



Modeling and evaluation of main maximum power point tracking algorithms for photovoltaics systems



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ABSTRACT

This paper presents modeling and evaluation of more widely used Maximum power Point tracking (MPPT) algorithms. These algorithms are simulated in Matlab/Simulink environment in order to provide a comparison in terms of sensors required, ease of implementation, efficiency, and the dynamic response of the Photovoltaics (PV) systems to variations in temperature and irradiance. This simulation based evaluation can be useful in specifying the appropriateness of the MPPT algorithms for the different PV system applications. It can be used as a reference modeling for future research related to the PV power generation. Furthermore, a novel artificial intelligence technique based on Adaptive Neuro-Fuzzy Inference System (ANFIS) is presented in this work. The solar irradiance and cell temperature are used as input to predict the duty cycle of the electronic switch of the DC–DC converter adopted in the system. The proposed technique provides high accuracy, stability, very fast tracking algorithm.

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1. Introduction

The key solution to overcome energy related problems of the world is the Renewable energy technologies [1]. However, only about 14% of total world energy demand are supplied by renewable energy resources [2]. Solar energy provides an unlimited, clean and environmentally friendly energy, So, it is regarded as one of the most promising renewable energy technologies [3–8].

The Photovoltaics systems appear to be one of the most promising technologies due to many reasons such as the electrical energy production close to where it is required, so that transport expenditure and energy losses can be avoided, no greenhouse gas emission, low maintenance cost and no noise because it do not require any moving parts [9]. The main applications of PV systems are in solar vehicles, water pumping, street lighting, remote areas electrification and space stations [10]. However, there are many drawbacks of PV systems: nonlinear behavior, the variation of the maximum power point with the climatic conditions which complicates the tracking task, low conversion efficiency which is less than 17% [11]; and high installation cost. So, it becomes necessary to use MPPT system in order to ensure the efficient operation of the solar array. MPPT is a switch-mode power converter can be used for extracting the maximum power despite the continuous changes in irradiance and temperature by the control technique which adjusts the power and achieves its greatest possible value [12]. Several MPPT algorithms have been proposed in the literature such as Fractional open circuit voltage algorithm [13], Perturb and Observe (P&O) algorithm [14], Incremental Conductance (IncCond) algorithm [15], Fuzzy Logic Control (FLC) based algorithm [16], Temperature measurement based algorithm [17] and ANFIS-based algorithm [18].

Both fractional open circuit voltage and fractional short circuit current algorithms are modified by Sayal [19] in order to overcome their limitations.

A modified P&O MPPT algorithm with variable perturbation step size is presented by Zhang et al. [20] in order to reduce the power oscillation around the MPP. A similar technique is developed by Piegari et al. [21].

Elgendy et al. [22] presented an experimental evaluation of the operating characteristics of the IncCond algorithm when employed by a PV pumping system.

In [23], Farhat et al. presented a single input fuzzy logic controller (SIFLC) based on the constant voltage algorithm. It is used as a MPPT control scheme for a stand-alone PV system.

In [24], Bin-Halabi et al. proposed an ANFIS-based MPPT algorithm.

These algorithms vary in complexity, sensors required, convergence speed, ease of implementation, popularity, and in other respects. The objective of this paper is to analyze, simulate and evaluate PV system employing different maximum power point tracking algorithms under varying operating conditions. The simulation tool SIMULINK[®] allows the direct evaluation of more widely used MPPT algorithms under the same operating conditions. Furthermore, this paper introduce a novel MPPT algorithm based on Adaptive Neuro-Fuzzy Inference system which can predict and track the maximum power point of PV system under rapidly changing environmental conditions in short time with minimum error and low oscillations. To be able to properly simulate the PV system, detailed mathematical model for the PV panel is presented and used to study the effect of different influences of the environmental conditions on its output characteristics.

2. Mathematical model of PV system

PV systems consist of PV panels, DC–DC converters, control technique and loads. A typical operation of MPPT system is depicted in Fig. 1, where the measured values of the output voltage and/or current of the PV panel are fed to the MPPT technique which updates the duty cycle (D) of the DC–DC converter to maximize the power delivered to the load [25].

2.1. PV panel model

The PV panel is composed of several PV cells connected in series or parallel or both. The equivalent circuit of the single-diode model for PV cells is shown in Fig. 2. The most commonly used expression of the output current I_{pv} and output voltage V_{pv} of a PV panel with N_s cells in series and N_p strings in parallel based on the single exponential model is found from Eq. (1) which describes the current–voltage characteristics of a PV module [26].

$$I_{pv} = GI_{phg} - I_{og} \left(e^{\Lambda_g(V_{pv} + I_{pv}R_{sg})} - 1 \right) - \left(\frac{V_{pv} + I_{pv}R_{sg}}{R_{shg}} \right) \tag{1}$$

where $\Lambda_g = q/nKT$; $\Lambda_g = \Lambda/N_s$; $R_{sg} = (N_s/N_p)R_s$; $R_{shg} = (N_s/N_p)R_{sh}$; $I_{og} = N_p I_o$; and $I_{phg} = N_p I_{ph}$ [20].

where I_{ph} is the light generated PV current, I_o is the reverse saturation current, n is the diode ideality factor, q is the charge of electron, K is the Boltzmann constant, T is the cell temperature, G is the solar radiation and R_s , R_{sh} are the series and parallel equivalent resistances of the solar cell respectively. The main electrical parameters of SM55 PV module used are summarized in Appendix A.

2.2. DC–DC converter

DC–DC converter is used for regulating the PV voltage by varying the duty cycle (D) using MPPT technique in order to maintain the operating point at the MPP of the PV panel.

DC–DC converters are classified into three types: boost converters, buck converters, buck–boost converters and Ćuk converter. The performance parameters of each type can be described by: voltage gain (A_v), boundary filter inductance (L_b) and minimum filter capacitance (C_{min}) [27].

