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A robust maximum power point tracking control for PV panel using adaptive PI controller based on fuzzy logic

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ABSTRACT

Most methods of maximum power point tracking (MPPT) for photovoltaic (PV) focus only on tracking performance while robustness against disturbances has rarely been addressed. This paper proposes a new MPPT control method that provides robustness against direct current (DC) link voltage disturbance as well as good tracking performance. The method uses indirect MPPT control topology which incorporates two controllers. For the external controller, we use an adaptive proportional-integral (PI) control which is real-time tuned by fuzzy logic (FL). New membership functions and rule base are proposed using only one fuzzy input variable and 10 fuzzy rules. The internal controller is a PI controller. The PV panel is connected to a boost DC-DC converter. The proposed MPPT control is compared with the fuzzy logic controller (FLC). Performance is evaluated under DC link voltage disturbance, steady-state condition, and rapid solar radiation changes. Simulation results indicate that the proposed method provides 41.2 % better robustness against DC link voltage disturbance as compared to the direct FLC. Experimental results under natural climate conditions with real solar radiation validate that the proposed method works well in regulating the MPP at steady-state solar irradiance as well as in tracking the MPP towards rapid solar irradiance changes. It yields the PV power tracking speed of 95.75 W/s.

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1. INTRODUCTION

Electric power generated from a photovoltaic (PV) panel depends on the intensity of solar radiation and temperature. There are several main factors which affect the maximum electric power output including short-circuit current, open-circuit voltage, and the maximum power voltage and current. In general, electric power generated from a PV panel is sent to a direct current-direct current (DC-DC) converter. The electric power output from the converter is sent to a direct current-alternating current (DC-AC) inverter, can be directly used for battery chargers, or even directly sent to the load if the PV system is off-grid. A maximum power point tracking (MPPT) control system is needed to maximize power conversion under different climatic conditions. Articles on MPPT control for PV panels have been widely published. According to the previous survey and comparison studies [1-3], the published MPPT methods may be classified as follows: Conventional methods such as incremental conduction (IC), perturb and observed (PO), hill climbing (HC), and the improved versions of them;

Soft computing methods including artificial neural networks (ANN), fuzzy logic control (FLC), and evolutionary algorithms (EA); analytical methods such as golden section optimization and extremum searching; and feedback control using dP/dV or dP/dI.

We can also classify MPPT control methods into direct MPPT control and indirect MPPT control. A controller that maximizes power conversion by directly modifying the duty ratio is a direct MPPT control. Several articles on direct MPPT control method have been published i.e. perturb and observe (PO) [4, 5], modified PO [6], IC [4, 5, 7, 8], incremental resistance (IR) [9], cuckoo search algorithm (CSA) [10], ICM with fuzzy logic [11], FLC [12-20], adaptive FLC based on two layers FLC [21], FLC using auto scaling variable step-size [22], and constant PID control [15, 16]. Genetic algorithm (GA) is used to optimize constant proportional-integral (PI) control [23], Ant colony algorithm (ACO) is utilized for optimizing constant PI control [24], gradient descend method is adopted for PID control optimization [25], FLC is used for adaptive PID control [26, 27], adaptive scaling factor is used for fuzzy gain scheduling (FGS) PID control [28], and Big Bang-Big Crunch (BB-BC) algorithm is used to tune a fuzzy PID controller [29]. In an indirect MPPT control an external controller sends a reference command signal to an internal controller. For the external controller, various methods have been proposed i.e. dP/dV feedback control [30-32], modified PO [33, 34], and PO with FLC [35]. For the inner loop controller, several controllers have been published i.e. proportional (P) [30, 31], proportional integral (PI) [33-37], the root-locus technique based PID controller [38], fuzzy logic based adaptive PID controller [39], adaptive MPPT using auto-tuning [40], and constant controller based on Youla parameterization [41].

