Implementation of a MPPT Neural Controller for Photovoltaic Systems on FPGA Circuit

NAOUFEL KHALDI, HASSAN MAHMOUDI, MALIKA ZAZI*, YOUSSEF BARRADI*
Mohammedia School of Engineer LEEP, * Higher School of Technical Education LMIP
Mohamed V University Agdal, * Mohamed V University Souissi
Avenue Ibnsina B.P. 765 Agdal, *Avenue des Forces Armées Royales B.P. 6207
Rabat, Morocco
naoufelkhaldi@gmail.com, m.zazi@um5s.net.ma, mahmoudi@emi.ac.ma, barradiyoussef@hotmail.fr

Abstract: - The maximum power point tracking (MPPT) system controls the voltage and the current output of the photovoltaic (PV) system to deliver maximum power to the load. Parameters values were extracted using Newton Raphson method from characteristics of Shell SP75 module. This paper presents a comparative analysis of incremental conductance (IC), and neural network based MPPT techniques. The Artificial Neural Network (ANN) method is used to deliver the appropriate duty cycle signal used to drive boost converter to track the MPP even with variations of the input values using Matlab/Simulink for the simulation and Hardware Description Language (VHDL) for the implementation on kit Field Programming Gate Array (FPGA) Spartan-3E of Xilinx.

Key-Words: - Artificial neural network, Photovoltaic systems, Incremental conductance, MPPT, VHDL, FPGA

1 Introduction

Demand for electrical energy has remarkably increased during the recent years with growing population and industrial progress. Since long time ago, fossil fuels have served as the major source of generating electrical energy. However the transfer of energy resulting from photovoltaic conversion remains relatively weak. Therefore, many tracking control strategies have been proposed in existing literatures, such as perturb and observe, incremental conductance, Variable voltage, and fuzzy logic methods [1,2,14]. But for this work a novel BP neural networks MPPT algorithm has been used. These new control techniques feature advantages of simplicity, high flexibility and less fluctuation around the maximum power point which increase efficiency of the PV system [3]. In [4], Newton Raphson method is used due to the nonlinearity of Current/Voltage (I-V) characteristics of PV module. Selection of appropriate converter is also very important for an efficient PV system [13]. There are a few topologies can be used with PV system for load connectivity, among them boost converter has been selected here due to its available use in standalone and grid connected PV system and simultaneous step up capability [5,6]. This paper results show that the proposed BP MPPT method can track maximum power point (MPP) in different temperature and irradiation, which has excellent output characteristic of high accuracy and good robustness as compare with method IC. Experimental results from implementation of a FPGA allow the validity of the proposed neural control and deliver the appropriate duty cycle signal under different values of solar radiation and temperature as comparing with Matlab/Simulink simulation.

The sequential work flow of this paper is as follows: In section 2, complete working procedure of the system has been described. Section 3 covers mathematical modelling of PV using a Newton Raphson method, and followed by discussion on boost dc-dc converter and MPPT algorithms in Sections 4 and 5 respectively. Simulation and experimental works and results are discussed in Section 6 and 7. Lastly, in section 8, a precise conclusion has been added to finalize the work.

2 Complete System Overview

A photovoltaic cell is basically a PN semiconductor junction diode and this cell converts solar light energy into electricity [7].

The complete system block diagram is shown in Fig.1 After that this energy will be supplied to the load through the buck-boost converter and the converter will be controlled by a MPPT controller.

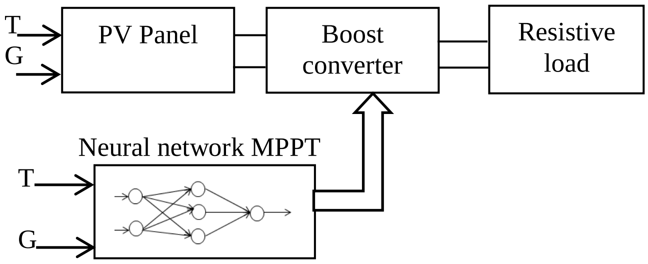

Fig. 1 Schematic arrangement for the complete system

3 PV Modelling

3.1 Mathematical Modeling

There are various methods to perform modeling work on the PV module, and the most of them is described by using mathematical modeling [8,9]. The equivalent circuit of a photovoltaic (PV) array can be depicted in Fig. 2 where I_{ph} is current source of PV array, R_{sh} is an equivalent shunt resistance, R_s is an equivalent series resistance, i_{pv} and v_{pv} are the output current and output voltage of PV array, respectively. In general, for simplicity R_{sh} and R_s are assumed to be open circuit and short circuit, respectively. The simplified mathematical model of the output current is given as[10]:

