Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 3159-0040
Vol. 2 Issue 5, May - 2015

An Accurate Algorithm for MPP Estimation of PV Generator

Mohamed Abd-El-Hakeem Mohamed,
Faculty of Engineering, Electric Eng.,
Al-Azhar University, Qena, Egypt

Mohamed.H.Osman,
Faculty of Engineering, Electric Eng.,
Al-Azhar University, Qena, Egypt.

Abstract—In this study, an accurate algorithm for Maximum Power Point (MPP) estimation of a photovoltaic (PV) generator is investigated. The PV generator is composed of solar PV module and DC-DC converter. For this purpose, the effects of parasitic of the filter elements, parasitic elements in MOSFETs, and climate forcing on MPP estimation of a PV generator are taken into consideration to obtain the proposed algorithm. Detail mathematical model of DC-DC Converter including the proposed factors have been developed for improving the accuracy of this model. In order to evaluate the effectiveness of the proposed algorithm, an accurate model for photovoltaic panels, based exclusively on datasheet parameters has been developed and implemented. The most important contributions of this paper are the clear description of the MPP estimation process based on an accurate effective model and also determination the expected added value of maximum generating power of a PV generator as a result of applying the proposed algorithm which take the proposed factors into consideration.

Keywords—Maximum Power Point (MPP), photovoltaic (PV) generator, DC-DC Converter, parasitic elements

Nomenclature

VL- the voltage across the inductor
Vpv- the photovoltaic voltage
D- Duty cycle
F_s-Switching frequency
CD-Capacitance of Schottky Diode
COSS-Capacitance of MOS Switch
STC- Standard Test Conditions (Eref =1000 W/m², Tref=25 °C, spectrum AM1.5).
Tref=25 °C.
Io - Dark saturation current in STC.
Rsh- Panel parallel (shunt) resistance.
Vmpp - Voltage at the Maximum Power Point (MPP) in STC.
Impp – current at the Maximum Power Point (MPP) in STC.
q- Electron charge.
VL- the voltage across the inductor
CSW-Total Capacitance of Switching Elements
IL - Inductor Current
I_o- Output Current
P_{SW}- Power Absorbed by All Switching Elements
r_L- Inductor Series Resistance
r_{SW} -Parasitic Switching Resistance
T- Cell Temperature, in Kelvin.
ns - Number of cells in series.
I_{ph} - the photo-generated current in STC.
R_s - Panel series resistance.
A - Diode quality (ideality) factor.
V_t - Junction thermal voltage.

I .INTRODUCTION

The growing energy demand coupled with the possibility of reduced supply of conventional fuels, evidenced by petroleum crisis, along with growing concerns about environmental conservation, has driven research and development of alternative energy sources that are cleaner, are renewable, and produce little environmental impact. Among the alternative sources, the electrical energy from PV cells is currently regarded as a natural energy source that is more useful, since it is free, abundant, clean, and distributed over the Earth and participates as a primary factor of all other processes of energy production on Earth [1]. There is a unique point on the I-V or (power –voltage) curve of the solar array called MPP, at which the entire PV system (array, converter, etc.) operates with maximum efficiency and produces its maximum output power. The location of the MPP is not known, but can be located, by different algorithms [2]. The studies on the Maximum Power Point Tracking (MPPT) area are normally grouped in two categories: the first one relates to the DC-DC converter optimization, focusing on methods to choose the suitable DC-DC converters to operate as MPPT [3-4]; and the second one refers to the maximum power point tracking algorithm [5-8]. the MPPT is achieved by a DC-DC converter ,there are many factors can be effect on the dc-dc converter performance ,The influence of filter elements on the performance of the converter has been studied[3].and also the effect of parasitic elements present in MOSFET switch considered in paper[4].

The most commonly used MPPT algorithm is P&O method. This algorithm uses simple feedback arrangement and little measured parameters. In this approach, the module voltage is periodically given a perturbation and the corresponding output power is compared with that at the previous perturbing cycle [5].The incremental conductance method is based on the derivative of PV output power with respect to the PV voltage. The derivation is zero at MPP, positive on the left side of MPP and negative on the right side of MPP [6].The constant voltage method has been suggested in paper [7]. Paper [8] presents a temperature-based MPPT algorithm applied to PV systems.

