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Development of A Bond Graph Control Maximum Power Point Tracker For Photovoltaic: Theoretical And Experimental

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Abstract:

Maximum power point tracking is important in solar power systems because it reduces the solar array cost by decreasing the number of solar panels needed to obtain the desired output power. Several different Maximum power point tracking (MPPT) methods have been proposed, but there has been no comprehensive experimental comparison between all the different algorithms and their overall maximum power point (MPP) tracking efficiencies under varying conditions (i.e., illumination, temperature, and load). In this paper, a new maximum power point tracking controller using bond graph approach (BG-MPPT) for a photovoltaic energy conversion system has been developed, consisting of a boost buck DC/DC converter, which is controlled by a bond graph algorithm. The main difference between the method used in the proposed MPPT system and the techniques used in the past is that the PV array output power is used to directly control the DC/DC converter, thus reducing the complexity of the system. The resulting system has high-efficiency, lower-cost, and can be easily modified to handle more energy sources. The experimental results show that the use of the proposed MPPT control increases the PV output power by as much as 15% compared to the case where the DC/DC converter duty cycle is set such that the PV array produces the maximum power at 1 kW/m2 and 25°C.

Keywords: Maximum Power Point Tracking; Buck-Boost Converter; Photovoltaic; Bond Graph.

1. Introduction

The use of renewable energy systems as an alternative way to produce electricity has been increasing over the past few years [1]. The need of a cleaner, more efficient, and cheaper method for generating electric power is helping this growth.

Among all the renewable energy systems, the photovoltaic (PV) energy is a solution among the promising energy options with advantages such as abundance, the absence of any pollution and the availability in large quantities in anywhere of the globe worldly [2].

Photovoltaic sources are used today in many applications such as battery charging, water pumping, home power supply, swimming-pool heating systems, satellite power systems, electric vehicles, hybrid systems military and space applications, refrigeration and vaccine storage, power plants and some applications where nonlinear power source is needed. They have the advantage of being maintenance and pollution-free but their installation cost is high and they require a dc/dc or dc/ac converter for load interface.

There are three major approaches for maximizing power extraction in solar systems. They are sun tracking, maximum power point tracking or both [3]. These methods need intelligent controllers (such as fuzzy logic controller) or conventional controller (such as PID controller). In the literature, many maximum power point tracking systems have been proposed and implemented ([4]; [5]). The fuzzy theory, based on fuzzy sets and fuzzy algorithms, provides a general method of expressing linguistic rules so that they may be processed quickly. The advantage of the fuzzy logic control is that it does not strictly need any mathematical model of the plant. It is based on plant operator experience, and it is very easy to apply. Hence, many complex systems can be controlled without knowing the exact mathematical model of the plant [6]. In addition, fuzzy logic simplifies dealing with nonlinearities in systems [7]. The advantage of using fuzzy logic control is that the linguistic system definition becomes the control algorithm.

Many tracking techniques and algorithms have been developed. The Perturbation and Observation method (P&O) ([8]; [9]; [10]), the Incremental Conductance method ([11]; [12]) as well as Fractional Open Circuit Voltage method ([13]) and Fractional Short Circuit Current method ([14]) are the most widely used. The P&O Method has been widely used because of its simple feedback structure and fewer measured parameters and easy to implement. The peak power tracker operates by periodically incrementing or decrementing the solar array voltage. If a given perturbation leads to an increase (or decrease) in array power, the subsequent perturbation is made in the same (or opposite) direction. In this manner,

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the peak power tracker, continuously hunts or seek the peak power conditions. Most maximum power trackers are based on the perturb and observe approach, implemented by a hill-climbing [15] algorithm often on a microcontroller. However, this approach is quite complex, can be slow and thus can become 'confused' if the MPP moves abruptly.

In this work, the aim is to control the voltage of the solar panel in order to obtain the maximum power possible from a P V generator, whatever the solar insolation conditions. Since quite a few control schemes had already been used and had shown some defects, it was necessary to find and try some other methods to optimize the output, bond graph controller seemed to be a good idea. The controllers by bond g raph can provide an order more effective than the traditional controllers for the nonlinear systems, because there is more flexibility.

This work is motivated by the need to optimize solar array performance in Setif's climate, which is characterized by rapidly varying environmental conditions. The main objective of this paper is to present an improved BG-MPPT in order to increase the tracking response and consequently increase the tracking efficiency.

