Performance of Different MPPT Control Techniques for Photovoltaic Systems

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***Abstract*— Photovoltaic (PV) energy being clean and inexhaustible is an important renewable energy source. For the efficient utilization of output energy of PV arrays, it is essential to operate PV systems in the Maximum Power Point (MPP). In contrast, the nonlinear behavior of PV systems, maximum power point variations with temperature and solar irradiance level make its tracking complicated. Since, there are various MPPT approaches proposed in the literature. This work presents a comparative study among three Maximum Power Point Tracking (MPPT) algorithms which are Proportional Integral Derivative (PID)-based incremental conductance, PID-based perturb and observe and Fuzzy Logic Controller (FLC) based modeling of PV systems. The controllers were stimulated using MATLAB/Simulink under various weather and load conditions in terms of efficiency, power quality and MPP error. The results of simulation show that the MPPT technique based on FLC is more efficient in comparison to other techniques, giving a fruitful energy conversion efficiency of 97.02%.**

Index Terms—Photovoltaic, Fuzzy Logic, MPPT Algorithms, Incremental Conductance, Perturb and Observe

I. Introduction

Photovoltaic systems being environmentally reliable energy sources are significant due their economical sustainability. However, the performance of PV modules is based on environmental factors, i.e., solar radiation and atmospheric temperature, which affects both current-voltage (I-V) and power-voltage (P-V) characteristics of the PV. Therefore, MPPT controller is required to reduce the impact of the environmental factors and to exploit the power from PV arrays optimally. Until now, various MPPT techniques have been proposed for extracting maximum power from PV systems. MPPT techniques are capturing much attention because of their significant improvements in the PV efficiency. There is no doubt that the initial installment cost of MPPT based PV system is quite high. Therefore, it is necessary to bring out some important simulations before going for practical implementation [1]–[6]. Different types of MPPT algorithms, e.g., perturb and observation, current feedback, hill climbing, incremental conductance, voltage feedback, neural network and fuzzy logic have been explained. Among the MPPT algorithms, voltage feedback and hill climbing are easy to deploy, but they are not efficient in maximum power point tracking when subjected to sudden changes in environmental factors. The conventional Incremental Conductance (IC) and Perturb and Observe (P&O) are much popular in the literature, since, they are easy to implement and show a better performance under various environmental factors. Unfortunately, the tracking process is slowed down by an extra *P-I* control loop.

Moreover, Fuzzy Logic (FL) control has been preferred for the MPPT of the PV system over the last several years. The MPPT controller based on FL is one of the most valuable control technique for the unpredictable PV system. Some recent researchers work related to FLCs are reported in [7]–[10]. The developed algorithm can track down the MPP with a remarkable speed and offers a dynamic behavior in response to the abrupt variations in environmental factors. Besides, the low cost practical execution of this technique can also be made based on existing components. In addition, the selection of an appropriate converter in PV-MPPT systems is also a big issue. Based on applications, various types of converters have been used [11], [12]. In this work three well known MPPT techniques, i.e., PID-based IC MPPT, PID-based P&O MPPT and FC based MPPT are developed and then compared.

The work is divided in five sections. The first one describes the PV with some methods used for (MPPT). The PV system model, MPPT algorithms and DC-DC boost converter are presented in Section II. MPPT techniques are discussed in section III with much focus is given to FLC based MPPT. Consequently, Section IV and V comprise necessary results, and brief conclusions, respectively.

II. Modeling of PV System

This section explains the modeling of proposed PV system. The layout of PV system connected with load is depicted in Figure 1. The PV system constitutes solar cells as their structural unit which can generate electricity using the solar irradiance. Generally, the PV system comprises of DC-DC boost converter. The model of a PV system can be characterized by following three differential equations [13].

$$\frac{dv_{pv}}{dt} = \frac{1}{C_a}\left(i_{pv} - i_{L1}\right) \tag{1}$$

$$\frac{dv_{L1}}{dt} = \frac{1}{L_1}\left(v_{pv} - vC_b\left(1-D\right)\right) \tag{2}$$

$$\frac{dv_{Cb}}{dt} = \frac{1}{C_b}\left(i_{L1}(1-D) - \frac{v_{Cb}}{R_L}\right) \tag{3}$$