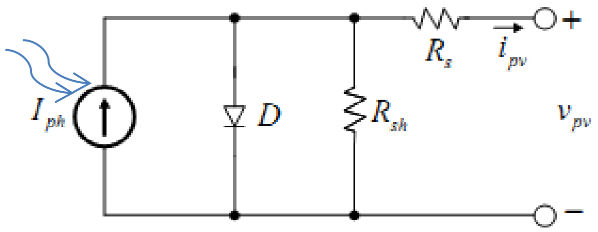

Fig. 2 The equivalent circuit of a PV array

$$i_{pv} = n_p I_{ph} - n_p I_{rs}\left[\exp^{\left(\frac{q}{pkn_s}\times\frac{v_{pv}}{T}\right)} - 1\right] \qquad (1)$$

Where q is the electron charge, k the Boltzmann's constant (1.38×10^{-23} J/°K), p is the p–n junction ideality factor (p=1~5), T is the cell temperature (°K) and I_{rs} is the cell reverse saturation current, n_s is the number of solar cells connected in series and n_p is the number of solar cells connected in parallel.

In addition, the mathematical model of the reverse saturation current is given below:

$$I_{rs} = I_r (T/T_{ref})^3 \exp^{\left\{\left(\frac{qE_g}{pk}\right)\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right\}} \qquad (2)$$

With

$$I_r = \frac{I_{sc}}{\left[\exp^{\left(\frac{v_{co}}{pn_s v_{tr}}\times\frac{v_{pv}}{T}\right)} - 1\right]} \qquad (3)$$

Where T_{ref} is the cell reference temperature, I_r is the reverse saturation current at T_{ref}, E_g is the band-gap energy of the semiconductor ($E_g \approx 1.1$eV) and V_{tr} is a thermal potential at T_{ref}.

The current source of PV array I_{ph}, varied according to solar irradiation and cell temperature, is given below:

$$I_{ph} = [(I_{sc} + K(T - T_r)] \times (\frac{E}{E_r}) \qquad (4)$$

Where I_{sc} is short-circuit current at reference temperature and radiation, E is the solar irradiance and K, the temperature coefficient for short-circuit current. Using the equations 1 to 4 the PV panel can be modelled. In this work the equation of solar module is solved with the help of Newton-Raphson method. A program of solar module is programed in MATLAB software and the different characteristics of solar module are obtained.

3.2 Newton Raphson Method

In determining the operational point of a nonlinear circuit, Newton Raphson method is commonly used. The method is based on linearizing the nonlinear equations and solving the resulting linear equations repeatedly [10,11]. For example, we will consider solving one variable equation $f(x) = (x \in \boldsymbol{R}, f: \boldsymbol{R} \to \boldsymbol{R})$. First, the initial value $x^{(0)}$ should be chosen to be close to the true solution $\hat{x}$. Considering a Taylor series expansion of $f(x)$ around $x^{(0)}$, $f(x)$ can be transformed to (5).

$$f(x) = f\left(x^{(0)}\right) + \left.\frac{df}{dx}\right|_{x=x^{(0)}} \left(x - x^{(0)}\right) + \frac{1}{2}\left.\frac{d^2f}{dx^2}\right|_{x=x^{(0)}} + \cdots \qquad (5)$$

The third term of (5) is expected to be very small due to the square. Therefore, the linearized model (6) can be formed.

$$f(x) = f\left(x^{(0)}\right) + \left.\frac{df}{dx}\right|_{x=x^{(0)}} \left(x - x^{(0)}\right) \qquad (6)$$

The proposed method using one variable Newton Raphson method, will allow us to calculate the current i_{pv} with the initial value $x^{(0)} = I_{ph}$ as shown in Fig. 3.