Some articles have carried out comparisons between the direct PID control, the direct FLC, and the direct adaptive PID control based on fuzzy logic. They concluded that direct FLC is better than the direct PID control [15, 16]. The direct adaptive PID Fuzzy controller provides better performance than PO method [27], the FGS PID control with the adaptive scaling factor gives better performance than PO method and constant PID controller [28]. It is important to note that those direct adaptive PID control methods incorporated two fuzzy input variables which yield a large number of fuzzy rules: 75 rules in [27], and many more rules in [28]. Additionally, the above direct adaptive PID control-based MPPT methods were only evaluated through computer simulations and were not validated through experimental studies. In the indirect MPPT control, a fuzzy adaptive PID controller is used in the internal loop while the external loop uses a dynamic set-point adjustment mechanism [39]. The authors concluded that the controller produced better tracking efficiency as compared to PO, incremental conductance (IC) with PI regulator, FLC, NN, and ANFIS. However, this indirect fuzzy adaptive PID controller needs 3 sensors i.e. current sensor, temperature sensor, and a solar radiation sensor. Moreover, the fuzzy logic involves as much as 147 rules.

The objective of this paper is to design an MPPT control which gives robustness performance against DC link voltage disturbance, good regulation performance, and satisfactory tracking performance under rapid solar radiation changes. A new MPPT control method for a PV panel is proposed based on indirect MPPT control topology. The controller only needs 2 sensors and as less as 10 fuzzy logic rules. Its performance is compared to a direct FLC. Furthermore, the effectiveness of the proposed MPPT control method is verified through experiments under natural climate conditions with real solar radiation.

This paper is organized as follows; section 1 is the introduction. Section 2 describes the research method including modeling of the PV module, modeling of the PV boost converter, previous studies on MPPT using fuzzy logic and PID control, and the proposed fuzzy adaptive PI MPPT control. Section 3 presents results and analysis. Finally, the conclusion is drawn in section 4.

2. RESEARCH METHOD

2.1. Modeling of the PV module

Relationship between current and voltage of a PV module is given below [42-44].

$$I = I_L - I_o\left\{e^{\left[\frac{(V+IR_S)}{a}\right]} - 1\right\} - \frac{V+IR_S}{R_{SH}} \tag{1}$$

$$a = \frac{N_S nkT}{q} \tag{2}$$

The PV module generates current I and voltage V. I_L is light current, I_0 is saturated diode reverse current, R_S and R_{SH} are equivalent serial and parallel resistances. N_S is the number of PV cells connected in series in the PV module, n is *p-n junction* factor, k is the Boltzmann's constant, T is PV panel temperature, and q is the electron charge. PV cell manufacturers usually provide values at standard testing conditions (STC) (1000 W/m^2, 25 °C) of short-circuit current I_{scn}, open-circuit voltage V_{ocn}, maximum power point (MPP) current I_{mpn}, maximum power point voltage V_{mpn}, and the number of cells N_s. Some parameter values depend on solar irradiance and the panel temperature. They are expressed below;

$$a = a_n\left(\frac{T}{T_n}\right) \tag{3}$$

$$I_L = \frac{S}{S_n}\left[I_{scn} + K_1 \cdot \Delta T\right] \tag{4}$$

$$I_0 = I_{0n}\left(\frac{T}{T_n}\right)^3 exp\left[\left(\frac{qE_g}{nk}\right)\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{5}$$

K_1 is coefficient of short circuit current, $\Delta T = T - T_n$, and band-gap energy E_g. A PV array that is constructed by PV modules in series and parallel connection, posseses the following relationships.

$$I = N_{pp}I_L - N_{pp}I_o\left\{e^{\left[\frac{(V+IR_SN)}{N_{ss}a}\right]} - 1\right\} - \frac{V+IR_SN}{R_{SH}N} \tag{6}$$

$$N = \frac{N_{SS}}{N_{pp}} \tag{7}$$

N_{SS} and N_{PP} denote number of modules connected in series and parallel, respectively.

Figure 1 shows the P-V characteristics of the PV panel used in this paper under various solar irradiance. The PV module has a maximum power point (MPP) at any time under different climate conditions. The value of MPP can be calculated by the gradient of power variation against voltage variation, e = dP/dV, equals zero. When the voltage is less than the MPP voltage it is positive, oppositely when it is larger than the MPP voltage the gradient is negative. The relationship between power and voltage can be shown in Figure 2.