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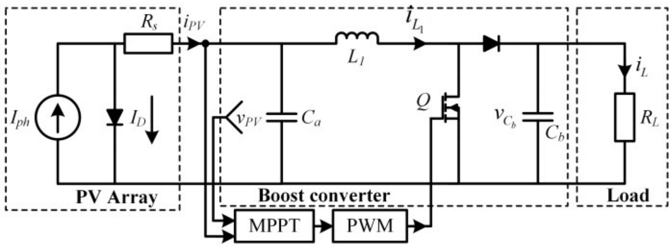

Figure 1: PV system

The P-V and I-V characteristics curves of PV array have non-linearity which is represented in terms of current and voltage and as follow:

$$i_{pv} = n_p I_{ph} - n_p I_D \left[\exp\left(\frac{v_{pv} + R_s i_{pv}}{n_s v_t} \right) - 1 \right] \quad (4)$$

where, v_t represents the terminal voltage, whereas n_p and n_s define the number of parallel and series connected cells in PV, respectively. The power generated by a PV system is given as:

$$P_{pv} = V_{pv} I_{pv} \quad (5)$$

The PV array holds non-linear characteristics which can be subjected to changes with respect to variations in temperature and solar irradiance level. The output power of PV array changes with respect to irradiance level and temperature. Therefore, the MPPT is necessary to track down the MPP existing on PV curve. In this research, a 250 kW PV array is used with various parameters which are given in table I.

Table I: Parameters of PV array

Parameter	Value
Model	SunPower SPR-305-WHT
VMPP of single module	54.7 V
IMPP of single module	5.58 A
No of series modules/string	13
No of cells/module	96
No of parallel strings	66
Open Circuit Voltage	64.2 V
Short-Circuit Current	5.98 A

2.1 DC-DC Boost Converter

The DC-DC boost converter is illustrated in figure 1. The purpose of this converter is to track down the MPP of PV by adjusting its duty cycle between [0,1]. According to the given duty cycle, the MOSFET (*Q*) is fed a pulse signal generated by a Pulse Width Modulation (PWM) generator. The nature of its non-linearity characterizes. The converter offers an input equivalent resistance as shown in below equation:

$$R_{eq} = R_i \left(1 - D\right)^2 \quad (6)$$

According to the principle of maximum power transfer, power transferred to the load is maximum when R_{eq} becomes equal to output resistance of PV array.

2.2 Maximum Power Point Tracking

As discussed earlier that the maximum power provided by PV arrays depends on the operating conditions such as temperature and solar irradiance. The role of MPP tracking is essential in drawing maximum power from PV arrays. It is important to set up MPPT algorithm that adjusts the power dynamically with reference to the prevailing conditions of weather and extracts maximum power out of PV arrays. The condition for the MPP is given as:

$$\frac{\delta p_{pv}}{\delta v_{pv}} = \frac{\delta v_{pv} i_{pv}}{\delta v_{pv}} = v_{pv} \frac{\delta i_{pv}}{\delta v_{pv}} + i_{pv} = 0 \quad (7)$$

whereas, the input error termed as *s* for MPP is determined using following equation:

$$s = \frac{\delta i_{pv}}{\delta v_{pv}} + \frac{i_{pv}}{v_{pv}} \approx \frac{i_{pv}(N) - i_{pv}(N-1)}{v_{pv}(N) - v_{pv}(N-1)} + \frac{i_{pv}(N)}{v_{pv}(N)} \quad (8)$$

whereas, *N* represents the no of iterations.

III. THE MPPT METHODS

3.1 Perturb and Observe (P&O)

The P&O is among one of the sophisticated and simplest MPPT methods employed in low cost systems. The principle is to observe the change because of disturbance made in voltage and current of PV module. The P&O change the current and voltage by comparing the power of previous and next step. The algorithm changes the reference values of voltage or current.

The P&O requires both current and voltage sensors as shown in figure 2 (a). To achieve better MPP, the step for converter's duty cycle is varied which results in an improved performance.

3.2 Incrementatl Conductance

There are some limitations of P&O, e.g., convergence speed and steady state error which can be overcome by the IC. It is easy and fast in response to solar irradiances. The technique uses the derivative of PV curve, as shown in figure 2 (b). The disturbance in operating point is less as compared to P&O which results in reduced error.