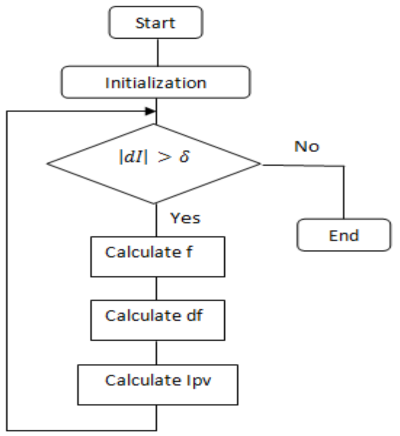

Fig. 3 A flow chart of the proposed method of calculating current i_{pv} of PV

3.3 Caracteristic of solar panels

A complete Simulink block diagram of PV system by varying the inputs is demonstrated bellow:

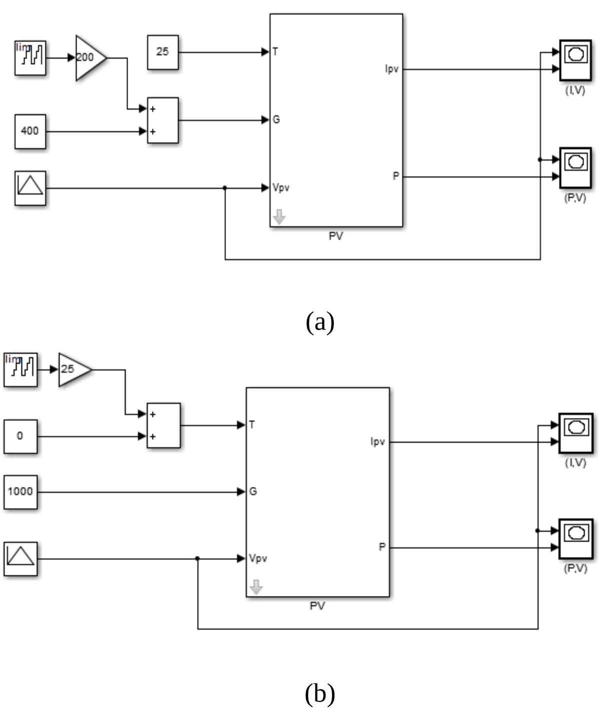

Fig. 4 External view of PV module in Simulink window using Newton Raphson method

Cell parameters are shown in Table 1. PV module is made by Shell solar company and product name is SP75.

Parameters	Values
Open Circuit Voltage(Voc)	21.7Volt
Short Circuit Current(Isc)	4.8Amp
Voltage at Pmax(Vmpp)	17Volt
Current at Pmax(Impp)	4.41Amp
Maximum Power (Pmpp)	75Watt
Number of Cell	36

Table 1 Parameters Of SHELL SP75

With the increment in the temperature short circuit current increases but the open circuit voltage of cell decreases. So the I-V characteristics shift to the left to previous curve. Power output of cell is also decreased. Figs. 5 and 6 show the variation in the characteristics curves at different temperature when the irradiance is kept constant at 1000w/m^2.Temperature varies from 0°C to 75°C, which is in degree Celsius.

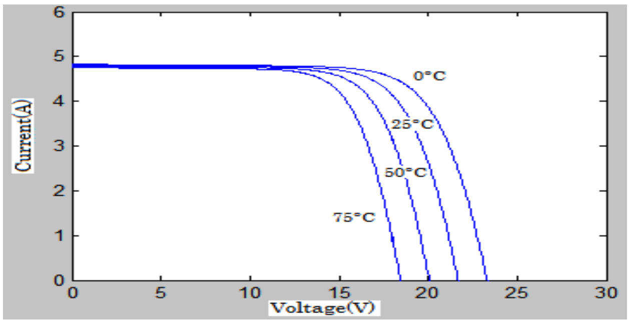

Fig. 5 I-V characteristics of solar module for different temperature

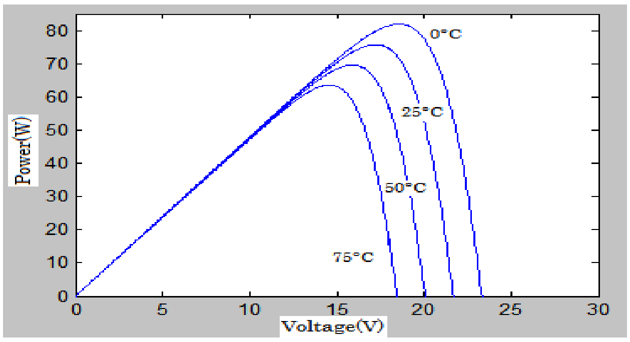

Fig. 6 P-V characteristics of solar module for different temperature

Fig. 7 and 8 show the variation in characteristics curve of the selected PV module by changing irradiance values from 400w/m^2 to 1000w/m^2 and T=25°C . The maximum power is higher if the irradiance is getting higher and for the current, if the irradiance is kept increasing, it also increases.

