Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 4 Issue 1, January - 2017

Photovoltaic Maximum Power Point Tracking by Artificial Neural Networks

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Abstract— **There are many advantages in using renewable energy resources (RER) such as wind and solar energy. RER are less in cost and pollution than fossil fuels. The application of solar energy to generate electricity by photovoltaic (PV) is suffering from low efficiency. So that, the PV control system should maximize the generated energy by operating the PV around the maximum power point (MPP).This MPP depends on the temperature and solar irradiation.**

This paper introduces a maximum power point tracking (MPPT) for PV system by artificial neural networks (ANN). The proposed system contains PV module equipped with DC-DC boost converter.

In this technique, the trained ANN determines the optimal boost converter duty cycle corresponding to MPP of each temperature and solar irradiation.

The proposed technique is simple for practical implementation and takes small time for both of training and execution.

Keywords—Renewable energy resources (RER); photovoltaic (PV); Maximum power point tracking (MPPT); Artificial neural networks (ANN).

I. Introduction

Energy is used in different fields in our life. Most of energies come from burning fossil fuels like oil, coal and natural gas which are called conventional or traditional energy resources. These conventional resources pollute the environment, and their cost is in a continuous increase especially since 1970's [1], [2]. Due to that a lot of researches work to deplete these resources with resources which have less running cost, less pollution and are not running out. These new resources are natural, energies like solar and wind which are called Renewable Energy Resources (RER) [3]. The expected share of renewable energy in electricity generation at 2020 is about 25% [4]. Egypt belongs to the global sun-belt with average sunshine 9-11 hour/day and annual direct normal energy density 2000-3200 kWh/m^2 [5].

This geographical position encourages Egyptian government to use solar energy applications. Generation of electricity from solar energy using PV has low efficiency. But to improve the PV utilization the system should operate around the MPP by proper MPPT technique.

The MPP of PV is dependent on the PV characteristics (c/cs), PV temperature and solar irradiation which makes the tracking is somewhat complex.

There are several methods to operate the PV around the MPP such as perturb and observe (P&O), Incremental Conductance, fuzzy controller and artificial neural networks.

In [3] the trained ANN senses the PV current and temperature to determine the optimal operating voltage corresponding to MPP. This optimal voltage is used to control the boost converter duty cycle. In [6], [7], [8] the ANN senses the ambient temperature and solar irradiation to determine the optimal voltage corresponding to MPP. In [9] the ANN is emerged with the incremental conductance where the ANN senses the PV current and voltage to determine the optimal PV voltage and current. In last work the ANN is large consists of 61 neurons , takes large time for training almost 1700 epochs and large time for execution. In [10] the ANN senses the PV open loop voltage and ambient temperature to determine the optimal PV voltage, whoever the open loop voltage technique needs a power electronic switch connected in series with the PV array. This switch is opened at regular intervals of time to measure the open circuit voltage, which means disconnecting the energy transfer from the PV during this period.

II. Photovoltaic Array Model

A PV system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays. The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors. More applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems and mainly to track the MPP of the device [11].

Usually for higher power applications, the PV cells are connected in series to form a module and the modules are connected in series/parallel to form an array.

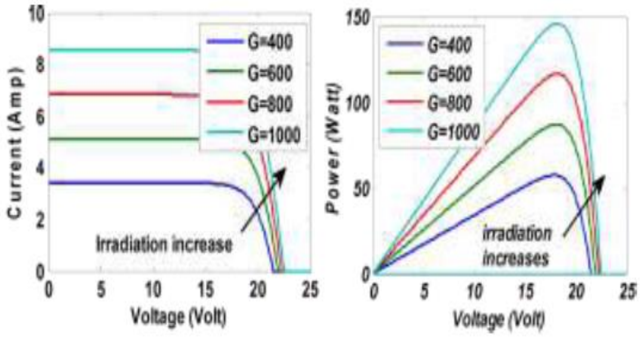

Fig. 1: Effect of irradiation (G) on PV c/cs and MPP

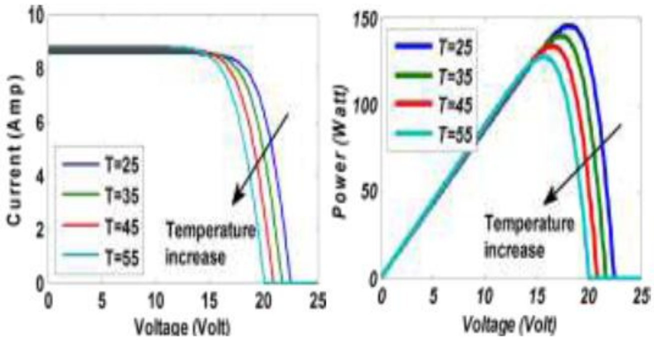

Fig. 2: Effect of temperature (T) on PV c/cs and MPP

The effect of solar irradiation (G) and temperature (T) on both P-V and V-I c/cs are shown in Fig. 1 and Fig. 2.

