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Maximum power point tracking techniques for solar water pumping systems

A. Daoud* and A. Midoun

Laboratory of Power Electronics and Solar Energy, Department of Electronics, Faculty of Electrical Engineering, University of Sciences and Technology of Oran, Mohamed Boudiaf
B.P. 1505, El M'naouer, Oran, Algeria

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Abstract - *In this paper, we present a comparative study of single sensor-based maximum power point tracking (MPPT) techniques for solar photovoltaic (PV) water pumping systems. A conventional hill climbing algorithm is employed to find and track the MPP, using the information obtained from either a voltage sensor or a tachometer or a manometer. The results of experiment are included and explained to validate the proposed techniques.*

Résumé - *Dans cet article, nous présentons une étude comparative, à base de simples capteurs pour le suivi du point de puissance maximale (MPPT) pour des systèmes de pompage photovoltaïques (PV). Un algorithme de recherche en escalier est employé pour chercher et suivre le point de puissance maximale, en utilisant l'information obtenue, soit auprès d'un capteur de tension ou d'un tachymètre ou un manomètre. Les résultats de l'expérience sont inclus et expliqués afin de valider les techniques proposées.*

Keywords: MPPT - DC/DC buck converter - Motor-pump - Sensors.

1. INTRODUCTION

Solar electricity, also known as photovoltaic's, has shown since the 1970s that the human race can get a substantial portion of its electrical power without burning fossil fuels (coal, oil or natural gas) or creating nuclear fission reactions. Photovoltaic's has shown that it can generate electricity for the human race for a wide range of applications, from power supplies for small consumer products to large power stations feeding electricity into the grid [1].

Water pumping for irrigation and water supply for rural communities represents an important area of standalone PV systems. These systems usually consist of a PV generator, source of water, a water storage tank, and a DC pump. However, direct interfacing between PV generator and DC pump introduces significant mismatch problems as the light intensity varies. The mismatch can be overcome by introducing a matching DC/DC converter that continuously seeks MPP of PV generator.

Numerous strategies and algorithms have been developed to find and track the MPP of a PV generator. Among all MPP tracking techniques, perturbation and observation and hill climbing methods are widely applied in the MPPT controllers due to their simplicity, easy implementation and requiring only voltage and current sensors [2].

A generalized sensor reduction technique, on the other hand, requires complex computation and, therefore, its primary advantage is only in improving reliability of the overall system by eliminating the current sensor [3].

* d_elamine@yahoo.com

A comparison of single sensor based MPPT methods for a solar PV water pumping system is investigated in this work. Based on widely used algorithm, these methods offer advantages of the simplified hardware configuration and low cost by using only one sensor to measure either the motor-pump rotational speed or the PV array voltage or the pump outlet pressure. These latter are used by a digital MPPT controller to maximize the power drawn from the PV array.

The proposed techniques are implemented on a low cost 8-bit RISC microcontroller (PIC16f877) to control the duty cycle of DC/DC buck converter with pulse width modulation (PWM) in a solar PV water pumping system including a PV array, a motor-pump and a water storage tank.

2. CHARACTERISTICS OF PV ARRAY AND MOTOR-PUMP

Solar or PV cells are made of semiconducting materials that c an convert sunlight directly into electricity. When sunlight strikes the cells, it dislodges and liberates electrons within the material which then move to produce a DC current.

PV cells are combined to make modules that are encased in glass or clear plastic. Modules can be aggregated together to make an array that is sized to the specific application. The produced power varies with amount of sun shining on the array and temperature.

If the latter is held constant, this power variation results in a variable current at a fixed voltage. Increasing (decreasing) temperature reduces (increases) PV array generated power.

Traditional $I-V$ characteristic curves of a PV array are given by the following equation:

$$I = n_p I_L - n_p I_{OS} \left\{ \exp\left[\frac{q(V + I.R_S)}{A k T n_s} \right] - 1 \right\} - \frac{V + I.R_S}{R_{Sh}} \tag{1}$$

where I_L is the light generated current, I_{OS} is the reverse saturation current, q is the electronic charge, V is the PV array output voltage, R_S stands for the series resistance, R_{Sh} is the PV array shunt resistance, A is the ideality factor, k denotes the Boltzmann's constant, T is the absolute operating temperature, n_s is the number of cells connected in series and n_p is the number of modules connected in parallel [4].

