Jurnal Kejuruteraan 35(5) 2023: 1069-1083
https://doi.org/10.17576/jkukm-2023-35(5)-08

Design of Fast Intelligence Hybrid Fuzzy Logic and Improved Incremental Conductance Based MPPT Technique

Khaleel Abed Abutaima[a], Ramizi Mohamed[a*] Mahidur R Sarker[b] & Radin Za'im Radin Umar[a]

[a]*Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment,*

Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia

[b]*Institute of IR 4.0, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia*

**Corresponding author: ramizi@ukm.edu.my*

Received 25 November 2022, Received in revised form 6 March 2023
Accepted 6 April 2023, Available online 30 September 2023

ABSTRACT

Presently, there has been a significant growth in the solar PV technology due to various factors such as clean technology, zero carbon emission and low maintenance. However, it becomes significant to extract the power in abundance from solar PV system due to its intermittent nature. To extract the significant power, a suitable maximum power point tracking (MPPT) technique has been presented. The MPPT technique is developed based on the hybrid fuzzy logic (FL) and improved incremental and conductance (IInC) method. The aim of developing hybrid FL-IInC technique for MPPT is to regulate duty cycle so that maximum power point (MPP) is achieved with stable and accurate outcomes during dynamic and steady state conditions. The IInC method was developed by regulating the duty cycle and step-size. of It was observed that proposed hybrid FL-IInC delivers accurate and stable results as compared with IInC method. During the model testing at the irradiance with 1000w/m2, the achieved MPPT efficiency was 99.96% as compared with the IInC with an outcome of 98.47% for the improved technique. Additionally, the settling time for the proposed hybrid FL-IInC was less compared with the IInC method. All the simulations were conducted with the MATLAB Simulink Platform. In future, the hybrid FL-IInC method can be employed with other conditions such as partial shading for better applicability.

Keywords: Maximum power point; fuzzy logic; Incremental and conductance; Photovoltaic module array; Renewable energy; Matlab/simulink

INTRODUCTION

Due to advantages of low carbon emissions, low air pollution, and cheap installation costs, renewable energy technologies are attracting attention from many sectors, including the social, economic, and government sectors (Mohamed et al. 2016). In addition, now a days, the scientific community is conducting a great deal of research especially in the hopes of making significant advancements in the area of solar PV based MPPT technology. The use of solar photovoltaic (PV) energy has been extensively researched over the past decade, but it still faces a number of obstacles due to its intermittent nature and short charging period. Several more studies are being conducted to improve the efficiency, accuracy, and stability of the solar PV system so that the system can convert the energy into useful energy (Najafi et al. 2018). Installing an MPPT mechanism, which improves the PV system's precision, robustness, and efficiency, is also a pressing concern for improving its efficiency in the present (Moutchou & Jbari 2020).

The suggested MPPT model employs a high-efficiency boost DC/DC converter to provide a target voltage. As a result, the PV system's output power varies with changes in solar light and temperature (Abunima et al. 2019). As a result, the output power characteristic of an array becomes nonlinear with respect to time because of changes in weather conditions. Thus, a DC-DC converter and inverter must be connected to the PV cells to stabilize the output system, as the PV cells exhibit nonlinear output behavior. Therefore, it is essential to run the PV system at full power under all possible conditions of radiation and temperature. It is common practise for PV power systems to employ a Maximum Power Point Tracking (MPPT) controller in order to get the maximum possible output from the PV array (M. T. Makhloufi et al. 2016). Nevertheless, the biggest disadvantage of a solar PV system is the poor efficiency of the solar panel with relation to the overall energy conversion. The system's MPPT changes with radiation and temperature according to the nonlinear properties of the PV system. In order to improve efficiency, it is necessary to use MPPT algorithms for tracking maximum current energy from the solar energy system at varying radiations. Various MPPT techniques are available such as perturb and observe (P&O), practical swarm optimization (PSO), incremental conductance (InC), fuzzy logic controller (FLC), neural network (NN), adaptive neuro-fuzzy inference system (ANFIS), genetic algorithm, artificial BEE Colony to track MPPT (Reddy & Natarajan 2018).

Mostly, Perturb and Observe (P&O) method is the widely employed MPPT control system to improve the power efficiency but suffers from challenges linked to output oscillations. Further, the tracking seen with P&O may track MPPT in the incorrect direction due to frequent changes in irradiation patterns. However, the efficiency, as well as power output of the MPPT system, is improved by the InC technique as compared with the P&O method but the efficiency of the system is decreased in the traditional control and instrumentation (InC) technique because of the fluctuation of output power around MPPT. Ahmed and Salam (Ahmed & Salam 2015) developed an enhanced P&O technique for evaluating the efficacy of the MPPT algorithm. In this technique, the steady state oscillations were decreased and acquired greater tracking ability. Even though, the proposed technique gave good findings but variable test condition with regards to the temperature should be addressed for better validation. Alik and Jusoh (Alik & Jusoh 2018) provided an improved P&O technique for tracking MPPT efficiency during partial shade situations. The proposed technique was created using MATLAB Simulink environment where the simulation of the solar module was done under partial shading situations. Belkaid et al. (Belkaid et al. 2016) designed a better I&C technique for adjusting the duty cycle of the implemented converter as well as avoid the divergence under quick changing of luminosity levels. The model was created and tested inside MATLAB/Simulink environment. But the provided technique may be expanded to various converter topologies as well as addressing the shading phenomena for the better validation of the given model. Furthermore, Boukenoui et al. (Boukenoui et al. 2017) offered an experimental examination of many MPPT technologies such as I&C technique for testing the performance in terms of efficiency, harmonics and computation time. Although, the experimental study includes of multiple model tests but missing the evaluation of the models during partial shade situations. In another work, Motahhir et al. (Motahhir, Chalh, et al. 2018) created an InC based MPPT method for obtaining high efficiency with short computing time and low cost. The estimated efficiency for the model was 98% but suffers from complicated programming structure. Simultaneously, Motahhir et al. (Motahhir, El Hammoumi, et al. 2018) suggested an enhanced I&C model for evaluating the MPPT algorithm efficiency under different irradiations data. The model gave good results but missing the data for the validation with temperature profile data. In recent times, Deboucha et al. (Deboucha et al. 2021) presented the particle swarm optimization (PSO) based global MPPT technique for partly shaded PV model. Even though, the tracking time was pretty short, but the provided model applicability still has to be further studied. While, Makhloufi and Mekhilef (S. Makhloufi & Mekhilef 2021) designed a Logarithmic PSO Based MPPT algorithm for partial shading situation of PV system. The results with relation to MPPT efficiency were considerable still, additional study might be conducted using different meta heuristic optimization strategies. In another work, Shams et al. (Shams et al. 2020) created a butterfly optimization strategy using MPPT model under different scenarios such like partial and uniform shading situations accordingly. Although, above that the stated studies proved substantial advantages, yet the complexity still exists with regards to easy execution.

Hence, it is necessary for the creation of a better MPPT method. In this study, an enhanced I&C technique is created to give higher stability in terms of output power fluctuation and less oscillatory characteristics (Anowar & Roy 2019). In this work, our major aims are to obtain decreased response time and improved efficiency in the MPPT stage. The paper proposed hybrid FL-IInC method to achieve the output under single conditions related with temperature and irradiance. Further, the results related with voltage, current and power and efficiency was extracted in MATLAB Simulink environment.

The article contains four sections. Section 1 provides an insight into the description of solar PV system. Section 2 is dedicated mathematical modelling Photovoltaic module, boost converter model, IInC technique and FL controller. Then, the simulation results are presented and discussed in Section 3. Finally, section 4 presents the conclusion.

