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Comparison of Fuzzy Logic and PI MPPT Algorithm with Indirect Controller for PV Systems

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Abstract: *This paper presented the Fuzzy Logic based on Maximum Power Point Tracking (FLC MPPT) with an indirect controller under varying weather conditions and steady state condition. Most of MPPT methods only were tested in a few regions under uncertain weather conditions. A simulation work handling with MPPT controller, and a boost converter with an indirect controller. Proportional-Integral (PI) controller and fuzzy logic controllers are compared to evaluate the performance in terms of tracking towards rapid irradiance change. The simulation results showed the fuzzy logic controller had better performance compared with the PI controller. The fuzzy logic controller can reduce oscillation and it provides rapid response under rapid solar irradiance changes. Furthermore, it did not require any tuning of the parameters, unlike conventional PI controller.*

Keywords: *SISOFLC, Fuzzy Logic MPPT, PI MPPT, DC/DC boost converter.*

1. INTRODUCTION

Photovoltaic (PV) energy is one of the most important renewable energy resouces. It has serveral advantages such as plentiful, clean, inexhaustible and low cost operational. However, there are some drawbacks of PV system, like as high installation cost and low conversion efficiency due to oscillation in conversion process [1]. In order to overcome these drawbacks, maximum power should be caught using maximum power point tracking (MPPT). Several methods of maximum power point tracking have been considered. These methods require intelligent controllers such as fuzzy logic controller (FLC) and conventional controllers such as proportional-integral (PI) controller. Genetic Algorithm is used for optimizing PI by offline control (GA) [4]. An intelligent control technique using fuzzy logic control is associated to an MPPT controller in order to improve energy conversion efficiency. There are observable voltage shifts where the MPP occurs. So, the MPPT controller is also required to track the new modified maximum power point in its corresponding curve whenever temperature and/or insolation variation occurs. [5]. The regular FLC with two inputs has been introduced in a photovoltaic system as MPPT, such in the work of [2],[3]. However, the setup and adjustment of the FLC rules huge numbers leads to a big computing time and more over using a big memory. Therefore a speed/accuracy trade-off is inevitable. Simulations have been performed in Matlab/Simulink on various weather conditions. It can be confirmed from simulation analysis that proposed method is quite able to track MPP efficiently even under fast changing weather conditions [7],[8],[9]. Also, it exhibits negligible power loss oscillation under static weather conditions.

This paper main contribution is to formulate a FLC with a reduced complexity and hence achieve a faster and easier implementation without compromising fuzzy capabilities [10],[12],[13]. This FLC is proposed with only a single-input that is an error and a voltage reference as an output (SISOFLC). This controller is used for boost converter control. The SISOFLC is expected to reduce the computational burden and the processing time because it has significantly fewer rules to evaluate. The proposed technique is compared with conventional PI technique. Comparison results indicate that the proposed method has the best perform than others.

1.1 Modeling of Solar Cells

PV model can be obtained through analysis of the equivalent circuit of solar cells as shown in Fig-1. The circuit consists of a current source (I_{ph}), diodes (I_D), shunt resistors (R_{Sh}) and series resistor (R_S) [6].

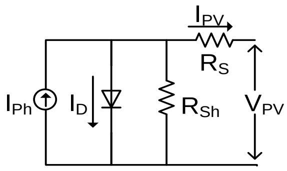

Fig 1: *Equivalent circuit of a solar cell [6]*

The output of the solar cell's equivalent circuit is a current I_{PV} and voltage V_{PV}. I_{pv} can be calculated by using analysis of Kirchhoff's current law to the circuit as shown in Equation (1):

$$I_{PV} = I_{Ph} - I_D - I_{Rsh} \tag{1}$$

The value of I_{ph} is heavily dependent on the irradiance (λ) and solar cell temperature (T_C). The I_{Ph} equation can be expressed by the following equation (3):

$$I_{PV} = (I_{SC}\lambda / \lambda_{ref}) + K_I(T_C - T_{ref}) \tag{2}$$

$$I_{Ph} = (I_{SC} + \mathrm{K_I}(\mathrm{T_C} - \mathrm{T_{ref}}))\ \lambda/\lambda_{\mathrm{ref}} \tag{3}$$

While the current is flowing through the diode I_D, as shown in the equation (4):

$$I_D = I_S\left(exp\left(\frac{q(V_{PV} + R_s I_{PV})}{AkT_c}\right) - 1\right) \tag{4}$$

