International Conference on Automation, Control Engineering and Computer Science (ACECS)
Proceedings of Engineering and Technology – PET
Vol.21pp.19-24

A new MPPT controller for a photovoltaic water pumping system

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***Abstract*—A power system consisting of Photovoltaic (PV) generator, DC motor pump and Boost converter for maximum power point tracking (MPPT) is considered in this paper. For given climatic conditions, The photovoltaic array output power is maximal when its voltage equals to a certain value. In the presence of temperature and irradiation variations, the duty cycle of the converter considered as the control law is adjusted continuously to track the maximum power point of the system. For the best robustness, a Backstepping controller is designed to be applied to the DC-DC converter in order to achieve the optimal PV array output voltage and to maximize the system power. This nonlinear control is based on Lyapunov functions assuring the local stability of the system. Simulations results at different operating conditions are given with MATLAB/SIMULINK, they show the best performance of the system when the proposed control law is applied.**

Keywords—Photovoltaic Pumping System; Boost DC/DC converter; Backstepping control; Maximum Power Point Tracking.

I. INTRODUCTION

Owing to the rising costs of traditional energy sources, the increase in environmentalism, and the energy source inexhaustibility, Solar energy is becoming today one of the most attractive sources of energy. The primary device for harnessing solar energy is the solar cell, which uses the photovoltaic effect to transform sunlight into electricity via a semiconductor device. Conditions such as cell parameters and atmospheric conditions (temperature and solar irradiation) affect the instantaneous PV array generated energy. Therefore, each PV module has only one Maximum Power Point (MPP) under particular conditions.

A DC-DC power converter, in this case a boost, which converts the DC power from one voltage level to another higher to the input voltage, has to be added at the output of the photovoltaic array to achieve the optimum voltage and to implement the MPPT. The MPP can be tracked through different MPPT algorithms that control the switching converter in order to obtain the maximum power under different conditions [1]-[2].There are various methods, some of them are based on the well-known principle of perturb and observe (P&O) [3]-[4],on sliding mode control method[5]-[6], artificial neuronal networks or fuzzy based algorithms [7]-[8].
In the first method mentioned above, P&O, the output power gets the equilibrium at MPP but it has an oscillatory behaviour and that point is not always achieved, and sometimes it obtains a local maximum instead of a global maximum. The artificial neural network and fuzzy logic control has a better performances but they require involved hardware and memories, and present complexities for real implementation.

In this work, we present a new methodology for the MPPT of a photovoltaic system consisting of a photovoltaic panel with a power electronic converter; the whole is feeding a motor pump group. This MPPT must usually be integrated with photovoltaic power systems so that the photovoltaic arrays should be able to deliver the available maximum power. The photovoltaic panel can only provide maximum power at optimal voltage which depends on irradiance, temperature, and panel state. In the presence of these variations the duty cycle of the converter, which is considered as the control variable, is adjusted continuously to track the maximum power point of the system. For the best robustness with respect these temperature and irradiation variations, the Backstepping technique is used to derive the control law and keep the PV power at its maximum. The stability of the control algorithm is demonstrated by means of Lyapunov analysis. Simulations results at different operating conditions are given with MATLAB /SIMULINK, they show the best performance of the system when the proposed control law is applied.

The paper is organized as follows. Section 2 presents the PV pumping system model, describing the model of the PV array, the boost converter and the DC motor pump. The proposed design of the Backstepping control to make the system track the MPP is developed in Section 3. Section 4 presents the simulation results and Section 5 describes the main conclusions.

II. PHOTOVOLTAIC PUMPING SYSTEM MODEL

The DC water pumping system is composed by a photovoltaic generator(PVG), boost converter, and electrical motor usually coupled to a centrifugal pump (Fig.1).

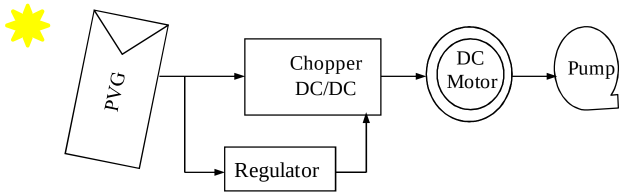

Fig 1. General diagram of the photovoltaic pumping system.

