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A novel photovoltaic maximum power point tracking technique based on grasshopper optimized fuzzy logic approach

Laxman Bhukya *, *Srikanth Nandiraju*

Department of Electrical Engineering, National Institute of Technology, Warangal, 506004, Telangana, India

HIGHLIGHTS

- A novel Adaptive fuzzy logic based MPPT technique is proposed.
- The GO algorithm optimizes the scaling factors of FLC for better MPPT.
- The proposed MPPT technique estimates the exact duty cycle for DC-DC converter.
- The test system is examined for variable values of irradiance and temperature.
- Proposed MPPT improves the dynamic performance under normal & abnormal conditions.

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ABSTRACT

The maximum power point tracking (MPPT) in the PV system has become complex due to the stochastic nature of the load, intermittency in solar irradiance and ambient temperature. To address this problem, a novel Grasshopper optimized fuzzy logic control (FLC) approach based MPPT technique is proposed in this paper. In this proposed MPPT, grasshopper optimization is used to tune the membership functions (MFs) of FLC to handle all uncertainties caused by variable irradiances and temperatures. The performance of the proposed grasshopper optimized FLC based MPPT is studied under rapidly changing irradiance and temperature. The proposed MPPT overcomes the limitations such as slow convergence speed, steady-state oscillations, lower tracking efficiency as encountered in conventional methods viz. perturb & observed (P&O) and FLC techniques. The feasibility of the proposed MPPT is validated through experimentation. The effectiveness of the proposed scheme is compared with P&O and also with FLC MPPT.

Introduction

The energy crisis, increasing energy demand due to population growth, and increased environmental concerns such as global warming effect and pollution have led to the research headed for the development of Renewable energy sources (RES). In this case, among all the RESs, photovoltaic (PV) systems are considered to be one of the most common RES due to its advantages such as no moving parts, abundant availability, free of charge, absence of fuel cost, exhaustible and non-depleted, a wide range of power scalability, safe and clean energy [1–3]. However, the PV systems have major drawbacks such as more installation cost and less power conversion

* Corresponding author.
E-mail addresses: blaxman@student.nitw.ac.in (L. Bhukya), nvs@nitw.ac.in (S. Nandiraju).
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efficiency (14–19%) depends on climatic conditions. The P–V as well as I–V characteristics are non-linear and depend on factors that are ambient temperature, irradiances, and loads. Generally, the PV system has one specific point on the P–V curve where it must be operated for maximum efficiency and needs to extract the maximum power available [4]. Hence, the PV system needs a suitable Maximum power point tracking (MPPT) controllers in order to extract the maximum power point (MPP) [3].

The MPPT method is an electronic system, which offers the duty cycle to the power conversion device to accomplish peak power production. However, there are many key issues in designing MPPT schemes for PV systems viz. efficiency, type of implementation, complexity, lost energy and cost [5]. Based on these, several MPPT techniques have been developed and divided into three major categories. The first category of MPPT technique measures MPP based on apriori data, without continuous tracking the current and voltage. The key advantage of these techniques is that they need less voltage and/or current sensors. However, such techniques do not track precise MPP for changing insolation and temperatures. Common MPPT techniques belong to these categories: Curve Fitting [6], Fractional short circuit current (FSCC) [7], Fractional open-circuit voltage (FOCV) [8], and Look-up tables [9]. The second category of MPPT technique tracks MPP without any prior empirical data. Moreover, these techniques are accurate for changing insolations and temperatures. The MPPT techniques belonging to this category are Perturb and observe (P&O), Hill-climbing (HC), Fuzzy logic controller (FLC) and Incremental conductance (IC) [10]. Conventional techniques suffer from fixed step size, furthermore, its innate oscillations effects in reduction of efficiency and move the operating point away from MPP [3]. The third category covers meta-heuristics techniques and hybrid MPPT techniques, which use both measurement and apriori data. For instance, the MPPT technique uses a neural network [11], a modified P&O MPPT with Genetic Algorithm (GA) optimized PID [12], combined Differential evolution and Particle Swarm Optimization (DEPSO) method [13], hybrid P&O and Learning Automata MPPT techniques [14]. The authors attempted a novel boost converter topology by combining conventional and quadratic boost with extended duty cycle for the MPPT of the PV system. However, it has a drawback that it uses two switches (S1 and S2) for hybrid boost working mode and are selected manually [15]. All MPPT techniques are used to produce the required duty cycle for the control circuitry of a boost converter that connects the PV system to the load. The authors [16,17] introduced the modified algorithms by incorporating the load for maximization of the output power of the PV system. The authors [18] proposed a sliding mode control technique to generate the required duty cycle to track the MPP of the PV system. However, this technique highly depends on the optimal selection of the sliding surface. The performance of the system may lead to unacceptable value if this sliding surface is not properly designed. Therefore the optimal selection of sliding surfaces is a complicated task. In common, the P&O MPPT technique is most widely used owed to its low implementation cost and operational simplicity [19,20]. Though the procedure of the P&O method depends on the step size of the reference voltage, in classical P&O, the MPPT techniques apply a fixed step size. If a large step size is applied, the controller achieves the MPP quicker with large steady state oscillations. If not; lower steady state oscillations with slow convergence speed for small step size, although, it loses the MPP for rapidly changing irradiance. For that reason, numerous alterations have been presented in the P&O MPPT technique based on Voltage (V)-Power (P) curve [21–25]. On the other hand, they are considered to be giving unsatisfactory results towards addressing these complications. To avoid these significant problems of conventional P&O, artificial intelligent based MPPT methods have been introduced. In particular, one of the most effective techniques for a PV system is the FLC based MPPT method due to its less oscillation at MPP and fast converging speed [26,27]. In general, most of the FLC based MPPT techniques track MPP after computing the Voltage (V)-Power (P) curve and the slope change in it. The drawback of FLC based MPPT method is that the operating point moves away from MPP for changing irradiances since variation in duty cycle is neglected [28]. Hence, authors in Ref. [29] proposed FLC with a duty cycle as input and array power is a variable. This method enhances the dynamic characteristics for variable climatic conditions but the steady state error occurs in the output power of the PV system. To increase the power level accuracy and dynamic characteristic, both methods have been combined [30]. In this FLC three inputs are introduced as duty cycle variation, PV power derivative with PV current derivative (dP/dI), and change of this derivative.

Several modifications and approaches have been introduced in FLC based MPPT to solve those problems. Among them, in Ref. [31] Particle swarm optimization algorithm is proposed to regulate the duty cycle of the DC-DC converter properly for classical FLC based MPPT when the irradiances vary rapidly. In Ref. [32] the authors developed a new FLC MPPT for a grid-connected PV system in which MFs of FLC are tuned based on the modified P&O technique. This method improves the speed of tracking but it produces oscillations around MPP. A hybrid MPPT technique combining quasi oppositional chaotic grey wolf optimizer and random forest algorithms have been developed [33]. However, it has slow convergence speed and produces high initial oscillations at MPP for sudden changes in irradiances when connected to the grid. In Refs. [34,35] the researchers developed an FLC approach based on modified HC and IC for MPP. Whilst the above proposals avoid the drift problem and reduces the fluctuations around MPP during changing irradiances but the implementation is more complex. Hence, the GA is used to optimize the scaling factors of membership functions to improve the performance of FLC based MPPT under changing temperature and irradiance conditions [36]. However, this technique reduces oscillation at MPP but convergence speed is slow.

This paper essentially focuses on the performance of MPPT to achieve MPP under variable temperature and irradiance using an intelligent method. The MPPT method that has been proposed includes Grasshopper optimization (GO) and Fuzzy Logic Controller. In this paper, a novel Grasshopper optimized Adaptive Fuzzy logic based MPPT is designed. In this proposed method, the GO algorithm is used to tune the Membership functions (MF) scaling factors of FLC. The GO algorithm automatically updates the MFs of output and inputs. The superiority of the proposed MPPT is compared with conventional P&O and also with FLC based MPPT.