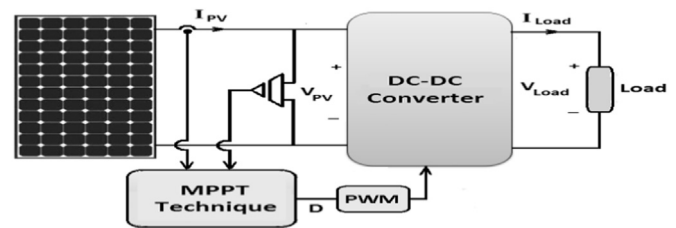


Fig. 1. Proposed PV system.

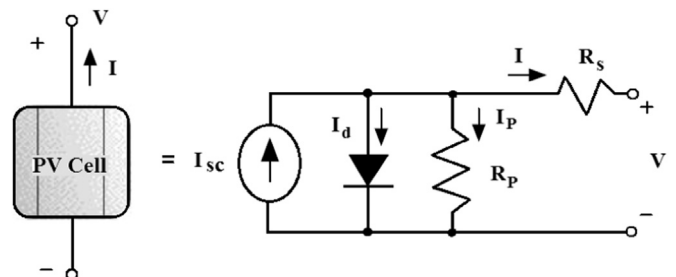


Fig. 2. Equivalent circuit of a PV cell using the single exponential model.

These parameters can be calculated using the relationships which are summarized in [27], Boost DC–DC converter, shown in Fig. 3, is chosen in the present work because its sensitivity to changes in D is larger than buck and buck–boost converter [27].

3. Simulation model of PV system

The proposed system mainly consists of SM55 solar module, Boost converter and resistive load. The control signal generated by each MPPT technique fed to a PWM for controlling the boost converter's switching MOSFET. The system was simulated in MATLAB/SIMULINK software environment as shown in Fig. 4.

The output characteristics of the PV module strongly influenced by changes in environmental conditions, as shown in Fig. 5. It is noted that MPP of the PV module is influenced by the irradiance (G) and temperature (T) changes and show that either the PV voltage or PV current can represent the MPP.

4. Main MPPT algorithms

MPPT is a switch-mode power converter introduced between the PV panel and the load. A typical operation of MPPT system is depicted in Fig.1, where the measured values of the output voltage and/or current of the PV panel are fed to the MPPT technique which updates the duty cycle (D) of the DC–DC converter in order to match the characteristics of the electrical load with those of the PV panel at MPP for maximum power transfer [25].

4.1. Modified Fractional Open Circuit Voltage Algorithm

Fractional open circuit voltage algorithm (FOCV) is based on the approximately linear relationship between the voltage at MPP (V_{MPP}) and the open circuit voltage (V_{OC}) of the PV panel under varying irradiance and temperature levels as described by the following equation:

$$V_{MPP} \cong K_1 \times V_{OC} \tag{2}$$

where K_1 is proportionality constant, which depends on the characteristics of the PV panel being used. The value of K_1 ranges

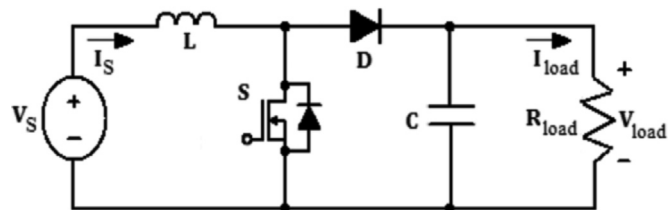


Fig. 3. Circuit diagram of boost DC–DC converter.

from 0.73 and 0.81 for SM55 PV module over a temperature range of 25–75 °C and irradiation levels from 200 to 1000 W/m² as shown in Fig. 6.

The modified fractional open circuit voltage algorithm is used to overcome the loss of power problem by measuring the temperature and irradiance in order to calculate V_{OC} using the following equations [19]:

$$V_{OC} = C_{TV} C_{GV} V_{OC}^{STC} \tag{3}$$

$$C_{TV} = \frac{V_{OC}}{V_{OC}^{STC}} = 1 + \frac{K_V}{V_{OC}^{STC}} (T - 25) \tag{4}$$

$$C_{GV} = 1 + \beta_T \alpha_G (G - 1000) \tag{5}$$

$$\alpha_G = \Delta T / (G - 1000) \tag{6}$$

where C_{TV} is the variation of V_{OC} with temperature, V_{OC}^{STC} is the open circuit voltage at standard test conditions (1000 W/m², 25 °C), K_V is the temperature coefficient of V_{OC} (it is taken –0.077 V/°C for SM55 PV module), C_{GV} is the variation of V_{OC} with solar irradiance, and ΔT is the temperature change due to change in irradiance. The values of β_T and α_G taken are 0.0016 and 0.006 respectively.

Once V_{OC} is calculated, V_{MPP} can be determined using (2) and it can be reached using PI controller which minimize the error between the output voltage of the PV panel and V_{MPP} by adjusting the duty cycle of the power converter. Fig. 7 shows the configuration of the modified FOCV algorithm in Simulink according to the flow chart shown in Fig. 8.

4.2. Perturb and observe algorithm

The perturb and observe algorithm (P&O) is based on periodical measuring the PV panel voltage $V(k)$ and current $I(k)$ to calculate the current PV output power $P(k)$, and perturbing (increasing or decreasing) the switching duty cycle (D) of the power converter to change the system operating point and then observing the output power variation ($\Delta P = P(k) - P(k-1)$). If the power increases (ΔP is positive), the MPP will be approached, therefore the perturbation should be kept the same for the following stage; otherwise the perturbation should be reversed. This process is repeated until the MPP is reached [15].

Fig. 9 shows the flow chart the P&O algorithm, where the configuration of the P&O algorithm in Simulink environment is shown in Fig. 10.

