Modeling of a PV Panel and Application of Maximum Power Point Tracking Command based on ANN

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Abstract: *The Photovoltaic (PV) systems are renewable and environmentally friendly. However, they still have numerous disadvantages such as high investment cost and low efficiency. For getting highest efficiency from a PV system in different operation conditions, PV panels and arrays should be operated at Maximum Power Points (MPPs). At MPP, PV arrays produce the electric energy at maximum efficiency and minimum losses. Some algorithms are used in PV systems to provide maximum efficiency and minimum losses. In this paper, a new PV panel model is proposed employing Matlab/Simulink, and three commands of the MPP Tracking (MPPT), are applied in our proposed PV system. These MPPT commands are (P&O), the Incremental Conductance (IC) and the ANN based one. Then, a comparative study between these three commands is performed. The simulations results obtained from Matlab/Simulink software, are presented for these approaches under rapid variation of insolation and temperature conditions. Those results confirm the effectiveness of the ANN based command both in terms of efficiency and fast response time and this compared to the two other commands (P&O and IC). Also compared to P& O and IC, negligible oscillations around the MPP is the main advantage of this ANN based command.*

Keywords: *MPPT controller, photovoltaic panel, insolation, temperature, ANN.*

1. Introduction

Today, problems of pollution effect and global warming are becoming the important issues for researches. Renewable Energy Sources are considered as a technological choice in order to producing clean energy and consequently to solve those problems. Amongst these sources, Photovoltaic (PV) [5, 17] systems have received a great attention since they are considered as ones of the most promising renewable energy sources. The difference between PV panel and a solar panel is that the latter turns solar energy into heat. It is used to have domestic hot water and for certain cases of domestic heating. However, a PV panel transforms sunlight into electricity. Due to its development and cost reduction, PV system becomes an efficient solution to the environmental problems [22]. However, the development for the improvement of the efficiency of the PV system is still a challenging research field. The PV cell is the basic unit of any PV system. It is in fact large area semiconductor. It can convert photon energy into the form of electrical signals, this technique of power generation doesn't harm to ecosystem. Hence PV power generation systems are becoming well known for generating in small scale as well as in large scale production [10]. In this context, numerous research works proposed diverse models, the most employed are single and double diode ones. The single diode model is extensively employed thanks to its simplicity and easy

to implement in various software [10]. It is named model with five parameters and characterized by photocurrent source parallel with diode and shunt resistance [10]. The detailed single diode models have been proposed for determining the behavior of a PV cell under diverse temperatures and solar levels [10]. The current-voltage and power-voltage are employed in order to describe the behavior of solar PV cell under the variation of temperature and solar irradiance and some physical parameters such as shunt resistance and series resistance [10]. The characteristic current-voltage is a non-linear equation with numerous parameters classified as follow: those provided by constructors, those known as constants and the ones which should be calculated. Occasionally, researchers develop simplified methods where, some unknown parameters cannot be calculated. They are therefore considered constants [2, 10]. Since the output power of the PV system varies dependently on irradiance and temperature and also load current, the PV system is not modeled as a source of constant Direct Current (DC) current [23]. Generally, the MPP Tracking (MPPT) command [16, 23, 25] is applied for tracking the Maximum Power Point in the PV system. The MPPT effectiveness is depending on both the MPPT command and the MPPT circuit. The MPPT command is normally applied in the DC-DC converter, which in general used as the MPPT [21] circuit. The typical flowchart of the

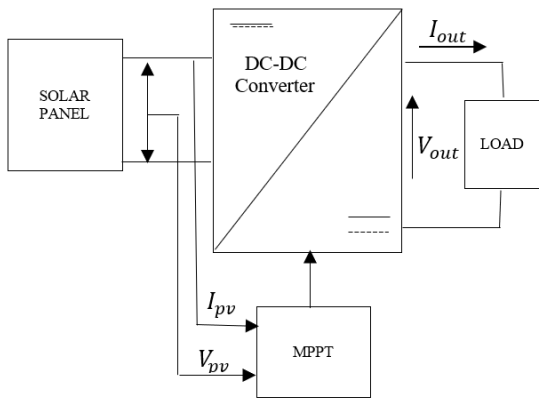MPPT connection in a PV system is illustrated in Figure 1.

Figure 1. Typical flowchart of the MPPT control in a PV system [7].

According to Figure 1, in a typical flowchart of the MPPT command in a PV system, the inputs of this sub-system are the voltage V_{PV} and the PV current I_{pv}. Those inputs are provided by this panel. The output of this system is the Pulse Width Modulation (PWM) signal that controls a DC-DC Converter. The latter is in turn connected to a load which can be a pump or a resistive. Among the MPPT commands we can mention the Perturb and Observe (P&0) method [20] and the Incremental Conductance (IC) one [18]. However, the drawbacks of P&O and IC commands are oscillations and convergence problem occurred at certain points during the tracking. In order to improve the performance of P&O command, Takun *et al*. [23] have applied the Fuzzy Logic in their MPPT Command. The necessity of this paper consists in comparative studying of a number of MPPT commands which are ANN based MPPT [3, 6, 11, 12, 13, 14, 15, 19], P&O and IC. The innovation of this article consists in modeling of PV panel and integrating it into a PV system including an MPPT command and a boost converter. This proposed model of PV panel is a modification of an existing PV panel [25]. In fact, this modification consists in making the temperature variable over time whereas it is constant in [25] and is equal to **25**°C. This temperature variation is performed in order to get closer to the real climatic conditions and to better approximate the Maximum Power Point (MPP). In our PV system, the role of the MPPT command based on ANN consists in tracking maximum power and obtaining maximum efficiency from the used PV panel. In section 2 of this paper, we will deal with Mathematical Modeling of PV Module. In section 3, we will detail the Modeling of our novel model of PV panel employing Matlab/Simulink. In section 4, we will be interested in MPPT commands including our proposed MPPT one based on Artificial Neural Network (ANN). In section 5, we will present Results and Discussion and finally we will conclude in section 6.