The key advantages of proposed MPPT are listed below:

1) A novel adaptive Fuzzy logic controller using grasshopper optimization is proposed.
2) In the proposed MPPT, the MFs of FLC are tuned by the grasshopper optimization algorithm to handle the uncertainties in irradiances and temperature.
3) The proposed MPPT is studied under stringent irradiances and temperature profiles.
4) The proposed MPPT can handle as possible abnormal conditions and improves the efficiency, convergence speed and reduce the steady-state oscillations.

PV system modelling

PV cell model

PV cell is a basic unit which converts sun light energy into electrical energy by the photovoltaic effect. The PV cell produces electrical energy when exposed to sun light. The equivalent circuit of practical PV cell which includes shunt and series resistances as shown in Fig. 1. Among various methods of modelling of PV cell, the single diode model is more accurate. The PV cell output current, I_{PVC} using KCL can be obtained as [37]:

$$I_{PVC} = I_{LC} - I_d - \frac{V_{PVC} + R_S{*}I_{PVC}}{R_{SH}} \tag{1}$$

where

I_{LC}: light produced current (A), I_d: diode current (A), V_{PVC}: PV cell voltage (V), R_S: series resistance of PV cell (Ω), R_{SH}: shunt resistance of PV cell (Ω).

The light-current, I_{LC} of a PV cell be subject to insolation as well as ambient temperature is expressed as:

$$I_{LC} = \frac{G}{G_{ref}}\left[I_{LCref} + \mu_{sc}(T_{cell} - T_{ref})\right] \tag{2}$$

where

T_{cell}: Cell temperature in Kelvin (K), T_{ref}: Standard temperature in Kelvin (K), G: Irradiance (w/m^2), μ_{sc}: Temperature coefficient.

Also the diode current, I_d is;

$$I_d = I_o\left(e^{\frac{V_{PVC}+R_S{*}I_{PVC}}{V_t}} - 1\right) \tag{3}$$

Where V_t: Thermal voltage (V).

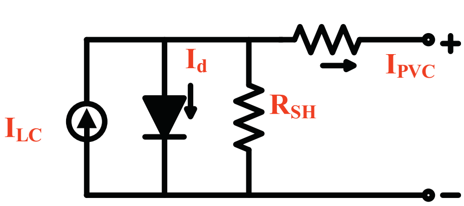

Fig. 1 – PV cell model.

The I_o, diode saturation dark current is proportional to temperature can be obtained as:

$$I_o = I_{o,ref}\left(\frac{T_{cell}}{T_{ref}}\right)^3 \exp\left[\left(\frac{q\varepsilon_G}{A.K}\right)\left(\frac{1}{T_{ref}} - \frac{1}{T_{cell}}\right)\right] \tag{4}$$

The PV system has a unique operating point on the V–P and V–I curves presented in Fig. 2, called MPP and it depends on ambient temperature and sun irradiance. The voltage of the PV module also depends on the impedance of the load. The MPP of a PV system drops to a new maximum point when it is connected to the load. To overcome this issue MPPT technique and a Boost converter are included between the PV system and the load.

Boost converter model

The maximum operating point of a PV system depends on the load curve that is represented as a line with the slope V–P curve and I = V/R. Hence, the maximum PV power point that can be transferred to the load based on the optimum value of the resistive load. To improve the excellence of the output of the PV system a boost converter (power conversion unit) is employed. Here, the resistive load and boost converter (BC) are connected in parallel to the PV module presented in Fig. 3. The purpose of the BC is to track the MPP of the PV system. In general, the BC is operated in two modes, i.e. continuous conduction mode operated for efficient conversion of power and discontinuous conduction mode for stand by operation. Here, the output voltage of a BC depends on the duty cycle which is adjusted using the MPPT technique [23]. The relation

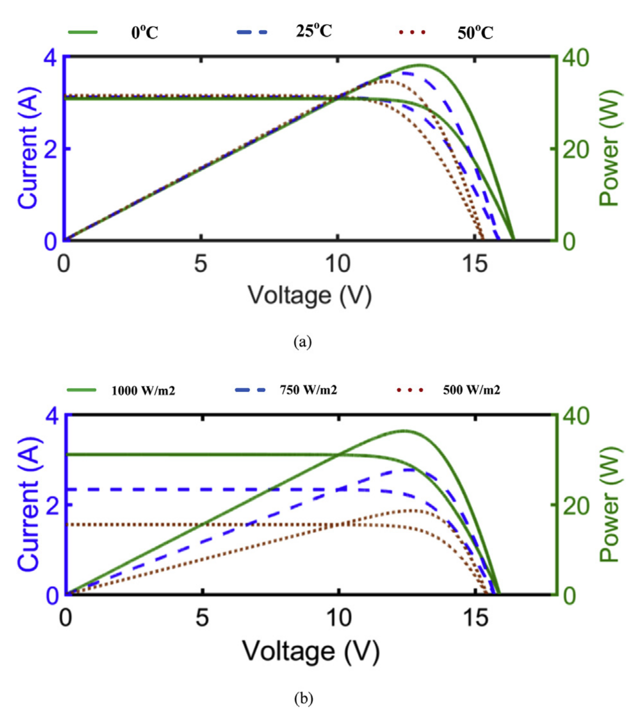

Fig. 2 – PV system characteristic curves for (a) different values of temperature and (b) different values of irradiances.

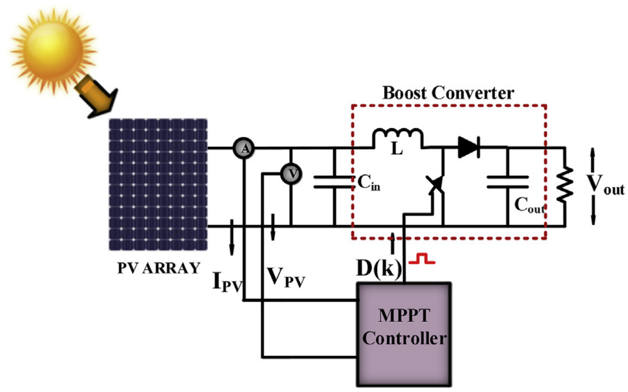

Fig. 3 – Block diagram of Solar PV connected Boost converter.

of the input and output voltage as a function of the duty cycle can be expressed as:

$$\frac{V_o}{V_i} = \frac{1}{1-D} \tag{5}$$

where

V_O = output voltage, V_i = Input PV voltage, and D = duty cycle.

MPPT system

Conventional FLC MPPT technique

In the last decade, FLC based MPPT method become most common for the PV system. The configuration of FLC can be divided into three stages viz. fuzzification, fuzzy inference engine and defuzzification represented in Fig. 4. In the fuzzification stage, the crisp input variables are transformed into linguistic labels based on defined Membership functions. In the second stage, the linguistics labels, output of fuzzification are called fuzzy inputs that are used to generate a verbal decision. Based on these fuzzy inputs the fuzzy inference engine uses the "if-then" concept that is in rule base to generate fuzzy output. In the last stage, the fuzzy outputs are transformed into crisp values [38,39].

The classical FLC based MPPT has two inputs and one output to achieve the MPP of the PV system. The input variables defined in equations (6)–(8) are

$$e(k) = \frac{\Delta P}{\Delta V} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{6}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{7}$$

And the output variable is

$$\Delta D = D(k) - D(k-1) \tag{8}$$

where

e(k) = change in slope of V–P curve
Δe(k) = change in its value of slope of V–P curve
ΔD = change in duty cycle.