4.3. Incremental conductance algorithm

The Incremental conductance algorithm (IncCond) is based

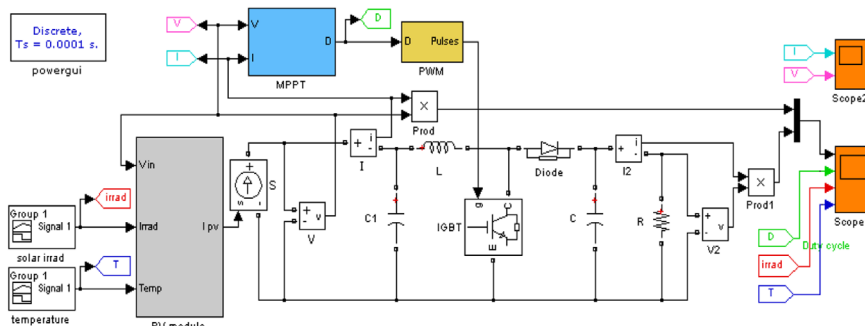


Fig. 4. Configuration of the PV system in Simulink environment.

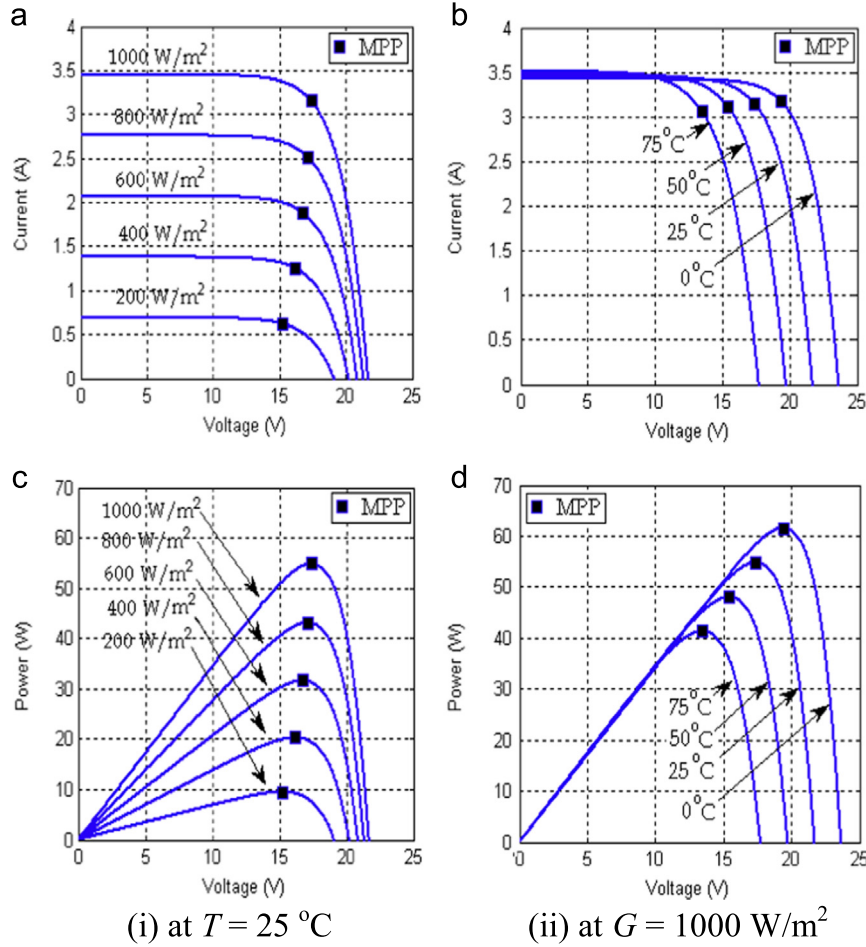


Fig. 5. The output characteristics of SM55 PV module for various values of solar irradiance and temperature: (a) I - V characteristics and (b) P - V characteristics.

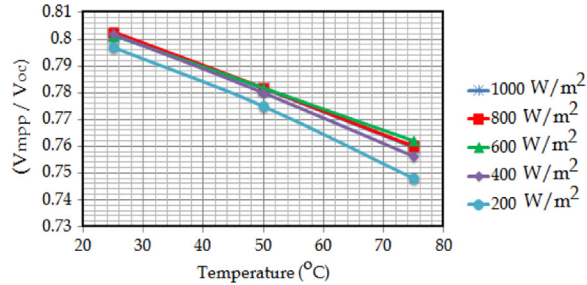


Fig. 6. The ratio of voltage at MPP to the open circuit voltage as functions of irradiance and temperature.

on the fact that the slope of the PV panel's power–voltage characteristics (dP/dV), represented by Eq. (7), is zero at the MPP.

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} = 0 \rightarrow \frac{dI}{dV} = -\frac{I}{V} \text{ at MPP} \quad (7)$$

$$\frac{dP}{dV} > 0 \rightarrow \frac{dI}{dV} > -\frac{I}{V} \text{ left of MPP} \quad (8)$$

$$\frac{dP}{dV} < 0 \rightarrow \frac{dI}{dV} < -\frac{I}{V} \text{ right of MPP} \quad (9)$$

where $(-I/V)$ is the reverse of the instantaneous conductance and (dI/dV) is the incremental conductance of the PV panel. The duty cycle of the converter should be increased or decreased according to Eqs. (8) and (9) for tracking the MPP. Fig. 11 shows the flow chart the IncCond algorithm, where the configuration of the IncCond algorithm in Simulink environment is shown in Fig. 12.

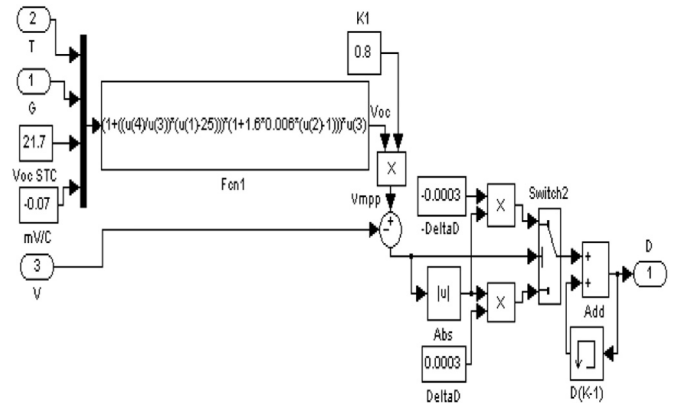


Fig.7. Configuration of the modified FOCV MPPT algorithm in Simulink environment.

