# Chapter 33
# A Development of System Control Strategy Applied to PV Pumping System

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## Introduction

The solar energy is a clean renewable energy used in the isolated sectors and rural areas to produce the needed electrical energy. The PV cell converts solar energy into electrical energy by a process called "photovoltaic effect" [1].

The use of photovoltaic (PV) energy as source to pumping water is considered one of the promising fields of PV application. Water can be pumped during the day and stored in tanks. With the increased use of this technology, greater attention has been paid to their design and their optimal use [2, 3]. Various studies have been done to define the optimal drive system, the choice of motor (DC motor or AC motor) [4] and pumps (centrifugal or volumetric), and other ways to control and optimize the water pumping system.

In this paper, the PV pumping system consists of PV panel, DC–DC boost converter, and DC motor pump, with the maximum power point tracking (MPPT) as online technique to track the maximum power point of the PV generator, which improves the efficiency of the system. Thus, several MPPT algorithms has been presented and implemented in the literature. The techniques vary in complexity, robustness, convergence speed, eases of implementation, and in other aspects. The most MPPT techniques used are: the P&O method [5, 6], Hill climbing [7], incremental conductance, and artificial intelligence-based algorithms [8]. However, in the recent publications, those techniques are developed to improve the accuracy of tracking, and the response speed time, including a novel variable step size incremental conductance [9], and combination of two techniques [10].

In this paper, we present a developed slide mode control strategy to track the maximum power point (MPP) of the PV generator, which improves the performance of

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the PV water pumping system. This technique presents the advantages of robustness, good accuracy, high stability, and efficiency. The developed method was tested in MATLAB/SIMULINK environment. The obtained results indicate the feasibility and improved functionality of the photovoltaic pumping system.

In the Modeling of Photovoltaic Pumping System section we present a modeling of PV pumping system. Slide Mode Control section brings out an explication about the proposed approach. Simulation Results section deals with the simulation results with a comparison between the developed method and the classical P&O method. Conclusion section presents critical observations and discussion followed by conclusion.

## Modeling of Photovoltaic Pumping System

The general block diagram of the photovoltaic pumping system is shown in Fig. 33.1. The whole system is composed of a PV panel, a power DC–DC adapter, and PMDC motor driving a centrifugal pump.

### *PV Cell Model*

The PV cell is a component that converts directly the solar energy into electrical power. Several papers have presented the modeling of PV cells, with one diode [9] and two diodes [10]. In order to provide the optimum power, we use the PV panel which is composed of many strings of solar cells in series, connected in parallel. Figure 33.2 shows the equivalent circuit of the PV cell.

The behavior of the PV array may be described by the following equations:

$$I = I_{ph} - I_d - I_p \tag{33.1}$$

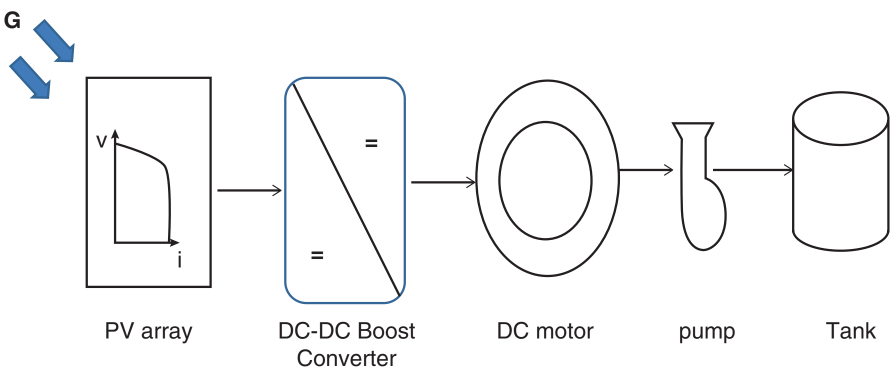


**Fig. 33.1** General configuration of a photovoltaic pumping system

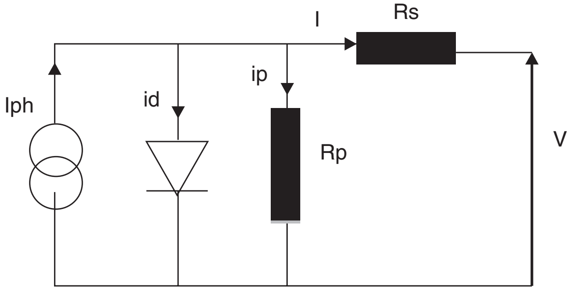


**Fig. 33.2** Equivalent circuit of PV cell

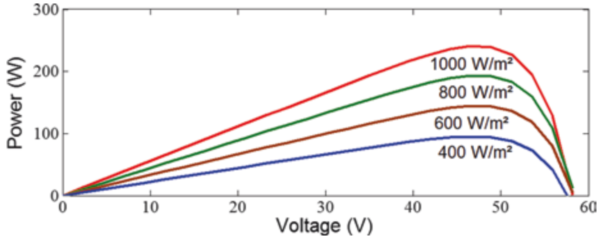


**Fig. 33.3** Power versus Voltage at different Solar Intensity level

with

$$I_d = I_0\left(\exp\left(\frac{V_j \cdot q}{K_0 \cdot T}\right)\right) - 1) \tag{33.2}$$

and

$$I_p = \frac{V + R_s \cdot I}{R_p} \tag{33.3}$$

$$I = I_{ph} - I_0\left(\exp\left(\frac{V_j q}{K_0 T}\right) - 1\right) - \frac{V + R_s \cdot I}{R_p} \tag{33.4}$$

where $V$ = PV output voltage, $I$ = PV output current, $I_{ph}$ = photocurrent, and $I_0$ = saturation current.

The output characteristics of voltage-power and voltage-current of PV panel, under different values of radiation, are presented in Fig. 33.3.

The equation of the output voltage can be expressed as:

$$V_o = \frac{1}{1-\alpha} V_{pv} \tag{33.5}$$

where $V_o$ and $V_{pv}$ are, respectively, the DC–DC converter output and input voltages.

## *DC Motor Model*

The choice of motor depends on many factors: the requirements of the size, efficiency, price, reliability, and availability. Among the different kinds of DC motors existing, the permanent magnet motors (PMDC) are most commonly used in PV pumping systems. They provide a high torque at startup.

The mathematical relationships that describe the model of a DC motor are expressed as follows:

Terminal voltage of the armature:

$$U = RI + E \tag{33.6}$$

Electromotive force:

$$E = K \cdot \omega \tag{33.7}$$

Electromagnetic torque:

$$\Gamma_e = K' \cdot I \tag{33.8}$$

The mathematical equation:

$$E = U\left(K_m \cdot \Phi\right) \tag{33.9}$$

$K_m$, the constant of the construction motor, depends on the number of pairs of poles and the number of conductors per section.

## *Centrifugal Pump Model*

For solar pump, the centrifugal pumps and the volumetric pumps are the most used [3]. The centrifugal pump applies a torque proportional to the square of the rotational speed of the motor [4]:

$$\Gamma_r = K_c \cdot \omega^2 \tag{33.10}$$

where $K_c$ is the proportionality constant [(Nm/rad.s$^{-1}$)$^2$] and $\omega$ is the rotational speed of the motor (rad.s$^{-1}$).

Any pump is characterized by its output power, which is given by:

$$P = \frac{P_u}{\eta} \tag{33.11}$$

with:

$$P_u = \rho \cdot g \cdot H \cdot Q \tag{33.12}$$

## Slide Mode Control

Several papers developed the sliding mode control method [1, 2] to track the MPP of the PV generator. It presents the advantages of simplicity and good performance. The control circuit adjusts the duty cycle of the switch with the different variation of radiation and temperature to track the MPP of the PV panel.

