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Comparison Between Perturb & Observe, Incremental Conductance and Fuzzy Logic MPPT Techniques at Different Weather Conditions

Nasir Hussein Selman¹, Jawad Radhi Mahmood²

Ph.D Student, Department of Communication Engineering, Technical Engineering College, Najaf, Iraq¹

Assistant Professor, Department of Electrical Engineering, Engineering College, Basrah, Iraq²

ABSTRACT: This paper is going to cover three maximum power point tracker (MPPT) control algorithms of solar system, namely; Perturb and Observe (P&O), Incremental Conductance (IC) and Fuzzy Logic (FL) algorithms. The three methods have been studied in details by the MATLAB/Simulink. The simulation took into account the insolation and temperature variation. The PV arrays model is interconnected with the DC-DC boost converter that works based on the output pulses of MPPT block to make the PV system operates at MPP. The simulation results for the three methods show good results in all studied cases with the observation that the FL method offers better efficiency than the others two methods.

KEYWORDS: Photovoltaic system, DC-DC boost converter, MPPT Techniques, P&O, IC, FL methods..

I. INTRODUCTION

The major disadvantages of solar module are relatively high manufacture cost and low efficiency (about 13%). Thus, it is necessary to operate the solar system at the MPP under varying environmental conditions. DC-to-DC converters and their control algorithms are integrated with PV system to extract the maximum power continuously under any circumstance [1].

There are many different techniques for the MPPT approach. Some of them are very robust and simple, whereas other techniques require very sophisticated logic devices such as microcontroller.

This work deals with the MPPT algorithm of solar system. The first part is to illustrate the importance of MPPT and how it can be achieved. Then overviews of the Perturb and Observe (P&O), Incremental Conductance (IC) and Fuzzy Logic (FL) MPPT methods have been discussed and analyzed in details. In the last part, the simulation of these three MPPT methods under different environment conditions has been simulated.

II. LITERATURE SURVEY

The vital importance of the MPPT algorithms of PV systems attracted a lot of researches on the design and control of these algorithms. The following are samples of the attempts in this context.

B. Subudhi and R. Pradhan [2] gave a comprehensive study of many MPPT methods applied to PV system in the literatures. The MPPT techniques have been classified based on features, such as implementation complexity number of sensor and control variables required, cost and speed of implementation. The work in this paper has been considered the best reference for future MPPT workers in PV systems.

V. Ramchandania et al. [3] presented a comparative study of Field Programmable Gate Array implementation of linear Kalman filter and unscented Kalman filter approaches that track maximum power point of a solar photovoltaic system.



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

These approaches had been became much faster than using the conventional P&O approach specifically in case of sudden weather changes. Using the linear kalman filter the MPP of a solar PV array had been tracked with an efficiency of 97.11% while using the unscented kalman filter technique was 98.3%. However, the MPP had been tracked at a much faster rate in case of using the linear kalman filter approach

C. L. Liu et al. [4] proposed an asymmetrical membership function (MF) of the FLC based MPPT algorithm for photovoltaic systems. The power variation and output voltage variation have been selected as inputs of the FLC. The proposed FLC was improved the dynamic and steady state performance of the PV system as compared with the P&O and symmetrical FLC-based MPPT methods.

M. Kumar et al. [5] gave a comparative study between IC and FL MPPT algorithms. The proposed methods have been adjusted the duty cycle of the DC-DC boost converter to track the maximum power of a solar PV system. The simulation results have been shown that the FL algorithm was exhibit a better performance on the one hand the max power extracted, fluctuations and response as compared with the IC method at all weather conditions.

III. LOAD MATCHING

When a solar panel is directly connected to loads as depicted in Fig. 1 (a), the solar panel's operating point will be at the intersection of its I-V curve and the load line that has a slope of $1/R_{load}$ [1]. In general, this point is not always at the solar panel's MPP as obviously illustrated in Fig. 1 (b). Such situation produces less power than that can be generated by the PV panel. A direct connected PV panel uses about (31%) of its capacity [3].