4.4. Temperature measurement based algorithm

Temperature measurement based algorithm is based on the fact that the PV output voltage is directly proportional to the temperature on the PV surface. A simple temperature measurement based technique called MPPT-temp is proposed in [17]. In this technique, the current sensor is substituted by a temperature sensor fixed on the PV back surface. The system starts measuring the PV output voltage V_{PV} and temperature T then evaluates the V_{MPP} by Eq. (10) and depending on the difference between the measured value of the PV output voltage V_{PV} and the desired

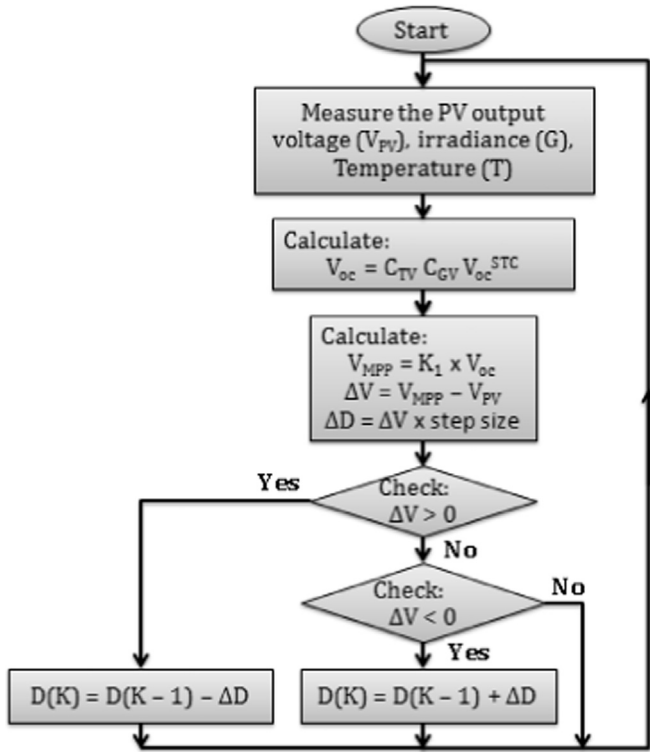


Fig. 8. Flow chart of Modified FOCV MPPT algorithm.

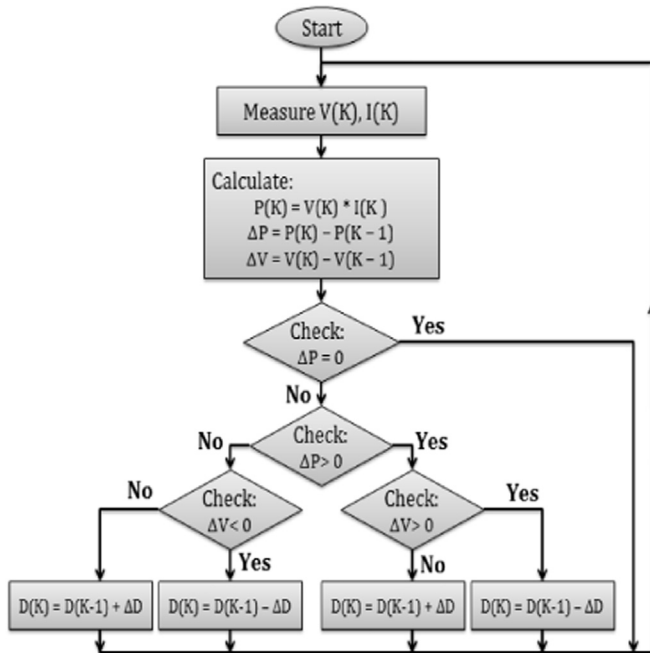


Fig. 9. Flow chart of P&O MPPT algorithm.

maximum power point voltage V_{MPP} , the duty cycle D is updated in order to keep the PV output voltage as close as possible to V_{MPP} .

$$V_{MPP} = V_{MPP}^{STC} + u_v(T - 25) \quad (10)$$

where V_{MPP}^{STC} is the maximum power point voltage at standard test conditions (1000 W/m², 25 °C) and u_v is the temperature coefficient of V_{MPP} (PV panel's datasheet information).

Fig. 13 shows the flow chart the temperature measurement based MPPT algorithm, where the configuration of the temperature

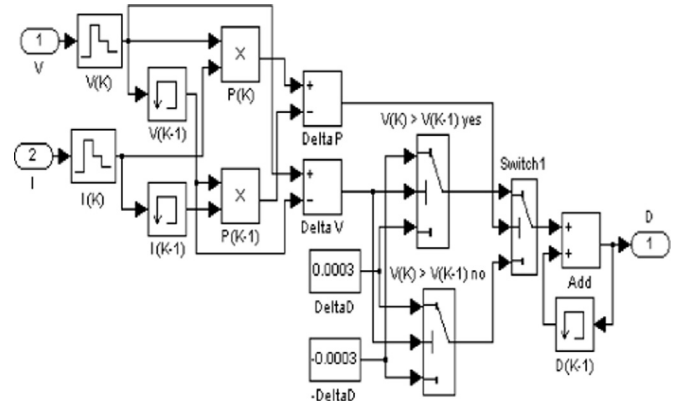


Fig.10. Configuration of the P&O MPPT algorithm in Simulink environment.