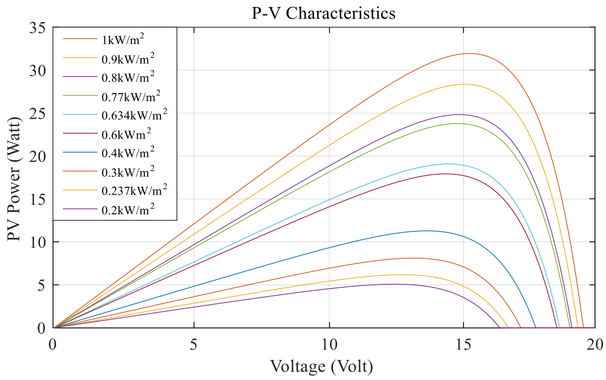


Figure 1. P-V characteristics of the PV panel

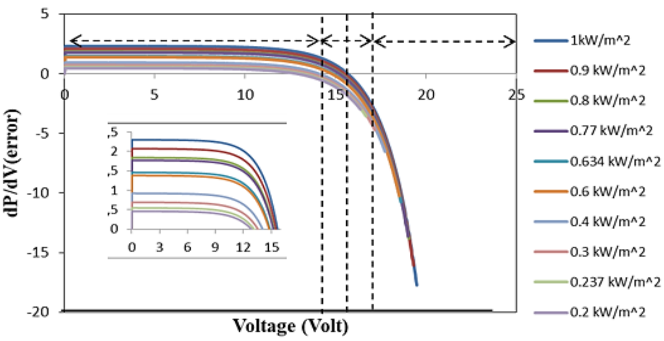


Figure 2. dP/dV-V characteristics of the PV panel

2.2. PV DC-DC boost converter model

The PV panel is connected to a DC-DC boost converter. A small-signal model of the converter has been derived and proven through experiments [45]. Determination of the dynamic model of the DC-DC boost converter in a PV system can be calculated with the same approach. The dynamic equation can be calculated as follows;

$$L\frac{di_L(t)}{dt} + ri_L(t) = V_{pv}(t) - uV_o(t) \tag{8}$$

$$C_i\frac{dV_{pv}(t)}{dt} = I_{sc} - \frac{V_{pv}(t)}{R_{pv}} - ui_L(t) \tag{9}$$

L, r, C_i denote inductance, internal resistance, and input capacitor. i_L is inductor current, and u represents switching mode. R_{pv} is dynamic resistance of the PV panel. The converter operates in closed mode (on) when $u = 1$ and in open mode (off) when $u = 0$. The relationship between input and output voltages is expressed as follows:

$$V_{pv} = (1 - D)V_o \tag{10}$$

where D denotes duty ratio. The dynamic resistance R_{pv} is given by the following equation,

$$R_{pv} = \frac{V_{pv}}{I_{pv}} \tag{11}$$

2.3. Previous study on MPPT using fuzzy logic and PID control

In this section different MPPT control methods previously published are revisited. Those are direct MPPT FLC, direct MPPT using adaptive PID-FLC, and indirect MPPT using adaptive PID-FLC. In a direct MPPT FLC, the fuzzy logic calculates the duty ratio. Error signal dP/dV and its rate of change are used as fuzzy input variables [11-13]. Each input and output variable has five fuzzy sets, and 25 fuzzy rules were used [12, 13]. In [12] the performance was assessed only by computer simulation and without solar irradiance rapid change. In [13] the performance was verified through computer simulation and experiments. It can be observed that it produced good tracking performance but oscillation existed at the steady-state conditions. Each input and output variables utilized seven fuzzy sets, and the rule base consisted of 49 fuzzy rules [14]. A computer simulation was conducted to assess its performance. The results demonstrated that the controller could give dynamic response against solar irradiance change but with a slow response. Figure 3 shows a block diagram of a direct MPPT adaptive PID control based on fuzzy logic [27]. It is termed as direct MPPT adaptive PID-FLC. The simulation results indicated that the controller could track the MPP better than the well-known PO method [27].

