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Comparative study of three MPPT methods for Photovoltaic systems

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Abstract

In order to ensure that the photovoltaic (PV) module always operates at the maximum power point for any weather conditions, a maximum power point tracking (MPPT) system is indispensable. This paper presents a comparative analysis of three methods MPPT: Perturb and observe (P&O), Fuzzy Logic Controller (FLC) and Backstepping Controller. The parameters considered for the comparison are the performance of these MPPTs such as the extracted power from the PV system, steady and dynamic response of the system under various conditions like changing solar irradiance or temperature. Simulations results, obtained by using MATLAB/Simulink, shown that the MPPT controller based on the Backstepping technique is the most robust controller under changing conditions.

Key Words: Maximum Power Point Tracking (MPPT), Backsteping, P&O, FLC, Photovoltaic (PV) System, Boost Converter

1. Introduction

In Vietnam, more than half a million people do not have access to electricity. They are mainly in mountainous regions or on islands. Moreover, our country has great potential for renewable energy such as solar, wind, hydroelectric, biomass power (Dang, 2014). In this context, these sources of energy can be regarded as promising solution that are both economically and environmentally sustainable for supplying electrical power. Solar energy is the most suitable source to supply villages with electricity because of the plentiful solar radiation and relatively easy maintenances of the structures.

Maximum power point tracking (MPPT) plays an important role in PV power systems because it maximizes the power output from a PV system, thus an MPPT can minimize the overall system cost. Over the years, many MPPT algorithms have been developed and implemented, ranging from simple to more complex methods depending on the weather conditions and the application (Al Nabulsi and Dhaouadi, 2012; Alik and Jusoh, 2017; Karami et al., 2017; Salas et al., 2006; Subudhi and Pradhan, 2013).

Numerous MPPT methods have been discussed in the literature; the Perturb and Observe (P&O) Methods (Karami et al., 2017) (Femia et al., 2005) , the Incremental Conductance (IncCond) Methods (Safari and Mekhilef, 2011) and the Fuzzy Logic Controller (FLC) Method (Tran et al., 2017) (Huynh, 2012) (Al Nabulsi and Dhaouadi, 2012)

In this study, a Backsteping controller is proposed and designed to implement the MPPT algorithm. A comparative study with P&O, FLC was conducted and show the effectiveness of the approach proposed. The parameters considered for the comparison are the performance of these MPPTs such as the extracted power from the PV system, steady and dynamic response of the system under changeable conditions like the temperature and the irradiation.

This paper is structured as follows. Section 2 explains the mathematical modelling of PV system and DC-DC Boost converter. Section 3 describes the different MPPT techniques in this work. The simulation results and conclusion are presented in Section 4 and 5, respectively.

2. Mathematical modelling of PV system

2.1. Solar cell model

A solar PV system configuration can be very simple, which have only two components (PV panel and load), or it can be complex, containing several components such as power source, controllers, energy storage units. In this work, the PV system consists of a solar module, a DC/DC converter, in this case a Boost converter, connected to a resistive load, and a MPPT algorithm.

In this study, a PV cell is represented by a current source. The photocurrent I_{ph} depends on the irradiation G and the cell temperature T_c (Figure 1).

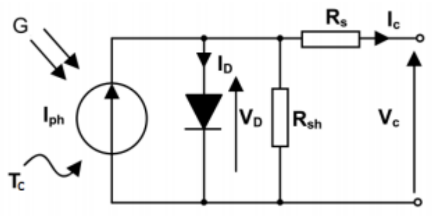

Figure 1 PV Module equivalent circuit.

The characteristic equation is:

$$I_c = I_{ph} - I_0\left(\exp\frac{e(V_c + R_s I_c)}{nkT_c} - 1\right) - \frac{V_c + R_s I_c}{R_{sh}} \quad (1)$$

Where:

I_0 is the saturation current;
e is the charge of an electron;
k is Boltzmann's gas constant;
n is the idealizing factor of the diode.
R_s represents the losses due to the contacts as well as the connection
R_{sh} represents the leakage currents in the diode

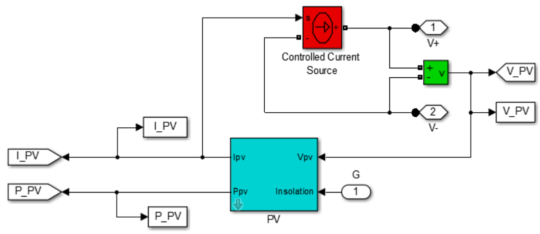

Figure 2 Implemented MATLAB Simulink.