The condition of IC is explained by the following expressions.

$$\frac{dP}{dV} = \frac{d(V.I)}{dV} = I.\frac{dV}{dV} + V.\frac{dI}{dV} = I + V.\frac{dI}{dV} \quad (9)$$

$$\frac{dP}{dI} = \frac{d(V.I)}{dI} = I.\frac{dV}{dI} + V.\frac{dI}{dI} = V + I.\frac{dV}{dI} \quad (10)$$

The values of *V* and *I* are utilized in making algorithm decisions by comparing the incremental and instantaneous conductance as given below:

i. $\frac{\Delta I}{\Delta V} > -I/V$: The operational point is on the left side of MPP.
ii. $\frac{\Delta I}{\Delta V} = -I/V$: The operational point is exactly at MPP.
iii. $\frac{\Delta I}{\Delta V} < -I/V$: The operational point is on the right side of MPP.

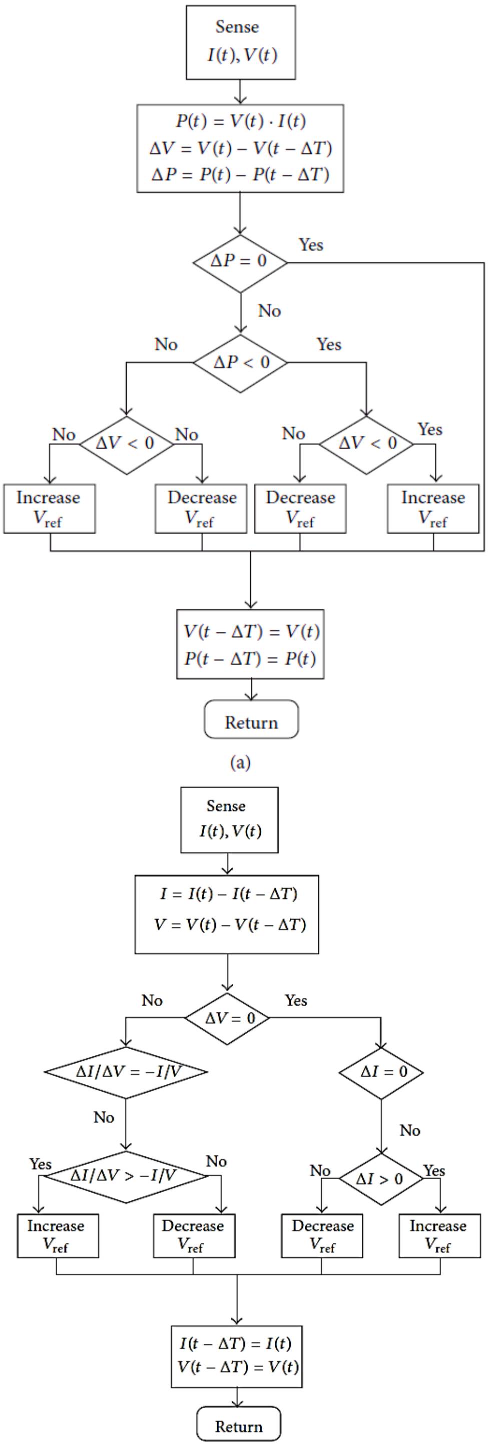

Fig. 2: Flowchart of algorithms (a) P&O (b) IC

3.3 The FLC based MPPT Controller Design

The nature of PV system is based on non-linearity. Therefore, for a conventional controller it is usually difficult to stimulate a non-linear system containing different parameters like regulation and damping, etc. Consequently, FLC is the best choice to control a non-linear system. The FLC has several inputs and its design needs expert knowledge. Based on FLC inputs, some rules are defined that corresponds to the FLC. There are majors three sections that constitutes the FLC namely Fuzzifier, Influence system and a Defuzzifier. The Fuzzifier converts crisp input values into the respective set referred to as a fuzzy set. The Influence system maps and apply fuzzy logic using the fuzzy set to create respective output which is also in the form of fuzzy set which is then converted into crisp value by a Defuzzifier via different conversion theorems. The model of FLC is shown in Fig. 3.