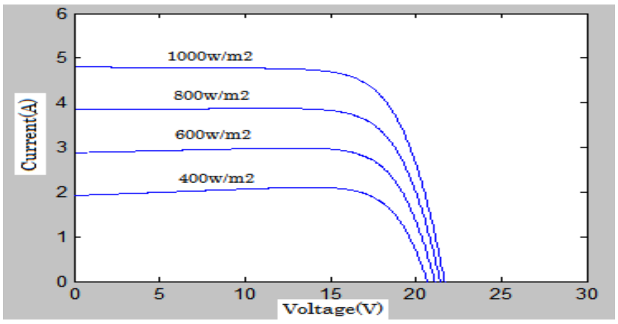

Fig. 7 I-V characteristics of solar module for different irradiance level

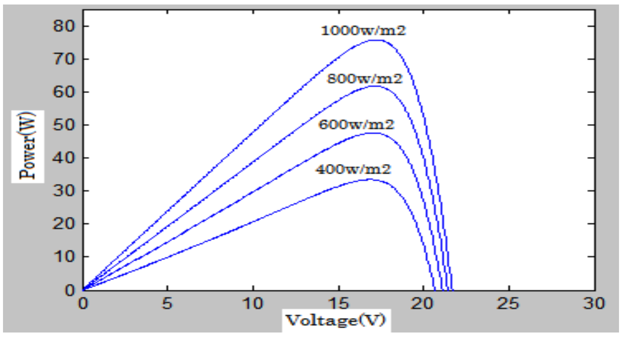

Fig. 8 P-V characteristics of solar module for different irradiance level

4 Dc-Dc Converter

DC-DC converters are used to transfer power of solar panel to load side ensuring that maximum power has been transferred [12]. The regulation is normally achieved by pulse within modulation (PWM) and the switching device is normally MOSFET or IGBT. Boost dc-dc converter's function is to step up dc voltage. Fig. 9 shows configuration of dc-dc boost converter with PV as input. Maximum power is reached when the MPPT algorithm changes and adjusts the duty cycle of the boost dc-dc converter.

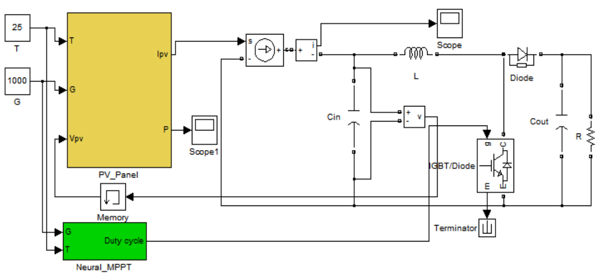

Fig. 9 Boost dc-dc converter with PV as input

5 The Proposed MPPT Scheme

Maximum power point tracking is a technique to extract maximum available power from PV module. This is done with the help of dc-dc converter which operate is such way that the output of converter is always give the maximum power that is produced by module in specific environment. At present, the most commonly used MPPT is IC method which is also has some shortcomings, such as the tracking speed is slow, and the output oscillation is big.

For this, this paper introduced a MPPT method based on back propagation neural network (BP NN). The trained neural networks can output the optimal voltage for the maximum power point under the various environment conditions. For training, gradient descent rule has been adopted. The two input (irradiance and temperature) and one output (duty cycle) is taken into consideration.

The training parameter of the network architecture is shown in Table 2.

Parameters	Values
Error Goal	0.000001
Epochs	10000

Table 2 Neural Network Parameter For Simulation

Fig. 10 shows the block diagram representation of neural network.

