Journal of Electrical Engineering & Technology (2021) 16:1879–1889
https://doi.org/10.1007/s42835-021-00734-4

ORIGINAL ARTICLE

A Novel Hybrid Maximum Power Point Tracking Controller Based on Artificial Intelligence for Solar Photovoltaic System Under Variable Environmental Conditions

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Received: 5 November 2020 / Revised: 23 December 2020 / Accepted: 22 March 2021 / Published online: 29 April 2021

Abstract

Solar Photo-voltaic (PV) arrays have non-linear characteristics with distinctive maximum power point (MPP) which relies on ecological conditions such as solar radiation and ambient temperature. In order to obtain continuous maximum power (MP) from PV arrays under varying ecological conditions, maximum power point tracking (MPPT) control methods are employed. MPPT is utilized to extract MP from the solar-PV array; high-performance soft computing techniques can be used. In this paper, the proposed hybrid MPPT algorithm is used in the solar-PV system with variable climatic conditions. The performance of the proposed hybrid MPPT algorithm with different membership functions is analyzed to optimize the MPP. Simulation results establish that with the application of MPPT controller such as Perturb and Observe, Fuzzy Logic and a proposed hybrid MPPT for the solar-PV system, the proposed hybrid MPPT controller provides more accurate performance and also reduces the fluctuation about the MPP as compared to other MPPT techniques.

Keywords Solar photo-voltaic · Maximum power point tracking algorithms · Perturb and observe · Fuzzy logic controller · Proposed hybrid controller

1 Introduction

The demand of power is increasing day-by-day throughout the world. The conventional power sources are reducing gradually and produce emissions of greenhouse gases to the environment. This issue can be overcome, to encourage society towards the innovative development of alternative renewable energy (RE) sources. Renewable energy sources are used in grid-connected and can be found in rural and remote areas where the public grid is not available. Solar PV array is the device that converts solar energy into electrical energy [1, 2]. Some benefits are offered by renewable energy sources such as PV system. PV systems are sustainable, clean and easy to maintain. It is non-linear RE sources, need of MPPT techniques for finding maximum power from solar-PV system. Numerous MPPT control techniques have been proposed and established to sustain the characteristics of PV renewable energy system operation at MPP. MPPT techniques are used to track the MPP by minimum deviations. PO, Incremental Conductance (INC) and hill-climbing methods are generally used in yielding the MPP at a uniform level of insolation [3–6]. The comparative analysis of PO and INC algorithm had simulated in the MATLAB/ SIMULINK environment [7]. These control techniques are failed under non-uniform insolation level.

Artificial Intelligence (AI) based MPPT control techniques such as FL Controller, Neural Network (NN) control method and Adaptive Neuro-Fuzzy Inference System (ANFIS) etc. These AI MPPT techniques have the advantage that no requirement of information about internal factors of the PV renewable energy system including less computational efforts and compact outcome in favour of the multivariable problems [8]. Sawant et. al [9] have been described various MPPT techniques based on swarm intelligence and evolutionary techniques. The main goal

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is to familiarize the guided artificial bee colony technique under rapidly changing conditions. The proposed Artificial Bee Colony (ABC) technique provides better results as compared to conventional MPPT techniques using MATLAB/ SIMULINK [10]. Ulapane et. al [11] has been presented the learned function for MP that has been validated through comparing the outputs of function i.e. Gaussian Process (GP) results in a contradiction of the manufacturer identified power values. Mahalakshmi et. al [12] has been a proposed algorithm which is simulated in MATLAB/ SIMULINK environment, the simulation of active and reactive (PQ) power which is control and analyzed and maintain the stability of the system using a Proportional Integral Derivative (PID) controller. PO based MPPT algorithm is used in micro-controller to control the duty-cycle of a dc-dc power converter for achieving the MP from solar PV system [13].

Implementation of hardware using ARM Cortex M3 32 bit microcontroller has been developed for 10 W PV array [14]. The proposed MPPT technique had provided fast and accurate tracking for every atmospheric condition and results validated by simulation in MATLAB/ SIMULINK [15]. The FL controller-based MPPT is provided better performance as compared to PO and Proportional Integral (PI) based MPPT techniques and is also validated with the experimental setup under variation of irradiation and temperature [16].

Nabizadeh et. al [17] has been presented an FL controller-based MPPT which obtained improved performance as compared to PI-based MPPT controller. FL controller-based MPPT has been compared with conventional PO MPPT technique in MATLAB/SIMULINK environment [18]. FL based technique was compared with conventional PO MPPT technique for PV system which is simulated in MATLAB/ SIMULINK environment [19–22].

Modelling of PV system using FL based MPPT technique has been designed by [23–26], the proposed system was applied for three different PV Arrays such as SOLKAR for 36 W, BP MXP for 60 W and KC 85 T for 87 W. Simulation analysis of optimization and rule firing in FL based MPPT technique for PV system [27]. In order to data analyzed by various simulation methods can be developed in power system which validates that the established approach performs well in the analysis of power study [28–33].

In this paper, different MPPT techniques such as PO, FL and proposed hybrid MPPT techniques are implemented in PV system using MATLAB/ SIMULINK. Based on simulation results, the comparison of PO, FL and proposed hybrid MPPT methods has been carried out for tracking the maximum power from the PV array due to variable irradiations and fixed temperature.