Based on the mathematical equation (1), a dynamic model for a PV module has been developed by using MATLAB/Simulink as shown in Figure 2.

2.2. DC-DC Boost converter

The MPPT is achieved by adding a power converter between the PV generator and the load. In order to track MPP, the converter must be operated with duty cycle corresponding to it. A Boost converter is a DC to DC converter with an output voltage greater than the source voltage, as shown in Figure 3

$$V_{out} = \frac{V_{in}}{1-D} \quad (2)$$

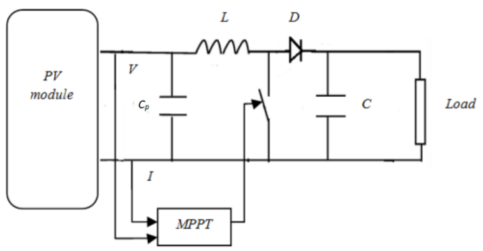

Figure 3 PV system with DC-DC Boost converter

3. MPPT algorithms for PV generator

The PV systems operation depends strongly on temperature, irradiation and the load characteristics. When a direct connection is carried out between the source and the load, the output of the PV module is not optimal. To overcome this problem, it is necessary to add an adaptation device. MPPT controller with a Boost DC-DC converter is presented in this section.

3.1. Perturbe and Observe (P&O)

This is one of the simplest and most popular methods of MPPT because it does not require any prior knowledge of the system or any additional sensor except the measurement of the power. The principle of algorithm is keep perturbing the control variable in the same direction until the power is decrease as shown in Table 1.

Table 1 Summary of P&O algorithm

Perturbation	Change in power	Next perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

Choosing a step size is a very important task in this method. A larger step size leads to a faster response but more oscillations around the MPPT point. On the other hand, a smaller step-size improves efficiency but reduces the convergence speed.

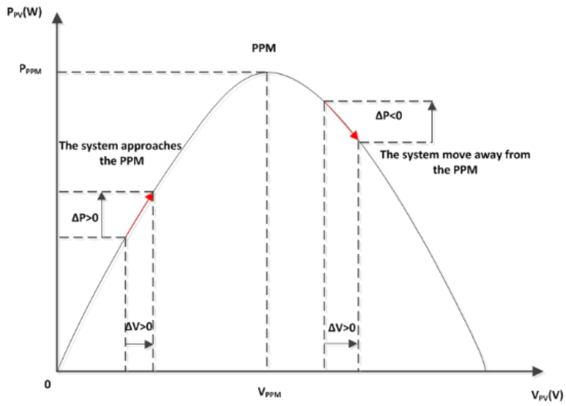

Figure 4 Principle of P&O method.

The principle of P&O method is presented by the flow chart in Figure 5.

3.2. Fuzzy control

The advantages of fuzzy logic controller (FLC) over the conventional methods are: (a) it does not need an accurate mathematical model; (b) it can work with imprecise inputs; (c) it can handle nonlinearity; and (d) it is more robust than conventional nonlinear controllers (Raviraj and Sen, 1997).

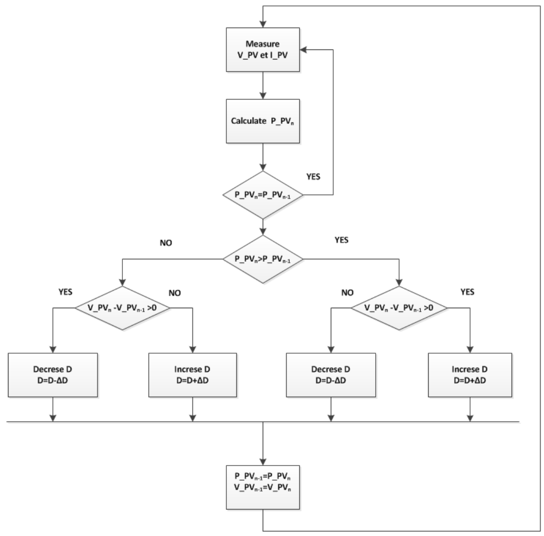

Figure 5 Flowchart of the P&O algorithm

FLC consists of four major elements: fuzzification, rules, interference engine and defuzzification as shown in Figure 6.

