International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 14, No. 4, December 2023, pp. 2409~2417
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v14.i4.pp2409-2417

Simulation analysis of DC motor based solar water pumping system for agriculture applications in Rural areas

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Article Info

Article history:

Received Feb 9, 2023
Revised Jun 11, 2023
Accepted Jun 25, 2023

Keywords:

Centrifugal pump
Incremental conductance
Maximum power point tracking
Permanent magnet DC motor
Solar water pump

ABSTRACT

Solar photovoltaic (PV) generators for agriculture purposes offer a practical alternative over traditional electric and diesel-based water pumps due to their low cost, sustainable and eco-friendly nature. These systems are suitable for remote locations in case of unreachable power grid. However, the operation of these generators is affected by various factor such weather status This article proposes a photovoltaic water pumping system (PVWPS) to drive a centrifugal pump using a permanent magnet DC motor (PMDC). Additionally, a boost converter for extracting the maximum power from PV panels was used in the system and an Incremental conductance (IC) algorithm was chosen in the controller circuit. The system was implemented and investigated using MATLAB/Simulink at various irradiance values (i.e., 400, 600, 800 and 1000) w/m^2. The results indicate that the efficiency of the proposed system is higher than 90% at all selected irradiance values proven that the integration of PV array with water pumping system without any energy storage devices is applicable at a daytime.

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1. INTRODUCTION

The field of renewable energy technologies has gained more attention in recent year for several reasons such as positive environmental effects, sustainable and inexpensive for long term. On the other hand, water-transferring requirements in remote areas for agriculture projects might be covered using traditional energy generators such as diesel generators. However, these power generators have some drawbacks if compared to renewable energy types, i.e. these generators are a source of pollution and require to be maintained continuously [1], [2].

Nowadays, several forms of renewable energy are available and applied widely such as solar energy, wind energy and bioenergy. The field of PV panel as one form of solar energy generators has taken a great deal of attention by manufacturers in recent year [3]. The operation of PV generators depends on weather conditions such as the temperature and solar radiation to achieve the maximum efficiency [4], [5]. In other words, the relation between the voltage and current of these panels is non-linear. Therefore, they need to be controlled effectively [6], [7].

Induction motors are used in the field of water pumping using solar energy for several reasons, including their ease of manufacturing and cheapness. On other hands, these motor have some drawbacks, for instance high starting torque problem and they require a complex control system [8]–[10]. Therefore, DC motors can be an acceptable choice in case of direct integration with PV panels through DC-DC converter to be devoted to work in such applications [11], [12].

DC motors have utilized in various applications including robotics, medical devices, and the automobile industry. In addition, they can be applied in water pumping systems. Several topologies of dc motor are available and each type has its characteristics and applications. Regarding the construction, permanent magnet dc motor is simplest type. Infect, the field circuit of the motor is replaced by permanent magnets in the stator, which leads to simplicity in design. Additionally, it is efficient and the size of the motor is smaller than other types for the same rating [13], [14].

A power maximization algorithm is used to maximize the performance of the Solar PV array as integrated with DC-DC convertor to produce a required duty cycle [15], [16]. Several algorithms were proposed in the literature to track and extract the maximum power point (MPP) from PV array such as hill climbing algorithm and slide mode control [17]. Each approach has its features related to cost, efficiency, and implementation. Because of its accuracy of tracking under sudden changes in solar irradiation, the incremental conductance (INC) MPPT method is used in this work [18]–[20].

This article presents a PVWPS to express the ability of integration of PV panels with boost convertor using incremental conductance (IC) controller to drive a mechanical load represented by centrifugal pump load through PMDC motor. The system was implemented and tested using MATLAB/Simulink under several irradiance values at 25 ^{0}C and the efficiency was recorded for each case.

2. COMPONENTS OF THE PROPOSED SYSTEM

The proposed system of PVWPS as shown in Figure 1 includes four power components as well as the MPPT controller. The power components are the solar panels, the boost converter, the PMDC motor and a centrifugal pump. A description of each component is explained in this section.