2. Proposed Method

Figure 1 s hows the proposed scheme for the MPPT. This system use a PV array (s x p) composed of sin series cells and p in parallel cells. It is then connected to a DC-DC converter in order to increase or decrease the desired voltage. It is then connected directly to the load. The duty cycle of the converter is controlled by a bond graph controller. Measurement of the PV array voltage, Irradiance and Temperature on the PV array surface are taken in order to estimate the optimal voltage for the maximum power, and then a n onlinear MPPT algorithm takes this value to produce the signal for driving the switching element of the DC/DC converter.

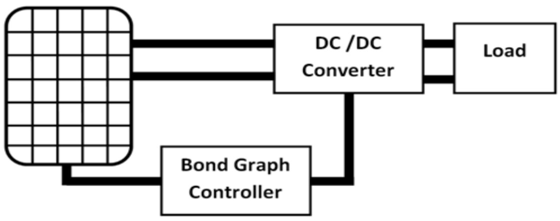

Figure 1. General scheme for the proposed method

3. Bond Graph Approach

Bond graph is an explicit graphical tool for capturing the structures among the physical systems and representing them as an energy network based on t he exchange of power ([16-19]). Others ([20-22]) have extended the bond graph concept to represent Phenomena such as chemical kinetics and to extract causal models and control structures from the bond graph networks. Bond graph, a graphical modeling language, provides a model formalism that decomposes the system into subsystems that map to the physical connections [23]. The resulting subsystems are essentially physical fields including mechanics, electronics, hydraulics, and chemistry. The time granularity for these domains is usually distinct.

A bond graph consists of subsystems linked together by lines representing power bonds. Each process is described by a pair of variables, effort e and flow f. Besides the effort and flow variables, two other types of variables are very important in describing dynamic systems; these variables, sometimes called energy variables, are the generalized momentum p as time integral of effort and the generalized displacement q as time integral of flow ([24, 25]).

4. PV Module Modelling

The use of equivalent electric circuits makes it possible to model characteristics of a PV cell. The typical model of a solar cell is shown in figure 2.

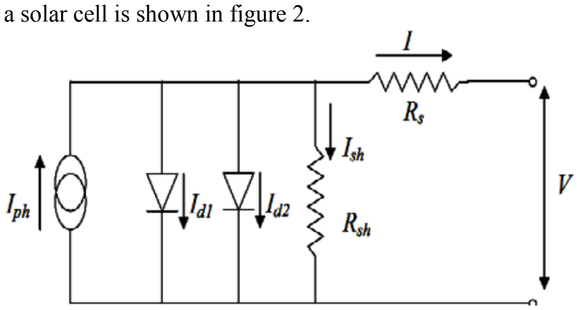

Figure 2. Equivalent circuit model of PV cell

A PV system directly converts sunlight into electricity. The basic device of a PV system is the photovoltaic cell; they may be grouped to form panels or arrays ([26]; [27]). This is the most classical model to be found in the literature [28], and it involves a cu rrent generator for modeling the incident luminous flux, two diodes for the cell polarization phenomena, and two resistors (R_s and R_{sh}) for the losses (figure 3).

The current provided by the cell is given by the relation (1)

$$I = I_{s1}\left[\exp\left\{\frac{q(V-R_sI)}{AKT}\right\}-1\right] + I_{s2}\left[\exp\left\{\frac{q(V-R_sI)}{AKT}\right\}-1\right] - I_{ph} + \frac{V-R_sI}{R_{sh}} \quad (1)$$

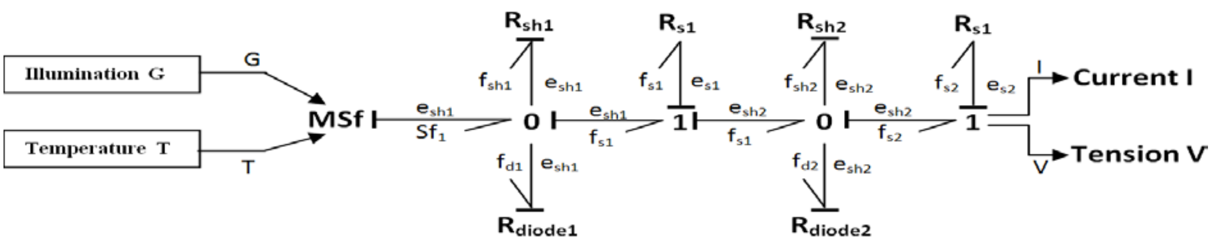

Figure 3. PV bond graph model with tow diodes

For the bond graph representation, the PV generator is then modeled by a flow source Sf= I_{ph} in parallel with two resistors R_{sh1} and R_{sh2}, the whole followed by a s erial resistance R_s ([29]; [30]). The PV diode bond graph representation is a non-linear resistor R_{diode}.