Many investigations were reported above, about MPPT algorithms of a pv panel through dc-dc converter but no attention was paid to the effects of parasitic of the filter elements, parasitic elements in MOSFETs, on MPPT estimation of a PV - DC-DC boost converter system, although neglecting the parasitic effects lead to unacceptable errors in the calculation of duty cycle of the converter. The most cited MPPT algorithms on the literature [5-8] it has some limitations, like slow response speed, and even tracking in wrong way under rapidly changing atmospheric conditions, increased complexity and suffers from low accuracy. Paper [8] presents the MPPT algorithm based on the values of temperature only. Therefore this algorithm may be suffered from low accuracy because the Vmpp depend on both the temperature and irradiance values. This motivates the authors to investigate an accurate algorithm for MPP estimation of a PV generator including the numerous factors which are ignored in previous works. In this paper the effects of parasitic elements present in MOSFET switch are considered beside effect of filter elements inductor and capacitor in order to construct an accurate algorithm for MPP estimation of a PV generator. This paper also presents algorithm the Vmpp is estimated based on both the temperature and irradiance values. In order to evaluate the effectiveness of the proposed algorithm, an accurate model for photovoltaic panels, based exclusively on datasheet parameters has been presented. The proposed algorithm has been implemented in Matlab, in order to verify it in wide range of different temperature and irradiance conditions based on an accurate model.

II. Description of the System under Study

The PV generator under study is composed of solar PV module and boost converter as shown in Fig.1. The photovoltaic cell converts the sunlight into electricity. Solar PV module generates DC power at its maximum using boost converter with MPPT algorithm, which is discussed in this study.

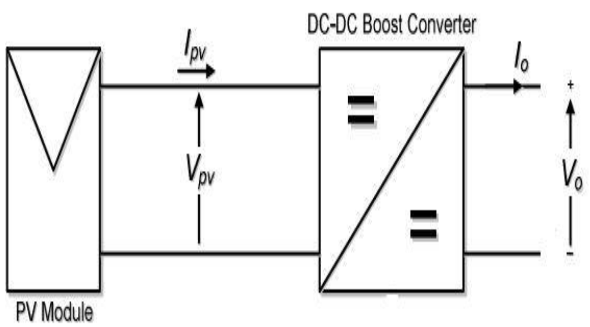

Fig.1. a PV generator configuration

A. An Accurate Model of Photovoltaic Module.

The effectiveness of the proposed algorithm can be evaluated by using an accurate model for photovoltaic panels, which is deduced based exclusively on datasheet parameters .Fig. 2.shows the equivalent circuit for a PV cell. The output current of the equivalent circuit, I_{pv} , can be expressed as a function of the PV cell's voltage, V_{pv} [1]:

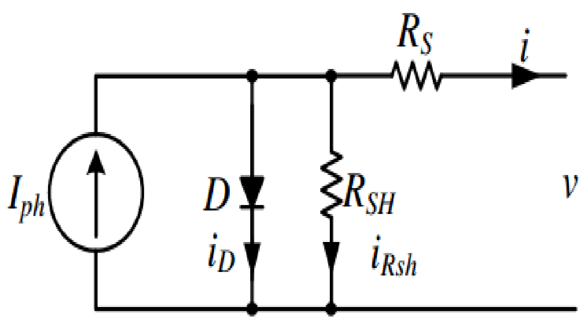

Fig.2. Equivalent circuit of a photovoltaic cell using the single exponential module

$$I_{pv} = I_{ph} - I_o\left(e^{\frac{V_{pv}+IR_s}{n_s V_t}} - 1\right) - \frac{V_{pv}+I_{pv}R_s}{R_{sh}} \quad (1)$$

In the above equation, Vt is the junction thermal voltage:-

$$V_t = \frac{AKT}{q} \quad (2)$$

Equation (1) can be written for the three key-points of the V-I characteristic: the short-circuit point, the maximum power point and the open-circuit point.