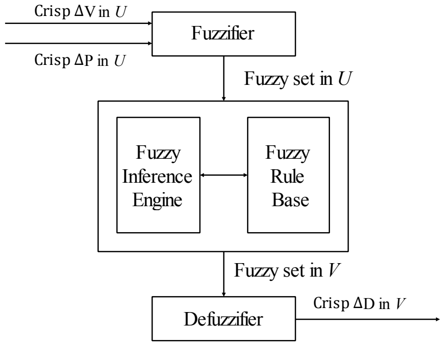

Figure. 3: FLC model

The FLC holds numerous inputs that are necessary to be defined first. In this work, the change in voltage (ΔV) and change in power (ΔP) are defined as inputs of FLC whereas, the change in the duty cycle (ΔD) is referred as the FLC output. Moreover, the ΔV, ΔP and ΔD have the following definitions:

$$\Delta P = \left[P(k) - P(k-1)\right] \times Y_1 \tag{11}$$

$$\Delta V = \left[V(k) - V(k-1)\right] \times Y_2 \tag{12}$$

$$D(k+1) = [D \pm \Delta D] \times Y_3 \tag{13}$$

In above expressions, time index is represented by k whereas, Y_1, Y_2 and Y_3 corresponds to the input and output scaling gains. Moreover, V_k and P_k represents the PV instantaneous voltage and power respectively. In this work, various linguistic variables are used and are listed in table II.

Table II: The FLC Linguistic variables

Change in Input Voltage (ΔV)		**Change in Input Power (ΔP)**		**Change in Output Duty Cycle (ΔD)**	
Positive Big	PB	Positive Big	PB	Positive Big	PB
Negative Big	NB	Negative Big	NB	Negative Big	NB
Positive Small	PS	Positive Small	PS	Positive Small	PS
Negative Small	NS	Negative Small	NS	Negative Small	NS
Positive Medium	PM	Positive Medium	PM	Positive Medium	PM
Negative Medium	NM	Negative Medium	NM	Negative Medium	NM
Zero	ZE	Zero	ZE	Zero	ZE

In literature different membership functions (MFs) have been used. By utilizing expert knowledge, Trapezium method is chosen to be the best based on its performance discussed in the literature [14]. Figures 4,5,6 show the MFs of inputs (ΔV and ΔP) and output (ΔD) respectively.

