Optimum Operation of Direct Coupled Photovoltaic-Water Pumping Systems

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---**ABSTRACT**---

The use of photovoltaics as the power source for pumping water is one of the most promising areas in photovoltaic applications. Photovoltaic powered water pumping systems require only that there be enough sunshine and a source of water which is adequate for many developing countries. Solar direct pumping systems are simple and less complex than battery systems. This paper presents a new design and simulation of a simple but efficient photovoltaic water pumping system using Matlab program. The maximum power point tracker (MPPT) is designed and simulated using actual irradiance data. The DC pump motor is modeled using Simulink and the model is then transferred into Matlab, so that the whole system is simulated in Matlab environment. The algorithms are tested with actual irradiance data in Kuwait. The simulations verify the system and functionality of MPPT. Simulations also make comparisons for the system without MPPT in terms of total energy produced and total volume of water pumped per day. The results validate that MPPT can significantly increase the efficiency and the performance of PV water pumping system compared to the system without MPPT.

Keywords: *Photovoltaic – Renewable energy - Solar Cell*

I. Introduction

Water resources are essential for satisfying human needs, protecting health, and ensuring food production, energy and the restoration of ecosystems, as well as for social and economic development and for sustainable development. There is a great and urgent need to supply environmentally sound technology for the provision of drinking water. Remote water pumping systems are a key component in meeting this need. It will also be the first stage of the purification and desalination plants to produce potable water.

In this paper, a simple and efficient photovoltaic water pumping system is presented. It provides modeling of PV and investigates in detail the maximum power point tracker (MPPT), a power electronic device that significantly increases the system efficiency. It presents Matlab simulations of the system and makes comparisons with a system without MPPT. Each subsystem in the PV water pumping system is modeled for Matlab simulations. Finally, the functionality of MPPT for water pumping systems is verified and validated.

II. The Proposed System

The water pumping system proposed in this paper is a stand-alone direct coupled system without backup batteries. As shown in Figure 1, the system consists of a PV module, a maximum power point tracker (MPPT), and a DC water pump. The following items explain in details each of these subsystems. The system including the subsystems will be simulated to verify the functionalities.
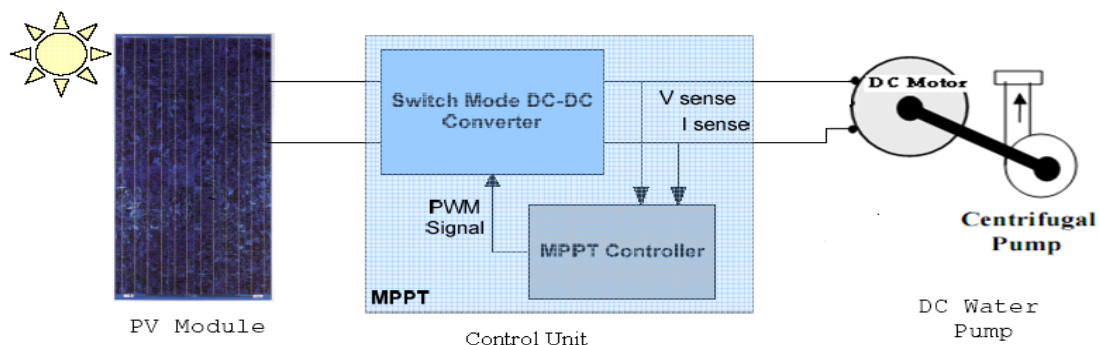

Figure 1: Block diagram of the proposed PV water pumping system

III. Modeling of PV Solar Cell

The PV cell can be modeled as an equivalent electric circuit. The use of equivalent electric circuits makes it possible to model characteristics of a PV cell and consequently the PV module. The simplest model of a PV cell is assumed as an equivalent circuit that consists of an ideal current source in parallel with an ideal diode. The current source represents the current generated by photons (often denoted as I_{ph} or I_L), and its output is constant under constant temperature and constant incident radiation of light. In a practical PV cell, there is a series of resistance in a current path through the semiconductor material, the metal grid, contacts, and current collecting bus. These resistive losses are lumped together as a series resister (R_s). There is also called a parallel or shunt resistance, which associated with a small leakage of current through a resistive path in parallel R_p with the intrinsic device [1].