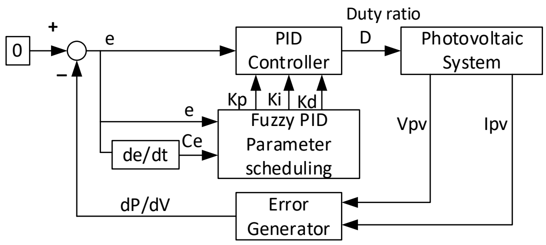


Figure 3. Direct MPPT adaptive PID-FLC [27]

The PID controller calculates the duty ratio using the error signal dP/dV. The PID controller's parameter values are auto-tuned using fuzzy logic. The fuzzy logic uses two fuzzy input variables i.e. the error signal dP/dV and its rate of change. Each fuzzy input and output variables are divided into five fuzzy sets. However, explanation regarding membership function, fuzzy input and output variables, fuzzification, and defuzzification methods could not be found [27]. No experiment result was reported.

An indirect MPPT adaptive PID control using fuzzy logic was published consisting of an adaptive PID current controller and a set point tracker [39]. It is named as indirect MPPT adaptive PID-FLC. The MPPT method gives larger efficiency when compared to PO, INC, fuzzy logic, and ANFIS under fast solar irradiance changes [39]. The setpoint tracker calculates the current set point using solar irradiance, the PV module temperature, and datasheet from the manufacturer. A specific factor is also needed [46]. The PID controller gets current reference from the setpoint tracker and sends duty ratio to the switching driver. The fuzzy logic tunes the PID controller's gain values in a real time manner. The fuzzy logic uses two inputs those are the current error signal and its rate of change. Each fuzzy input and output variables are divided into seven fuzzy sets. Its fuzzy rule base involves 147 rules. The requirement of the mentioned three sensors and the quite amount of fuzzy rules might prohibit the method to be implemented.

2.4. The proposed fuzzy adaptive PI MPPT control

This paper proposes a new MPPT method which incorporates an internal PI controller and an external adaptive PI controller which is auto-tuned by an FLC. The advantages of this MPPT method are two folds: it only requires two sensors for voltage and current measurements; the FLC only needs one fuzzy input and 10 fuzzy rules. Moreover, this indirect MPPT topology can enhance robustness against DC link voltage disturbance while maintaining a good tracking response towards fast solar radiation changes. Figure 4 shows a block diagram of the proposed MPPT control.

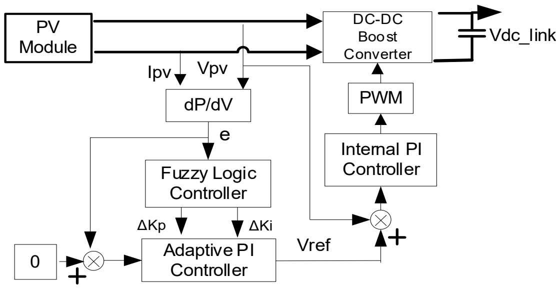


Figure 4. The proposed indirect MPPT control based on adaptive PI control using fuzzy logic

The internal PI controller is used to regulate the PV voltage V_{pv} so that it tracks the reference V_{ref}. The reference is generated by the external adaptive PI controller in such a way so that $e = \frac{dP}{dV_{pv}}$ being zero. V_{ref} is given by the external adaptive PI controller in (12).

$$V_{ref}(t) = -K_p e(t) - K_i \int_0^t e(\tau)d\tau \qquad (12)$$

Initial values of the adaptive PI controller's gains are (K_{pi}, K_{ii}). The controller parameters values (K_p, K_i) are auto tuned by fuzzy logic as follows;

$$K_p = K_{pi} + \Delta K_p \qquad (13)$$

$$K_i = K_{ii} + \Delta K_i \qquad (14)$$

The FLC only uses the error signal as the input and calculates the fuzzy output variables ΔK_p and ΔK_i. Each fuzzy input and output variables are divided into five fuzzy sets, viz. negative big (NB), negative small (NS), zero (Z), positive small (PS), and positive big (PB). A total number of only 10 rules are necessary as shown in Table 1. This reduces the computation burden so that it is more implementable as compared to the previously published methods described in the previous section.