2. Mathematical Modeling of PV Module

The single-diode model was employed in order to investigate the relation between the current *I* and voltage V and in the following equation [1]:

$$I = I_{sc} - I_o \left(exp \left(\frac{V + R_s I}{a V_t} \right) - 1 \right) - \frac{V + R_s I}{R_{sh}} \qquad (1)$$

In this equation we have: *I* is the cell current (A), I_{sc} is the light generated current (A), I_0 is the saturation current, R_s is the cell series resistance (Ohms), R_{sh} is the cell shunt resistance (Ohms), V_t is the thermal voltage (*V*), *V* is the cell voltage (*V*).The modeling of the single diode corresponding circuit of a PV device is illustrated in Figure 2.
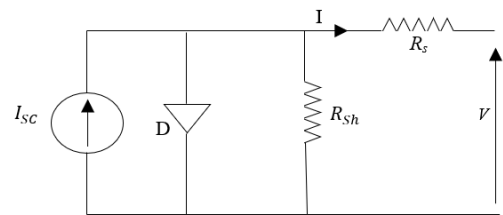

Figure 2. The single-diode model comparable circuit of a photovoltaic cell [1].

The PV model can compute the output power by the simplest form [9] employing the following equation:

$$P = I \cdot V = \left[I_{sc} - I_o \left(exp \left(\frac{V + R_s I}{a V_t} \right) - 1 \right) - \frac{V + R_s I}{R_{sh}} \right] V \qquad (2)$$

For a monocrystalline PV cell, the ideality factor of diode, *a*, is equal to 1.2 [1, 24].

3. The Modeling of a PV Panel using Matlab/Simulink

In this work, every simulation is performed under Matlab and using Matlab/Simulink library. In this section, the proposed model of PV panel is conceived by modifying the old model of PV panel proposed in [25]. This modification is performed by adding the temperature as a third input in the proposed model. The two other inputs are the current I_{pv} and the insolation. In Figure 3 is detailed the old model of PV Panel proposed in [25]. Also, this temperature addition is performed via the thermal voltage (V_t) expression which is given as follow:

$$V_t = \frac{kT}{q} \qquad (3)$$

Where *k* is the Boltzman constant and its value is 1.38×10^{-23} J/K, *T* is the temperature expressed in Kelvin and *q* is the electron charge and its value is $1.602 \cdot 10^{-19}$ C.
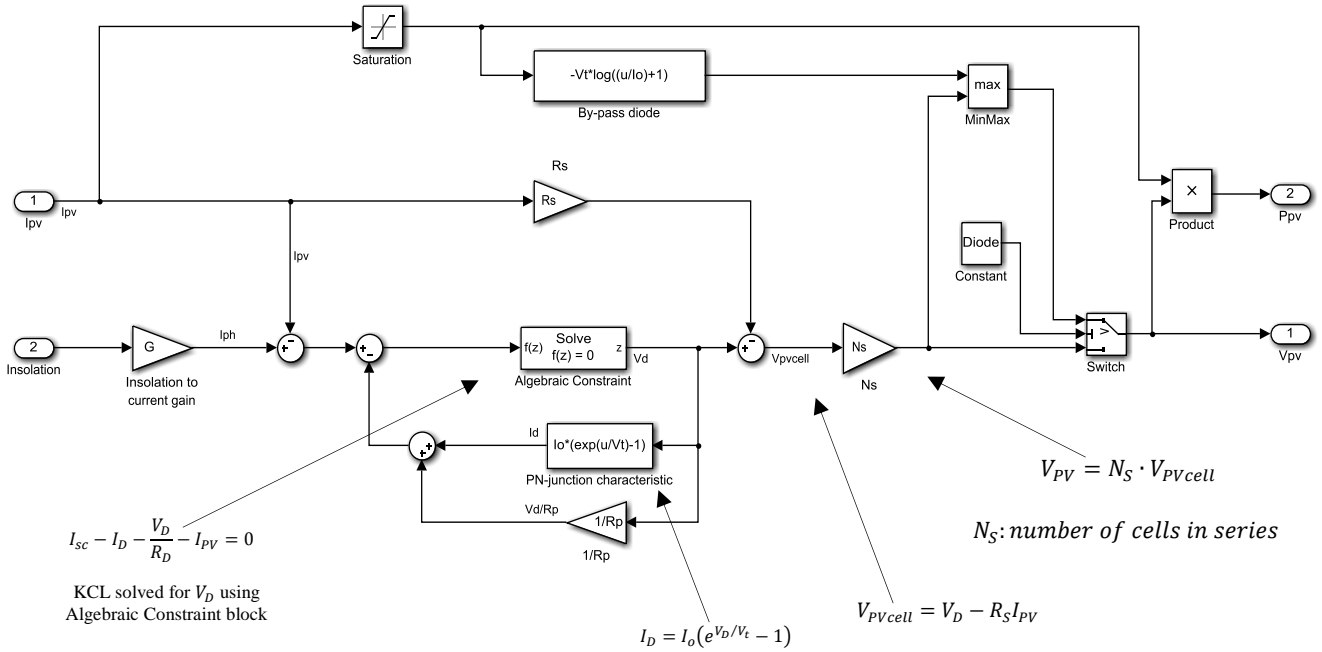
Figure 3. The model of a current-input PV Panel proposed in [25].

As shown in Figures 3 and 4, to conceive our proposed model of PV Panel, we have exploited the expression of thermal voltage, V_t (Equation (3)) for making temperature variable instead of constant in the old model proposed in [25]. The specifications of the proposed PV panel and the old one proposed in [25], are listed in Table 1.

In Figure 4 is illustrated our proposed model of PV Panel. In Figures 5 to 8 are illustrated the characteristics I-V and P-V obtained by simulation of the proposed model and the old one proposed in [25]. These characteristics are obtained in the two following cases: (G=1000W/m^2, T=25°C) and (G=750W/m^2, T= 20°C.