$$I_{sc}=I_{ph} - I_o\, e^{\frac{I_{sc}R_s}{n_s V_t}} - \frac{I_{sc}R_s}{R_{sh}} \quad (3)$$

$$I_{mpp}= I_{ph} - I_o e^{\frac{V_{mpp}+ I_{mpp}R_s}{n_s V_t}} - \frac{V_{mpp}+I_{mpp}R_s}{R_{sh}} \quad (4)$$

$$I_{oc} = 0 = I_{ph} - I_o\, e^{\frac{V_{oc}}{n_s V_t}} - \frac{V_{oc}}{R_{sh}} \quad (5)$$

An additional equation can be derived using the fact that is on the P-V characteristic of the panel, at the MPP, the derivative of power with voltage is zero.

$$\left.\frac{dP}{dV}\right|_{\substack{V=V_{mpp}\\ I=I_{mmp}}} = I_{mpp} - V_{mpp}\frac{-\frac{(I_{sc}R_s+V_{oc}-I_{sc}R_{sh})e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{n_s V_t}}}{n_s V_t R_{sh}}+\frac{1}{R_{sh}}}{1-\frac{(I_{sc}R_s+V_{oc}-I_{sc}R_{sh})R_s e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{n_s V_t}}}{n_s V_t R_{sh}}+\frac{R_s}{R_{sh}}} = 0 \quad (6)$$

The fifth equation can be derived using the fact that is on the P-I characteristics of a PV system at the maximum power point, the derivative of power with respect to current is zero.

$$\left.\frac{dP}{dI}\right|_{\substack{V=V_{mpp}\\ I=I_{mmp}}} = V_{mpp} - I_{mpp}\frac{1-\frac{(I_{sc}R_s+V_{oc}-I_{sc}R_{sh})R_s e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{n_s V_t}}}{n_s V_t R_{sh}}+\frac{R_s}{R_{sh}}}{-\frac{(I_{sc}R_s+V_{oc}-I_{sc}R_{sh})e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{n_s V_t}}}{n_s V_t R_{sh}}+\frac{1}{R_{sh}}} = 0 \quad (7)$$

equations. (3) And (5) can be inserted into Eq. (4), which will take the form

$$I_{mpp} - I_{sc} + \frac{V_{mpp}+I_{mpp}R_s-I_{sc}R_s}{R_{sh}} + \left(I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_{sh}}\right) e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{n_sV_t}} = 0 \quad (8)$$

The Newton-Raphson calculate the three unknown parameters (Rs, A, and Rsh) of PV panel model Rsh using equations. (6), (7) and (8).Then, the other parameters (I_o, and Iph) are calculated directly from equations (9, 10) respectively.

$$I_o = \left(I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_{sh}}\right)e^{-\frac{V_{oc}}{n_sV_t}} \quad (9)$$

$$I_{ph} = I_o e^{\frac{V_{oc}}{n_sV_t}} + \frac{V_{oc}}{R_{sh}} \quad (10)$$

B- An Accurate Model of DC-DC Converter.

In order to begin analysis, it is important to observe the converter behavior without any added parasitics (switch resistance, inductor resistance, diode forward voltage drop, et cetera). Thus, Fig. 3. will be used for the ideal derivations.

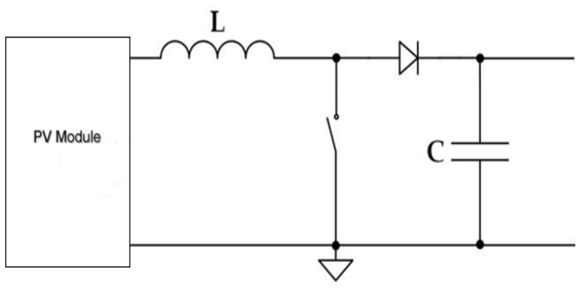

Fig.3. Ideal boost converter circuit

During the switch is closed, the voltage across the inductor, VL is equal to the photovoltaic voltage, Vpv, and the inductor current is approximately constant (in that it is increasing linearly), it can be said that:

$$\Delta i_{L,closed} = \frac{V_{pv}D}{LF_s} \quad (11)$$

Next, the switch is open. As such, the voltage across the inductor becomes Vpv − VO, and referring to the inductor current graph for shown in Fig.4. rearranging the equation for voltage in an inductor yields:

$$\Delta i_{L,open} = \frac{(V_{pv}-V_o)(1-D)}{LF_s} \quad (12)$$

In steady-state, the total change in inductor current must equal zero, thus by using (11) and (12):

$$0 = \Delta i_{L,closed} + \Delta i_{L,open}$$
$$= V_{pv}D + V_{pv}(1-D) - V_o(1-D) \quad (13)$$