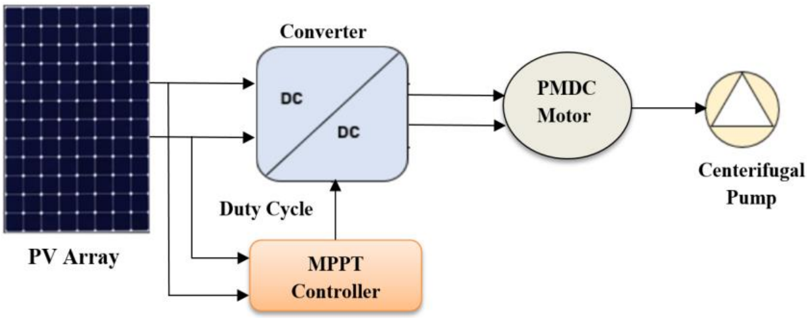


Figure 1. Block diagram of proposed work

2.1. PV array characteristics

The main element of each PV panel is the photovoltaic cell which converts the solar energy to electrical energy. The electrical model of PV cell is shown in Figure 2, contains a diode which is a nonlinear device, the series and parallel resistors (R_{ser} and R_{par} respectively) and the photocurrent source (I_c) [21], [22].

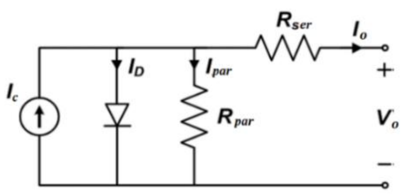


Figure 2. PV cell model

According to circuit theory analysis, the output current (I_o) produced by PV cell is,

$$I_o = I_c - I_{sat}\left[Exp(\frac{q(V_o+I_oR_{ser})}{n_D\,K\,T}) - 1\right] - (V_oR_{par} + I_oR_{ser}R_{par}) \quad (1)$$

where I_{sat} represents the diode saturation current, T is the temperature, V_o is the output voltage and both n_D and q are the ideality parameter of the diode and the electronic charge respectively.

It can be seen clearly from as (1) that the relation between the output voltage and output current of PV cell depends on the value of photocurrent and the temperature if all other parameters are assumed constants. In this work, a combination of series and parallel of Yangtze PV panels YS2500P-60 are used as the power source of the proposed system. The features of YS2500P-60 PV panel are listed in Table 1.

Table 1. Parameters of Yangtze YS250P-60 solar panel

Parameters	Value	Parameters	Value
(P_max) at STC	250 Wp	MPP Current (I_mpp)	9.18
(V_oc)	37.5	No. of series solar cells, (N_s)	60
(V_mpp)	30.5	Temp. Coeff. at I_sc	0.06
(I_sc)	8.85	Temp. Coeff. of at V_oc	-0.31

2.2. Step-up converter

For matching requirements of the power generated by solar panels with the load, a step-up converter (as shown in Figure 3) is utilized to maximize the efficiency of the design. In fact, the operation of such converter depends on switching principle which can be controlled by suitable MPPT controller [23], [24]. The conversion voltage ratio according to this type is:

$$\frac{V_{in}}{V_{out}} = \frac{1}{1-D} \tag{2}$$

where V_{in} , V_{out} are the input and output volages respectively and D is the duty cycle.

The parameters of the converter which is used in this work are listed in Table 2. The input capacitor (C_{in}) is added to force the converter to operate in continuous conduction mode (CCM). In other word, the inductor current must not reach zero value and that is important for the operation of MPPT controller.