The MFs of the input and output variable of FLC is demonstrated in Fig. 5. Five MFs are used for input and output variables as positive big (PB), positive small (PS), zero (Z), negative small (NS), and negative big (NB). The rule base given in Table 1 is used to reduce oscillations and quick tracking speed at a steady state. The min-max method, which is a well-known and widely used is applied in this study. To work with FLC, The centroid of area defuzzification method is used and expressed as:

$$\Delta D = \frac{\sum_j^{25} \in (D_j) D_j}{\sum_j^{25} D_j} \tag{9}$$

where D_j = centre of max-min method composition at the output MF.

The performance of FLC is highly depended on its parameters viz. rule base and MFs. These parameters selection would not be suitable without precise information about the system. Hence, conventional FLC may not provide optimum performance for changing insolation and temperature. To solve the above issue, a GO algorithm is used to optimize the scaling factors of MFs.

Proposed Adaptive FLC based MPPT technique

The conventional FLC approach has some depicts with the improper selection of MFs. To solve this problem, several authors used swarm optimization techniques to tune the scaling factors of inputs and output parameters of MFs. There are many approaches to tune fuzzy parameters [36,40–42]. In this, based on the complexity and requirements of MPPT for the PV system, a novel Grasshopper optimization (GO) technique is used for tuning the scaling factors of MFs of FLC. The detailed

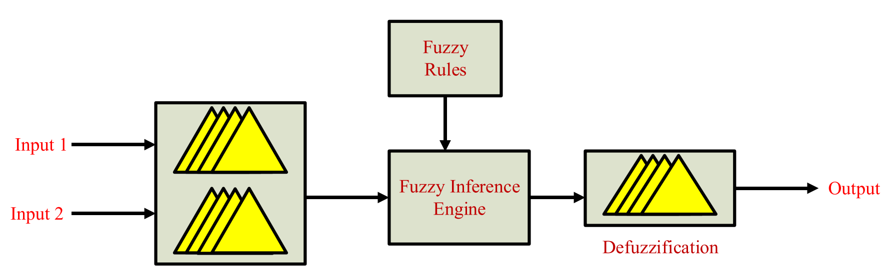

Fig. 4 – Fuzzy logic system.

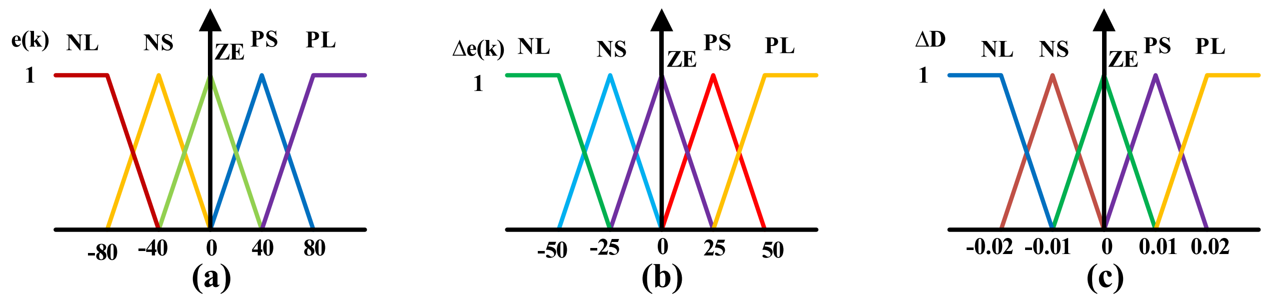

Fig. 5 – Membership functions for (a) input (b) change in input and (c) output.

Table 1 – The FLC rule base used for the system.

e	Δe				
	NB	NS	ZE	PS	PB
NB	ZE	ZE	ZE	NB	PS
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

explanation of GO presented in Ref. [43]. The structure of the proposed controller is demonstrated in Fig. 6. The reason for tuning of scaling factors of MFs instead of fuzzy set ranges is the number of variables for optimization is reduced. The objective of tuning the scaling factors is to reach MPP with fast-tracking speed. The integral time absolute error (ITAE) criteria are used for the cost function and expressed as:

$$ITAE = \int_0^{\infty} t * |e(t)| dt \tag{10}$$

GO algorithm for tuning scaling factors of MFs

The MPP tracking starts with an initial duty cycle. The voltage, V_{PV} and input current, I_{PV} of BC are measured to calculate the power P_{PV} (k) of the PV system. Now, based on initial changes in power, the controller increases the duty cycle. At this stage, new current, I_{PV} and voltage, V_{PV} are measured and new power P_{PV} (k + 1) is calculated. Based on past and present data of the PV power, the controller decides to increase or decrease the duty cycle. This process of tracking continuous until the MPP reaches.

Grasshopper optimization (GO) algorithm is a recent nature-inspired optimization technique based on grasshopper's food search process [43]. GO algorithm mimics the behavior of grasshopper's swarms and their social interaction. Grasshoppers are destructive insects according to their damage to agriculture. The grasshoppers have two swarm phases in their life cycle: larval and adulthood. In the larval phase, the grasshoppers move slowly and eat all vegetation on their path. While in adulthood phase they develop wings and move fast in the air to form a swarm. In both the phases, the food search process of grasshoppers is divided into exploration and exploitation. In the exploration phase, the search agents (grasshoppers) tend to move quickly while in the exploitation phase they are encouraged to move locally. The mathematical modelling of grasshoppers swarming behavior is summarized as follows:

$$X_i = r_1 S_i + r_2 G_i + r_3 A_i \tag{11}$$

where

X_i = ith grasshopper position, S_i = ith grasshopper social interaction, G_i = ith grasshopper gravity force, A_i = ith grasshopper wind advection, and r_1, r_2, r_3 = random numbers.

The value of S_i is obtained from equation (12)

$$S_i = \sum_{j=1,\, j\neq i}^{N} S(D_{ij})\, \overrightarrow{D_{ij}} \tag{12}$$

where D_{ij} defines the distance from ith to jth grasshopper and calculated as $D_{ij} = |x_j - x_i|$. $\overrightarrow{D_{ij}}$ is unit vector from ith to jth grasshopper.

The 'S' function is used to define the strength of social forces and calculated as:

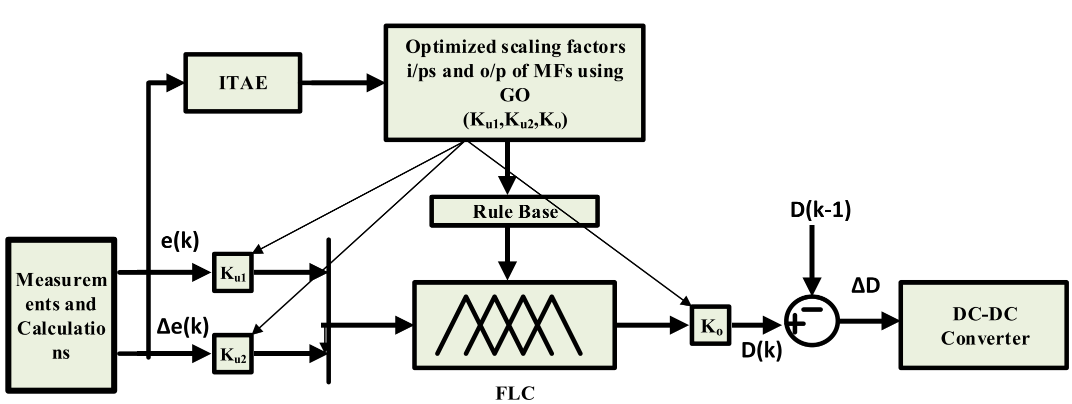

Fig. 6 – Proposed adaptive FLC.

$$S(r) = f e^{-\frac{r}{l}} - e^{-r} \tag{13}$$

where f indicates intensity of attraction, and l represents attractive length scale.