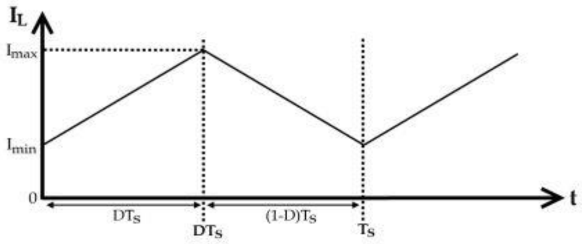

Fig.4. Inductor Current in Boost Converter

Rearranging the above equation to solve for the DC output-to-input transfer unction yields:

$$\frac{V_o}{V_{pv}} = \frac{1}{1-D} \quad (14)$$

Fig.5.shows the boost converter circuit with parasitics added in. In order to derive the output voltage of the non-ideal boost converter, the concept of energy conservation [4] is used where in:

$$P_{pv} = P_o + P_{loss} \quad (15)$$

Thus it is necessary to observe what mechanisms will cause power loss in the non-ideal model. The dynamic switching losses in both the transistor switch and the diode, given by (16).

$$P_{C_{sw}} = \frac{1}{2}C_{sw}V^2_{sw}F_s \quad (16)$$

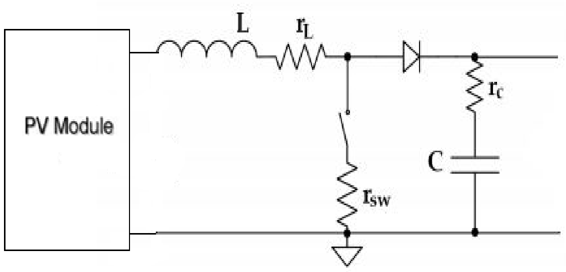

Fig.5.Non-Ideal Boost Converter Circuit

Using Schottky diodes in switched DC-DC converter circuits caused increasing that capacitance causes a corresponding linear increase in power consumption as evidenced by plugging (17) into (16).

$$C_{sw} = C_{oss} + C_D \quad (17)$$

Assuming that the diode on-resistance is small and that the forward voltage drop will be the primary source of static loss in the diode, the total power loss can be given as,

$$P_{Loss} = P_{rL} + P_{sw} + P_D \quad (18)$$

where P_{sw} is equal to both the conduction loss due to the switch, PrSW, as well as the dynamic switching losses, PCSW and PD is equal to the conduction loss due to the diode.

Likewise, since the diode is only conducting for the time interval of (1 − D) TS, the average power absorbed by the diode is just (1 − D) VD IL. This yields the equation:

$$P_{Loss} = r_l I^2{}_L + D r_{sw} I^2{}_L + \frac{1}{2} C_{sw} V_o{}^2 F_s + (1 - D) V_D I_L \quad (19)$$

Since,

$$P_s = P_o + P_{rL} + P_{sw} + P_D \quad (20)$$

$$\therefore V_{pv} I_{pv} = V_o I_o + r_l I^2{}_L + D r_{sw} I^2{}_L + \frac{1}{2} C_{sw} V_o{}^2 F_s + (1 - D) V_D I_L \quad (21)$$

Since current through the diode is equal to (1− D) IL, and all of the DC component of the diode current must be delivered to the load, the following relationship can be established and

then solved for IL :

$$(1 - D)\,IL = I_o$$

$$\therefore IL = \frac{I_o}{(1 - D)} \quad (22)$$

Dividing (21) through by IL and plugging (22) into IL yields:

$$V_{pv} = (1 - D) V_o + r_L \frac{I_o}{1-D} + D r_{sw} \frac{I_o}{1-D} + \frac{1-D}{2 I_o} C_{sw} V_o{}^2 F_s + (1 - D) V_D \quad (23)$$

III. AN ACCURATE ESTIMATION OF MAXIMUM POWER POINT.

An accurate algorithm for MPP estimation of a PV system based on accurate model of DC-DC boost converter which is describe in the previous section and the climate forcing on MPP estimation of a PV generator have been assessed and taken into consideration as cleared in the following steps.

step1. The PV module surface temperature T, irradiances G, and the output voltage Vo which can be measure or estimated [9] are applied as input data for the tracking algorithm.