ISSN 2356-5608

A. *Model of the PV array*

The solar cell turns the light into electrical energy. Its well-known model consists of a current source I_{Ph} that represents the current generated by the photons, (it will be constant if the irradiation and the temperature are constants too), an anti-parallel diode D, a shunt electrical resistance R_{sh}, which represents the current leakage, and a series resistance R_s, which models the ohmic losses. PV cells are grouped in larger units called PV modules which are further interconnected in series-parallel configuration to form PV arrays or PV generators. The equivalent circuit of a PV module is shown in Fig.2.

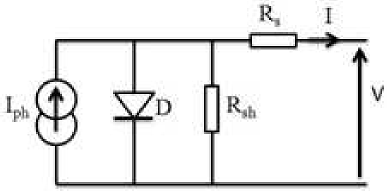

Fig. 2. Equivalent circuit of a PV module

The considered PV module in this paper is SM55. It has serries connected polycrystalline cells. The nonlinear current-voltage characteristic of a PV module is governed by this equation:

$$I = I_{Ph} - I_s\left[\exp\left(\frac{V + R_s I}{N\gamma V_T}\right) - 1\right] - \frac{V + R_s I}{R_{sh}} \qquad (1)$$

Where, I_{Ph} is the insolation current, I_s is the reverse saturation current, R_s is the series resistance, R_{sh} is the parallel resistance, V_T is the thermal voltage (KT/q) ,K is the Boltzman constant, T is the temperature in Kelvin, q is the charge of an electron, γ is the ideality factor. The PVG is composed by many strings of PV module in series, connected in parallel, in order to provide the desired values of output voltage and current of DC motor system [9]. The PV array mathematical model is represented by the equation:

$$i_P = I_{php} - I_{sp}\left[\exp\left(\frac{v_P + R_{sp} i_p}{N_s N\gamma V_T}\right) - 1\right] - \frac{v_P + R_{sp} i_p}{R_{shp}} \qquad (2)$$

Where i_P is the PV array output current; v_P is the PV array output voltage, N_s is the number of cells in series and N_p is the number of cells in parallel, $R_{sp} = R_s \dfrac{N_s}{N_p}$

$R_{shp} = R_{sh}\dfrac{N_s}{N_p}$; $I_{php} = N_p I_{ph}$ and $I_{sp} = N_p I_s$.

The cell reverse saturation current varies with temperature according to the following equation:

$$I_s = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{qE_{G0}}{\gamma k}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \qquad (3)$$

Where T_r is the cell reference temperature, I_{rr} is the cell reverse saturation at temperature T_r and E_{G0} is the band gap of the semiconductor used in the cell. The photo current depends on the solar irradiation and cell temperature as follows:

$$I_{ph} = \left[I_{SCR} + K_i\,(T - T_r)\right]\frac{\lambda}{1000} \qquad (4)$$

Where I_{scr} is the cell short-circuit current at reference temperature and radiation, K_i is the short-circuit current temperature coefficient, and λ is the solar irradiation in W/m^2.

B. *Model of Boost Converter*

The boost power converter used in this work, consists of power electronic components such as capacitor and inductor elements connected as is shown in the Fig.3.

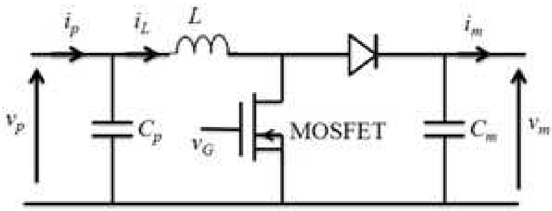

Fig. 3. Boost converter

In closed loop, the function of the control is to regulate the voltage of the solar module by means of the duty cycle, in order to achieve the maximum power. The input capacitor C_p and the inductor L are selected to limit ripple of the PVG input voltage and the output capacitor C_m to limit ripple of the output voltage. v_g is the switched control signal that can only take the discrete values 0 (opened switch) and 1 (closed switch).

Using the state averaging method [10], the switched model can be redefined by the average model as follows:

$\alpha + \beta = \chi.$ (1) (1)

$$\begin{cases} C_p \dfrac{dv_p}{dt} = i_p - i_L \\ L\dfrac{di_L}{dt} = v_p - (1-\alpha)v_m \\ C_m \dfrac{dv_m}{dt} = -i_m + (1-\alpha)i_L \end{cases} \qquad (5)$$

Where α is the averaging value of duty cycle, i_p and v_p are the average states of the output current and voltage of the PVG, i_L is the average state of the inductor current and v_m is the average state of the DC/DC converter output voltage.