The symbols I, V, R_S and R_{Sh} in (1) can be defined as:

$$I = n_p I_{Cell} \tag{2}$$

$$V = n_s V_{Cell} \tag{3}$$

$$R_S = R_{SCell} \times \frac{n_s}{n_p} \tag{4}$$

$$R_{Sh} = R_{Rh\,Cell} \times \frac{n_s}{n_p} \tag{5}$$

Since the shunt resistance R_{Sh} is much greater than the series resistance R_S; the last term in (1) becomes very small with respect to the other terms (Fig. 1). Therefore, the last term will be neglected as it will not cause a large error in the PV array model [5].

The motor-pump comprises a surface centrifugal water pump (Electropompe CM100) coupled to permanent magnet DC motor (180 V, 4.7 A, 1750 rpm). Figure 2 shows motor-pump $I-V$ characteristic superimposed on $I-V$ curves where a variable DC voltage source was used to represent motor-pump curve.

At any time, the operating point is the intersection of the two characteristics. At different irradiance levels, the intersection points are on the left of the MPP curve, thus the PV array voltage must be increased to reach the optimal power curve which is done using a DC/DC buck converter.

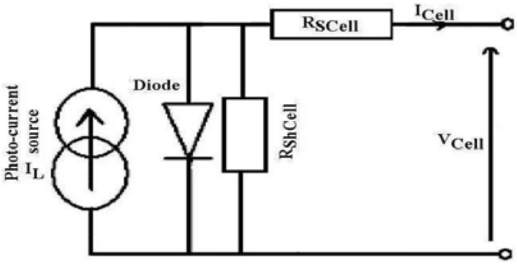

Fig. 1: Solar cell model

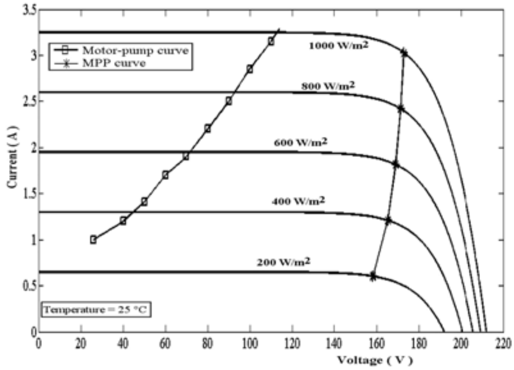

Fig. 2: PV Array and motor-pump characteristics

3. MPPT CONTROL ALGORITHMS

3.1 Hill Climbing Algorithm

Hill climbing algorithm is widely used in practical PV systems because of its simplicity and because it does not require prior study or modeling of the source characteristics and can account for characteristics drift resulting from ageing, shadowing or other operating irregularities.

It starts with measuring the present values of the PV array voltage $(V(k))$ and current $(I(k))$. Therefore, the generated power $(P(k))$ can be calculated and compared to its value calculated in the previous iteration. According to the result of comparison; the sign of a 'slope' is either complemented or remains unchanged and the PWM output duty cycle is changed accordingly [6]. The hill climbing algorithm is shown in Fig. 3.

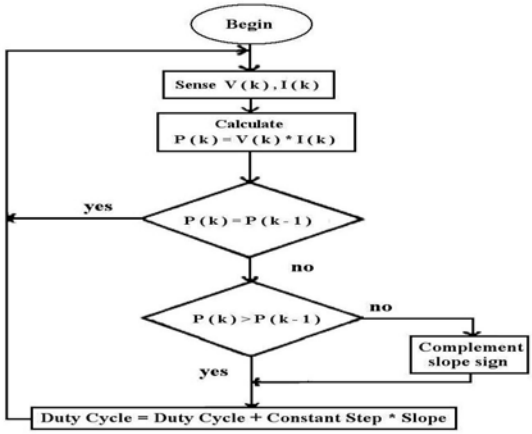

Fig. 3: Flow chart of the hill climbing based MPPT algorithm

3.2 Speed control based MPPT algorithm

The conventional tracking methods involve sensing the instantaneous voltage and current. However in this case, only rotational speed information is required for power tracking.