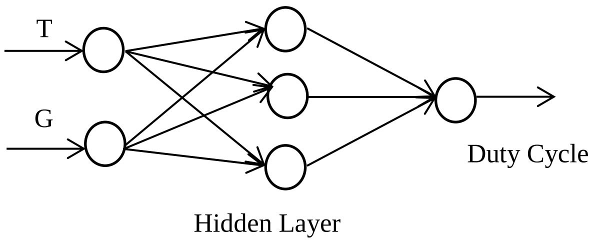

Fig. 10 Neural Network Block Diagram

The trainlm function is used to train the network, which has three hidden layer. The selection of architecture for our neural network will come down to trial and error. The output of the function will give the output of the network. This algorithm updates the network weights so as to minimize the SSE (sum square error) function.

The weights and bias are extracted during the learning phase (Fig. 11).

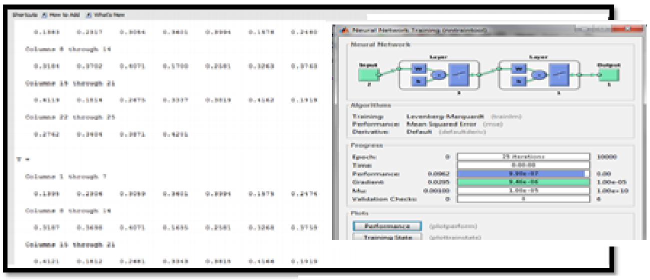

Fig. 11 Results of Training ANN in Matlab/Simulink

The ANN method is used to deliver the appropriate duty cycle signal used to drive boost converter to track the MPP even with variations of the input values (temperature, irradiation). The algorithm is described in the flowchart Fig. 12:

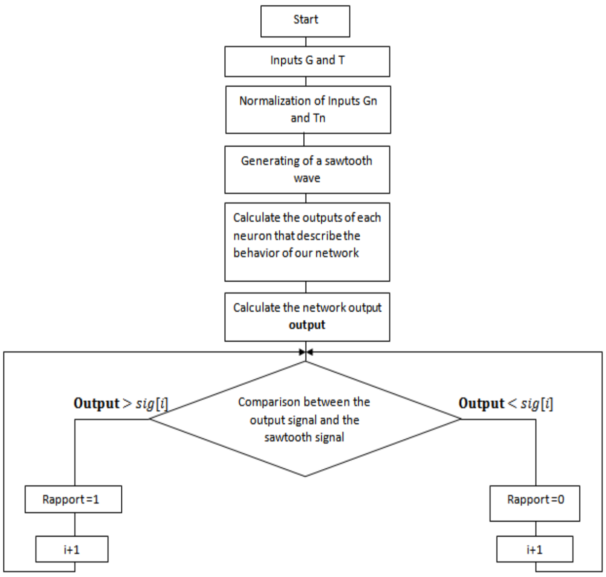

Fig. 12 Proposed ANN Based Algorithm

We normalize climatic conditions in order to unify the range of variation of our inputs:

Tn=T/60; Gn=G/1000.

Fig. 13 and 14 shows the curves of our inputs by changing climatic conditions, in case to validate the behavior of our neural control.

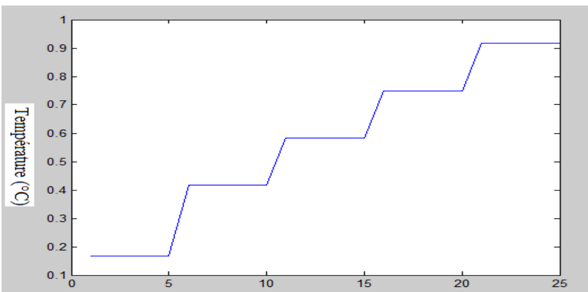

Fig. 13 Curve of temperature

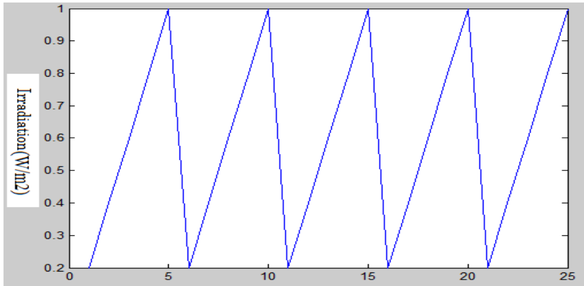

Fig. 14 Curve of irradiation

The figure below shows the generation of sawtooth wave with a frequency f = 8 kHz.