The G component of equation (11) can be determined as:

$$G_i = -g\vec{e_g} \tag{14}$$

Here, g indicates gravitational constant and $\vec{e_g}$ is the unit vector to the Centre of earth.

The A component of equation (11) can be determined as:

$$A_i = u\,\vec{e_w} \tag{15}$$

Here, u indicates constant drift and $\vec{e_w}$ is the unit vector in the direction of wind.

Therefore, using the components S, G and A, equation (11) can be written as:

$$X_i = r_1\left(\sum_{j=1,\, j\neq i}^{N} S(|x_j - x_i|)\frac{x_j - x_i}{D_{ij}}\right) - r_2 g\vec{e_g} + r_3 u\,\vec{e_w} \tag{16}$$

where N is the number of agents (grasshoppers).

To converge towards the specified point equation (16) can be modified as:

$$X_i^d = c\left(\sum_{j=1,\, j\neq i}^{N} c\frac{ub_d - lb_d}{2} S\left(\left|x_j^d - x_i^d\right|\right)\frac{x_j - x_i}{D_{ij}}\right) + \vec{T_d} \tag{17}$$

where ub_d and lb_d are upper and lower bounds, $\vec{T_d}$ is indicates the target value (best solution), here c is the decreasing co-efficients to shrink comfort region, repulsion region, and attraction region. The coefficient c can be updated using equation (18) to increase the exploitation and decrease the exploration proportional to the iteration.

$$c = c_{max} - l\frac{c_{max} - c_{min}}{Iter\_max} \tag{18}$$

where c_{min}, c_{max} are minimum and maximum limits of decreasing coefficient; l represents current iteration; and $Iter\_max$ is the maximum number of iteration. Due to the tremendous advantages such as simplicity, less number of controlling parameters, easy implementation structure, and fast convergence characteristics, GO algorithm is applied to various fields of engineering problems [43–45]. Based on these advantages, in this work, the GO algorithm is used to optimize FLC parameters. Fig. 7 depicts the flowchart of GO based tuning of scaling factors of FLC Parameters.

Simulation results and discussions

The PV system model has been developed using MATLAB/SIMULINK software to validate the performance of the

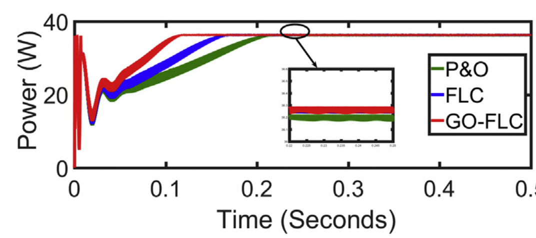

Fig. 8 – The output power of PV system for P&O, FLC and AFLC.

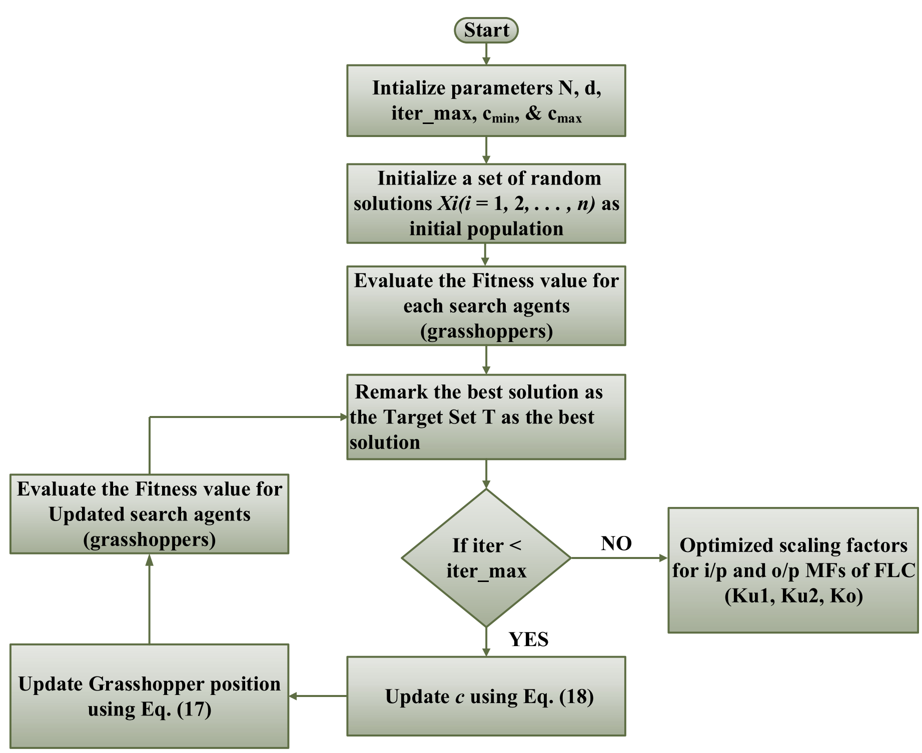

Fig. 7 – Flow chart of GO.

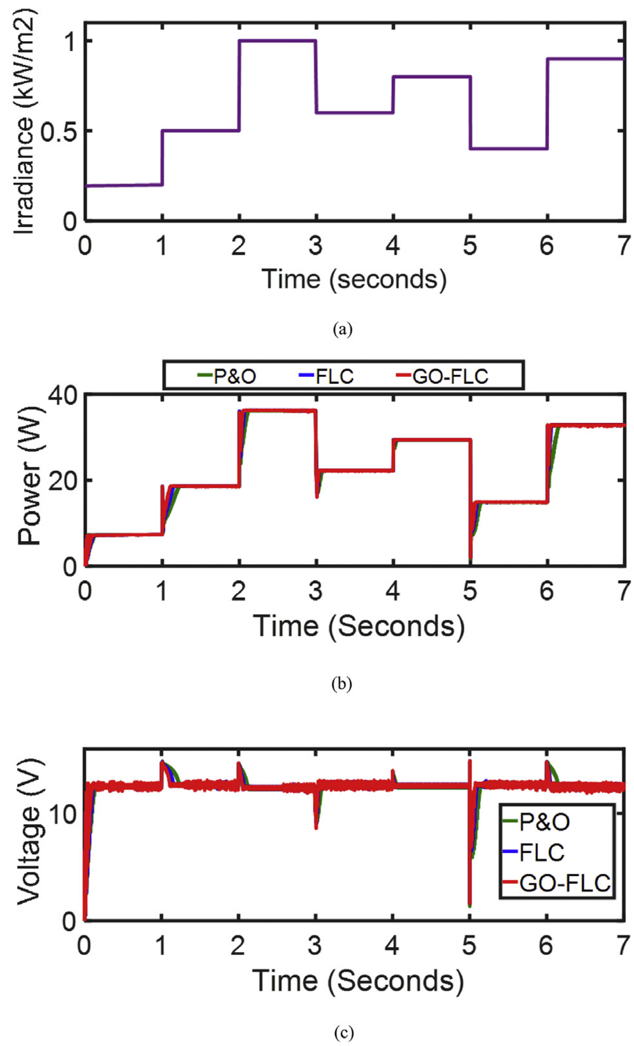

Fig. 9 – The PV system response for fast changing irradiances (a) irradiance profile (b) the output power (c) the output voltage.