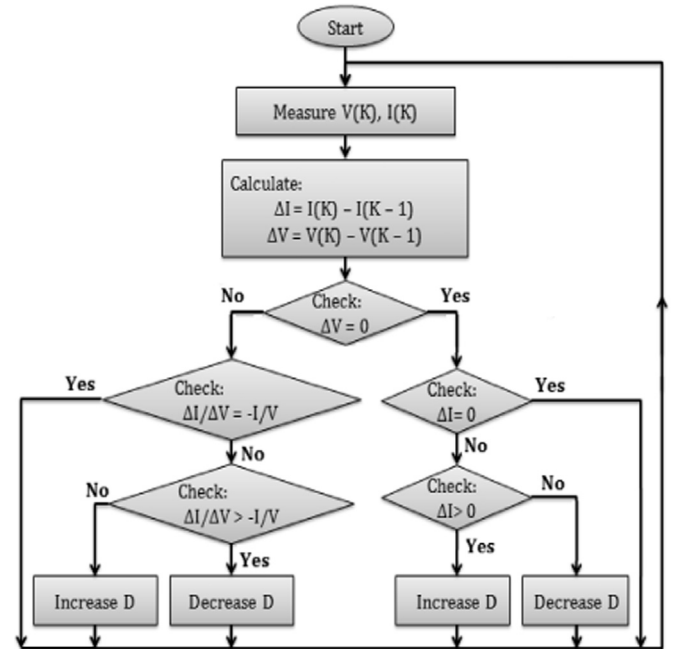


Fig. 11. Flow chart of IncCond MPPT algorithm [14].

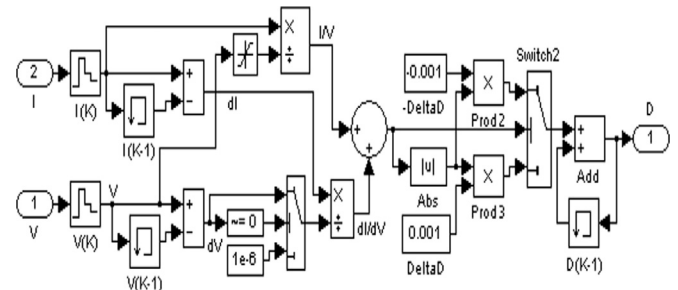


Fig. 12. Configuration of the IncCond MPPT algorithm in Simulink environment.

measurement based MPPT algorithm in Simulink environment is shown in Fig. 14.

4.5. Fuzzy logic control based algorithm

Fuzzy logic control (FLC) consists of three stages: fuzzification, decision-making and defuzzification as depicted in Fig. 15.

In this algorithm, the FLC rules and membership functions are designed taking into account the behavior of the PV panel at different environmental conditions to provide fast and stable

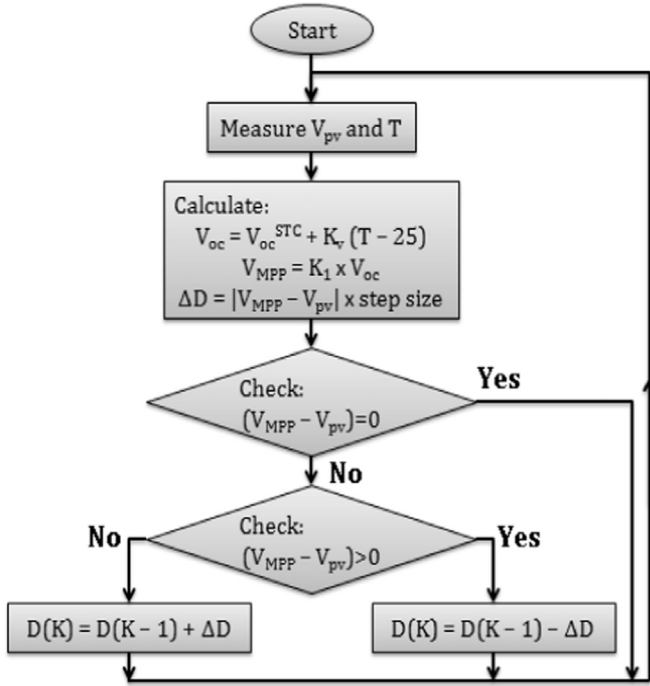


Fig. 13. Flow chart of temperature measurement based MPPT algorithm in Simulink environment.

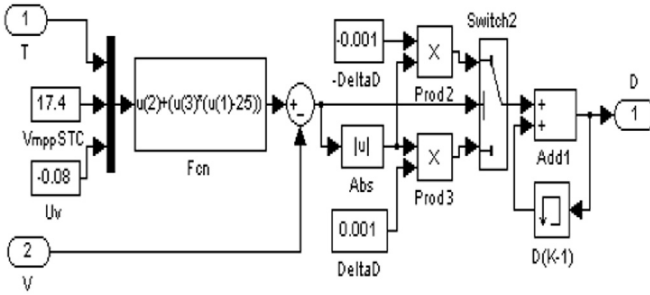


Fig. 14. Configuration of temperature measurement based MPPT algorithm in Simulink environment.

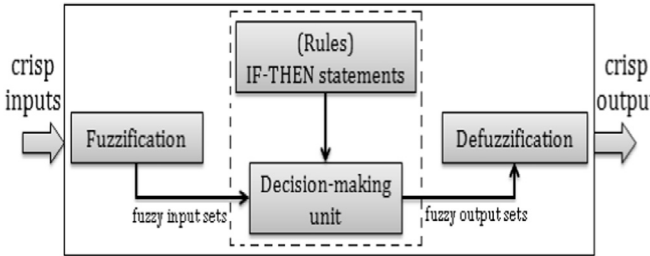


Fig. 15. The basic configuration of fuzzy logic controller.

tracking for MPP of PV system. The inputs of the fuzzy logic controller are chosen to be the change in the PV output power ΔP and the change in the output voltage ΔV which are defined by Eqs. (11) and (12) and the output is the change in the duty cycle of the power converter ΔD as proposed in [16].

$$\Delta P = P(K) - P(K - 1) \quad (11)$$

$$\Delta V = V(K) - V(K - 1) \quad (12)$$

The triangular membership function is used for its simplicity and it can be defined using a minimal amount of information as compared to other membership functions. Seven fuzzy levels are

Table 1
Rule base used in the fuzzy logic controller.