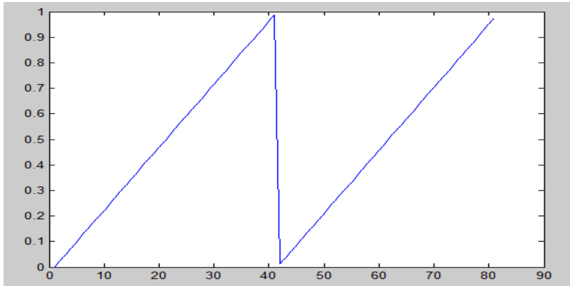

Fig. 15 Curve of temperature

Fig. 16 and 17 shows respectively the variation in the duty cycle at different temperature when the irradiance is kept constant, and by changing irradiance value with a constant temperature.

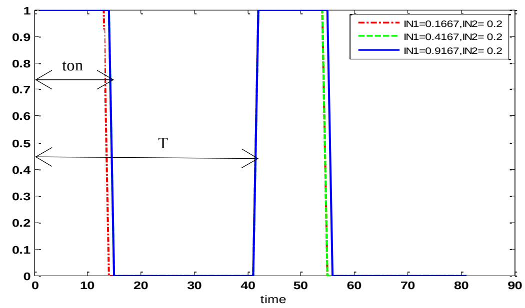

Fig. 16 Duty cycle Variation with different temperature

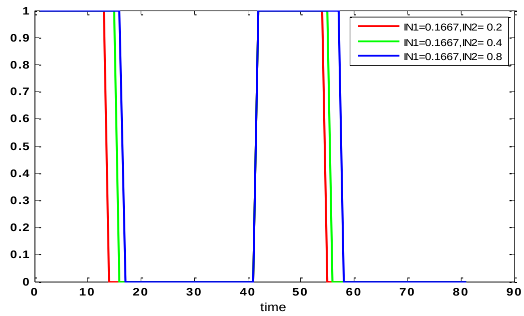

Fig. 17 Duty cycle Variation with different irradiation

The Duty cycle $\alpha = \dfrac{ton}{T}$

6 Simulation Results

The results are obtained in MATLAB Simulink environment. The proposed PV module was connected to boost dc-dc converter to form a unit of PV system. Simulation works were carried out with conventional IC algorithm, and further with a neural network MPPT control algorithms respectively for evaluation and comparison analysis. The output of dc-dc converter was 24V, The inductor value was 82.5 mH, the input capacitor was 150 µF, the output capacitor was 320 µF, and the load was 10 ohm.

The main importance factor to analyze performance of each MPPT algorithm is time response, oscillation, overshoot and stability. In Fig. 20 the output current curve by using the BP NN method has more excellent output characteristic and smaller oscillation than the conventional IC method. Fig. 21 shows effect of each MPPT algorithm towards the maximum power point, the conventional IC did not work well, it contributes to the slowest time response, high oscillation and not that stable as compared with the BP NN.

Despite effect towards maximum power point, the algorithms should also affect the boost dc-dc converter. From Fig. 22, the IC produces high overshoot and oscillation as compared with BP NN method.

All simulations are done with a variation of temperature and irradiations. Fig. 18, Fig. 19.