This paper is structured as follows: the mathematical model of the photo-voltaic system is given in Sect. 2. Section 3 described the proposed model of the photovoltaic system. The methodology is given in Sect. 4. The results and discussions are given in Sect. 5. Section 6 described the comparative analysis of different MPPT methods in the PV system. Finally, conclusions are given in Sect. 7.

2 Mathematical model of Photo-Voltaic System

PV cell is defined as an electrical gadget which converts the light energy into electrical power by using semiconducting materials that display the photo-voltaic impact. It is a type of photo-voltaic cell characterized as an electrical device whose electrical variables like current, voltage and resistance, fluctuate to light. The solar cell equivalent circuit as illustrated in Fig. 1 [34].

The bandgap of the semiconductor is base energy which is required to energize an electron that is stuck in its bound state goes into a free state where it can partake in conduction. This model consists of a diode, resistance and a light created source which is arranged in parallel connection. The numerical articulations of the solar cell equivalent circuit of PV module are expressed as Eq. (1), (2) and (3) [35].

$$I = I_{ph} - I_d \left[\exp\left(\frac{qV}{k_v AT} \right) - 1 \right] \tag{1}$$

$$I_{ph} = I_r \left[I_{scr} + k_i \left(T - T_r \right) \right] \tag{2}$$

$$I_d = I_o \left[\frac{T}{T_r} \right] \exp\left(\frac{E_g q}{kAQ} \left[\frac{1}{T_r} - \frac{1}{T} \right] \right) \tag{3}$$

where, I = total current (A), V = output voltage (V), T = temperature of solar cell, q = electron charge, k_i = temperature coefficient of short-circuit current, I_r = irradiance of solar cell, k_v = temperature coefficient of open circuit voltage and k = Boltzmann's constant, A = ideality factor, I_{ph} = PV solar cell current, I_{scr} = short-circuit current at reference condition, I_d = diode current, I_o = saturation current at T_r, T_r = reference temperature, Q = total electron charge, E_g = band-gap energy.

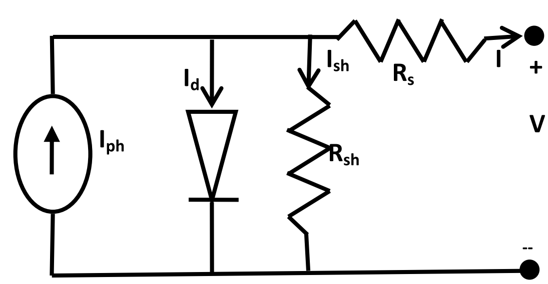

Fig. 1 Solar Cell Equivalent Circuit

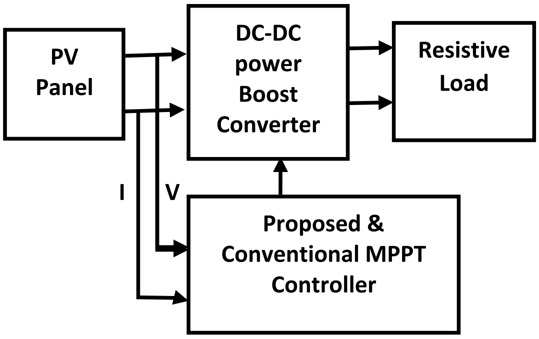

Fig. 2 Block Diagram of Proposed PV Renewable Energy System

3 Proposed Photo-Voltaic System

Proposed PV system contains the following mechanisms such as PV panel, a power boost converter, MPPT controller and resistive load. The duty cycle of the boost converter is measured using conventional and proposed MPPT algorithms. Figure 2 shows the proposed block diagram of the photo-voltaic renewable energy system. The main aim of the control system is to maximize the power generation with a variable is given irradiations from the PV panel. Using the MPPT method, it should ensure that the DC power is transformed into the load with high efficiency.

4 Methodology

MPPT technique is used for improving power from the solar-PV framework and transferring, energy into the load. A dc-dc power converter effectively transfers MP from the PV modules to the heap. By varying the duty-cycle, the load impedance for example observed by the source is altered and matched at the point of the peak power with the source therefore as to transfer the MP. MPPT controllers are required to maintain the operating of PV arrays at its MPP. In this research article, Proposed hybrid MPPT technique has the leads of simple design and do not need the knowledge of the exact model. Instead, conventional MPPT controllers require full information about the performance of Photovoltaic system.

4.1 Perturbed and Observe Based MPPT

PO control method is frequently used for achieving MP from the PV system. This control technique uses a humble feedback arrangement and modest dignified parameters.

In PO based MPPT technique, the voltage of solar-PV array has periodically specified a perturbation and analogous output power is matched by that at prior perturbing cycle [36]. If the power rises due to the perturbation after that the perturbation is sustained in the identical track. Subsequently, the peak power is touched, the power at the MPP is zero and subsequent instantaneous decreases and then perturbation reverses as shown in Fig. 3.

4.2 Fuzzy Logic Controller Based MPPT

This method offers the benefit of being relatively easy to design and robust due to no requirement of knowledge of the PV panel parameters. FL Controller offers fast results by the expertise and measured database. In the algorithm of FL based MPPT is based on three steps such as fuzzification, inferences and defuzzification [27, 37–39]. The fuzzification, FL inference system and defuzzification are the three major stages of FL. The fuzzification is the alteration of real data into a fuzzy linguistic variable based on the membership function. A defuzzification is the change of the output linguistic variable into a suitable control signal. The IF–THEN relations between the input and output variable signal are set in the fuzzy inference system block.

