Renewable and Sustainable Energy Reviews 81 (2018) 994–1001

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

PV system fuzzy logic MPPT method and PI control as a charge controller

Unal Yilmaz[a], Ali Kircay[a,*], Selim Borekci[b]

[a] Electrical and Electronics Engineering, Harran University, 63000 Sanliurfa, Turkey
[b] Electrical and Electronics Engineering, Akdeniz University, Antalya, Turkey

A R T I C L E I N F O

Keywords:
PV systems
MPPT methods
DC-DC converters
PI control
Charge controllers

A B S T R A C T

This paper puts forward to Fuzzy Logic MPPT (Maximum Power Point Tracking) method applied photovoltaic panel sourced boost converter, under variable temperature (25–60 °C) and irradiance (700–1000 W/m2) after that the PI control was applied buck converter to behave as a charge controller. The voltage and current of PV panels are nonlinear and they depend on environmental conditions such as temperature and irradiance. Variable environmental conditions cause to change voltage, current and also cause to change maximum available power of PV panels. To increase efficiency and decrease payback period of the system, it needs to operate PV panels at maximum power point (MPP). Under any environment conditions there is unique MPP. To operate PV panels at that point (MPP) there are many MPPT method in literature, FLC MPPT method was preferred in this study because, its rapid response to changing environmental conditions and not affecting by change of circuit parameters. The accuracy of FLC MPPT method used in this system to find MPP changes, from 94.8% to 99.4%. To charge a battery there are two traditional methods which are constant current (CC), and constant voltage (CV) methods. For fast charging with low loss constant current and voltage source is a need. One of the methods providing constant is PI control which used in this study. PI control is not only well developed and a simple technique but also it provides satisfactory results. The goal of this study is operating PV panel at maximum power point under variable environment conditions to increase efficiency and reduce cost and also provide appropriate current and voltage for charging battery to charge quickly, reduce losses and also increase life cycle of battery. This system was established and analyzed in MATLAB/Simulink.

1. Introduction

In recent years, insufficient of fossil fuels, increasing energy needs and also rising pollution led the science world to deeper study on renewable energy sources. Because of its effective solution and reducing cost, Photovoltaic (PV) systems have attracted considerable attention [1–3]. PV systems have advantages like being clean energy source, supplied by nature and producing electrical energy anywhere there is sunlight [4–6], on the other hand there are some disadvantages like that The efficiency of PV panels is low (9–17%) and also the current and voltage of PV panels are affected by variable environment conditions such as (temperature and irradiance) [7,8]. Changing environment conditions cause to change current, voltage and maximum power point of PV panels. To increase efficiency and decrease the cost of PV system, it is need to operate PV panels at MPP (Maximum Power Point) [9,10]. Many MPPT algorithms are developed in literature such as Perturb & Observe [11], Inc. Conductance [12], Fuzzy Logic (FLC) [13], and etc… MPPT algorithms are vary in some ways such as speed, cost, accuracy. The FLC method responds quickly to changing environmental conditions and does not need any information about system parameters. PV systems consist of PV panels and DC-DC converters such as boost converter, buck converter buck-boost converter SEPIC converter [14–16]. MPPT algorithms get voltage and current from polarity of PV panels and regulate the duty cycle of PWM (Pulse width Modulation) which applied to switch (MOSFET, IGBT.etc) of DC-DC converters to regulate voltage and current of converter. After boost converter, current and voltage change constantly due to changing environmental conditions and the characteristics of the circuit elements used. To charge a battery there some methods which are constant current and constant voltage methods [17–19]. To charge battery quickly and reduce losses its need constant current and appropriate voltage while charging and also charging battery quickly lead to increase life cycle of battery [20]. To provide constant current and appropriate voltage for battery, PI controller applied buck converter after boost converter. The reason why the PI controller is preferred in this study is that it is easy to implement and gives excellent results for this study. The proposed system is schematized in Fig. 1.

* Corresponding author.
E-mail addresses: uyilmaz@harran.edu.tr (U. Yilmaz), kircay@harran.edu.tr (A. Kircay), sborekci@akdeniz.edu.tr (S. Borekci).

http://dx.doi.org/10.1016/j.rser.2017.08.048
Received 22 April 2016; Received in revised form 3 February 2017; Accepted 12 August 2017
1364-0321/

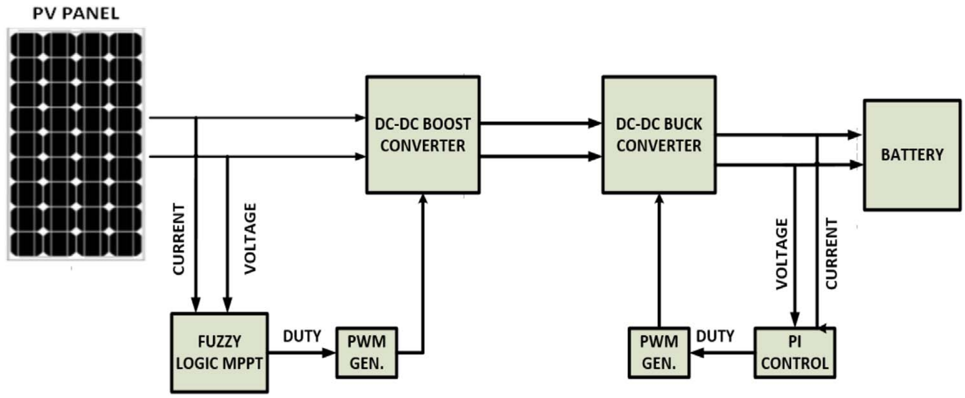

Fig. 1. PV system MPPT algorithm and PI control charge circuit.