The experimental characteristic given by Fig. 4 confirms the assumption that any increase in the PV array generated power will increase the rotational speed of the motor-pump; consequently the flow rate will increase.

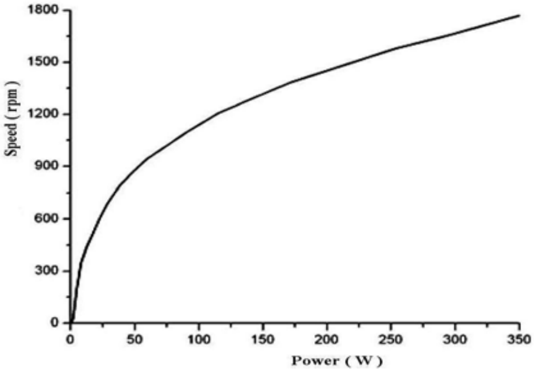

Fig. 4: Motor-pump rotational speed vs. PV array generated power

The tracking method operates by periodically incrementing or decrementing the duty cycle of a DC/DC converter and comparing the present motor-pump rotational speed $(SP(k))$ value with the previous measurement (Fig. 5).

If the duty cycle changing leads to an increase (decrease) in motor-pump rotational speed, which means an increase (decrease) in array's power, the subsequent changing is made in the same (opposite) direction.

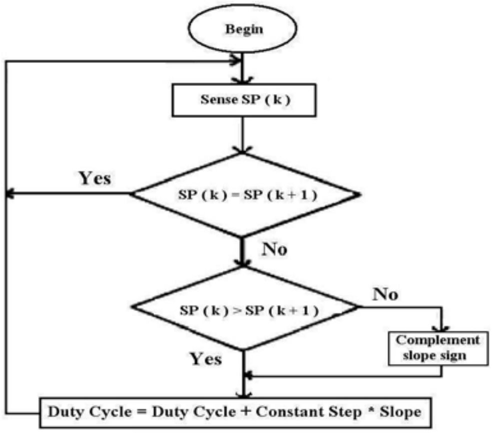

Fig. 5: Flow chart of the speed control based MPPT algorithm

3.3 Pressure control based MPPT algorithm

In this section, the operating voltage is periodically changed in constant steps. If the pump outlet pressure (PR(k)) increases from one step to the next, the search direction is retained, otherwise it is reversed (Fig. 6). In this way, the MPP is found and the operating point oscillates around the actual MPP.

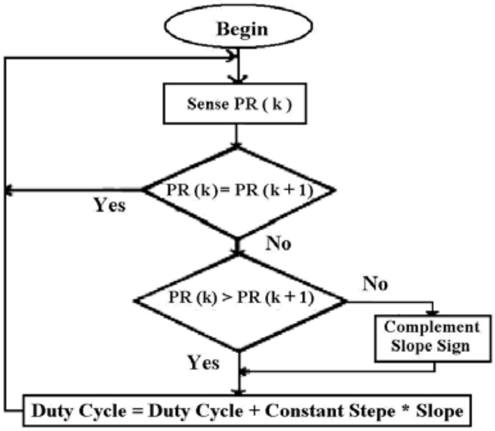

Fig. 6: Flow chart of the pressure control based MPPT algorithm

3.4 Voltage control based MPPT algorithm

MPP trackers are basically DC/DC converter and can be represented as shown in figure 7. The control signal of the switch S usually has a constant period and the duty cycle, D defined as:

$$D = V_0 / V_i \tag{6}$$

where V_0 is the load voltage and V_i is the PV array voltage. The relationship between input and output power defines the DC/DC converter efficiency, η:

$$\eta = \frac{V_0 \times I_0}{V_i^2 \big/ R_{eq}} \tag{7}$$

where I_0 is output current of the converter, R_{eq} is the reflected resistance of the PV source. From (6) and (7), the expression for R_{eq} is derived as:

$$R_{eq} = \frac{\eta \times R_L}{D^2} \tag{8}$$

where R_L is a constant resistive load. The expression for the PV array generated power is given by:

$$P = \frac{V_i^2 \times D^2}{\eta \times R_L} \tag{9}$$

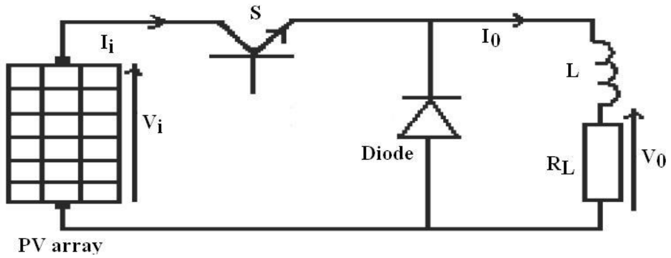

Fig. 7: DC/DC Buck converter

Since the duty cycle, and hence the power value is changed by a small amount between two consecutive sampling cycles, the converter efficiency (η) can be assumed to constant over this period. Therefore, (9) is reduced to obtain the following expression:

$$VD = \sqrt{P} \equiv V_i \times D \tag{10}$$

Clearly, the maxima of both power and its corresponding expression VD will coincide as the constants are eliminated [7].

For the motor-pump load, when duty cycle of the buck converter changes from 0 to 1 slowly, the curves between the power of the PV array and the expression VD are very similar (Fig. 8), and there is the same D basically at the MPP and the maximum point of VD [8]. Therefore the MPPT is equivalent with searching for the maximum point of the curve of VD. The flow chart corresponding to the voltage control MPPT algorithm is given by figure 9.

4. EXPERIMENTAL VERIFICATION

To interface the PV array output to DC motor driven centrifugal pump, a microcontroller-based DC/DC buck converter was designed and built (Fig. 10). By measuring the following parameters: PV array voltage and current, voltage generated by an analog tachometer, and voltage produced by a digital manometer, we can easily determine PV array generated power, rotational speed of motor-pump, and pump outlet pressure respectively.

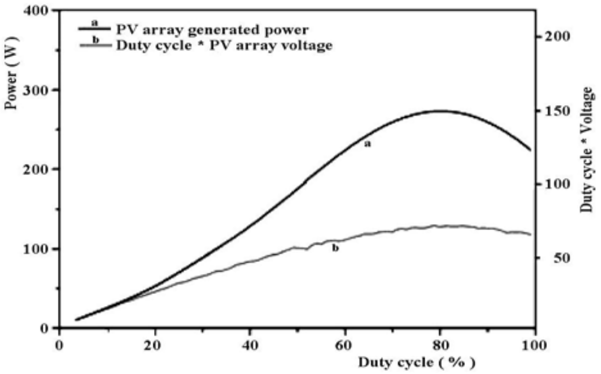

Fig. 8: Experimental characteristics for the voltage control method

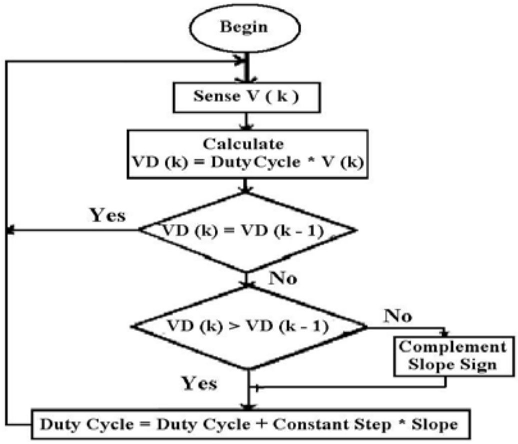

Fig. 9: Flow chart of the voltage control based MPPT algorithm

After that the controller on chip 10-bit PWM generator output drives the DC/DC buck converter according to each algorithm [9]. The buck converter comprises: MOSFET switch IRF740, diode BYT08, coil ($L = 100\,\mu H$) and PV array voltage filtering capacity ($C = 1000\,\mu F$) [10].

The switching frequency (6 kHz) is designed to obtain low output ripple. PIC microcontroller can send data to PC with a line drive and receiver chip (MAX232) and a null modem cable.

The test of MPPT algorithms was conducted on sunny day (average insolation: 609 W/m^2, average temperature: 21.4 °C). According to the PV array generated power and voltage, rotational speed, and pressure information, the microcontroller computes the output and generates a command representing the duty cycle given by the microcontroller PWM pin which is isolated by an optocoupler (6N135), amplified by a hex buffer-inverter converter (HEF4049) and applied to MOSFET switch.