BP Solar BP SX 150S PV module is chosen for a Symbols simulation model. The module is made of 72 multi-crystalline silicon solar cells in series and provides 150W of nominal maximum power. T able 1 s hows its electrical specification.

Table 1. Electrical Specification

Electrical Characteristics	Value
Maximum Power (P_{max})	150W
Voltage at Pmax (V_{mp})	34.5V
Current at P_{max} (I_{mp})	4.35A
Open-circuit voltage (V_{oc})	43.5V
Short-circuit current (I_{sc})	4.75A
Temperature coefficient of I_{sc}	0.065 ± 0.015%/ °C
Temperature coefficient of V_{oc}	-160 ± 20 mV/ °C
Power temperature coefficient	-0.5 ± 0.05 %/ °C
NOCT	47 ± 2 °C

In order to characterize the solar cell, we used the model presented to provide the values of the tension V, of the current I and of the generated power produces P.

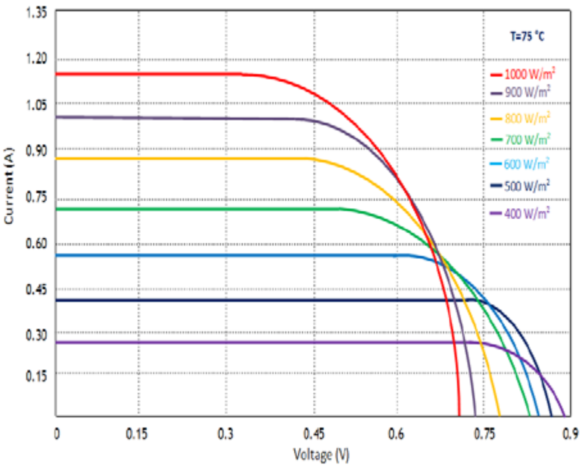

Figure 4. (I-V) characteristic for various illuminations.

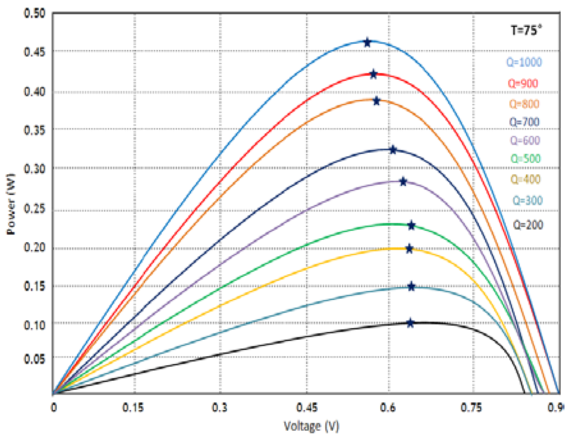

Figure 5. (P-V) characteristic for various illuminations

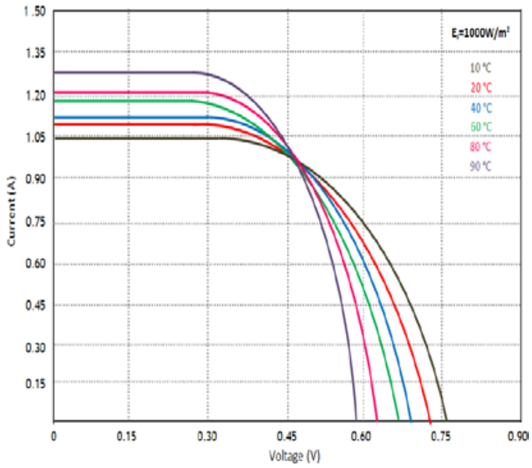

Figure 6. (I-V) characteristic for the various temperatures

If the temperature of the cell increases, the photo current I_{ph} also increases; this is mainly due to the reduction in the forbidden band dispatcher of material. This increase is about 0.1% by °C the forward current of the junction increases also, but much more quickly and involving a reduction in the open circuit tension of about 2mV by cell. The reduction in the provided power is estimated at approximately 0.5% by °C for a module.

5. Modeling of Dc-Dc Buck-Boost Converter

A buck-boost converter provides an output voltage that can be controlled above and below the input voltage level. The output voltage polarity is opposite to that of the input voltage.

Figure 7 shows the circuit diagram of a buck-boost converter. This converter either steps up or steps down the input DC voltage fed from the diode rectifier. The converter consists of a DC input voltage source Vs, inductor L, controlled switch S, filter capacitor C, diode D, and load resistance R.

