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Comparison between Fuzzy-logic MPPT and the Exciting Incremental Conductance Method under Fast Varying of Irradiance

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Abstract: In this research, a comparison between fuzzy logic (FL) and incremental conductance (INC) for photovoltaic module maximum power point tracking (MPPT) is presented. The mathematical analysis of the photovoltaic (PV) for the single-diode circuit and the DC/DC boost converter is conducted. The proposed PV system is simulated using MATLAB/Simulink software to test the performance of the proposed FL-MPPT technique under different irradiance levels. Moreover, the fast change profile for irradiance is applied to both techniques to show the dynamic response of the PV module for each technique. This paper aims to track the optimum power of the PV module under fast varying irradiance using FL and traditional INC methods. Simulation results have shown that the proposed FL technique's main novelty is achieved by presenting good agreement for the MPPT by achieving the peak power with a shorter time and lower ripple resolution than the INC technique. The simulation results also show that the PV module has the best performance and higher efficiency when operated with the FL-MPPT technique.

Keywords: maximum power point tracking, incremental conductance, fast varying irradiance, boost converter, fuzzy logic.

輻照度快速變化下的模糊邏輯最大功率點跟踪與激勵增量電導法的比較

摘要：在這項研究中，比較了用於光伏模塊最大功率點跟踪的模糊邏輯和增量電導。對單二極管電路和直流電/直流電升壓轉換器的光伏進行了數學分析。使用矩陣實驗室/模擬鏈接軟件對所提出的光伏系統進行仿真，以測試所提出的模糊邏輯最大功率點跟踪技術在不同輻照度水平下的性能。此外，輻照度的快速變化曲線適用於兩種技術，以顯示光伏模塊對每種技術的動態響應。本文旨在使用模糊邏輯和傳統增量電導方法跟踪快速變化輻照度下光伏組件的最佳功率。仿真結果表明，所提出的模糊邏輯技術的主要新穎性是通過與增量電導技術相比，以更短的時間和更低的紋波分辨率實現峰值功率，從而為最大功率點跟踪提供良好的一致性。仿真結果還表明，採用模糊邏輯最大功率點跟踪技術運行時，光伏組件具有最佳性能和更高的效率。

关键词：最大功率點跟踪、增量電導、快速變化的輻照度、升壓轉換器、模糊邏輯。

1. Introduction

Nowadays, renewable energy sources such as Photovoltaic (PV) energy sources are most commonly used in different countries. PV energy is harnessed by using the PV cells meant by the photo (light) and voltaic (voltage) [1]. Furthermore, a solar PV cell is a silicon semiconductor device produced by two layers of mobile carriers, electrons in the conduction band and holes in the valence band [2]. The produced power from the PV cell is small, and therefore in this technology, more PV cells are connected in series to form a panel to increase the overall PV voltage. After that, several panels are integrated into parallel to raise the panel's current and forms arrays [2-4]. The

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nonlinear characteristics of the PV cell are utilized because it is affected by irradiation and the ambient temperature.

An increase in ambient temperature causes the PV voltage to decrease due to the negative sign of the voltage coefficient based on ambient temperature, which leads to a decrease in PV power. On the other hand, the increase in ambient temperature makes the current increase slightly. Unlike, if irradiation value is increased, the current will become large, which makes the output power extracted from the PV large because the current is proportional directly to irradiance, but these changes in the irradiance make the PV voltage expose little increasing [5, 6]. These nonlinear characteristics of the PV module required a robust controller to truck the optimal point of the power-voltage (P-V) and the current-voltage (I-V) curves under different weather conditions. Recently, a maximum power point tracking controller (MPPT) technique has been used for this objective [7]. Several researchers are proposed and reviewed different MPPT techniques. However, selecting an MPPT technique may have limitations such as cost, response speed, complexity, oscillation around the MPP, sensors.