3.1 PV Mathematical Model

The electric model used in this study is shown in the Figure 2, and provides fairly accurate results. The model consists of a current source (I_{sc}), a diode (D), and a series resistance (R_s). The effect of parallel resistance (R_p) is very small, thus the model does not include it. To make a better model, it also includes temperature effects on the short-circuit current (I_{sc}) and the reverse saturation current of diode (I_o). It uses a single diode with the diode ideality factor (*n*) set to achieve the best *I-V* curve match ("*n*" is sometimes denoted as "*A*" and takes the value between 1 and 2) [2].
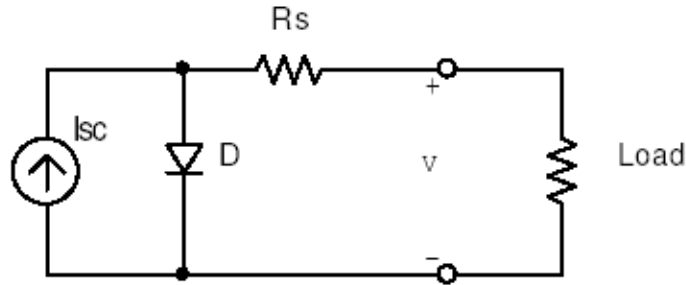

Figure 2: Equivalent circuit used in the MATLAB simulations

The following equation describes the current-voltage relationship of the PV cell [1]:

$$I = I_{sc} - I_o \left[e^{q\left(\frac{V+I \cdot R_s}{nkT}\right)} - 1 \right]$$

(1)

where:

I cell current (*the same as the module current*),
V cell voltage = *{module voltage} ÷ {Number of cells in series}*,
T cell temperature in *Kelvin* (*K*),
q electron charge (1.602×10^{19}C),
k Boltzmann's constant (1.381×10^{23} J/K).

First, calculate the short-circuit current (I_{sc}) at a given cell temperature (T):

$$I_{sc}\big|_T = I_{sc}\big|_{T_{ref}} \cdot \left[1 + a\left(T - T_{ref}\right)\right]$$

(2)

where:

T_{ref} is the reference temperature of PV cell (*K*), usually 298 *K*,
a is the temperature coefficient of I_{sc} in percent change per degree temperature also given in the datasheet.

The short-circuit current (I_{sc}) is proportional to the intensity of irradiance, thus I_{sc} at a given irradiance (G) is:

$$I_{sc}\big|_G = \left(\frac{G}{G_o}\right) I_{sc}\big|_{Go}$$

(3)

where: G_o is the nominal value of irradiance, which is normally 1 KW/m^2.

The reverse saturation current of diode (I_o) at the reference temperature (T_{ref}) is given by the following equation with the diode ideality factor added:

$$I_o = \frac{I_{sc}}{(e^{qV_{oc}/nkT} - 1)}$$

(4)

The reverse saturation current (I_o) is temperature dependant and the I_o at a given temperature (T) is calculated by the following equation:

$$I_o \mid_T = I_o \mid_{T_{ref}} \cdot \left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}} \cdot e^{\frac{-q \cdot E_g}{n \cdot k}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)}$$

(5)

The equation for R_s is derived by differentiating the equation (1) and then rearranging it in terms of R_s [3]:

$$R_s = -\frac{dI}{dV} - \frac{nkT/q}{I_o \cdot e^{q\left(\frac{V+I \cdot R_s}{nkT}\right)}}$$

(6)

Then, evaluate the last equation at the open circuit voltage that is $V = V_{oc}$ (also let $I=0$).

$$R_s = -\frac{dV}{dI}\bigg|_{V_{oc}} - \frac{nkT/q}{I_o \cdot e^{\frac{qV_{oc}}{nkT}}}$$

(7)

where:

$\dfrac{dV}{dI}\bigg|_{V_{oc}}$ is the slope of the *I-V* curve at the *Voc* (use the *I-V* curve in the datasheet then divide it by the number of cells in series),

V_{oc} is the open-circuit voltage of cell (found by dividing V_{oc} in the datasheet by the number of cells in series).

3.2 PV Model Simulation Results
A Matlab program has developed to represent the solar cell mathematical equations. The program is simulated using actual data of a BP SX 150S PV-module [4].