Fig. 1 shows that the maximum available power is increased as the solar irradiation increases, while Fig. 2 displays that the maximum power is decreased as the temperature increases. It is clear that changing in temperature or irradiation changes the MPP [3].

III. Boost Converter

The PV modules can be connected in series or parallel to produce the required amount of energy and voltage level. The series connection increases the voltage, while parallel connection increases the current. In PV grid connection and residential application the series connection is traditional solution to reduce the intermediate components for voltage step up. On the other hand in series connection, the produced energy is decreased greatly with modules mismatch, partial shading especially in the urban areas [3]. The parallel connection satisfies the safety requirements in residential applications and the generated energy is less affected by modules mismatch, but the parallel connection needs to step up voltage converter. The combination between series – parallel connection is most suitable solution for economic, safety and efficiency requirements. However the PV array voltage still low and needs to step up converter. Fig. 3 shows DC-DC step-up, regulated converter (boost converter) consists of current smoothing inductor L, voltage filtering capacitor C, diode, power electronic switch device IGBT and PV array voltage V_s. The boost converter is used to step up the PV array voltage to suitable level for PV application. Also the converter can be considered as a controlled load to draw the maximum power from the PV array.

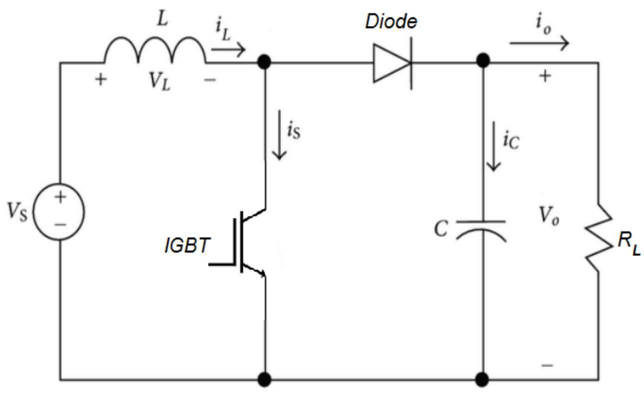

Fig. 3: PV DC-DC boost converter

And the power electronic switch is used to modulate the energy transfer from the input source to the load by varying the duty cycle D. The relationship between input voltage (V_i) and output voltage (V_o) of boost converter operating at steady state condition is given by (1) [12].

$$V_o/V_i = 1/(1-D) \quad (1)$$

When the switch is turned on the inductor current increases and PV voltage decreases. During this interval the PV array charges the inductor, while the output capacitor discharges into the load. When the switch is turned off the PV array and inductor charge the capacitor and supply the load.

The control strategy lies in the manipulation of the duty cycle of the switch which causes the voltage change. When the switch is closed and the inductor is charged by the source through the switch. The charging current is exponential in nature but for simplicity is assumed to be linearly varying. The diode restricts the flow of current from the source to the load and the demand of the load is met by the discharging of the capacitor. When the switch is open and the diode is forward biased. The inductor now discharges and together with the source charges the capacitor and meets the load demands. The load current variation is very small and in many cases is assumed constant throughout the operation [12].

The steady state output voltage is given by (2). The boost converter's inductor and capacitor are selected using (3) and (4) [13]. It should be noted that, PV array voltage (V_s) is not constant but depends on the array temperature, solar irradiation and array current. As the duty cycle increases the inductor current increases and the PV array voltage decreases this is the key point for MPPT.

$$V_o = V_s/(1-D) \quad (2)$$
$$L > V_s D/(f_s \Delta i_L) \quad (3)$$
$$C > D P_o/(f_s V_o \Delta V_o) \quad (4)$$

where:

D is the duty cycle

f_s is the switching frequency

Δi_L is inductor current ripple

P_o is the output power

ΔV_o is the output voltage ripple

IV. ARTIFICIAL NEURAL NETWORKS

Artificial neural networks (ANN) are composed of simple elements operating in parallel. These elements are inspired by biological nervous systems. As in nature, the connections between elements largely determine the network function. ANN can be trained to perform a particular function by adjusting the values of the connections (weights) between elements.

