Comparison of Fuzzy and Neuro-Fuzzy Controllers for Maximum Power Point Tracking of Photovoltaic Modules

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Abstract. The paper make a comparison among two control methods for maximum power point tracking (MPPT) of a photovoltaic (PV) system under varying irradiation and temperature conditions: the fuzzy control method and the neuro-fuzzy control method. Both techniques have been simulated and analyzed by using Matlab/Simulink software. The power transitions at varying irradiation and temperature conditions are observed and the power tracking time realized by the fuzzy logic controller against the neuro-fuzzy logic controller has been evaluated.

Key words

Photovoltaic Module; MPPT; Fuzzy Logic Controller; Neuro-Fuzzy Logic Controller; Matlab/Simulink models.

1. INTRODUCTION

Electrical energy generated by Photovoltaic Power Plants is becoming increasingly important due to its advantages: incurring no fuel costs, not being polluting, required little maintenance, and emitting no noise, among others.

The photovoltaic current-voltage (*I-V*) characteristic is nonlinear and changes with irradiation and temperature. There is a point on the *I-V* characteristic or on the power-voltage (*P-V*) characteristic, called the Maximum Power Point (MPP), at which PV module produces the maximum output power corresponding to the current values of solar irradiation and cells' module temperature. The state-of-the-art techniques to track the maximum available output powers of PV systems are called the maximum-power point tracking (MPPT). Controlling MPPT for the solar array is essential in a PV system in order to reduce the cost of yielded electrical energy. There are many techniques developed to implement MPPT; these techniques are different in their efficiency, speed, hardware implementation, cost, popularity.

In this paper, intelligent control techniques using fuzzy logic control and neuro-fuzzy logic control are associated to an MPPT controller in order to improve energy conversion efficiency. Simulation and analysis in Matlab/Simulink environment of these control techniques are presented, and its performances are evaluated.

2. THE MODEL AND CHARACTERSITICS OF A PV MODULE

The PV cell equivalent electric circuit can be represented as in Fig. 1. It consists in an ideal current source (I_{PV}), an ideal diode, a parallel resistor (R_P) a series resistor (R_S). The current source I_{PV} is the light generated current which is directly proportional to the solar irradiation G (measured in W/m^2). The series and the parallel resistances are representative for the voltage loss on the way to the cell terminals and for the cell's leakage current, respectively.
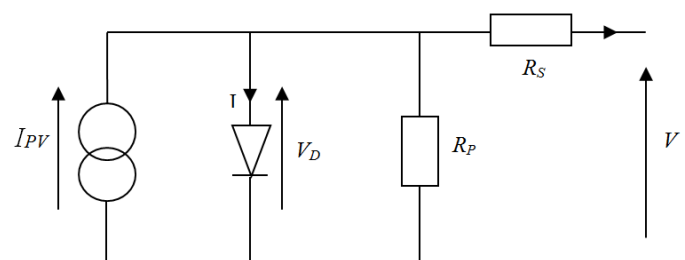
Fig. 1 Equivalent circuit of a PV cell

For a PV module, with ns cells in series and np cells in parallel, the characteristic I-V is given by the equation (1):

$$I = n_p I_{PV}$$

$$- n_p I_0 \left(\frac{T_C}{T_{ref}}\right)^3 e^{\frac{qE_g}{ak}\left(\frac{1}{T_{ref}} - \frac{1}{T_C}\right)} \left[e^{\frac{q(V+IR_S)}{akT_C n_S}} - 1\right] - \frac{V + IR_S}{R_P} \quad (1)$$

where I_0 is the reverse saturation current of the diode, E_g is the value of the energy band of the diode material, a is the ideality factor of the diode, k is the Boltzmann's constant, q is the electron charge, and T_C is cells' temperature in Kelvin.

The analyzed PV module has the electric specifications given in the TABLE 1.