Fig. 1: Load matching: (a) Direct connected PV module with resistive load, (b) I-V curve of solar panel with different loads

To mitigate this problem and raise the efficiency of the solar system, a MPPT algorithm can be used to keep the solar panel's operating point at the MPP. The maximum power harvesting is performed by adjusting the duty cycle (D) of the DC-to-DC converter, i.e. a duty cycle adjustment is performed with MPPT algorithm as given in the Fig. 2 [6].



Fig. 2: MPPT control block of PV system

The approach how to control the duty ratio is based on the maximum power transfer theorem. The duty cycle controls the load resistance seen by the source (matching between the internal PV system resistance and the equivalent load resistance seen by the PV system).



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

Consider a boost converter is used between solar system and load as appeared in Fig. 3. Its average output voltage is given by:



Fig. 3: Circuit of the MPPT system

$$V_{out} = \frac{V_{in}}{1 - D} \tag{1}$$

Assuming the conversion efficiency of the converter is 100%, the relationship between the output current (I_{out}) and the input current (I_{in}) can be written as:

$$\frac{I_{out}}{I_{in}} = \frac{V_{in}}{V_{out}} = 1 - D \tag{2}$$

Then,

$$I_{out} = (1 - D)I_{in} \tag{3}$$

From equations (1) and (3), the relation between the input resistance seen by PV module (R_{equiv}) and the output load impedance (R_{load}) can be described using the following equation:

$$R_{equiv} = \frac{V_{in}}{I_{in}} = \frac{(1-D)V_{out}}{\frac{I_{out}}{1-D}} = (1-D)^2 \frac{V_{out}}{I_{out}} = (1-D)^2 R_{load}$$
(4)

By varying duty cycle, R_{equiv} can be matched with the optimal resistance at which the maximum power will be extract from solar system. Therefore, the impedance of the load can be mapped into the value that guarantees maximum power transfer to the load.

If the equation (4) is solved for the duty cycle:

$$D = 1 - \sqrt{\frac{R_{equiv}}{R_{load}}}$$
(5)

To illustrate how to draw the maximum power from the Mitsubishi PV-UE125MF5N (125W) solar panel at different loads, the resistance at maximum voltage (V_{mpp}) and maximum current (I_{mpp}) should be calculated. According to I-V characteristic of this PV panel that is given in Fig. 4, the load resistance which extracts max power is given by:

$$R_{Load} = \frac{V_{mpp}}{I_{mpp}} = \frac{17.3}{7.23} = 2.4\,\Omega \tag{6}$$

As the weather conditions change, the maximum power's resistance must also change. Now, if a (5Ω) resistor is connected directly to PV panel, only about 80W power can be extracted. To harvest max power, boost converter should be placed between the solar panel and the load. For this situation, the duty ratio should be:

$$D = 1 - \sqrt{\frac{R_{equiv}}{R_{load}}} = 1 - \sqrt{\frac{2.4}{5}} = 0.3$$

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Vol. 5, Issue 7, July 2016



Fig. 4: I-V characteristics of Mitsubishi PV-UE125MF5N solar panel with 2.4 Ω and 5 Ω resistive loads

IV. MPPT TECHNIQUES

In the literature, various MPPT methods are available to enhance the performance of PV system by effectively tracking the MPPT. However, the three most frequently used techniques are discussed here.

A. P&O Technique (or Hill Climbing Technique)

This method is commonly employed in PV systems since its simple, low computational demand and requires only measure the PV panel voltage and current. Here, the voltage of the PV panel is perturbed by a small magnitude (ΔV) and the changing of power (ΔP) is observed. Adjustments are made in the same direction until there is no more increment in power [3,7]. If the ΔP is less than zero, the working point will move far from the MPP, and the direction of perturbation must be inverted to return toward the MPP. This technique is summarized in Table 1.

| Perturbation | Change in Power | Next Perturbation | |
|--------------|-----------------|-------------------|--|
| Positive | Positive | Positive | |
| Positive | Negative | Negative | |
| Negative | Positive | Negative | |
| Negative | Negative | Positive | |

Table 1: Summary of P&O technique

P&O method is also called "Hill climbing method" because it climbs the power curve to reach the MPP [3]. The flow chart of the P&O method is depicted in Fig. 5.