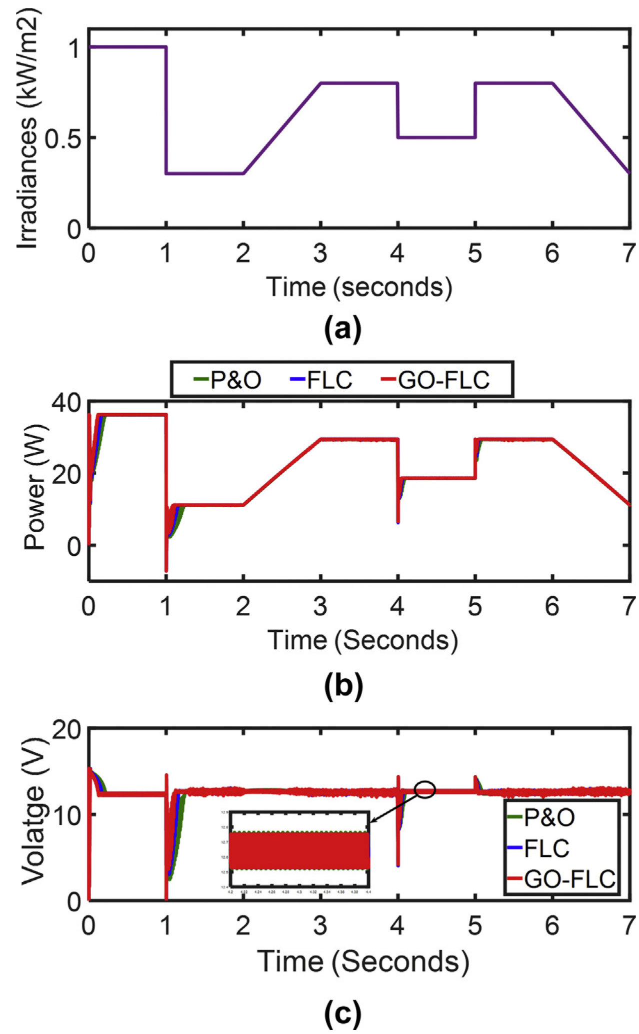

Fig. 10 – The PV system response under step and ramp changing irradiances (a) irradiance profile (b) the output power (c) the output voltage.

proposed method. The PV system comprises of PV module, Boost converter with MPPT technique and a resistive load shown in Fig. 3. How better the proposed MPPT technique in improvement of tracking speed and efficiency over the other techniques like conventional P&O and the FLC method is demonstrated with various insolation, temperature, and real-time irradiance profiles. The simulation parameters considered to model the PV module are Pmax = 36.3 W, Vmpp = 12.36 V, and Impp = 2.93 A, Voc = 16 V, Isc = 3.11 A. The components of boost converter used in simulation are chosen as L = 10 mH, C_{in} = 100 μF, C = 300 μF.

Uniform irradiance

In this case, the input irradiance for the PV system considered is uniform (1000 W/m^2) at 25 °C. The output power of PV system using three MPPT techniques is shown in Fig. 8 and the quantitative analysis of Fig. 8 shown in Table 2. From Table 2, it is observed that the proposed GO optimized FLC MPPT converges to MPP of 36.265 W with quick tracking speed and little chattering which is more effective than all other MPPT techniques in literature. These output power varies when the insolation level increases or decreases.

Step changing irradiance

In this scenario, a step changes irradiance profile shown in Fig. 9(a) is used to experiment the performance of proposed GO optimized FLC over the conventional P&O and FLC MPPT techniques. The output power and voltages under the fast-changing irradiances is shown in Fig. 9 (b) and (c). It is witnessed that the simulation results presented in Fig. 9(b) shows the proposed MPPT technique can handle power under fast-changing irradiances and it outperforms both conventional P&O and FLC concerning the convergence of MPP, speed of tracking, steady-state oscillations, and efficiency. It can be confirmed that the PV voltages are less affected with the change of irradiances.

Step and ramp changing irradiances

To examine the effectiveness of the proposed GO optimized FLC a step and ramp changing irradiances presented in Fig. 10(a) is used in this scenario. Fig. 10(b) and (c) represents the output power and the PV output voltage for step and ramp changing irradiances. From the figure, it can be observed that the proposed GO optimized FLC achieves MPP faster than conventional MPPT methods in every step change in irradiance and also it tracks continuous MPP in ramp changing irradiance without oscillations around the MPP.

Variable temperature

In this case, to ensure the supremacy of the proposed GO-FLC MPPT technique a variable temperature profile (i.e., 0 °C, 25 °C, and 50 °C at 0sec, 1sec, and 2sec) with irradiance of 1000 W/m^2 depicted in Fig. 11 (a) is considered. The output power and voltage under this scenario is shown in Fig. 11 (b) and (c). It is clear from Fig. 11, that the proposed GO-FLC based MPPT technique is enough efficient to converge at MPP with better tracking speed and efficiency.

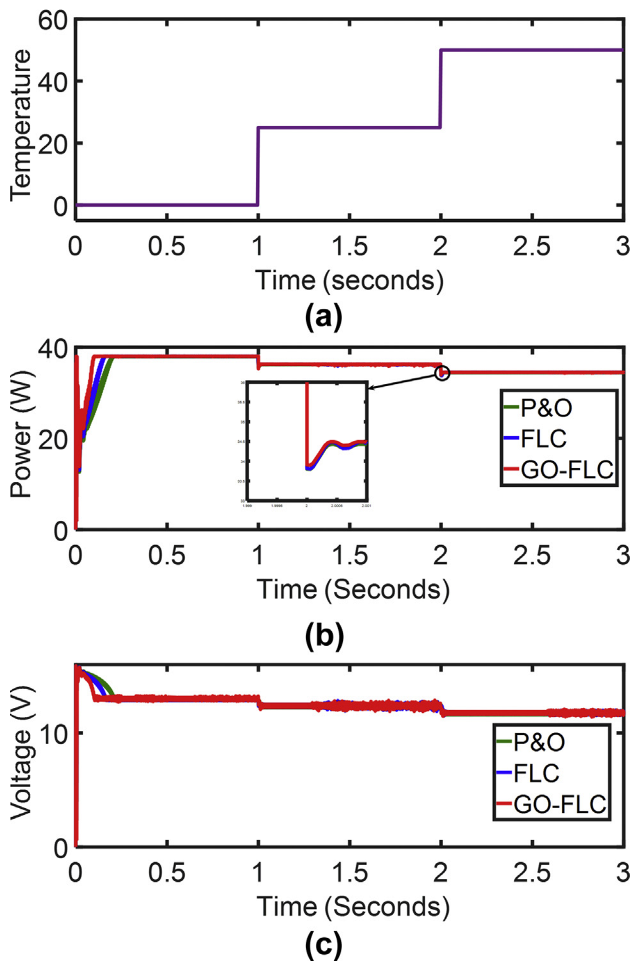

Fig. 11 – The PV system response under variable temperature (a) temperature profile (b) Output power (c) Output voltage.

Real time irradiance profile

To validate the proposed GO optimized FLC, a real time one day irradiance profile at the temperature 25 °C is considered in this scenario. Fig. 12 (a) depicts the real time 24 h irradiance profile and Fig. 12 (b) shows the PV output power. It is evident that, the zoomed view of Fig. 12 (b) shows the proposed GO optimized FLC tracks power continuously with better

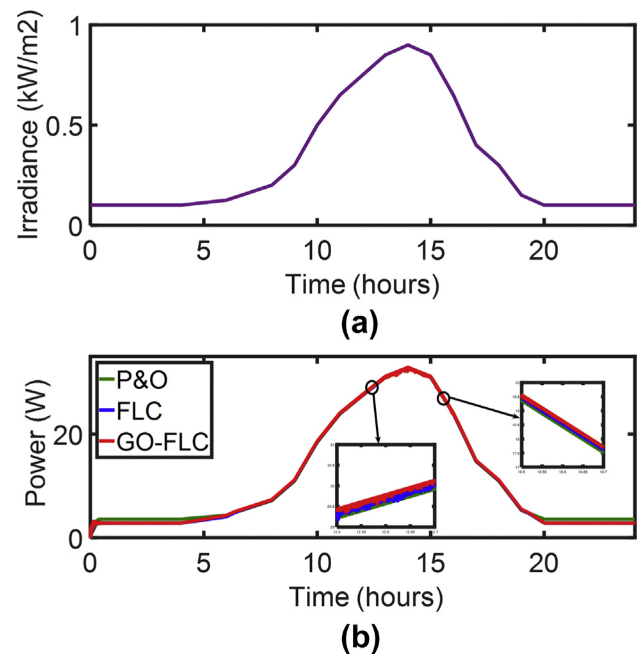

Fig. 12 – (a) Real time irradiance profile (b) The PV system output power.