TABLE 1: Specific Data of **BPMSX60** PV Module

Rated Power	60 W
Current at Maximum Point	3.25 A
Voltage at Maximum Point	16.8 V
Short circuit current	3.56 A
Short circuit voltage	21.6 V
Number of cells in parallel	1
Number of cells in series	36

For various values of the solar irradiance G, and cells' temperature T_C, the I-V characteristics of the analyzed PV module are shown in Fig. 2.
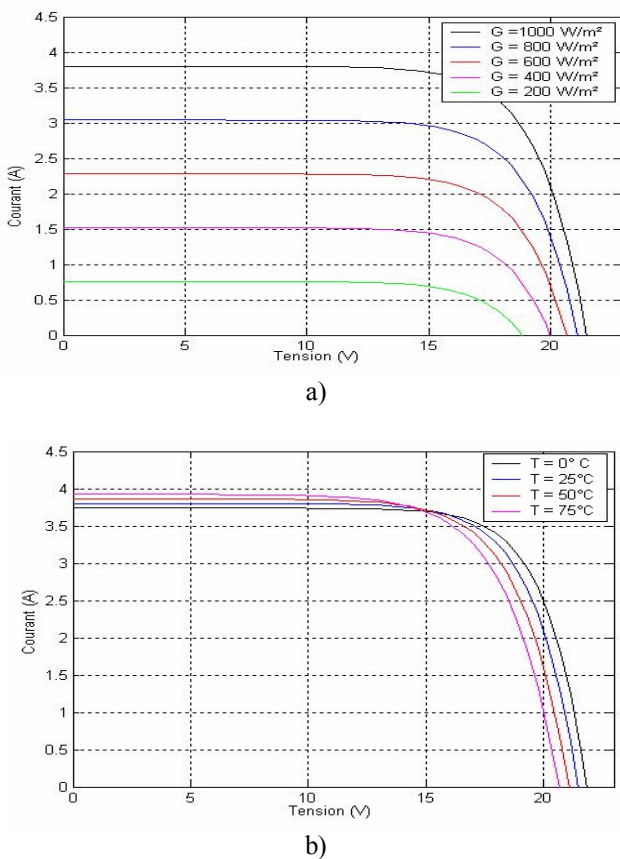

a)

b)

Fig. 2 The PV module PV characteristics for various values of G, and $T_C = 25\ ^0$C (a) and for $G = 1000$ W/m² and various values of T_C (b).

3. THE MPPT CONTROL STRATEGIES

In Fig. 3 is shown the block diagram of a PV module with MPPT controller. The controller performs a continuous research of the MPP, according to an appropriate algorithm. During this research, the controller acts on the duty factor d of the DC-DC converter in a manner that allows to the instant load connected to the PV module to extract the maximum power which the PV module is capable of produce at the current solar irradiation G and module cells' temperature T_C. The photovoltaic module operation depends on the load characteristics at which it is connected to. So when connected to load directly, the output of the PV array rarely works at MPP. However, to adapt the load and extract maximum power from a PV module, a DC-DC boost converter is used by adjusting its duty cycle under control of the selected controller (in our case fuzzy and neuro-fuzzy algorithms) based MPPT controller such that the maximum solar panel output power is extracted under all operating conditions. In Fig. 3, DC-DC converter is a step-up power converter.

The power flow through DC-DC converter is controlled by varying the duty factor d. The relationship between input and output voltages of DC-DC converter is given by equation (2):

$$\frac{V_O}{V_I} = \frac{1}{(1-d)} \quad (2)$$

where V_O is the output voltage and V_I is the input voltage of the boost converter.

A. The MPPT Controller With Fuzzy Logic

The general structure of a controller algorithm based on fuzzy logic consists of three stages: fuzzification, rule base and defuzzification. During fuzzification, numerical input variables are converted into linguistic variable based on a membership function. For the MPPT controller with fuzzy logic, the inputs are taken as a change in power and voltage as well. There is a block for calculating the error (E) and the change of the error (dE) at sampling instants k:

$$E(k) = \frac{dP}{dV} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \quad (3)$$

$$dE(k) = E(k) - E(k-1) \quad (4)$$

where $P(k)$ is the power of delivered by PV module and $V(k)$ is the terminal voltage of the module.

