ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 10, October 2015

A Fast-Converging MPPT Technique for Photovoltaic System with Modified SEPIC Converter under Fast- Varying Solar Irradiation and Load Resistance

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ABSTRACT: A fast-converging maximum power point tracking (MPPT) system is very essential for the photovoltaic (PV) system to ensure the rapid response with minimum power losses under fast-varying solar irradiation and load resistance. Traditionally, maximum power point (MPP) locus was used to provide such a fast response. However, the algorithm requires extra control loop or intermittent disconnection of the PV module. Hence, this paper proposes a simpler fast-converging MPPT technique, which excludes the extra control loop and intermittent disconnection. In the proposed algorithm, the relationship between the load line and the *I*–*V* curve is used with trigonometry rule to obtain the fast response. Results of the simulation and experiment using Modified SEPIC converter(which provide more static gain than simple SEPIC converter) showed that the response of the proposed algorithm is four times faster than the conventional incremental conductance algorithm during the load and solar irradiation variation. Consequently, the proposed algorithm has higher efficiency.

KEYWORDS:. Fast converging, incremental conductance, maximum power point tracking (MPPT), photovoltaic (PV) system, Modified SEPIC.

I.INTRODUCTION

Solar energy is gaining popularity in the field of electricity generation. The advantages of solar power, such as no air pollution, no fuel costs, noiseless, and low maintenance, have boosted the demand on this type of energy However; the high expense in acquiring the photovoltaic (PV) module has slowed down the adoption of PV system in electricity generation. Furthermore, the power of PV modules is unstable and strongly dependent on solar irradiation and load. Hence, the maximum power point tracking (MPPT) controller is introduced to ensure the PV system always provide high efficiency despite the variation in solar irradiation and load resistance.

Many MPPT algorithms have been introduced to improve the efficiency of the PV system, including fractional open circuit voltage, fractional short circuit current, fuzzy logic, neural network, hill climbing or perturbation and observation (P&O), and incremental conductance. Among those algorithms, P&O and incremental conductance are the most popular algorithms. If a dc–dc converter is connected in between the PV module and the load, the switching duty cycle of the dc–dc converter is regulated to ensure the PV system always operates at the maximum power point (MPP) . For P&O, the power of the PV module is determined, and then the duty cycle of the converter is either increased or decreased to achieve the MPP. Generally, the perturbation keeps going in both directions near the MPP, and thus, oscillations occur in the power of PV module. Unlike P&O, the slope of the power-against-voltage (*P*–*V*) curve of PV module is used by the incremental conductance algorithm to vary the duty cycle of the converter .By varying the duty cycle of the converter, the voltage of the PV module is able to be increased or decreased and thus the PV system is able to operate at the peak of the *P*–*V* curve. In actual operation, the PV module rarely operates at the peak of the *P*–*V* curve due to the truncation error in the numerical differentiation inside the microcontroller. Thus, permitted error is required in the algorithm. Apart from that, both the conventional P&O and incremental conductance algorithms vary the duty cycle in fixed step size. When there is variation in the solar irradiation level or load resistance, the responses of fixed step size algorithm are slow. Hence, variable step size algorithms are introduced. These algorithms use the slope of the *P*–*V* curve in the duty cycle perturbation. But, the step size becomes smaller when the algorithms close to the peak of the *P*–*V* curve, and the convergence of the system is also slower.

A few modified algorithms have been introduced to improve the converging speed during the variation in solar irradiation level and load. The relationship between the load line and the MPP locus is used in [1]–[3] to present a fast-converging algorithm. The MPP locus is a line which approximately connects all the MPP for all levels of solar irradiation. In [31] and [2], a control loop is introduced to ensure the PV system operates in accordance with the MPP locus and thus the MPP searching time is reduced. However, tuning is required in the control loop, and it further complicates the MPPT system. In [3], the control loop is eliminated, but the short circuit current and open circuit voltage are required. Thus, disconnection of PV module is required to collect the data and the power is wasted during disconnection. Although the aforementioned algorithms can provide fast response, the complexity of the systems is greatly increased. Therefore, this paper proposes a modified MPPT algorithm, i.e., able to provide fast response without the requirement of an extra control loop. Other than that, the proposed system also does not require the intermittent disconnection. The proposed PV system simply consists of a dc–dc converter which connected in between the PV module and load. Then, the current and voltage of the PV module are sensed by a PIC controller, which is also used to execute the modified MPPT algorithm.