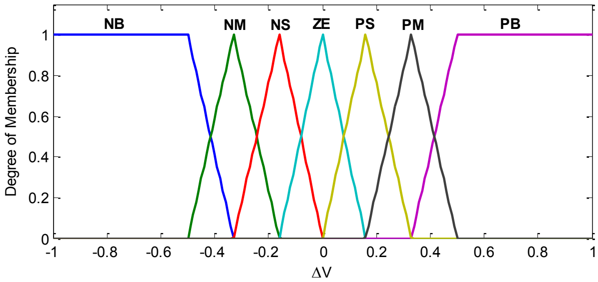

Fig. 4: The MF for input ΔV

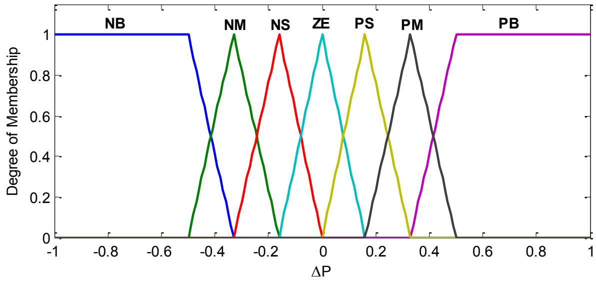

Fig. 5: The MF for input ΔP

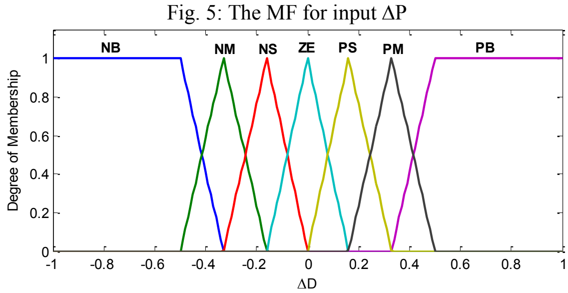

Fig. 6: The MF for output ΔD

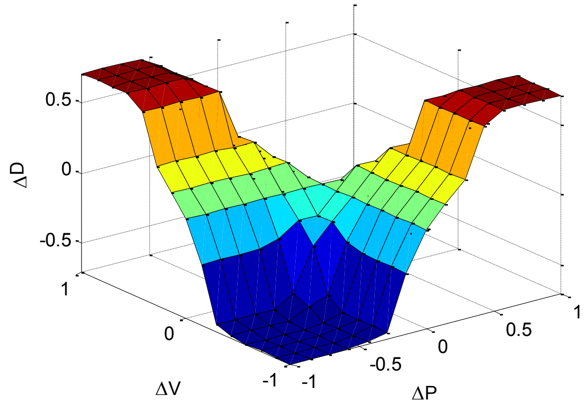

Fig. 7: The FLC I/O surface waveform

To develop an efficient FLC, fuzzy rules are the keys to consider. Moreover, the relationship between input and output is clarified by the surface waveform which is shown in figure 7. In addition to the expert knowledge used in the development fuzzy rules, there are some other parameters, e.g., error manipulation and system parameters that are also helpful in the definition of fuzzy rules when subjected to investigation. In this work, the proposed FLC model is stimulated using IF-THEN rule as listed in table III. To design FLC, Mamdani model is utilized.

Table III: The FLC rule base

ΔV / ΔP	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NM	ZE	PS	PM	PB
NM	NB	NM	NS	ZE	PS	PM	PM
NS	NM	NS	NS	ZE	PS	PS	PS
ZE	ZE	ZE	ZE	ZE	ZE	ZE	ZE
PS	PS	PS	PS	ZE	NS	NS	NM
PM	PM	PM	PS	ZE	NS	NM	NB
PB	PB	PM	PS	ZE	NM	NB	NB

The computational cost is increased when no of rules of FLC are increased. For modeling complex non-linear system, large no of rules are needed to be defined for its better performance and control. Therefore, in this research 49 rules are defined instead of 25. In this way curve of PV will track down the maximum power point effectively. The change that occurs in input parameters (ΔV and ΔP) is sensed by FLC and produces an output signal (ΔD), respectively. The control block generates a duty cycle D which is then fed to the boost converter as a PWM signal. Moreover, the value of D is calculated using the defuzzification algorithm referred as the Center of Gravity (COG) [15].

$$D = \frac{\sum_{j=1}^{k} D_j u_A(D_j)}{\sum_{j=1}^{k} u_A(D_j)} \tag{14}$$

IV. Simulation Results

This research is carried out both in winter and summer for a single day, e.g., 16th January, 2017 corresponds to winter day while 22nd June, 2017 corresponds to summer day. Moreover, Pakistan Metrological Department (PMD) Bahria Town, Islamabad, Pakistan has provided the data corresponding to the solar irradiance [16], [17]. Figure 8 (a) shows the solar irradiance data of both winter and summer plotted against time axis while the figure 8 (b) represents temperature variation with change in time (minutes).

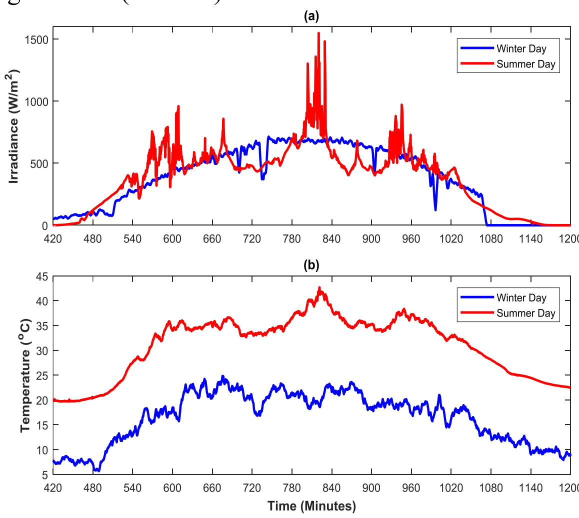

Fig. 8: Climate conditions for summer and winter day (a) Solar Irradiance (b) Temperature