Saturation current (I_S) of solar cells can be expressed in a mathematical equation that has a relationship with the temperature of the solar cell as follows:

$$I_S = I_{RS}\left(\frac{T_C}{T_{ref}}\right)^3 exp\left(\frac{qE_G\left(\frac{1}{T_{ref}} - \frac{1}{T_C}\right)}{kA}\right) \tag{5}$$

where,

$$I_{RS} = I_{SC} / (e^{\frac{qV_{oc}}{AkT_c}} - 1) \tag{6}$$

The current I_{Rsh} in a closed loop can be determined by using Kirchhoff's voltage law analysis, which is expressed in equation (7):

$$I_{Rsh} = \frac{I_{PV}.R_S + V_{PV}}{R_{sh}} \tag{7}$$

Therefore, the output current (I_{PV}) were previously expressed by equation (1), can be restated by equation (8):

$$I_{PV} = I_{Ph} - I_S\left(e^{\frac{q(V_{PV} + R_s I_{PV})}{AkT_c}} - 1\right) - \frac{V_{PV} + R_S I_{PV}}{R_{Sh}} \tag{8}$$

A PV array is a group of several PV modules which are electrically connected in series (Ns) and parallel (Np) for generating more power. The equivalent circuit of a PV array is expressed as follows:

$$I_{PV} = N_P I_{Ph} - N_P I_S\left(e^{\frac{q(V_{PV}/N_S + R_s I_{PV}/N_P)}{AkT_c}} - 1\right) - \frac{V_{PV} N_P / N_s + R_S I_{PV}}{R_{Sh}} \tag{9}$$

where I_{PV} is the output current of solar cells (Ampere), I_{Ph} is photocurrent (Ampere), I_S is saturation current of solar cells (Ampere), V_{PV} is output voltage of solar cells (Volt), I_{SC} is short circuit current (Ampere), λ is Irradiance (kW/m^2), λ_{ref} is Irradiance reference (kW/m2), T_C is the temperature of the solar cell (Kelvin), K_I is temperature coefficient, T_{ref} is the reference temperature of Solar Cells (Kelvin), I_{RS} is reverse saturation current (Ampere), K is Boltzmann's constant (1.38x10-23), A is ideality factor of PV technology, q is electron charge (1.6x10-19 Coloumb), and V_{oc} is open circuit voltage (Volt). These simulation used parameter values which are shown in Table 1.

Table 1: *Parameter values of PV panel (STC)*

Parameter	Value	Unit
Maximum power, Pmax	50	Watt
Open circuit voltage, Voc	22.5	Volt
Short circuit current, Isc	3.04	Ampere
Temperature coefficient of Isc	1.52 x10^{-3}	A/°C
Number per module	36	-

Fig -2 shows characteristics of I-V curve under varying solar irradiance, while Fig -3 shows characteristics of P-V curve. The PV panel has a maximum power point (MPP) under various climate conditions. The MPP can be determined by calculating gradient of the variation of power against variation of voltage is equal to zero [$e = I + \left(dI.\frac{V}{dV}\right)$]. When the voltage is less than the MPP voltage the gradient is positive, otherwise when it is larger than the MPP voltage the gradient is negative. Fig -4 shows the relationship between the power gradient and voltage.