Step2.Estimation of MPP take the temperature and irradiances into consideration based on the fact that the output photovoltaic voltage and current are directly proportional to the temperature and irradiances values on the photovoltaic surface [10]. The maximum power point voltage and current are calculated as follow.

$$V_{mpp} = V_{mpp,ref} + V_t \ln\left(\frac{G}{G_{ref}}\right) + K_v (T - T_{ref}) \quad (24)$$

$$I_{mpp} = I_{mpp,ref} \frac{G}{G_{ref}} + K_i (T - T_{ref}) \quad (25)$$

Step3. The values of duty cycle of the converter to operate at MPP can be calculated based on equations (21,24 and 25) which is take the different factors (parasitic of the filter elements, parasitic elements in MOSFETs, and climate forcing) into consideration and it can be given as follow

$$D_{accurate} = 1 - \frac{V_{mpp} I_{mpp} - r_l I^2{}_{mpp} - D r_{sw} I^2{}_{mpp} - \frac{1}{2} C_{sw} V_o{}^2 F_s}{I_{mpp}(V_o + V_D)} \quad (26)$$

Step4.To verify the effectiveness of this algorithm The value of maximum generating power of the system with the proposed algorithm (P_{mg1}) from equation (27) and the opposite values based on ideal calculation (P_{mg2}) are calculate using equation (28). And also the percentage added value to maximum generating power(P_{add}%) of a PV system as a result of applying the proposed algorithm which take the proposed factors into consideration can be calculated using equation(29).

$$P_{mg1} = V_{pv1} I_{pv1} - r_l I^2{}_L - D r_{sw} I^2{}_L - \frac{1}{2} C_{sw} V_o{}^2 F_s - (1 - D_{accurate}) V_D I_L \quad (27)$$

$$P_{mg2} = V_{pv2} I_{pv2} - r_l I^2{}_L - D r_{sw} I^2{}_L - \frac{1}{2} C_{sw} V_o{}^2 F_s - (1 - D_{ideal}) V_D I_L \quad (28)$$

$$P_{add} = \frac{P_{mg1} - P_{mg2}}{P_{mg2}} * 100\% \quad (29)$$

Where

($V_{pv1,}I_{pv1}$) Is the operating point of a PV model which calculated based on accurate model of a PV and accurate duty cycle of the converter values which is calculated by using equation (26)

($V_{pv2,}I_{pv2}$) Is the operating point of a PV model which calculated based on accurate model of a PV and ideal duty cycle values of the converter values which is calculated by using equation (14)

IV. RESULTS AND DISCUSSION

Section (2.1) describes the construction of an accurate PV panel model which is used to verify the effectiveness of the algorithm for MPP estimation of a PV generator .So an accurate PV panel model has been implemented in Matlab and tested using manufacturer data sheet. In order to verify it in different temperature and irradiance conditions. The temperature dependencies of the model's V-I and P-V curves have been verified by plotting the characteristics for three different temperatures as shown in figures 6 and 7.

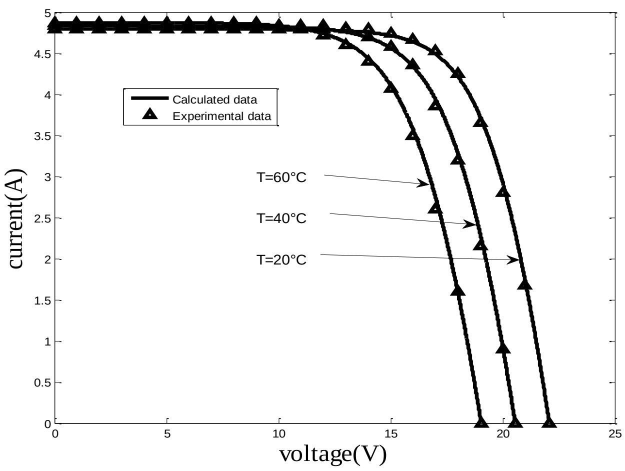

Fig. 6.Voltage current characteristics of the shell SP75 model at three different temperatures and standard irradiation.