3.2.1 I-V Characteristics
Figure 3 shows the plots of *I-V* characteristics at various module temperatures simulated. Data points superimposed on the plots are taken from the *I-V* curves published on the manufacturer's datasheet.
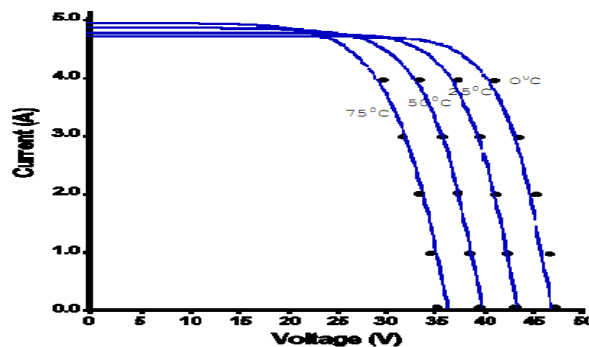

Figure 3: I-V curves of BP SX 150S PV module at various temperatures
Simulated with the Matlab model (1KW/m^2, 25^oC)

3.2.2 Impact of series resistance

The impact of series resistance (R_s) of the PV module on the PV characteristics is investigated. Figure 4 shows the results of changing R_s on the *I-V* curve. It can be concluded that the series resistance of the PV module has a large impact on the slope of the *I-V* curve near the open-circuit voltage (V_{oc}).
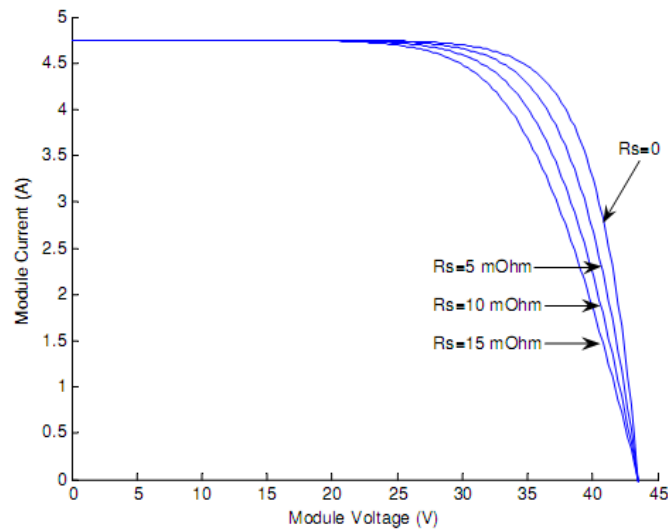

Figure 4 Impact of series resistances by Matlab simulation (1KW/m^2, 25°C)

3.2.3 Impact of ideality factor

The diode ideality factor (n) is unknown and must be estimated. It takes a value between 1and 2; the value of $n=1$ (for ideal diode) is, however, used until the more accurate value is estimated later by curve fitting [3]. Figure 5 shows the results of varying ideality factor.

After many trials with various diode ideality factors, the Matlab model chooses the value of $n = 1.62$ that attains the best match with the *I-V* curve on the datasheet as shown before in Figure 3. The results show good correspondence between the data points and the simulated *I-V* curves. The PV model is validated and can be used with the other subsystems.
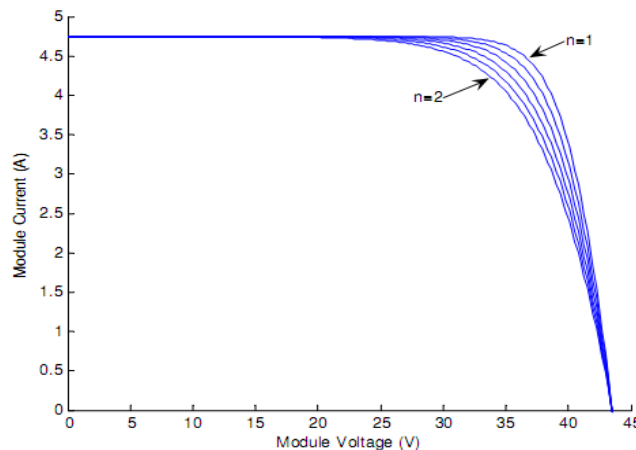

Figure 5: Impact of ideally factors by Matlab simulation (1KW/m^2, 25°C)

IV. Modeling of Maximum Power Point Tracker

When a PV module is directly coupled to a load, the PV module's operating point will be at the intersection of its *I–V* curve and the load line which is the *I-V* relationship of load. The impedance of load dictates the operating condition of the PV module. A PV array is usually oversized to compensate for a low power yield during winter months. This mismatching between a PV module and a load requires further over-sizing of the PV array and thus increases the overall system cost. To mitigate this problem, a maximum power point tracker (MPPT) is used to maintain the PV module's operating point at the MPP. MPPTs can extract more than 97% of the PV power when properly optimized [5].