DESCRIPTION OF SOLAR PV SYSTEM

The solar Photovoltaic system's advantages include clean energy, decreased carbon emissions, low cost, and a long life, but it also has drawbacks including its unpredictable nature and its reduced operating hours relating to maximum daylight hours. (Hanif et al. 2018). Hence, it is important to develop methods for optimising the transformation of solar PV energy to maximise output while also improving efficiency and precision. (Doshi & Vyas 2018). Unlike the battery system, the solar PV system's output power varies due to its intermittent nature and dependence on temperature and irradiance. The PV output is only a maximum of STP condition, i.e., at 25 ° C and 1000W / m2 irradiation. So, PV energy varies during the day depending on the weather and other factors. As the produced energy is dependent on the amount of radiation and the warmth of the sun, Photovoltaic is not a static source of output power like a battery.

The efficiency of photovoltaic (PV) cells reduces as the temperature inside the units rises (Alias & Yaacob 2016). Parallel and series connections of solar cells are used to achieve the required electrical characteristics of current and voltage, respectively. (Suria 2019). Strong light has a linear relationship with the spread of crystalline silicon units. The yield of a solar photovoltaic system can be reduced by 0.5% for every degree of temperature change in the environment. In addition, a difference of 10-30% between the theoretical yield under ideal lighting conditions (STC) and the practical output under actual lighting conditions is to be expected. (Alias & Yaacob 2016). When the cell under shading, reverse current flows through the shunt, creating a hotspot in the local ohmic shunt that is wired to the solar cell and ultimately destroying the module. The greater temperature of the PV modules is equivalent to the reverse current. These phenomena become critical when some cells function under the reverse bias mode, in turn, damage specific cells, therefore disturbing the entire PV system (Aminou Moussavou et al. 2019).

MATHEMATICAL MODELLING OF SOLER PV SYSTEM

SOLAR PV MODULE

The composition of solar cells is essentially a p-n junction constructed from a thin semiconductor plate. The energy from solar radiation can be directly transformed into electricity due to the PV effect (Pandiarajan & Muthu 2011).

For Figure 1, the characteristic current output voltage of solar PV cell is provided by the expressions 1. Further, in equation (1) the current generated by the ideal current source due to solar radiation. The PV panel can be modelled as given in expression (1)-(8).

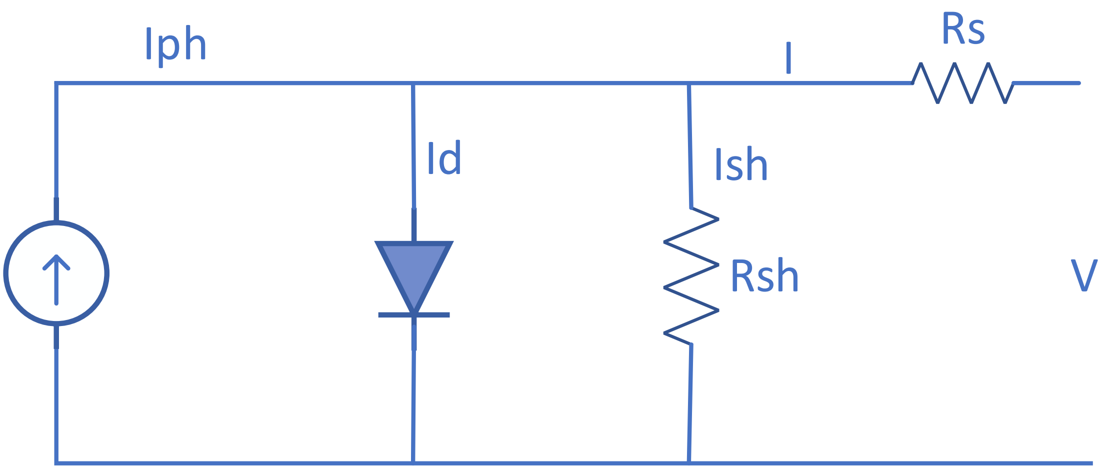


FIGURE 1. Circuit Diagram of PV Array in Simulink

In this model, the photovoltaic current , diode current the output and short circuit current can be expressed as follows:

$$I_{Ph} = [\, I_{sc} + K_i(\mathrm{T} - 298)] \left(\frac{G}{1000}\right) \qquad (1)$$

$$I_d = I_{scr} \left[\exp\left(\left(\frac{q}{aKT}\right)\right)(V + IR_s)\right) - 1] \qquad (2)$$

$$I_{sh} = \left(\frac{V+IR_s}{R_{sh}}\right) \qquad (3)$$

Where, $V = k\,\frac{T_c}{q}$

The total current I can be expressed as

$$\mathrm{I} = I_{Ph} - I_d - I_{sh} \quad (4)$$

$$I = [\, I_{sc} + K_i(\mathrm{T} - 298)]\left(\frac{G}{100}\right) - I_o\left[\exp\left(\left(\frac{q}{aKT}\right)\right)(V + IR_s)\right) - 1] - \left(\frac{V+IR_s}{R_{sh}}\right) \quad (5)$$

The module saturation current is given as

$$I_o = I_{rs} * [\frac{T}{Tr}]^3 * \exp\left[\left(\frac{q*E_{go}}{a*k}\right)\left(\frac{1}{Tr} - \frac{1}{T}\right)\right] \quad (6)$$

The expression for is given as

$$I_{rs} = {I_{scn}}\Big/\left(exp\,\frac{V_{ocn}}{aN_sV_{tn}} - 1\right) \quad (7)$$

where, *v* represents the output voltage of the PV cell (V), constitute short-circuit current of the PV cell (A) at ambient temperature, expresses saturation current at reference condition (*A*), refers to short-circuit temperature coefficient, represents the reference temperature (*K*), *G* denotes solar irradiance(W/m2), refers to saturation current at reference temperature (*A*), *q* is the electron charge (1.6e-19), *K* is the Boltzmann constant (1.38e-23), a is the diode Idealist factor, *T* is the temperature (*k*), is the series resistance of the PV cell (Ω), and is the parallel resistance of the PV cell (Ω), is the open circuit voltage (Yatimi & Aroudam 2018). The equivalent model of the PV unit is expressed by equations (3) where represents series solar cells per unit, and *N* denotes parallel solar cells per unit.

$$\mathrm{I} = N_pI_{ph} - N_pI_o * I_s\left(exp\,\frac{(V+IR_s * N_{sp}/N_{ps})}{aN_sV_t} - 1\right) - \frac{(V+IR_s * N_{sp}/N_{ps})}{R_p * {N_{sp}}/{N_{ps}}} \quad (8)$$

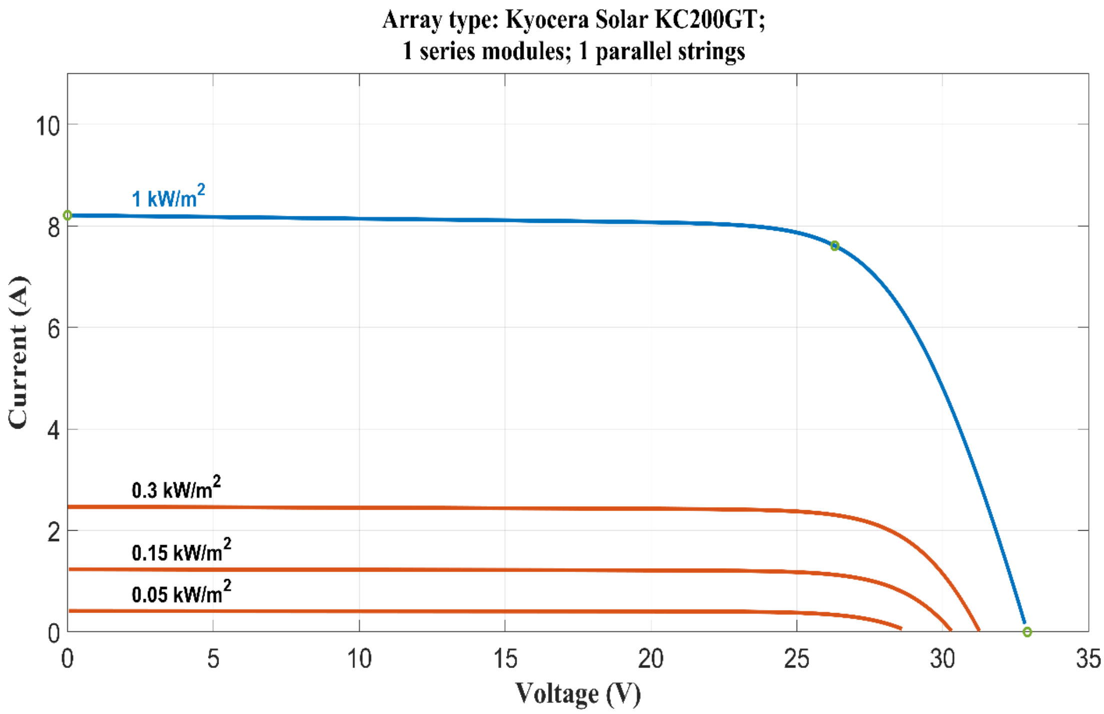
The PV cell array simulation in MATLAB /Simulink will be modelled according to the parameters in Table 1.