To compare the system with related studies; Taohid Latif and friends [21] in 2014 studied on a system which Incremental conductance MPPT method applied to SEPIC converter and PI control applied to buck converter to charge battery. Proposed system is different and the FLC MPPT method doesn't need information about any parameters of system and as a DC-DC converter, the boost converter has fewer circuit elements, so the losses are less and the implementation is simpler. But SEPIC converter has advantage like that it can be used as a boost converter or as a buck converter

Harishankar Suresh and friends [22] in 2014 studied on a system which Perturb & Observe MPPT methods and buck-boost converter used to regulate current and voltage of PV panel and also Open circuit method used to control charge of battery. The proposed system is different and as MPPT method accuracy of FLC is better than Perturb & Observe method, because the Perturb & Observe method Oscillates around maximum power point and this cause power losses, but Perturb & Observe method is easy to implement and cheap as method cost.

2. Model and characteristic of the photovoltaic panels

Solar Cells can be classified as a semiconductor device when solar irradiation penetrates to the Solar Cells surface, DC current flow through the PV panels [1]. Equivalent circuit of a PV cell is shown in Fig. 2. There are two resistances and a diode. The parallel R_P resistance represents the loss which small leakage current flow through the parallel path (High value order of kΩ), R_S (about 1 Ω) represents the losses which are loss of metal grid, contacts and current collecting bus, diode represent a cross current which associated with p-n junction, semiconductor devices [14].

The equations relation of the output current and PV module are;

$$I_{out} = I_{SC} - I_D \tag{1}$$

$$I_D = I_0 * \left(e^{q \cdot \frac{(V+IRs)}{nKT}} - 1 \right) \tag{2}$$

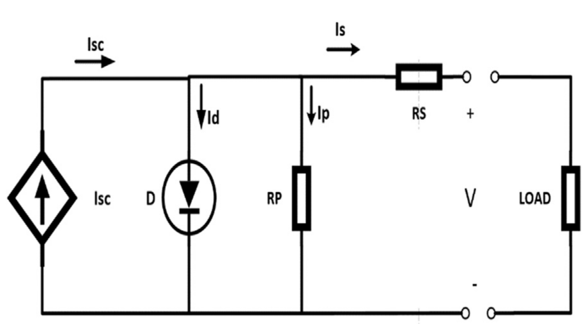

Fig. 2. Equivalent circuit of solar cell.

$$I_{out} = I_L - I_O * \left[e^{\frac{q(V+IRs)}{nKT}} - 1 \right] - \frac{V + R_S * I}{R_P} \tag{3}$$

I_L is the current of photovoltaic array I_o represents the PV array reverse saturated current, q means the electron charge K is the Boltzmann constant ($1.38*10^{-23}$ J/K) T is the temperature of the p-n junction, n is the p-n junction curve constant [16]. The power produced by a solar cell is so low (1–1.5 W) so to get desired power, solar cells must be connected series or parallel to create PV panel shown in Fig. 3.

The most important step to determine maximum power point of a PV panel, it is need to determine Power-voltage and Current-voltage characteristic curve of PV panel. Increasing irradiation lead to increase power and voltage of PV panel but increasing temperature has negative effect on power and voltage. The P-V and I-V characteristic curves under variable temperature and irradiance are shown in Fig. 4(a,b,c,d)

3. Fuzzy logic controller MPPT method

Even though Fuzzy Logic Control method MPPT has some difficulties to construct, it has facility to find maximum power point of PV panels. Fuzzy logic MPPT method doesn't need the knowledge about model of the system, Inputs of the fuzzy logic controller are the error of the system which is E and the change of error is CE the following equations clarify E and CE [13,23,24]

$$E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{4}$$

$$CE(k) = E(k) - E(k-1) \tag{5}$$

where P_k is power, V_k is voltage of the PV panel and P_{k-1}, V_{k-1} are the previous power and voltage of PV panels. To understand Fuzzy logic MPPT algorithm it is required to looking at Figs. 5 and 6 respectively.

When change in power ($P_k - P_{k-1}>0$) and voltage ($V_k - V_{k-1}>0$) are positive, to reach the MPP, the voltage should be increased. That is illustrated with red arrow in Fig. 5. When change in power is positive and change in voltage is negative, to reach the MPP, the voltage should be decreased. That is illustrated with purple arrow in Fig. 5. When change in power is negative and change in voltage is positive, to reach the MPP, the voltage should be decreased. That is illustrated with green arrow in Fig. 5. When change in power and voltage are is negative, to

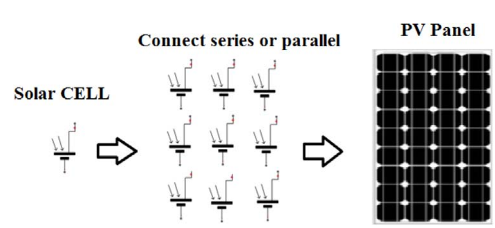

Fig. 3. From solar cell to PV panels.