Fig. 5: Flow chart of P&O method



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

B. Incremental Conductance (IC) Technique

IC method is based on the fact that the slope of the P-V curve of solar panel (dP/dV) is zero at the MPP, positive on the left of the MPP, and negative on the right as shown in Fig. 6 [3].



Fig. 6: P-V curve of solar panel and signs of its slop at various regions

This algorithm uses equation $\left(\frac{dP}{dV}=0\right)$ at MPP) which can be expressed by the voltage and current as:

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV}$$
(7)

at MPP

$$\frac{dP}{dV}\Big|_{\substack{I=\mathrm{Im}\,pp\\V=Vmpp}} = 0 \Longrightarrow \frac{dI}{dV}\Big|_{\substack{I=\mathrm{Im}\,pp\\V=Vmpp}} = -\frac{I_{mpp}}{V_{mpp}}$$
(8)

Where, dI_{pv}/dV_{pv} symbolizes incremental conductance(IC) of solar panel and I_{pv}/V_{pv} symbolizes the instantaneous conductance.

Note from the equation (8), when the ratio of IC equals to the negative of instantaneous conductance, the solar panel will work at MPP.

In practice, the equality of Eq. (8) is impossible to achieve. Thus practical IC method supposes the MPP reached when the working point is within a small marginal error(ε) [8]:

$$\frac{dP}{dV} = \pm \varepsilon \tag{9}$$

Where ε goes to zero at the MPP.

The step size must be smaller than the margin in order to avoid tracking pass it. Also, the incremental variations can be computed approximately by subtracting of actual value of V_{PV} and I_{PV} in two following sampling time.

$$dI \approx \Delta I = I(t) - I(t-1)$$

$$dV \approx \Delta V = V(t) - V(t-1)$$
(10)

Therefore the governing equations become:

$$\frac{\Delta I}{\Delta V} = -\frac{I}{V} \quad for V = V_{mpp} \\
\frac{\Delta I}{\Delta V} > -\frac{I}{V} \quad for V < V_{mpp} \\
\frac{\Delta I}{\Delta V} < -\frac{I}{V} \quad for V > V_{mpp}$$
(11)

The flowchart of IC algorithm is illustrated in Fig. 7.



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016



Fig. 7: Flow chart for IC algorithm

C. Fuzzy Logic (FL) MPPT Algorithm

FL is one of the most strong technique method in the extracting of the MPP in solar systems since it has several advantages (robust, works with imprecise inputs, can handle the nonlinearity, no require to have accurate mathematical model, and relatively simple to design) [9]. But, the effectiveness of FLC depends a lot on the knowledge and experience of the designer in selecting the suitable inputs and tuning the rule-base table. In some applications, an adaptive FLC is used to tune the memberships (MFs) and the rule-base table to achieve the optimum performance. However, the complexity of FLC is very high, especially the defuzzification stage, and adaptive FLC has an even higher complexity [4].

The behaviour of the FLC depends on the shape of MFs of the rule-base. Triangular membership functions are selected to reduce the computation complexity. The domain of each MF is decided by the preceding information of the planed scheme parameters.

The general block of the FLC is given in Fig. 8. It includes three main parts: fuzzification, rule-base table/inferenceengine and defuzzification[5]. These functions are illustrated as follows:



Fig. 8: General block diagram of FLC

i. Fuzzification: In this stage, the crisp input variables are transformed into linguistic variables based on the MFs. In this work, the fuzzy control MPPT method has two input variables, namely error (E) and change in error(ΔE), and one output variable, change in duty cycle(ΔD). The MFs for them are given in Fig. 9.



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016



Fig.9: Membership functions of the input and output variables: (a) Membership function of input variable ($E=\Delta P/\Delta V$) (b) Membership function of input variable (ΔE) (c) Membership function of output variable (ΔD)

There are five different fuzzy levels are used for inputs and output variables [NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big)]. Therefore, the proposed FLC will be controlled by 25 different rules. These fuzzy rules are included in Table 2.