C. *Dynamic Model of DC Motor and Centrifugal pump*

The mathematical model that describes the dynamic model of a DC motor with constant magnetic flux (Fig.4) can be expressed as follows [9]:

$$\begin{cases} v_m = R_m i_m + L_m \dfrac{di_m}{dt} + K_e \omega \\ C_{mot} - C_r = J \dfrac{d\omega}{dt} \end{cases} \tag{6}$$

where ω is the angular velocity, i_m is the motor current, v_m the motor voltage, J is the motor total inertia constant, $C_{mot} = K_m i_m$ and C_r are motor torque and resistant torque, R_m and L_m are resistance and inductance of armature circuit, K_e and K_m are electromechanical coupling constant and electric couple constant.

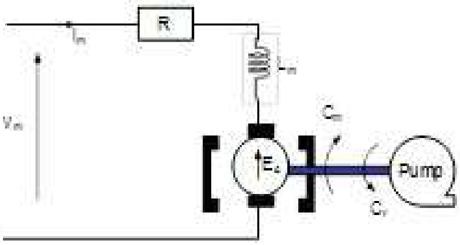

Fig. 4. Electrical model of the DC motor

For PV water pumping systems, two types of pumps are widely used: the volumetric pump and the centrifugal pump. This work is founded on the case of the centrifugal pump with the load characteristic is in closer proximity to the PVG maximum power locus [11]. The centrifugal pump opposes to the motor a resistant torque C_r which is given by the following equation [12]:

$$C_r = K_r . \omega^2 \tag{7}$$

Where K_r is the proportionality coefficient.

D. *Model of the Overall System*

The use of electrical and electromechanical equations governing the operation of the motor pump, PV generator and DC/DC boost converter makes it possible to give the nonlinear model of following state:

$$x = [x_1, x_2, x_3, x_4, x_5]^T = [v_p, i_L, v_m, i_m, \omega]^T \ ; \ u = \alpha$$

$$\begin{cases} \dot{x}_1 = -\dfrac{1}{C_p} x_2 + \dfrac{I_{php}}{C_p} - \dfrac{I_{sp}}{C_p}\left[\exp(\beta x_1) - 1\right] \\ \dot{x}_2 = -\dfrac{1}{L}(1-u)x_3 + \dfrac{1}{L} x_1 \\ \dot{x}_3 = -\dfrac{1}{C_m} x_4 + \dfrac{1}{C_m}(1-u)x_2 \\ \alpha + \beta = \chi. \qquad (1) \qquad (1) \\ \dot{x}_4 = -\dfrac{K_e}{L_m} x_5 + \dfrac{1}{L_m} x_3 - \dfrac{R_m}{L_m} x_4 \\ \dot{x}_5 = \dfrac{K_m}{J} x_4 - \dfrac{K_r}{J} x_5^2 \\ y = \dfrac{\partial P}{\partial V_p} \end{cases} \tag{8}$$

The MPPT method is based on the fact that the slope of the PV array power versus voltage curve $\dfrac{\partial P}{\partial v_p}$ equal to zero at the MPP. Due to the relatively high cost of the PVG, it is recommended to operate it at this MPP at all values of irradiation and temperature. Let us investigate $y = \dfrac{\partial P}{\partial v_p} = \dfrac{\partial (v_p i_p)}{\partial v_p} = i_p + v_p \dfrac{\partial i_p}{\partial v_p}$ is the controlled output.

After the second derivative of the output of the system we obtain the following expression:

$$\ddot{y} = f(x, t) + g(x, t)\, u \tag{9}$$

With

$$f(x,t) = \left(3\frac{\partial^2 i_g}{\partial x_1^{\,2}} + x_1 \frac{\partial^3 i_g}{\partial x_1^{\,3}}\right)\left(\frac{\partial x_1}{\partial t}\right)^2 + \frac{\partial^2 i_g}{\partial x_1^{\,2}}\left[\frac{1}{C_i^2}\frac{\partial i_g}{\partial x_1}(i_g - x_2)\right] - \frac{x_1}{C_i L_0}$$

and $g(x,t) = \left(2\dfrac{\partial i_g}{\partial x_1} + x_1 \dfrac{\partial^2 i_g}{\partial x_1^{\,2}}\right)\dfrac{x_3}{C_i L_0}$

III. BACKSTEPPING CONTROLLER DESIGN

The main objective of the proposed control is to extract the maximum power of the PVG. In order to do this, a Backstepping controller is designed to control the duty cycle of the boost converter, considered as the control law, to track the maximum power point of the system.

