

# A distributed hybrid controller for photovoltaic panel under partial shading effect

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## Abstract

In this paper, a novel method of maximum power point tracking has been proposed. The Artificial neuronal network (ANN) was used to generate the reference of optimal voltage. While, the Integral feedback linearization controller was designed to pursue the reference voltage generated by the ANN controller. The integral action was introduced to ensure a zero-static error. In addition, to avoid the problems of mismatching and non-uniform solar insolation, each DC/DC converter has been integrated with each photovoltaic module. This topology is called Distributed Maximum Power Point (DMPPT). The tracking performances of the proposed method were tested and validated on the MATLAB/Simulink environment.

*Keywords: Artificial neural network, DMPPT topology, integral feedback linearization, partial shading Effect, PV panel*

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## 1. Introduction

The conventional energy has a real danger on our environment. The need of the clean power motivated researchers to develop the renewable energy that comes from the natural, non-polluting and inexhaustible sources. The power produced by the photovoltaic panel is not maximal and depends on the load and insolation. Several methods have been proposed to optimize the photovoltaic efficiency. Perturb and Observe (P&O) and Incremental conductance (IC) algorithms [1], [2] are widely used, thanks to their simplicity of implementation. However, these algorithms pose the trade-off between speed and accuracy. In [3], the author designed the Backstepping controller to improve the tracking performance of the IC command. While in [4], the same controller, combined with the P&O algorithm, was proposed. However, the system accuracy and speed have been marginally improved.

On the other hand, under the partial shading effect, the Power-Voltage curve (P-V) contains multiple Local Maximum Power Points (LMPP) and one Global Maximum Power Point (GMPP). Here, the methods previously proposed cannot differentiate between the LMPP and the GMPP. So, it tracks the first maximum found, which leads to the high drop in power. In [5], [6] and [7], the PSO, POC and OC&P commands were respectively proposed. These commands are able to pursue the GMPP, and consequently improve the photovoltaic (PV) panel efficiency. But, there is still a considerable drop in power under non-uniform insolation. The control topologies DMPPT and MIC presented respectively in [8] and [9], in spite of their cost which corresponds to the number of sensors and DC/DC converters, can extract the power of each PV module and consequently produce the higher power. In addition, these topologies avoid the use of the bypass diodes.

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In this paper, a hybrid method has been designed to pursue the maximum power point (MPP), this technique consists of two loops, the first one is ANN and the second one is Integral Feedback Linearization (IFL). The combination of these two algorithms makes it easy to track the desired point of power and makes the system fast and accurate whatever the insolation. Moreover, to have a system with good power efficiency under partial shading effect, each hybrid controller has been integrated with each DC/DC converter, obtaining hybrid DMPPT.

This paper is organized as follows, section 2 presents the modeling of the PV module and the BOOST converter. Section 3 is devoted to the description of the proposed hybrid method. Section 4 presents the simulation results by using MATLAB/SIMULINK environment. Finally, the conclusion is presented in section 5.