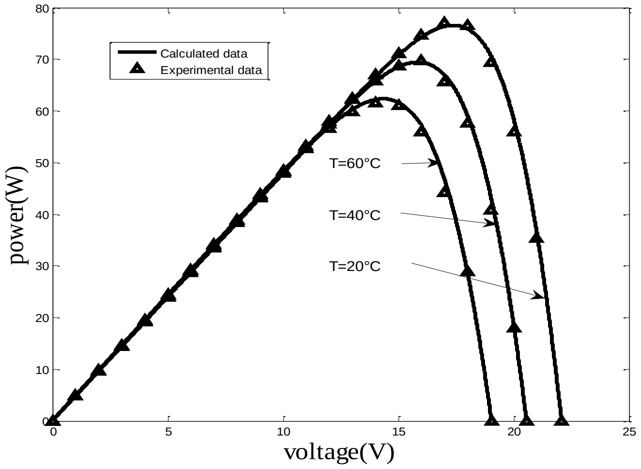

Fig.7. Voltage-power characteristics of the shell SP75 model at three different temperatures and standard irradiation.

The effect of the irradiance on the voltage-current (V-I) and voltage-power (V-P) characteristics of shell SP75 solar panel under various irradiances level is best depicted in Figures8, 9.

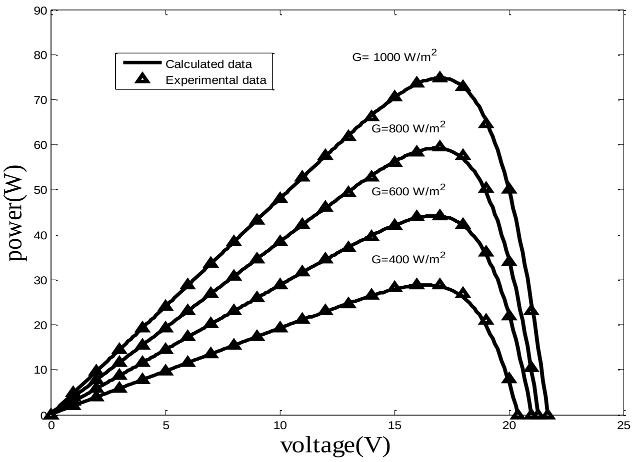

Fig. 9.Voltage –power characteristics of the shell SP75 model at different irradiation and standard temperature.

From figures (6-9) it can be noted the calculated (I-V, P-V) curves based on proposed an accurate model are in good agreement with the experimental data for different effects of the environment (temperature and irradiance) and it can be used to verify the effectiveness the algorithm for MPPT estimation of a PV system.

Section (3) describes the construction of the proposed algorithm for MPP estimation of a PV system. It has been implemented in Matlab, in order to verify it in wide range of different temperature and irradiance conditions based on an accurate model which is tested previously. Fig.10. show the calculated values of duty cycle using the proposed algorithm which is take the different factors (parasitic of the filter elements, parasitic elements in MOSFETs, and climate forcing) into consideration and the calculated values using conventional algorithm [9] (ignore the proposed factors)

From Fig.10. it can be noted that ,there are unacceptable errors in the calculation of duty cycle of the converter was found due to ignore the proposed factors which are included into the proposed algorithm.

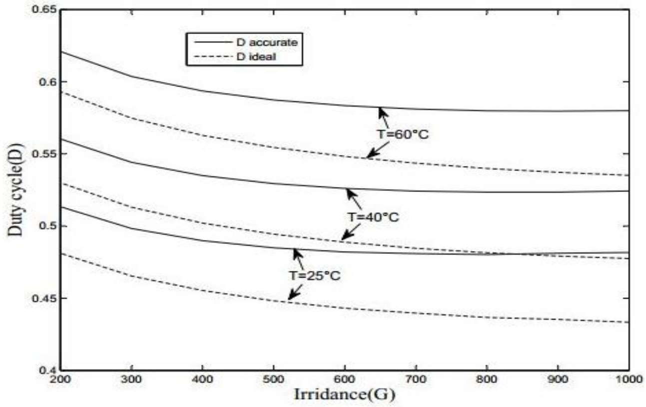

Fig. 10. Duty Cycle versus irradiance Comparison for proposed and conventional algorithms

Fig.11. show the values of maximum generating power (P_mg1) of a PV generator using the proposed algorithm which is take the different factors into consideration against the values based on the conventional algorithm (P_mg2).