ΔP	ΔV						
	NB	NM	NS	ZE	PS	PM	PB
NB	NS	NM	NS	PS	PS	PM	PS
NM	NM	NS	NM	PS	PM	PS	PM
NS	NB	NB	NS	PS	PS	PB	PB
ZE	PB	PB	PB	PS	NB	NB	NB
PS	PE	PM	PS	NS	NS	NM	NB
PM	PM	PS	PM	NS	NM	NS	NM
PB	PS	PM	PS	NS	NS	NM	NS

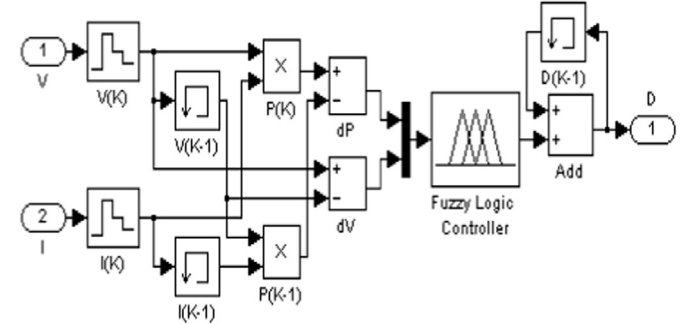


Fig. 16. Configuration of FLC based MPPT algorithm in Simulink environment.

chosen to control each variable: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), PB (positive big).

Once ΔP and ΔV are calculated and converted to linguistic variables, the fuzzy logic controller output ΔD can be looked up in a rule base table such as Table 1 which is proposed for the boost converter used in this work.

These rules are based on the fact that if the change in the voltage causes the power to increase, the moving of the next change is kept in the same direction otherwise the next change is reversed. Fig.16 shows the configuration of the FLC based MPPT algorithm in Simulink environment.

4.6. Proposed ANFIS based algorithm

The proposed ANFIS-based MPPT algorithm uses the irradiance level (G) and the cell temperature (T) of PV module as input parameters and the optimal load resistance (R_{opt}) as output parameter.

The optimal load resistance can be calculated by solving two Eqs. (13) and (14) using the equations solver (solve) in Matlab in order to get the maximum power point voltage and current (V_{mp} , I_{mp}) at different irradiance levels and temperature;

$$I_{mp} = GI_{phg} - I_{og} \left(e^{A_g(V_{mp} + I_{mp}R_{sg})} - 1 \right) - \left(\frac{V_{mp} + I_{mp}R_{sg}}{R_{shg}} \right) \quad (13)$$

$$\frac{I_{mp}}{V_{mp}} = \frac{A_g I_{og} e^{A_g(V_{mp} + I_{mp}R_{sg})} + \frac{1}{R_{shg}}}{1 + A_g R_{sg} I_{og} e^{A_g(V_{mp} + I_{mp}R_{sg})} + \frac{R_{sg}}{R_{shg}}} \quad (14)$$

The ANFIS function (Genfis1) in Matlab toolbox is used to generate Sugeno-type fuzzy inference system which initializes the membership function parameters [28]. The ANFIS function uses actual data of G , T and R_{opt} to learn the ANFIS model by adapting the membership functions parameters and the output parameters of Sugeno output equations by applying a hybrid learning rule algorithm. The least-squares optimization method calculates the consequent parameters in the forward pass. The back-propagation

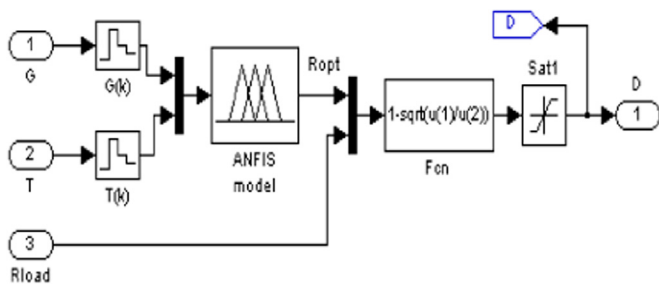


Fig. 17. Configuration of ANFIS based MPPT algorithm in Simulink environment.

gradient descent method uses the error between the training data and predicted output in backward pass to calculate the error in different nodes and update the membership functions parameters [29].

After predicting the optimal resistance of the load using the ANFIS model at specific irradiance level and temperature, the duty cycle D can be calculated as follows:

$$R_{op} = R_{load}(1 - D)^2 \tag{15}$$

The generated ANFIS model is imported to Simulink, as depicted in Fig. 17

5. Simulation results and discussion

In this section, the simulations were performed on a PV system for comparing the MPPT algorithms in terms of their efficiency, dynamic response based on simulations in the Matlab/Simulink software. The comparison results are summarized in a table which can be used as a selection guide.

5.1. Model description

The PV system used in the simulations is shown in Fig. 4. This system consists of SM55 solar module which provides a maximum power of 55 W, a DC–DC boost converter operating at 10 kHz, a filter inductance of 2 mH, a filter capacitor of 1000 μ F and a resistive load of 20 Ω . The input of the power converter is connected to the PV panel, the output is connected to the resistive load and the control signal generated by each MPPT technique fed to a PWM for controlling the boost converter's switching MOSFET. The system was simulated in MATLAB/SIMULINK software environment.

5.2. Simulation results

The following different types of changes in the solar irradiance and temperature are used during the simulation to test the MPPT algorithms at different operating conditions as shown in Fig. 18.

The MPPT algorithms have been simulated and the results have been depicted in Fig. 19. After the transient, it is noted that the PV output power is established on the maximum power point power P_{max} locus according to Table 2.

6. Discussions

In the previous section, the performance of various MPPT algorithms was simulated in SIMULINK[®] under varying environmental conditions. These algorithms vary in complexity, sensors required, convergence speed of tracking the MPP, ease of implementation, efficiency. In this section, the various MPPT is compared according to these specifications.

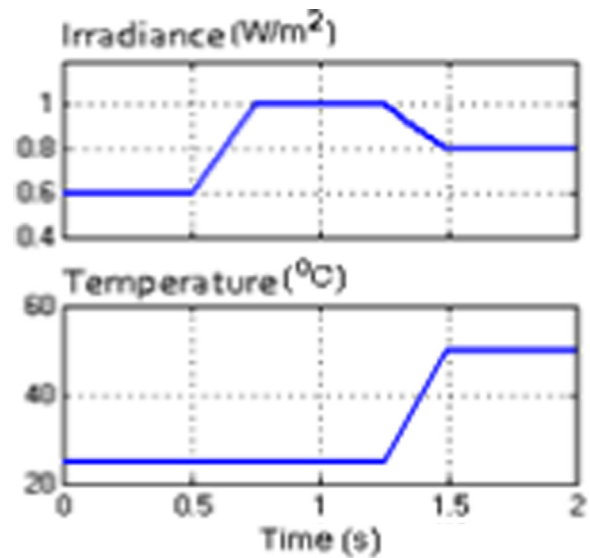


Fig. 18. Solar irradiance and temperature behavior during the simulation.