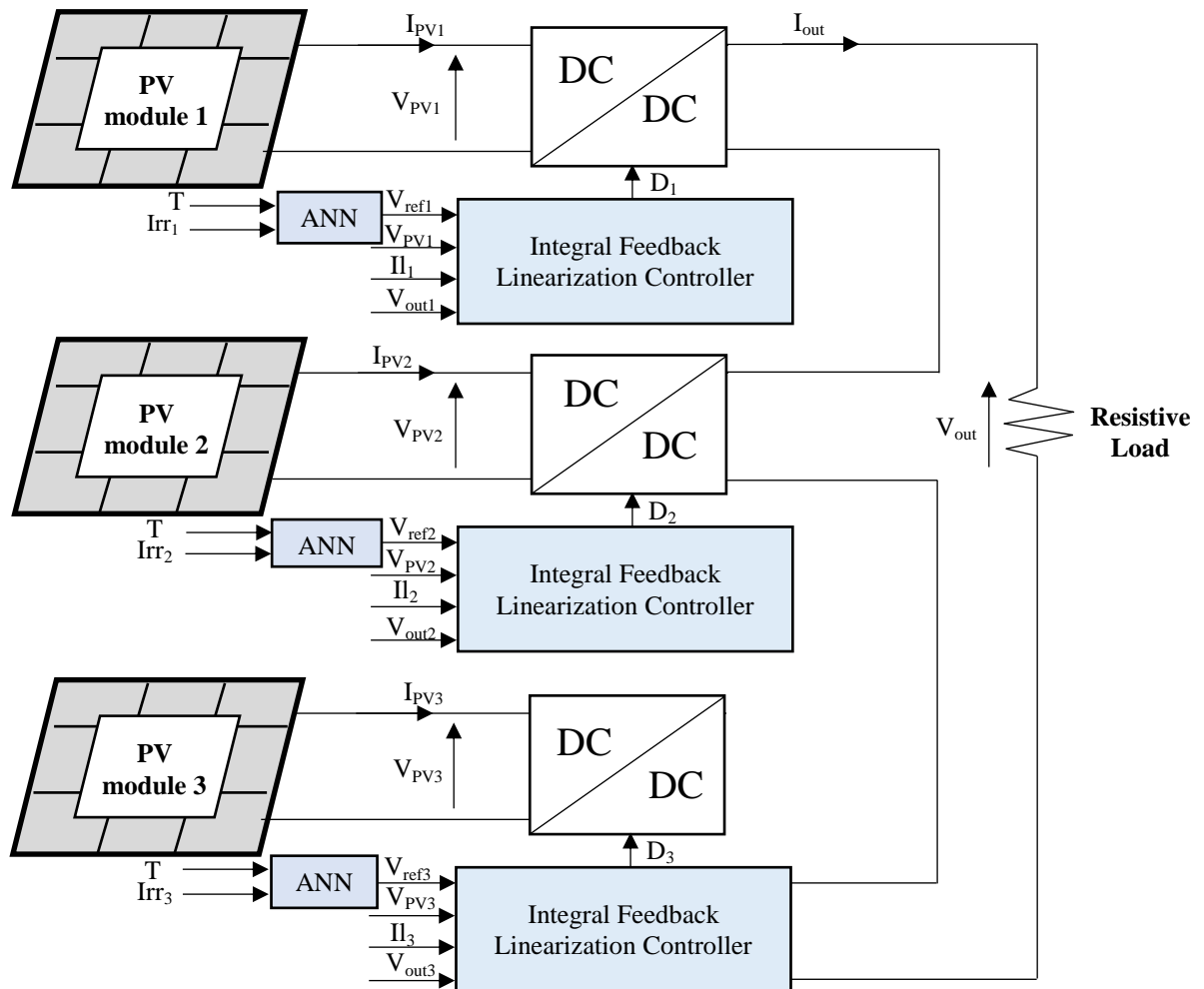


Fig. 1. Hybrid DMPPT technique.

## Nomenclature

$C_{out}$ : Output capacitor	$C_{PV}$ : Input capacitor	$\xi$ : Damping coefficient
$\omega_n$ : Cutoff pulse	D: Duty cycle	$I_l$ : Coil Current
$I_{out}, V_{out}$ : Output current and voltage	$I_{PV}, V_{PV}$ : Current and voltage of the PV module	$N_s, N_p$ : Number of series and parallel modules
$I_{cell}, V_{cell}$ : Current and voltage of the PV cell	$R_s, R_{sh}$ : Series and parallel resistor of the PV cell	IFL: Integral Feedback linearization
$\lambda$ : Ideality coefficient	L : Inductance of coil	$p_1$ : Additional pole
T: Temperature	$I_{tr}$ : Irradiation	$I_{ph}$ : Photo-current of PV cell
$V_t$ : Thermal voltage	y: Output variable to control	$y_{ref}$ : Output Reference
$k_1, k_2, k_3$ : The regulation parameters	$\varepsilon_y$ : Error between the output y and its reference	$I_s$ : Saturation current

## 2. Photovoltaic System

The proposed PV system consists of three BOOST converters connected in series, each one was integrated with each PV module. The DC/DC converter is an adaptation stage that serves to maximize the power of the PV module and adapt its power to the load. In this study, the load is a resistor. The proposed PV system is shown in Fig. 1.