By using the PV cell array simulation data in MATLAB/Simulink, the characteristics for various curve such as I-V, P-V for constant irradiation i.e., G=1000W/m^2 at different temperatures can been presented in Figure 2. (a) and (b) It is observed that when the value of irradiation is varied from 50W/m^2 to 1000W/m^2, the open circuit voltage i.e., V_{oc} is increased but with the same conditions, the linear increase in the short circuit current i.e., I_{sc} is observed. Additionally, the power output of the selected PV module is increased due to the increase in the product of V_{oc} and I_{sc}.

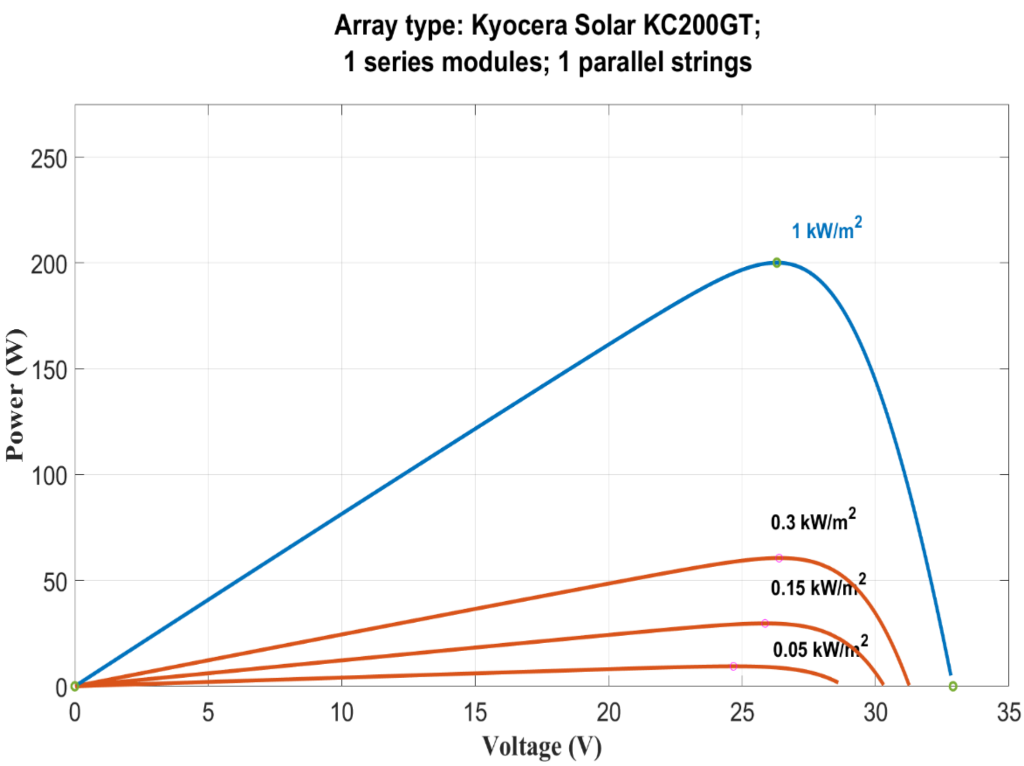
Moreover, when the temperature is varied from 0ºC to 65 ºC, it is observed that the component of I_{sc} is marginally increased but results in the decrease in the V_{oc} in a linear manner as displayed in the figure 3. (a) and (b) Therefore, the obtained output power from the selected PV module is lower with higher temperature as compared to operate the PV module with a low value of temperature.

TABLE 1. The parameter of PV array cells simulation

Parameter	Value
maximum power (Pmax)	200.143W
maximum Voltage (Vmax)	26.3V
maximum Current (Imax)	7.61A
open circuit Voltage (VOC)	32.9V
short circuit Current (ISC)	8.21A
irradiation (G)	50-1000W/m2
temperature (T)	25 C

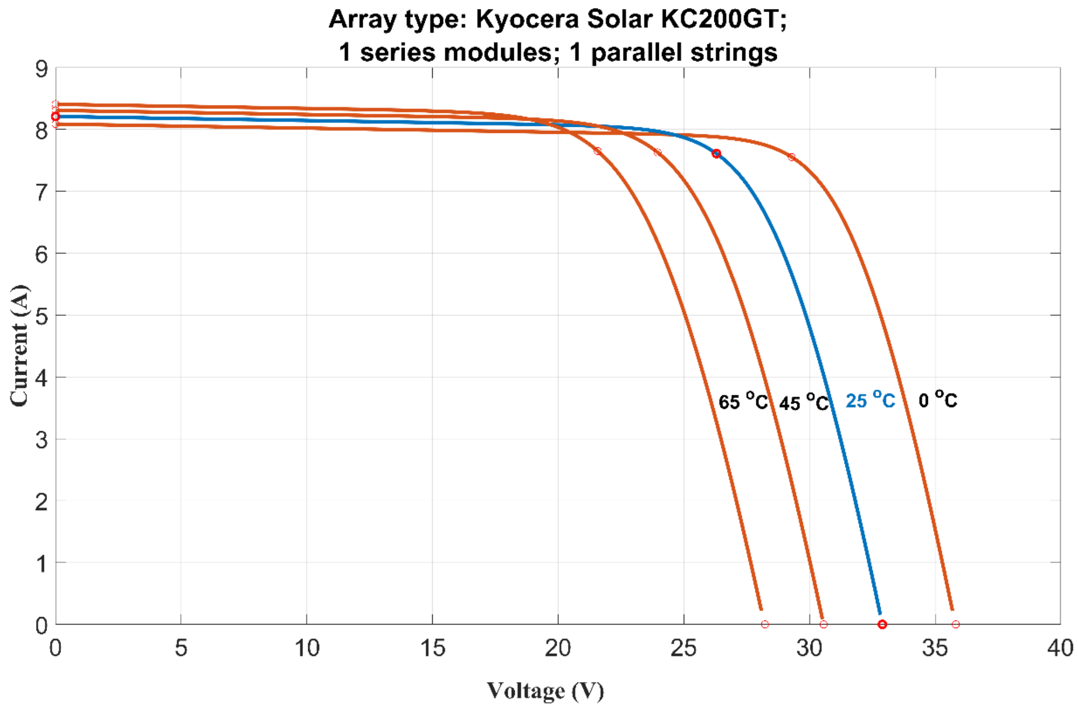


(a)