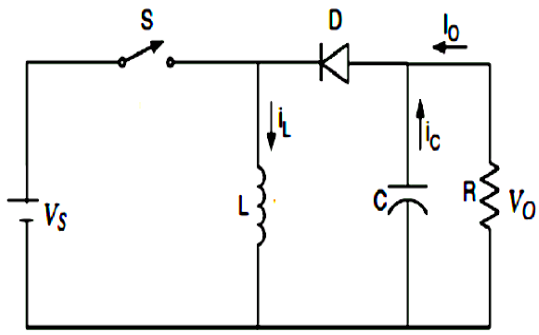

Figure 7. Circuit of Buck Boost Converter

There are two modes of operation of the converter. In Mode I, the switch is turned ON, the inductor current increases and the diode is in the OFF condition. In Mode II, the switch is turned OFF, the diode is turned ON and provides a path for the inductor current. The inductor current now decreases ([31,32]). In both the modes, the load current is assumed constant i_0=I_0 .

The bond graph model of the buck-boost is thus given by the figure (8).

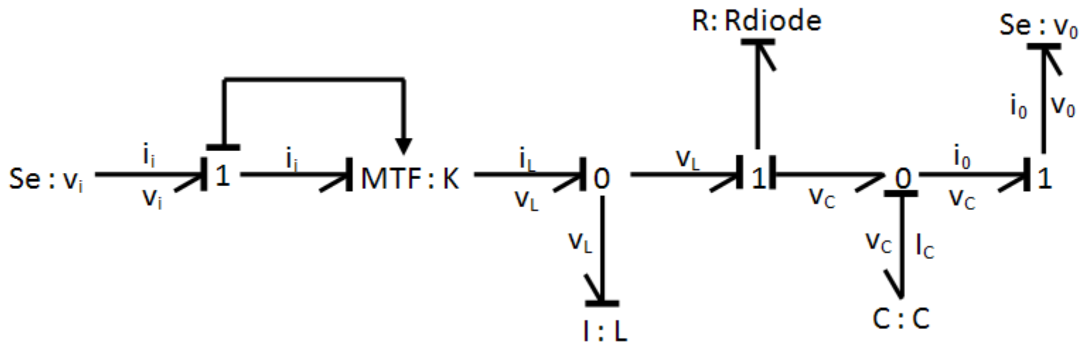

Figure 8. Bond graph model buck-boost converter

6. Perturbation And Observation (P&O)

The P&O algorithm is probably the most frequently used in practice, mainly due to its easy implementation [33]. Its operation is briefly explained as follows: assume that the PV array opera test a given point, which is outside the MPP. The PV array operational voltage is perturbed by a small DV, and then the change in the power (DP) is measured. If DP >0, the operation point has approached the MPP, and therefore, the next perturbation must take place in the same direction as the previous one (same algebraic sign).If, on the contrary, DP <0, the system has moved away from the MPP and, consequently, the next perturbation must be performed in the opposite direction. As stated before, the advantages of this algorithm are its simplicity and easy implementation. However, it h as limitations that reduce its tracking efficiency. When the light intensity decreases considerably, the P–V curve becomes very flat. This makes it difficult for the MPPT to locate the MPP, since the changes that take place in the power are small as regards perturbations occurred in the voltage.

Another disadvantage of the “P&O” algorithm is that it cannot determine when it has exactly reached the MPP. Thus, it remains oscillating around it, changing the sign of the perturbation for each DP measured. It has also been observed that this algorithm can show misbehaviour under fast changes in the radiation levels [34]. The flowchart of the P&O method is shown in figure (9).