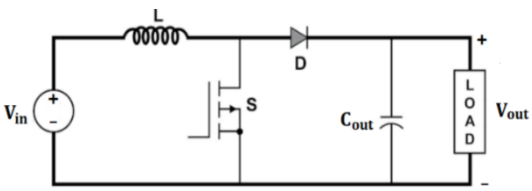


Figure 3. Step-up converter

Table 2. Parameters of step-up converter

Parameter	Value
Inductor (L)	0.0208 H
Input Capacitor (C_{in})	2.7488e-04 F 29
Output Capacitor (C_{out})	2.7488e-04 F

2.3. Incremental conductance (INC) MPPT technique

The incremental conductance (INC) approach is utilized in this work to track the maximum power point (MPP). Figure 4 represents the flow-graph of this technique and the relations in Table 3 and the (3) describe its operation [25], [26].

$$\frac{dP}{dv} = \frac{d(VI)}{dv} = I + V\frac{dI}{dv} \tag{3}$$

Table 3. Parameters of step-up converter

Relation	Explanation
$\frac{dP}{dV} = 0$	Max power point
$\frac{dP}{dV} > 0$	Left Max power point
$\frac{dP}{dV} < 0$	Right Max power point

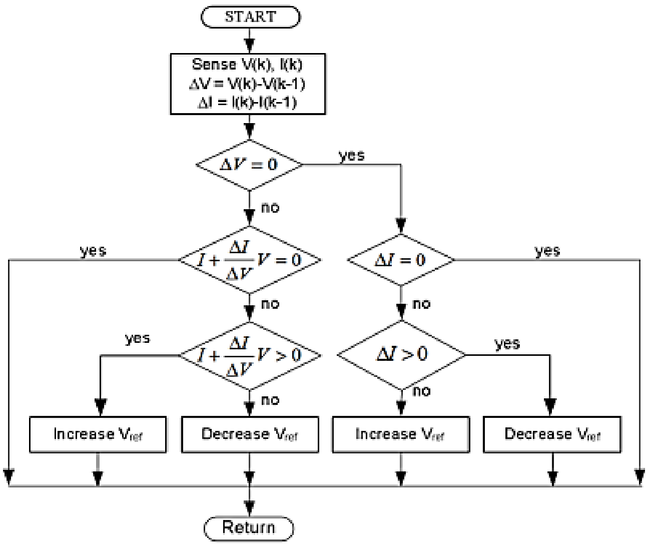


Figure 4. Incremental conductance approach for MPPT

2.4. Permanent magnet DC motor

Permanent magnet DC motors (PMDC) are applicable in several applications especially when integrated with PV solar panels. In fact, it can be powered directly by the DC power generated by the panels through a DC-DC converter without the need for additional components such as inverters. Furthermore, they offer an acceptable efficiency and starting torque when compared to other types [27]. However, the limited loading aspect of such motors is considered in this work due to the constant applied load that can be handled under low irradiance values. The (4)-(6) shows the relations of electrical and mechanical parameters of PMDC motor. As shown in Figure 5, the applied voltage (E) is a function of reverse electromotive force (E_r) and the current in armature windings (i_{ar}) as (4).

$$E = E_r - I_{ar}R_{ar} + L_{ar}\frac{di_{ar}}{d_t} \quad (4)$$

The motor E_r is determined as (5),

$$E_r = c_m\omega_m \quad (5)$$

where c_m and ω_m are the constant and the speed of the motor respectively. The electromechanical torque can be determined as (6).

$$T_{em} = c_m i_{ar} \quad (6)$$

The specifications of PMDC motor that is used in article are listed in Table 4.

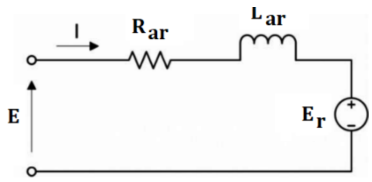


Figure 5. PMDC motor circuit diagram

Table 4. PMDC motor specifications

Parameter	Value
I_{Rated} (A)	9.2
E (Volt)	120
R_{ar} (Ω)	1.5
L_{ar} (H)	0.2
Moment of inertia (J) (Kg.m^2)	0.02365
Rated ω_m *(Rad/s)*	157.079
c_m *(Nm/A)*	0.67609

2.5. Centrifugal pump

Centrifugal pumps are commonly used in many applications such as irrigation systems for water transferring. The higher efficiency is key feature of these pumps over positive displacement pumps so it is used in this work. The pump is simulated using (7).

$$P = \frac{\rho Q g h}{Eff} \quad (7)$$

Where ρ is the density of water in kg/m^3, $Q$is the discharge of pump in m^3/sec, h refers to total hight in m, the gravity of acceleration in m2/sec is g and the effiency of the pump is Eff .