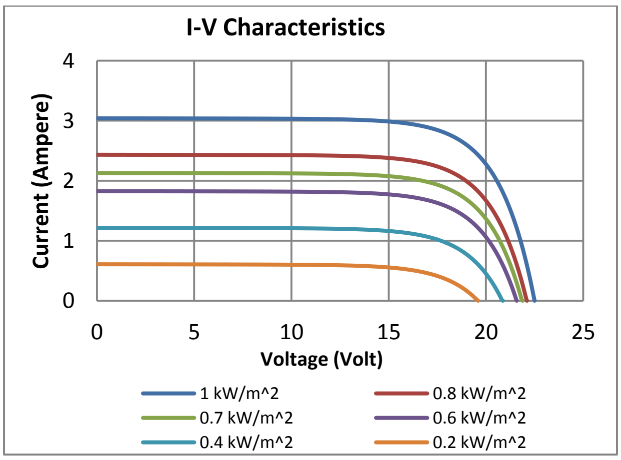

Fig 2: *I-V characteristics of the PV panel*

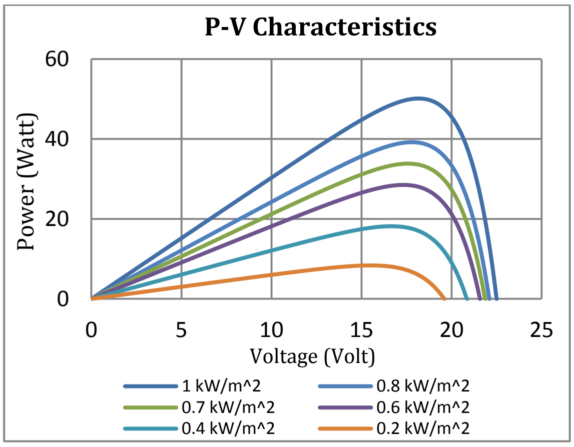

Fig 3: *P-V characteristics of the PV panel*

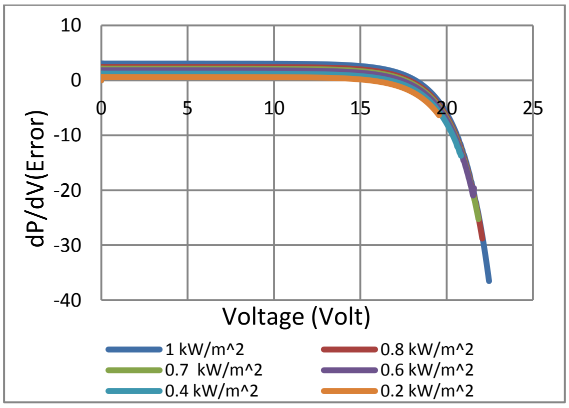

Fig 4: *dP/dV-V characteristics of the PV panel.*

1.2 Modeling of DC-Dc Boost Converter

Fig -5 shows the boost converter that has been connected with PV module. The output voltage of PV (V_{PV}) can be adjusted by controlling the duty cycle on the switch of a boost converter circuit while the output voltage of the boost converter is kept constant. R_L is a parasitic resistance in the inductor L. I_{C1} is a current flowing through the capacitor C_1, while I_L is the current flowing in the inductor. V_D is voltage of diode. The boost converter dynamics is modeled by the following equations:

$$L\frac{di_L(t)}{dt} = V_{pv}(t) - R_L I_L(t) - uV_o(t) \qquad (9)$$

$$C_1\frac{dV_{pv}(t)}{dt} = I_{sc} - Ipv(t) - uI_L(t) \qquad (10)$$

where u represents switching mode which the closed mode when $u = 1$, and opened mode when $u = 0$. The equation of relationship between input and output voltages is expressed by equation (11):

$$V_o = \frac{V_{pv}}{(1-D)} \qquad (11)$$

where D denotes duty ratio. A parameters of boost converter which used in this simulation is shown in Table 2.

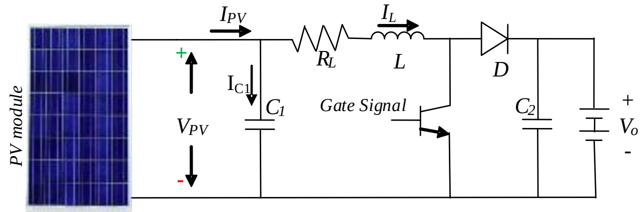

Fig 5: *PV module and dc-dc boost converter*

Table 2: *DC-DC boost converter parameters*

Parameter	Value	Unit
Maximum power	50	Watt
Ouput voltage	30	Volt
Switching frequency	100	kHz
C1	680	uF
C2	2x820	uF
L	100	uH

2. DESIGN OF PI AND FLC MPPT

2.1 Design of PI MPPT

The external PI MPPT controller used $[e = I + \left(dI.\frac{V}{dV}\right)]$ as error which is used for calculating voltage reference.The inner PID controller is used to regulate deviation between the voltage reference (Vpv_ref) and the output voltage of PV which is read by the voltage sensor. The input variable of external PI MPPT is given as follows.

$$e = I + (V.\frac{dI}{dV})$$

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau$$

The inner PID controller output is given as follows.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d\frac{de(t)}{dt}$$