The scheme such an FL based MPPT technique has been shown in Figs. 4 and 5 illustrations the block diagram of the

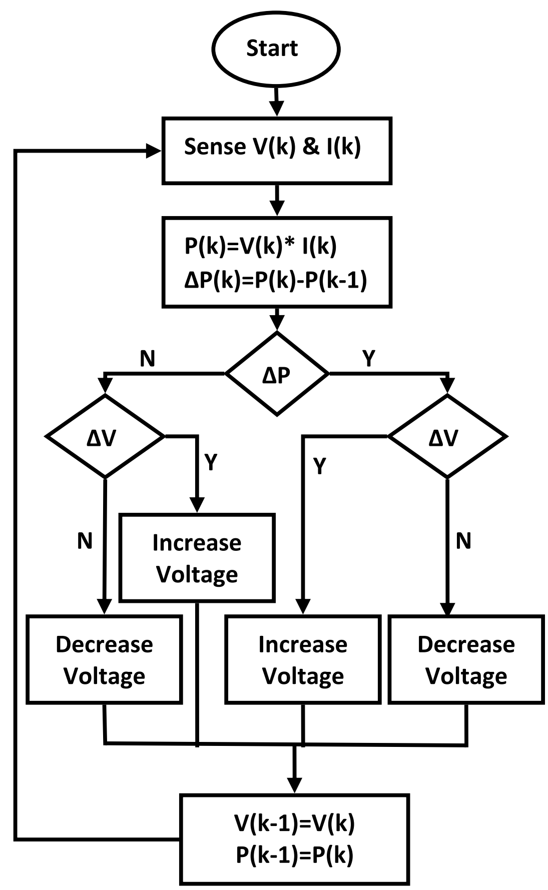

Fig. 3 Flow Chart of PO Control Method

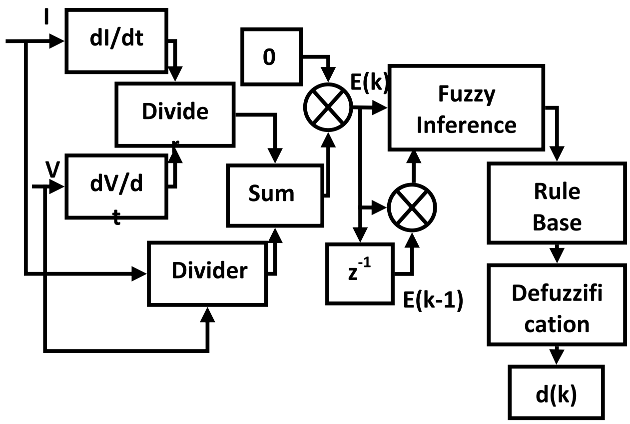

Fig. 4 Block Diagram of FL Based MPPT Technique

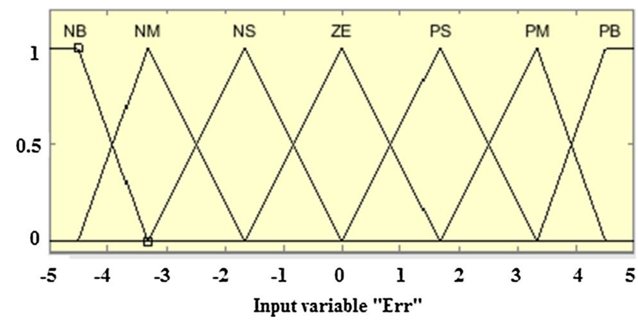

Fig. 6 Membership Function (MF) of Input (Err)

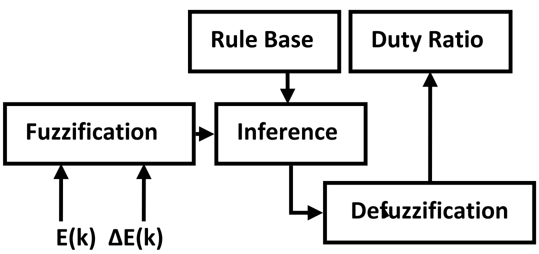

Fig. 5 Block Diagram of FL Approach

FL approach. According to the FL based MPPT technique in Fig. 5, the two inputs are fed to the fuzzification that is an error (E) and change in error (ΔE), based on the rule base, it yields optimum duty-cycle using defuzzification of the FL controller. Duty cycle (D) associated with fuzzy sets which are described as Zero Error (ZE), Negative Big (NB), Positive Big (PB), Negative Medium (NM), Negative Small (NS), Positive Small (PS), Positive Medium (PM), is defined to designate each linguistic variable. The fuzzy rules of the proposed system are given in Table 1.