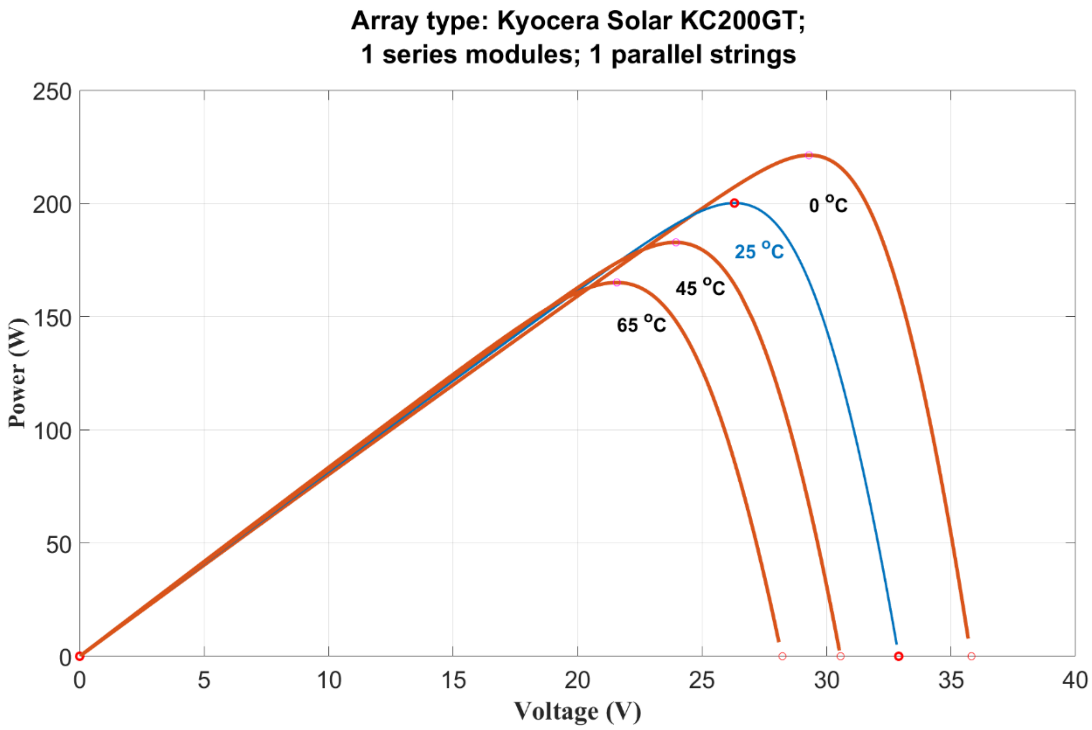


(b)

FIGURE 2. Output curve for (a) I-V characteristics (b) P-V Characteristic of PV cell at varying irradiance



(a)



(b)

FIGURE 3. Output curve for (a) I-V characteristics (b) P-V Characteristic of PV cell at varying temperature

BOOST CONVERTER MODEL

The generation of high DC voltage output from low DC voltage input is performed with a boost converter circuit as shown in Figure 4. The energy is stored with a circuit consisting of L-C with necessary diode circuitry and additional switch while keep the magnitude of output current lower to input current (Kumar et al. 2016).

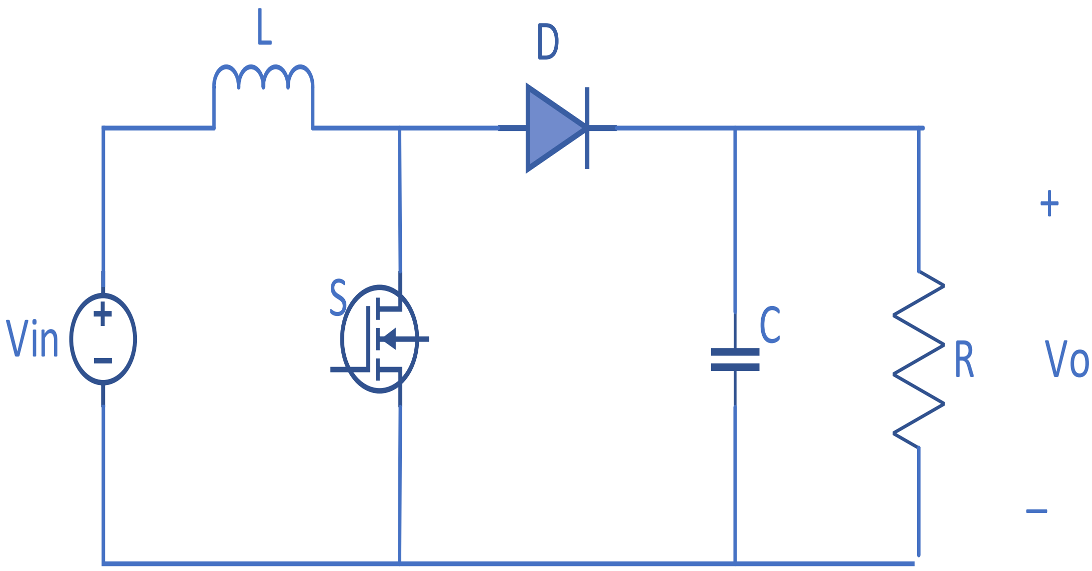


FIGURE 4. Circuit of boost converter

The expression for the obtained output voltage is expressed by the following expression as presented in Eq.9.

$$P_{max} = U * I \tag{9}$$

Where, *D* is the duty cycle and is input voltage, respectively.

IMPROVED INCREMENTAL AND CONDUCTANCE BASED MPPT TECHNIQUE

P-V characteristic of photovoltaic cell is a single peak curve under constant illumination intensity. The InC method achieves MPPT by comparing with instantaneous conductance of PV cells. According to the characteristic curve of the PV array in Figure 2 and Figure 3(Qin & Che 2019). The presented expression illustrates the methodology for the InC algorithm for MPPT based solar tracking system. Further, the slope obtained for MPPT is zero for presented Figures 2 and Figure 3 (Xuesong et al. 2010).

$$P_{max} = U * I \tag{10}$$

$$\frac{dP}{dU} = 1 + U * \frac{dI}{dU} = 0 \tag{11}$$

$$\frac{dI}{dU} = -\frac{I}{U} \tag{12}$$

The improved incremental and conductance (IInC) MPPT technique for solar PV model successfully utilize the variable ΔD for tracking the MPP to obtain high performance and efficiency at various environmental conditions such as temperature and irradiation. The ΔD refers to the duty cycle step which is used to control the variable step voltage. Further, an error is defined for minimizing the oscillations occurring around the MPP which detects when the system obtains the MPP. Additionally, due to the inclusion of the tracking mechanism, the tracking speed for improved incremental and conductance (IInC) method is faster with regards to the conventional INC technique. Moreover, the power losses is minimized at various temperature in the (IInC) MPPT algorithm. The flowchart for the improved incremental and conductance (IInC) algo-.rithm has been presented in figure 5

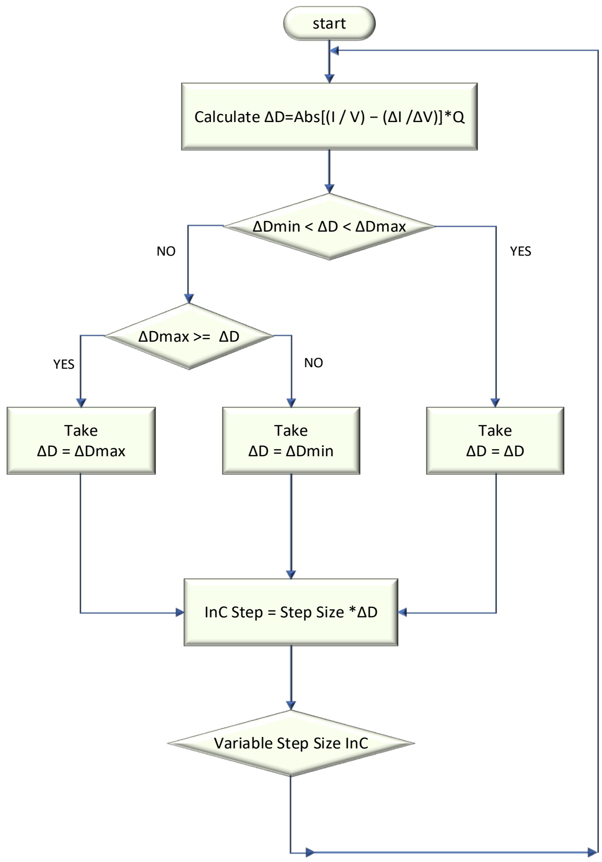


FIGURE 5. Flowchart of the improved Incremental Conductance Algorithm Technique based MPPT method.