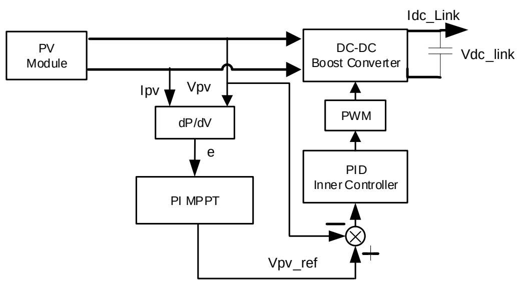

Fig 6: *PI MPPT control with inner PID controller*

2.2 Design of FLC MPPT

The design of FLC with indirect controller is shown in Fig -7. The input variable of the FLC is $e\frac{dP}{dV_{pv}}$ which is used for calculating voltage reference. After that, the voltage reference will be fed to the inner PID controller. The input (fuzzification block) consists of five membership function subsets: Negative big(NB), Negative small(NS), Zero(ZE), Positive small(PS), and Positive big(PB) which shown in Fig -8. The rule base of the FLC also consist of five membership function subsets: Small scale(SS), Medium Scale-1(MS1), Center scale(CS), Medium Scale-2(MS2), Big scale(BS) which shown in Fig -9. Mamdani's with Max-Min method is used for inference process. When the error either big negative or big positive which means the operating point is far from the MPP(maximum power point). Therefore, the large adjusting duty cycle is needed to reach the MPP quickly.. When the error almost close to zero, the operating point is reached and remains near the MPP.

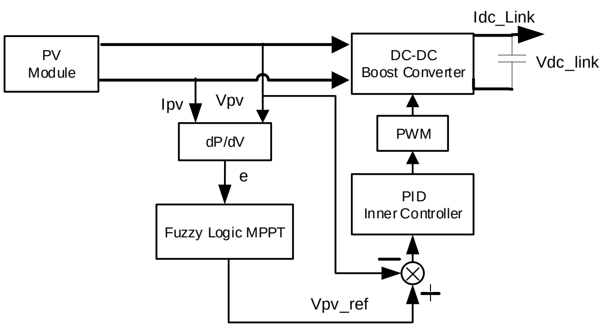

Fig 7: *FLC MPPT control with inner PID controller*

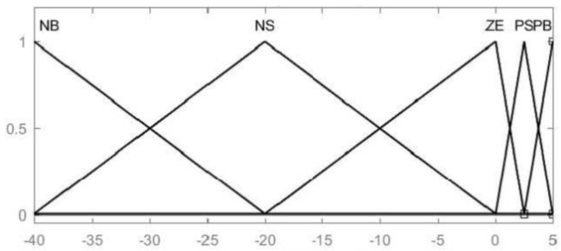

Fig 8: *Membership function of input variable*

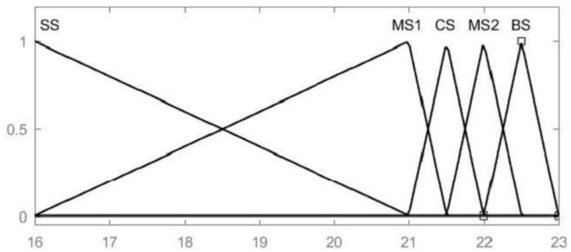

Fig 9: *Membership function of voltage reference*

Table 3: Membership function of voltage reference

Output	Input: Error $e(k)$				
	NB	**NS**	**Z**	**PS**	**PB**
Vpv_ref	SS	MS1	CS	MS2	BS

3. SIMULATION RESUTLS AND DISCUSSION

3.1 Dynamic Weather Conditions

To verify the both methods of PI MPPT and FLC MPPT with indirect control, a Matlab/Simulink model was designed (Fig -4) that included a mono crystalline PV block. The spesifications of PV are listed in Table 1. The parameters of dc-dc boost converter are shown in Table 2. Fig -10 shows the profile variation of irradiation step change condition from 200(W/m²) to 1kW/m² in 0.5 seconds, then the irradiance falls from 1kW/m² to 200(W/m²) in 0.5 seconds.

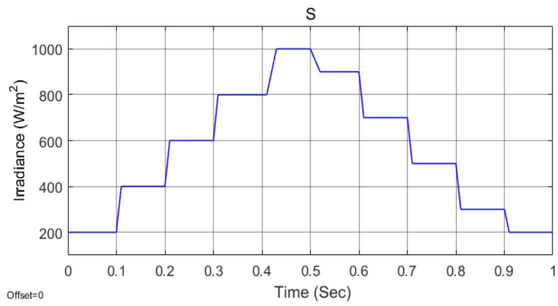

Fig 10: *Profile of irradiance (W/m²-Sec)*

Fig -11 shows the output voltage of PV occurred large oscillation when the radiation above 600 (W/m²). Fig -12 shows the output power of PV occurred also large oscillation and a power drop when the radiation changed from 700(W/m²) to 500 (W/m²).