4.1 DC-DC Converter

The heart of MPPT hardware is a switch-mode DC-DC converter. It is widely used in DC power supplies and DC motor drives for the purpose of converting unregulated DC input into a controlled DC output at a desired voltage level [6]. MPPT uses the same converter for a different purpose: regulating the input voltage at the PV MPP and providing load matching for the maximum power transfer.

There are a number of different topologies for DC-DC converters. They are categorized into *isolated or non-isolated topologies*. In PV applications, the grid-tied systems often use isolated topologies [6], whereas, the non-isolated topologies are almost always used in DC motor drives [7]. These topologies are further categorized into three types: step down (buck), step up (boost), and step up & down (buck-boost). The buck topology is used for voltage step-down. In PV applications, the buck type converter is usually used for charging batteries and in a linear current booster (LCB) for water pumping systems.

4.1 Maximum Power Point Tracking Algorithms

There are a number of methods that have been proposed to detect the location of the MPP in the *I–V* plane [5]. In this study we will use the Perturb & Observe (P&O) algorithm, which is a very popular and the most commonly used in practice because of its simplicity in algorithm and the ease of implementation [8]. In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power, ΔP, is observed. If the ΔP is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP. If the ΔP is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP. A flowchart of the P&O algorithm is shown in Figure 6.
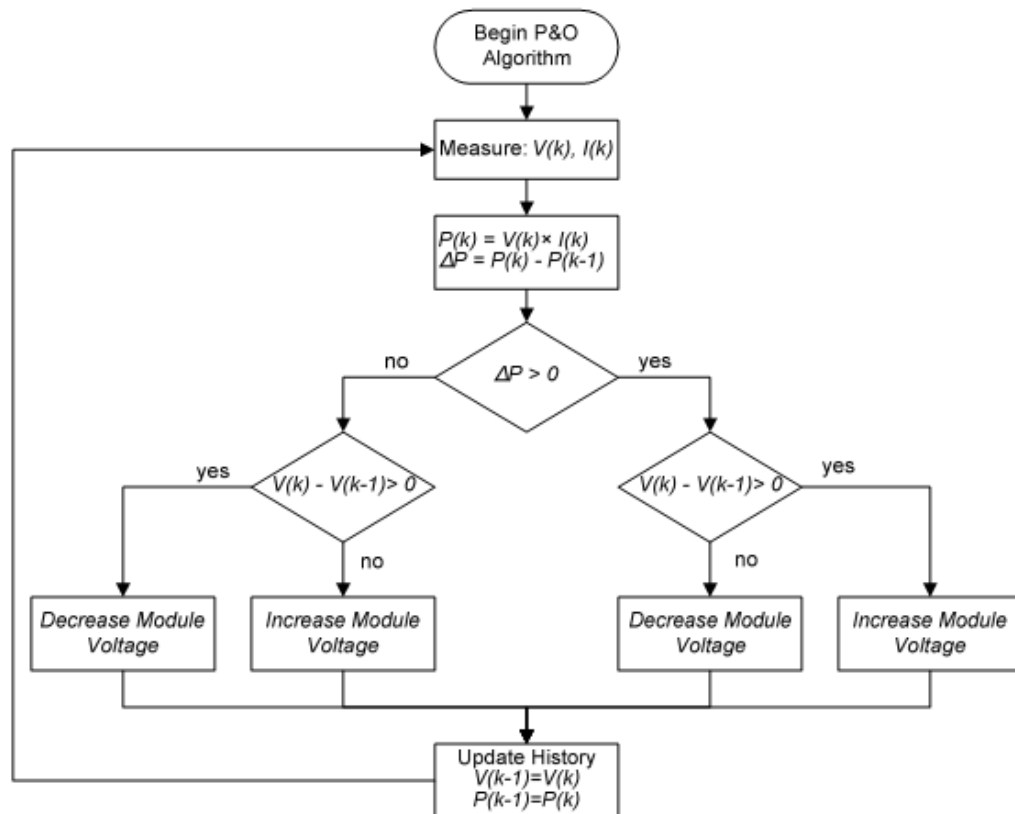

Figure 6: Flowchart of the P&O algorithm

The advent of digital controller made implementation of algorithm easy; as a result many variations of the P&O algorithm were proposed to claim improvements. The problem of oscillations around the MPP can be solved by the simplest way of making a bypass loop which skips the perturbation when the ΔP is very small which occurs near the MPP. The tradeoffs are a steady state error and a high risk of not detecting a small power change. Another way is the addition of a "waiting" function that causes a momentary cessation of perturbations if the direction of the perturbation is reversed several times in a row, indicating that the MPP has been reached [5].