Typically, neural networks are adjusted values of the connections (weights) between elements, or trained, so that a particular input leads to a specific target output. Fig. 4 illustrates such a situation. There, the network is adjusted, based on a comparison of the output and the target, until the network output matches the target. Typically, many such input/target pairs are needed to train a network.

As shown in Fig. 5, the scalar input p is transmitted through a connection that multiplies its strength by the scalar weight w, to form the product wp, again a scalar. Here the weighted input wp. The neuron has a bias b, which is summed with the weighted input to form the net input n. This sum, n, is the argument of the transfer function f, which produces the scalar output ɑ.

There are many transfer functions. Four of the most commonly used functions are shown in Fig. 6.

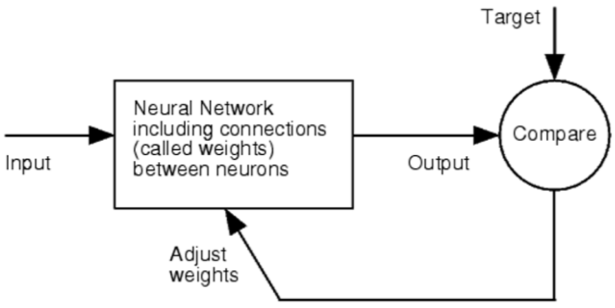

Fig. 4: Operating of ANN

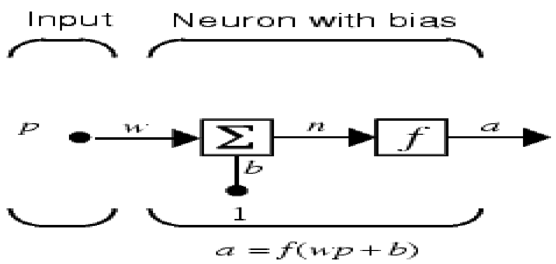

Fig. 5: Neuron with single input

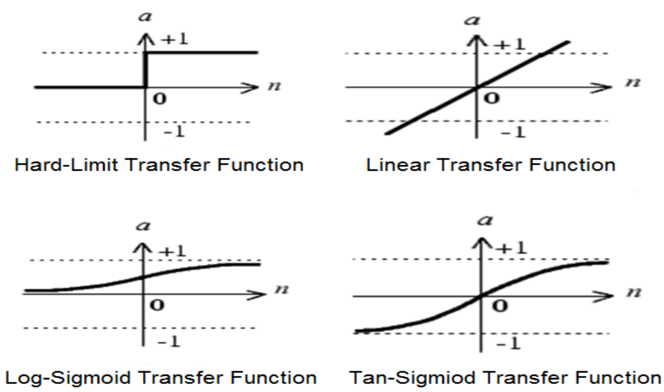

Fig. 6: Types of neuron transfer functions

ANN is formed from a group of highly interconnected artificial neurons. Theses neurons are ordered in layers. The most common ANN contains three layers: input layer, hidden layer and output layer. The input layer receives the ANN inputs and spreads them to the neurons of hidden layer. The output layer produces the final ANN output. The hidden layer performs the ANN intermediate calculations from input layer to output layer. The number of neurons in the input and output layers depends on the number of problem inputs and outputs respectively, while the number of neurons in the hidden layer depends on the required accuracy and computation time.

V. OPERATION OF MAXIMUM POWER POINT TRACKING TECHNIQUE BY ARTIFICIAL NEURAL NETWORKS

In this paper the proposed ANN for MPPT uses the PV irradiation and temperature sensor signals to estimate the optimal boost converter duty cycle as shown in Fig. 7. This duty cycle is used to control the boost converter through a PWM generator (DC-DC). The proposed MPPT scheme is checked at variable values of temperature and irradiation using MATLAB/SIMULINK platform to ensure its capability for MPPT. The system SIMULINK model is shown in Fig. 8.

The proposed ANN structure that shown in Fig. 9 receives the ambient temperature and solar irradiation as ANN inputs; consequently the input layer has two neurons. The hidden layer has ten neurons. All hidden layer neurons are tan-sigmoid type. The optimal duty cycle is the target; therefore the output layer has one neuron. The output layer neuron is pure-line. The advantage of using a few numbers of neurons in the proposed ANN is less time for both of training and execution.