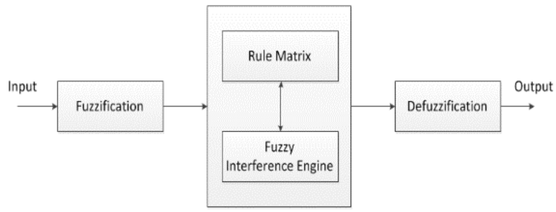

Figure 6 Principle of Fuzzy logic controller.

To implement the FLC for MPPT algorithm, the input and output variables should be determined. In this study, two inputs are considered: change in PV power (dP/dV) and its derivative. The output is duty cycle D of the Boost converter.

The output given as:

$$D(n) = D(n-1) + \Delta D(n) \quad (3)$$

<u>Membership Functions:</u> The input and output variables are expressed by linguistic variables. The linguistic terms used are:

• dP/dV [VeryNegative, Negative, Zero, Positive, VeryPositive] (Figure 7)

• (dP/dV)’ [Negative, Zero, Positive] (Figure 8)

The five various terms of (dP/dV) and three terms of its derivative (dP/dV)' are shown in the Table 2.

Table 2 Rules of ΔD.

ΔD		$(dP_{PV}/dV_{PV})'$		
		Negative	Zero	Positive
dP_{PV}/dV_{PV}	NB	3%	3%	3%
	NS	3%	1%	1%
	ZE	0%	0%	0%
	PS	-1%	-1%	-3%
	PB	-3%	-3%	-3%

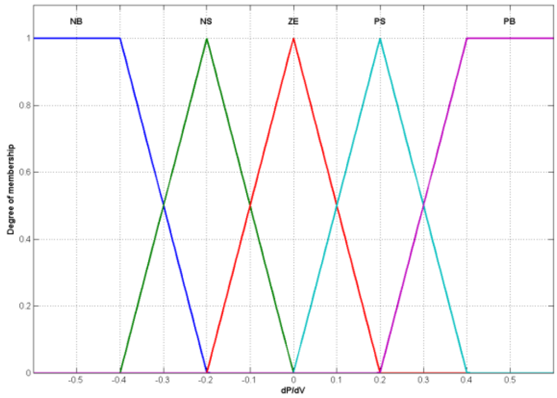

Figure 7 Membership Function (dP/dV)

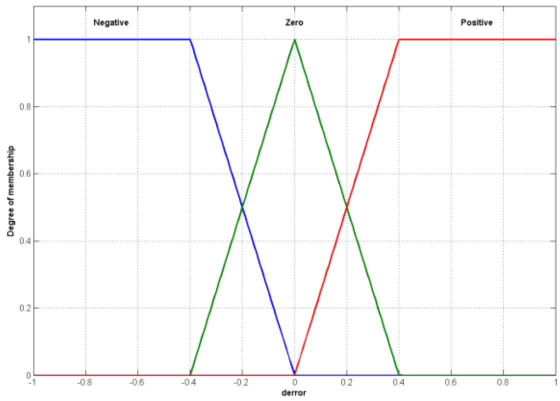

Figure 8 Membership Function (dP/dV)'

<u>The Control Rules:</u> The fuzzy rules are defined as follows:

IF (dP/dV) is A_i **AND** (dP/dV)' is B_i, **THEN** ΔD(n+1) is C_i

There are several known methods in order to get the output of inference. This paper used the min-max inference and Takagi-Sugeno system. They are designed to achieve zero error at the state of the Maximum Point Puissance (MPP). The idea is to bring operating point to MPP by increasing or decreasing the duty ratio D. If the operating point is distant from the MPP, the duty ratio D will increase or decrease largely.

<u>Defuzzification:</u> After the fuzzification, the defuzzification is performed which converts the fuzzied value into defuzzied value. This study used the centre gravity defuzzification method. The weighting factor is obtained by minimum operation, which is given by:

$$w_i = \min\left\{\mu_{dP/dV}, \mu_{(dP/dV)^*}\right\} \quad (4)$$

The final output of the system is the weighted average of all rules output:

$$\Delta D(k) = \frac{\sum_{i=1}^{N} \omega_i C_i}{\sum_{i=1}^{N} w_i} \quad (5)$$

3.3. Backstepping MPPT control

The Backstepping method is based on the statement of errors in function of the system parameters and instructions. The main objective is to reset these errors to zero by applying the control law respecting the *Lyapunov* stability conditions (Hassan, 2001).