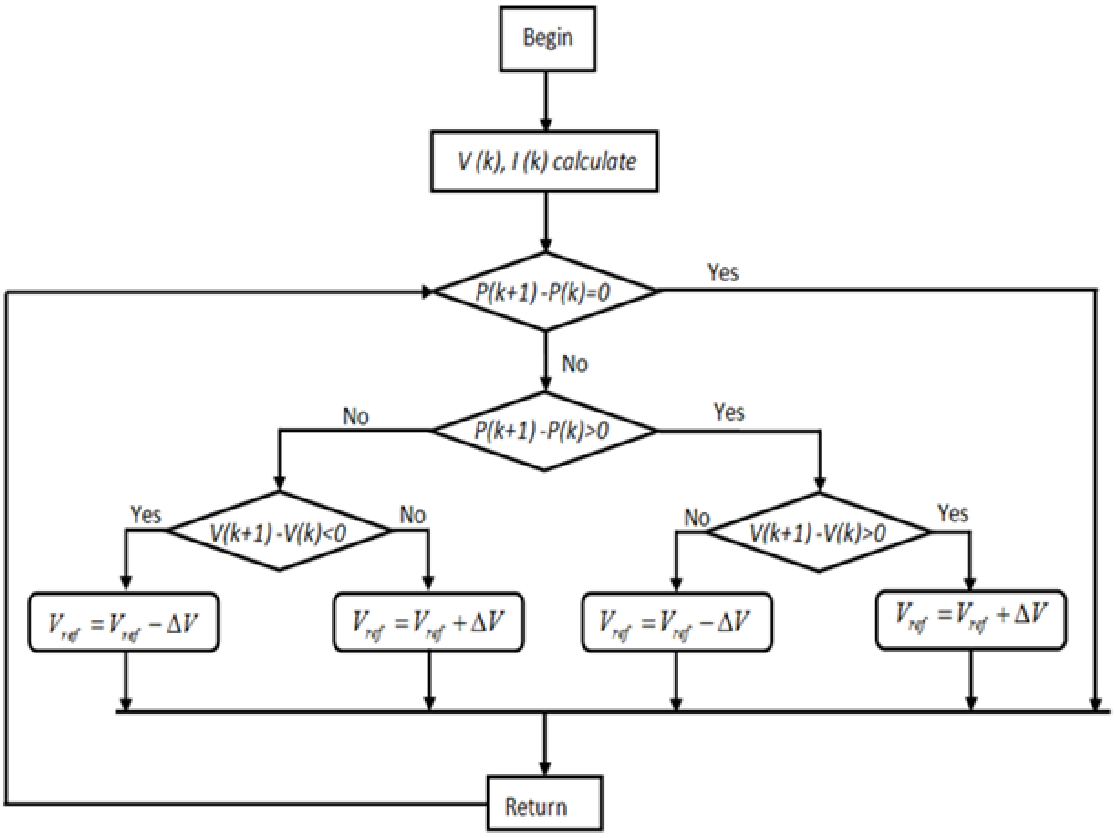

Figure 9. Flowchart of perturb and observe method

The P&O MPPT method can be implemented using a minimal amount of components; however, its speed is limited by the size and the period of the perturbation. The P&O method also has the problems of erroneous responses to quick changing conditions, and in steady state conditions will oscillate around the MPP causing losses. A more advanced technique for choosing direction can be employed by comparing the current power to the two previous power points which helps reduce errors.

7. Bond Graph Controller

The block diagram of the bond graph MPPT control is shown in figure (10). The proposed control consists of two loops, the maximum power point tracking loop is used to set a corresponding SE1 to the charger input, the regulating voltage loop is used to regulate the solar array output voltage according to SE1 which is set in the MPPT loop.

The controller senses the solar array current and voltage to calculate the solar array output power, power slope and SE1 (figure 10) for maximum power control.

The bond graph control requires that variable used in describing the control rules has to be expressed in elements of bond graph (elements R, I and C) with bond graph junction (0, 1 and TF). In this paper, the bond graph control MPPT method has two input variables, namely ΔP(k) and ΔU(k), at a sampling instant k.

The output variable is ΔU(k+1), which is voltage's increase of PV array at next sampling instant k+1. The variable ΔP(k) and ΔU(k) are expressed as follows:

$$\Delta P(k) = P(k) - P(k-1) \quad (1)$$

$$\Delta U(k) = U(k) - U(k-1) \quad (2)$$

Where P(k) and U(k) are the power and voltage of PV array, respectively. So, ΔP(k) and ΔU(k) are zero at the maximum power point of a PV array.

In figure (10), e25, SE1 and e6 are respectively the converter switching duty ratio, the demanded cell voltage and the actual cell voltage in the jth MPPT controller cycle, where j = k, k+1.

The MPPT controller calculates the new cell voltage set point based on the converter switching duty ratios and the measured cell voltages in the past and at present. The lead compensator (e27) forces the cell voltage to follow the demanded cell voltage signal. In the practical design of the control software, the threshold ε, which is a small positive number close to zero, is used to determine whether the MPP has been reached and e26 is used as a positive increment in the demanded cell voltage.