Duty cycle of each MPP value obtained from PV at each actual applied temperature and irradiation, is determined using MATLAB/SIMULINK through PV module with resistance load (R_L). The next step is implementing certain temperature and irradiation for example 25 °C and 1000 W/m^2 with load resistance of 0 Ω and then increasing resistance value to reach MPP of PV, voltage at MPP (V_{mp}) and current at MPP (I_{mp}). Subsequently the optimal duty cycle for boost converter in this case is calculated by Eq. 5.

$$D = 1 - (V_{mp}/V_o) \quad (5)$$

As such in each actual applied both of temperature and irradiation. Then ANN is trained with all these values to obtain duty cycle depends on temperature and solar irradiation applied.

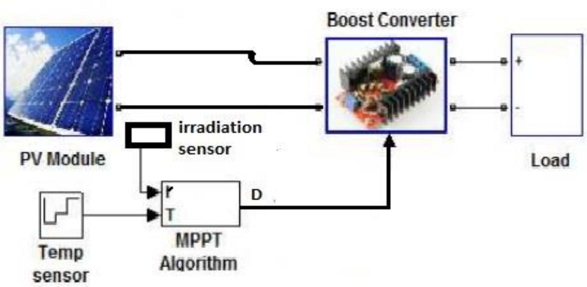

Fig. 7: Proposed MPPT scheme using ANN

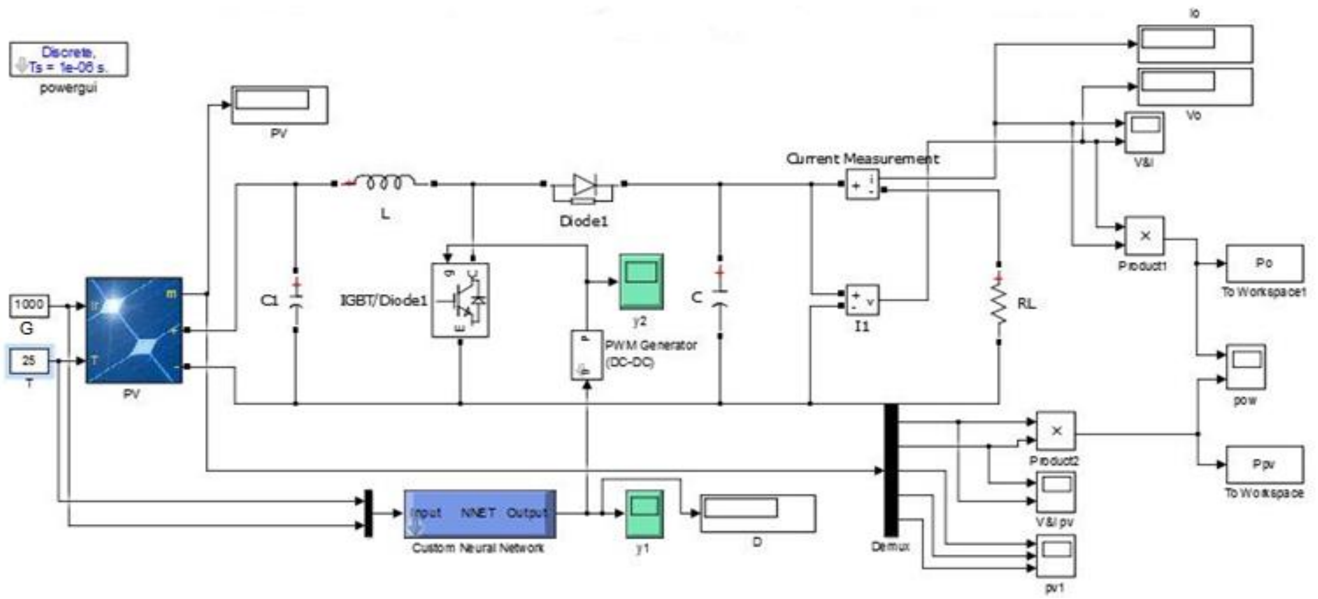

Fig. 8: SIMULINK model of the proposed system

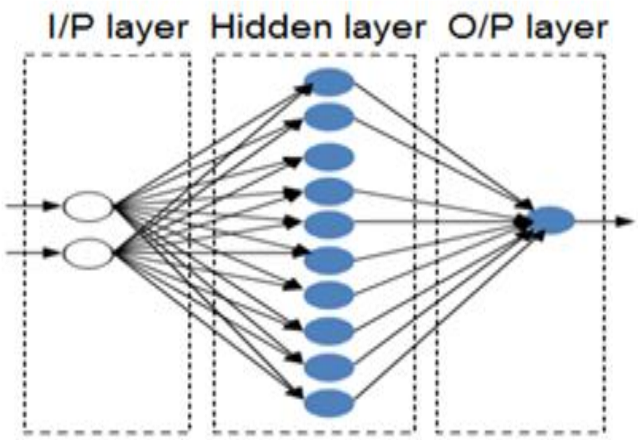

Fig. 9: Proposed ANN structure

VI. Simulation Results

Simulations are carried out at different values of temperature, irradiation and loads, on SIMULINK/MATLAB as following:-