The membership functions of input and output variables are shown in Figs. 6, 7, 8 and 9 shows the surface viewer of FL controller. In FL controller design, one should detect the variables of the controller and find the sets that define the values of each linguistic variable and their range. The input variables of the FL Controller are the error $E(k)$ and change in error $\Delta E(k)$ of the fuzzification. The output of the FL Controller is the change in duty-cycle (ΔD) of the pulse width modulation (PWM) signal, which controls the output voltage. The linguistic variable ranges are – 10–10 and – 5–5 for input variables and – 0.2–0.2 for the output variable. The FL based MPPT does not necessitate the exact information of the PV model for its design. They are given by Eqs. (4) and (5) [40]:

$$E(k) = \Delta I/\Delta V + I/V \tag{4}$$

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

where I is the output current from the renewable energy system, ΔI is the change in current for two consecutive instants given by $I(k)$-$I(k-1)$, V is the output voltage from the array and ΔV is the change in voltage for two consecutive instants given by $V(k)$-$V(k-1)$. In the proposed approach, the fuzzy inference (FI) can be carried out with one of the different

Table 1 Rules of the FL controller

E(k)→ ΔE(k)→	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	ZE	NS	NM	PM	PM	PB
NM	ZE	ZE	ZE	NS	PS	PM	PB
NS	ZE	ZE	ZE	ZE	PS	PM	PB
ZE	NB	NM	NM	ZE	PS	PM	PB
PS	BB	NM	NM	ZE	ZE	ZE	ZE
PM	NB	NM	NM	PS	ZE	ZE	ZE
PB	NB	NM	NM	PM	PS	ZE	ZE

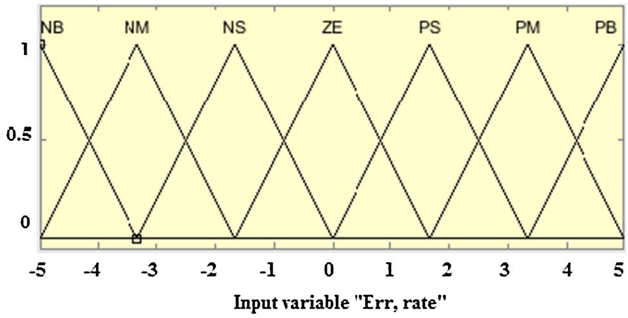

Fig. 7 Membership Function (MF) of Input (Err, ate)

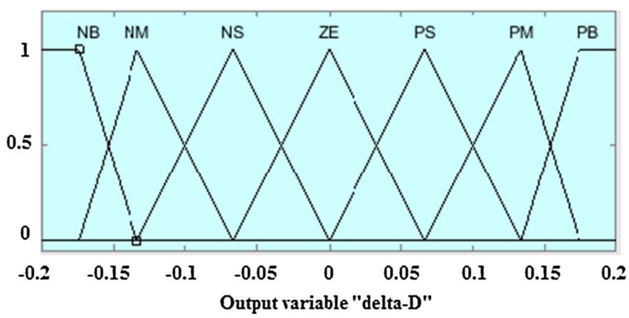

Fig. 8 Membership Function (MF) of Output (delta-D)

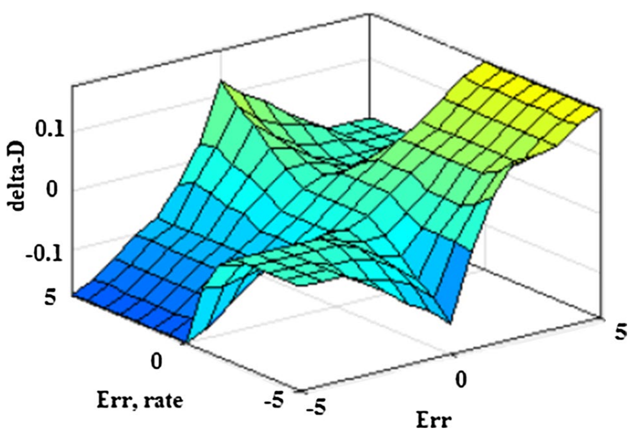

Fig. 9 Surface Viewer of FL Controller

obtainable methods. FL controller (Mamdani's method) based MPPT has been used, and defuzzification centre in favour of gravity technique is used to compute the yield of FL controller (change in duty-ration: ΔD).