Table 2: Fuzzy rule-table

| ΕΔΕ | NB | NS | ZE | PS | PB |
|-----|----|----|----|----|----|
| NB | ZE | ZE | NB | NB | NB |
| NS | ZE | ZE | NS | NS | NS |
| ZE | NS | ZE | ZE | ZE | PS |
| PS | PS | PS | PS | ZE | ZE |
| PB | PB | PB | PB | ZE | ZE |

The two input variables *E* and ΔE , at a sampling instant *t* are given by:

$$E(t) = \frac{P(t) - P(t-1)}{V(t) - V(t-1)} = \frac{\Delta P}{\Delta V} = \frac{\Delta I}{\Delta V} + \frac{I}{V}$$
(12)
$$\Delta E(t) = E(t) - E(t-1)$$
(13)

where P(t) and V(t) are the power and voltage of the solar system, respectively.

Based on these two inputs, FLC decides the next operating point depending on the used membership functions and a rule table. The input E(t) gives an information about how far the current operating point is from that of the MPP, while the input $\Delta E(t)$ expresses how fast the operating points is moving towards or far from the MPP. If the value of E(t) is greater than zero the controller change the duty cycle to rise the voltage until the power is maximum or the value $(\Delta P/\Delta V) = 0$, if this value less than zero the controller changes the duty cycle to decrease the voltage until the power is maximum.

ii. Inference engine: Once *E* and ΔE are evaluated, they are transformed into linguistic variables with five membership functions, which are depicted in Fig. 9 (a & b). After the classification of the values, a decision is made based on a rule shown in Table 2 (This table based on the DC-DC converter). These rules are expressed as (IF-THEN statements) and the syntax is as follows:

IF (E is PB) AND $(\Delta E \text{ is } NB)$ THEN $(\Delta D \text{ is } PB)$.

This rule states that when the error is (PB) and the change in error is (NB), that's mean the duty cycle must be increased (PB) to increase the output voltage. A MATLAB/Simulink rule editor is given in Fig. 10.



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

| <u> </u> | | | | Rule Editor: MPPT1 | × |
|----------|---------|-----------|----------------|----------------------------------|-----|
| File | Edit | View | Options | | |
| 1. lf (| error=D | P/DV is N | IB) and (Derro | r is NB) then (Dduty is Z) (1) | |
| 2. If (| error=D | P/DV is N | B) and (Derro | r is NS) then (Dduty is Z) (1) | |
| 3. If (| error=D | P/DV is N | IB) and (Derro | r is Z) then (Dduty is NB) (1) | E |
| 4. lf (| error=D | P/DV is N | B) and (Derro | r is PS) then (Dduty is NB) (1) | |
| 5. If (| error=D | P/DV is N | IB) and (Derro | r is PB) then (Dduty is NB) (1) | |
| 6. lf (| error=D | P/DV is N | IS) and (Derro | r is NB) then (Dduty is Z) (1) | |
| 7. lf (| error=D | P/DV is N | IS) and (Derro | r is NS) then (Dduty is Z) (1) | |
| 8. If (| error=D | P/DV is N | IS) and (Derro | r is Z) then (Dduty is NS) (1) | |
| 9. If (| error=D | P/DV is N | IS) and (Derro | r is PS) then (Dduty is NS) (1) | |
| 10. If | (error= | DP/DV is | NS) and (Derr | or is PB) then (Dduty is NS) (1) | |
| 11. If | (error= | DP/DV is | Z) and (Derro | r is NB) then (Dduty is NS) (1) | |
| 12. If | (error= | DP/DV is | Z) and (Derro | r is NS) then (Dduty is Z) (1) | |
| 13. If | (error= | DP/DV is | Z) and (Derro | r is Z) then (Dduty is Z) (1) | |
| 14. If | (error= | DP/DV is | Z) and (Derro | r is PS) then (Dduty is Z) (1) | |
| 15. If | (error= | DP/DV is | Z) and (Derro | r is PB) then (Dduty is PS) (1) | |
| 16. If | (error= | DP/DV is | PS) and (Derr | or is NB) then (Dduty is PS) (1) | |
| 17. lf | (error= | DP/DV is | PS) and (Derr | or is NS) then (Dduty is PS) (1) | |
| 18. If | (error= | DP/DV is | PS) and (Derr | or is Z) then (Dduty is PS) (1) | |
| 19. If | (error= | DP/DV is | PS) and (Derr | or is PS) then (Dduty is Z) (1) | |
| 20. If | (error= | DP/DV is | PS) and (Derr | or is PB) then (Dduty is Z) (1) | |
| 21. If | (error= | DP/DV is | PB) and (Derr | or is NB) then (Dduty is PB) (1) | |
| 22. If | (error= | DP/DV is | PB) and (Derr | or is NS) then (Dduty is PB) (1) | 1.1 |
| 23. If | (error= | DP/DV is | PB) and (Derr | or is Z) then (Dduty is PB) (1) | E |
| 24. If | (error= | DP/DV is | PB) and (Derr | or is PS) then (Dduty is Z) (1) | |
| 25. If | (error= | DP/DV is | PB) and (Derr | or is PB) then (Dduty is Z) (1) | 1 |