II. LITERATURE REVIEW

C. Paravalos [2014] proposed a methodology for the design optimization of PV plants, which is based on a parallel processing- based implementation of GAs. In contrast to the conventional PV plant design approaches, the proposed optimization technique is capable to be executed using high time resolution (i.e., 1-min) values of the meteorological input data, thus increasing the time step resolution and volume of meteorological input data processed during each step of the optimization process by a factor of 60.
M. N. Kabir, [2014] introduced the use of coordinated control of PV inverters and droop-based BES to keep voltage in the acceptable range with high penetration of rooftop PVs in residential distribution systems. There may be over voltage issues in the feeder due to the unity power factor real power injection from PV inverters in some residential feeders. Utilizing the reactive power capability of PV inverter is proposed to overcome this issue.
R. A. Mastromauro [2012] introduced a survey on three of the main control issues for single-stage PVS: MPPT and current and voltage control. MPPT algorithms aim at maximizing the power extraction from the PV panels. The current and voltage control of the PV converter aims at injecting the extracted power into the grid and at providing ancillary functions such as voltage support at load level and at system level.

III. ANALYSIS OF PROPOSED SYSTEM

The proposed PV system simply consists of a dc–dc converter which connected in between the PV module and load. Then, the current and voltage of the PV module are sensed by a PIC controller, which is also used to execute the modified MPPT algorithm. A PV module consists of numbers of solar cell connected in series or parallel and the total power generated is the sum of the power contributed by all of the individual solar cells.
Under different levels of solar irradiation, the PV module produces different levels of power. Fig. 2 shows the *I*–*V* curve of PV module under different levels of solar irradiation and also the MPPs which can be connected approximately by a straight line (MPP line)

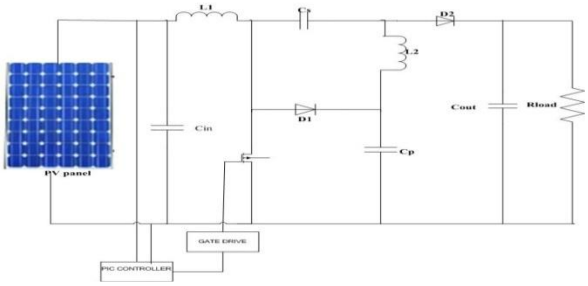


Fig. 1 block diagram of the proposed PV system.

A load line is generated and it can be imposed on the I–V curve when the PV module supplies power to the load. The power generated by the PV module is the product of the voltage and current of PV module at the intersection point between the load line and the I–V curve.

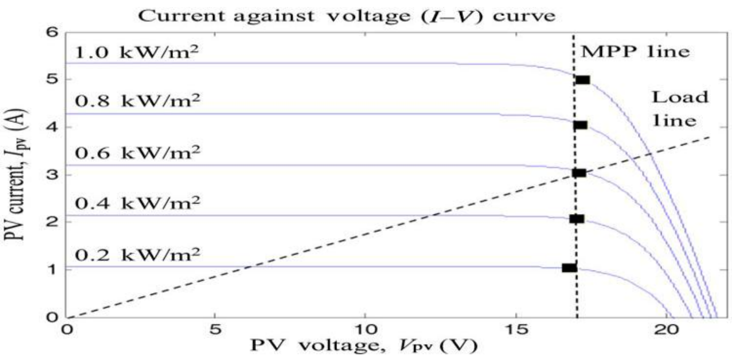


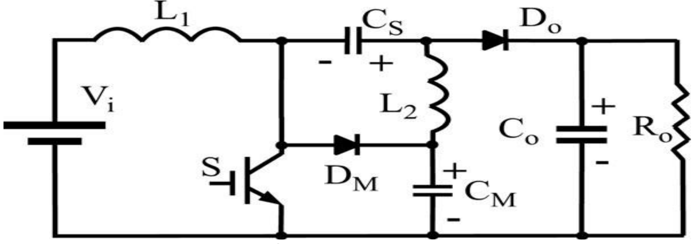
Fig. 2. MPP line and load line on the I–V curves for different levels of solar irradiation.