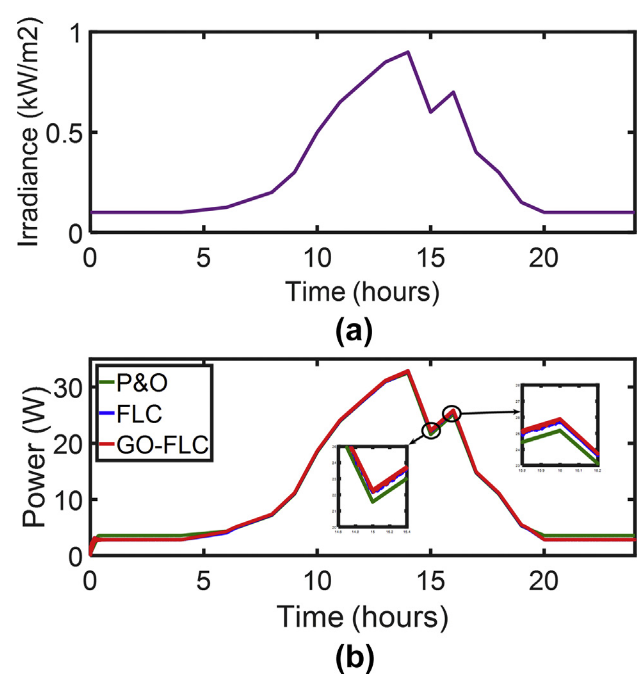

Fig. 13 – (a) Fluctuating real time irradiance profile (b) The PV system output power.

Table 2 – Quantitative analysis of MPPT techniques.

Method	Power at MPP (KW)	Maximum Power (KW)	Tracking speed (sec)	Tracking efficiency
P&O	36.185	36.34	0.22	99.57
FLC	36.24		0.18	99.72
Proposed GO-FLC	36.265		0.13	99.79

efficiency. Further, a sudden fluctuating real time 24 h irradiance profile shown in Fig. 13 (a) is considered to test the proposed GO optimized FLC. Fig. 13 (b) shows the PV system output power. From the zoomed view, it is evident that the proposed GO optimized FLC accurately tracks the power under fluctuating real time one day irradiance profile. A qualitative comparison among proposed and other conventional MPPT techniques is presented in Table 3.

Experimental results

To validate the efficacy of the proposed GO optimized FLC MPPT method, experiments have been carried out for different irradiance levels. Fig. 14 shows the experimental setup. In the experiment, the components of boost converter values are the same as in the simulation. A 10-bit analog to digital conversion is used to convert the current and voltage of the PV system. The voltage sensor (LV25-P) and current sensor (LA55-P) are used to sense the voltage and current of the PV system. The PV simulator (Magna Power Electronics XR600–9.9/415 + PPPE + HS) is used to generate the V–P and V–I characteristics of the PV system for different irradiance levels. The proposed GO optimized FLC MPPT method for this study is coded and executed by using an Arduino UNO controller.

To verify the effectiveness of the proposed GO-FLC based MPPT, experiments were carried out for different irradiance levels such as uniform irradiance, step changing irradiance, and step ramp changing irradiances. Fig. 15 represents the experimental output power of the PV system for uniform irradiance (1000 W/m^2) at 25 °C. It is observed that the experimental results are similar to the simulation results presented in Fig. 8. The proposed GO optimized FLC MPPT tracks the MPP within 0.15 s and with tracking efficiency of above 98% resulting in considerable oscillations around the MPP.

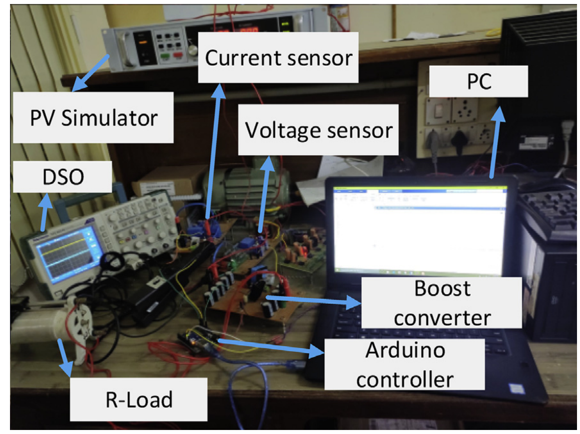

Fig. 14 – Experimental set up for proposed MPPT scheme.

In the next experiment, a step changing irradiance profile shown in Fig. 9 (a) is used to examine the proposed GO optimized FLC MPPT technique. The experimental output power of the PV system under this scenario is shown in Fig. 16. The experimental results are similar to the simulation results shown in Fig. 9 (b). The experimental results are witnessed that the proposed MPPT can handle the fast-changing irradiances.

Then, the proposed MPPT was also validated under step and ramp changing irradiance profile shown in Fig. 10 (a). The experimental output power of the PV system for this scenario is shown in Fig. 17 which is similar to the simulation result shown in Fig. 10 (b). From Fig. 17, it is evident that the proposed GO optimized FLC MPPT tracks the maximum power accurately with small oscillations around the MPP for every step and ramp changing irradiances.

Table 3 presents the performance evaluation of the proposed GO optimized FLC MPPT against five other established MPPT techniques stated in the literature. In comparison with the hybrid boost topology discussed in Ref. [15], the proposed GO optimized FLC MPPT tracks MPP with fewer oscillations and fast-tracking speed. Moreover, the complexity with hybrid boost topology is more because it has two switches (S1 and S2) for hybrid boost working mode which are manually operated. Therefore, the proposed MPPT is a highly reliable and has fast response to variable irradiance level. In the QOCGWO-RFA [33] hybrid boost topology is replaced with a conventional boost converter to reduce the complexity but the

Table 3 – Qualitative comparison of MPPT techniques.

Criteria	P&O	FLC	Topology in Ref. [15]	QOCGWO-RFA [33]	Fuzzy-PSO [24]	Proposed GO-FLC
Tracking accuracy	Moderate	Moderate	Moderate	Moderate	Moderate	Accurate
Tracking speed	Low	Medium	Medium	Medium	Medium	Fast
Oscillations at MPP	Large	Medium	Moderate	Low (initial oscillations are high)	Large	Less
Computational time	Less	Less	More	More	Moderate	Less
Complexity	Low	Low	High	Moderate	Moderate	Low
Reliability	Low	Moderate	Moderate	Moderate	High	High
Tracking efficiency	Low	Medium	High	Medium	Medium	High
Response to variable irradiance level	Slow	Moderate	Moderate	Moderate (initial oscillations are high)	Moderate (high oscillations)	Fast