4.2 Control of MPPT

As explained in the previous section, the MPPT algorithm tells a MPPT controller how to move the operating voltage. Then, it is a MPPT controller's task to bring the voltage to a desired level and maintain it. There are several methods often used for MPPT. In this study the direct control method is used. This control method is simpler and uses only one control loop, and it performs the adjustment of duty cycle within the MPP tracking algorithm as shown by Figure 7
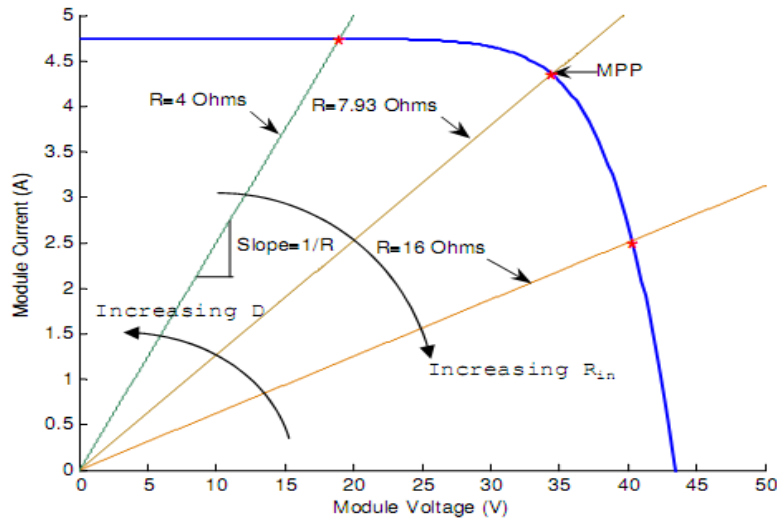

Figure 7: Relationship of the input impedance of DC-DC converter and its duty cycle

V. Modeling of DC Water Pump

The flow rate of water in positive displacement pumps is directly proportional to the speed of the pump motor, which is governed by the available driving voltage [9]. They have constant load torque to the pump motors, and it is expressed by the total dynamic head in terms of its equivalent vertical column of water; for example, vertical lift and friction converted to vertical lift [10]. Figure 8, shows the relationship between flow rate of water and total dynamic head for the Kyocera SD 12-30 solar pump to be modeled. It has the normal operating voltage of 12 to 30V and the maximum power of 150W.

In this study we use the Simulink model of a permanent magnet DC motor, correspond to the actual pump motor to draw the maximum power of 150W at the maximum voltage of 30V [11]. Then data are transferred to Matlab, and the cubic curve fitting tool in Matlab provides the following equation give the load resistance (R_{load}) corresponds to the water pump:

$$R_{load} = 9.5 \times 10^{-5}.V_o^3 - 8.7 \times V_o^2 + 0.37.V_o + 0.2 \tag{8}$$

where : V_o is the output voltage of converter.
This equation characterizes the DC pump motor, and MATLAB uses it in the simulations. Since the water pump is a positive displacement type, the load torque is also constant. The value is selected to draw the maximum power of the studied pump and can be modified to any other pump.
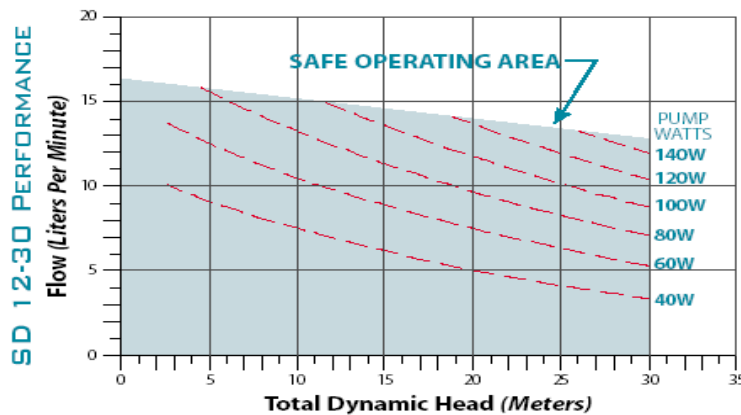

Figure 8: Kyocera SD 12-30 water pump performance chart [12]