Therefore, the output power of PV module varies according to the solar irradiation (I–V curve) and the resistance of the load (load line). Generally, a dc–dc converter is connected in between the PV module and the load. Then, the MPPT controller is used to regulate the duty cycle of the dc–dc converter to ensure the load line always cuts through the I–V curve at MPP. Thus, the variation in the voltage and current of PV module during the variation in solar irradiation or load as shown in Table I must be considered by the MPPT controller.

Table i
Variation in the voltage and current of the pv module
During the variation in solar irradiation and
Load resistance

		Variation of voltage (dv)	Variation of current (dI)
Solar irradiation	Increase	Positive	
	Decrease	Negative	
Load resistance	Increase	Positive	Negative
	Decrease	Negative	Positive

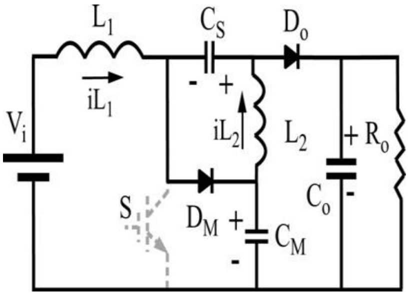
If the duty cycle of dc–dc converter is fixed, the variation in solar irradiation will either increase or decrease both the voltage and current of PV module simultaneously. Meanwhile, load variation will increase (decrease) the voltage and decrease (increase) the current of PV module. Variations in the voltage and current are always in the opposite direction under load variation. The MPPT controller should only regulates the duty cycle of dc–dc converter after the variation in solar irradiation or load is determined. The relationships of the voltage and current of the dc–dc converter between the input and output sides are shown in (1) and (2). Modified SEPIC converter is used in this paper.



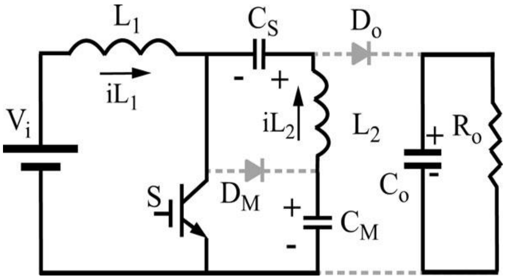
Modified SEPIC converter

DOI: 10.15662/IJAREEIE.2015.0410004

The modification of the SEPIC converter is accomplished adding only two components with the inclusion of the diode D_M and the capacitor C_M. Many operational characteristics of the classical SEPIC converter are changed with the proposed modification, as the elevation of the converter static gain. The capacitor C_M is charged with the output voltage of the classical boost converter. The polarity of the C_S capacitor voltage is inverted in the proposed converter and the expressions of the capacitors voltages and other operation characteristics are presented in the theoretical analysis.
The continuous conduction mode (CCM) of the modified SEPIC converter presents two operation stages. All capacitors are considered as a voltage source and the semiconductors are considered ideals for the theoretical analysis.