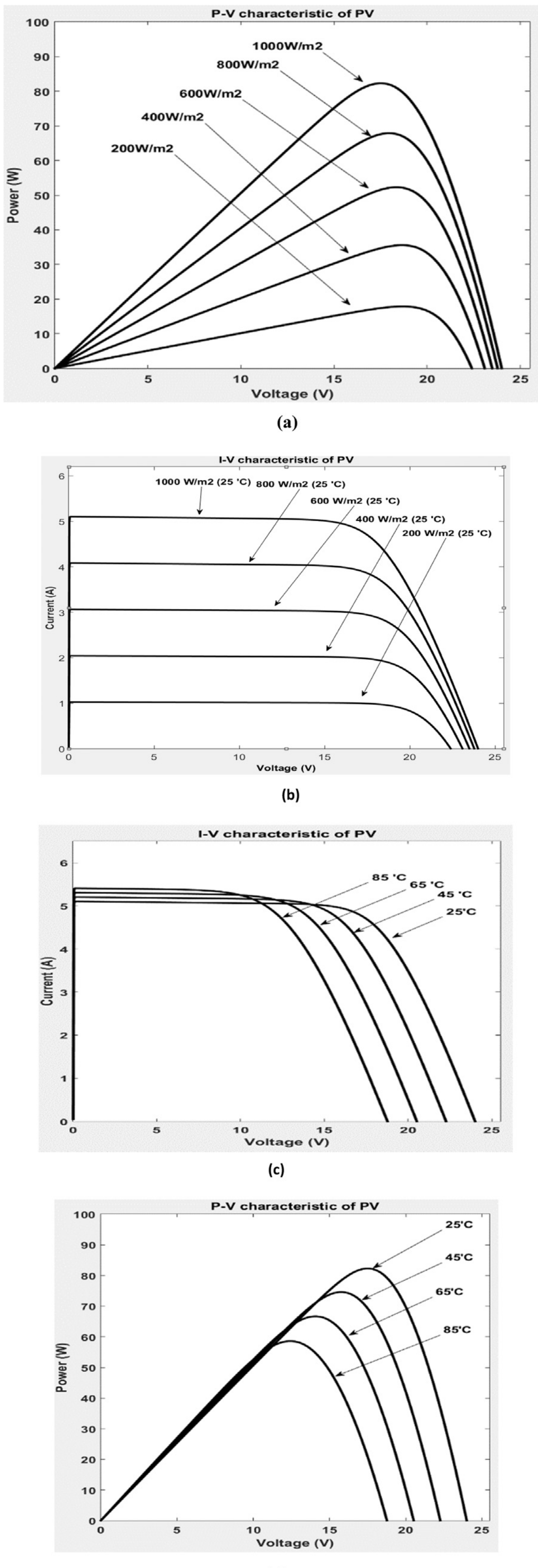

Fig. 4. (a) P-V characteristic variable irradiance, (b) I-V characteristic variable irradiance, (c) I-V characteristic variable temperature, (d) P-V characteristic variable temperature.

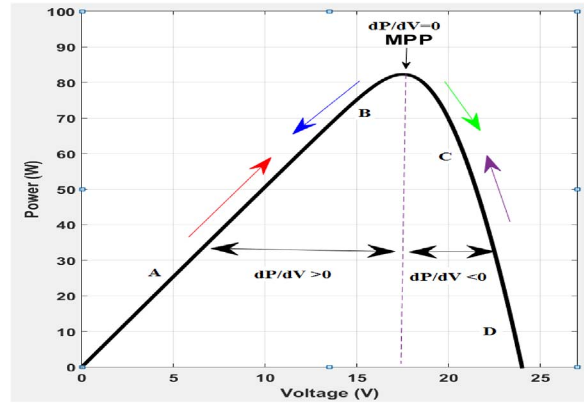

Fig. 5. P-V characteristic of PV panel for MPPT algorithm. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

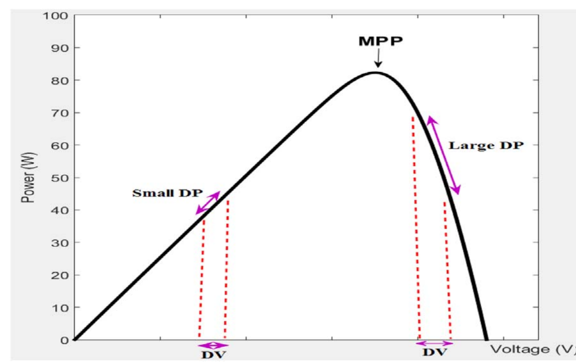

Fig. 6. P-V characteristic of PV panel for speed of MPPT.

reach the MPP, the voltage should be increased. That is illustrated with blue arrow in Fig. 5 [13,23,25].

The Fig. 6 is important for speed of Fuzzy logic MPPT because to compare right side of P-V characteristic curve the change of power according to change of voltage is small at left side of curve the situation must be regulated at equation of 5. The next step is creating rule table and membership function for Fuzzy logic. The rule table of MPPT is shown in Table 1, and the membership functions are shown in Fig. 7(a,b,c).

The Fuzzy logic MPPT algorithm created in Matlab/Simulink is shown in Fig. 8

4. Design of the DC-DC converters

DC-DC converters are the electronic circuit which are ensure less loss of energy when transferred to between different circuits and also converters used to change the DC voltage level shown in Fig. 9, in this system boost converter is used as MPPT circuit to operate PV panel at

Table 1
The rule table for FLC.

E/CE	PB	PM	PS	ZE	NS	NM	NB
PB	ZE	ZE	ZE	NB	NB	NB	NB
PM	ZE	ZE	ZE	NM	NM	NM	NM
PS	ZE	ZE	ZE	NS	NS	NM	NM
ZE	NS	NS	ZE	ZE	ZE	PS	PS
NS	PM	PM	PS	NS	ZE	PS	ZE
NM	PM	PM	PM	PB	ZE	ZE	NS
NB	PB	PM	PM	PB	ZE	ZE	ZE