3. DISCUSSION OF SIMULATED RESULTS

The implementation of the proposed system is done using MATLAB/Simulink as shown in Figure 6. The measurements are recorded at the load and PV array at different irradiance values. The analysis of the readings is used to prove the ability of using such system efficiently at a day time without the usage of energy storage devices.

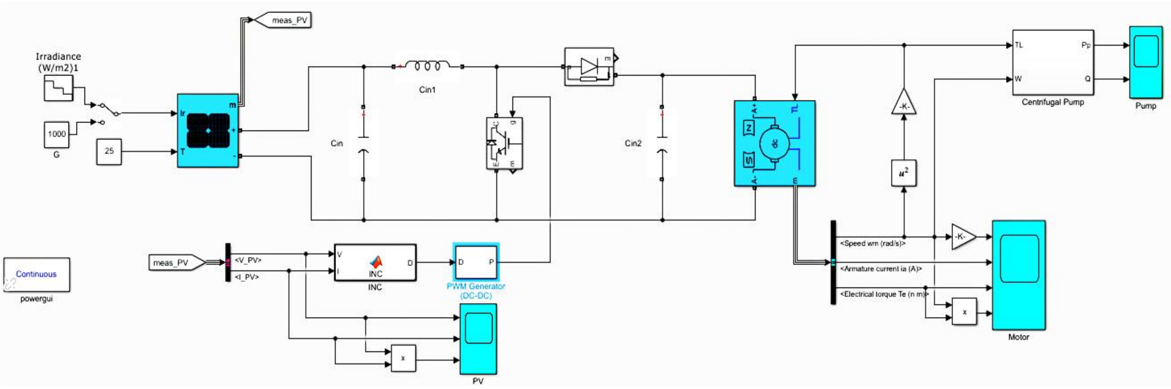


Figure 6. MATLAB/Simulink model of solar PWPS

3.1. PV array measurements

The measurements of PV array of the proposed design are shown in Figure 6 which include the voltage, the current and the power of the array under various irradiance values at 25 °C. The PV power and current change according to irradiance values (e.g., at 1000 W/m^2 the power is about 3000 W and the current is about 22 A while at 800 W/m^2, 600 W/m^2, 400 W/m^2 and 200 W/m^2 the power and currents are decreased accordingly as shown in Figures 7(a) and 7(b). However, as shown in Figure 7(c), the PV voltage is kept constant at around 150 V, validating the operation of the IC MPPT controller.

3.2. PMDM measurements

The speed, current, torque, and power measurements of PMDM at each irradiance value are shown in Figure 8. The speed of the motor changes proportionally with irradiance change. For instance, at 1000 W/m^2 irradiance the speed of the motor is about 1500 rpm while at 800 W/m^2 irradiance the speed decreased to about 1380 rpm as can be seen in Figure 8(a). Regarding the current of the motor, it can be concluded that the higher current is drawn under rated conditions, the higher irradiance is applied as shown in Figure 8(b). The motor current range at all selected irradiance values is about (3-8) A. The effect of changing irradiance to the motor torque is shown in Figure 8(c). The highest torque which is about 20 Nm releases form the motor at 1000 W/m^2 irradiance and decreases as the irradiance decrease to reach the lowest value of about 8 Nm at 200 W/m^2 irradiance. The motor power as can be seen in Figure 8(d) changes proportionally with the irradiance. For instance, the power is about 3000 W at 1000 W/m^2 irradiance while it decreases to less than 2000 W at 600 W/m^2 irradiance. As expected, all the measured parameters of PMDM are reduced as the irradiance decreases.