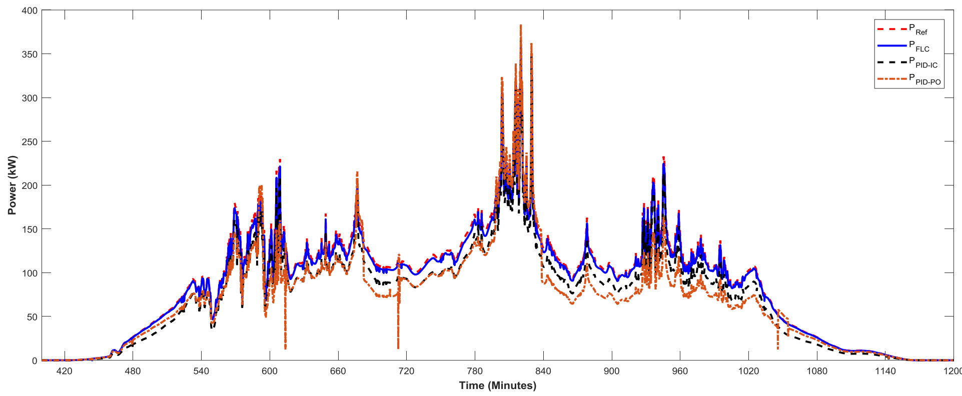

Fig. 9: The comparison of PV output power for proposed FLC, P&O and IC for summer day

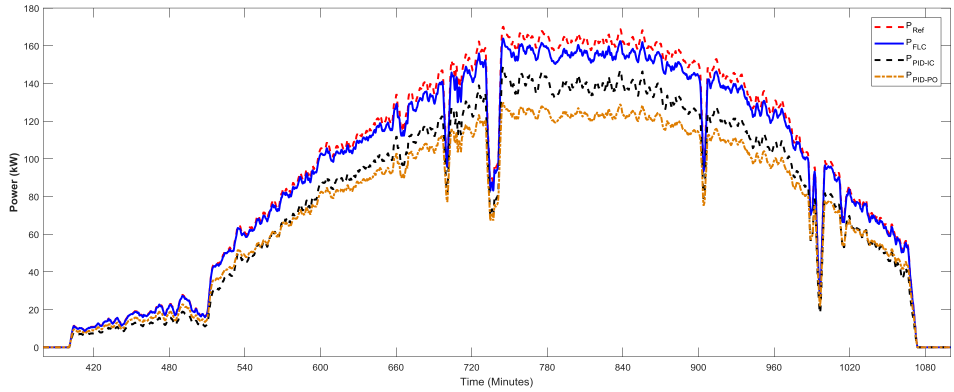

Fig. 10: The comparison of PV output power for proposed FLC, P&O and IC for winter day

At first, each module of the proposed system is individually modeled followed by the verification of each component. To avoid stability issues, all the modules are then combined for the sake of uninterruptable and reliable power transfer. To necessary make comparisons to the proposed algorithm, MPPT based incremental conductance IC and P&O controller are also designed.

Figure 9 shows the comparison plot of PV output power for the proposed FLC, P&O and IC recorded in summer. Similarly, the output power data of PV for the winter day are plotted in figure 10. The theoretical value of PV output power is calculated using equation 5 which is referred as reference power P_{Ref} in figure 9 and 10. It is observed from figure 9 and 10 that the output power of all controllers is almost same for low irradiance level below 200 W/m^2 both in summer and winter. When the solar irradiance increases, e.g., around 480 minutes and above, a lag in the performance of both the IC and P&O controllers are observed both in summer and winter showing various undershoots and poor responses. In contrast, the FLC controller showed excellent performance both in summer and winter following the reference output power curve while keeping the slope close to zero.

During the peak sun hours in summer around 700-900 minutes, the irradiance level is recorded to have maxima at 1500 W/m^2. The corresponding MPP located in figures 9 is identified to be 380 KW. The proposed FLC controller has tracked down the MPP to an efficient level of 370 KW. Similarly, during winter around 700-850 minutes, the maximum irradiance level is around 600 W/m^2. The MPP identified in power curve corresponding to the maximum irradiance level is 170 KW. The FLC perfectly tracks down the MPP giving 160 KW at its output as shown in figure 10. In contract, the performance curves of both the IC and P&O controllers show significant gaps with respect to the P_{Ref}.