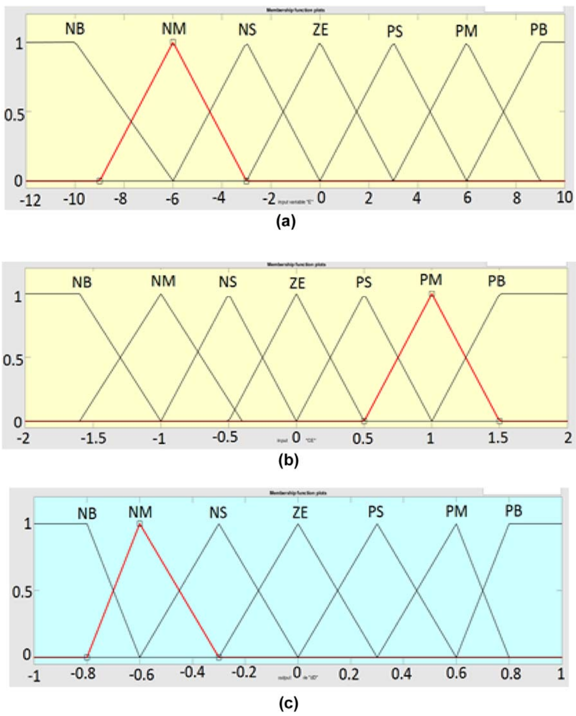

Fig. 7. (a) The input of FLC (Error, E), (b) The input of FLC (Change of error, CE) (c) The output of FLC (Duty, D).

maximum power point. Fuzzy logic control method is applied to switch (mosfet) of boost converter to adjust duty cycle of PWM [14].

4.1. Operation of boost converter

Mosfet is used as a switch and it is in on or off state. When D is defined as duty ratio, during 0 < t < DT, the mosfet is on state and the diode is reverse biased. The voltage across inductor is $V_L = V_{in}$. During DT < t < T, the mosfet is in off state and the diode becomes forward bias [17]

The voltage across inductor $V_L = V_{in} - V_{out}$

Operation at the steady state condition the total change of current on inductor must be zero in a period of switching [14]

$$V_{in} = V_{out} \cdot (1 - D) \tag{6}$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 - D} \tag{7}$$

To find inductor and capacitor of boost converter the following equation

$$\Delta I_L = \frac{V_{in\_min} \cdot D}{fs \cdot L} \tag{8}$$

$V_{in(min)}$ = minimum input voltage, f_s = switch frequency, D = duty cycle, L = inductor

$$L = \frac{V_{in} \cdot (V_{out} - V_{in})}{\Delta I_L fs \cdot V_{out}} \tag{9}$$

V_{out} = output voltage, V_{in} = input voltage, ΔI_L = estimated inductor ripple current [20]

$$C = \frac{I_{out} \cdot D}{fs \cdot \Delta V_{out}} \tag{10}$$

C = capacitor, I_{out} = output current, D = duty cycle, f_s = switching frequency, Δv_{out} = estimated output ripple voltage [26].

4.2. Operation of buck converters

Buck converter circuit is shown in Fig. 10. During 0 < t < DT, the mosfet is in on state and diode is reverse-biased. The voltage across inductor $V_L = V_{in}$-V_{out} when the mosfet is in off state (DT < t < T), the diode is conducting and voltage across inductor $V_L = -V_{out}$. In the steady state operation, the total change of current in the inductor must be zero in a switching period. PI control applied to buck converter to provide constant level current-voltage for charging battery [21].

$$v_{out} = D \cdot v_{in} \tag{11}$$

To find inductor of buck converter [21];

$$\Delta I_L = \frac{v_{out} \cdot (v_{out} - v_{in})}{f_s \cdot L \cdot v_{in}} \tag{12}$$

To find capacitor of buck converter [21];

$$\Delta V_{rpl} = \frac{D \cdot I_L}{8 \cdot fs \cdot C} \tag{13}$$

$\Delta\iota_L$ = inductor current, Vout = output voltage, Vin = input voltage, fs = switching frequency, L = inductor, D V_{rpl} = ripple voltage, C = capacitor.

5. Design of PI control for buck converter

PI control is used to regulate the output voltage and power of buck converter to charge battery shown in Fig. 11. The parts of PI control are integral gain and proportional gain. Ziegler-Nichols method used to determine the proportional gain Kp and integral gain Ki. Proportional gain, Kp is effective to reduce the step up time but it is not exact solution to eliminate the steady state error. The integral controller Ki, is effective to eliminate steady state error [27,28].

PI control applied to buck converter to regulate voltage, the system construct Matlab/Simulink shown in Fig. 12

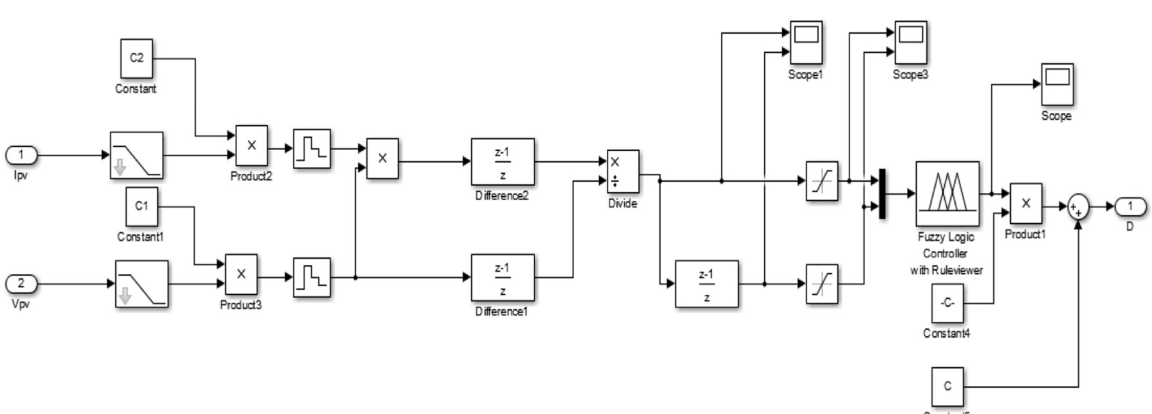

Fig. 8. The MPPT algorithm in Matlab/Simulink.