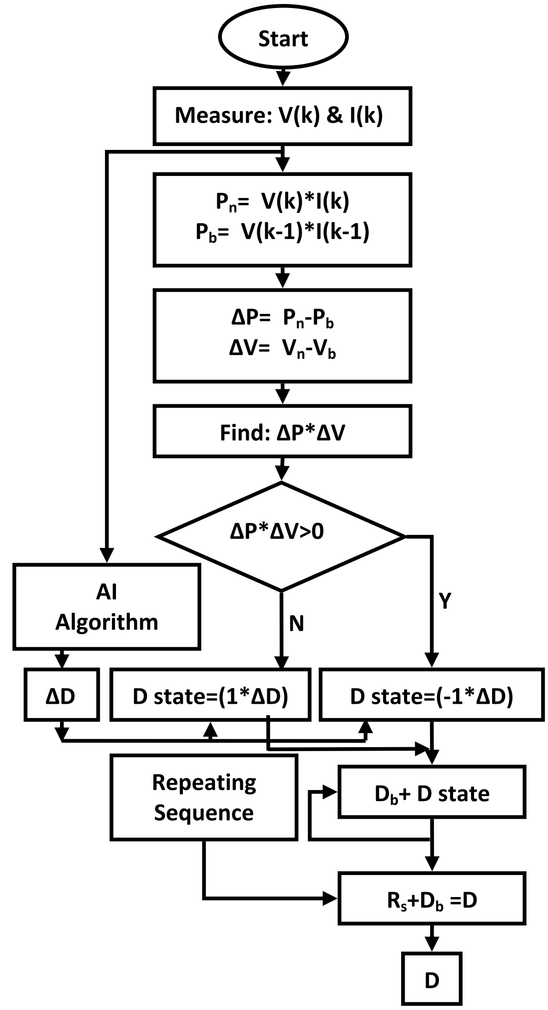

Fig. 10 Flowchart of AIAPO MPPT Controller

4.3 Proposed Algorithm of Artificial Intelligence Based Adaptive Perturb and Observe (AIAPO) MPPT Controller

The proposed MPPT algorithm determines the MPP and enhances the efficiency of the solar PV renewable energy system. As shown in the flowchart of Fig. 10, which operates by varying the duty cycle of the dc-dc converter depends on the requirement of converters. Consequently varying the output voltage of the PV system, and observe the resulting power to increase or decrease the duty cycle in the next cycle. If the increase of the duty cycle produces an increase of the power, then the direction of the perturbation signal is the same as the previous cycle. Conflicting, if the perturbation duty cycle produces a decrease of the power, then the direction of the perturbation signal is the opposite from the previous cycle. The increase or decrease in the duty cycle is based on the perturbation (ΔD) which is generated by an AI system.

where,

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

D state is the increment or decrement step according to perturbation (ΔD).

The flowchart of AIAPO MPPT Controller (shown in Fig. 10) has been implemented by using MATLAB™/SIMULINK™ and MATLAB function of PO MPPT controller is shown in Fig. 15. A novel hybrid technique which is a combination of fuzzy logic based MPPT technique and adaptive PO based MPPT technique has been employed. Since, the FL controller as described in Sect. 4.2, with the membership functions and rule base for PV system has been employed here for the development of the subsystem as shown in Fig. 15. PO algorithm receives voltage and current data for computing duty-ratio. The initial values of the PO MPPT parameters can be set (i.e. initial value (0.8), the upper limit (0.95), and lower limit (0.1)), including nominal duty-ratio, maximum and minimum values of the duty-ratio along with the perturbation size (ΔD).

The FL based MPPT technique produces an optimal change of duty-cycle (ΔD), which is fed into the PO based MPPT technique and thus produces an optimum value of duty ratio (D). This D value is then fed into the corresponding DC-DC converters. The developments of AI controller are increasing due to its ability to solve the complex mathematical model in an easier way. The FL controller is a most widely used AI, which works on human behaviour and there is no need to know the actual mathematical model for generating the results. The FL controller is more flexible than a conventional controller, the oscillation at MPP and tracking time are the major issue of conventional PO MPPT. The proposed hybrid MPPT method is used to overcome the drawback of conventional MPPT and FL controller, but it increases the mathematical computation of controller design.

In this paper, the duty-cycle adjusted automatically by the proposed hybrid MPPT controller to achieve the MP tracking for improving the efficiency of the proposed system. The features are estimated to improve power track with reducing the steady-state fluctuations of output power and enhance the transient performance.

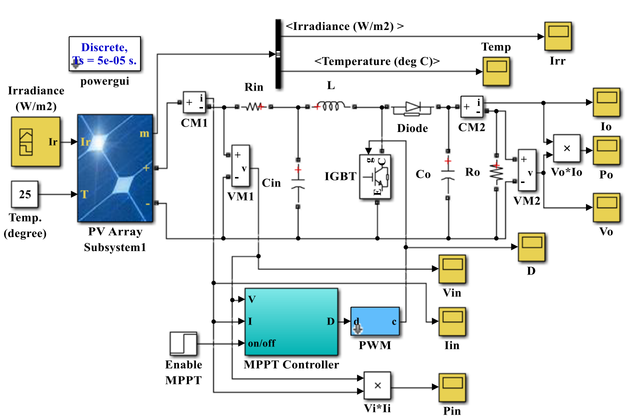

Fig. 11 Subsystem of Proposed AIAPO Controller

4.4 Simulation Model of PV System using MATLAB/SIMULINK

A simulation model of the proposed solar-PV system consists of PV arrays, boost converter, PO, FL and proposed AIAPO MPPT techniques, and resistive load. The

Table 2 Parameters and their values of Proposed System

Parameters	Values
Open circuit voltage (V_{oc})	44.00 V
The voltage at MPP (V_{mp})	34.70 V
Current at MPP (V_{mp})	7.80 V
Short circuit current (I_{sc})	8.10A
Maximum power (W)	270.66 W
Cells per module	72
Series connected module per string	2
Open circuit voltage temperature coefficient (k_v)	− 0.36 (%/°C)
Short-circuit current temperature coefficient (k_i)	0.025 (%/°C)
Switches used	IGBT
Diodes used	P-N Diode
Saturation current of diode	$2.5*10^{-10}$A
Ideality factor of diode	0.982
Input resistance (R_{in})	1.10Ω
Input capacitance (C_{in})	2000.00µF
Inductance (L)	10.00mH
Output capacitance (C_{out})	2000.00µF
Load resistance (R_L)	90.00Ω