### 2.1. Photovoltaic panel

The chosen photovoltaic panel consists of three PV modules (Reference: Siemens SM55), each one produces a power of 55W. The PV cell consists of a single diode  $D_i$ , the series resistor  $R_s$ , the parallel resistor  $R_{sh}$  and the photocurrent  $I_{ph}$ , as shown in Fig. 2. In practice, the series resistor is negligible while the parallel resistor is too high.

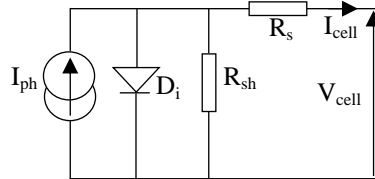


Fig. 2. Equivalent circuit of one diode PV cell.

The mathematical modeling of a PV panel composed of  $N_s \times N_p$  PV modules in series-parallel connection is given by:

$$I_{PV} = N_p I_{ph} - N_p I_s \left[ \exp\left(\frac{V_{PV}}{N_s N \gamma V_T}\right) - 1 \right] \quad (1)$$

With  $V_{PV}$  and  $I_{PV}$  are respectively the voltage and the current of the PV panel,  $\gamma$  is the ideality coefficient of the junction,  $V_t$  is the thermal voltage,  $N_s$  and  $N_p$  are respectively the number of the PV modules connected in series and in parallel,  $N$  is the number of cells in the PV module.  $I_s$  is the saturation current that depends on the temperature.  $I_{ph}$  is the photo-current that depends on both the irradiation and the temperature. The detailed modeling of the photovoltaic panel has been explained in [10].

### 2.2. BOOST converter

The photovoltaic panel is controlled by the BOOST converter (see Fig. 3) to produce the maximum power. This type of converters increases the voltage of the PV generator. The modeling of this component passes through the analysis of two operating sequences, which depend on the state of the switch K, this is well detailed in [11]. Using the average value method, the equation describing the BOOST operation is

given by the following nonlinear form:

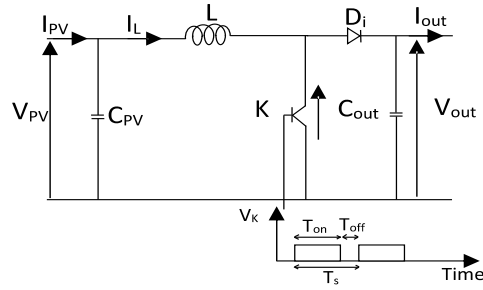


Fig. 3. The DC/DC boost converter.

$$\begin{cases} \frac{dV_{PV}}{dt} = \frac{1}{C_{PV}} I_{PV} - \frac{1}{C_{PV}} I_L \\ \frac{dI_L}{dt} = \frac{1}{L} V_{PV} - \frac{1}{L} (1 - D) V_{out} \\ \frac{dV_{out}}{dt} = \frac{1}{C_{out}} (1 - D) I_L - \frac{1}{C_{out}} I_{out} \end{cases} \quad (2)$$

### 3. Proposed System

The proposed method consists of two loops, the first loop is the Artificial Neural Network. This one is used to generate the optimal voltage, which corresponds to the maximum power. The second loop is the Integral Feedback Linearization, this one is designed to track the voltage reference generated by the first loop. These two controllers were associated to control the duty cycle of the DC/DC converter to produce the desired photovoltaic power. In addition, each hybrid controller has been integrated with each BOOST converter and PV module constituting the DMPPT topology.

#### 3.1. Artificial neural network design

The mathematical model of the Artificial Neural Network is inspired from the biological neuron, like the human brain. Indeed, a neuron is a unit capable of performing some elementary calculations, a number of units composes a network capable of solving more complex problem. The structure, size of the network and the learning mechanism used depend on the type and complexity of the application in question.

The design procedures of the neural network are summarized in three steps as following:

- Collection of the database: This step was done Off-line to acquire the input-output data. In this study, the ANN inputs are the irradiation and temperature while the output is the voltage.
- Choice of the Artificial Neural Network Architecture: In this step, the ANN Fitting Tool is used by typing 'nnstart' in the MATLAB command window. Then, the Fitting App is chosen to adjust the input-output curve. The neural network accuracy depends on the training database, the learning algorithm and the number of the hidden layers. For these reasons and to obtain the training performance shown in Fig. 4(a), the ANN is designed as follows: The input layer with two neurons: Irradiation and temperature. The hidden layer with 50 neurons, and the output layer with one neuron (the optimal voltage). The neural network is trained to adapt the input-output by choosing the Bayesian Regularization Backpropagation algorithm. Indeed, this latter requires more computing time than Levenberg-Marquardt backpropagation algorithm, but can result in good generalization for difficult, small or noisy data sets.
- Training and testing of the algorithm performances: This step is devoted to training the neuronal network to find the weights that minimize some measurement errors such as SSE (sum of

squared errors) or MSE (mean squared errors) [12]-[13]. The Bayesian Regularization Back-propagation algorithm previously discussed was used to minimize the mean square error (MSE). After the training process, it led to the performance summarized in Fig. 4(b).

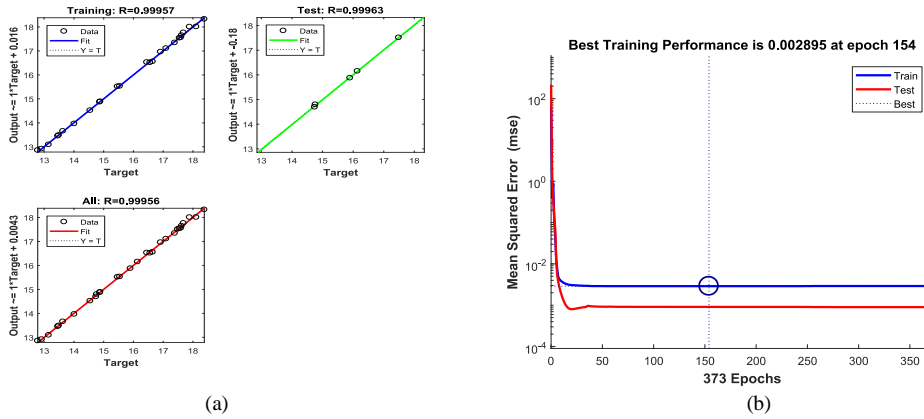


Fig. 4. (a) The regression of training process, (b) Training performance.

### 3.2. Integral feedback linearization design

The IFL command is designed to pursue the reference voltage generated by the ANN controller. So, the photovoltaic voltage  $V_{PV}$  is proposed as an output variable to control:

$$y = V_{PV} \quad (3)$$

Successive derivatives have been made to give the desired control (Duty cycle). The first derivation of the chosen output directly gives the following expression:

$$\dot{y} = \frac{1}{C_{PV}} I_{PV} - \frac{1}{C_{PV}} I_L \quad (4)$$

A second derivative is necessary to make appear the desired control:

$$\ddot{y} = \frac{1}{C_{PV}} \frac{dI_{PV}}{dt} - \frac{1}{C_{PV}} \frac{dI_L}{dt} \quad (5)$$

Using equation (1), the derivative of the current is as follows:

$$\frac{dI_{PV}}{dt} = -\frac{N_p I_s}{N_s N \gamma V_T} \exp\left(\frac{V_{PV}}{N_s N \gamma V_T}\right) \dot{V}_{PV} \quad (6)$$

Finally, from equation (2), (5) and (6) the desired control was obtained:

$$D = -\frac{\ddot{y}}{\frac{1}{C_{PV}L} V_{out}} + \frac{\frac{1}{C_{PV}} \left( F \dot{V}_{PV} - \frac{1}{L} (V_{PV} - V_{out}) \right)}{\frac{1}{C_{PV}L} V_{out}} \quad (7)$$

where:

$$F = \frac{dI_{PV}}{dt} \quad (8)$$

The law control with order three described in equation (9) has been proposed to regulate the chosen output to its reference. This allows an asymptotic convergence of the error  $y = y_{ref} - y$  to zero.

$$(\ddot{y}_{ref} - \ddot{y}) + k_1(\dot{y}_{ref} - \dot{y}) + k_2(y_{ref} - y) + k_3 \int (y_{ref} - y) \tag{9}$$

The integral part is introduced to ensure a zero-static error in steady state. The equation (9) is equivalent to a third-order equation relating to the error.

$$\ddot{\varepsilon}_y + k_1 \dot{\varepsilon}_y + k_2 \varepsilon_y + k_3 \int \varepsilon_y = 0 \tag{10}$$