Depending on the position of the switch $S$, the equations can be written as follows:

$$\frac{dV_{pv}}{dt} = \frac{1}{C}\left(I_{pv} - I_1\right) \tag{33.13}$$

$$\frac{dI_1}{dt} = \frac{1}{L}\left(V_{pv} - \left(1 - D\right) \times V_o\right) \tag{33.14}$$

With the use of the concept of the approaching control [5], the sliding surface is selected as:

$$\frac{dP_{pv}}{dV_{pv}} = 0 \tag{33.15}$$

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d\left(V_{pv} \times I_{pv}\right)}{dV_{pv}} \tag{33.16}$$

$$\frac{dP_{pv}}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} \tag{33.17}$$

So, from the precedent equations, the sliding surface ($\sigma$) can be written as follows:

$$\sigma = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} \tag{33.18}$$

The duty cycle $D$ can be controlled by the following equations:

$$D = D + \Delta D \text{if} \quad \sigma > 0 \tag{33.19}$$

$$D = D - \Delta D \text{if} \quad \sigma < 0 \tag{33.20}$$

Eq. 33.17 can be written in general form of the nonlinear time invariant system [10].

$$\dot{\sigma} = \left[\frac{d\sigma}{dx}\right]^T \times \dot{X} = 0 \tag{33.21}$$

$$\dot{\sigma} = \left[\frac{d\sigma}{dx}\right]^{\mathrm{T}} \times \left(f\left(X\right) + g\left(X\right) \times D'\right) = 0 \tag{33.22}$$

The equivalent control $D'$ obtained is [10]:

$$D' = \frac{\left[\frac{d\sigma}{dx}\right]^{\mathrm{T}} \times f\left(x\right)}{\left[\frac{d\sigma}{dx}\right]^{\mathrm{T}} \times g\left(x\right)} = 1 - \frac{V_{\mathrm{pv}}}{V_{\mathrm{o}}} \tag{33.23}$$

The equivalent duty cycle $D'$ must vary between $0 < D' < 1$, and the real duty cycle control $D$ is proposed as [10]:

$$D = 1 \quad \text{if} \quad D' + K\sigma \geq 1 \tag{33.24}$$

$$D = D' + k\sigma \quad \text{if} \quad 0 < D' + k\sigma < 1$$

$$D = 0 \quad \text{if} \quad D' + k\sigma \leq 0$$

To improve the accuracy of tracking of MPP and convergence time, the choice of the right surface of searching is very important. Figure 33.4 shows the proposed surfaces chosen to track the MPP.

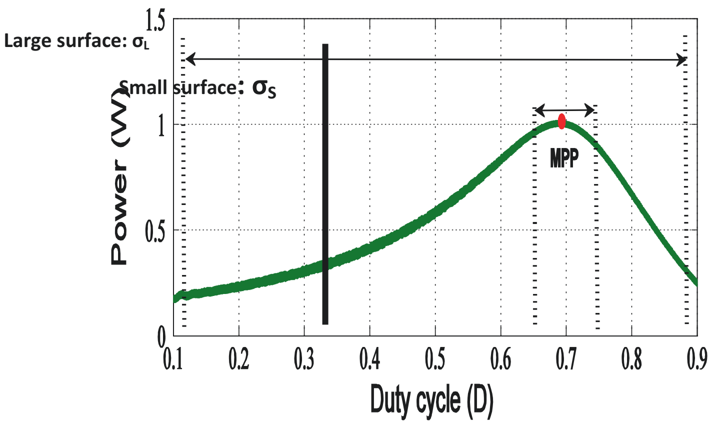


**Fig. 33.4** The proposed surfaces of the proposed SMC to track the MPP of PV array

The principle of search of the MPP is based on dividing the position surface into two surfaces. One is near (small surface, $\sigma_S$) and the other is far (large surface, $\sigma_l$) from MPP. In our method, we insert a switch between these two surfaces by exploiting the variable $\frac{|\Delta P|}{|\Delta V|}$. If the obtained value is far from the MPP, the searching is done on the large surface $\sigma_{s,}$ which improves the efficiency of tracking and the response speed time. Else, if we are near to MPP of the PV panel, the surface of tracking is the small surface, to minimize the oscillations around the MPP, and reach it quickly. The equations of the novel duty cycle with the proposed technique become:

The equivalent duty cycle must varies between $0.1 < D' < 0.9$. The real controls signal $D$ is proposed as:

$$D - 0.9 \quad \text{if} \quad D' + k\sigma \geq 0.9 \tag{33.25}$$

$$D = D' + k\sigma \quad \text{if} \quad 0.1 < D' + k\sigma < 0.9 \tag{33.26}$$

$$D = 0.1 \quad \text{if} \quad D' + k\sigma \geq 0.1 \tag{33.27}$$

The equivalent duty cycle varies as $0.6 < D' < 0.8$. The real controls signal $D$ is proposed as:

$$D = 0.8 \quad \text{if} \quad D' + k\sigma \geq 0.8 \tag{33.28}$$

$$D = D' + k\sigma \quad \text{if} \quad 0.6 < D' + k\sigma < 0.8 \tag{33.29}$$

$$D = 0.6 \quad \text{if} \quad D' + k\sigma \leq 0.6 \tag{33.30}$$

The proposed equation of the reference power allows calculating the novel power simultaneously with variation of insolation and temperature. It determines the position of the power at each moment, which facilities the task of tracking MPP.

The simulation results of the proposed SMC technique are presented in the next section; they show clearly the efficiency of the method.

## Simulation Results

In order to verify the efficiency of the proposed sliding mode control method, and its influence in the performance of the PV water pumping system driven by DC motor coupled to a centrifugal pump, a simulation is done using MATAB/SIMULINK environment. The PV generator source used is SES96M; it has the characteristics recorded in Table 33.1. Also, the parameters of the DC–DC boost converter employed have been noted in Table 33.2.

To show the effectiveness of the developed sliding mode control method, we compare it with the classical P&O method.

**Table 33.1** Electrical parameters of SES96M

| | |
|---|---|
| Maximum power (Pmpp) | 240 W |
| Voltage at MPP (Vmpp) | 48.5 V |
| Current at MPP (Impp) | 4.95 A |
| Open circuit voltage (Voc) | 58.2 V |
| Short circuit current (Isc) | 5.55 A |

**Table 33.2** Electrical characteristics of DC–DC boost converter

| | |
|---|---|
| C1 | 2 mF |
| C2 | 800 uF |
| L | 10 mH |
| R | 100 Ω |

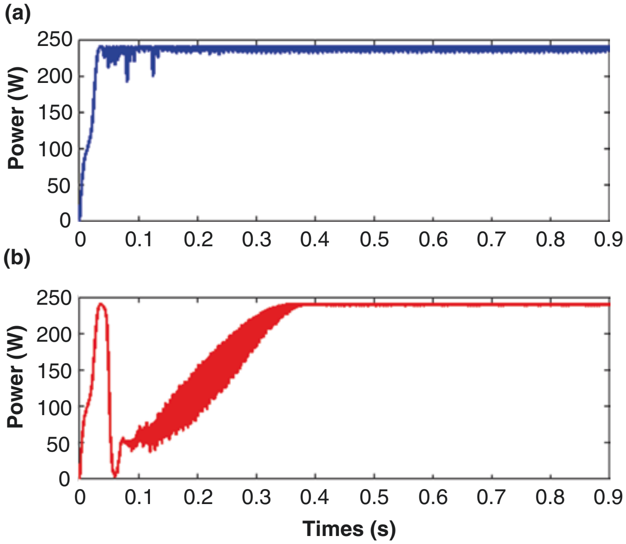


**Fig. 33.5** Output power of the PV panel (**a**) proposed SMC, (**b**) classical P&O

Figures 33.5 and 33.6 present the output power, and output voltage of the PV panel with proposed SMC method and classical P&O technique, respectively, at $T = 25$ °C and $E = 1000$ W/m$^2$. It proves the utility of the developed method, in fact a considerable minimization of oscillations, and a clear improvement of response speed. Figure 33.7 shows the behavior of the output speed motor of the PV pumping system.

The output motor speed of the PV pumping system with the proposed sliding mode control and the classical P&O method as presented in Fig. 33.7 shows clearly the influence of the proposed SMC in this element of the system; it improves the accuracy and the speed of response time. The speed is stabilized from 0.15 s. However, with the use of P&O method, the speed begins to stabilize till 0.5 s. To demonstrate the feasibility of the proposed method with variation of radiation, we test it in MATLAB/SIMULINK at different values of radiation (Figs. 33.8 and 33.9).