However, the recent MPPT techniques that available in the market such as perturb and observe (P&O) [8, 9], incremental conductance (IC) [10, 11], fractional open-circuit voltage, fractional short-circuit current [12, 13], Hill Climbing (HC) [14] have fewer advantages in terms of the efficiency. Unlike artificial intelligence techniques such as fuzzy logic systems, neural networks, adaptive fuzzy-neural are considered the attractive solution for this purpose [15-19]. In this paper, an FL-MPPT technique has good efficiency compared to incremental conductance (INC). Also, MATLAB/Simulink software is used to validate and simulate the overall PV system used in this research. Moreover, the DC/DC boost converter is analyzed and studied theoretically to enhance the MPPT techniques. Then, the output power of the PV system is maximized using a more efficient FL-MPPT technique for fast values of solar irradiance. Many researchers used new techniques to convert DC to AC to link with the grid [20, 21], and other researchers used an HVDC system to convert AC to DC.

2. Photovoltaic Module Modeling

The PV cell equivalent circuit called the single-diode model is utilized in this research as presented in Fig. 1. In this mode, the recombination loss produced in the semiconductor materials for the depletion region is negligible [18-21]. The simplicity of this model represents the main advantage of this model and makes it suitable for different PV applications.

However, series and shunt resistors are inserted into the single-diode mode to report the electrical circuit's silicon material and leakage current losses. Moreover, from the theory of semiconductors, the Shockley diode equation that represents the I–V characteristic of the ideal PV cell is [19]:

$$I_{pv} = I_{ph} - I_0 \left[\exp\left(\frac{q\, V_{pv}}{\alpha\, K\, T}\right) - 1\right] \tag{1}$$

where V_{pv} is the PV cell voltage, I_{ph} – the photocurrent source, I_0 – the reverse saturation current of the diode, q – the charge of electron ($1.60217646 \times 10^{-19}$C), α – the diode ideality factor (α =1.3), K – the constant of Boltzmann (1.3806503×10^{-23} J/°K) and the ambient temperature in °K is denoted by T.

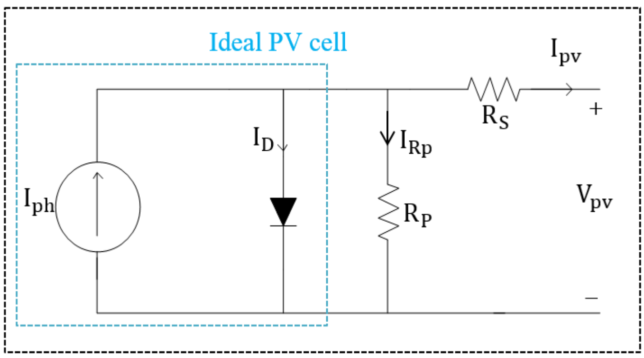


Fig. 1 Single-diode model

The main PV panel current can be written as [19, 20]:

$$I_{pv} = I_{ph} - I_0 \left[\exp\left(\frac{q\, V_{pv}}{\alpha V_T}\right) - 1\right] - \frac{V_{pv} + R_S\, I_{pv}}{R_P} \tag{2}$$

The source of photocurrent of PV module (I_{ph}) depends mainly on irradiance, and it is affected little by the temperature according to the following equation [18, 19].

$$I_{ph} = \left(I_{phn} + K_i \Delta T\right)\frac{G}{G_n} \tag{3}$$

where I_n is the photocurrent at Standard Test Conditions (STC), ΔT is the temperature change and G_n=1000W/m² at STC conditions. Also, K_i represents the coefficient for the temperature in the case of short circuit current. Several researchers have assumed that the source photocurrent (I_{ph}) is the same for the short circuit current (I_{sc}), assuming a low value of the series resistance and a higher parallel resistance value. An improved equation that defined the diode current for saturation case can be written as [12, 19]:

$$I_0 = \frac{(I_{scn} + K_i \Delta T)}{\exp\left[\frac{(V_{ocn} + K_v\, \Delta T)}{\alpha V_T}\right] - 1} \tag{4}$$

where K_V is an open-circuit voltage coefficient. Furthermore, the terms of the equation can be defined as:

- I_D is the current of the diode
- I_{Rp} is the parallel resistance current
- $V_T (= N_S K\, T/q)$ is the thermal voltage (25.7 mV at 25°C) with N_S number of cells.

- R_P and R_S are parallel and series resistances, respectively.