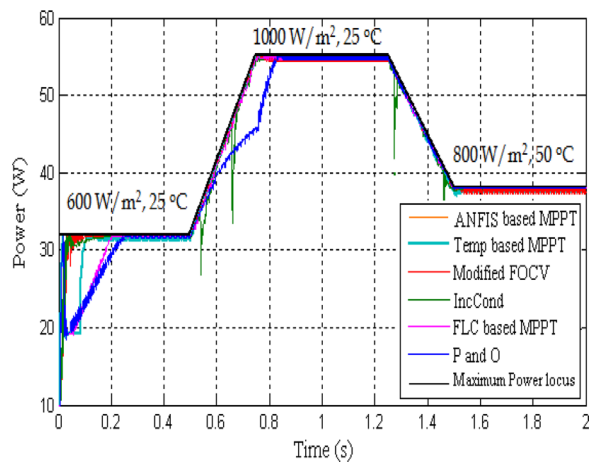


Fig. 19. The PV output power in changes of irradiance and temperature with different MPPT algorithms.

Table 2
The maximum power point parameters at different test conditions.

Test conditions		Parameters		
G (W/m ²)	T (°C)	P_{max} (W)	I_{mp} (A)	V_{mp} (V)
1000	25	54.95	3.158	17.4
600	25	31.79	1.874	16.96
800	50	38.03	2.502	15.20

6.1. Dynamic response

The simulation results indicate that the modified FOCV algorithm, the IncCond algorithm, the FLC based algorithm, the proposed ANFIS-based algorithm as well as the temperature based algorithm are all able to track the MPP for fast changes in the solar irradiance and temperature but the P&O algorithm fails to do that as depicted in Fig. 19.

The accuracy of the modified FOCV algorithm and the temperature based algorithm suffers because their equations are approximated; however, they have excellent convergence speed. Furthermore, the P&O algorithm has the worst tracking speed and it can be improved by increasing the perturbation step size. In

Table 3

The characteristics of the simulated MPPT algorithms.

MPPT Algorithm	Type	PV panel parameters knowledge	Convergence speed	Efficiency (%)	Digital or Analog	Number of sensors
Proposed ANFIS-based MPPT	Artificial Intelligence	Necessary	Very fast	99.4	Digital	3
Modified FOCV	Computational Method	Necessary	Fast	98.46	Both	3
FLC based MPPT	Artificial intelligence	Not necessary	Fast	98.1	Digital	2
IncCond	Hill Climbing method	Not necessary	Medium	97.6	Digital	2
P&O	Hill Climbing method	Not necessary	Low	97.5	Both	2
Temp.-based MPPT	Computational method	Necessary	Fast	96.2	Both	2

terms of the tracking speed consideration, the MPPT algorithm can be ranked as follows:

- (1) the proposed ANFIS-based algorithm,
- (2) the modified FOCV and temperature based algorithms,
- (3) the FLC based algorithm,
- (4) the IncCond algorithm,
- (5) the P&O technique.

6.2. Efficiency

The efficiency of the MPPT technique is a very important consideration for special PV system applications such as the power supply used in space stations and satellites. It can be determined by the following equation [30]:

$$\eta = \frac{1}{m} \sum_{i=0}^m \frac{P_i}{P_{max,i}} \quad (15)$$

where p_i is the PV output power, P_{max} is the maximum power and m is the number of samples.

The simulation results indicate that the proposed ANFIS based algorithm, FLC based algorithm as well as the modified FOCV algorithm has the best efficiency as compared to the other algorithms.

6.3. Implementation

The ease of implementation of the MPPT technique has a large impact on the overall cost of the PV system. Whether the MPPT algorithm is an analog or digital implementation and the sensor requirements are important factors specifying its ease of implementation. The analog implementation is easier and cheaper than the digital one as it does not need microcontroller and

programming. As a result, the P&O algorithm as well as the temperature measurement based algorithm is easier and cheaper than the other algorithms because they are analog implementation and need double sensors.

Different characteristics of the simulated MPPT algorithms determined from the simulations are summarized in Table 3.

7. Conclusion

In this work, the most widely used MPPT algorithms have been modeled and evaluated according to simulations in Matlab/Simulink environment based on the dynamic response of the PV system, the tracking speed of convergence, the efficiency and the ease of implementation.

The results indicate that the modified fractional OC voltage algorithm, the FLC based algorithm and the IncCond algorithm provide an excellent tracking performance independently on the climatic conditions. The temperature measurement based algorithm is characterized by its simplicity of implementation but it has the lowest efficiency because of its bad accuracy. Finally, the performance of the P&O algorithm depends on the perturbation step size.

A novel ANFIS-based MPPT algorithm was proposed and compared with the other algorithms. The deviation from the MPP, as observed with the conventional techniques, did not occur. Moreover, it provides a very fast response under rapidly changing environmental conditions. This made the efficiency of the proposed algorithm to be above 99%.

Finally, this simulation based evaluation can be useful in specifying the appropriateness of the MPPT algorithm for the various PV system applications.

Appendix

Electrical parameters of the SM55 PV module [31].

Maximum power rating, P_{max}	55 W
Rated current IMPP	3.15 A
Rated voltage, V_{MPP}	17.4 V
Short circuit current, I_{SC}	3.45 A
Open circuit voltage, V_{OC}	21.7 V
Temperature coefficient of I_{SC}	1.2 mA/OC
Temperature coefficient of V_{OC}	−0.077 V/ OC

References

- [1] Cuce E, Cuce PM, Bali T. An experimental analysis of illumination intensity and temperature dependency of photovoltaic cell parameters. *Appl Energy* 2013;111:374–82.
- [2] Cuce E, Cuce PM, Wood CJ, Riffat SB. Toward aerogel based thermal super-insulation in buildings: a comprehensive review. *Renew Sustain Energy Rev* 2014;34:273–99.