Table. 1. The specifications of the proposed PV Panel.

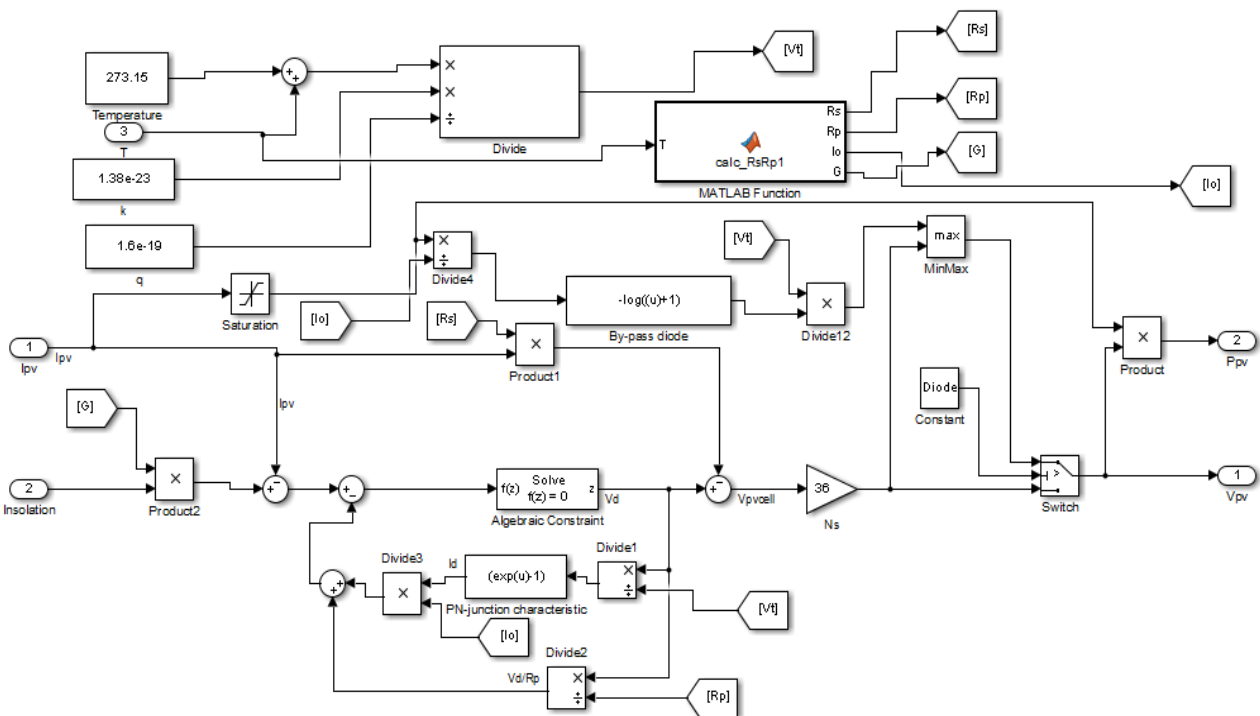|	
Short Circuit Current (I$_{sc}$)	5.45 A
Open Circuit Voltage (V$_{oc}$)	22.2 V
Current at Pmax (I$_r$)	4.95 A
Volt at Pmax (V$_r$)	17.2 V

Figure 4. The block diagram of the proposed model of PV Panel.
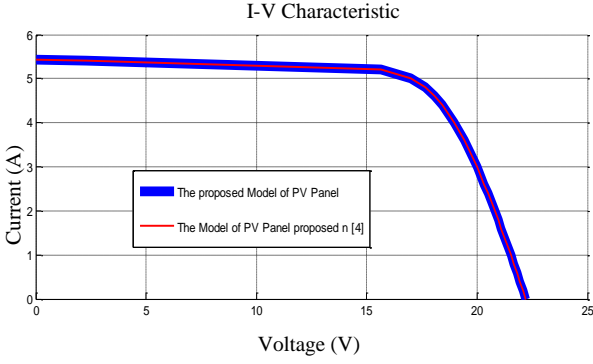
Figure 5. I-V Characteristic for the proposed model in Blue Color, I-V Characteristic for the model proposed in [25] in Red Color: I-V Characteristics obtained in Standard Conditions ($G = 1000 \, \text{W/m}^2$ and $T = 25°C$).
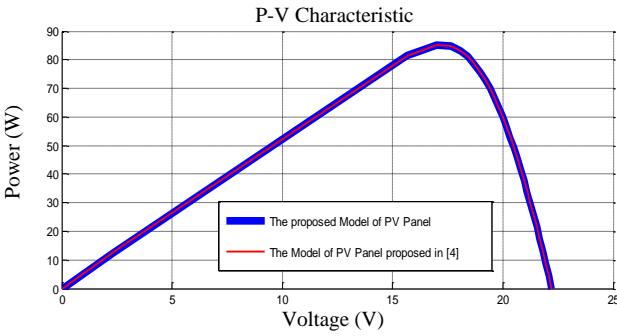

Figure 6. P-V Characteristic in Blue Color for the proposed model, P-V Characteristic in Red Color for the model proposed in [25]: P-V Characteristics obtained in Standard conditions ($G = 1000 \, \text{W/m}^2$ and $T = 25°C$).
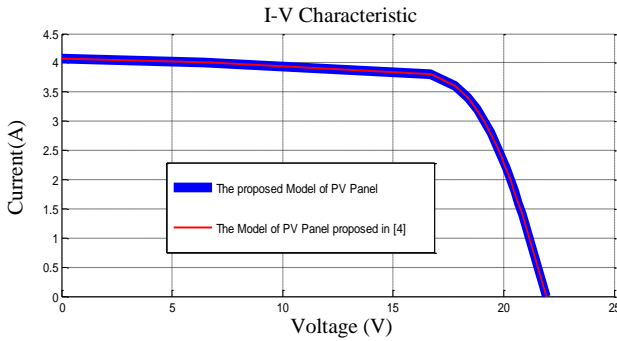