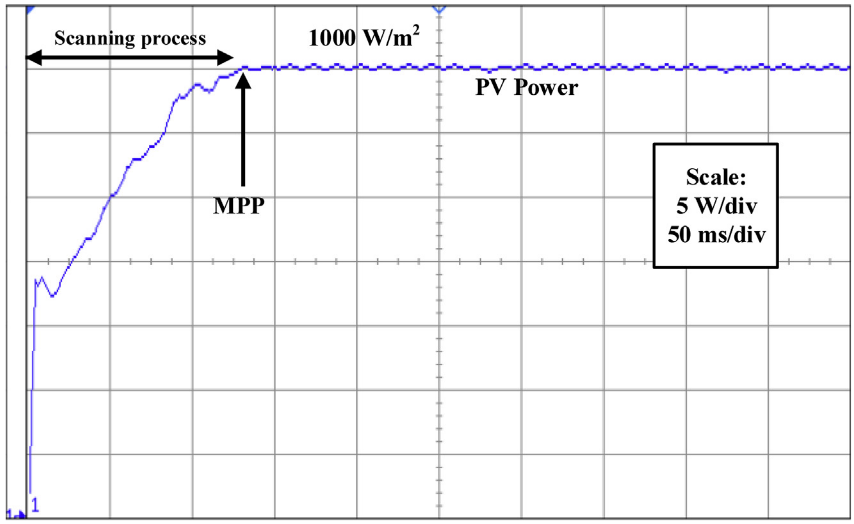

Fig. 15 – **Experimental output power of the PV system for uniform irradiance.**

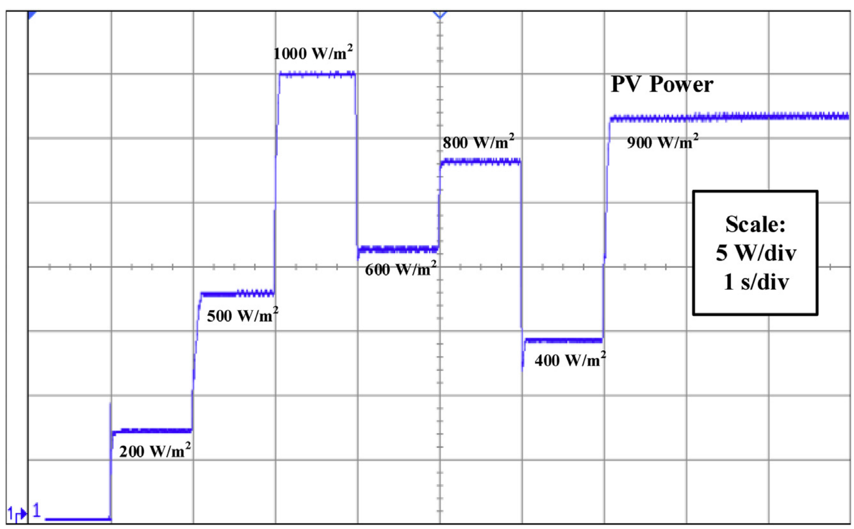

Fig. 16 – **Experimental output power of the PV system for step changing irradiances.**

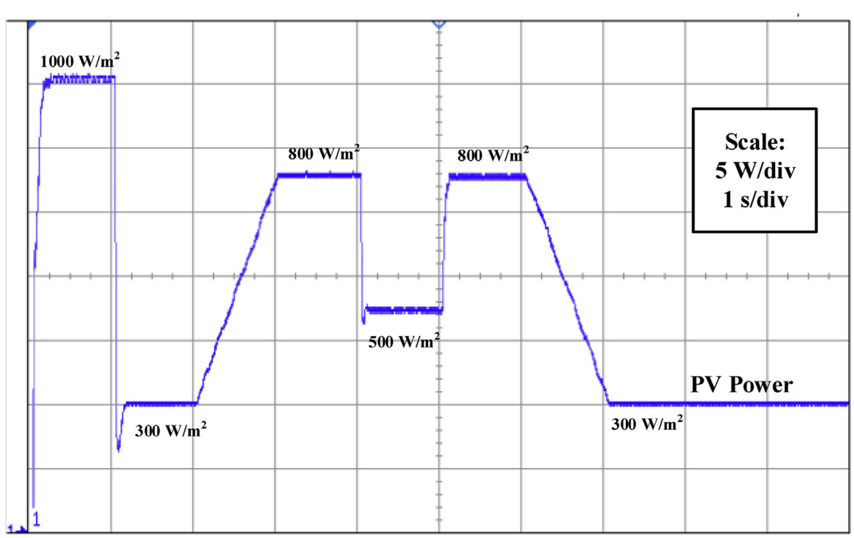

Fig. 17 – **Experimental output power of the PV system for step and ramp changing irradiances.**

tracking speed is slow and produces high initial oscillations for fast-changing irradiances when connected to the grid. Moreover, the performance of meta-heuristic techniques depends on the appropriate selection of their algorithm-specific parameters and hence any inappropriate selection of parameters may lead to divergence of the algorithm. In the Fuzzy-PSO [24] the MFs of FLC are automatically adjusted using PSO to track MPP. However, PSO has slow convergence due to the more number of initialization parameters (c1, c2, r1, r2) and improper selection of parameters may lead to divergence. The computational time for PSO is more compared to grasshopper optimization. Hence, the proposed GO FLC MPPT has fewer oscillations, fast-tracking speed and fast response for rapidly changing irradiances.

The proposed technique is a little difficult for implementation concerning P&O or IC due to the fuzzification and defuzzification process. The proposed GO FLC needs some scan and storing procedure to converge at the right MPP under some partial shading conditions. However, the proposed MPPT technique has fast-tracking speed, fewer oscillations at MPP, high tracking efficiency and reliable compared to the conventional P&O and FLC methods. The experimental results are witnessed that the proposed GO optimized FLC MPPT can track the MPP for fast-changing irradiances.

Conclusion

In this paper, a novel Adaptive fuzzy logic controller based MPPT technique is proposed to improve the efficiency and robustness of the PV system under abnormal conditions such as a change in irradiance and ambient temperature. To improve the performance of the proposed MPPT technique, the parameters of the FLC are tuned using a grasshopper optimization algorithm. The performance of the proposed MPPT technique is compared with various standard and recent techniques in the literature. From the simulation and experimental results, it is evident that the proposed MPPT technique improves the convergence speed, tracking efficiency and decreases the steady-state oscillations over other techniques in the literature. Hence, the proposed MPPT technique can be adopted for real-time implementation of the PV-MPPT application.

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REFERENCES

[1] Mekhilef S, Saidur R, Safari A. A review on solar energy use in industries. Renew Sustain Energy Rev 2020;15(4):1777–90.

[2] Solangi KH, Islam MR, Saidur R, Rahim NA, Fayaz H. A review on global solar energy policy. Renew Sustain Energy Rev 2011;15(4):2149–63.

[3] Seyedmahmoudian M, et al. State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV systems – a review. Renew Sustain Energy Rev 2016;64:435–55.

[4] Huynh DC, Dunnigan MW. Development and comparison of an improved incremental conductance algorithm for tracking the MPP of a solar PV panel. IEEE Trans sustain Energy Oct. 2016;7(4):1421–9. https://doi.org/10.1109/TSTE.2016.2556678.

[5] Birane M, Larbes C, Cheknane A, Mat S. Comparative study and performance evaluation of central and distributed topologies of photovoltaic system. Int J Hydrogen Energy 2016:1–9.

[6] Khatib TTN, Mohamed A, Amim N. An improved indirect maximum power point tracking method for standalone photovoltaic systems, 10. AEE; 2010. p. 56–62.

[7] Sher HA, et al. An intelligent control strategy of fractional short circuit current maximum power point tracking technique for photovoltaic applications an intelligent control strategy of fractional short circuit current maximum power point tracking technique for photovoltic applications. J Renew Sustain Energy 2015;7:13114-1–13114-15.

[8] Ahmad J. A fractional open circuit voltage based maximum power point tracker for photovoltaic arrays. In: 2010 2nd International conference on software technology and engineering, San Juan, PR; 2010. V1-247–1-250. https://doi.org/10.1109/ICSTE.2010.5608868.

[9] Vitorino MA, Hartmann LV, Lima AMN, Corrêa MBR, Paraíba CG. Using the model of the solar cell for determining the maximum power point of photovoltaic systems. In: 2007 European conference on power electronics and applications, Aalborg. vol. 1; 2007. p. 1–10. https://doi.org/10.1109/EPE.2007.4417684.