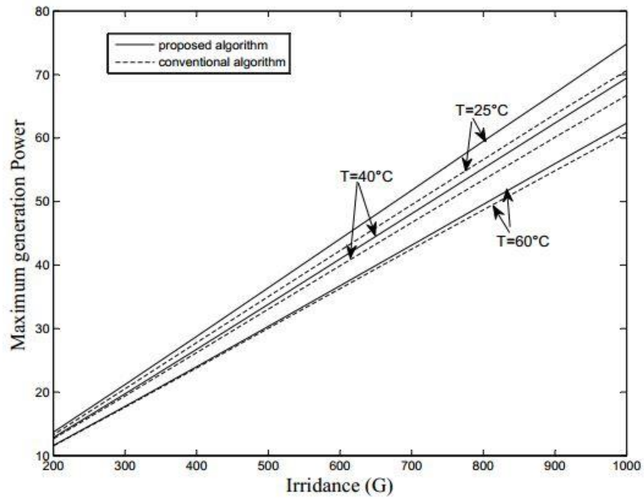

Fig. 11. Maximum generation Power versus irradiance Comparison for proposed and conventional model

As can be seen in Fig.11. the proposed algorithm achieve high maximum generating power of a pv generator compare to the values which are achieved by using the conventional algorithm at the same environment conditions

This difference between the proposed and conventional model Illustrated clearly by calculated the percentage added value to maximum generating power of a pv generator due to use of the proposed algorithm as shown in Fig.12.

From Fig.12. it can be noted that, the added value to maximum generating power of a PV system as a result of applying the proposed algorithm which take the proposed factors into consideration reached to 6 % from the corresponding values of conventional algorithm.

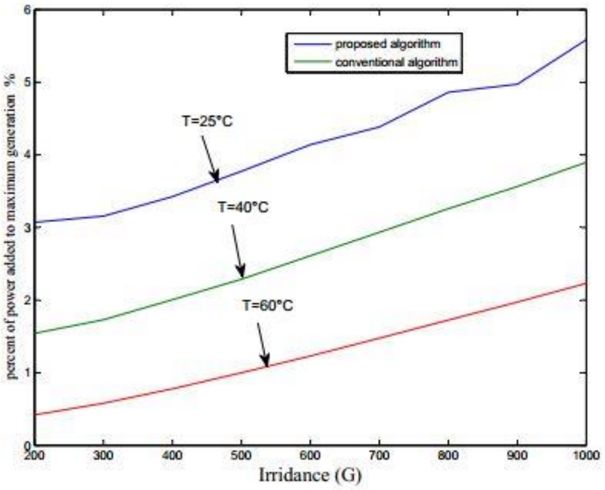

Fig. 12 .percent of power added to maximum generation at versus temperature and irradiance

V. CONCLUSION

This paper investigates an accurate algorithm for MPP estimation of a PV generator. This algorithm including the effects of parasitic elements present in MOSFET switch beside effect of filter elements inductor and capacitor. Also a new tracking algorithm, based on the PV surface temperature and irradiances is introduced. From the present analysis, one can draw the following main conclusions:-

The effects of parasitics (parasitic of the filter elements, parasitic elements in MOSFETs) have been taken into consideration for improving the DC-DC boost converter accuracy, to avoid unacceptable errors in the calculation of duty cycle of it.

The proposed algorithm, estimate Vmpp based on both the temperature and irradiance values.

The proposed algorithm is more reliable because An accurate PV panel model which is used to verify the effectiveness of the algorithm for MPP estimation of a PV system give (I-V, P-V) curves are in good agreement with the experimental data for different effects of the environment (temperature and irradiance).

The percentage added value to maximum generating power (P_{add}) of a PV generator as a result of applying the proposed algorithm which takes the proposed factors into consideration reached to 6 %.

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