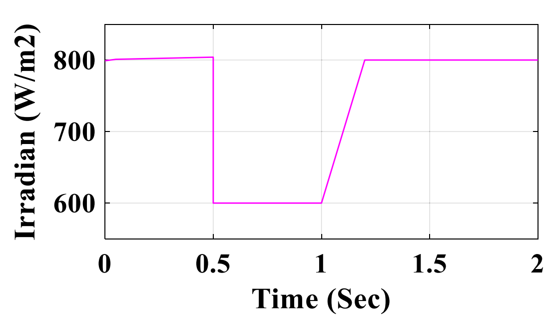

Fig. 12 Simulation Model of Solar-PV System using MPPT Controller

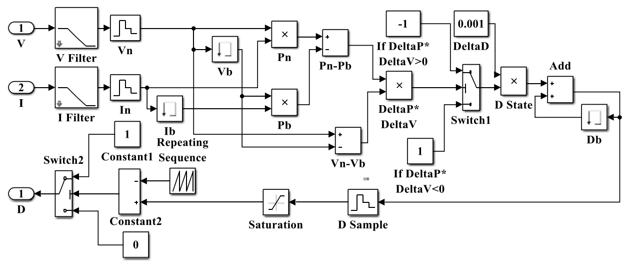

Fig. 13 Irradiation Pattern of Input for PV Panel

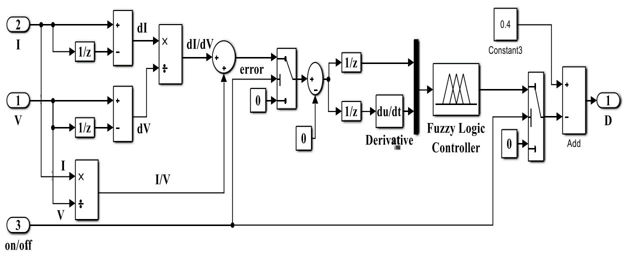

Fig. 14 Subsystem of PO Controller

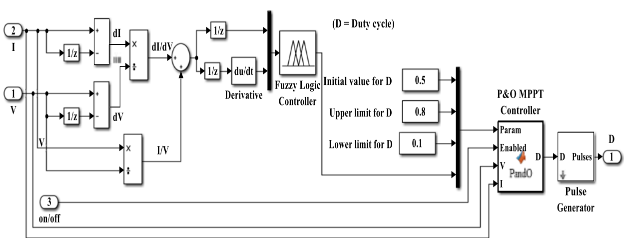

Fig. 15 Subsystem of Fuzzy Logic Controller

parameters and their values of the proposed system are given in Table 2.

The simulation model of the solar-PV system with boost converter using various MPPT controllers is shown in Fig. 11. The various MPPT techniques such as PO, FL controller and proposed AIAPO techniques under variable conditions are simulated. Figure 12 shows the irradiation pattern of input for the PV array, in this pattern the rapid changing of radiations from 0.5 to 1 s at 25 °C constant temperature have been taken.

Figure 13 and Fig. 14 show the subsystems of PO, FL and proposed AIAPO MPPT methods. The investigator analyzed the system by including the subsystem of PO, FL and proposed controllers in the block MPPT controller in the simulation model shown in Figs. 13, 15, 15.

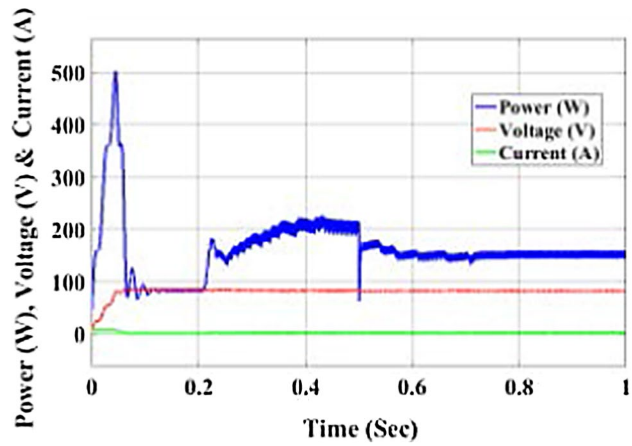

Fig. 16 Input Power, Voltage and Current of Boost converter without MPPT Method

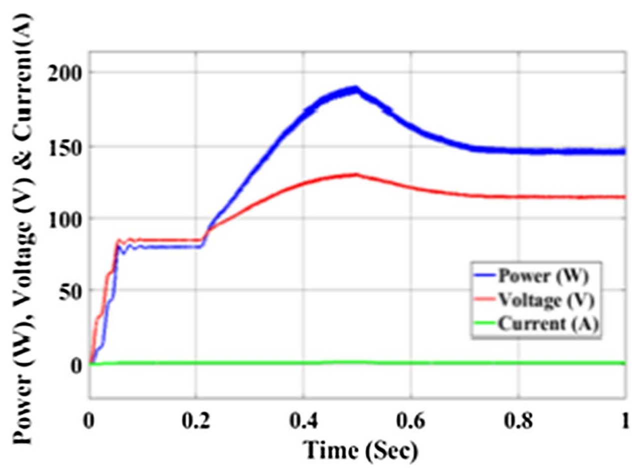

Fig. 17 Output Power, Voltage and Current of Boost Converter with PO Based MPPT Method