A. *At T = 25 °C, G = 1000 W/m² and R_L = 55.3 Ω*

As shown in Fig. 10, the output power of boost converter is optimum (about 853 W). This happens because of two reasons. Firstly the temperature and irradiation are at standard values. Secondly the load resistance consumes maximum power ($R_L = V_{mp}/I_{mp}$).

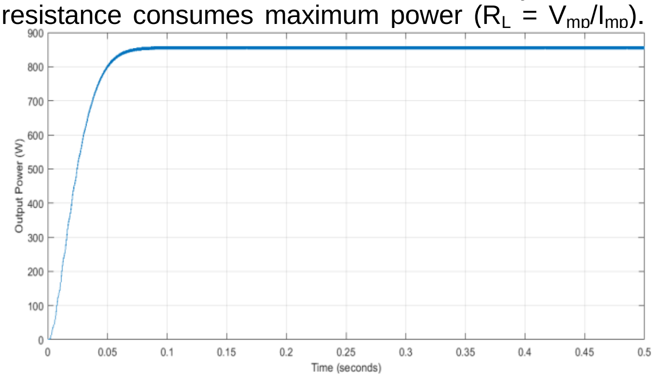

Fig. 10: Output power (P_o) when T = 25 °C & G = 1000 W/m² & R_L = 55.3 Ω

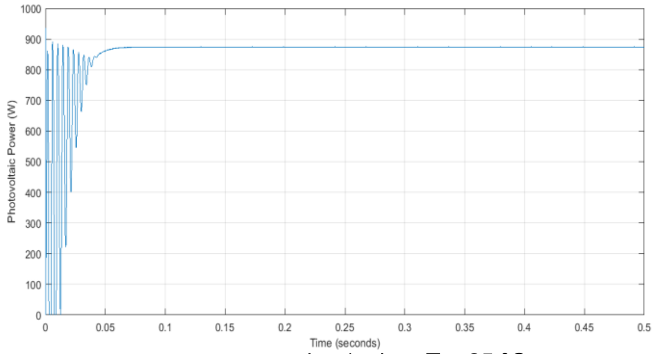

Fig. 11: PV power (P_{PV}) when T = 25 °C & G = 1000 W/m² & R_L = 55.3 Ω

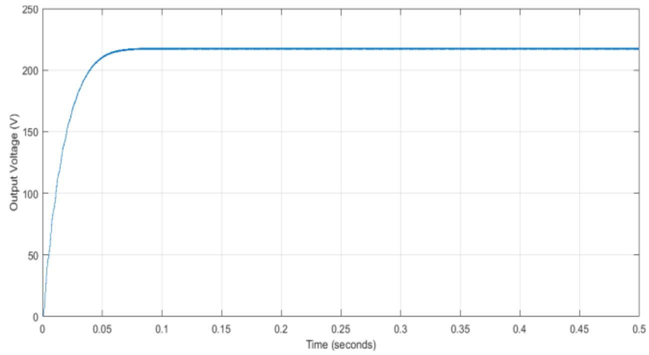

Fig. 12: Output voltage (V_o) when T = 25 °C & G = 1000 W/m² & R_L= 55.3 Ω

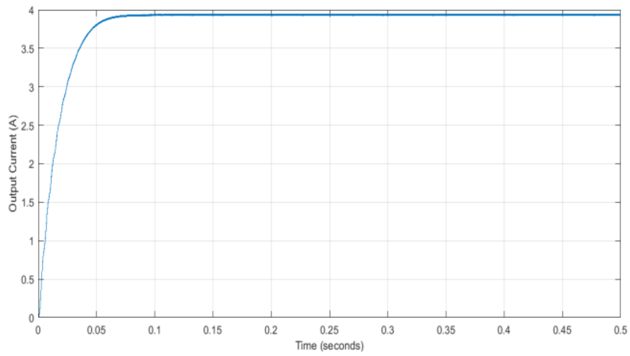

Fig. 13: Output current (I_o) when T = 25 °C & G = 1000 W/m² & R_L = 55.3 Ω

B. *At T = 25 °C, G = 1000 W/m² and R_L = 100 Ω*

As shown in Fig. 14, the output power is decreased (from 853 W to 625 W) with increased load, since the decrease in output current (from 3.96 A to 2.5 A) dominates the increase in output voltage (from 216 V to 250 V).