Value of the error $E(k)$ determines the MPPT controller output according to the sign. By example, if the operating point is located to the left of the MPP of the characteristic (P-V), the sign of the error $E(k)$ is positive and the reported load resistance to the PV terminal have to be increased. As a consequence, the duty factor d has to be decreased. Also, in order to avoid the final oscillations around the MPP, when
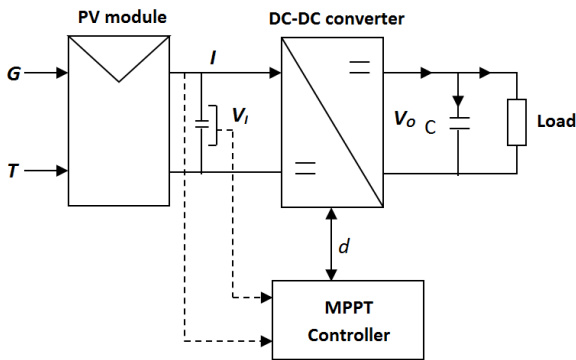
Fig. 3 The block diagram of a PV module with MPPT controller

Fig. 5 Matlab/Simulink window of the Fuzzy Logic Controller

the change of the error $dE(k)$ decreases, the speed of convergence to the operating point has to be reduced. As a consequence, the decreasing increment of the duty factor has to be reduced. This is the way the MPPT controller can decide what will be the variation of the duty cycle that must be impose on the DC-DC boost converter to approach MPP. Once $E(k)$ and $dE(k)$ are calculated and converted to the linguistic variables, the fuzzy logic controller output, which is duty ratio d of the power converter, can be looked up in a rule base table.

The linguistic variables assigned to the duty factor d for the different combinations of $E(k)$ and $dE(k)$ was established according to our knowledge.

In the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function.

In Matlab/Simulink environment, there is a Fuzzy Toolbox that allows to the user to manage this structure and formulate fuzzy rules. Using this tool the user can program the command used subsequently in the block Fuzzy Logic Controller with *Rule viewer*.

In Fig. 4 is shown the Matlab/Simulink model of a PV module with MPPT fuzzy logic controller, and in Fig. 5 is shown the Fuzzy Logic Matlab/Simulink windows which make up the MPPT controller (its inputs $E(k)$ and $dE(k)$, its output d and different parameters of the fuzzification, involving the aggregation and the defuzzification can be monitorized from this window).
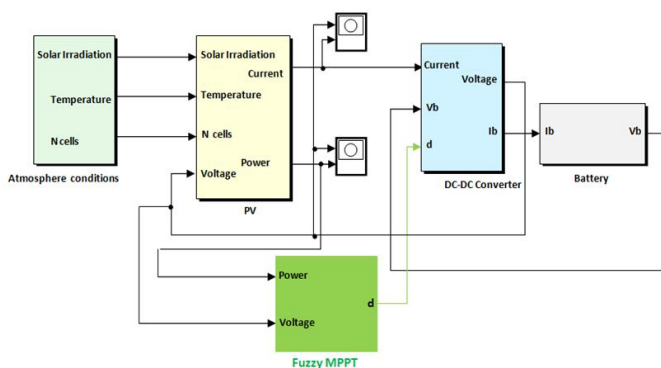

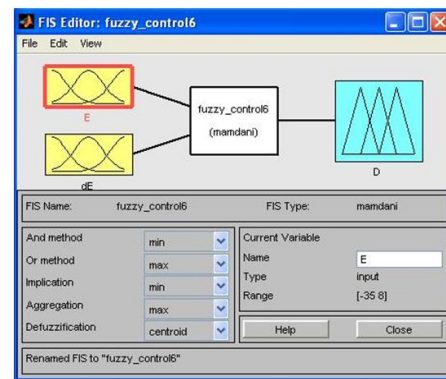Fig. 4 Simulink model of the PV module with MPPT fuzzy logic controller