First operation stage



Second operation stage

1) First Stage:, Switch S is turned-off and the energy stored in the input inductor L1 is transferred to the output through the CS capacitor and output diode Do and also is transferred to the C_M capacitor through the diode D_M . Therefore, the switch voltage is equal to the C_M capacitor voltage. The energy stored in the inductor L2 is transferred to the output through the diode Do .
2) Second Stage: Switch S is turned-on and the diodes D_M and Do are blocked and the inductors L1 and L2 store energy. The input voltage is applied to the input inductor L1 and the voltage $V_{CS}-V_{CM}$ is applied to the inductor L2. The V_{CM} voltage is higher than the V_{CS} voltage.
The maximum voltage in all diodes and in the power switch is equal to the C_M capacitor voltage. The output voltage is equal to the sum of the CS and C_M capacitors voltage. The static gain of the proposed converter is higher than the obtained with the classical boost

$$\frac{V_{in}}{V_{out}} = \frac{1-D}{1+D}$$

Thus, (1) and (2) are specifically required for Modified SEPIC which operates in continuous-conduction mode and may be different for other types of converter. Equation (3) shows that the duty cycle can be regulated to force the input resistance (load line) of the converter to be varied until the load line cuts through the *I*–*V* curve at MPP

$$V\text{in} = \frac{1-D}{1+D}\text{Vout}\ldots\ldots\ldots\ldots\ldots..(1)$$

$$\text{I in} = \frac{1+D}{1-D}\text{Iout}\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Equation (1) is then divided by (2) to obtain (3) as follows:

$$\text{R in} = \frac{(1-D)^2}{(1+D)^2}\text{Rout}\ldots\ldots\ldots....(3)$$

where V_{in} is the input voltage of the converter or the voltage of the PV module V_{pv}, I_{in} is the input current of the converter or the current of the PV module I_{pv}, R_{in} is the input resistance of the converter or the resistance seen by the PV module, and Rout is the output resistance of the converter or load resistance R_{load}.

Proposed modified mppt algorithm

The proposed algorithm adopts the relationship between the load line and the *I*–*V* curve to introduce a fast-converging algorithm. In the proposed system, only the voltage and current of
PV module is sensed by the MPPT controller.

In the PV system, (3) can be rewritten to obtain (4) and (5) as follows:

$$\frac{V_{PV}}{I_{PV}} = \frac{(1-D)^2}{(1+D)^2} R_{load} \text{ ……………}\mathbf{(4)}$$

$$R_{load} = \frac{(1+D)^2}{(1-D)^2}\frac{V_{pv}}{I_{pv}} \text{……………}\mathbf{(5)}$$

Under any operating point, the load resistance can be calculated by substituting the duty cycle, voltage, and current of PV module into (5). After the value of load resistance is obtained, (5) can be rewritten into (7). Then, the duty cycle can be calculated by substituting the desired voltage (*V*mpp) and current (*I*mpp) of PV module into (7) as follows:

$$\frac{(1+D)^2}{(1-D)^2} = \frac{I_{pv}}{V_{pv}} R_{load} \text{ …………..}(6)$$

$$D = \frac{\sqrt{a}-1}{1+\sqrt{a}} \text{……………………..}(7)$$

where

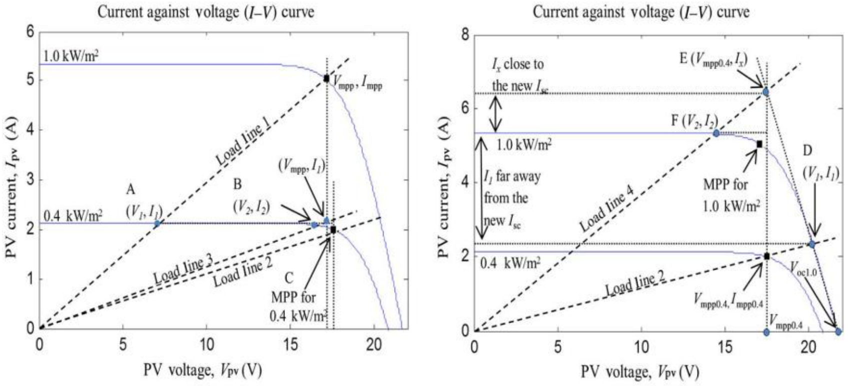
$$a = \frac{I_{pv}}{V_{pv}} R_{load}$$

In the proposed algorithm, the load of the PV system is calculated by using (5). Then, (7) is used to ensure that the system responds rapidly and operates near to the new MPP whenever there is variation in solar irradiation. For the case of load variation, (5) is used to calculate the new load resistance, then V_{mpp} and I_{mpp} are substituted into (7) to obtain the new duty cycle.