5.1 I-V Characteristics of DC Motors

Many PV water pumping systems employ DC motors (instead of AC motors) because they could be directly coupled with PV arrays and make a very simple system. Among different types of DC motors, a permanent magnet DC (PMDC) motor is preferred in PV systems because it can provide higher starting torque. The following figure (Fig. 9) shows an electrical model of a PMDC motor. When the motor is turning, it produces a back e.m.f, or a counter electromotive force, described as an electric potential (E) proportional to the angular speed (ω) of the rotor.
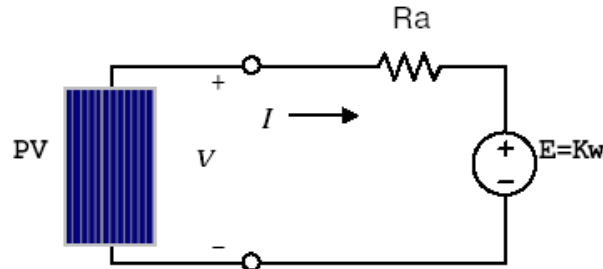

Figure 9: Electrical model of permanent magnet DC motor

From the equivalent circuit, the DC voltage equation for the armature circuit is:
$$V = I.R_a + K\omega$$
where: R_a is the armature resistance.

   K is the constant, and ω is the angular speed of rotor in *rad/sec*.

The current-voltage relationship (*I-V* curve) of a DC motor is shown in   Figure 10. Applying the voltage to start the motor, the current rises rapidly with increasing voltage until the current is sufficient to create enough starting torque to break the motor loose from static friction [13]. At start-up (ω =0), there is no effect of back e.m.f, therefore the starting current builds up linearly with a steep slope of *$1/R_a$* on the *I-V* plot as shown in Figure 10. Once it starts to run, the back e.m.f takes effect and drops the current, therefore the current rises slowly with increasing voltage.

As mentioned already a simple type of PV water pumping systems uses a direct coupled PV-motor setup. This configuration has a severe disadvantage in efficiency because of a mismatched operating point, as shown in Figure 10. For this example, the water pumping system would not start operating until irradiance reaches at 400W/m^2. Once it starts to run, it requires as little as 200W/m^2 of irradiance to maintain the minimum operation. This means that the system cannot utilize a fair amount of morning insolation just because there is insufficient starting torque. Also, when the motor is operated under the locked condition for a long time, it may result in shortening of the life of the motor due to input electrical energy converted to heat rather than to mechanical output [1].
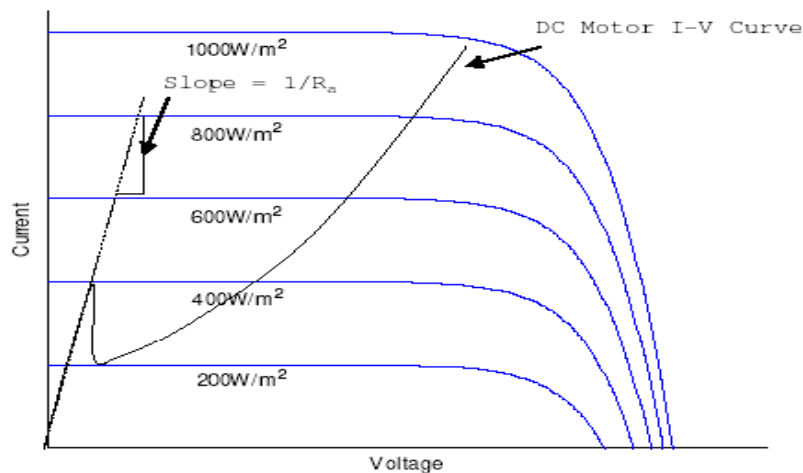

Figure 10: PV I-V curves with varying irradiance and a DC motor I-V curve

VI. Simulations of the PV water pumping system

The proposed PV water pumping system is modeled using Matlab environment. The model was evaluated using Matlab 7.4. The model parameters are evaluated during execution using the equations listed in the previous sections. Next, the algorithms are tested with actual irradiance data in Kuwait [14]. The program can locate and maintain the PV operating point very close to the MPPs without much difference in their performance.