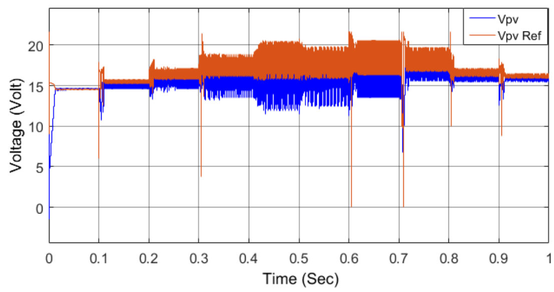

Fig 11: *Output voltage of PV using PI MPPT*

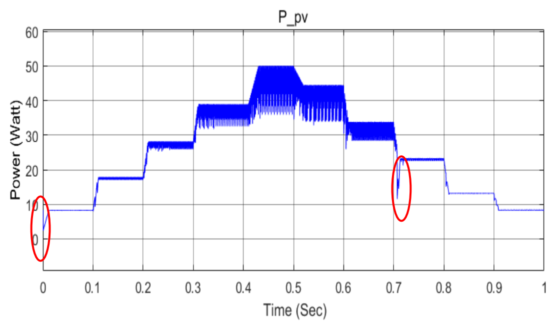

Fig 12: *Output power of PV using PI MPPT*

Fig -13 shows the output voltage of PV occurred small oscillation when the radiation exceeds 800 (W/m²).

Fig -14 shows the output power of PV occurred also small oscillation and capable overcome the power drop when the radiation changed from 700(W/m^2) to 500 (W/m^2).

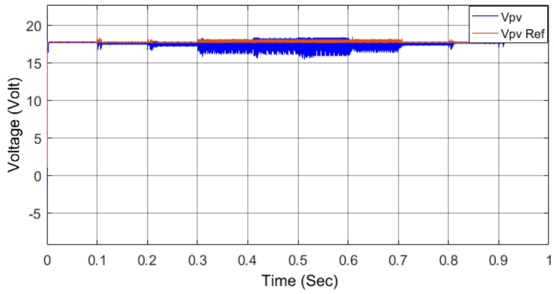

Fig 13: *Output voltage of PV using FLC MPPT*

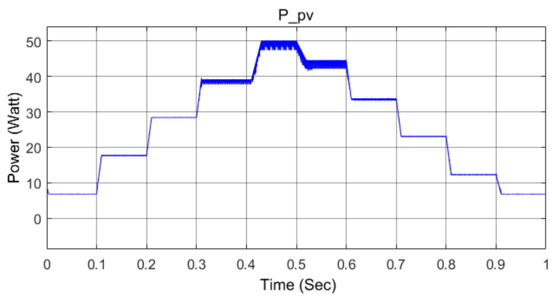

Fig 14: *Output power of PV using FLC MPPT*

Table 4: *Oscillation results of MPPT control*

MPPT Control	Maximum Oscillation Peak (V)	Period of Oscillation (second)	Irradiance (W/m^2)
PI	4	1	700
FLC	0.6	1	700

3.2 Steady Weather Conditions

To compare the average power results between conventional PI MPPT control and FLC MPPT was used the constant radiation 700 (W/m^2). Fig -15 shows the average power of FLC was 33.68 Watt, and standard deviation 0.15. Otherwise in Fig -17, PI MPPT method shows the output average power 33 Watt, and standard deviation 0.85. Fig -16 and Fig -18 shows oscillation difference the PV output voltage with FLC MPPT and PI MPPT, respectively.