A. Decrease in Solar Irradiation Level

If the PV module operates at load line 1 and the solar irradiation is 1.0kW/m2, the current and voltage of PV module are Vmpp and Impp as shown in Fig. 3(a). Then, if the solar irradiation decreases to 0.4kW/m2, while the duty cycle of the dc–dc converter remains unchanged, the operating point of PV module is at point A (V1, I1) of load line 1 which is far away from the MPP of 0.4kW/m2, point C in Fig. 3(a). In order to perturb the operating point of the PV module to the new MPP by using (7), the voltage and current of the new MPP is required. However, these two values are unknown. Therefore, approximated values are substituted into (7) to ensure the PV module operates near to the new MPP

As shown in Fig. 3(a), the current of point A, I_1 is close to the short circuit current of 0.4kW/m2 and the current of MPP is always approximately 0.8 * I_{sc}. Thus, I1 is approximated as the current of new MPP. Then, Fig. 2 shows the voltages of MPP for each level of solar irradiations are closed to one another. Hence, the previous MPP voltage, Vmpp is approximated as the voltage of new MPP. Subsequently, Vmpp and I_1 are substituted into (7) to perturb the operating point of PV module to load line 3, point B (V2, I2) which is near to the new MPP. With only single perturbation, the operating point of the PV module converged from point A to point B rapidly. Finally, a few more steps of conventional incremental conductance algorithm are used to track the new MPP, point C. Therefore, the convergence time from point A to point C is greatly reduced.



(a) (b)

Fig. 3. Load lines on I–V curves for solar irradiation level of 0.4 and 1.0 kW/m2 during (a) decrease of solar irradiation and (b) increase of solar irradiation.

B. Increase in Solar Irradiation Level

If the PV module operates at load line 2 and the solar irradiation is 0.4 kW/m2, the current and voltage of the PV module are Vmpp0.4 and Impp0.4 as shown in Fig. 3(b). Then, if the solar irradiation increases to 1.0 kW/m2, while the duty cycle of the dc–dc converter remains unchanged, the operating point of PV module is at point D (V1, I1) of load line 2 which is far away from the MPP of 1.0 kW/m2. Similar to the algorithm used in the case of decrease in solar irradiation level, the approximated values are substituted into (7) to ensure the PV module operates near to the new MPP. However, the operating current, I1 is far away from the short circuit current of 1.0 kW/m2 as shown in Fig. 3(b). Thus, an additional step is required to ensure the operating current of PV module is near to the Isc of new MPP. As shown in Fig. 3(b), point E, Voc1.0, and Vmpp0.4 form a right-angled rectangle By applying the trigonometry rule in (8), the operating current Ix, which is near to the Isc of 1.0kW/m2 is obtained. The open circuit voltage Voc of the PV module in (9) is the approximated open circuit voltage obtained from Vmpp/0.8. Then, Vmpp is the voltage of the MPP before the variation in solar irradiation. V1 is the voltage of PV module after the variation in solar irradiation.

$$\frac{V_1 - V_{mpp}}{I_x - I_1} = \frac{V_{oc} - V_{mpp}}{I_x} \quad \ldots\ldots\ldots\ldots\ (8)$$

Equation (8) is rearranged to obtain (9)

$$I_x = \frac{V_{oc} - V_{mpp}}{V_{oc} - V_1} I_1 \quad \ldots \quad \ldots\ldots\ldots\ldots\ (9)$$

In the second step, Ix and the voltage of the previous MPP Vmpp0.4 are substituted into (7) to obtain the new duty cycle. With the new duty cycle, the PV module operates at point F (V2, I2) of load line 4, which is close to the new MPP at 1.0kW/m2. Then, the conventional incremental conductance algorithm is used to track the MPP.