Backstepping design is a systematic recursive design procedure for nonlinear systems in strict feedback form, based on the choice of Lyapunov functions. The main concept of this design is to treat the system variable as an independent input for subsystems and each step results in a new virtual controller for the next step.

The virtual control law for each step is adopted with satisfaction of selected Lyapunov functions such that the stability of each subsystem can be guaranteed.

The main idea is to steer the output of the system (8) to zero in finite time, that the output voltage is forced to it optimal value and then the maximum power tracking is assured.

Our system is the second order; the design of the control can be obtained in two steps.

Backstepping design procedure:

Step 1. Let us introduce the following tracking error: $\varepsilon_1 = y - y_d$ with $y_d = 0$.

The first subsystem is considered:

$$\dot{\varepsilon}_1 = \dot{y} \tag{10}$$

The stabilization of ε_1 can be obtained by introducing a new virtual control $\alpha_1 = \dot{\varepsilon}_1 = \dot{y}$

Considering the first positive definite Lyapunov function:

$$V_1 = \frac{1}{2}\varepsilon_1{}^2 \tag{11}$$

The time derivative of V_1 is computed as: $\dot{V}_1 = \varepsilon_1\dot{\varepsilon}_1$ and must be negative definite.

We chose $\dot{\varepsilon}_1 = -k_1\varepsilon_1$. The time derivative of V_1 becomes $\dot{V}_1 = -k_1\varepsilon_1^2 < 0$, where k_1 is a positive constant.

The virtual control law would be:

$$\alpha_1 = -k_1\varepsilon_1 \tag{12}$$

Step 2: Let us propose the error variable considering the virtual controller as a reference, $\varepsilon_2 = \dot{y} - \alpha_1$. This next step must study the behaviour of the error ε_2 in order to achieve the control aim. The time derivative of this error is:

$$\dot{\varepsilon}_2 = \ddot{y} - \dot{\alpha}_1 \tag{13}$$

Substituting $\dot{y} = \varepsilon_2 + \alpha_1$ into equation (10), $\dot{\varepsilon}_1$ becomes: $\dot{\varepsilon}_1 = \varepsilon_2 + \alpha_1$

Introducing (11), we obtain the time derivative of ε_1 as $\dot{\varepsilon}_1 = -k_1\varepsilon_1 + \varepsilon_2$, and the time derivative of V_1 as:

$$\dot{V}_1 = -k_1\varepsilon_1^2 + \varepsilon_2\varepsilon_1 \tag{14}$$

Considering the final Lyapunov function candidate:

$$V_2 = V_1 + \frac{1}{2}\varepsilon_2{}^2 \tag{15}$$

The time derivative of this function is:

$$\dot{V}_2 = \dot{V}_1 + \varepsilon_2\dot{\varepsilon}_2 \tag{16}$$

Combining (15) and (13), we obtain the following expression:

$$\begin{aligned} \dot{V}_2 &= -k_1\varepsilon_1^2 + \varepsilon_2\varepsilon_1 + \varepsilon_2\dot{\varepsilon}_2 \\ &= -k_1\varepsilon_1^2 + \varepsilon_2(\varepsilon_1 + f + g.u - \dot{\alpha}_1) \end{aligned} \tag{17}$$

$\alpha + \beta = \chi.$ (1) (1)

The real control u chosen to force $\dot{V}_2$ to be negative definite is given by:

$$u = \frac{-k_2\,\varepsilon_2 - \varepsilon_1 - f + \dot{\alpha}_1}{g} \tag{18}$$

$\alpha + \beta = \chi.$ (1) (1)

Where k_2 is a positive constant. The above choice yields:

$$\dot{V}_2 = -k_1\varepsilon_1^2 - k_2\,\varepsilon_2^2 < 0 \tag{19}$$

Which means that ε_1 and ε_2 converge asymptotically to the origin, which implies that $y = \frac{\partial P}{\partial v_p}$ converges asymptotically to the origin, fulfilling the tracking control objective. Therefore, the output power tracks the maximum power point of PVG.

