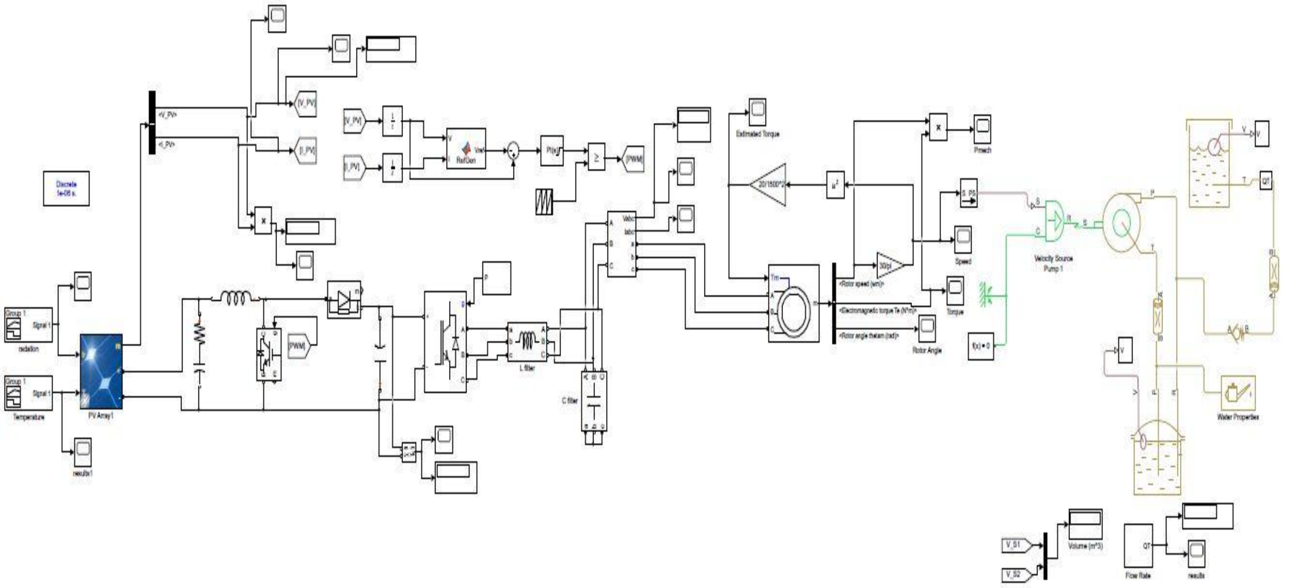


**Fig. 17** The proposed system model in Simulink

The complete model of solar water pumping system whichis based on Simulink is shown below in figure 17. Simulationresults have shown that the output power is changingcorresponding with the irradiation and temperature variationwith the MPPT and boost converter as figure 18,19,20and21. Also, increasing in temperature directly affects the PVoutput as it goes down, while decreasing in temperatureimproves the performance of the PV array. Moreover, as figure 22 illustrates, the flow rate requirement which is the system output was being fulfilled.

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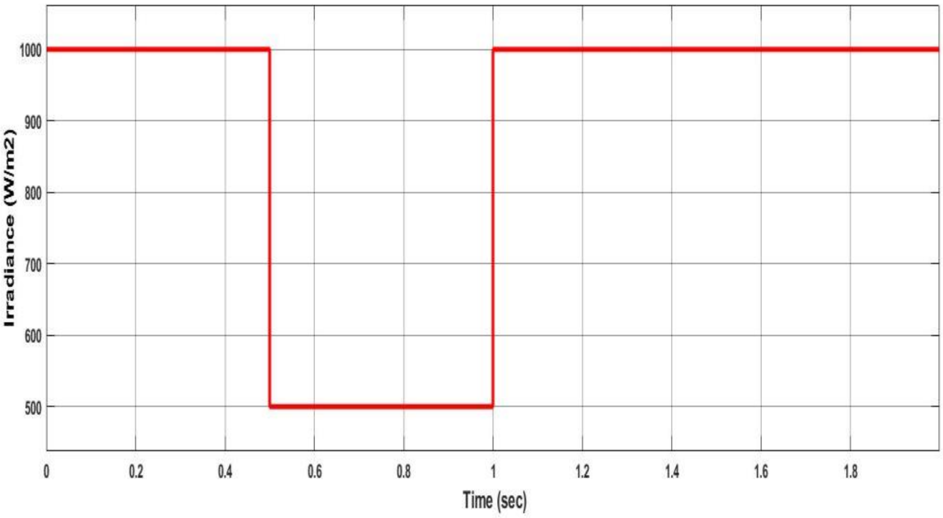