C. Load Variation

Table I is used to identify the existence of load variation. After the load variation, the operating point of the PV module diverts from the MPP (load line no longer cut through MPP). A new duty cycle is required to ensure the PV module operates at the MPP again (load line cut through MPP). As variation only exists in the load, the voltage and current at the MPP should be the same (I–V curve unchanged). Thus, (5) is used to obtain the new resistance of the load. Then, by substituting the voltage and current at the MPP into (7), the new duty cycle can be calculated. With the new duty cycle, the PV module operates at the point close to the MPP and then, the conventional algorithm is used to track the MPP. Fig. 4 shows the flowchart for the proposed algorithm. A flag value is used to indicate that the PV system is operating at the MPP if it is set to 1. Therefore, the flag is set to 0 initially. Then, the conventional incremental conductance algorithm is used to track the MPP. A permitted error of 0.06 as shown in (10), is used in the proposed algorithm to eliminate the steady-state oscillation in the system after the MPP is reached

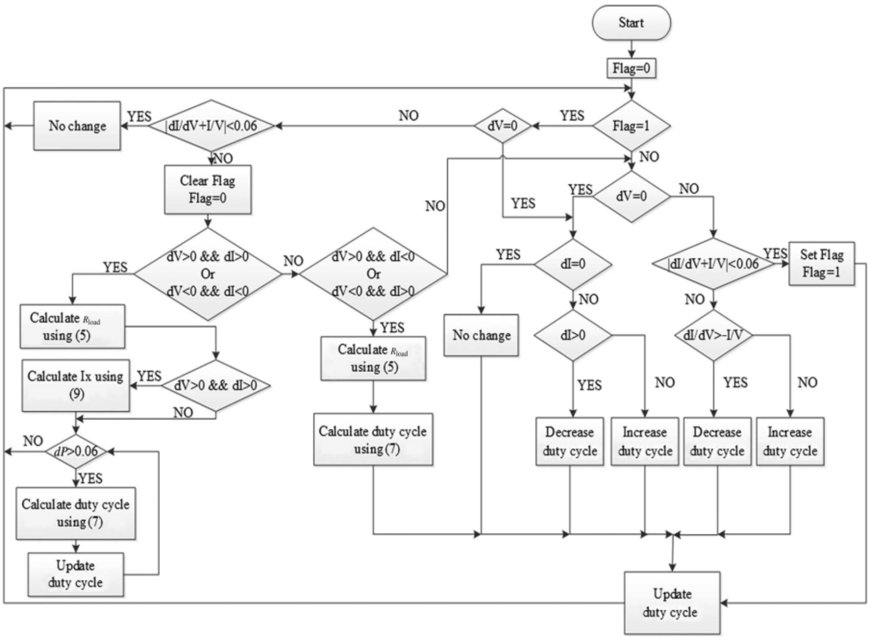


Fig. 4. Flowchart of the proposed MPPT algorithm.

$$\left|\frac{dI}{dV}+\frac{I}{V}\right| < 0.06\ldots\ldots\ldots\ldots\ldots\ldots(10)$$

After the algorithm tracked the MPP, the flag is set to 1, and the program is loaded into the proposed algorithm. Then, (10) is checked, and the duty cycle does not regulated if (10) is satisfied. When the solar irradiation or load is varied, (10) no longer holds and the flag is set to 0. Then, the resistance of the load is calculated by using (5) and the direction of variation in the solar irradiation or load is determined. If both the current and voltage of the PV module are decreased, (7) is used to calculate the new duty cycle. If both the current and voltage of the PV module are increased, *Ix* is calculated by using (9), and then, the new duty cycle is calculated by using (7). In the case of a nonlinear load, the response of the system is slower (the PV system is unable to operate near to the new MPP in single perturbation). Thus, changes in the power of the PV module are monitored. If the power of the PV module increases after the perturbation in duty cycle, (7) is used to calculate the new duty cycle again. Until the difference in power (dP) is smaller than 0.06, only then the conventional algorithm is applied. Meanwhile, for load variation, the new duty cycle is calculated by using (7) after the resistance of the load is obtained by (5).