The regulation parameters  $k_1$ ,  $k_2$  and  $k_3$  were obtained by making the identification of the characteristic polynomial of (10) term to term to the polynomial  $p(s)$  given in equation (11).

$$(s + p_1)(s^2 + 2\xi\omega_n s + \omega_n^2) = 0 \tag{11}$$

Then, it comes:

$$\begin{cases} k_1 = 2\xi\omega_n + p_1 \\ k_2 = 2\xi\omega_n p_1 + \omega_n^2 \\ k_3 = p_1 \omega_n^2 \end{cases} \tag{12}$$

where  $\xi$  is the damping coefficient and  $\omega_n$  is the cutoff pulse. These parameters are chosen so as to ensure a good tracking dynamic.  $p_1$  is an additional pole that adjusts the pursuit dynamic.

#### 4. Simulation Result

In this section, the performances of the proposed controller were tested under uniform and non-uniform meteorological conditions, as shown in Fig. 5. The studied photovoltaic panel is composed of three PV modules (Reference: Siemens SM55) connected in series. Each one produces a power of 55W under standard conditions of insolation (Irradiation of 1000 W/m<sup>2</sup> and Temperature of 25 °C). Subjected to these conditions, the optimum voltage and current of each PV module are respectively 17.4 V and 3.5A. The input and output capacitors of the DC/DC BOOST converter are respectively  $C_{PV} = 4700 \mu\text{F}$  and  $C_{out} = 470 \mu\text{F}$  while the value of the coil inductance is  $L=0.53\text{mH}$  and that of the resistive load is  $150\Omega$ .

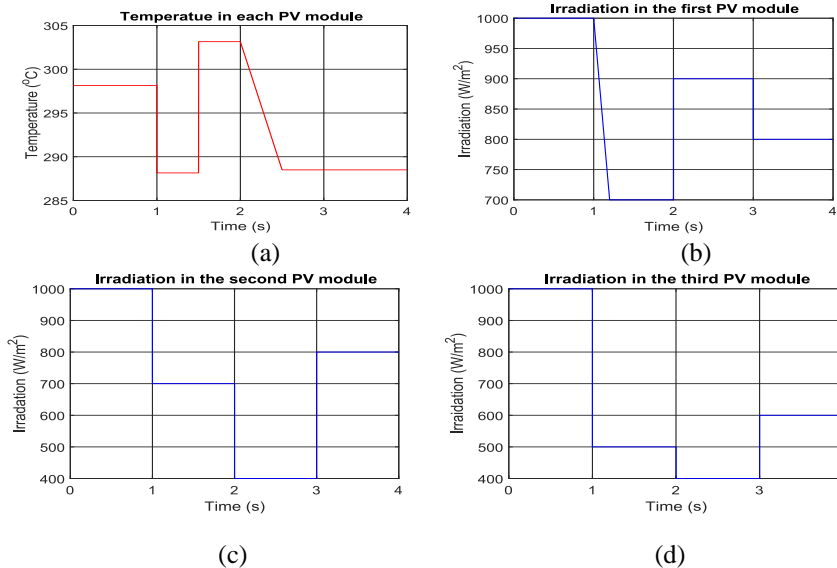


Fig. 5. Temperatures and irradiancies.

The photovoltaic module parameters:

$$N=36; N_p = 1; N_s = 1; \gamma = 1.7404; I_{scr} = 3.45A; I_{Tr} = 4.842 \mu A; K_i = 4 \times 10^{-4} A/K; T_r = 298.15K.$$

The controller parameters are given as follows:

$$\xi=0.7, \omega_n=200rad/s, p1=100rad/s.$$

Fig. 6 illustrates the curves of the optimal voltages generated by each ANN controller. Here, it is noticed that the ANN reacts quickly to each change of insolation, producing a new value of voltage. The same figure presents the voltages of three photovoltaic modules integrated in DMPPT topology, these voltages pursue quickly and accuracy the reference voltage using the Integral Feedback Linearization controller. The output power of the PV system is illustrated in Fig. 8(c), from this latter, it is noticed that the high yield of power is produced under the partial shading effect. Therefore, the distributed hybrid controller has made it possible to obtain a system with good power efficiency and better tracking performance. The current and voltage across the load are illustrated respectively in Fig. 8(a) and Fig. 8(b). The duty cycles of each photovoltaic module those shown in Fig. 7(a), Fig. 7(b) and Fig. 7(c), are the control laws generated by the three IFL controllers. It is noticed that these control laws change without any overshoot and oscillation and remain within the desired limits.