$\alpha + \beta = \chi.$ (1) (1)

IV. SIMULATION RESULTS AND DISCUSSION

The performances of the proposed robust control design are illustrated through simulations In MATLAB /SIMULINK to validate the proposed control strategy to rapid temperature and solar irradiance change. A simulation study was made to illustrate the response of the system to solar irradiance λ and array temperature T variation. For this purpose, the irradiance λ and array temperature T, which are initially at $\lambda = 800W/m^2$ and $T = 289.15K$, are respectively switched at 5s and 10s to $\lambda = 1200W/m^2$ and $T = 319.15K$ as shown in the simulation figures.

$\alpha + \beta = \chi.$ (1) (1)

Fig.5 shows in detail, the dynamic variation of the MPPT in diverse changes of temperature and solar irradiation. In the power-voltage characteristic, It can be noted that the output power of the PV array reaches after a smooth transient response without oscillations.

$\alpha + \beta = \chi.$ (1) (1)

Fig.6. Shows the converter duty cycle behaviour, which is chosen as the controller law, it is adjusted by the backstepping technique to track the MPP.

Fig.7 allows proving the well tracking of the PVG output voltage v_g when solar irradiance and array temperature change.

Fig.8 and Fig.5 show that for any solar irradiance and array temperature, the PVG power perfectly follows the MPP.

While the primordial objective in the end of this work is to make system pumps the maximum water quantity at given climate state, then the DC motor speed should be also maximal, and Fig.10 shows the motor speed track clearly the maximal value.

Fig.11 shows that for the solar irradiance and array temperature variation, the output of the system (y) converge to zero and the maximum PV power is reached.

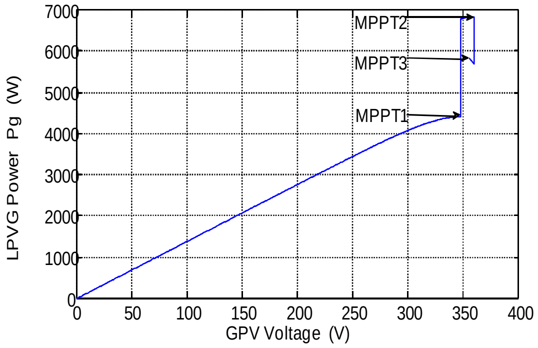

Fig.5. Behavior of the PVG power to track the MPP for different solar irradiance and the array temperature.

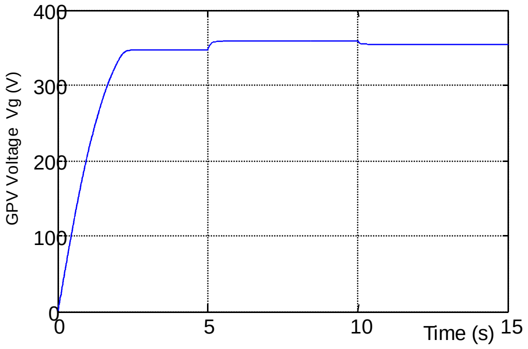

Fig. 7. Behaviour of the PVG output voltage for different solar irradiations and temperatures

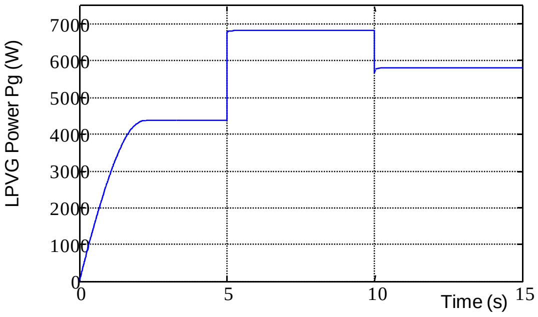

Fig.8. PVG power evolution with irradiation and temperature

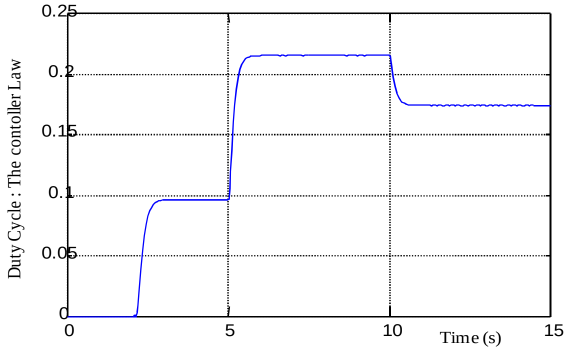

Fig.6. Wave form of backstepping control law $\alpha(t)$ with irradiation and temperature variation.