IV. RESULT AND DISCUSSIONS

Fig 5 shows the simulation circuit of proposed modified SEPIC converter with Fast converging MPPT technique. The program is executed by matlab function block.

ISSN (Print) : 2320 – 3765
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Vol. 4, Issue 10, October 2015

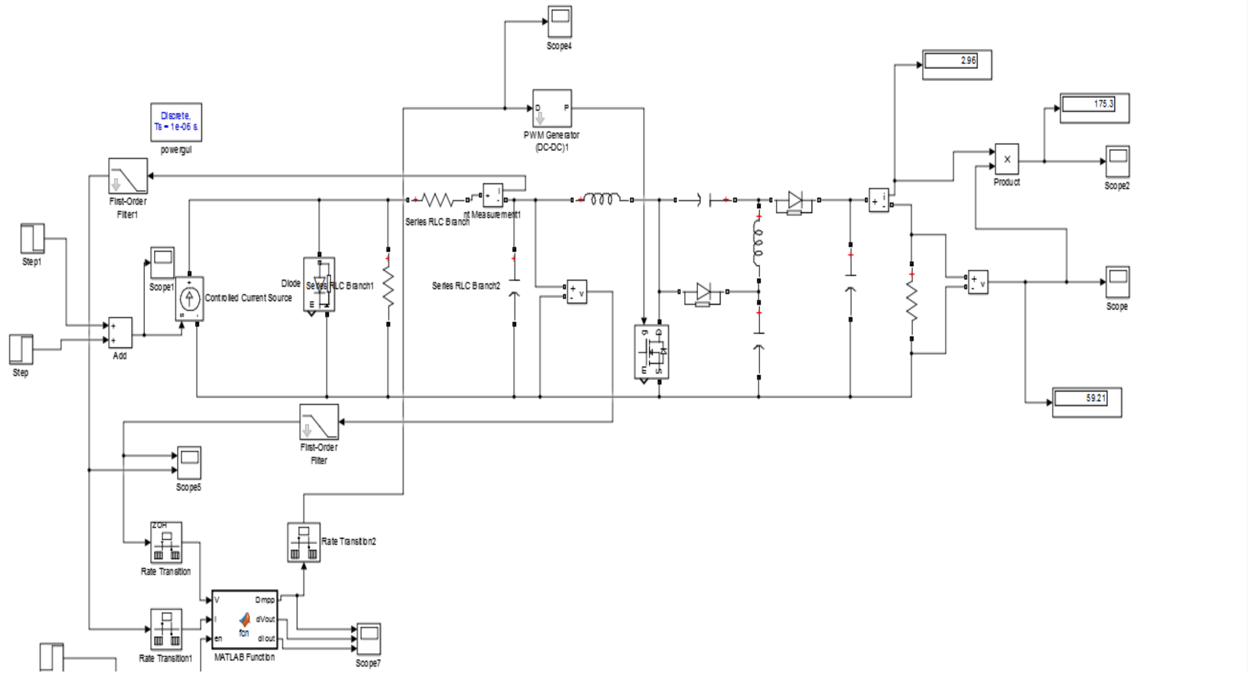

Fig. 5 Simulation Diagram of proposed converter with fat converging algorithm. Simulink model of the MPPT system consisting of the PV module, Modified SEPIC, MPPT controller, and load. The switching frequency for the MOSFET is set to 20 kHz.