3. MPPT Techniques

3.1. Incremental Conductance Technique

The main target of the INC technique is to derive the relationship between the voltage and power of the PV panel under different weather conditions. This relation can be defined by the change in power to the change in the voltage as dP/dV. Moreover, based on the operating point of the PV panel, the MPP is detected when the derivative becomes zero, as illustrated in Fig. 2 [18]. The INC algorithm can be desired based on the slope of the I-V curve. Hence, the slope on the left side of MPP is negative, while the positive slope of the derivative becomes on the right side of the MPP that means the operating point of the PV moves according to the state of the change of the voltage with power and MPP is achieved by increasing duty cycle of the converter until the dP/dV becomes zero [11].

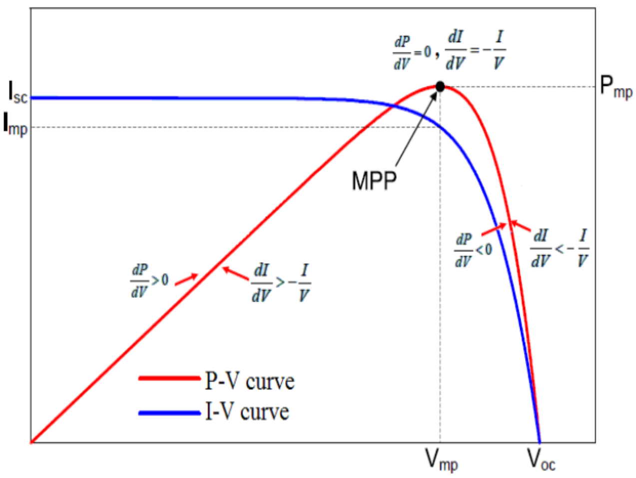


Fig. 2 I-V and P-V curves for INC algorithm

The main drawback in the INC technique is the instability and oscillation that occurred due to the operation derivative. Another point occurred in the INC, which is influenced during the low values of the irradiance. In order to show the relation between the current and voltage across the INC algorithm, the following expressions are written:

$$\begin{cases} \frac{dI}{dV} = -\frac{I}{V} & \text{At MPP} \\ \frac{dI}{dV} > -\frac{I}{V} & \text{Left of MPP} \\ \frac{dI}{dV} < -\frac{I}{V} & \text{Right of MPP} \end{cases}$$

3.2. Fuzzy Logic Technique

FL-MPPT is one of the artificial MPPT techniques used to track the MPP of the PV panel under different values of irradiance and temperature. FL-MPPT is used mostly due to its advantages, such as the nonlinear control method, robust in low irradiance levels, and operated with imprecise inputs [15, 16]. On the other hand, the designer should build the FL-MPPT technique because it needs more experience and knowledge to select the specified inputs and produce the rule-base table. An adaptive FLC is considered to produce the optimal memberships (MFs) and the table of the rule-base to obtain the target performance under various irradiance and ambient temperature values. Moreover, the general behavior of the FL-MPPT technique is affected by the shape of MFs used in the simulation. For this reason, in this paper, the triangular membership functions are used to utilize the complex computation process in the simulation. In order to understand the behavior of the FL technique, a general block in Fig. 3 is presented.

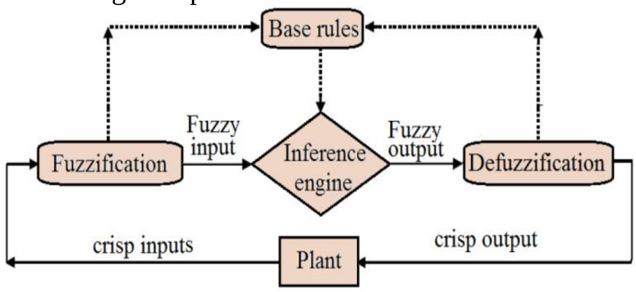


Fig. 3 Fuzzy logic diagram

The FL technique can generally be summarized into four sections: fuzzification, an inference engine, a rule base unit, and defuzzification. In this paper, the inputs of the proposed FL-MPPT are the error E and the change in the error ΔE used to implement the FL algorithm and track the MPP during the simulation. In addition, FL has a single output variable, which is the change in the duty cycle ΔD for the boost converter. So, the error can be written as:

$$E = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} = \frac{\Delta P}{\Delta P} = \frac{\Delta I}{\Delta V} + \frac{I}{V} \qquad (5)$$

where $P(k)$ and $V(k)$are the power and voltage of the PV panel, respectively. Also, the error can be expressed as:

$$\Delta E = E(k) - E(k-1) \qquad (6)$$

Furthermore, FL generates the next operating point based on the MFs and its table of the rules by these variables. So, the most far operating point is shown according to the one input (E), which tells the algorithm information on how to track the MPP and extract the maximum optimal power from the PV panel. On the other hand, the second input ΔE decides how fast the operating point is moving to the right side or the left side of the MPP on the I-V and P-V curves. As a result, when the E value is positive, the duty cycle of the boost converter is changed to raise the PV voltage until it reaches to MPP point. Unlike if the E value is negative, according to the algorithm, the duty cycle will change to decrease the PV voltage until it reaches an MPP point again. As discussed before, the fuzzy rules table is proposed for inputs of the error and the change in the error, which are negative big NB, negative small (NS), zero (Z), positive small (PS), and positive big (PB). The flowchart of the proposed FL-MPPT technique used in this work is shown in Fig. 4

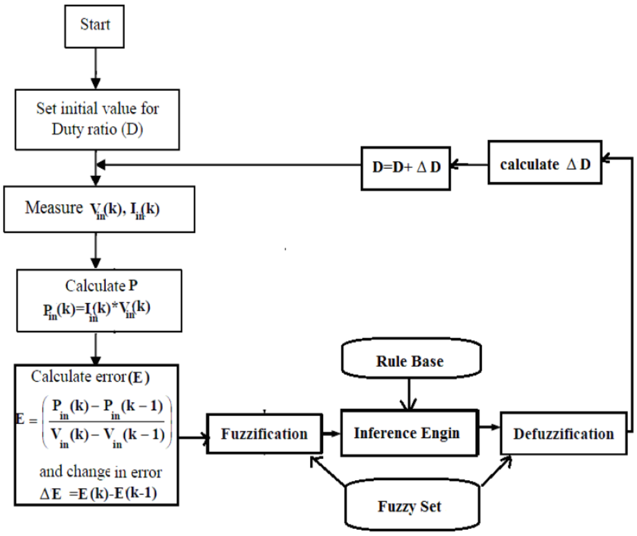


Fig. 4 Flowchart of the FL-based MPPT

4. DC/DC Boost Converter

Boost converter or step-up converter is widely used in PV applications such as MPPT controller as shown in Fig. 5. Fig. 6 illustrates the boost converter's electrical circuit, consisting of an inductor, single diode, semiconductor switch like MOSFET or IGBT, and input and output capacitors [21]. Moreover, the MOSFET of the boost converter is controlled by adjusting the duty cycle *d* during the ON/OFF state operation. Therefore, the principal action of this converter can be divided into two. When the switch is ON, current flows in the inductor and switch, and then energy is stored in magnetizing the inductor inductance. After that, when the PWM signal is removed, this energy will deliver to the output load through the output capacitor filtered by the output waveform [19, 21]. In order to show the mathematical behavior of the boost converter, continuous conduction CCM mode is used in this work. The voltage and current waveforms during CCM mode are indicated in Fig. 7.