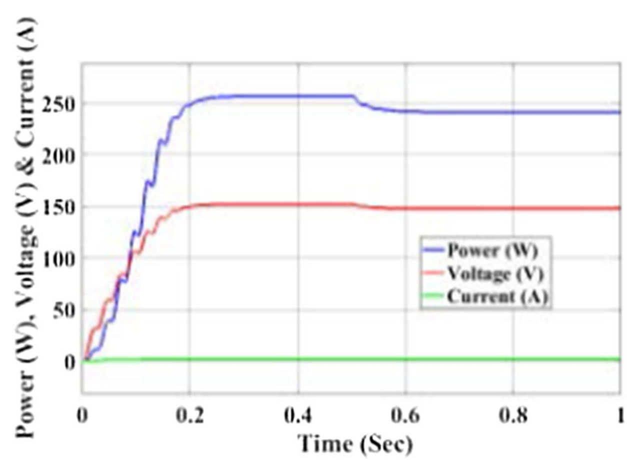

Fig. 18 Comparative Characteristics of Power using PO, FL and Proposed MPPT Method

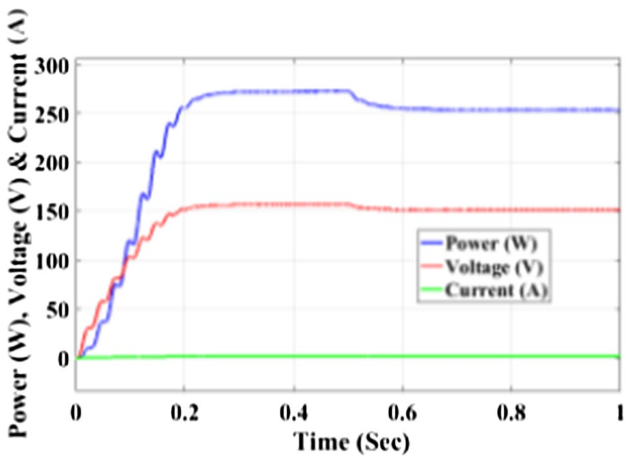

Fig. 19 Comparative Characteristics of Power using PO, FL and Proposed MPPT Method

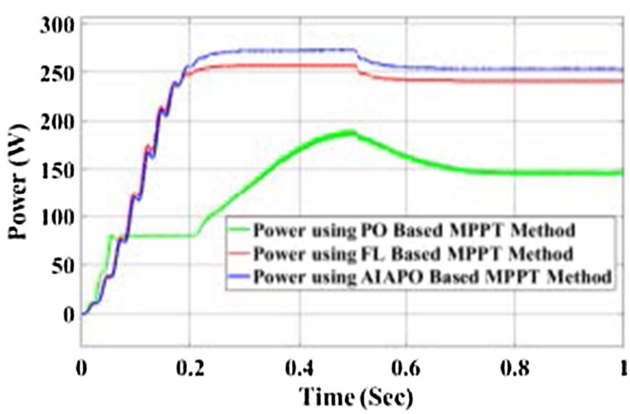

Fig. 20 Comparative Characteristics of Voltage using PO, FL and Proposed MPPT Method

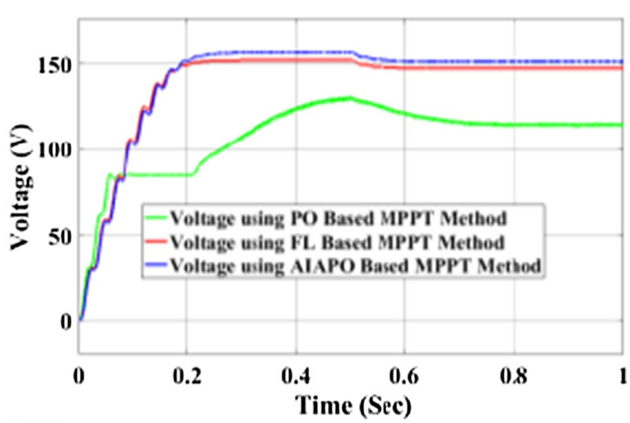

Fig. 21 Comparative Characteristics of Current using PO, FL and Proposed MPPT Method

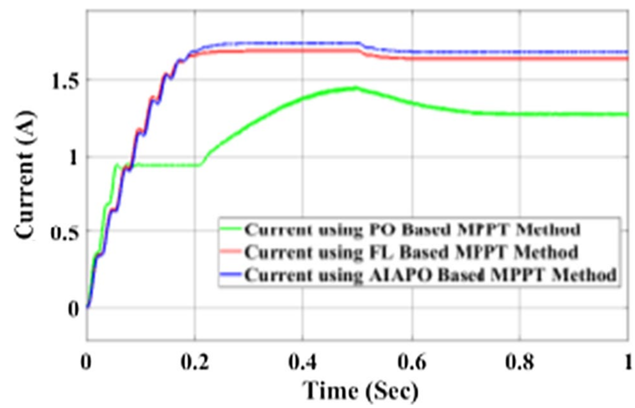

Fig. 22 Output Power, Voltage and Current of Boost Converter with FL Based MPPT Method

5 Results and Discussions

Figure 16 shows the input power, voltage and current characteristics of boost converter without MPPT Method. Figures 17, 18 and 19 show the output power, voltage and current characteristics of a boost converter with PO, FL and proposed AIAPO MPPT Method respectively. Figures 20, 21, and 22 show the comparative characteristics of the output power, voltage and current using PO, FL and proposed MPPT controller.