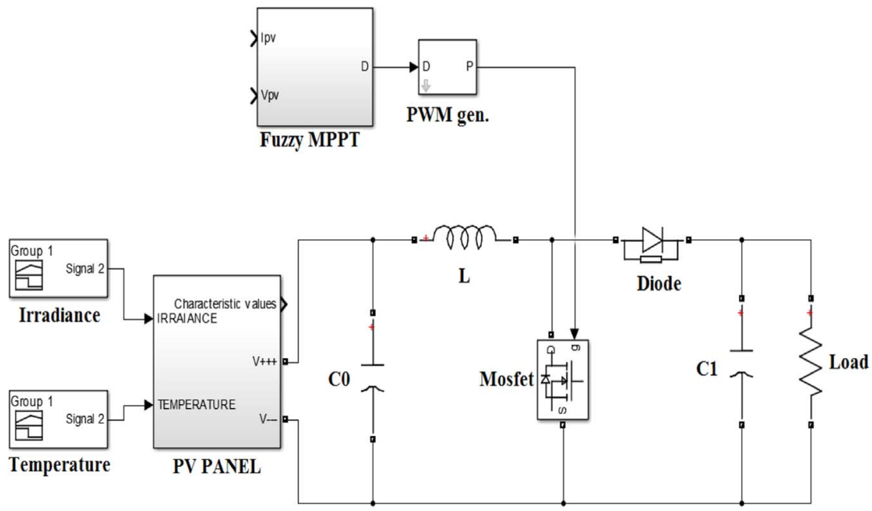

Fig. 9. Boost converter.

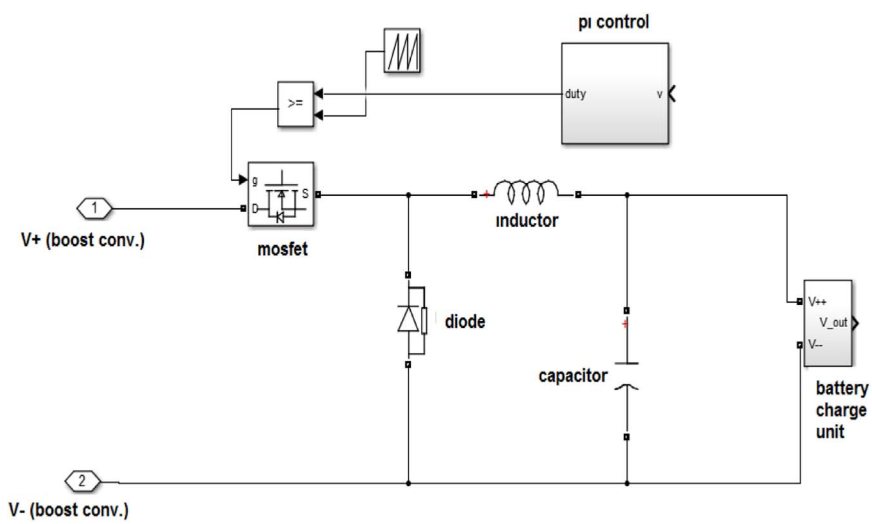

Fig. 10. Buck converter.

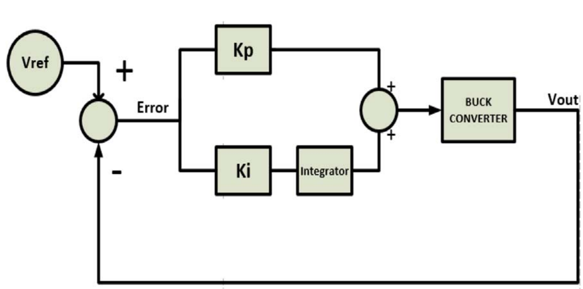

Fig. 11. PI control system.

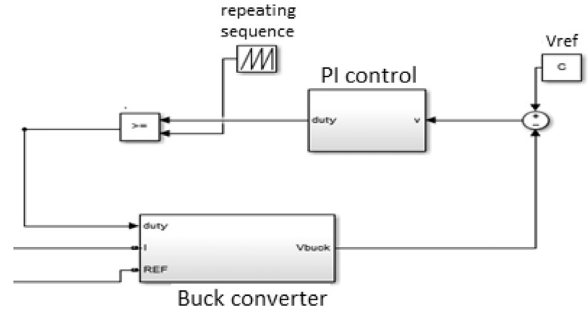

Fig. 12. PI control applied buck converter.

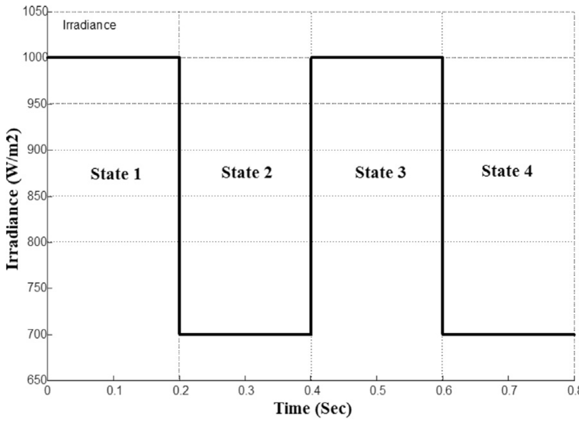

Fig. 13. Variable irradiance.

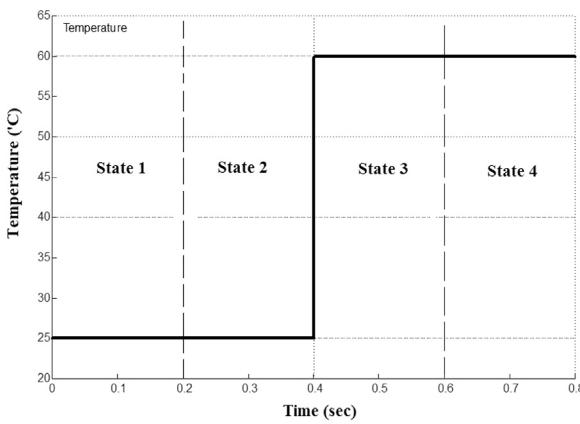

Fig. 14. Variable temperature.