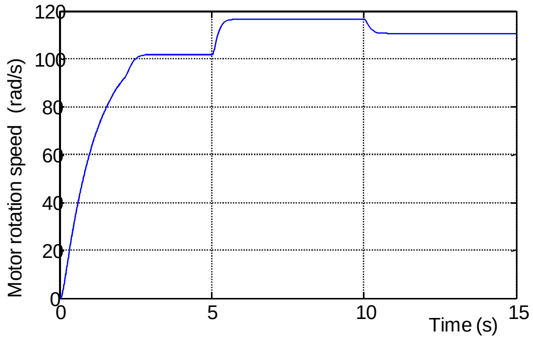

Fig.9. Motor rotation speed evolution with irradiation and temperature variation.

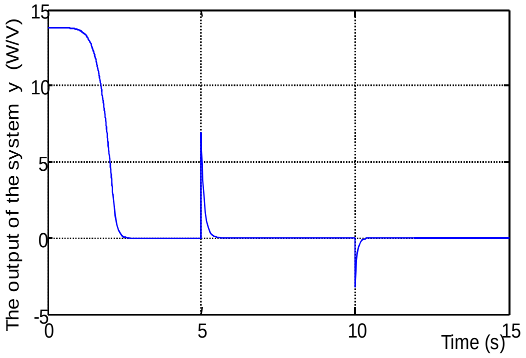

Fig.10. Wave form of the output $y(t)$ of the system for different solar irradiation and temperature.

V. APPENDIX

In this section, the specifications of the system are presented in the following tables:

TABLE I
ELECTRICAL PARAMETERS OF PV PANEL (SM55)

Parameter	Name	Value
R_s	Series resistance.	0.1124Ω
R_{sh}	Parallel resistance.	6500Ω
N_s	Number series PV.	20
N_p	Number parallel PV.	5
γ	Ideality factor.	1.7404
I_{scr}	Short circuit current at 298.15K and $1000W/m^2$.	3.45A
I_{rr}	Cell saturation current at short circuit current.	$4.842\mu F$
K_i	Temperature coefficient.	$4.10^{-4} A/K$
T_r	Reference temperature.	298.15K

TABLE II
ELECTRICAL PARAMETERS OF DC/DC CONVERTER

Parameter	Name	Value
L	Converter inductance	$3.5mH$
C_p	Input capacitance	$4700\mu F$
C_m	Output capacitance	$470\mu F$

TABLE III
ELECTRICAL AND ELECTROMECHANICAL PARAMETERS OF DC MOTOR (ABBDMI 180 B)

Parameter	Name	Value
V_{mn}	Motor Nominal Voltage	$400V$
I_{mn}	Motor Nominal Current	$12.2A$
ω_n	Nominal Rotation Speed	$104.7 rad/s$
R_m	Motor resistance	9.84Ω
L_m	Motor inductance	$0.12H$
J	Motor total inertia	$0.03Kg/m^2$
K_e	Electromechanical coupling constants	$2.674V.s/rad$
K_m	Electric couple constant	$2.541N.m/A$
K_r	Proportionality coefficient of resistant torque	$2.810^{-2} N.m.s^2/$

VI. CONCLUSION

In this paper, a new MPPT control strategy, based on the Backstepping technique, was shown. A Backsepping controller is derived and applied to a photovoltaic system in order to track the optimal operating point. The system is consisting of a photovoltaic panel with a boost converter; the whole is feeding a motor pump group. Backstepping design is a systematic recursive design procedure for nonlinear systems in strict feedback form, based on the choice of Lyapunov functions to assure the local stability of the system. The proposed control diagram is very simple; from a global nonlinear model of the PV system, a nonlinear control law is calculated and applied to the power switch. The drive system performance has been simulated for different solar irradiations and temperature, and it's found to be satisfactory. The simulation shows that the use of the proposed controller gives good results for the maximum power tracking

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