3.3. Centrifugal pump measurements

Both the power and discharge of centrifugal pump as irradiance changes from 1000 W/m^2 to 200 W/m^2 in steps of 200 W/m^2 are measured as shown in Figure 9. At 1000 W/m^2 irradiance the power of centrifugal pump is about 2400 W as can be seen in Figure 9(a) and the discharge of the pump is about 3.7 lit/sec as can be noticed in Figure 9(b). As the irradiance decreases, both the power and discharge of the pump decrease. The lowest values of such measurements occur at 200 W/m^2 irradiance (e.g., the pump power value is about 500 W while the discharge of the pump is about 0.7 lit/sec).

3.4. Efficiency of the system

The PV power that supplies the system and the load power (pump power) as shown in Figure 10(a) are used to calculate the efficiency of the proposed design under various irradiance values. It can be seen from Figure 10(b) that the efficiency is greater than 90% at all irradiance values, demonstrating the capability of direct integration of a PV array with a water pumping system during the day without the use of any energy storage system such as batteries.

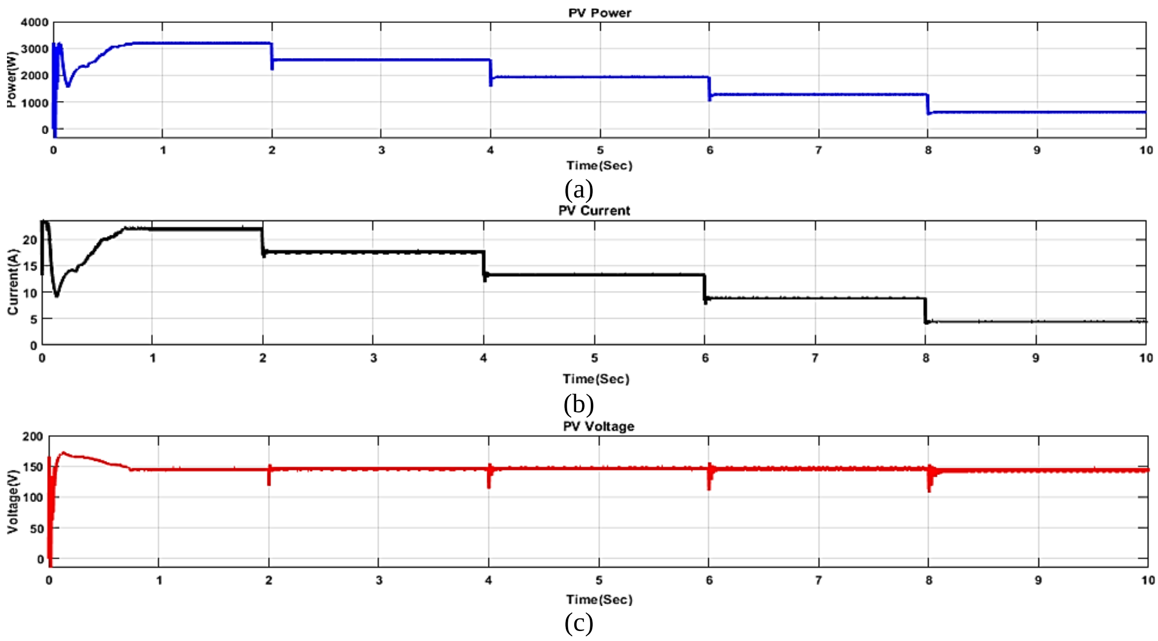


Figure 7. Output of PV under (STC) and varying solar irradiance: (a) PV power, (b) PV current, and (c) PV voltage