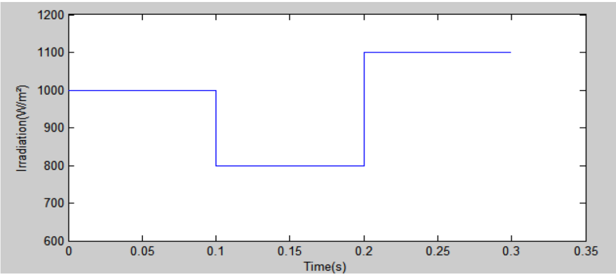

Fig. 18 The Irradiations variation versus time

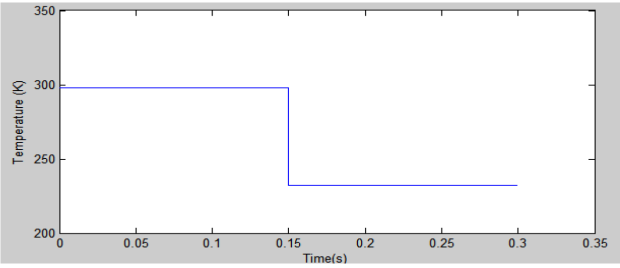

Fig. 19 The Temperature variation versus time

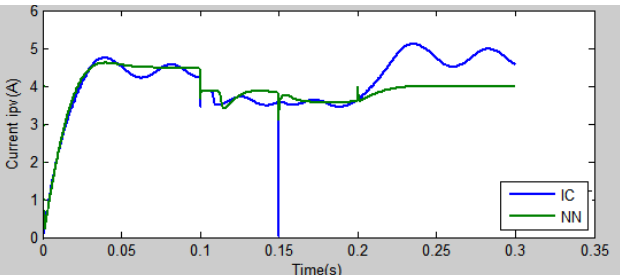

Fig. 20 IC method output current and BP NN method output current

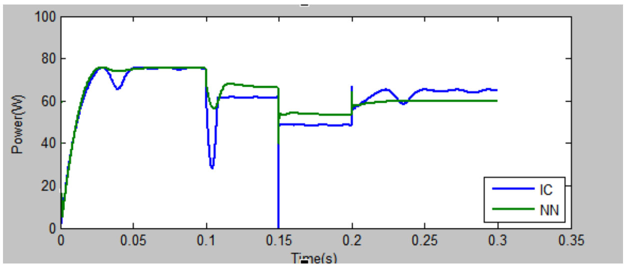

Fig. 21 IC method output power and BP NN method output power

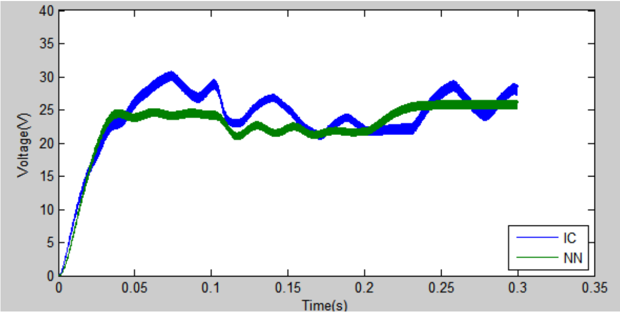

Fig. 22 Boost voltage effect with various algorithms MPPT

Sequentially all these figures coincide with theoretical prediction and company specified value which ensures the validity of the system.

7 Experimental Results

In order to simulate the ANN controller on VHDL language, the data was coded on 10 bits in fixed-point. The algorithm is written in VHDL under this structure divided into three main blocks as follows (Fig. 23):

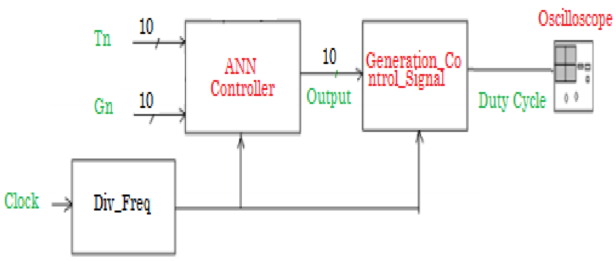

Fig. 23 Detailed Block Diagram of Neuronal MPPT

Fig. 24 shows the reconfiguration FPGA hardware used for implementing the designed neuronal MPPT based on VHDL, while Fig. 25 shows architecture of Register Transfer Level (RTL) which implemented in FPGA.