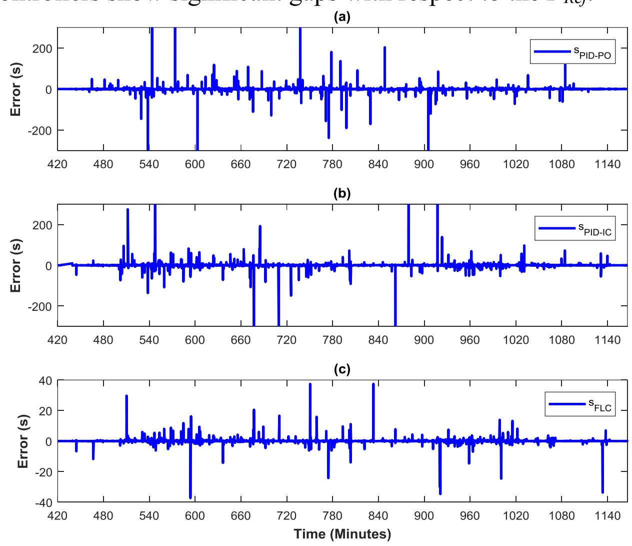

Fig. 11: MPP tracking error comparison for summer day (a) P&O (b) IC (c) FLC

The validity of the proposed algorithm is ensured through the negligible deviation observed between output power of FLC controller and P_{Ref}. In order to evaluate the performance of each controller in a better way, it is necessary to analyze the MPP error tracking plot for each controller. The MPPT tracking error for both the days are shown in figures 11 and 12. The spikes in the curves are due to rapid changes in the solar irradiance level. The MPP changes its position with respect to the change in the irradiance level, which in turn changes the value of s. Moreover, the controller adjusts its duty cycle to mitigate this error. It is observed from the figures 11 and 12 that the FLC based MPPT controller shows error up to 40 for both summer and winter. This is a clear edge of FLC controller over the IC and P&O controllers showing error up to 200. The proposed FLC controller captures the MPP so quickly and efficiently that the error spikes do not exceeds 40.

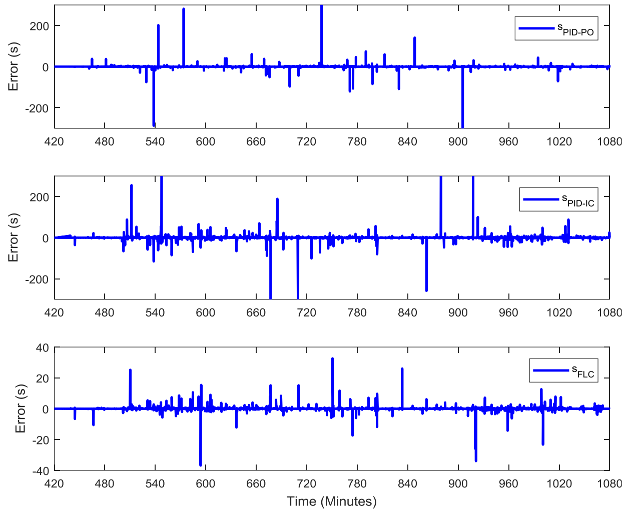

Fig. 12: MPP Tracking error comparison for winter day (a) P&O (b) IC (c) FLC

Table IV: The PV Efficiencies: FLC, IC and P&O

Controllers	η_{PV} (%age)	$\eta_{PV\text{-}av}$ (%age)
FLC	97.02	94.68
PID-IC	84.21	80.12
PID-PO	81.54	77.64

On the basis of the output power of various controllers stimulated, the efficiency and average efficiency of PV are calculated using the following equations:

$$\eta_{pv} = -\int_0^t P_{pv}(t)dt \Big/ \int_0^t P_{ref}(t)dt \times 100\% \qquad (15)$$

$$\eta_{pv-avg} = \frac{1}{T}\eta_{pv} \qquad (16)$$

whereas, η_{pv} and $\eta_{pv\text{-}avg}$ is the PV efficiency and PV average efficiency, respectively. The efficiency results of controllers stimulated for 1440-minutes under a sampling frequency of 10^{-6} are given in table III.

V. Conclusions

In this work, three well known MPPT techniques, viz., IC MPPT, P&O MPPT and FC based MPPT are simulated and then compared. The simulation results along with the efficiencies comparison table have shown that FLC based MPP tracker can track down the maximum power point more quickly and efficiently showing high robustness towards the parameter variations compared with the traditional MPPT techniques. Furthermore, IC MPPT is slightly performing well than P&O MPPT in terms of efficiency and MPPT error, but its implementation is easier than IC MPPT and FLC MPPT controller. In terms of dynamic response and transitional states, the FLC controller proposed showed a better behavior as clarified from the MATLAB results.

VI. Acknowledgments

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