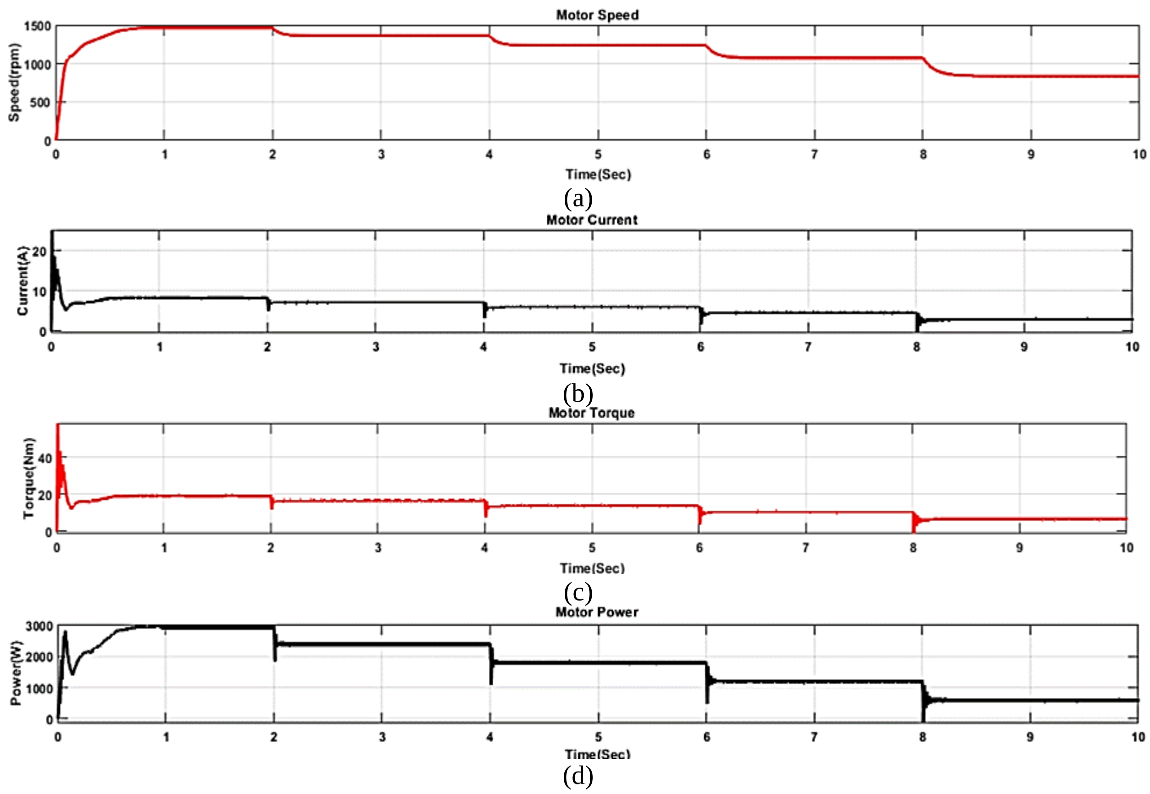
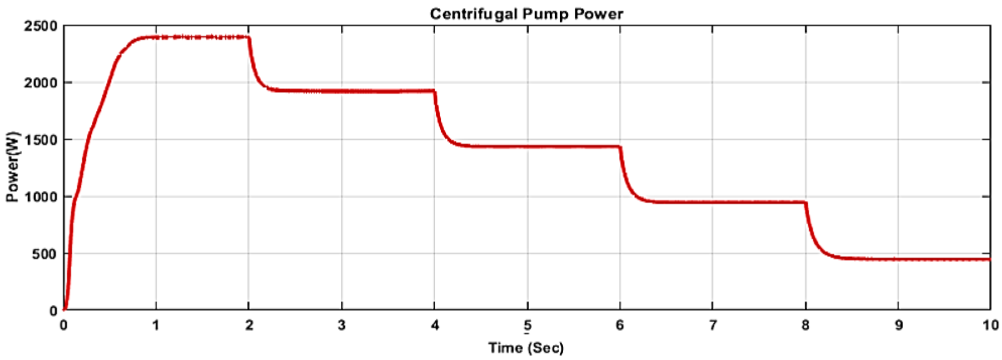
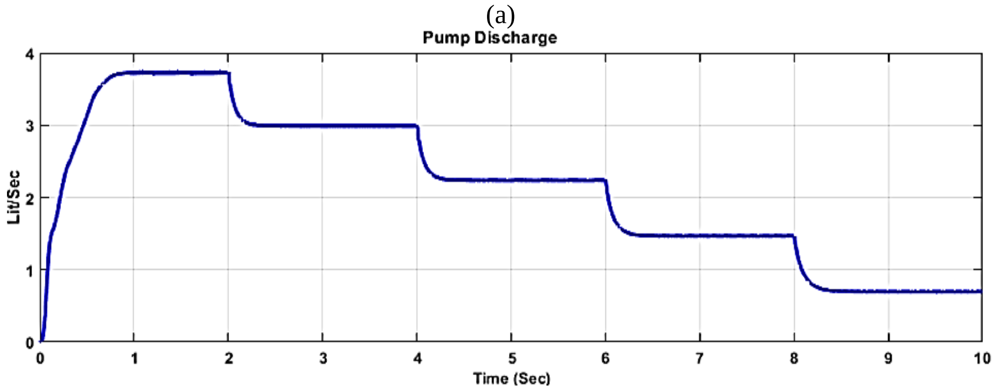