The variable δ j can be defined as:

$$\delta 1 = e_2 + e_4 + e_5 - e_3 \quad (3)$$

$$\delta 2 = e_{31} - e_{28} \quad (4)$$

$$\delta 3 = e_{31} + \left(e_2 + e_4 + e_5 - e_3\right)\frac{\delta 2}{\delta 1} \quad (5)$$

When | δ1 | > ε, the MPPT controller can be simplified as:

$$SE_1(k+1) = SE_1(k) + e20, \; \delta 3 > \varepsilon 3 \quad (6)$$

$$SE_1(k+1) + SE_1(k), |\delta 3| > \varepsilon 3 \quad (7)$$

$$SE_1(k+1) = SE_1(k) - e20, \delta 3 < -\varepsilon 3 \quad (8)$$

When | δ1 | < ε1, the MPPT controller can be simplified as:

$$SE_1(k+1) = SE_1(k) + e20, \delta 2 > \varepsilon 2 \quad (9)$$

$$SE_1(k+1) = SE_1(k), |\delta 2| < \varepsilon 2 \quad (10)$$

$$SE_1(k+1) = SE_1(k) - e20, \; \delta 2 < -\varepsilon 2 \quad (11)$$

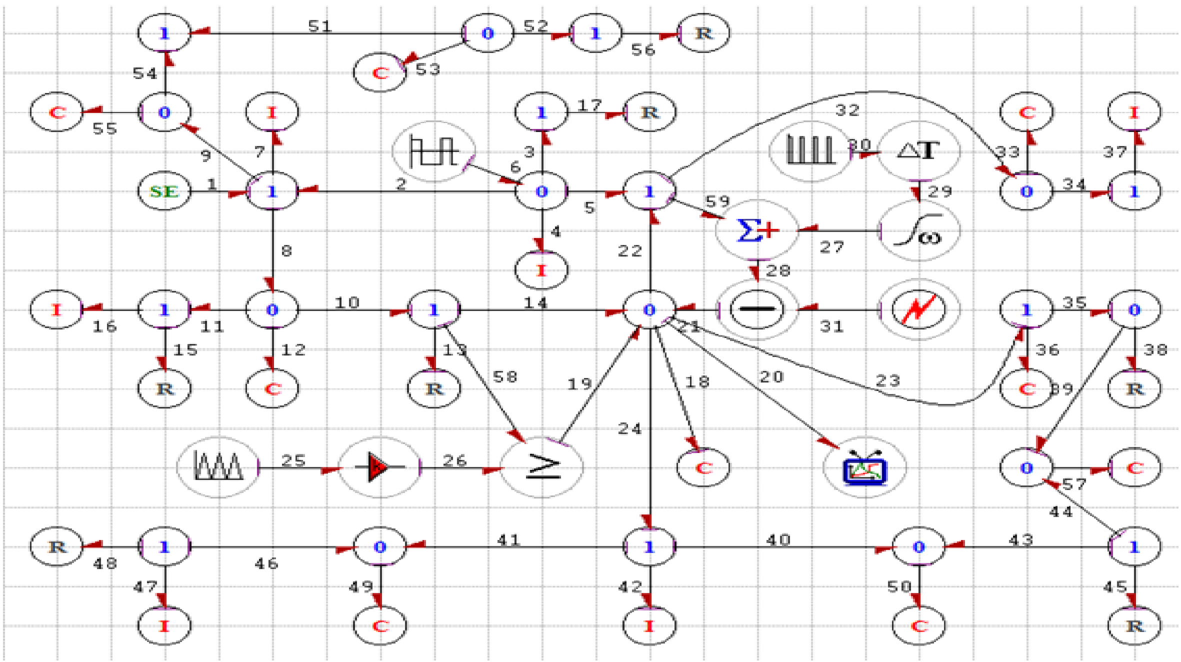

Figure 10. Bond graph MPPT control.

8. Exprimental Results

A prototype MPPT system (figure 11) has been developed using the described method and tested in the laboratory

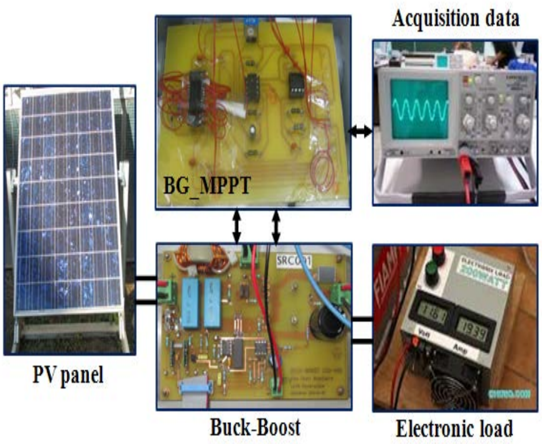

Figure 11. PV Global view of the prototype.