Table 2
Electrical characteristic of PV panel.

The open circuit voltage (Voc)	24 V
The short circuit current (Isc)	5.1 A
The voltage at MPP (Vmpp)	17.5 V
The current at MPP (Impp)	4.8 A
The power of MPP (Pmpp)	84 W
Temperature coefficient of open circuit voltage (%/deg.C)	−0.36099
Temperature coefficient of Isc (%/deg.C)	0.102
Number of cell (N.cell)	20

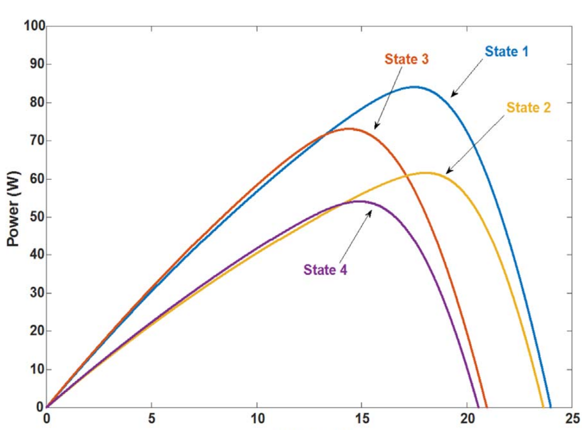

Fig. 15. The P-V curves under variable temperatures and irradiance.

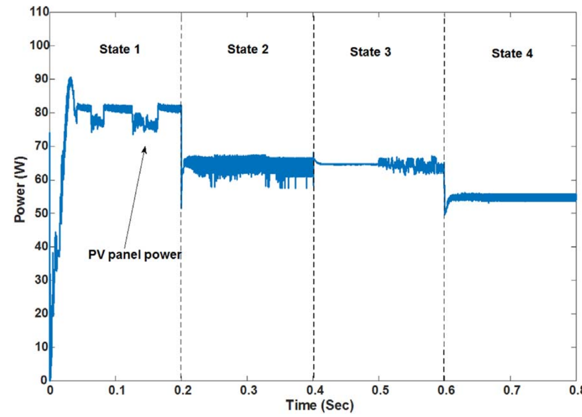

Fig. 16. The Power of PV panel.

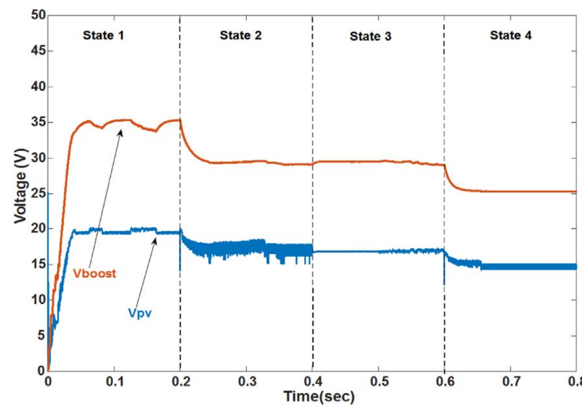

Fig. 17. The Voltage of PV panel and load of boost converter.

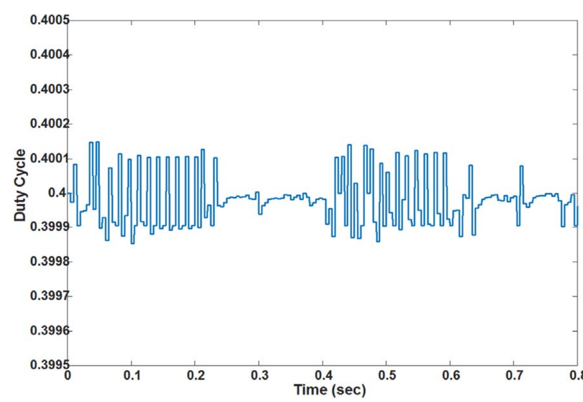

Fig. 18. The duty cycle regulated by FLC MPPT.

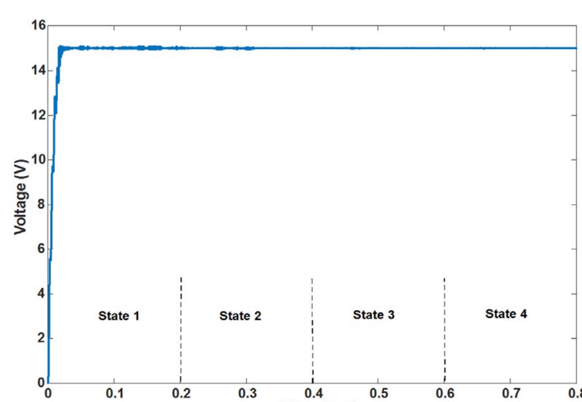

Fig. 19. The load voltage of buck converter.

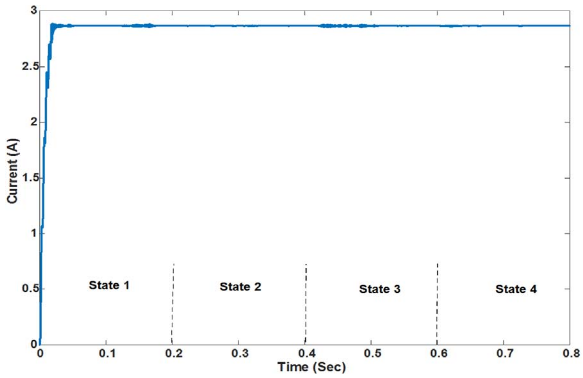

Fig. 20. The load current of buck converter.