Figure 8. Output of PMDC motor: (a) motor speed, (b) motor current, (c) motor torque, and (d) motor power

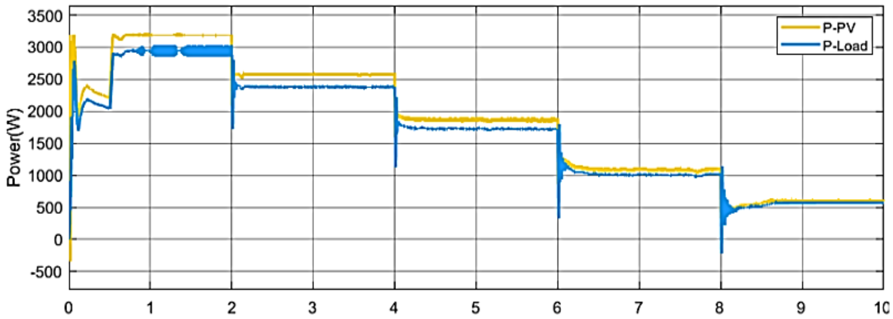


(a)

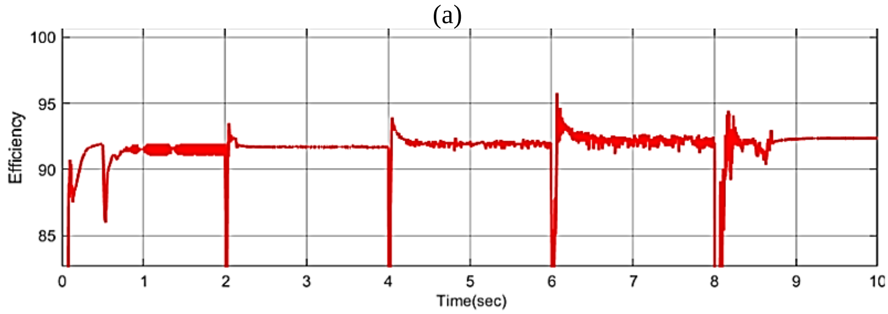


(b)

Figure 9. Output of centrifugal pump: (a) centrifugal pump power and (b) centrifugal pump discharge



(a)



(b)

Figure 10. Power and efficiency of proposed design: (a) PV power, load power and (b) efficiency

4. CONCLUSION

A solar water pumping system is proposed and implemented in this work using MATLAB/Simulink. The system includes PV array, step-up converter, PMDM and the centrifugal pump as a load. An IC MPPT technique is used to extract the maximum power from PV array at various irradiance values at 25 ˚C. The irradiance values were chosen to cover most of expected conditions at a day time; i.e., at standard conditions

(1000 W/m^2) and at variable irradiance values (800 W/m^2, 600 W/m^2, 400 W/m^2 and 200 W/m^2). At standard test conditions, the solar array generates about 3000 W to power the system with discharge of 4lit/sec while at other irradiance values; as expected, the discharge of centrifugal pump decreases as irradiance decreases. The smallest discharge value of 0.7lit/sec is reached at 200 W/m^2. The efficiency of the system at all irradiance values is higher than 90%. The proposed work validates the use of PV array to supply an acceptable electrical power to water pumping system at a day time without any energy storage systems such as batteries which lead to reduce the cost and complexity.

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