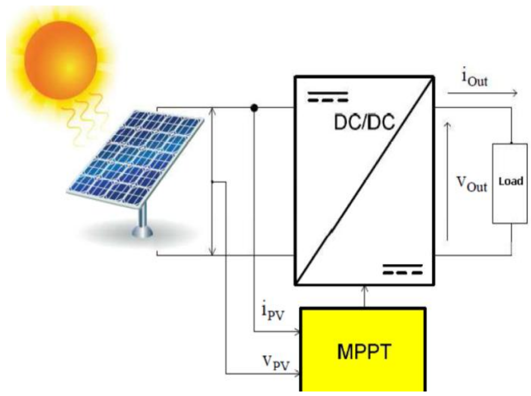


Fig. 5 Boost converter with MPPT controller

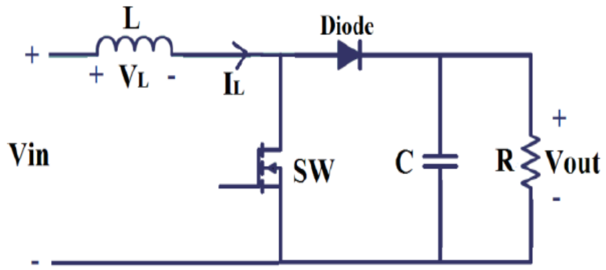


Fig. 6 Electrical circuit of the boost converter

The relationship between the output and input voltage is expressed as [21].

Table 1 Boost converter parameters

Parameter	Value
L	1.8 mH
Co	100 μF
f_s	5000 Hz
C_{in}	220 μF
d_{max}	0.8

$$V_O = \frac{1}{1-d} V_{in} \tag{7}$$

$$I_O = I_L \ (1-d\ ) \tag{8}$$

In order to calculate the parameters of the boost converter at CCM mode the equation 2.8 should be investigated as:

$$L = \frac{V_{in}\ d}{f_s\ \Delta I_L} \tag{9}$$

where f_s is the switching frequency, and $\Delta I_L = 0.3 I_L$. In addition, the output capacitor can be determined from the following equation [19]:

$$C_O = \frac{I_O\ d}{f_s\ \Delta V_O} \tag{10}$$

where $\Delta V_O = 0.02 V_O$. So, the selection of C_O must be higher than the determined value to sure that the ripple in the output voltage of the boost converter remains with the specific range. Also, the input capacitor is very important to decoupling the PV power and reducing the harmonics in its voltage so that it can be calculated from the following equation [19]:

$$C_{in} \geq \frac{d}{8\, f_s^{\ 2}\ \times\ L \times 0.01} \tag{11}$$

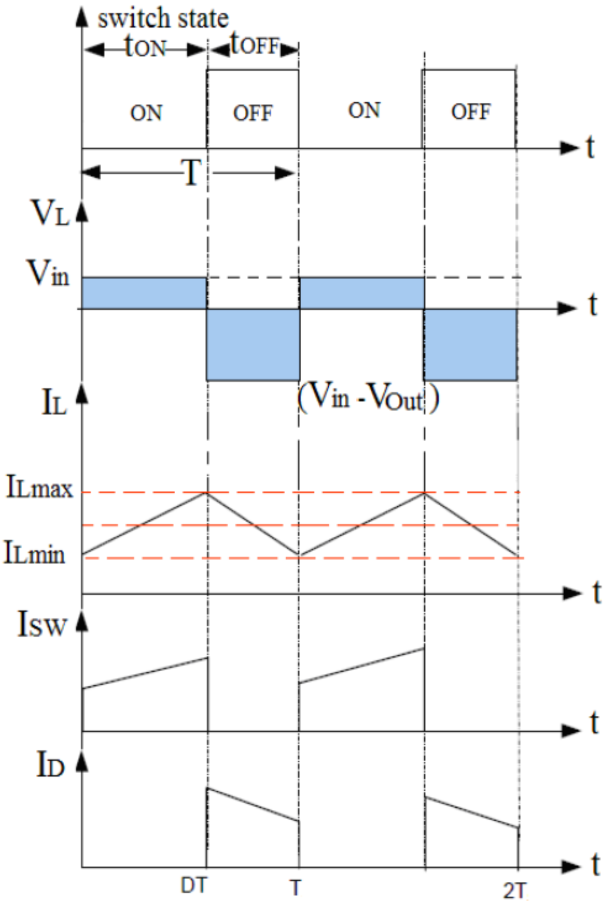


Fig. 7 Waveforms of the voltage and current during CCM mode

However, the boost converter design is obtained based on the previous equations.