The converter duty cycle is adjusted such that maximum PV array output power is extracted under all operating conditions and transferred to motor-pump which in turn draws water from a storage tank in a closed hydraulic system.

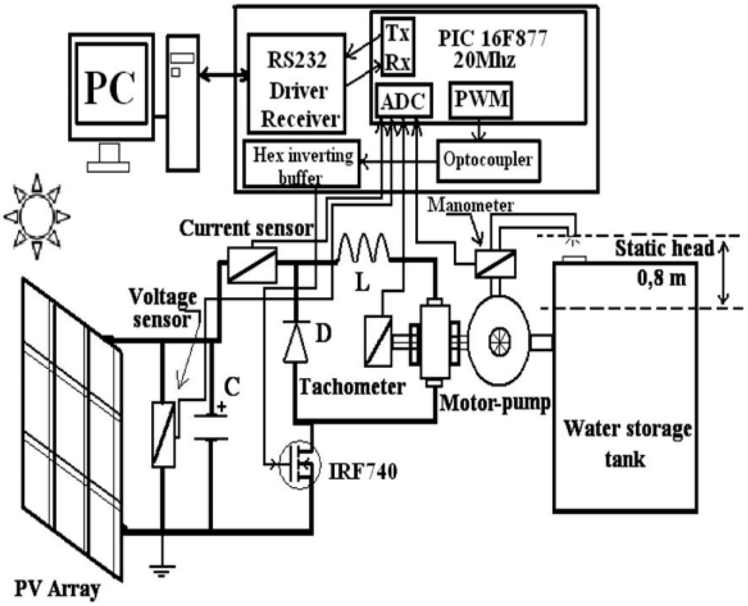

Fig. 10: Sketch of the experimental set-up

Fig. 11 shows PV array voltage obtained by application of hill climbing, voltage, speed, and pressure control methods. It can be seen from the previous figure that the voltage decreases to reach the optimal voltage, whereas the PV array current increases (Fig. 12).

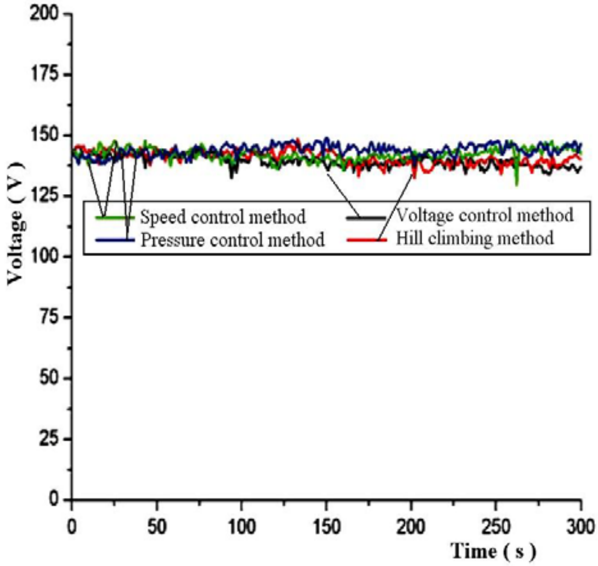

Fig. 11: PV array voltage

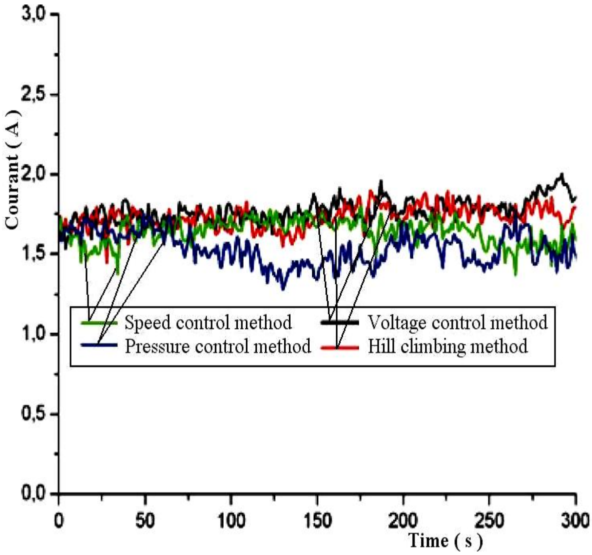

Fig. 12: PV array current

The PV array generated power is given by Fig. 13 where hill climbing and voltage control algorithms seek the MPP with small deviation whereas speed control algorithm gives medium deviation which decreases in the steady state.