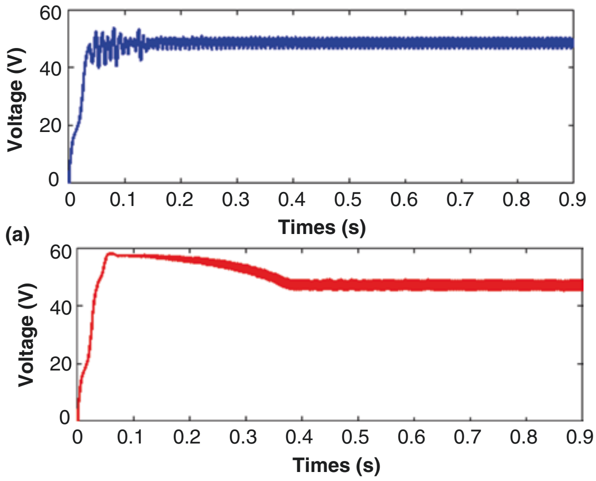


**Fig. 33.6** Output voltage of the PV panel (**a**) proposed SMC, (**b**) classical P&O

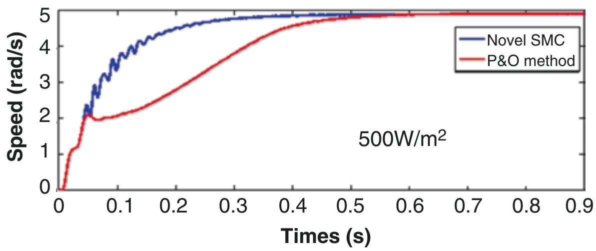


**Fig. 33.7** Output characteristics of the motor speed with novel SMC and P&O method

# Conclusion

In this paper, an online novel strategy of sliding mode control is developed to optimize the functioning of the global PV water pumping system driven by DC motor and coupled to a centrifugal pump. The main concluding remarks are summarized as follows:

- The obtained simulation results have shown the good performance of the proposed controller in terms of accuracy of output power of the PV generator
- It has also shown the improvement of the stability of the output motor speed, which influences the efficiency of the pump
- Furthermore, the expected insensitivity of the proposed SMC commands against variation of radiation and temperature.

The proposed sliding mode control provides a highly online accurate tracking of the optimal point of the PV pumping systems driven by conventional electrical components, and can become a standard regulator for optimizing such systems.

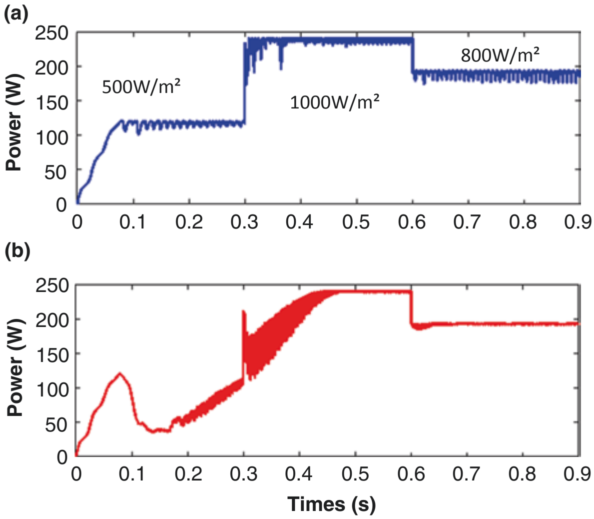


Fig. 33.8 Output power of PV panel at different value of radiation. (a) Proposed SMC, (b) P&O method

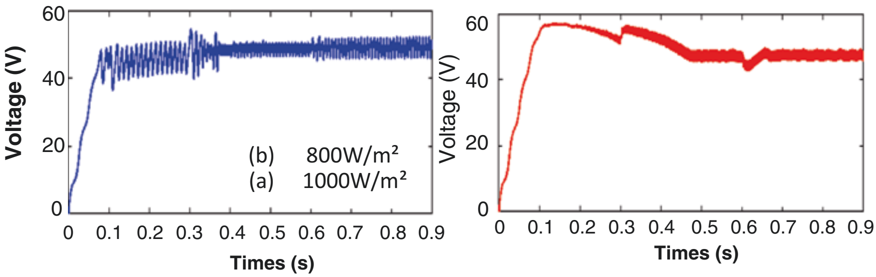


Fig. 33.9 Output power of PV panel at different value of time

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