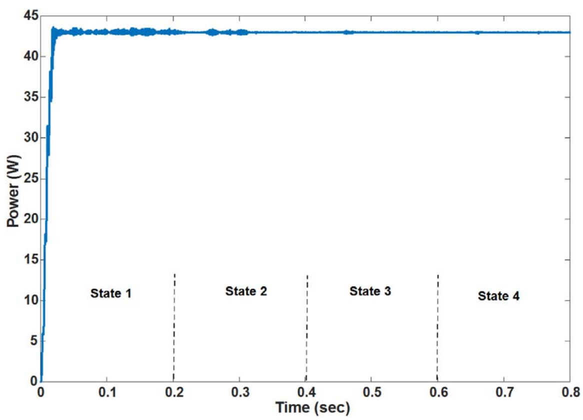

Fig. 21. The power regulated by PI control.

6. Simulation results

The simulation results are presented in this section. The system was operated for four states:

State 1: 1000 W/m2 and 25 °C
State 2: 700 W/m2 and 25 °C
State 3: 1000 W/m2 and 60 °C
State 4: 700 W/m2 and 60 °C

The Irradiance and temperature signals are shown in Figs. 13 and 14 respectively.

Table 3
The power of MPP, accuracy of MPPT, Power of PV and current, voltage of Buck converter.

States	P_{MPP}	$P(pv)$	Accuracy %	I_{buck}	$Vbuck$
State 1 (1000 W/m2 and 25 °C)	84 W	79.7 W	94.8%	2.934 A	15.01 V
State 2 (700 W/m2 and 25 °C)	64.7 W	63.3 W	97.8%	2.932 A	15.03 V
State 3 (1000 W/m2 and 60 °C)	71.2 W	65.8 W	92.4%	2.933 A	15.015 V
State 4 (700 W/m2 and 60 °C)	51.6 W	51.3 W	99.4%	2.932 A	15.03 V

The electrical characteristic of PV panel is shown in Table 2

The P-V curves of PV panel and maximum power points under variable temperature and irradiance are shown in Fig. 15.

The power of PV panel operated with FLC MPPT method is shown in Fig. 16.

The voltages of PV panel operated with FLC MPPT and voltage of Boost converter are shown in Fig. 17.

To obtain constant voltage and current, PI fuzzy controller adjusts the pulse width shown in Fig. 18 to reach MPP.

To supply constant current and voltage to the load, PI technique is implemented on buck converter. The load voltage and current are shown in Figs. 19 and 20 respectively.

The Load power of buck converter regulated by PI control is shown in Fig. 21.

The proposed System constructed in Matlab/Simulink is shown in Fig. 22. The MPPT analyze and load current, voltage of buck converter are shown in Table 3.

7. Conclusion

The proposed system has been studied under four different conditions. Responses of system under varying radiation and temperature was observed. The accuracy of the MPPT algorithm to find MPP varied from 94.8% to 99.4%. The load current and voltage of buck converter remained constant level until end time of system (2.39 A, 15.03 V respectively shown in Table 3). The efficiency we wanted to get from the system has been reached to a great extent. In some cases the efficiency of buck converter can be low but the desired point to be reached in this system is getting the maximum yield from the PV panel

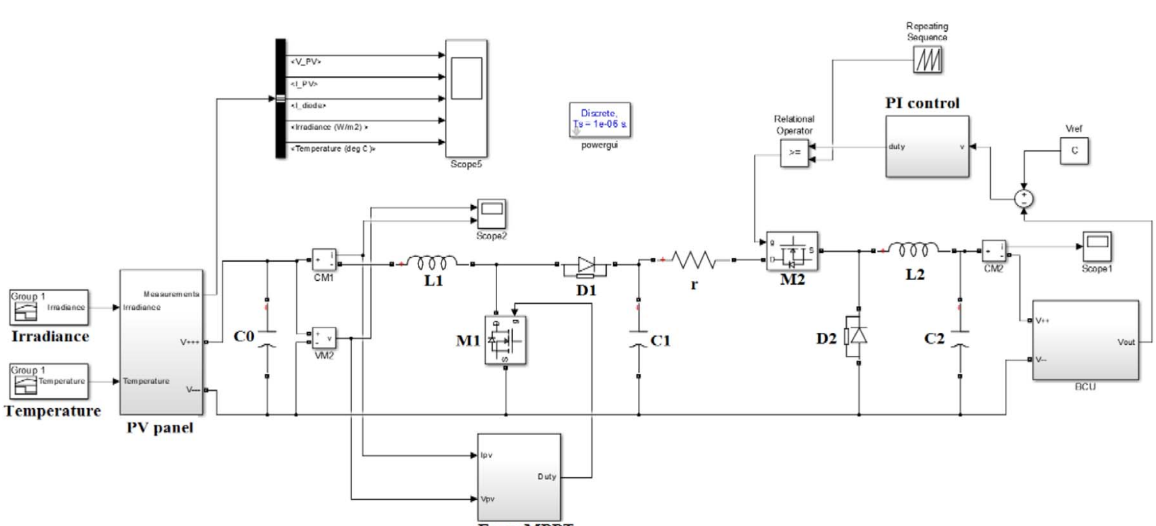

Fig. 22. The System constructed in Matlab/Simulink.

to reduce cost and to charge the battery with constant current and appropriate voltage to reduce losses, fast charge and increase life cycle of battery. If there is a meaningful support to the material, the system will be realized in real life.