FUZZY LOGIC CONTROLLER

The basic structure of fuzzy controller is shown in Figure 6, where crisp inputs are converted to fuzzy inputs according to their membership functions and degree of membership (the fuzzification process). Based on the degrees of the membership function and the rule base, the inference engine generate the fuzzy output using the implication and the aggregation methods(Ali et al. 2021).

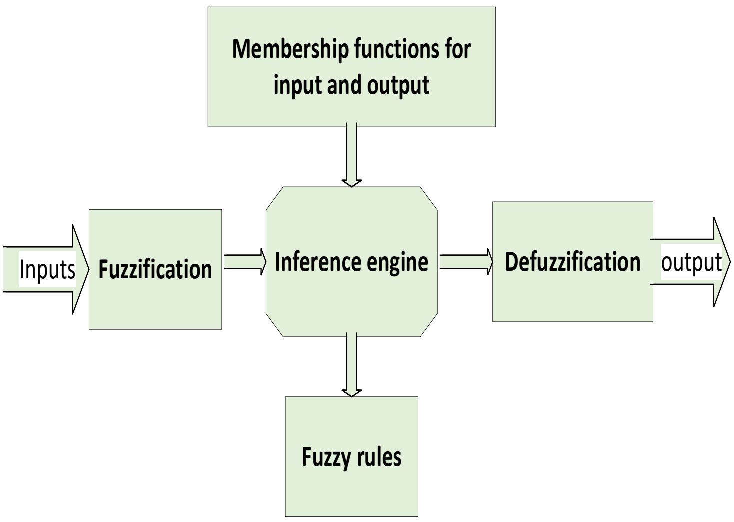


FIGURE 6. The basic structure of fuzzy Logic based controller (Ali et al. 2021)

The fuzzy output is converted to converter, the variable voltage step is controlled through a variable duty cycle step (ΔD), which is considered as the fuzzy output. So, referring to the proposed flowchart of the hybrid FL-IInC based MPPT method in Figure 8, the voltage step () is variable and is controlled through (ΔD) based on fuzzy inputs and the proposed intuitive decision rule base. The proposed algorithm employs FLC for varying the step size of voltage increment or decrement of the InC MPPT method. The inputs and the output of FLC include only three fuzzy subsets: Small(S), Medium (M), and Large (L). Hence, there are nine rules for our fuzzy controller. These rules are based on the minimization of the P-V curve absolute slope.

We use Mamdani's method with Max-Min for fuzzy combination. The rules of fuzzy control based on the below principles:

1. When the operating point is far from the MPP, the change of duty cycle must be large in order to reach the MPP quickly (which means the Step must be large).

2. When the operating point is near the MPP, a small change of duty cycle is required (which means the Step must be small).

3. When the operating point is reached and steady at MPP, no change in duty cycle, the step must be steady and very small.

Depending on these criteria, the fuzzy controller contains nine rules that are detailed below:

1. If A_P is L and A_{P1} is L $\Delta D_{stepsize}$ than is L.

2. If A_P is L and A_{P1} is M than $\Delta D_{stepsize}$ is L.

3. If A_P is L and A_{P1} is S than $\Delta D_{stepsize}$ is M.

4. If A_P is M and A_{P1} is L than $\Delta D_{stepsize}$ is L.

5. If A_P is M and A_{P1} is M than $\Delta D_{stepsize}$ is M.

6. If A_P is M and A_{P1} is S than $\Delta D_{stepsize}$ is S.

7. If A_P is S and A_{P1} is L than $\Delta D_{stepsize}$ is S.

8. If A_P is S and A_{P1} is M than $\Delta D_{stepsize}$ is S.

9. If A_P is S and A_{P1} is S than $\Delta D_{stepsize}$ is S.

The partition of fuzzy subsets and the shape of the membership function in both of the inputs and the output that are shown in Figure 7.

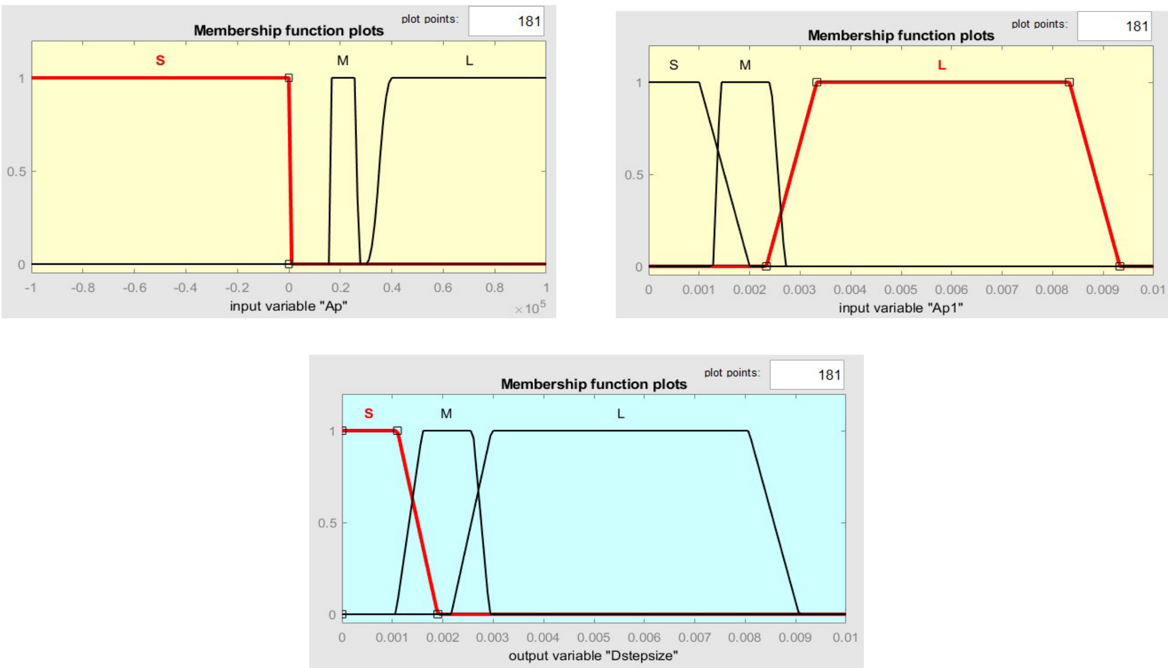


FIGURE 7. The membership functions of inputs and A_P and A_{P1} output $\Delta D_{stepsize}$ of FLC

The defuzzification is the last step in fuzzy controller, which interprets the membership degrees of the fuzzy sets into the crisp real value outputs or specific decision.

DISCUSSION OF SIMULATION RESULTS

Figure 9 shows results based on improved Incremental Conductance technique which then later improved with improved hybrid FL-IInC algorithms as shown in Figure 10. Both are implemented using the PV system in order to acquire for the maximum power. The performance of MPPT algorithms is analyzed at irradiation and temperature in different conditions. The PV models and the proposed method employed in which the system is developed in MATLAB/Simulink environment. The platform utilizes an inbuilt solar PV array in connection with a DC-DC .boost converter, and PWM generator

The main specifications for the boost converter include = 10μF, = 3500μF, L = 8mH, and switching frequency = 25 kHz. The load resistance was set at 10 Ω the results output of the simulation is presented in Figures 12.