In Fig. 6 is shown the structure of the fuzzy controller used from Simulink library.
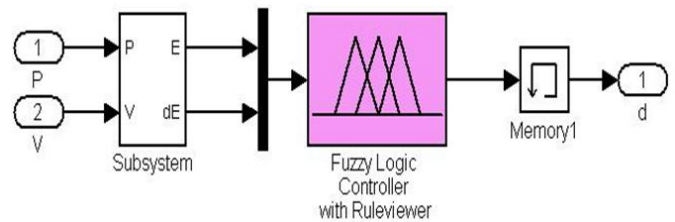

Fig. 6 Simulink Model of a fuzzy logic controller with Rule viewer

1) The Fuzzification:

The following linguistic variables have been used for the MPPT fuzzy controller: PG (positive big), PP (Positive Small), ZE (Zero), NP (negative small), NG (large negative).

The generation of the membership functions of these variables was performed based on user experience. After several tests under different atmospheric conditions, the $E(k)$ and $dE(k)$ variables have been defined for solving continuing problems of maximum power point. The five membership functions are given in Fig.7.

2) The Inference Rules:

For the MPPT fuzzy controller it was chosen the Mamdani type inference rules with logical operators MIN and MAX. These rules are introduced into the controller to obtain the right decision for its output d. In the TABLE 2 are shown the selected rules:

TABLE 2: The Fuzzy Logic Controller Inference Rules

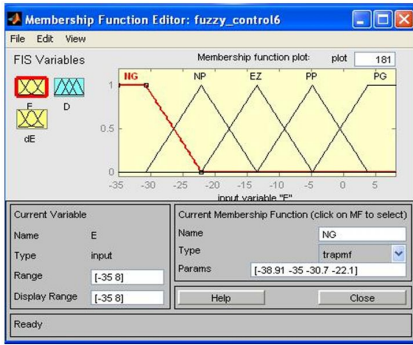| E	dE				
	NG	NP	ZE	PG	PP
NG	PG	PG	PG	PG	PG
NP	PG	PP	PP	PP	ZE
ZE	PP	PP	ZE	NP	NP
PG	NP	NP	NP	NP	NP
PP	NG	NP	NP	NP	ZE
NG	PG	PG	PG	PG	PG

Fig. 7 The membership functions of variables $E(k)$ and $dE(k)$

3) The Defuzzification:

This operation converts the inferred fuzzy control action into a numerical value at the output by forming the union of the outputs resulting from each rule. The method of the gravity center has been chosen for the defuzzification. In the Fig. 8 is shown the surface output $d = f(E, dE)$ of the MPPT controller.

B. The MPPT controller with neuro-fuzzy logic

This simulation is based essentially on the Matlab/Simulink toolbox ANFIS that combines in its structure five layers on a Fuzzy Inference System type Sugeno and, also, the possibility of introducing a learning table to take the advantage of the neuron network approach when passing from one layer to another.

In order to implement the MPPT neuro-fuzzy controller, for each of the two inputs E and dE were chosen five membership functions and was created a knowledge base. After the learning table has been loaded, for each input pair (E, dE) adequate
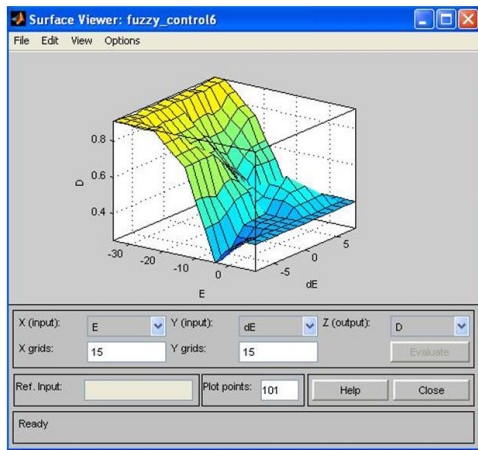

Fig. 8 The surface $d = f(E, dE)$ of the MPPT controller output.

output d = f (E, dE) were described, and file created in the fuzzy toolbox has been made, the neuronal structure was obtained. At this stage the Fuzzy and the learning table are loaded, and one can start learning to get the outputs generated by the ANFIS. In the Figure 9 is shown the surface of the MPPT neuro-fuzzy controller output d based on the appropriate entries.