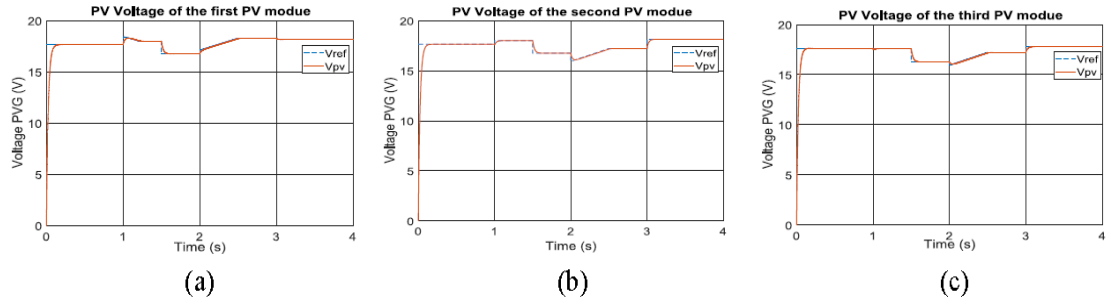


Fig. 6. The PVG voltage and its references of: (a) 1<sup>st</sup> Model, (b) 2<sup>nd</sup> Model, (c) 3<sup>rd</sup> Model.

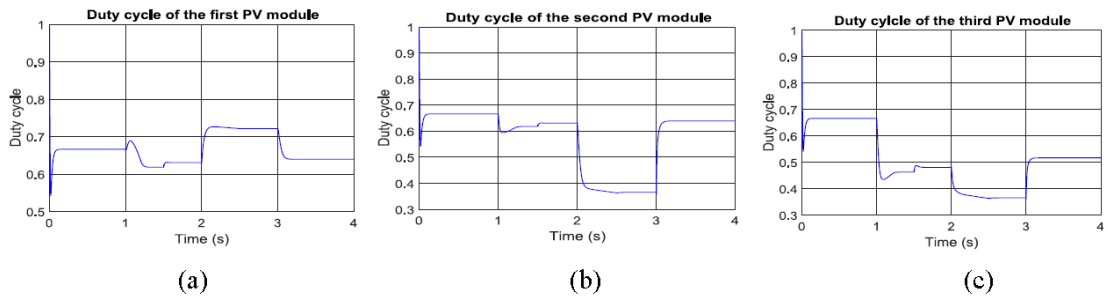


Fig. 7. The Duty cycles of each DC/DC converter.

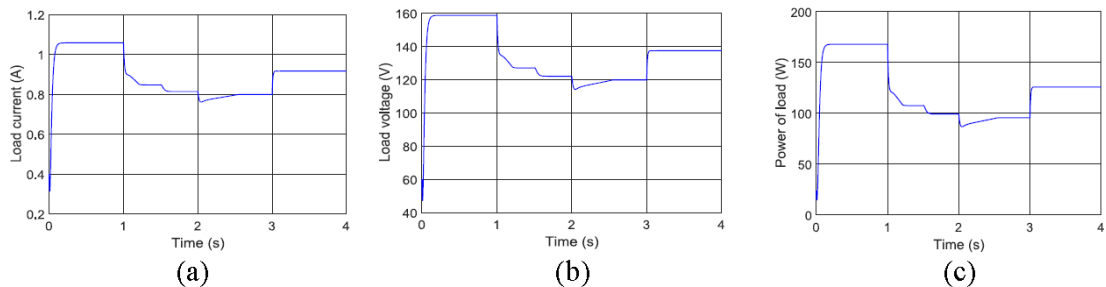


Fig. 8. The PV system outputs: (a) Current, (b) Voltage, (c) Power.