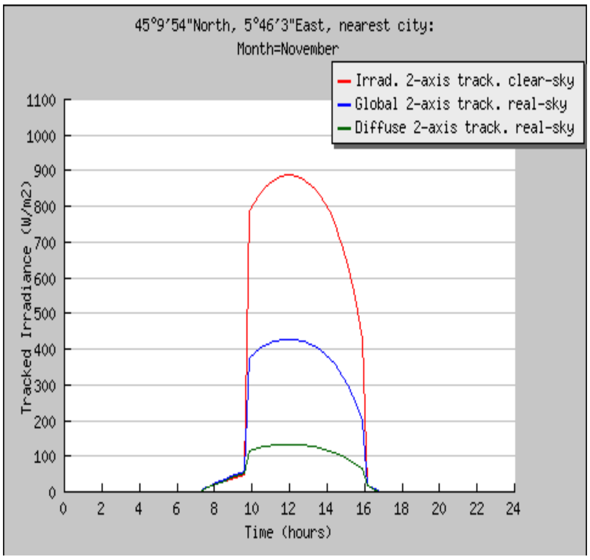

Figure 12. Characteristics of the site.

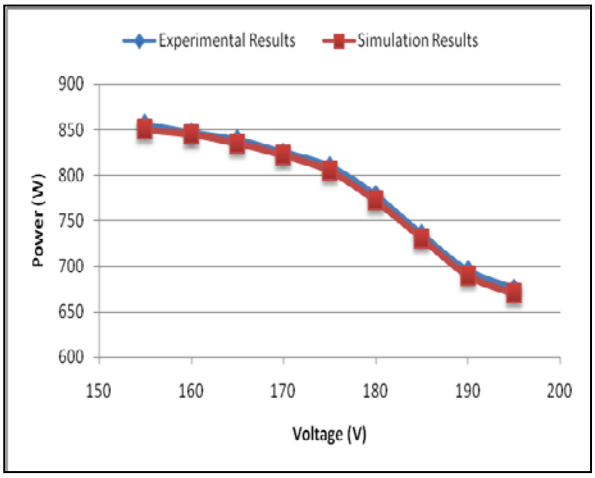

Figure 13. Variation of power according to the voltage.

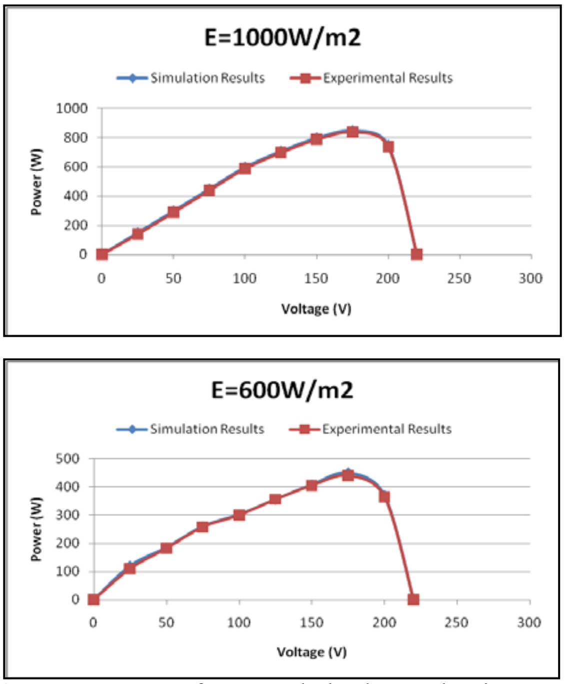

Figure 14. PV power of MPPT method under step changing irradiance.

The response time of the maximum PV power tracking, due to a step irradiance input, reflects the tracking speed of the bond graph MPPT method (shown in figure (13) and figure (14)) and present the PV power of MPPT method under step changing irradiance.

9. Comparative study

The proposed algorithm was validated by means of simulations performed with the Symbols code in two different situations, the former assuming the presence of the proposed control system and the latter its absence.

The simulation results of the PV system using a BG-MPPT and P&O algorithm are discussed in this section. Figure (15) compares the obtained P-V characteristics of the PV module from using the P&O algorithm and the proposed BG-MPPT algorithm.

From the figure, it is shown that by using the proposed algorithm, the location of the maximum power point (MPP) of the PV module is the nearest to the theoretical power as compared to the P&O algorithm.