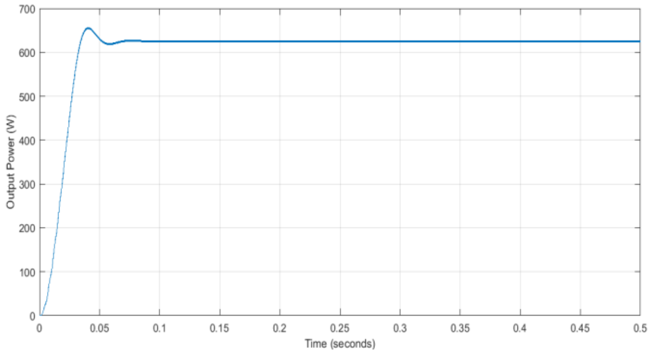

Fig. 14: Output power (P_o) when T = 25 °C & G = 1000 W/m² & R_L = 100 Ω

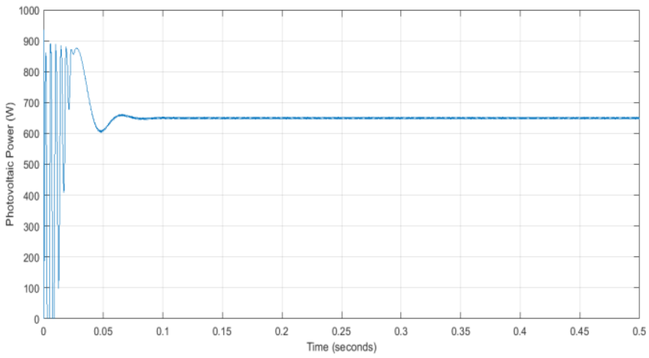

Fig. 15: PV power (P_{PV}) when T = 25 °C & G = 1000 W/m² & R_L = 100 Ω

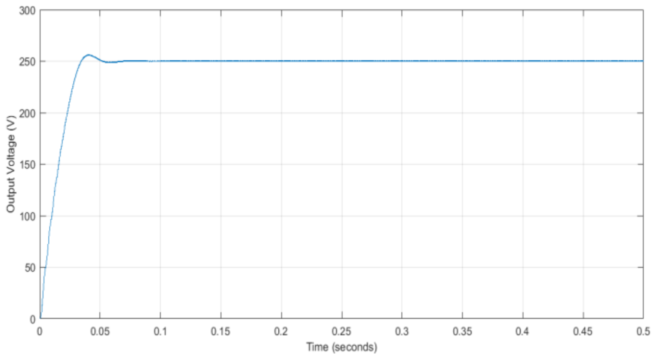

Fig. 16: Output voltage (V_o) when T = 25 °C & G = 1000 W/m2 & R_L= 100 Ω

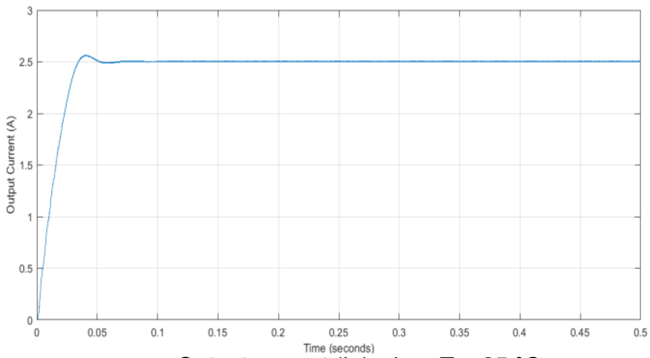

Fig. 17: Output current (Io) when T = 25 °C & G = 1000W/m² & R_L =100 Ω

C. *At T = 25 °C, G = 600 W/m² and R_L = 55.3 Ω*

As shown in Fig. 18, the output power is decreased from 853 W to 350 W because the decreased irradiation reduces both of the output voltage and the output current of boost converter from 216 V & 3.95 A to 140 V & 2.5 A respectively.