In this work, the objective of Backstepping controller is to keep the ration $\partial P / \partial V = 0$. The development of the control law imposes a general knowledge of the model of the system. The equations of the system in the Figure 3 defined are:

$$\begin{cases} C_p \dfrac{dV_{PV}}{dt} = i_{PV} - i_L \\ L\dfrac{di_L}{dt} = V_{PV} - (1-\alpha)V_{DC} \\ C\dfrac{dV_{DC}}{dt} = (1-\alpha)i_L - i_{DC} \end{cases} \quad (6)$$

The variable of our control is:

$$y = \frac{\partial P_{PV}}{\partial V_{PV}} = i_{PV} + V_{PV} \frac{\partial i_{PV}}{\partial V_{PV}} \quad (7)$$

The purpose of the Backstepping command is to assume a variable y, whose value is equal $\frac{\partial P_{PV}}{\partial V_{PV}}$,then make this variable move towards a reference $y_{ref} = 0$.

The control is based on two main steps.

Step 1 : The first error considered in designing the Backstepping controller is : $z_1 = y - y_{ref}$ with $y_{ref} = 0$.

The tracking error derivative is written as follows:

$$\dot{z}_1 = \frac{1}{C_P}(i_{PV} - i_L)(2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}}) \quad (8)$$

To study the stability of the system, we introduce the 1st function of Lyapunov: $V_1 = \frac{1}{2}z_1{}^2$

Deriving it we obtain the equation:

$$\dot{V}_1 = z_1(\frac{1}{C_P}(i_{PV} - i_L)(2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}})) \quad (9)$$

The stability condition of the Lyapunov function requires that its derivative be strictly negative. The choice of $\dot{V}_1 = -k_1 z_1$ lead us $\dot{V}_1 < 0$

$$\frac{1}{C_P}(i_{PV} - i_L)(2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}}) = -K_1 z_1 \quad (10)$$

Where K_1 is the positive coefficient representing design constant.

As i_L is not the effective command of the system, it behaves as a virtual control input, we pose γ_1 whose is considered as the desired value for i_L and called the first stabilization function. We can obtain the equation:

$$\gamma_1 = i_{PV} + \frac{K_1 C_p}{2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}}} z_1 \quad (11)$$

Step 2 : We consider the second errors as z_2 :

$$z_2 = i_L - \gamma_1 \quad (12)$$

Its derivate is:

$$\dot{z}_2 = \frac{1}{L}\left[V_{PV} - (1-\alpha)V_{DC}\right] - \dot{\gamma}_1 \quad (13)$$

Substituting (13) into (8) and (9), gives that

$$\dot{z}_1 = \frac{1}{C_P}(2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}})(i_{PV} - z_2 - \gamma_1) \quad (14)$$

$$\dot{V}_1 = -K_1 z^2{}_1 - \frac{1}{C_P}(2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}}) z_1 z_2 \quad (15)$$

Introduce the 2nd candidate function of Lyapunov: $V_2 = \frac{1}{2}z_1{}^2 + \frac{1}{2}z_2{}^2$

Its derivate is:

$$\dot{V}_2 = -K_1 z^2{}_1 - \frac{1}{C_P}(2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}}) z_1 z_2 + \frac{1}{L}\left[V_{PV} - (1-\alpha)V_{DC}) - \dot{\gamma}_1\right] z_2 \quad (16)$$

The stability condition of Lyapunov's 2nd candidate function imposes $\dot{V}_2 < 0$ so:

$$-\frac{1}{C_P}(2\frac{\partial i_{PV}}{\partial V_{PV}} + V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2{}_{PV}}) z_1 + \frac{1}{L}\left[V_{PV} - (1-\alpha)V_{DC}\right] - \dot{\gamma}_1 = -K_2 z_2 \quad (17)$$

Where K_2 is the positive coefficient representing design constant.