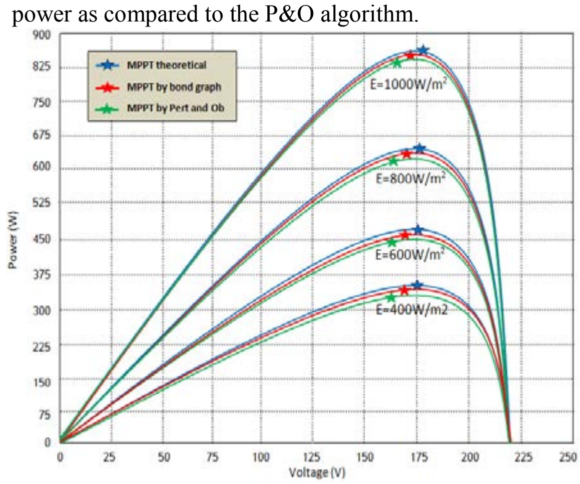

Figure 15. Comparing P-V characteristics.

To evaluate the performance of the proposed system, a comparison between the P&O algorithm and the proposed BG-MPPT algorithm is carried out for a set of solar radiation and the results are plotted in figure (16). From this figure, it is noted that the power of the proposed algorithm is higher than the classical P&O algorithm.

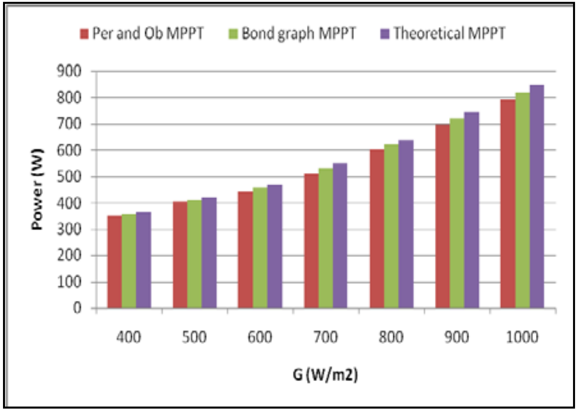

Figure 16. Comparing PV module powers.

In terms of efficiency, the efficiency of classical P&O algorithm is calculated by dividing the obtained power by the theoretical maximum power of PV module, while the efficiency of the proposed algorithm BG-MPPT is obtained by dividing the predicted power by the theoretical maximum power of PV module. According to the results, the tracking efficiency of proposed algorithm is not less than 92% as compared to using the P&O algorithm as shown in figure (17).

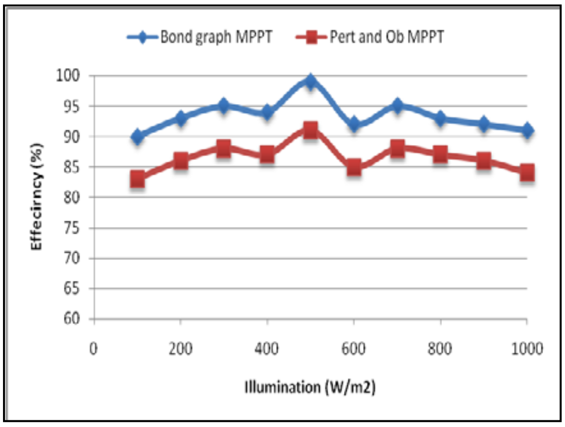

Figure 17. Comparing efficiency of PV system.

From the previous figures, the bond graph method is most effective among all the other methods. The second method is slower (speed point of view), given the number of iterations required to reach the MPP (180 iterations) and for slow changes in illumination, but with power losses due to the oscillation around the MPP, these losses may be even more important when weather conditions fluctuate rapidly (as a day cloud).

Such weather conditions are a problem for the search of MPP whatever the algorithm used, in fact, so that it can be effective, it is necessary that the static converter operates in steady state before new disturbances are made like bond graph method. In terms of speed the latter technique is faster, given the number of iterations required to reach the MPP (152 iterations).

10. Conclusions

This paper proposed the maximum power point tracker, using bond graph control, is developed to increase the energy generation efficiency of the solar cells. The proposed method involves implementing a maximum power point tracker controlled by bond g raph controller and using buck boost converter to keep the PV output power at the maximum point all the time. This controller is tested using Symbols program, and the results were compared with a perturbation and observation controller applied on the same system. The comparison shows that the bond graph controller is better in response and does not depend on knowing any parameter of PV panel. T he information required for bond graph control is only generating power; therefore, the hardware is simple and the cost of this system is inexpensive.

A general approach on modelling photovoltaic modules is presented. The proposed BG-MPPT is based on a DC/DC converter control with an original algorithm. The theoretical evaluations of the MPPT advantages, based on the proposed model, suggest that the power gain, obtained by MPP tracking, is higher than 27%.

The experimental results were compared with the simulated ones, for the same conditions and panel parameters. This comparison reveals that the differences between experimental data and simulated characteristics were less than 1%.

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