6.1 Matlab Simulation Results

The simulation is carried out with the irradiance is increased linearly from 20W$/m^2$ to 1000W$/m^2$ at a rate of 0.3W$/m^2$ per sample. Figure 11 shows the trace of operating point staying close to the MPPs for P-V characteristics, whereas, Figure 12 shows the trace of operating point staying for I-V characteristics. Figure 13 shows the relationship between the output power of converter and its duty cycle. Figure 14 shows the current and voltage relationship of converter output which is equal to the DC motor load. It shows that the output current rises rapidly with increasing voltage until the current is sufficient to create enough torque to start the motor. Once it starts to run, the back e.m.f takes effect and drops the current, therefore the current rises slowly with increasing voltage.
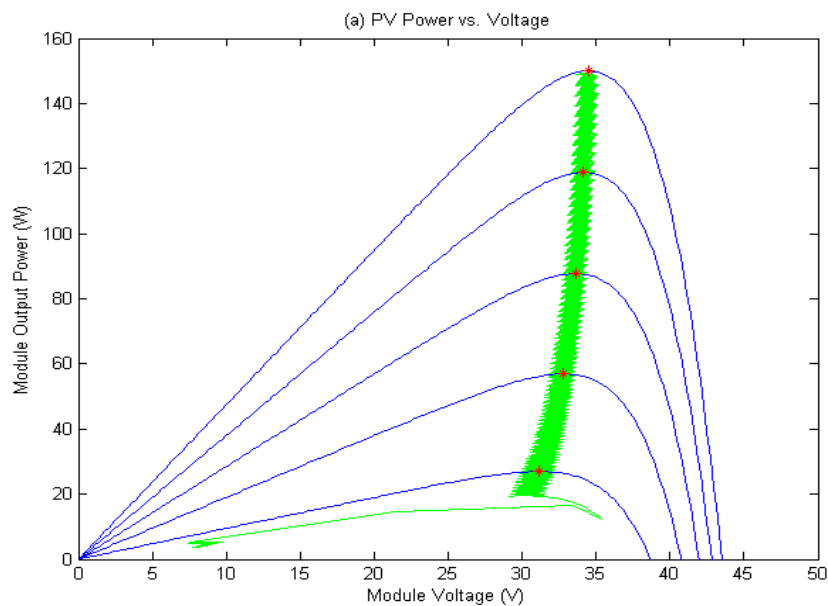

Figure 11 Trace of operating point staying close to the MPPs for P-V characteristics
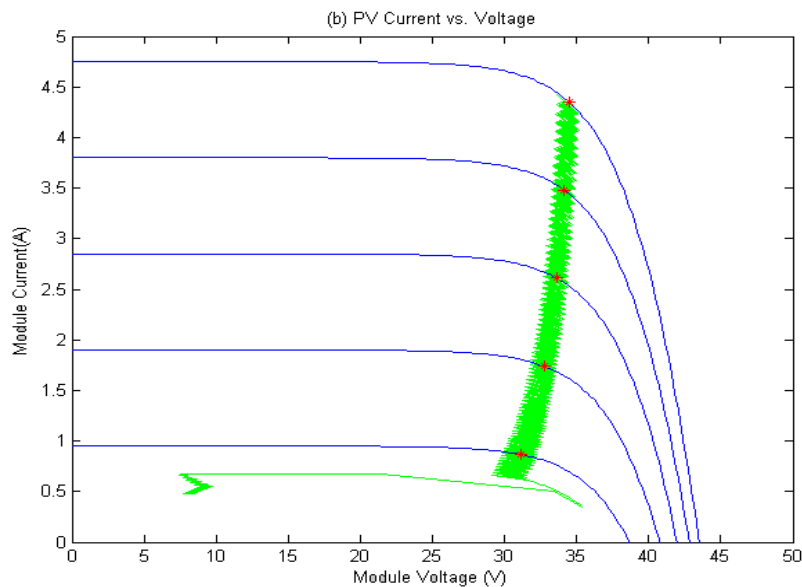