Finally, we obtain the control law of DC-DC Boost converter for maximum power tracking given by equation

$$\alpha = \frac{L}{V_{DC}}\begin{bmatrix} -K_2 z_2 + \frac{1}{C_P}\left(2\frac{\partial i_{PV}}{\partial V_{PV}} + \right. \\ \left. V_{PV}\frac{\partial^2 i_{PV}}{\partial V^2_{PV}}\right) z_1 + \frac{1}{L}(V_{DC} - V_{PV}) + \dot{\gamma}_1 \end{bmatrix} \quad (18)$$

4. Simulation results

The system is implemented in MATLAB Simulink as show in Figure 9.

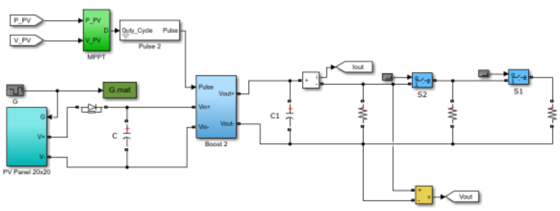

Figure 9 Implemented MATLAB Simulink.

The model parameters used in the simulation are given in Table 3. The PV array is made of 20 strings of 20 series connected modules each other, connected in parallel. All modules are considered to be identical, and to work in the same conditions of temperature and irradiance.

Table 3 The PV model parameters at G=1000W/m^2

I_{sc}	1 A
V_{oc}	19,34 V
I_{mpp}	0.904 A
V_{mpp}	15.138 V
P_{mpp}	13.69 W

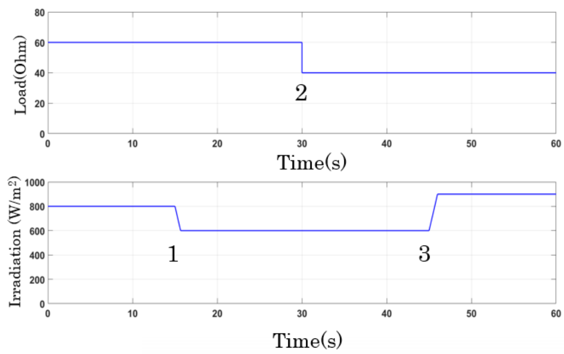

Figure 10 Various climatic and operating conditions

Irradiation and load demand are varied within 60 seconds to test the controllers in various climatic and operating conditions.

In the first 15 seconds, the system operates in G=800 w/m^2 and T=25 °C. Our controller has chosen the good value of D to make power generated around 4.56 kW. From 15th seconds to 45th seconds, when the irradiation decreases from 800 w/m^2 to 600 w/m^2, the PV system moves toward to the new MPP. The controller adjusts the duty cycle which make power around 3.9 kW. Other tests are also applied when irradiation increases from 600 w/m^2 to 900 w/m^2. From the simulation results, when irradiation changes, P&O, FLC and Backstepping controller work well to track the MPP of the PV array (at the 15th second, 45th second) to produce the maximum power output. Besides, the Figure 11 show that the controller also works well to track the maximum power point when load demand change at 30th second.

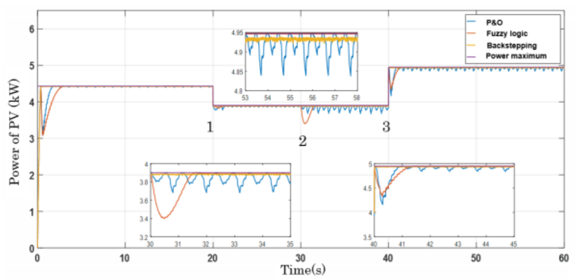

Figure 11 Power output under varying irradiation and load

Table 4 Tracking efficiency of MPPT

	Method		
	Back-stepping	Fuzzy Logic	P&O
Response time (variation of irradiation)	0.022 0.05	1.2 1.4	1.5 1.5
Response time (variation of load)	0.02	1.5	0.5
Convergence speed	Very fast	Average	Average

However, these results still have some oscillations in P&O method because of non-linear voltage-current characteristic in the PV systems, but it does not affect the result. Compared with P&O method and FLC, a

Backstepping controller not only get a quick response under various conditions but also had small oscillation at the maximum power point and small transient response time as shown in Table 4.

5. Conclusion

This paper presents simulation of three MPPT algorithms based respectively on the P&O, the fuzzy logic and the sliding mode for Photovoltaic Energy Conversion System. Based on the simulation results it can be concluded that with both P&O, FLC and Backstepping controller can track the maximum power. However, the MPPT controller based on the Backstepping approach is the most robust controller under changing conditions, the transient response time is very small.

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