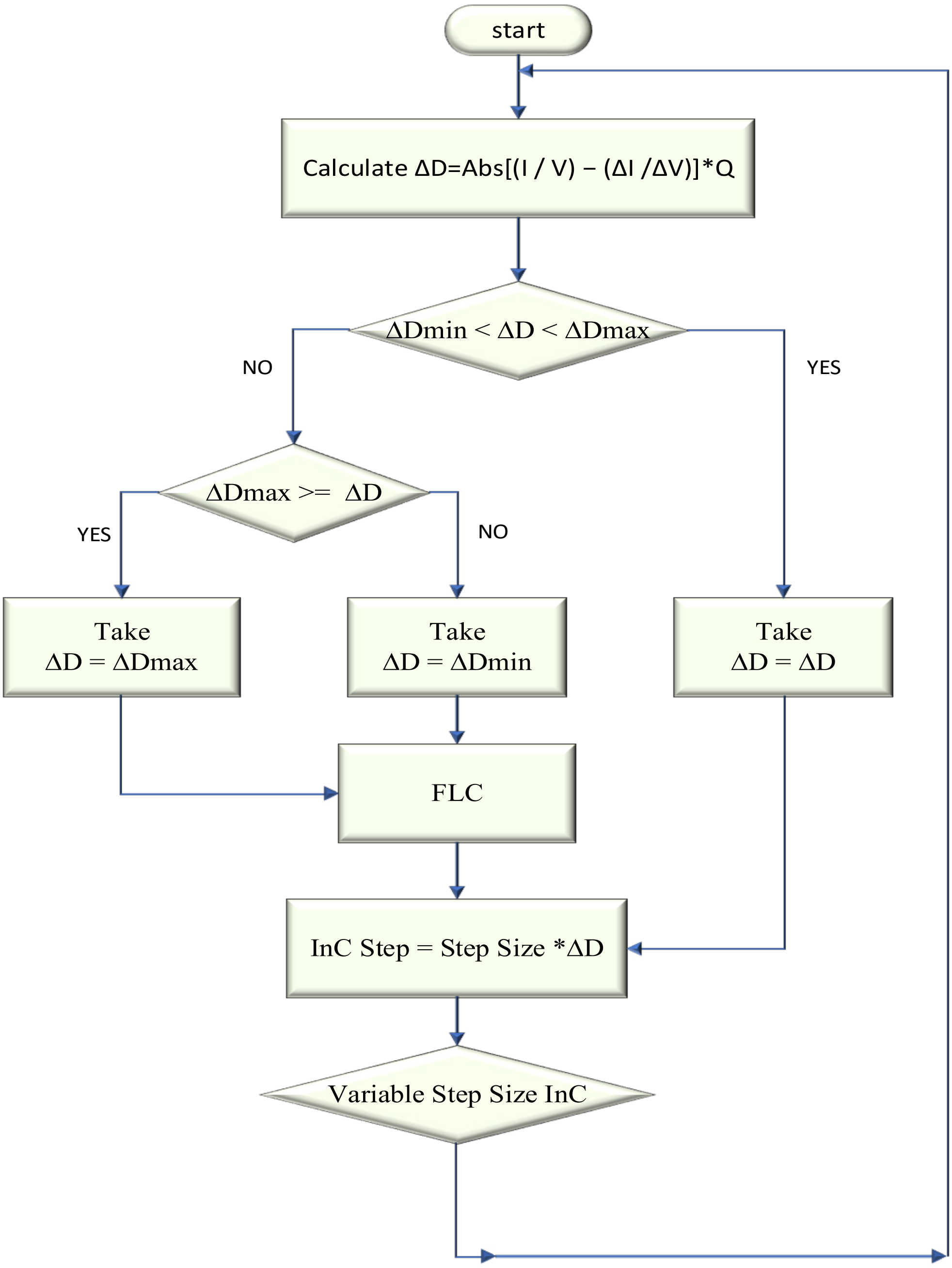


FIGURE 8. Flowchart of the hybrid FL-IInC based MPPT method.

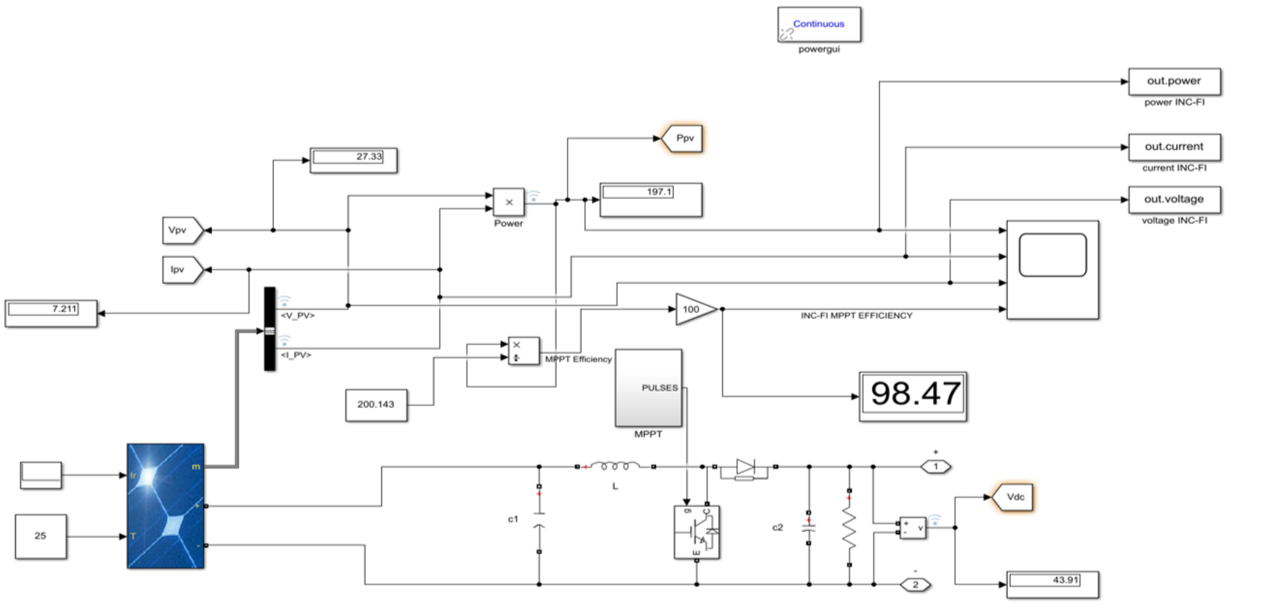


FIGURE 9. Simulation model of PV array in Simulink with improved Incremental Conductance Algorithm Technique

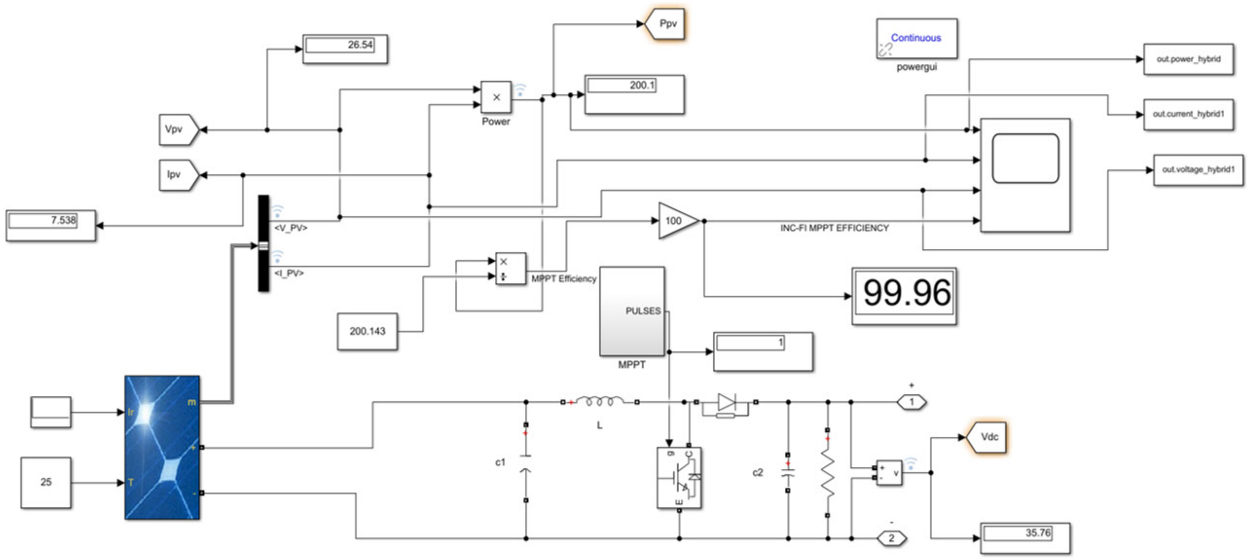


Figure 10. Simulation model of PV array in Simulink with the hybrid FL-IInC MPPT method

In Figure 11, *u* and *I* refer to the voltage and current sampling value; *u0* and *i0* denote the voltage and current sampling value in the preceding cycle; *D* refers to the initial duty ratio of the boost converter.