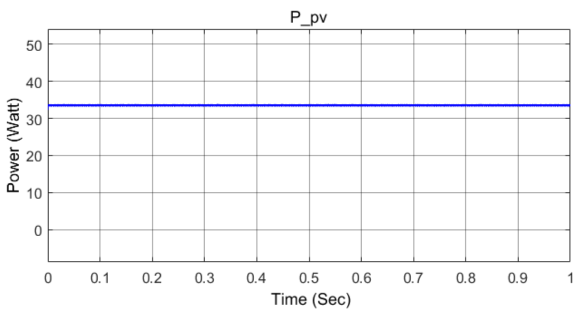

Fig 15: *PV output power with FLC MPPT*

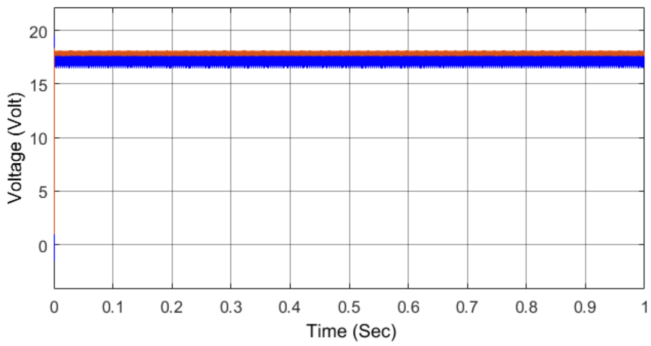

Fig 16: *PV output voltage with FLC MPPT*

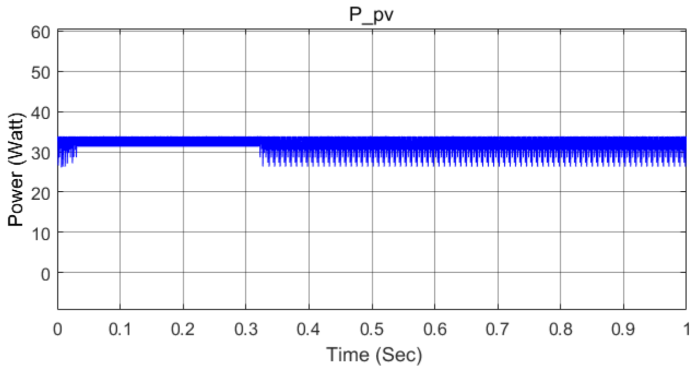

Fig 17: *PV output power with PI MPPT*

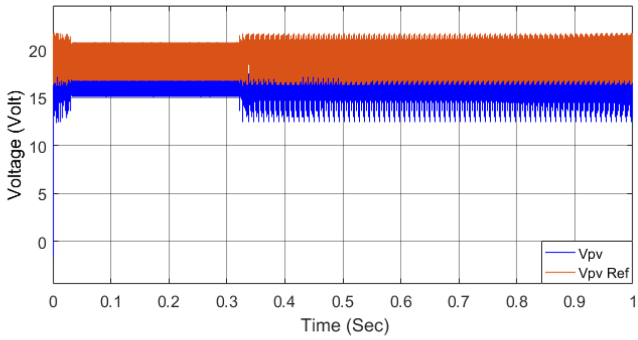

Fig 18: *PV output voltage with PI MPPT*

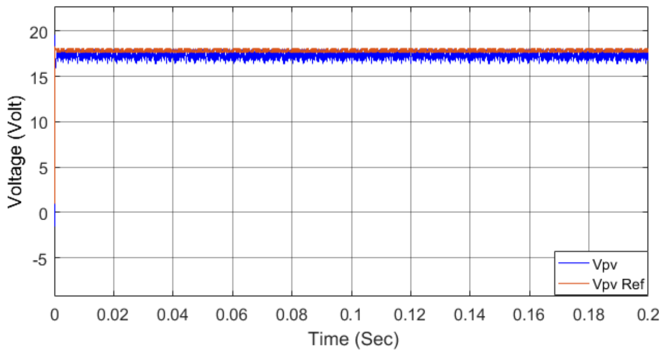

Fig 19: *Output voltage of using FLC MPPT*

Fig -19 and Fig -20 reinforced the oscillation between the FLC MPPT and PI MPPT. The data can be taken for 0.2 seconds to avoid the data over storage in memory of the computer simulation.

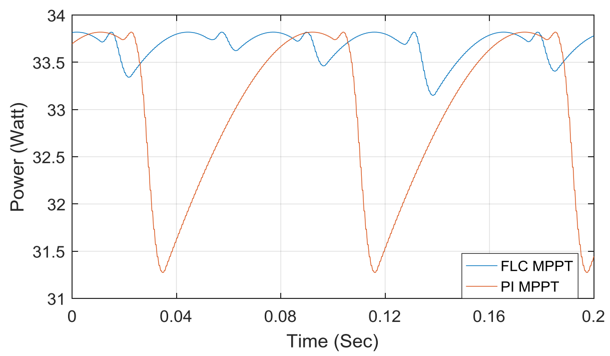

Fig 20: *Comparison of output power of PV*

4. CONCLUSIONS

From the simulation results the following conclusion can be drawn. The developed controller can regulate to track the maximum power point under irradiance in insolation. The power efficiency can be improved under steady state condition around 2% than conventional PI MPPT. These results prove that the FLC MPPT with indirect method has fast time response, less overshoot and better power efficiency than a conventional PI method. It can be concluded that the developed control system satisfies the design specification.

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