Figure 7. I-V Characteristic in Blue Color for the proposed model, I-V Characteristic in Red Color for the model proposed in [25]: I-V Characteristics obtained in cases of ($G = 750 \, \text{W/m}^2$ and $T = 20°C$).
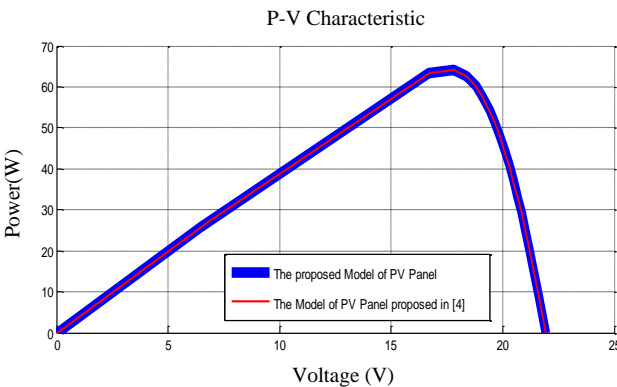

Figure 8. P-V Characteristic in Blue Color for the proposed model, P-V Characteristic in Red Color for the model proposed in [25]: P-V Characteristics obtained in cases of ($G = 750 \, \text{W/m}^2$ and $T = 20°C$).

These Figures show the similarity of the two I–V Characteristics and also of the two P–V Characteristics. This is expected because the proposed model is practically the same one proposed in [25] and the only difference between those two models is that in the proposed one, the temperature is varying while it is constant and equals to 25°C in the old one proposed in [25]. In order to obtain the I–V and P–V characteristics when $T = 20°C$ and $G=750 \text{W/m}^2$ by the old model proposed in [25], we should modify the value of the thermal Voltage (V_t) by replacing $25°C$ by the $20°C$ and employing the new value of V_t in this model [25]. Therefore, for the two models, are obtained similar I–V and P–V characteristics in case of $T = 20°C$ and $G = 750 \, \text{W/m}^2$.

4. Maximum Power Point Tracking Commands

4.1. Perturb and Observation (P and O)

The most common and simple MPPT algorithm is the P and O one [20]. The main concept of this algorithm is to push the system for operating at the direction in which the output power obtained from the PV system is increasing. Equation (4) is describing the power change which defines the strategy of the P and O command:

$$\Delta P = P_k - P_{k-1}$$

(4)

When the power change (Equation (4)) is positive, the system will keep the direction of the incremental current (decrease or increase the photovoltaic current) as the same direction. When the change is negative then the system will change the direction of incremental current command to the opposite direction. This technique is well working in the steady state condition (temperature and radiation conditions are slowly changing). Though, the P&O technique fails in tracking MPP in case of rapid changes of the atmospheric conditions.

4.2. Incremental Conductance (IC)

Concerning the conventional Incremental Conductance (IC) [18], the PV curve slope $\frac{dP}{dV}$ is expressed as follow:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{d(V_{pv}I_{pv})}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} \qquad (5)$$

With P_{pv}, V_{pv} and I_{pv} are respectively the PV's power, voltage and current. When the PV curve slope is null, then the power is highest. The MPPT algorithm is given as follow [18]:

$$\frac{dI_{pv}}{dV_{pv}} > -\frac{I_{pv}}{V_{pv}} \equiv \frac{dP_{pv}}{dV_{pv}} > 0 => \text{Increase } d.$$

$$\frac{dI_{pv}}{dV_{pv}} < -\frac{I_{pv}}{V_{pv}} \equiv \frac{dP_{pv}}{dV_{pv}} < 0 => \text{Decrease } d.$$

With d is the DC/DC converter duty ratio.

For applying the velocity estimator, $\frac{dP_{pv}}{dV_{pv}}$ is replaced

by the ratio of the time derivative of both $V(t)_{pv}$ and $P(t)_{pv}$ as follow:

$$\frac{dP_{pv}}{dV_{pv}} = \frac{\frac{dP_{pv}}{dt}}{\frac{dV_{pv}}{dt}} \qquad (6)$$

The following relations are verified:

$$\frac{dP_{pv}}{dt}\frac{dV_{pv}}{dt} > 0 => \frac{\frac{dP_{pv}}{dt}}{\frac{dV_{pv}}{dt}} > 0 \qquad (7)$$

$$\frac{dP_{pv}}{dt}\frac{dV_{pv}}{dt} < 0 => \frac{\frac{dP_{pv}}{dt}}{\frac{dV_{pv}}{dt}} < 0 \qquad (8)$$

The above relations enable us to avoid a division by zero error.

4.3. The proposed MPPT Technique Based on an Artificial Neural Network

The Artificial Neural Network (ANN) is an artificial network that mimics the human biological neural networks behavior. It is widely used in modeling complex relationships between inputs and outputs in nonlinear systems. ANN can be defined as parallel distributed information processing structure consisting of inputs, and at least one hidden layer and one output layer. These layers have processing elements called neurons interconnected together. The first step in designing an ANN consists in collecting historical data on the problem to be solved using the network. In MPPT case, lots of array solar irradiances and temperatures. In [4], the MPPT controller for *PV* system was developed by practicing ANN. Also, the performance of this controller was compared with *P&O*, *IC* and fractional open circuit voltage method. Simulations were done by employing MATLAB/SIMULINK in order to analyze results. Also, Khanam and Foo [14] presented their work on MPPT using neural network. The MATLAB/ Simulink was used to establish a model of PV array. The Simulink model was tested with different values of temperature and irradiation and resultant I-V and P-V characteristics proved the validation of simulink model of PV array. Khanam and Foo [14] collected a set of data from the Simulink model of PV array after simulated under a range of irradiation and temperature. The data collected from the system was used to train the neural network. When Khanam and Foo [14] tested their used neural network with different irradiance and temperature, they see that the neural network can accurately predict the maximum power point of a PV array. In [14], the back propagation training algorithm was used to train their used neural network. Comparisons of MPPT with P & O algorithm and without MPPT tracker were also shown in [14]. It was shown that the neural network based MPPT tracking requires less time and provide more accurate results than the P&O algorithm based MPPT [14]. That's why in this

paper, we also use ANN based command.