- [3] Cuce E, Bali T, Sekucoglu SA. Effects of passive cooling on performance of silicon photovoltaic cells. *Int J Low-Carbon Technol* 2011;6(4):299–308.
- [4] Riffat SB, Cuce E. A review on hybrid photovoltaic/thermal collectors and systems. *Int J Low-Carbon Technol* 2011;6(3):212–41.
- [5] Cuce PM, Cuce E. A novel model of photovoltaic modules for parameter estimation and thermodynamic assessment. *Int J Low-Carbon Technol* 2012;7(2):159–65.
- [6] Cuce E, Bali T. Improving performance parameters of silicon solar cells using air cooling. In: *Proceedings of the Fifth International Ege Energy Symposium and Exhibition*. Denizli, Turkey; June 27–30, 2010.
- [7] Cuce E, Bali T. A comparison of energy and power conversion efficiencies of m-Si and p-Si PV cells in Trabzon. In: *Proceedings of the Fifth International Advanced Technologies Symposium*, May 13–15, 2009. Karabuk, Turkey.
- [8] Cuce E, Bali T. Variation of cell parameters of a p-Si PV cell with different solar irradiances and cell temperatures in humid climates. In: *Fourth International Energy, Environment and Environment Symposium*. Sharjah, United Arab Emirates. April 19–23, 2009.
- [9] Masters, Gilbert M. *Renewable and efficient electric power systems*. John Wiley & Sons Ltd; 2004. p. 445–8.
- [10] Tends In Photovoltaic Applications. Report IEA-PVPS; 2010.
- [11] Messenger Roger, Jerry V. *Photovoltaic systems engineering*. 2nd ed. CRC Press; 2003.
- [12] ESRAM T, Chapman PL. Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Trans Energy Convers* 2007;22:439–49.
- [13] Hohm DP, Ropp ME. Comparative study of maximum power point tracking algorithms. *Prog Photovolt: Res Appl* 2003;11:47–62.
- [14] de Brito MAG, Galotto L, Sampaio LP, de Azevedo Melo G, Canesin CA. Evaluation of the Main MPPT techniques for photovoltaic applications. *IEEE Trans Ind Electron* 2013;60(3):1156–67.
- [15] Eltawil Mohamed A, Zhao Zhengming. MPPT techniques for photovoltaic applications. *Renew Sustain Energy Rev* 2013;25:793–813.
- [16] Noman Abdullah M, Addoweesh Khaled E, Mashaly Hussein M. A fuzzy logic control method for MPPT of PV systems. In: *Proceedings of IECON–38th annual conference on IEEE Industrial Electronics Society*; 2012. p. 874–80.
- [17] Coelho Roberto F, Concer Filipe M, Martins Denizar C. A MPPT approach based on temperature measurements applied in PV systems. In: *Proceedings of the 9th IEEE/IAS international conference on industry applications*; 2010.
- [18] Kharb RK, Shimi SL, Chatterji S, Ansari MF. Modeling of solar PV module and maximum power point tracking using ANFIS. *Renew Sustain Energy Rev* 2014;33:602–12.
- [19] Sayal. MPPT techniques for photovoltaic system under uniform insolation and partial shading conditions. In: *Proceedings of 2012 Students Conference on Engineering and Systems (SCES)*; 2012. p. 1–6.
- [20] Zhang C, Zhao D, Wang J, Chen G. A modified MPPT method with variable perturbation step for photovoltaic system. In: *Proceedings of Power Electronics and Motion Control Conference*; 2009. p. 2096–9.
- [21] Piegari L, Rizzo R. Adaptive perturb and observe algorithm for photovoltaic maximum power point tracking. *IET Renew Power Gener* 2010;4(4):317–28.
- [22] Elgendy M, Zahawi B, Atkinson D. Assessment of the incremental conductance maximum power point tracking algorithm. *IEEE Trans. Sustain. Energy* 2013; vol. 4(1):108–17.
- [23] Farhat M, Barambones O, Sbita L. Efficiency optimization of a DSP-based standalone PV system using a stable single input fuzzy logic controller. *Renew Sustain Energy Rev* 2015;49:907–20.
- [24] Bin-Halabi A, Adel Abdennour, Mashaly H. An accurate ANFIS-based MPPT for solar PV system. *Int J Adv Comput Res* 2014;4(2):588–95.
- [25] Reisi Ali Reza, Moradi Mohammad Hassan, Jamasb Shahriar. Classification and comparison of maximum power point tracking techniques for photovoltaic system: a review. *Renew Sustain Energy Rev* 2013;19:433–43.
- [26] Atlam O, Kolhe M. Performance evaluation of directly photovoltaic powered DC PM (direct current permanent magnet) motor-propeller thrust system. *Energy* 2013;57:692–8.
- [27] Farahat MA, Metwally HMB, Mohamed Ahmed Abd-ElFatah. Optimal choice and design of different topologies of DC–DC converter used in PV systems, at different climatic conditions in Egypt. 2012;43:393–402.
- [28] REN21. Renewables 2014 global status report. (http://www.ren21.net/wpcontent/uploads/2015/07/REN12GSR2015_Onlinebook_low1.pdf) [accessed 17.04.15].
- [29] Mellit A, Kalogirou S. ANFIS-based modelling for photovoltaic power supply system: a case study. *Renew Energy* 2011;36:250–5.
- [30] Xiao W, Elnosh A, Khadkikar V, Zeineldin H. Overview of maximum power point tracking technologies for photovoltaic power systems. In: *Proceedings of IECON 2011–37th annual conference on IEEE Industrial Electronics Society*; 2011. p. 3900–5.
- [31] Siemens Solar Industries. Solar Module SM55. Available: (<http://www.solarquest.com/microsolar/suppliers/siemens/sm55.pdf>) [accessed 10.10.14].