5. Simulation Results and Comparison

In order to verify the proposed work, MATLAB/Simulink software is used to validate and test the proposed PV system with the MPPT techniques used here, as presented in Fig. 8. In this research, both INC and FL MPPT techniques are used to track the output power of the 200W PV module type KC200GT under different weather conditions. Fig. 9 shows the PV module curves under varying values of the irradiance and fixed temperature, while Fig. 10 presents the PV module curves for various temperatures and constant irradiance. The Simulink model of the boost converter used in this paper is shown in Fig. 11. As shown, the boost converter is controlled by the MPPT duty cycle to estimate the maximum power from the PV system by the PI controller, reducing the error between the estimated and measured PV voltages. As presented in Fig. 12, the INC-MPPT algorithm is modeled using the m-file function, and the parameters of the PI controller are obtained by trial and error method, which is obtained as $K_p = 0.9$ and $K_i = 0.04$.

In addition, the FL-MPPT algorithm is implemented using MATLAB/Simulink, as presented in Fig. 13. Hence, the voltage and the PV system current are sensed and then used to calculate the PV power to calculate the error and the change in the error. The PWM block of 5000 kHz is used to generate the proper pulses of the duty cycle for the boost converter. Also, the rules editor of the FL is indicated in Fig. 14. The MFs of the input and output variables of the FLMPPT controller used in this work are shown in Fig. 15. The input variables are represented by the PV, V_n, and output power of the PV system P_n while the output variable is the duty cycle of the boost converter D.

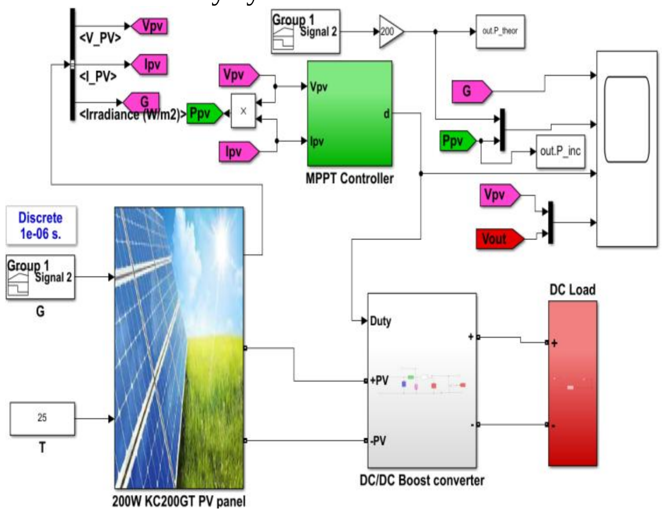


Fig. 8 Proposed PV system with MPPT techniques

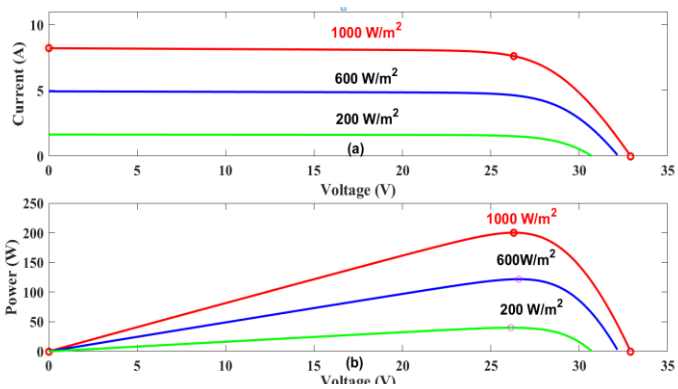


Fig. 9 I-V (a) and P-V (b) curves at various values of irradiance and fixed temperature $T = 25°C$

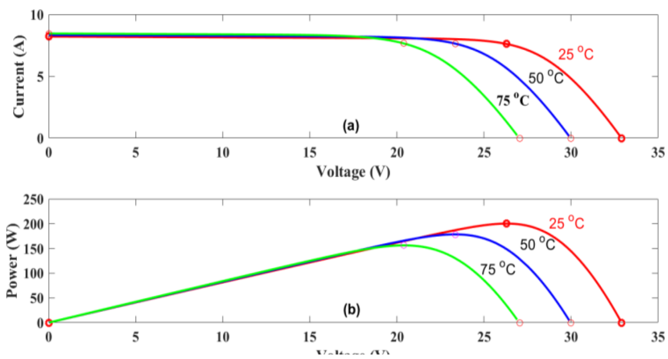


Fig. 10 I-V (a) and P-V (b) curves at varying temperature and fixed irradiance $G = 1000$ W/m²