4.3.1. Selecting Network Structure

As previously mentioned, a neural network is constituting of a minimum two layers. The first layer is a hidden one and the second is the output layer. The input information is connected to the hidden layers through weighted connections where the output data is calculated. The number of hidden layers and that of the neurons in each layer control the network performance [6]. The ANN in used in this work has two inputs which are temperature and insolation. This ANN has two layers (one hidden and one output). The hidden layer has ten neurons having tansigmoid activation function and the output layer has just one neuron having purelin activation function. The output of this neuron is the current at maximum power point, I_{MPP}. In Figure 9 is illustrated the ANN used in this work.
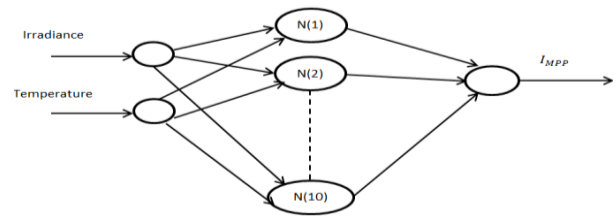

Figure 9. The proposed ANN structure for MPPT.

The activation functions tansigmoid and pure line are respectively expressed by Equations (9) and (10).

$$tansig\ (n)\ =\ 1/(1 + exp(-n)) \qquad (9)$$

$$Purelin\ (n)\ =\ n \qquad (10)$$

4.3.2. Training the Network

The collected training points are passed into the designed network. This is performed in order to teach this network how to process the testing points which are generally different from the training ones. Training points should be obtained in order to start our work with the used ANN. In this paper, they are obtained through varying the irradiance and temperature and taking values of voltage, currents and maximum power. The different parameters employed for the training of the used neural network are the epochs number which is equal to 5000, the momentum, μ or Mu which is equal to 0.1, the gradient minimum which is equal to 1e-7. The used training algorithm is Leverberg-Marquardt. Some of the collected test points are kept as test ones. Those test points are used for testing the conceived ANN performance after its training is finished. In fact, they will be new to it. Consequently, one can judge if it gives or not accurate results. The proposed MPPT control consists of two main parts, ANN and current control, as depicted in Figure 10.
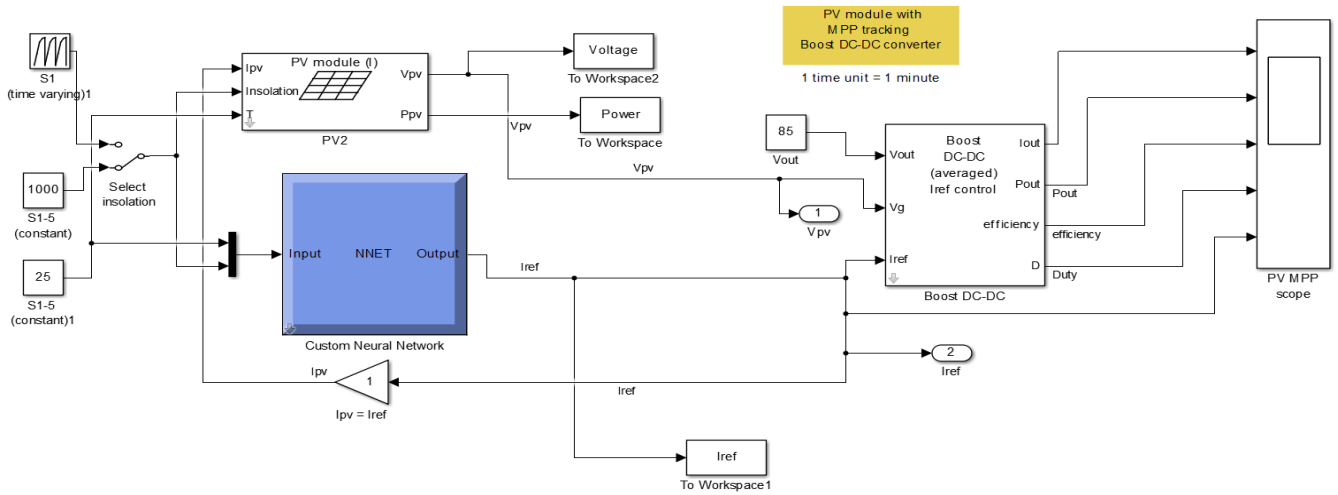
Figure 10. Model of the developed PV system under MATLAB/Simulink.

As shown in this figure, our PV system is constituting of our proposed model of PV panel (Figure 4), the MPPT command based on ANN and the Boost converter [25]. The inputs of the MPPT subsystem (the blue box in Figure 10) are the insolation and temperature. The output of this subsystem is the reference current $I_{ref}=I_{MPP}$ corresponding to the maximum of power provided by the used PV panel. This current I_{ref} is also the input of the used Boost converter which has two other inputs, I_g and V_{out} and its outputs are Efficiency, Duty Cycle, I_{out} and P_{out}. The current I_g is delivered by the used PV panel and the value of V_{out} is 85V. Concerning the database used for training and testing the used ANN, it is constituted of a number of couples where each of them is a couple of an ANN input and the corresponding target. Each input is in turn a couple of one value of temperature and one value of insolation and the corresponding target is the corresponding value of the reference current I_{ref} or I_{MPP}. The latter is the current at the maximum of Power provided by the used PV panel. Those couples of temperature and insolation are chosen in a manner that they cover the climatic conditions of the four seasons. They are obtained as follow: For each value of temperature, we associate four values of insolation so we obtain four couples of Temperature and Insolation. For example, for 15℃ we have the following four couples: (15,200), (15,350), (15,500) and (15,650) and the corresponding Targets are respectively the following values of I_{ref}: 0.8400, 1.6200, 2.4000, 3.2000. In summery we have the following table:

Table 2. Examples of couples of Inputs and the corresponding Targets.