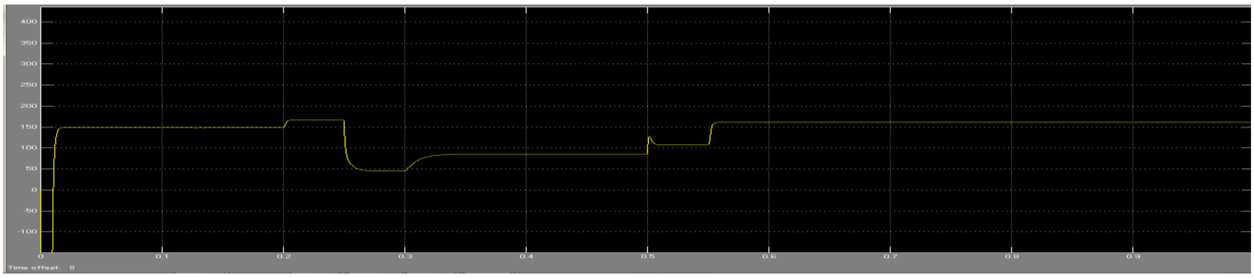

Fig.6 Power waveform of PV module. The maximum output power of PV module is 195W .The variation of power with solar irradiation is shown in figure.

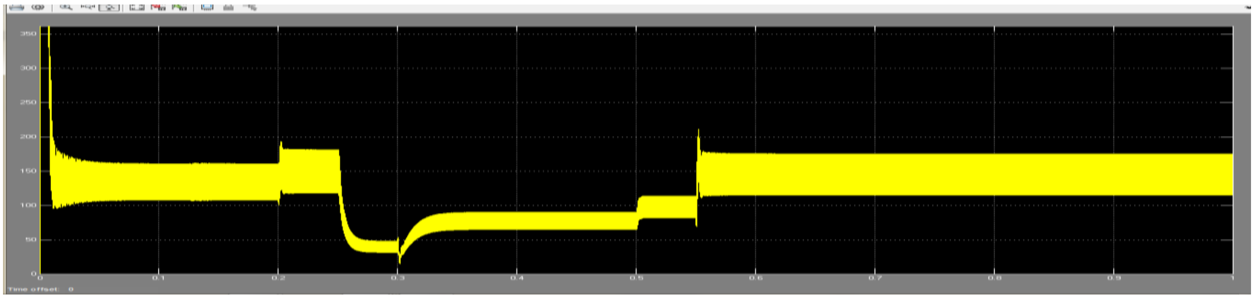

Fig.7 Output power of converter. The output power obtained is 200W. The static gain of Modified SEPIC converter is very high compared with simple SEPIC converter. Hence the output voltage and the power of Modified SEPIC is higher than SEPIC converter.

DOI: 10.15662/IJAREEIE.2015.0410004

Sampling time for the MPPT controller is 0.05 s, Simulation time is 2 s, and solar irradiation level varies from low (0.4kW/m2) to high (1.0kW/m2 in order to investigate the performance of the system under fast-varying solar irradiation level.

Initially, the irradiation level is 1 kW/m2 .At t = .25 s, the solar irradiation level decreases to 0.4 kW/m2 and at t = .3 s, the MPPT controller is sampled, (5) and (7) are used to obtain the resistance of the load and the new duty cycle.

With the new duty cycle, the PV module operates at near to the MPP for 0.4 kW/m2.

The solar irradiation is increased to 1.0 kW/m2 at t=.5s, At t = 0.52 s, the MPPT controller detected the increased in both the current and voltage of the PV module. Hence, (5) is used to calculate the resistance of the load, and then, (9) and (7) are used to calculate *Ix* as well as the new duty cycle. As the power of the PV module has been increased (dP > 0.06), the proposed algorithm continues to perturb the duty cycle by substituting *Ix* and voltage of the PV module into (7) and track the MPP for 1.0kW at t = .55 s. In both cases the tracking time are very fast than other MPPT methods.

The input to the converter is 22V, the output power obtained is 200W.

V.CONCLUSION

The proposed system only requires a dc–dc converter and a PIC microcontroller which is simpler than those which requires extra control loop and intermittent disconnection. Furthermore, the proposed algorithm responds to the variation in solar irradiation and load faster than the conventional algorithm. In addition there is no steady-state oscillation in the proposed algorithm and thus reduce the power losses.

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