Fig. 10: MATLAB/Simulink rule editor for FL MPPT controller

iii. Defuzzification: The output of FLC is a fuzzy subset. As the real systems require a crisp value of Control, defuzzication is needed. Defuzzifier is employed to transform the linguistic fuzzy sets back into actual mathematical equivalents magnitude. This generates an analog signal that will control the DC-DC converter to the MPP. The defuzzification is carried out using the centroid method (weighted average method) which is generally employed in the design of FLCs because it has good averaging properties and it gives good results. This method is expressed as [10]:

$$\Delta D = \frac{\sum_{i=1}^{n} \mu(D_i) D_i}{\sum_{i=1}^{i} \mu(D_i)}$$
(14)

where ΔD is the crisp value output value, Di is the center of max-min composition at the output MFs, $\mu(D_i)$ is the maximum of the *ith* membership function, Di is the *ith* input value.

The crisp output (ΔD) of the FLC should be added to the previous value of duty ratio and the resultant value is transferred to the MOSFET's gate of the boost converter. The flowchart of FL MPPT controller is given in Fig. 11.



Fig. 11: Flow chart of Fuzzy logic MPPT



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

V. SIMULATION OF MPPT ALGORITHMS

MATLAB/Simulink permits to divide a simulated system into a number of sub-systems. These sub-systems can be modelled and verified individually and then interconnected later. This makes it possible to design the sub-systems such as solar panel, DC-to-DC converter, and MPPT as independent parts and verify their operation. Finally these sub-systems can be interconnected to form a complete PV system, as displayed in Fig. 12.



Fig. 12: Total MATLAB/Simulink blocks of solar system

The detail PV system MATLAB/simulink model is given in Fig. 13. This system is consisting of (12) Mitsubishi UE125MF5N solar panel which are connected in series and parallel (2 parallel strings and 6 series panels for each string). The whole PV system specifications are listed in Table 3 at Standard Test Conditions (STC).



Fig. 13: PV system MATLAB/Simulink model

Table 3: Whole solar system specifications at STC

| | - | | |
|--|-------------------------|--|--|
| Characteristics of Parameters | Specifications | | |
| maximum power point (P _{mpp}) | 125 x 12 = 1500 W | | |
| Voltage at MPP (V _{mpp}) | 17.3 x 6 = 103.8 V | | |
| Current at MPP (I _{mpp}) | 7.23 x 2 = 14.46 A | | |
| Open circuit voltage (V _{oc}) | 21.8 x 6 = 130.8 V | | |
| Short circuit current (I _{sc}) | 7.9 x 2 = <u>15.8 A</u> | | |

Table 4: Specifications of the DC-DC boost converter

| Switching frequency | 10 kHz |
|---|-------------|
| V_{out} ripple (ΔV_{out}) | \leq 0.5% |
| I_{in} ripple (ΔI_{in}) | \leq 20% |
| Output capacitor $C_{out} \ge \frac{I_{out}D}{f_{sw}\Delta V_{out}}$ | 330 μF |
| Critical Inductance , $L_{critical} \ge \frac{V_{in}D}{f_{sw}\Delta I_{L}}$ | 1 mH |



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

The DC-DC boost model has been simulated in MATLAB (illustrated in Fig. 14) based on the specifications listed in the Tables 3 and 4 above. The output of MPPT block is series of pulses of D that supplied to the boost converter. Converter works based on these pulses to make the PV system operate at MPP.