Input: (T,G)	Target: I_{ref}
(15,200)	0.8400
(15,350)	1.6200
(15,500)	2.4000
(15,650)	3.2000

In this table, T designates the Temperature and G is the insolation and I_{ref} or I_{MPP} designates the current corresponding to the maximum of power provided by

the used PV panel. For the training of the employed ANN we used 80% of the used database which contains 104 elements. The rest of this database (20%) is used for validation and testing this employed ANN [8].

5. Results and Discussions

As previously mentioned, in this work, not only, we proposed a new model of PV panel but also, we tested it with other types of commands which are the IC and a command based on ANN. Consequently, in our proposed PV system we tested three MPPT controllers which are P & O used in [25], IC and the ANN based controller and we will make a comparative study between them. This study is in terms of reference current (I_{ref}), the duty cycle (D), the output Power (P_{out}), the output current (I_{out}) and efficiency. The duty cycle (D), P_{out}, I_{out} and the efficiency are all the outputs of the Boost DC-DC and the overall PV system. Figures 11, 12, 13, 14, and 15 illustrate the temporal variations of D, P_{out}, I_{out}, efficiency and I_{ref}. These variations are obtained in case of Standard Conditions (Irradiance, G=1000W/m^2 and Temperature, $T = 25℃$).
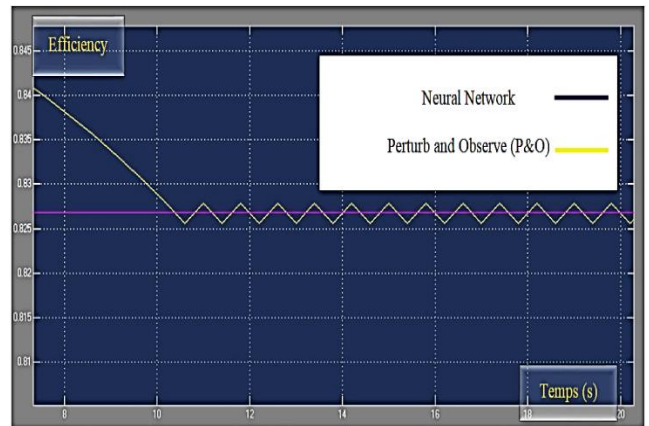

Figure 11. Temporal variation of the Efficiency: zoomed curve in yellow color for MPPT controller *P & O*; zoomed curve in purple color for MPPT controller using ANN.
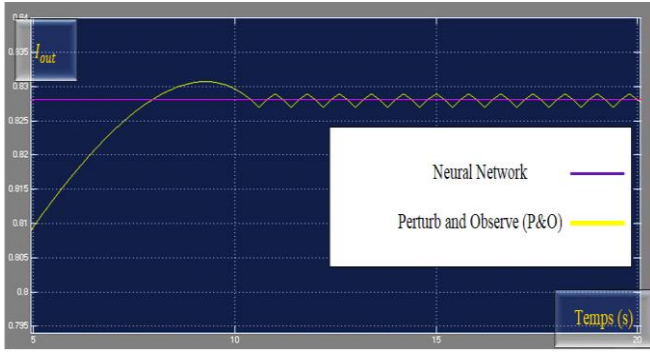
Figure 12. Temporal variation of the output current (I_{out}): zoomed curve in yellow color for MPPT controller, *P & O*; zoomed curve in purple color for MPPT controller using ANN.
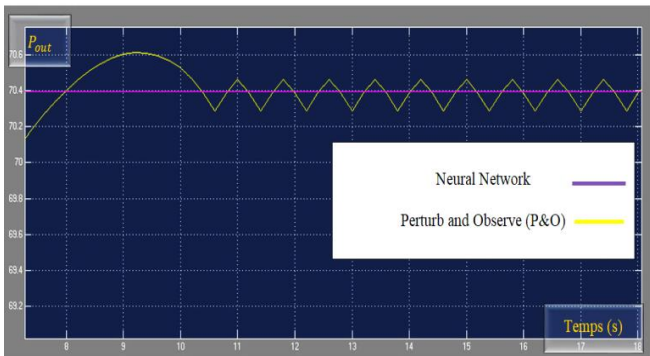

Figure 13. Temporal variation of the output power (P_{out}): zoomed curve in yellow color for MPPT controller, *P & O*; zoomed curve in purple color for MPPT controller using ANN.
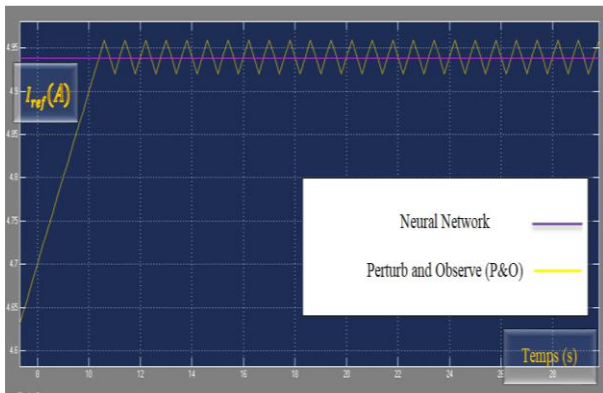

Figure 14. Temporal variation of the reference current (I_{ref}): zoomed curve in yellow color for MPPT controller, *P & O*; zoomed curve in purple color for MPPT controller using ANN.
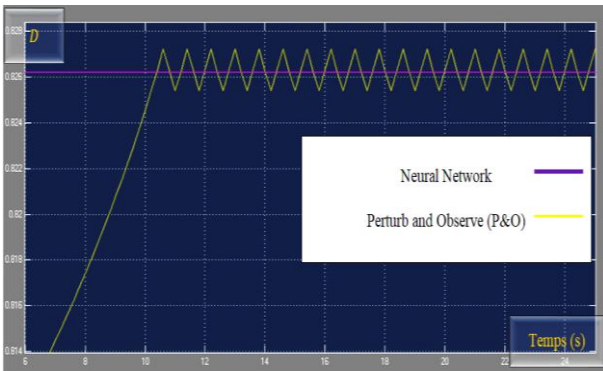

Figure. 15. (a) Temporal variation of the Duty Cycle (D): zoomed curve in yellow color for MPPT controller *P & O*; zoomed curve in purple color for MPPT controller using ANN.