**Fig. 18** Simulation results of step irradiation PO MPPT (a) Solar Irradiation

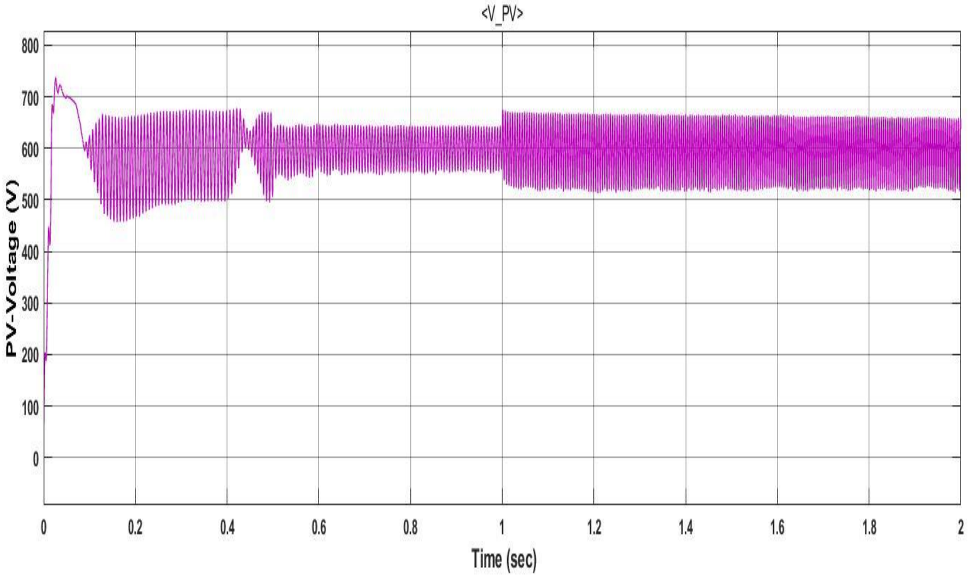

**Fig. 19** Simulation results of step irradiation PO MPPT (b) Terminal voltage of thearray

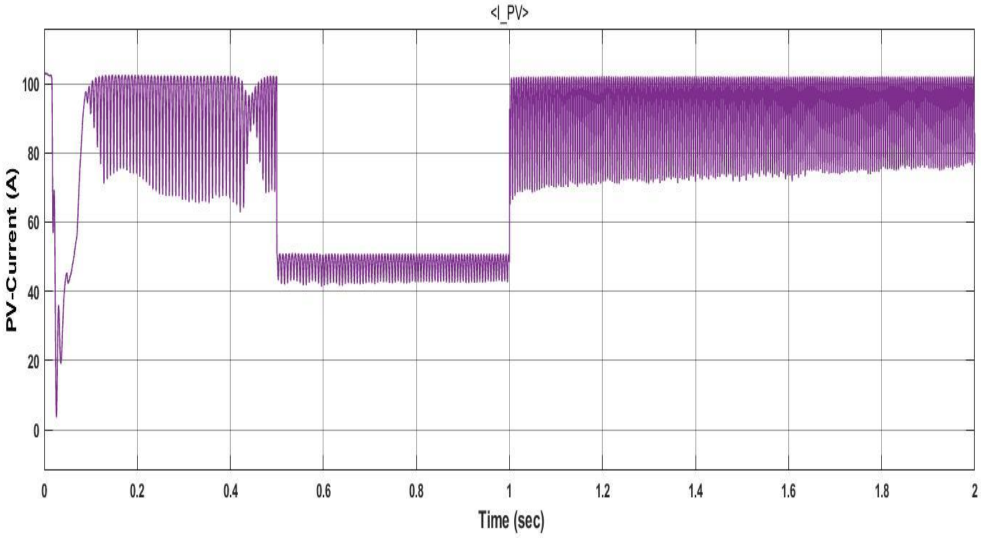

**Fig. 20** Simulation results of step irradiation PO MPPT (c) Terminal current of the array

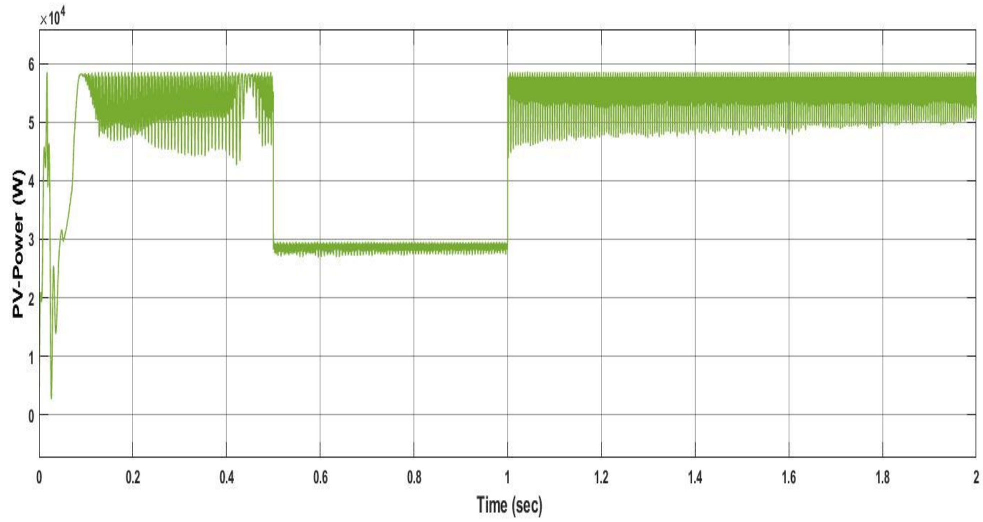

**Fig. 21** Simulation results of step irradiation PO MPPT (d) DC power output of the PV array

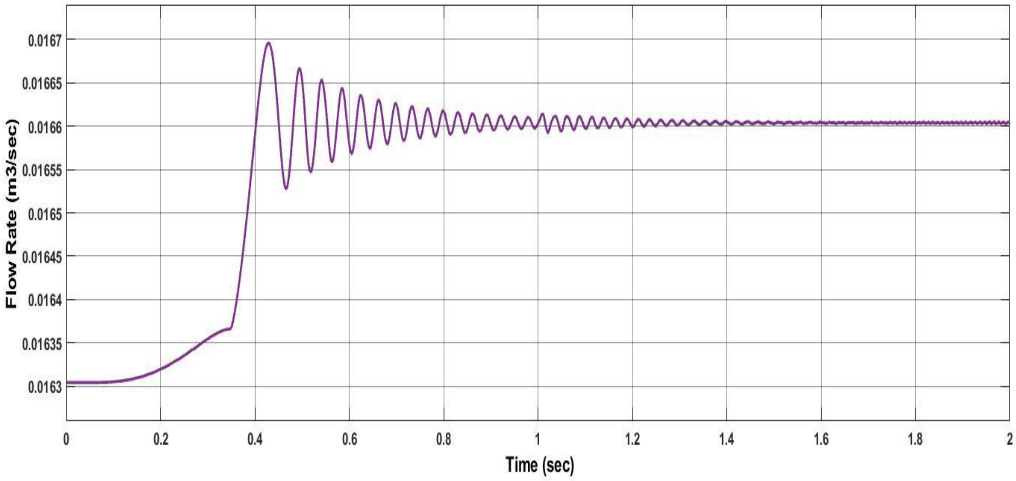

**Fig. 22** Flow rate, 0.0166 $m^3$/s

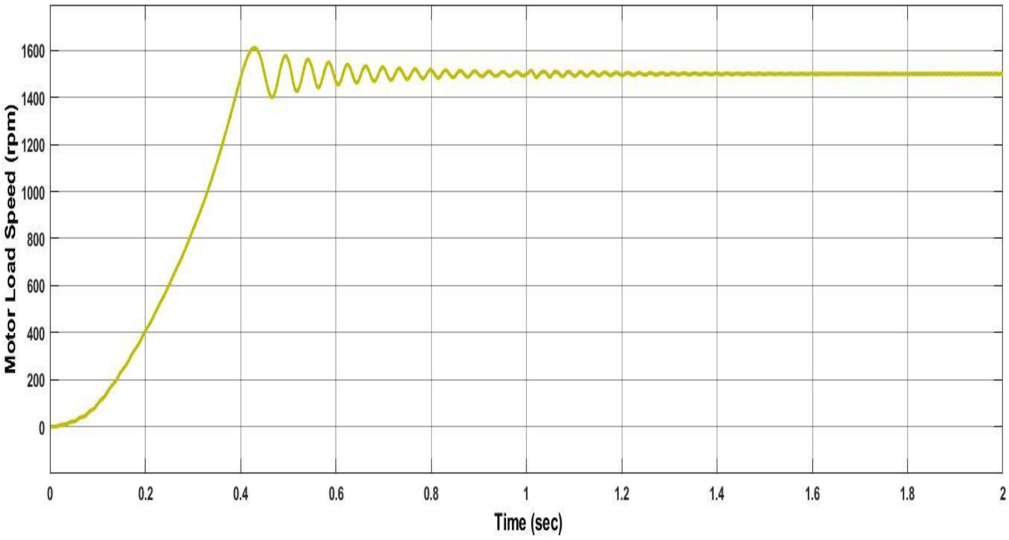

**Fig. 23** Motor load speed, 1480 rpm.

## 7. SIMULATION RESULTS AND DISCUSSIONS

This study has shown dynamic modeling of a large scale solar powered water pumping system which is fed by 58 kWPV source. The system simulation has been investigated andcarried out using Matlab/Simulink, thus, it was shownsatisfactory results. Dynamic results indicate that MPPTalgorithm for DC-DC converter and controller are able to achieve the objective for a variation in the input temperature and input solar irradiance.

Moreover, the feasibility of using such system in Egypt is much higher than any elsewhere since there is an enormoussolar resources available. Even though the study only focusedon one location which is Wadi Elnatron which is a moderate spot, there are some regions in Egypt have higher total solar radiation suchas southern area [10].

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