[10] Safari A, Mekhilef S. Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter. IEEE Trans Ind Electron 2011;58(4):1154–61.

[11] Chang S, Wang Q, Hu H, Ding Z, Guo H. An NNwC MPPT-based energy supply solution for. Energies 2019;12:101.

[12] Harrag A, Messalti S. Variable step size modified P & OMPPT algorithm using GA-based hybrid of fl ine/online PID controller. Renew Sustain Energy Rev 2015;49:1247–60.

[13] Seyedmahmoudian M, et al. Simulation and hardware implementation of new maximum power point tracking technique for partially shaded PV system using hybrid DEPSO method. IEEE Trans Sustain Energy 2015;6(3):850–62.

[14] Mohammed SS, Devaraj D, Ahamed TPI. A novel hybrid maximum power point tracking technique using perturb & observe algorithm and learning Automata for solar PV system. Energy 2016;112:1096–106.

[15] Belhimer S, et al. A novel hybrid boost converter with extended duty cycles range for tracking the maximum power point in photovoltaic system applications. Int J Hydrogen Energy 2018;43:6887–98.

[16] Soon TK, Mekhilef S. A fast-converging MPPT technique for photovoltaic system under fast-varying solar irradiation and load resistance. IEEE Trans Ind Informatics 2015;11(1):176–86.

[17] Tey KS, Mekhilef S. Modified incremental conductance algorithm for photovoltaic system under partial shading conditions and load variation. IEEE Trans Ind Electron 2014;61(10):5384–92.

[18] Ramos-Hernanz J, et al. Novel control algorithm for MPPT with Boost converters in photovoltaic systems. Int J Hydrogen Energy 2017;42:17831–55.

[19] Femia N, Petrone G, Spagnuolo G, Vitelli M. Optimization of perturb and observe maximum power point tracking method. IEEE Trans Power Electron 2005;20(4):963–73.

[20] Liu X, Lopes LAC. An improved perturbation and observation maximum power point tracking algorithm for PV arrays. In: 2004 IEEE 35th annual power electronics specialists conference (IEEE cat. No.04CH37551), Aachen, Germany. vol. 3; 2004. p. 2005–10. https://doi.org/10.1109/PESC.2004.1355425.
[21] Fathabadi H. Novel fast dynamic MPPT (maximum power point tracking) technique with the capability of very high accurate power tracking. Energy 2016;94:466–75.
[22] Kollimalla SK, Mishra MK. A novel adaptive p&o mppt algorithm considering sudden changes in the irradiance. IEEE Trans Energy Convers 2014;29(3):602–10.
[23] Ali AIM, Sayed MA, Mohamed EEM. Modified efficient perturb and observe maximum power point tracking technique for grid-tied PV system. Electr Power and Energy Syst 2018;99(December 2017):192–202.
[24] Rizzo LPR. Adaptive perturb and observe algorithm for photovoltaic maximum power point tracking. IET Renew Power Gener July 2010;4(4):317–28. https://doi.org/10.1049/iet-rpg.2009.0006.
[25] Killi M, Samanta S. Modified perturb and observe MPPT algorithm for drift avoidance in photovoltaic systems. IEEE Trans Ind Electron 2015;62(9):5549–59.
[26] Ben Salah C, Ouali M. Comparison of fuzzy logic and neural network in maximum power point tracker for PV systems. Elec Power Syst Res 2011;81(1):43–50.
[27] Ozdemir S, Altin N, Sefa I. Fuzzy logic based MPPT controller for high conversion ratio quadratic boost converter. Int J Hydrogen Energy 2017:1–12.
[28] Won C, Kim D, Kim S, Kim W, Kim H. A new maximum power point tracker of photovoltaic arrays using fuzzy controller. In: Proceedings of 1994 power electronics specialist conference - PESC'94, Taipei, Taiwan. vol. 1; 1994. p. 396–403. https://doi.org/10.1109/PESC.1994.349703.
[29] Simdes MG, Franceschetti NN. Fuzzy optimisation based control of a solar array system. IEE Proc Elec Power Appl Sept. 1999;146(5):552–8. https://doi.org/10.1049/ip-epa:19990341.
[30] Masoum MAS, Sarvi M. A new fuzzy-based maximum power point tracker for photovoltaic applications. Iran J Electr Electron Eng 2005;1(January).
[31] Soufi Y, Bechouat M, Kahla S. Fuzzy-PSO controller design for maximum power point tracking in photovoltaic system. Int J Hydrogen Energy 2016:1–9.
[32] Al-Majidi Sadeq D, et al. A novel maximum power point tracking technique based on fuzzy logic for photovoltaic systems. Int J Hydrogen Energy 2018;43:14158–71.
[33] Arther Jain A, et al. Application of QOCGWO-RFA for maximum power point tracking (MPPT) and power flow management of solar PV generation system. Int J Hydrogen Energy 2020;45:4122–36. https://doi.org/10.1016/j.ijhydene.2019.12.071.
[34] Alajmi BN, Ahmed KH, Finney SJ, Williams BW. Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system. IEEE Trans Power Electron 2011;26(4):1022–30.
[35] Harrabi N, Souissi M, Aitouche A. Modeling and control of photovoltaic and fuel cell based alternative power systems. Int J Hydrogen Energy 2018:1–10.
[36] Obeidi T, Zerguerras A, Larbes C, Aı SM. Genetic algorithms optimized fuzzy logic control for the maximum power point tracking in photovoltaic system. Renew Energy 2009;34(10):2093–100.
[37] Bellia H. A detailed modeling of photovoltaic module using MATLAB. NRIAG J Astron Geophys 2014;3(1):53–61.
[38] Khaehintung N, Kunakorn A, Sirisuk P. A novel fuzzy logic control technique tuned by particle swarm optimization for maximum power point tracking for a photovoltaic system using a current-mode boost converter with bifurcation control. Int J Contr Autom Syst 2010;8:289–300.
[39] Bhukya L, et al. Fuzzy logic approach based novel frequency control strategy by wind turbine generator in a wind-diesel autonomous microgrid. In: 2019 IEEE 1st International conference on energy, systems and information processing (ICESIP), Chennai, India; 2019. p. 1–6. https://doi.org/10.1109/ICESIP46348.2019.8938393.
[40] Adly M. An optimized fuzzy maximum power point tracker for stand alone photovoltaic systems : ant colony approach. In: Proceedings of the 2012 7th IEEE Conference on industrial electronics and applications, ICIEA; 2012. p. 113–9. https://doi.org/10.1109/ICIEA.2012.6360707.
[41] Jouda A, Elyes F, Rabhi A, Abdelkader M. Optimization of scaling factors of fuzzy – MPPT controller for stand-alone photovoltaic system by particle swarm optimization. Energy Procedia 2017;111(September 2016):954–63.
[42] AnilKumar A, Srikant NV. Load frequency control for diverse sources of interconnected two area power system: an adaptive fuzzy approach. In: 2016 International conference on control, computing, communication and materials (ICCCCM), Allahabad; 2016. p. 1–4. https://doi.org/10.1109/ICCCCM.2016.7918218.
[43] Zahra S, Seyedali M, Shahrzad M, Hossam S, Aljarah I. Grasshopper optimization algorithm for multi-objective optimization problems. Appl Intell 2018;48:805. https://doi.org/10.1007/s10489-017-1019-8.
[44] El-fergany AA. Electrical characterisation of proton exchange membrane fuel cells stack using grasshopper optimiser. IET Renew Power Gener 2018;12(1):9–17. https://doi.org/10.1049/iet-rpg.2017.0232.
[45] Mafarja M, et al. Evolutionary population dynamics and grasshopper optimization approaches for feature selection problems. Knowl Base Syst 2018;145:25–45.