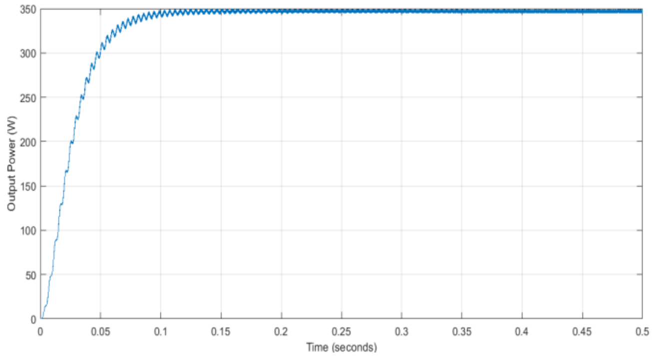

Fig. 18: Output power (P_o) when T = 25 °C & G = 600 W/m² & R_L = 55.3 Ω

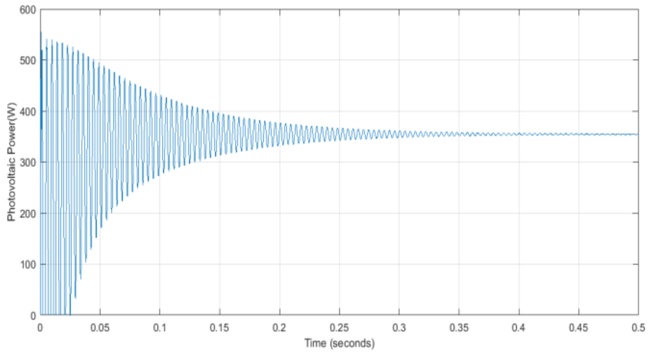

Fig. 19: PV power (P_{PV}) when T = 25 °C & G = 600 W/m² & R_L = 55.3 Ω

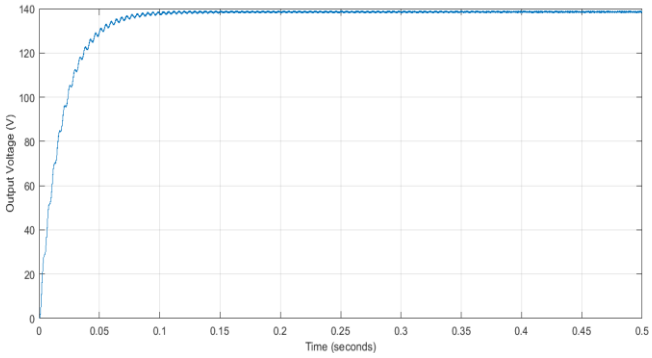

Fig. 20: Output voltage (V_o) when T = 25 °C & G = 600 W/m² & R_L = 55.3 Ω

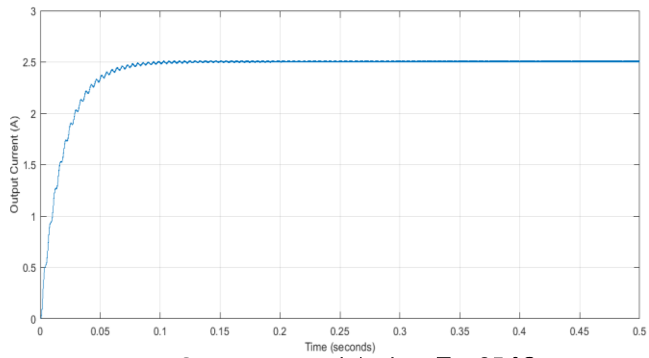

Fig. 21: Output current (I_o) when T = 25 °C & G = 600 W/m² & R_L = 55.3 Ω

D. *At T = 45 °C, G = 1000 W/m^2 and R_L = 55.3 Ω*

As shown in Fig. 22, the output power is decreased from 853 W to 760 W because the increased temperature reduces both of the output voltage and the output current of boost converter from 216 V & 3.95 A to 206 V & 3.69 A respectively.