The simulation results for the proposed hybrid FL-IInC technique and IInC method has been presented in figure 11. The outcomes for both the technique have been compared under variable irradiance condition and constant solar temperature at $1000W/m^2$. It is seen that improved hybrid FL-IInC technique delivers more accurate results and limits the power losses within the desired range at constant temperature. Further, the improved hybrid FL-IInC method deliver better tracking capability for MPP during simulation.

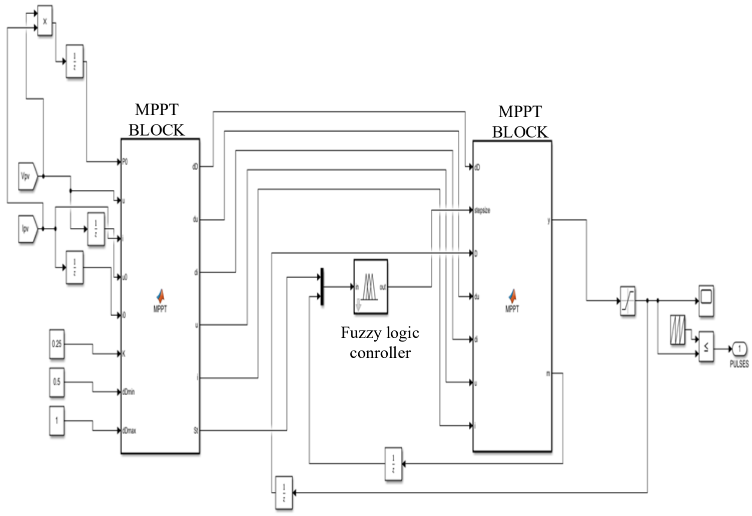
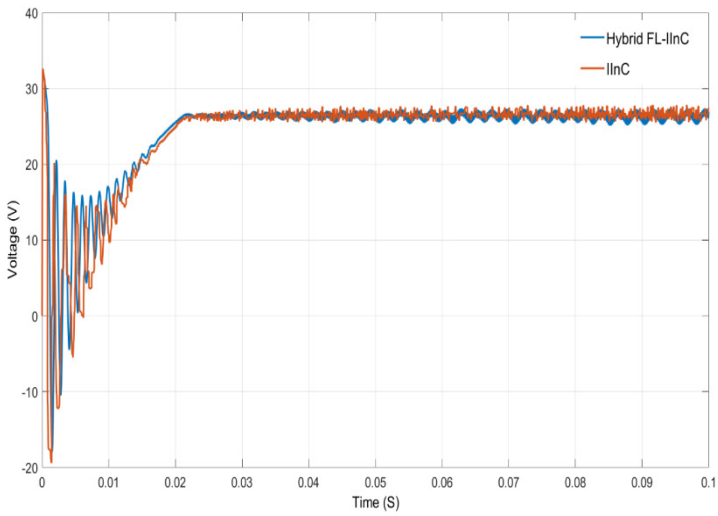
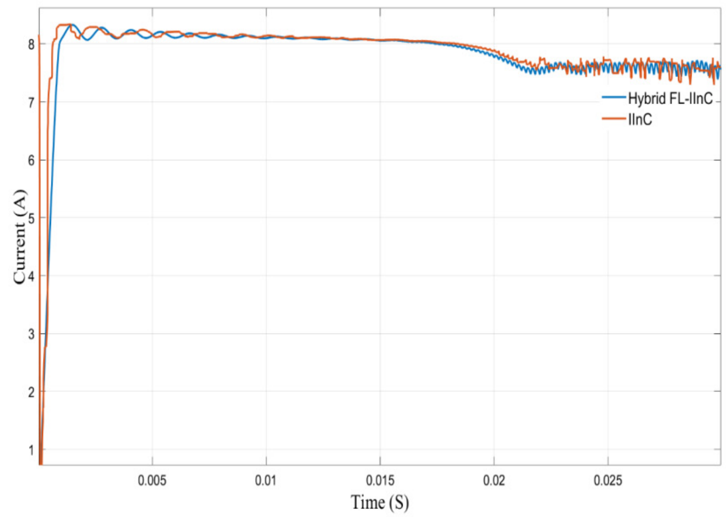


FIGURE 11. Block module chart of MPPT in hybrid FL-IInC based on the MPPT method

The power loss can be minimized significantly by utilizing the proposed method during variable irradiance conditions. On the other hand, it is observed that better stability at steady state for various outcomes of PV array such as power, current, voltage and efficiency has been achieved by hybrid FL-IInC technique. Nevertheless, the stability as well as transient state condition for the IInC model was not appropriate. With regards to the power efficiency of the PV array, the improved hybrid FL-IInC technique depicts better outcomes for tracking efficiency under variable irradiance condition and solar temperature as shown in figure 11. It is observed that the MPPT efficiency of the IInC method was 98.47 as compared to 99.96 for the proposed hybrid FL-IInC technique. The fast tracking was achieved with the proposed method with a time of 0.02 s (approx) compared to the IInC method i.e 0.02 s (approx). The proposed InC-FI method forecasted better accuracy to estimate the MPPT efficiency. The decrease in the power efficiency for the IInC method was due to the inability to track the power at variable irradiance whereas, the drawback was minimized in the proposed method which displayed better outcomes. Also, high fluctuation were comman during the operation for the IInC method which were reduced with the proposed technique. The tracking speed for the proposed method was significantly increased as the steady state condition in the simulation results was achieved in less time as compared to the IInC method.





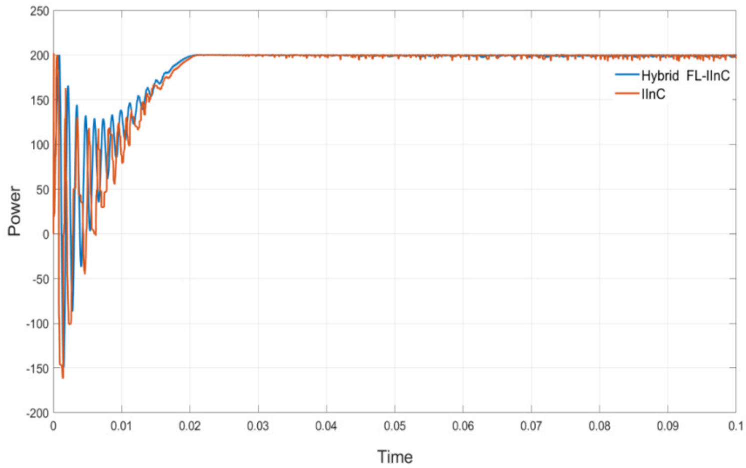


FIGURE 12. Simulation result comparison between the improved IInC and hybrid FL-IInC method under the scenario of temperature variation with constant solar irradiance 1000 W/m2

TABLE 2. Comparitive analysis for various MPPT tecnhiques based on critical factors

Method	Tracking time	Efficiency (%)	Tracking accuracy	Transient oscillations	sensor	Reference
Proposed algorithm	10s	99.96	high	high	Voltage, current	---
Modified GA and FA	30 s	95	high	---	Voltage, current	(Y.-P. Huang et al. 2018)
Spline Model Guided	20 s	98.5	high	high	Voltage, current	(C. Huang et al. 2019)
FFA With SPP MPPT	15 s	80	low	high	Voltage, current	(Y.-P. Huang et al. 2020)
Global/Local MPPT	20 s	99	high	high	Voltage, current	(S. Makhloufi & Mekhilef 2021)

A comparison analysis for various MPPT technologies has been analyzed as depicted in table 2. It is observed that different technology possesses different strength and weaknesses. However, the proposed hybrid FL-IInC MPPT technology displayed better performance regarding high performance and fast-tracking application.