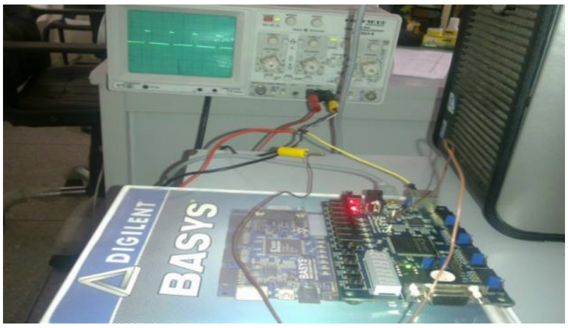

Fig. 24 FPGA Hardware

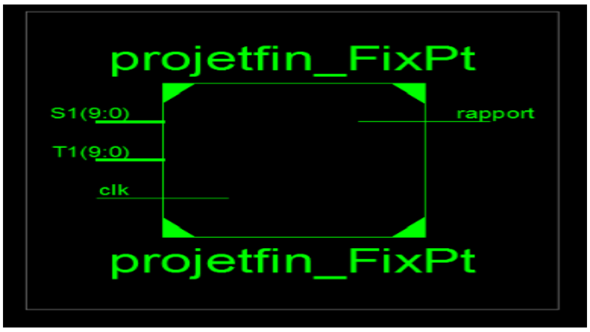

Fig. 25 Architecture RTL

Thus, the implementation is done with the same inputs taken into simulation in Matlab/Simulink, the results based on FPGA are presented in Figures below:

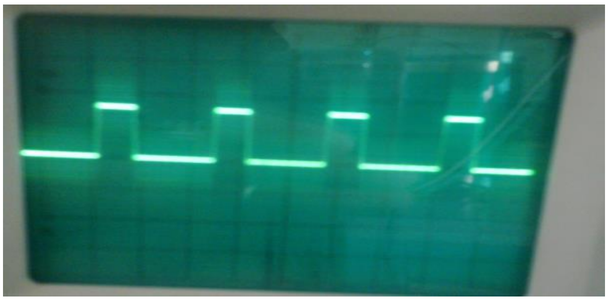

Fig. 26 Duty cycle with Tn1=0.1667, Gn1= 0.2

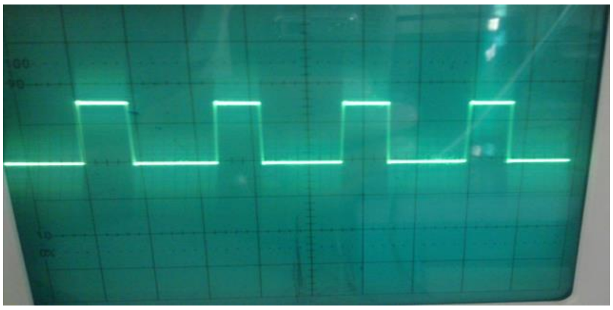

Fig. 27 Duty cycle with Tn2=0.1667, Gn2= 0.4

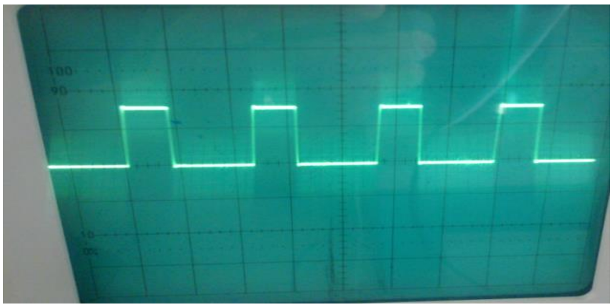

Fig. 28 Duty cycle with Tn3=0.9167, Gn3= 0.2

The FPGA has been used for simulating the proposed architecture based on the VHDL, once the architecture is implemented. Figs 26,27,28 and Figs 16,17 shows a comparison between FPGA and Matlab results. In addition, according to Table 3, we note that a good concordance between estimated output signal (Duty cycle) by Matlab and thus obtained by FPGA for different values of inputs. The error is very small , which is very satisfactory and then we cannot distingue the difference between results obtained by Matlab and FPGA (VHDL).

Inputs / Duty cycle	Tn1=0.1667 Gn1=0.2	Tn2=0.1667 Gn2=0.4	Tn3=0.9167 Gn3=0.2
Matlab	α=**0.3109**	α=**0.3841**	α=**0.3414**
FPGA	α=**0.2916**	α=**0.3750**	α=**0.3333**

Table 3 Duty cycle comparison

8 Conclusion

In this paper, a proposed neural network algorithm for MPPT control in boost dc-dc converter is presented. The output characteristic of PV system by using BP neural network MPPT method is compared with the conventional IC MPPT method, and the simulation result shows that the proposed method gives very satisfactory results with a good efficiency. The ANN adjusts the duty cycle by guiding the dc-dc converter to MPP immediately, Whole algorithm is experimented well in kit FPGA Spartan3E-100 TQ144 II pro of Xilinx.

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