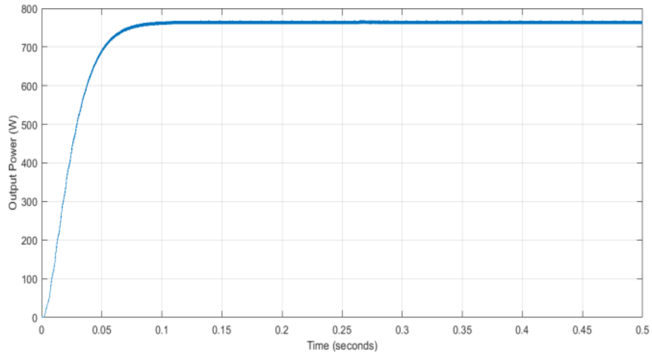

Fig. 22: Output power (P_o) when T = 45 °C & G = 1000 W/m^2 & R_L = 55.3 Ω

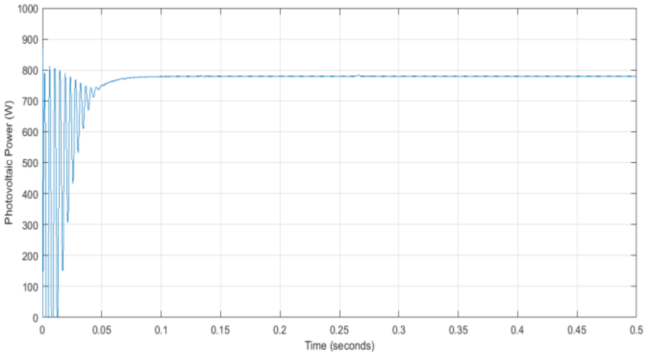

Fig. 23: PV power (P_{PV}) when T = 45 °C & G = 1000 W/m^2 & R_L = 55.3 Ω

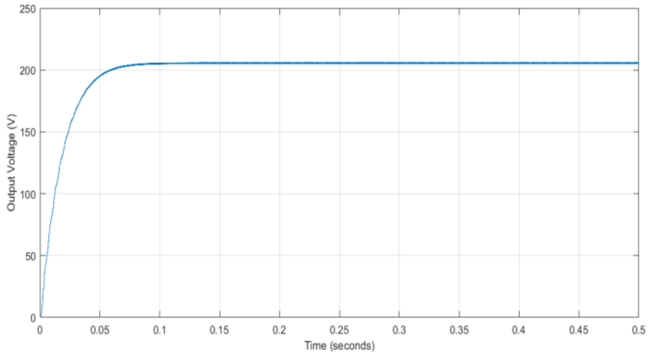

Fig. 24: Output voltage (V_o) when T = 45 °C & G = 1000W/m^2 & R_L = 55.3 Ω

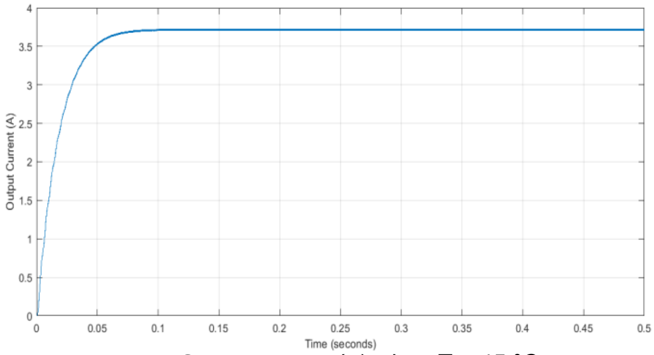

Fig. 25: Output current (I_o) when T = 45 °C & G = 1000 W/m^2 & R_L = 55.3 Ω

VII. CONCLUSION

The PV control system should maximize the generated energy by operating the PV around the maximum power point (MPP); this MPP depends on the temperature and solar irradiation. DC-DC boost converter is used to track MPP of PV array.

This paper introduces an ANN based on sensing the temperature and solar irradiation to determine the optimal boost converter duty cycle corresponding to MPP of each temperature and solar irradiation.

The simulation results prove that the required ANN is simple for implementation and takes small time for training almost 960 epochs and small time for execution. Finally, it should be noted that the proposed technique depends on the PV c/cs, so it should be adapted for each PV array.

ACKNOWLEDGMENT

The authors wish to thank Prof. Dr. Karam Sharshar for his guidance, support and encouragement until the achievement of this paper.

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Appendix

A. Parameters of PV array

Maximum power = 875.5 W,
open circuit voltage (V_{oc}) = 73.2 V,
short circuit current (I_{sc}) = 15.94 A,
voltage at MPP (V_{mp}) = 58.6 V,
current at MPP (I_{mp}) = 14.94 A.

B. Parameters of boost converter

Inductance (L) = 6.3 mH,
capacitance (C) = 330 µF,
switching frequency (f_s) = 9 kHz.