Those simulation results (the temporal variations of D, P_{out}, I_{out}, Efficiency and I_{ref}) presented for these two MPPT commands based on ANN and P&O [25], confirm the effectiveness of the proposed MPPT command employing ANN (Figure 9) both in terms of efficiency and fast response time. No oscillations around the maximum power point and easy implementation are the main advantages of this command. The latter has a convergence time better than that of the conventional P&O technique. In the rest of this section, we will make a comparative study between the two commands based on ANN and IC [18]. Also, this comparative study is in terms of temporal variations of Duty Cycle (D), of reference current (I_{ref}), of output current (I_{out}), of Efficiency, and of the different Powers (P_{out} and P_{Pv}). All these temporal variations are obtained for two commands where the first one is based on ANN and the second one is IC command [18]. In Figures 16 to 20 are illustrated the different curves of temporal variations of P_{out}, I_{out}, Efficiency, Duty Cycle, P_{Pv} and I_{ref} and this for the two commands IC and ANN. They are obtained in standard conditions: G=1000W/m² and T = 25℃. Those simulation results (temporal variations of D, P_{out}, I_{out}, Efficiency and I_{ref}) presented for these two MPPT commands, confirm the effectiveness of the proposed MPPT command employing ANN (Figure 9) both in terms of efficiency and fast response time. No oscillations around the maximum power point and easy implementation are the main advantages of this command. The latter has a convergence time better than that of the conventional IC command.

6. Conclusions

In this paper we proposed a novel model of PV panel employing Matlab/Simulink. It was conceived by modifying a model of PV Panel proposed in literature. The latter considers the temperature as constant and equals to 25℃. Though, in real conditions we should take in consideration the variation of temperature. For this reason, we modified this existing model of PV Panel by adding the temperature as an input of this model. We applied with this novel PV Panel three different MPPT commands where the first one is P&O, the second one is based on IC and the third one is based on ANN. A comparative study was made between those three MPPT commands and this in terms of temporal variations of the duty cycle (D), the output power (P_{out}), the output current (I_{out}), the efficiency and the reference current (I_{ref}). Efficiency, D, P_{out} and I_{out} are the output of the Boost DC-DC and I_{ref} or I_{MPP} is its input. These different temporal variations (for the case where T = 25℃ and G=1000W/m²), confirm the effectiveness of the proposed MPPT command employing ANN (Figure 9) both in terms of efficiency and fast response time. No oscillations around the maximum power point and easy implementation are the main advantages of this command. The latter has a convergence time better than