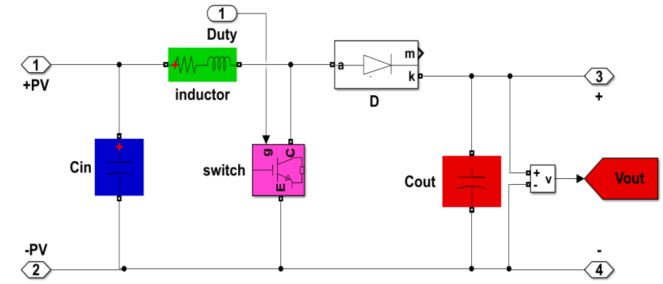


Fig. 11 Boost converter circuit in MATLAB/Simulink

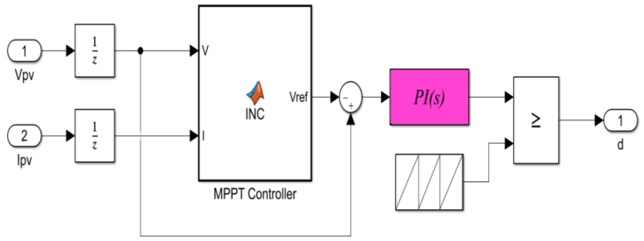


Fig. 12 Proposed INC-MPPT technique in MATLAB/Simulink

The relationship between the PV voltage and power and duty cycle in 3-D shape is presented in Fig. 16. As observed, the surfer graph shows the best performance for the proposed MPPT tracker during the simulation.