Fig. 14: Simulink model of the DC-DC boost converter

The proposed MPPT simulink model, based on a P&O, IC and FL algorithms are presented in the following subsections.

A. Simulation Model of P&O Algorithm

The detailed Simulink model of P&O algorithm is depicted in Fig. 15. It works as follows:

- i- Read $V_{pv}(t)$ and $I_{pv}(t)$.
- ii- Calculate P(t) by multiplying $V_{pv}(t)$ and $I_{pv}(t)$.
- iii- Call previous values of *P* and V[P(t-1) and V(t-1)] from the memory.
- iv- Calculate ΔV and ΔP , where , $\Delta V = V_{pv}(t) V_{pv}(t-1)$ and $\Delta P = P(t) P(t-1)$.
- v- Check the sign of (ΔP) and the sign of (ΔV) as follows:
 - If (ΔP) greater than zero pass (+1), else pass (-1),
 - if (ΔV) if greater than zero, pass (+1), else pass (-1).

vi- Multiply the sign of (ΔP) and (ΔV) , then multiply the result by the step's increment value of the duty $(\Delta D=0.001)$, to update the duty ratio (D). So if (-1) is passed, it will be (-1*0.001) will be added to the previous duty cycle value, else (+1*0.001) will be added. This means that the MPPT algorithm decides whether D output to the circuit should be increased, decreased, or kept as it is.

vii- The update value of D is first passed to saturation block to limit the duty cycle to be within the range (0.1-0.9). The saturation block output is then passed to the pulse generator to produce the adjustable pulses to drive the switching element of the boost converter.



Fig. 15: MATLAB/Simulink model of P&O method



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

B. Simulation Model of IC Algorithm

The detailed Simulink model of IC algorithm is illustrated Fig. 16. The steps of this algorithm can be sort as follow: i- Read $V_{pv}(t)$ and $I_{pv}(t)$.

ii- Call I(t-1) and V(t-1) from the memory. (i.e. Call required previous values)

iii- Calculate ΔV and ΔI , where , $\Delta V = V_{pv}(t) - V_{pv}(t-1)$ and $\Delta I = I(t) - I(t-1)$.

iv- Divide (ΔI) by (ΔV) to get the incremental conductance $(\Delta I_{pv} \Delta V_{pv})$ and calculate the instantaneous conductance by $(I_{pv}(t)/V_{pv}(t))$.

v- If (ΔV) equals zero, pass the output of control *switch1* else pass the output of control *switch2*.

- The output of control *switch1* depends on the value (ΔI) as follows:

(if $\Delta I=0$, then pass zero, else if $\Delta I>0$, then pass 1, else pass -1)

- The output of control *switch2* depends on the error value $(e=\Delta I/\Delta V + I_{pv}/V_{pv})$ as follows:

(*if* $abs(e) \le \varepsilon$, then pass zero, else *if* error > ε , then pass 1, else pass -1)

vi- Multiply the output of *switch3* by the duty cycle increment value (ΔD) which will be added to the previous value of D to get the new value of duty cycle.

vii- The update value of D is passed through saturation block before being sent to the pulse generator to obtain the control pulses that drive the switching element of the boost converter.



Fig. 16: MATLAB/Simulink model of IC method

C. Simulation Model of MPPT Fuzzy Logic Algorithm

The FLC based MPPT control algorithm adopted here can be summarized by the following steps:

i- Read $V_{pv}(t)$ and $I_{pv}(t)$.

ii- Calculate P(t) by multiplying $V_{pv}(t)$ and $I_{pv}(t)$.

iii- Call P(t-1) and V(t-1) from the memory (call previous values of P and V).

iv- Calculate ΔV and ΔP , where , $\Delta V = V_{pv}(t) - V_{pv}(t-1)$ and $\Delta P = P(t) - P(t-1)$.

v- Divide (Δp) by (ΔV) to obtain the error [E(t)]. This error represents the first input to FL controller.

vi- Call E(t-1), then calculate ΔE , where $\Delta E = E(t) - E(t-1)$. The change in error (ΔE) represents the second input to FL controller.

vii- The output of the FLC represents duty cycle increment value (ΔD) which will be add to the previous value of duty cycle value and then produce new value.