Simulation analysis using MATLAB/ SIMULINK is performed to calculate MP from the PV array. The simulation of the model has completed in one second. In Fig. 16 it is observed that the input power, voltage and current values of the boost converter are 154 W, 82 V and 0.67A respectively. Figure 17 clearly shows that the output power, voltage and current values of the boost converter with PO MPPT method are 156 W, 115 V and 1.27A respectively.

Figure 18 shows that the boost converter output in the form of power, voltage and current values with FL based MPPT technique are 240 W, 147 V and 1.63A respectively and Fig. 19 shows that the output power, voltage and current values of a boost converter with proposed MPPT technique are 255 W, 157 V and 1.8A respectively.

The output of the boost converter shows an increase during 0–0.5 s. During the period 0.5–1 s, when there is a fall in irradiation (as shown in Fig. 12), There is the case when a PO based MPPT controller is used. With FL and proposed MPPT controller, the drop in values of the output voltage and power of boost converter during 0.5–1 s is reduced as is seen in Figs. 17, 18 and 19. Hence the output values increase to 255 W, 157 V and 1.8A. Using proposed AIAPO MPPT provides a more accurate and stable result as compared to PO and FL based MPPT Technique.

Table 3 Comparison of performance parameters in proposed PV System with different MPPT Methods

Sr. No	Method	Power (W)	Voltage (V)	Current (A)
1	Without MPPT	154 W	82 V	0.67A
2	PO based MPPT	156 W	115 V	1.27A
3	FL based MPPT	240 W	147 V	1.63A
4	Proposed MPPT	255 W	157 V	1.8A

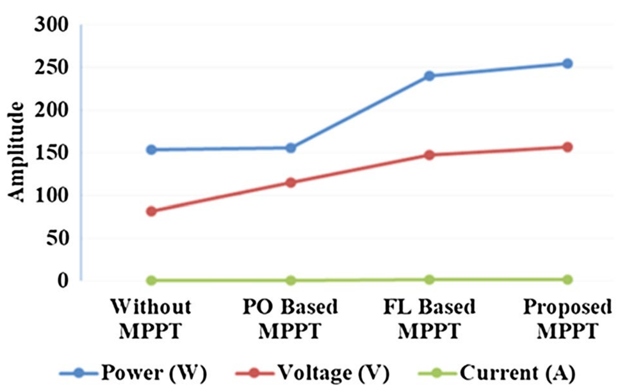

Fig. 23 Comparative Characteristics of Different MPPT techniques in proposed PV System

As per experimentation are performed of proposed model by various MPPT techniques. Figures 20, 21 and 22 are indicating that the comparative analysis of power, voltage and current performance of PV system (i.e. have been recorded 255 W, 157 V and 1.8A) using proposed MPPT method which is better than the PO based MPPT (i.e. 156 W, 120 V, 1.27A) and FL based MPPT technique (i.e. 240 W, 147 V, 1.63A) correspondingly.

In order to show the feasibility and performance of the proposed AIAPO MPPT controller, a simulation study has been carried out using the PV system. Combined results with different MPPT systems for power, voltage and current waveforms are as shown in Figs. 20, 21 and 22 respectively. Proposed MPPT technique based system is always found to be a better option for obtaining maximum values of power, voltage and current correspondingly.

5.1 Comparative Analysis of Different MPPT Controllers in Solar-PV System

The simulation results for different MPPT techniques for the solar PV system are described in this research article. The comparative analysis of the performance parameters such as power, voltage and current are shown in Figs. 20, 21 and 22. The summarized simulation results are given in Table 3 and graphical representation are shown in Fig. 23.

It is found that the power generation from the proposed hybrid MPPT technique is more as compared to PO and FL based MPPT techniques. Therefore integration of two MPPT techniques is very important for power production in the solar PV system. The proposed hybrid MPPT method is found to be more efficient in producing power in PV system i.e. 255 W as compared to other MPPT techniques.

It is clearly seen that the proposed hybrid technique gives better performance as compared to other MPPT technique.

6 Conclusions

In this study, the different MPPT methods of the photo-voltaic system such as PO, FL and Proposed hybrid method is used to find a most feasible method for the photo-voltaic system. The aim of this paper is to track maximum power point from the solar-PV array by the proposed hybrid controller for irradiation changes and comparing results with conventional PO and FL controllers. Various MPPT techniques have been used to compute MPP and improved efficiency of the solar PV system. In this research article, PO, FL and Proposed AIAPO MPPT methods have been chosen to obtain this objectives. Simulation results showing that the system in which proposed control method has been used gives better performance and reduce fluctuations of the maximum power point as compared to PO and FL based MPPT technique at rapid changes of irradiation.

It is also evident that the maximum power produced by the proposed hybrid technique is considerably high. The investigator would like to assert that the hybrid technique of renewable energy source like solar PV system for power generation is a better option for rural areas where conventional power supply from the grid is rarely available.

This research is utilized for the stand-alone system as well as a grid. Further research in MPPT based system assistances to pick particular MPPT control method for a precise application, and correspondingly in the area of MPPT techniques and hybrid MPPT techniques. Use of this technique may enhance the output of the proposed system. In order to fabricate a reliable and real-time hybrid system, there is a massive scope of research to develop multi-input renewable energy systems.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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