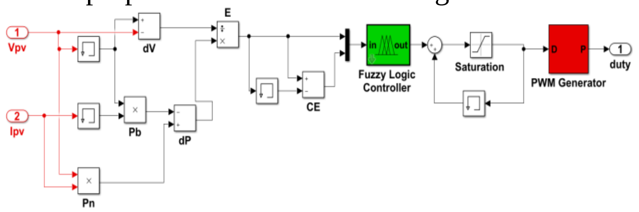


Fig. 13 Fuzzy logic MPPT technique model in MATLAB/Simulink

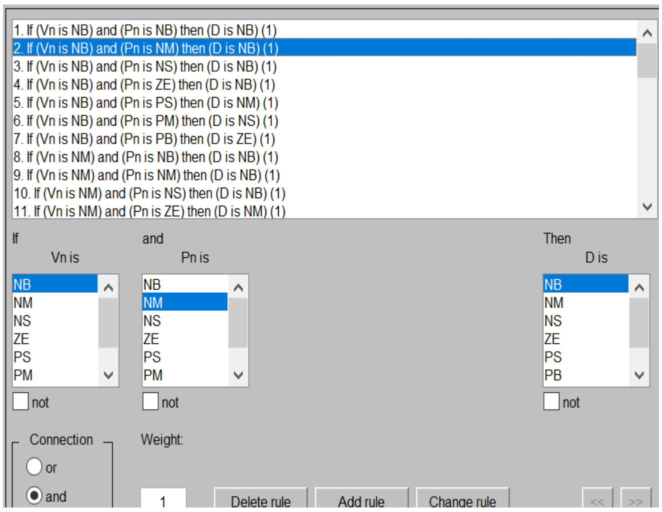


Fig. 14 Rule editor of fuzzy logic MPPT in MATLAB

Fig. 15 MFs of the input and output variables for fuzzy logic MPPT

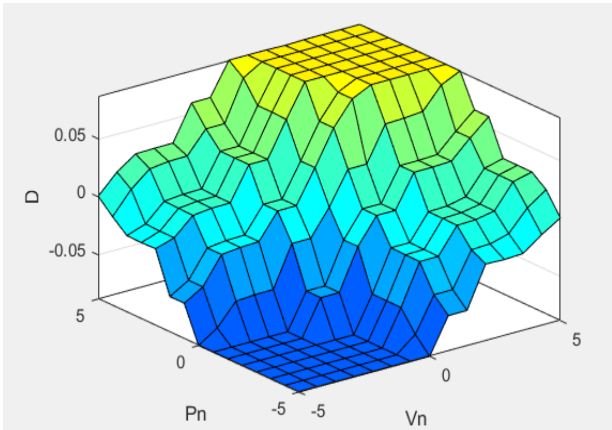
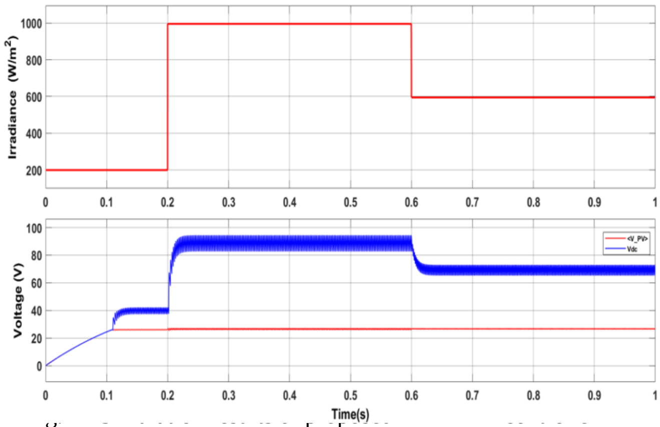


Fig. 16 Surface 3-D shape for fuzzy logic MPPT

In order to test the performance of the proposed MPPT techniques, the step change in solar irradiance G is used with constant temperature $T = 25°C$. As observed in Fig. 17, the solar irradiance changes from a lower-level value of $G = 200\ W/m^2$ at time $t = 0.2s$ to $G = 1000\ W/m^2$ at $t = 0.6s$. It is clear that PV voltage is little affected, and the boost converter increases due to irradiance increase from 40 to 85V. After that, the irradiance is moved from 1000 to 600 W/m² at $t = 0.6s$ to $t = 1s$. Thus, more efficient power from the FL-MPPT is obtained compared to INC-MPPT. As a result, a large oscillation in INC-MPPT has occurred, and the speed of response is low. While the best performance is achieved using the FL-MPPT technique according to the theoretical power of the PV system, as reported in Fig. 18. As a result, the FL-MPPT technique is the best choice for the PV system used in DC load operation.



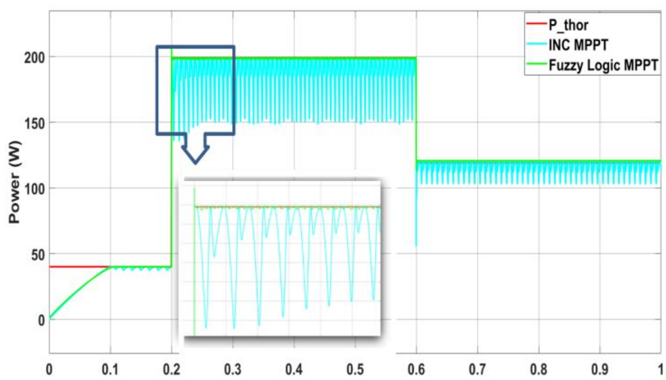


Fig. 18 Comparison between INC and FL MPPT techniques during the fast change in irradiance

6. Conclusion

In this research, a comparison between the intelligent fuzzy logic (FL) and conventional incremental conductance (INC) techniques based on maximum power point tracking (MPPT) for the photovoltaic (PV) module is presented. First, the mathematical model of the PV circuit is studied, and DC/DC boost converter circuit is also analyzed to enhance the proposed work. Second, the entire proposed system is modeled and simulated in MATLAB/Simulink including PV module, boost converter, and MPPT techniques. In order to validate the performance of the proposed FL-MPPT technique, a simulation with different weather conditions is done. Moreover, the fast change in solar irradiance is used to clear the dynamic response of the PV module under both FL and INC techniques. As a result, the proposed FL technique achieves the MPPT with the small-time response and lower ripple resolution. From the comparison, it is clear that the proposed FL-MPPT technique has well performance in maximizing the real power of the PV module during the fast change in the irradiance compared to the results of the traditional IC technique, which produce large oscillation and less speed response.

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