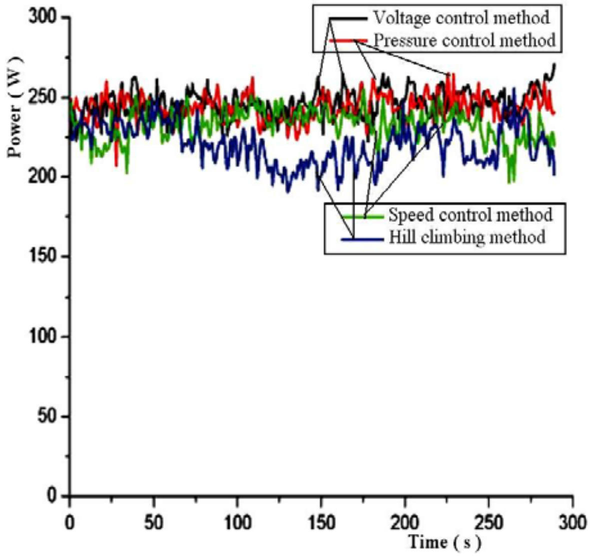

Fig. 13: PV array generated power

Pressure control algorithm generates a large deviation due to fast variation of pump outlet pressure (Fig. 14). The tracking efficiencies are 94.1 %, 94.4 %, 90.7 % and 85.6 % for hill climbing, voltage control, speed control and pressure control algorithms respectively.

Fig. 15 confirms that the algorithm based on voltage control generates small deviation around MPP with fast convergence to reach the MPP, and therefore more rotational speed will increase flow rate.

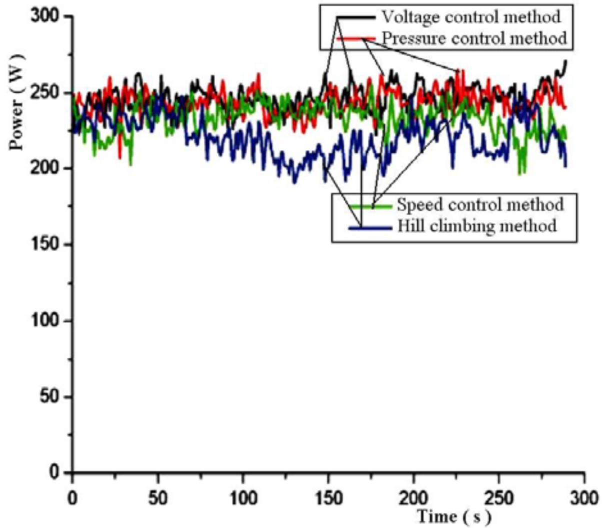

Fig. 14: Pump outlet pressure

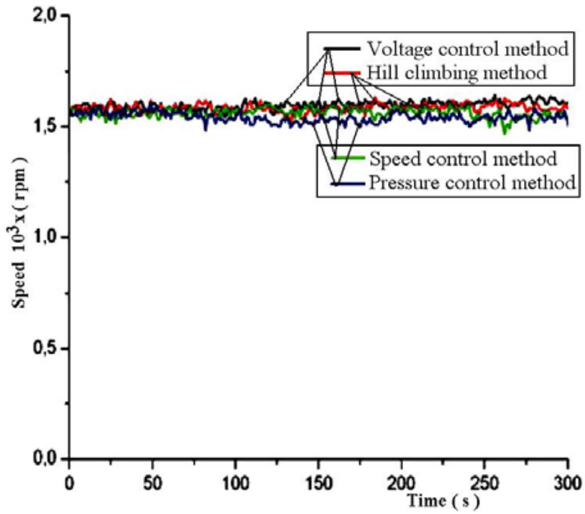

Fig. 15: Motor-pump rotational speed

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