References

[1] Takun P, Somyot Kaitwanidvilai S, Jettanasen C. Maximum power point tracking using fuzzy logic control for photovoltaic systems" 2011 preceedings of the international multiconference of engineer and computer scientist 2011. IMECS 2011;vol II:1–3.
[2] Vasantharaj S, Vinodhkumar G, Sasikumar M. Development of a fuzzy logic based, photovoltaic maximum power point tracking control system using boost converter, In: Proceedings of the third international conference onsustainable energy and intelligent system (SEİSCON 2012), VCTW, Tiruchengode, Tamilnadu, India; 27–29 December, 2012. p. 2–5.
[3] Roy CP, Vijaybhaskar C, Maity T. Modellıng of fuzzy logıc controller for varıable step MPPT ın photovoltaıc system. Int J Res Eng Technol 2013;2(8):426–8, eıssn: 2319-1163 pıssn: 2321-7308.
[4] Subudhi B, Raseswari Pradhan R. A comparative study on maximum power point tracking techniques for photovoltaic power systems. IEEE Trans Sustain Energy 2013;4:89–97.
[5] Kolsi S, Samet H, Ben Amar M. Design analysis of DC-DC converters connected to a photovoltaic generator and controlled by MPPT for optimal energy transfer throughout a clear day. J Power Energy Eng 2014;2:27–34.
[6] Bendib B, Belmil H, Krim F. Conventional and advanced algorithms applied For photovoltaic systems. Renew Sustain Energy Rev 2015;45:638–47.
[7] Ishaque K, Salam Z, Syafaruddin . A comprehensive MATLAB simulink PV system simulator with partial shading capability based on two-diode model. Sol Energy 2011;85:2217–27.
[8] Singh D, Yadav R, Jyotsana . Perturb and observe method MATLAB simulink and design of PV system using buck boost converter. Int J Sci Eng Technol Res 2014;3:1692–5.
[9] Francis Williams K, Shanifa Beevi S, Mathew Johnson. MATLAB/simulink PV module model of P & O and DC link CDC MPPT algorithms with labview real time monitoring and control over P & O technique. Int J Adv Res Electr Electron Instrum Eng 2014;3:92–101.
[10] Borekci Selim, Kandemir Ekrem, Kircay Ali A simpler single-phase single-stage grid connected PV system with maximum powerpoint tracking controller, In: Elektronika ir elektrotechnika, ISSN 1392-1215, vol. 21(4); 2015 p. 44–7, [Manuscript received December 21, 2014; Accepted April 12, 2015].
[11] Agarwal Nidhi. Design and simulink of intelligent solar energy improvement with PV modul. Int J Inf Comput Technol 2014;4:619–28.
[12] Saravana Selvan D. Modeling and simulation of incremental conductance MPPT algorithm for photovoltaic applications. Int J Sci Eng Technol 2013;2:681–5.
[13] Cheng Po-Chen, Peng Bo-Rei, Liu Yi-Hua, Cheng Yu-Shan, Huang Jia-Wei. optimization of a fuzzy-logic-control-based MPPT algorithm using the particle swarm optimization technique. Energies 2015:5339–45.
[14] Noman Abdullah M, Addoweesh Khaled E, Mashaly Hussein M. A fuzzy logic control method for MPPT of PV systems, 978-1-4673-2421-2/12; İEEE 2012. pp. 875–377.
[15] Chin1 CS, Neelakantan P, Yoong HP, Teo KTK. Logic based MPPT for photovoltaic modules influenced by solar irradiation and cell temperature, In: Proceedings of the 13th international conference on modelling and simulation in İEEE 2011 (UKSim); 2011. p. 376–80.
[16] Yan Shijie, Yuan Jia, Xu Lei. Fuzzy logic control of MPPT for photovoltaic power system, In: Proceedings of the 9th international conference on fuzzy systems and knowledge discovery in IEEE (FSKD 2012); 2012. p. 448–9.
[17] Cho Shin-Young, Lee Il-Oun, Moon Sang cheol, Moon Gun-Woo, Kim Bong-Chul, Young Kim Ki. Constant current charging in series-series compensated non-radiative wireless power link. IEEE 2013:2792–5.
[18] Chen Bo-Yuan, Lai Yen-Shin. New digital-controlled technique for battery charger with constant current and voltage control without current feedback. IEEE Trans Ind Electron 2012;59:1545–53.
[19] Borage M, Tiwari S, Kotaiah S. Constant-current,constant-voltage half-bridge resonant power supply for capacitor charging. Inst Eng Technol 2006;153:343–7.
[20] Jana J, Bhattacharya KD, Saha H. Design & implementation of MPPT algorithm for battery charging with photovoltaic panel using FPGA. IEEE 2014:1–5.
[21] Latif T, Hussain Syed R. Design of a charge controller based on SEPIC and Buck topology using modified Incremental Conductance MPPT, In: Proceedings of the 8th international conference on electrical and computer engineering. Dhaka, Bangladesh; 20–22 December, 2014.
[22] Suresh H, Baskaran A, Sudharsan KP, Vignesh U, Viveknath T, Sivraj P, Vijith K, Amrita Vishwa Vidyapeetham. Efficient charging of battery and production of power from solar energy, In: Proceedings of the international conference on embedded systems (ICES 2014). p. 231–7.
[23] Cheema Tejpal Singh, Kaur Jaspreet. Fuzzy logic based MPPT algorithm for solar PV systems. Int J Innov Res Dev 2014:367–9.
[24] Cheema TS, Kaur J. Fuzzy logic based MPPT algorithm for solar PV systems. Int J Innov Res Dev 2014;3:367–70.
[25] Nabulsi Ahmad Al, Dhaouadi Rached. Efficiency optimization of a DSP-based standalone PV system using fuzzy logic and dual-MPPT control. İEEE 2011:1–7.
[26] Texas Instruments. Application report SLVA372C; November 2009, Revised January 2014. p.1–8.
[27] Dave Mitulkumar R, Dave KC. Analysis of boost converter using PI control algorithms. Int J Eng Trends Technol 2012;3:71–3.
[28] Dave Mitulkumar R, Dave KC. "Analysis of boost converter using PI control algorithms" [2012]. Int J Eng Trends Technol 2012;3(2):71–2.