CONCLUSION

This paper has presented a hybrid FL-IInC based MPPT technique to achieve the MPP at constant irradiance and temperature. The proposed hybrid FL-IInC technique delivers accurate and stable outcomes based on the MPP. Additionally, the outcomes of the hybrid FL-IInC technique is compared with improved IInC method which depicts the superiority of the proposed model. The achieved MPPT for the hybrid FL-IInC method was 99.96% as compared with 98.47% for the improved IInC method. Additionally, the stability of various parameters regarding harmonics content was lower with the proposed hybrid FL-IInC method compared with the improved IInC method. In future, the proposed MPPT technique can be upgraded by employing various meta-heuristic optimization techniques and extensive research can be conducted based on the partial shading conditions.

ACKNOWLEDGEMENT

This work was supported by the Universiti Kebangsaan Malaysia.

DECLARATION OF COMPETING INTEREST

None

REFERENCES

Abunima, H., Teh, J. & Jumma, H. 2019. Reactive-active power control for grid-connected PV arrays to enlarge the hosting capacity in a low voltage distribution system. *Jurnal Kejuruteraan* 31(1): 107–114.

Ahmed, J. & Salam, Z. 2015. An improved perturb and observe (P&O) maximum power point tracking (MPPT) algorithm for higher efficiency. *Applied Energy* 150: 97–108.

Ali, M. N., Mahmoud, K., Lehtonen, M. & Darwish, M. M. F. 2021. An efficient fuzzy-logic based variable-step incremental conductance MPPT method for grid-connected PV systems. *Ieee Access* 9: 26420–26430.

Alias, N. N. & Yaacob, K. A. 2016. Natural dye sensitizer in dye sensitized solar cell. *Sains Malaysiana* 45(8): 1227–1234.

Alik, R. & Jusoh, A. 2018. An enhanced P&O checking algorithm MPPT for high tracking efficiency of partially shaded PV module. *Solar Energy* 163: 570–580.

Aminou Moussavou, A. A., Raji, A. & Adonis, M. 2019. Impact study of partial shading phenomenon on solar pv module performance. *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE* 2018-Augus: 1–7.

Anowar, M. H. & Roy, P. 2019. A modified incremental conductance based photovoltaic MPPT charge controller. *2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*, hlm. 1–5. IEEE.

Belkaid, A., Colak, I. & Isik, O. 2016. Photovoltaic maximum power point tracking under fast varying of solar radiation. *Applied energy* 179: 523–530.

Boukenoui, R., Ghanes, M., Barbot, J.-P., Bradai, R., Mellit, A. & Salhi, H. 2017. Experimental assessment of Maximum Power Point Tracking methods for photovoltaic systems. *Energy* 132: 324–340.

Deboucha, H., Shams, I., Belaid, S. L. & Mekhilef, S. 2021. A fast GMPPT scheme based on collaborative swarm algorithm for partially shaded photovoltaic system. *IEEE Journal of Emerging and Selected Topics in Power Electronics* 9(5): 5571–5580.

Doshi, J. P. & Vyas, B. Y. 2018. Islanding Phenomena In Microgrid based on PV Generation. *2018 International Conference on Current Trends towards Converging Technologies (ICCTCT)*, hlm. 1–4. IEEE.

Hanif, M., Khattak, M. K., Khan, M., Ramzan, M. & Abdurab. 2018. Energy, exergy and efficiency analysis of a flat plate solar collector used as air heater. *Sains Malaysiana* 47(5): 1061–1067.

Huang, C., Wang, L., Zhang, Z., Yeung, R. S., Bensoussan, A. & Chung, H. S. 2019. A novel spline model guided maximum power point tracking method for photovoltaic systems. *IEEE Transactions on Sustainable Energy* 11(3): 1309–1322.

Huang, Y.-P., Chen, X. & Ye, C.-E. 2018. A hybrid maximum power point tracking approach for photovoltaic systems under partial shading conditions using a modified genetic algorithm and the firefly algorithm. *International Journal of Photoenergy* 2018.

Huang, Y.-P., Huang, M.-Y. & Ye, C.-E. 2020. A fusion firefly algorithm with simplified propagation for photovoltaic MPPT under partial shading conditions. *IEEE Transactions on Sustainable Energy* 11(4): 2641–2652.

Kumar, M., Kachhwaya, M. & Kumar, B. 2016. Development of MATLAB/Simulink based model of PV System with MPPT. *2016 7th India International Conference on Power Electronics (IICPE)*, hlm. 1–4. IEEE.

Makhloufi, M. T., Abdessemed, Y. & Khireddine, M. S. 2016. An Efficient ANN-Based MPPT Optimal Controller of a DC/DC Boost Converter for Photovoltaic Systems. *Automatika* 57(1): 109–119. doi:10.7305/automatika.2016.07.798

Makhloufi, S. & Mekhilef, S. 2021. Logarithmic PSO Based Global/Local Maximum Power Point Tracker for Partially Shaded Photovoltaic Systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics*.

Mohamed, R., Yusop, A. M., Mohamed, A. & Nordin, N. I. 2016. Behavioral Analysis of Thermoelectric Module under Different Configurations and Temperature Gradient. *Jurnal Kejuruteraan* 28: 19–27.

Motahhir, S., Chalh, A., El Ghzizal, A. & Derouich, A. 2018. Development of a low-cost PV system using an improved INC algorithm and a PV panel Proteus model. *Journal of Cleaner production* 204: 355–365.

Motahhir, S., El Hammoumi, A. & El Ghzizal, A. 2018. Photovoltaic system with quantitative comparative between an improved MPPT and existing INC and P&O methods under fast varying of solar irradiation. *Energy Reports* 4: 341–350.

Moutchou, M. & Jbari, A. 2020. Fast photovoltaic IncCond-MPPT and backstepping control, using DC-DC boost converter. *International Journal of Electrical and Computer Engineering* 10(1): 1101.

Najafi, E., Faizi, M. & Khanmohammadi, M. A. 2018. a review of energy efficient systems integrated into building envelopes. *Journal of Building Performance ISSN* 9(1): 2018.

Pandiarajan, N. & Muthu, R. 2011. Mathematical modeling of photovoltaic module with Simulink. *2011 1st International Conference on Electrical Energy Systems*, hlm. 258–263. IEEE.

Qin, G. & Che, X. 2019. An Incremental Conductance Method Based on Fuzzy Control. *2019 IEEE 8th Data Driven Control and Learning Systems Conference (DDCLS)*, hlm. 477–482. IEEE.

Reddy, J. & Natarajan, S. 2018. Control and analysis of MPPT techniques for standalone PV System with high voltage gain interleaved boost converter. *Gazi University Journal of Science* 31(2): 515–530.

Shams, I., Mekhilef, S. & Tey, K. S. 2020. Maximum power point tracking using modified butterfly optimization algorithm for partial shading, uniform shading, and fast varying load conditions. *IEEE transactions on Power Electronics* 36(5): 5569–5581.

Suria, P. K. S. 2019. Inexpensive Current-Voltage System with Electronically-Controlled Resistance under Xenon Arc Light for Solar Cell Efficiency Measurements. *Jurnal Kejuruteraan* 31(2): 335–340.

Xuesong, Z., Daichun, S., Youjie, M. & Deshu, C. 2010. The simulation and design for MPPT of PV system based on incremental conductance method. *2010 WASE international conference on information engineering*, hlm. Vol. 2, 314–317. IEEE.

Yatimi, H. & Aroudam, E. 2018. MPPT algorithms based modeling and control for photovoltaic system under variable climatic conditions. *Procedia Manufacturing* 22: 757–764.