that of both the conventional P&O and IC commands. In our future work, we will apply the MPPT command based on Fuzzy logic in our PV system proposed in this work. Moreover, we will make a comparative study between the four commands: ANN, Fuzzy logic, P&O and IC.
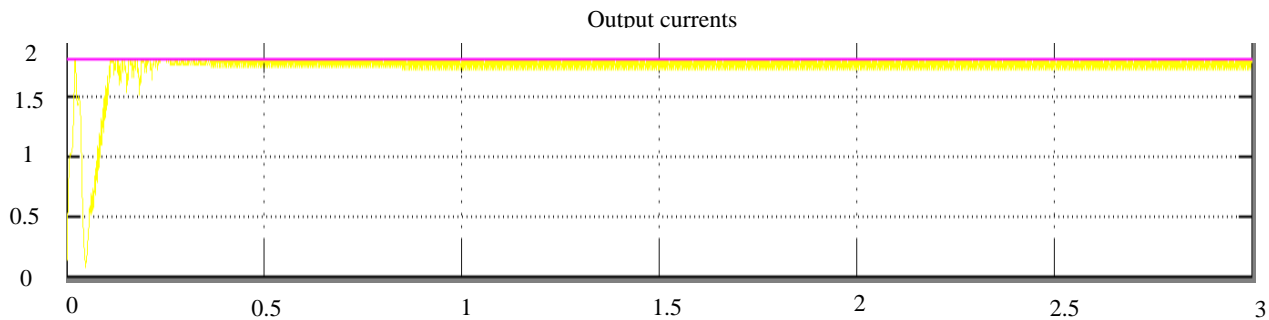
Figure 16. Temporal variations of the currents, outputs from the Boost converter.
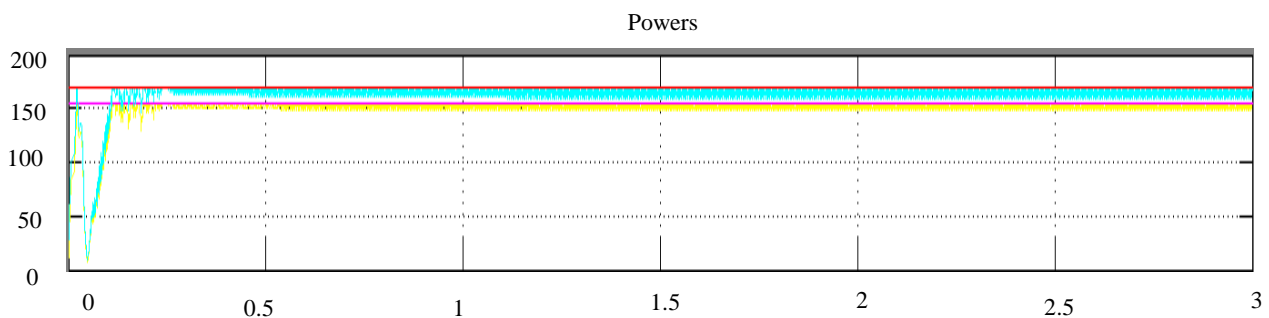
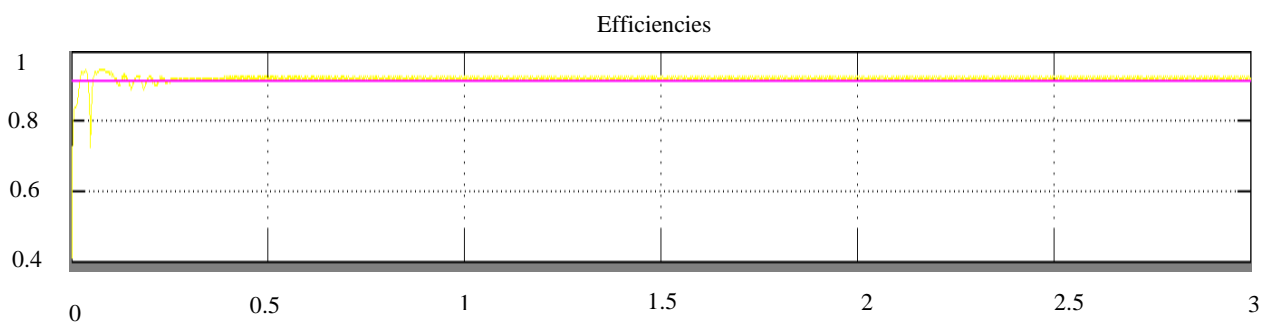Figure 17. Temporal variations of the different powers.
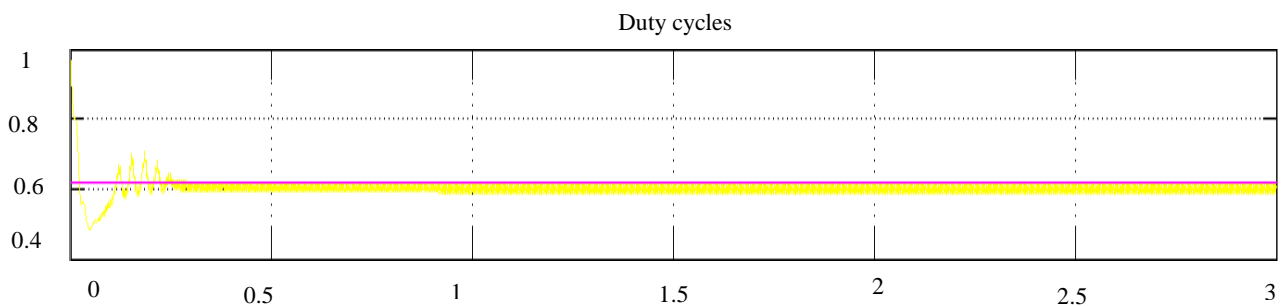
Figure 18. Temporal variations of the efficiencies.

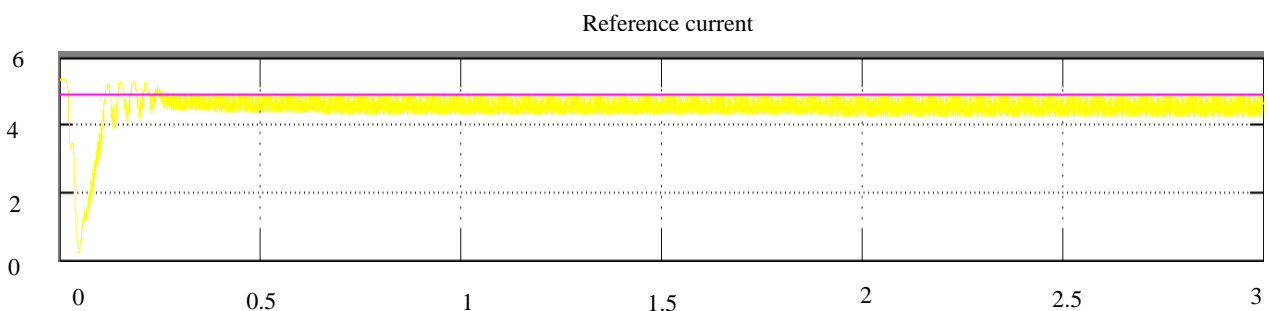Figure 19. Temporal variations of Duty cycles.

Figure 20. Temporal variations of reference current.

According to this figure, the curve in purple color (Figure 16) obtained in case of ANN based MPPT and is of current output of the boost converter. The curve in yellow color (Figure 16) obtained in case of IC based MPPT [24] and is of output current. The curve in red color (Figure 17) is obtained in case of ANN based MPPT and is of the power provided by the PV generator. This power is the power maximum. The curve in blue color (Figure 17) is obtained in case of IC based MPPT [24] and is of the power provided by the PV generator. Curve in purple color (Figure 17) obtained in case of ANN based MPPT and is of the power output of the boost converter. Curve in yellow color (Figure 17) is obtained in case of IC based MPPT [24] and is of the power output of the boost converter. The curve in purple color (Figure 18) is obtained in case of ANN based MPPT and is of the Efficiency output of the boost converter. The curve in yellow color (Figure 18) is obtained in case of IC based MPPT [24] and is of the Efficiency output of the boost converter. The curve in purple color (Figure 19) is obtained in case of ANN based MPPT and is of the Duty cycle output of the boost converter. The curve in yellow color (Figure 19) is obtained in case of IC based MPPT [24] and is of the boost converter. The curve in purple color (Figure 20) is obtained in case of ANN based MPPT and is of the reference current, $I_{ref}=I_{MPP}$. The curve in yellow color (Figure 20) is obtained in case of IC based MPPT [24] and is of the reference current, $I_{ref}=I_{MPP}$.

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