Figure 12 Trace of operating point staying close to the MPPs for I-V characteristics
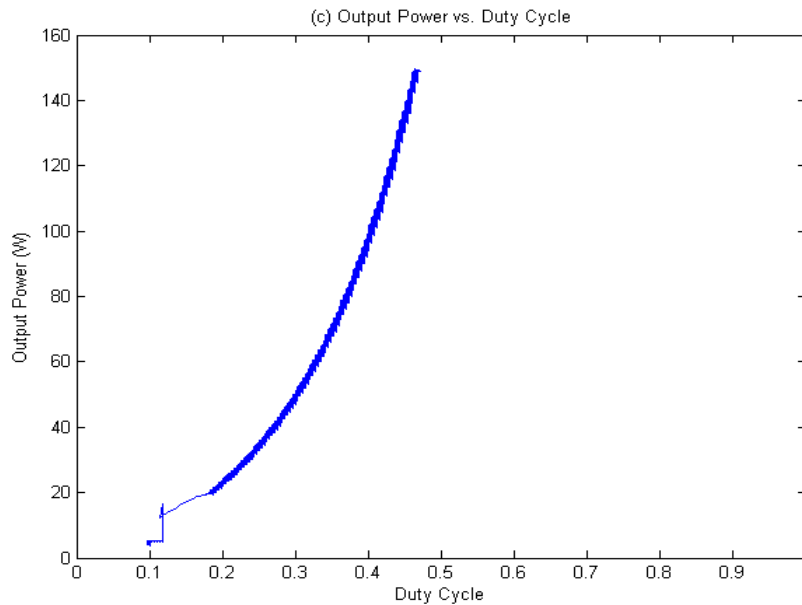
Figure 13 Relationship between the output power of converter and its duty cycle.
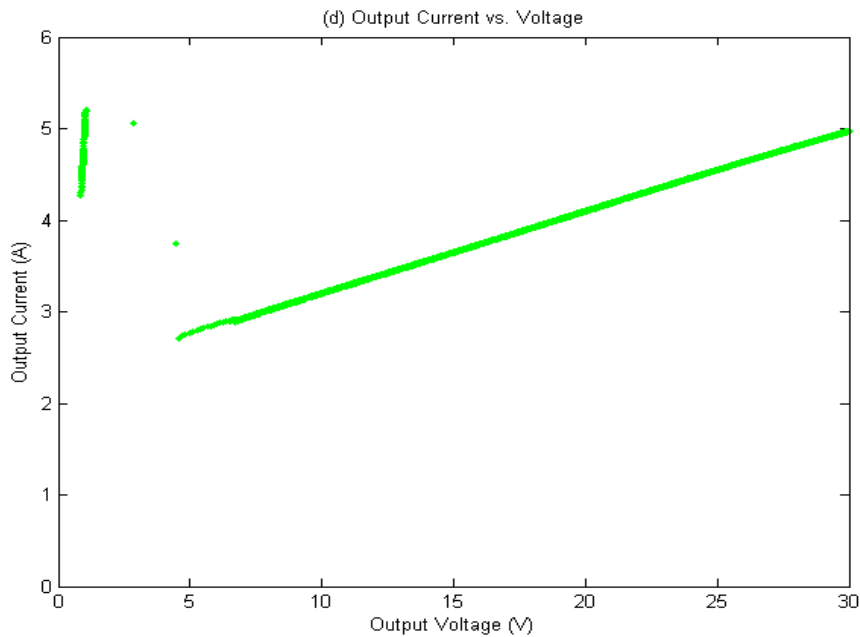

Figure 14 Relationship between the output power of converter and its duty cycle.

6.2 Result Analysis

The simulation is carried out using the radiation data of for Kuwait airport site [14]:

- The result shows that the system with MPPT can utilize more than 99% of PV capacity. Assuming a DC-DC converter has efficiency more than 90%, the system can increase the overall efficiency by more than 35% compared to the system without MPPT.
- The total volume of water pumped for the 12-hour period is also calculated for both systems (with and without MPPT). The results show that MPPT offers significant performance improvement. It enables to pump up to 87% more water than the system without MPPT. Even if the efficiency of converter is set to 90%, it can still pump 67% more water than the system without MPPT.
- The results show that the direct-coupled PV water pumping system has a severe disadvantage because the pump stays idle for nearly two more hours in the morning while the same system with MPPT is already pumping water. Similarly, it goes idle nearly two hours earlier than the system with MPPT in the afternoon. The flow rate of water is also lower throughout the operating period.

- The speed of pump motor is proportional to the converter's output voltage which is relative to irradiation. Thus, when the sun shines more, it simply pumps more water.
- The MPPT stops its original task if the load cannot consume all the power delivered.
- For the stand-alone system, when the load is limited by its maximum voltage or current, the MPPT moves the operating point away from the MPP and sends less power. It is very important to select an appropriate size of load, thus it can utilize the full capacity of PV module and array.

VII. Conclusion

The use of photovoltaics as the power source for pumping water is one of the most promising areas in photovoltaic applications.

This paper presents a new design and simulation of a simple but efficient photovoltaic water pumping system. It models each component and simulates the system using Matlab. The algorithms are tested with actual irradiance data in Kuwait.

The simulations verify the system and functionality of MPPT. Simulations also make comparisons for the system without MPPT in terms of total energy produced and total volume of water pumped per day. The results validate that MPPT can significantly increase the efficiency of energy production from PV and the performance of the PV water pumping system compared to the system without MPPT. The result shows that the system with MPPT can utilize more than 99% of PV capacity.

It is necessary for PV system engineers to perform economic analysis of different systems and also necessary to seek other methods of efficiency improvement such as the use of a sun tracker.

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