TABLE 3: Simulation results of P_{max} checking with fuzzy and neuro-fuzzy controllers in comparison with theoretical values.

G [W/m2]	T [°K]	P_{max} [W]		
		Fuzzy Controller	Neuro-Fuzzy Controller	Theoretical values
1000	300	50,261	50.262	50,262
900	295	45,738	45.736	45,739
800	290	40,849	40.856	40,874
700	285	35,614	35.633	35,709
600	280	30,133	30.156	30,251

4. SIMULATION RESULTS

In TABLE 3 are given the theoretical and simulation results obtained with Fuzzy and Neuro-Fuzzy Controller, in checking the MPP of the analyzed PV module, for various values of solar irradiation G and cells' temperature T.

The Figure 10 and 11 shows the evolution of the power produced by the PV module delivered MPP checking by the considered algorithms, under the solar irradiation $G = 1000$ W/m^2 and PV cells' temperature $T_C = 300$ ^{0}K.
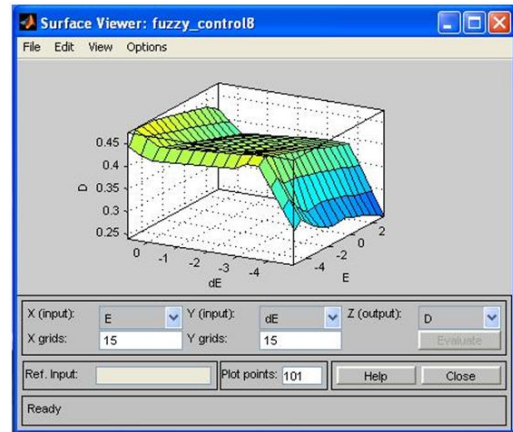

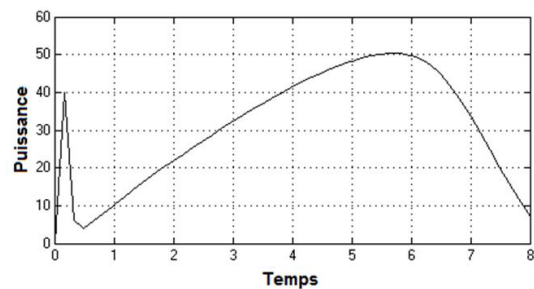Fig. 9 Surface Rule Viewer of Neuro-Fuzzy controller

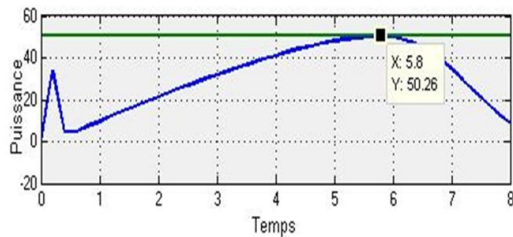Fig. 10 The power evolution during MPP checking by the fuzzy algorithm.

Fig. 11 The power evolution during MPP checking by the neuro-fuzzy algorithm.

5. Conclusion

Two MPPT control strategies based on Fuzzy Logic and Neuro-Fuzzy logic have been compared. It is found that the control of the DC / DC by the Neuro-Fuzzy approach more reliable than the other approach as it combines fuzzy logic and neural networks to extract the maximum power point, taking advantage of the flexibility of the first and the learning capacity of the second.

Acknowledgement

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