The above steps have been implemented using simulation facility as pictured in Fig. 17.



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016



Fig. 17: MATLAB/Simulink model of FL MPPT method

VI. SIMULATION RESULTS

To select the more suitable MPPT technique, the PV system has been tested under the control of three MPPT algorithms (P&O, IC and FL). The testing activities take into account the insolation and temperature variations.

A. Solar Insolation Variation

To cover this case, the insolation profile given in Fig. 18 has been applied to the PV system. This profile is not very realistic, but it will be equivalent to very fast cloudy day and allow giving an thought of measure of how speed the controller respond.



Fig. 18: Insolation profile variation

Figure 19 shows the generated power from the solar arrays system with P&O, IC and FL MPPT techniques under the considering of Top = 25° C and resistive load =48 Ω . They are collected in one figure to be clear comparison between the three methods. The Figure illustrate that all tested MPPT controllers try to maintain the PV output power at it's or close to its maximum value.



Fig.19: Output power of the P&O, IC and FL MPPT methods under different insolation levels and constant temperature



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

Also the Fig. 19 offers the maximum ideal power (or theoretical power) curve that can be obtained from P-V curve of the PV arrays given in Fig. 20.



Fig. 20: P-V curves of the proposed PV system at different insolation

Table 5 summarized the calculated efficiencies for the three MPPT techniques under different insolation levels. The calculation results appear that the efficiencies are good for all techniques even in rapid changes in insolation. But, the efficiency is slightly better with the FL algorithm with lower steady state oscillation.

| Irradiance (W/m ²) | | 1000 | 600 | 400 | 200 |
|--|------------|------|-------|-----|-----|
| Power from PV curve (W) | | 1500 | 880 | 570 | 272 |
| P&O MPPT | Power (W) | 1300 | 750 | 470 | 260 |
| | Efficiency | 87% | 85% | 83% | 96% |
| IC MPPT | Power (W) | 1350 | 765 | 470 | 260 |
| | Efficiency | 90% | 87% | 83% | 96% |
| FL MPPT | Power (W) | 1365 | 850 | 530 | 260 |
| | Efficiency | 91% | 95.4% | 94% | 96% |
| The MPPT efficiency is calculated by the following relation: <i>Efficiency</i> = power from MPP technique/P-V curve ideal power | | | | | |

Table 5: MPPT efficiency under various insolation

B. Temperature Variation

In this case the simulation has been performed under the assumption that the temperature variation takes the profile shown in Fig. 21. The resistive load of 20Ω was chosen while the insolation level has been taken constant at 800 W/m^2 .



Fig. 21: Temperature variation profile

Figure 22 collects the power generated from the PV arrays system using P&O, IC, and FL MPPT techniques. The figure gives an indication that all MPPT controllers make the power produced from PV arrays very close to the maximum power during temperature variation. Thus the efficiency of all methods is excellent (more than 95%).



(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016



Fig. 22: Output power of the P&O, IC and FL MPPT methods under different temperature levels and constant insolation

VII. CONCLUSIONS

This paper is covered three of MPPT algorithms (P&O, IC, and FL). The modeling and simulations of these methods have been introduced and done in MATLAB/Simulink. The results indicate that all studied MPPT controllers are capable to extract the maximum power of the solar system at different weather conditions. From the simulation results, the following conclusions are extracted:

- All algorithms offer high efficiency during all studied conditions. The efficiency depends on the level of disturbance.
- FL controller based MPPT extract higher average power under all the conditions.
- P&O and IC algorithms produce almost identical output power curves and very similar performance even though they use two different tracking approaches.
- All three MPPT techniques show ripple caused by oscillations around the MPP that reduce the value of average output power.

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