## 5. Conclusion

In this work, a new MPPT technique has been designed, two controllers were associated: the first one based on the artificial intelligence while the second one resulting from the nonlinear commands, allowing the system to react quickly under any change in environmental conditions. Indeed, the optimal voltage was found rapidly by the ANN command, the Integral Feedback Linearization controller pursued quickly and accurately the voltage reference generated by the first command. This MPPT controller, called hybrid technique, tracked the maximum power point of the PV module that is subjected to the rapid change of insolation and different meteorological conditions. In addition, the use of the DMPPT topology helps to extract the maximum power of each PV module under uniform and partial shading conditions, producing better power efficiency. The simulation results validated the performance of the proposed technique.

## Conflict of Interest

"The authors have declared that there are no conflicts of interest."

## Author Contributions

Mr. Mohcine MOKHLIS, as the corresponding author, has designed the Feedback linearization controller as well as the artificial neural network loop. Also, he has modeled the proposed system on Matlab/Simulink environment; Prof. Mohammed FERFRA has proposed the DMPPT topology because of its contribution in improving power production of the photovoltaic panel under the partial shading effect as well as the uniform weather conditions; Prof. Ahmed ABOU has provided the database necessary for designing the artificial neural network; Prof. Mohammed CHRAYGANE contributed to the writing of this paper; all authors approved the final version.

## References

- [1] Canchola Zamora A, Vazquez G, Sosa JM, Martinez-Rodriguez PR and Juarez M.A. Efficiency based comparative analysis of selected classical MPPT methods. *2017 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), Rope, Harbour*, 2017:1–6.
- [2] Gökhan Y and Naci MA. A hybrid variable step size MPPT method based on P&O and INC methods. *2017 10th International Conference on Electrical and Electronics Engineering (ELECO)*, 2017: 949–953.
- [3] Abderrahim T, Ahmed A, Mohammed A, Abderrahmane O, Radouane M, MPPT design for photovoltaic system using backstepping control with boost converter, IRSEC 2016. In: *Proc. of 2016 International Renewable and Sustainable Energy Conference, ISBN 9781509057139*, 2016:469–475.
- [4] El Idrissi R, Ahmed A, Salahdine R, Mahdi S. Maximum power point tracking of photovoltaic systems using backstepping controller. *2017 International Conference on Engineering and Technology (ICET)*, Antalya, Turkey, 2017.
- [5] Sakthigokulrajana C, Ravi K. Combined role of derived array configurations and MPSO based MPPT in improving the energy yield under partial shading conditions. *IEEE Journal of Photovoltaics*, 2017; 9:125–34.
- [6] Archila Valderrama J, Mantilla VM, Barrero PJ, Petit SJ, and Ordóñez PG. A maximum power point tracking algorithm for photovoltaic systems under partially shaded conditions. *Ing. Univ.*, 2016: 20(2):391–409.
- [7] Alonso R, Ibáñez P, Martínez V, Ramón E, and Sanz A. An innovative perturb, observe and check algorithm for partially shaded PV systems. In: *Proc. of 13th Eur. Conf. Power Electron. Appl.*, 2009:1–8.
- [8] Muralidhar K and Susovon S, Output voltage sensor based DMPPT with parallel configuration for PV systems under partial shading conditions. IEEE, Department of Electrical and Electronics Engineering Manipal Institute of Technology Manipal, Department of Electrical Engineering National Institute of Technology Rourkela, India 769008, 2016.
- [9] Reza R, Mohammad Ab, Ali YV, Reza B. New strategy of grid connected photovoltaic system using module integrated converters with B4 inverter to overcome partial shading effect. In: *Proc. of 30th Power System Conference (PSC2015)*, Niroo Research Institute, Tehran, Iran, November 2015:23–25.
- [10] Guisser M, EL-Jouni A, Aboulfatah M, Abdelmouniim E. Nonlinear MPPT controller for photovoltaic pumping system based on robust integral backstepping approach. *International Review on Modeling and Simulations (I.R.E.MOS)*, June 2014; 7(3), ISSN 1974-9821.
- [11] Foreyth AJ, Mollov SV. Modeling and control of DC-DC converters. *IEEE Power Engineering Journal*, 1998; 12(5):229–236.

- [12] Sabir M, Abd GH, Abd EL. A new neural networks MPPT controller for PV systems. IREC 2015, 2015 6th International Renewable Energy Congress, ISBN 9781479979479, 2015.
- [13] Krishna S, Padiyar KR. Transient stability assessment using artificial neural networks. *IEEE Transactions on Power Systems*, 2000:627–632.

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