Table 1. Rule base for the fuzzy ouput variables

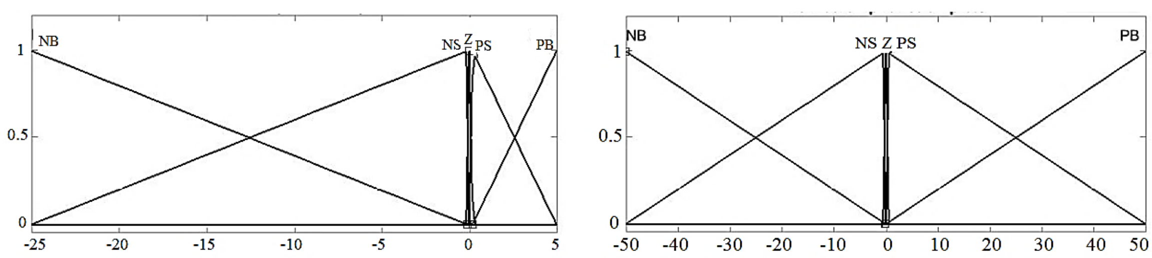
Output	Input: Error $e(k)$				
	NB	NS	Z	PS	PB
ΔK_p	NB	NS	Z	PS	PB
ΔK_i	NB	NS	Z	PS	PB

3. RESULTS AND ANALYSIS

The proposed MPPT method has been implemented into computer simulation as well as experiments. Through computer simulations, its performance is compared with the direct FLC to evaluate robustness performance against DC link voltage disturbance and tracking performance towards solar irradiance step-like changes as well as steady-state conditions. Then, its effectiveness is validated through experiments under natural climate conditions with real solar radiation.

3.1. Simulation

Computer simulation is conducted using a physical model represented in Simulink®. The PV model is built using S-function, the converter is built using Simulink model components, and a discrete time controller is designed. Solar irradiance is varied and the produced PV power is evaluated. For performance comparison study, a direct MPPT FLC has also been designed using error signal e and its rate of change de as fuzzy input variables. Five membership functions are used for each fuzzy input. The duty ratio is used as the fuzzy output variable. Figures 5 and 6 show its membership functions of fuzzy input and output variables, respectively. The values of each fuzzy set are determined based on values deviation obtained through simulation. It involves a total number of 25 rules, and Mamdani fuzzy interference method is used.



(a) (b)

Figure 5. Membership functions of fuzzy input of the direct FLC: (a) error signal e, (b) rate of change de

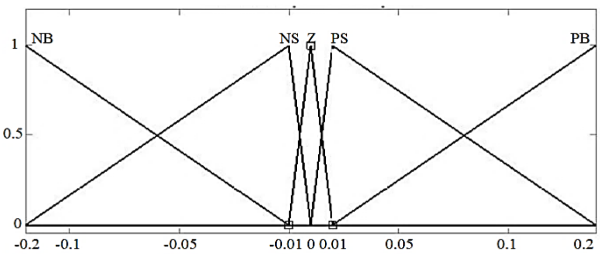


Figure 6. Membership functions of fuzzy output of the direct FLC MPPT

Two kinds of testing have been conducted. Each objective and scenario are as follow:
- Testing 1. Its objective is to evaluate the robustness performance of an MPPT control system against DC link voltage disturbance. During operation under certain solar irradiance conditions, a disturbance is suddenly applied in the DC link voltage, and the produced power is observed to assess the effect of the disturbance to PV power. Such disturbance may come from the load or the grid.
- Testing 2. Its objective is to evaluate tracking performance towards the variation of solar irradiance as well as regulation performance under steady-state conditions throughout various solar irradiances. Its solar irradiance profile is composed of step-like changes with different slopes and different step hight in small, medium, and high solar irradiance zones.

In testing 1 solar irradiance is set constant at 770 (W/m^2) while the DC link voltage is originally 30 (V). Since it is in steady-state condition the power produced by the PV panel is assessed by comparing with the static P-V curve in Figure 2. Suddenly the DC link voltage drops to 25 (V), and the PV power is monitored to observe its dynamics. Figures 7 (a) and (b) plot power produced by the PV panel using the proposed MPTT control method and the direct FLC, respectively. The horizontal axis denotes time in seconds and the vertical axis represents power in Watt.

In testing 2, the solar irradiance profile is generated as shown in Figure 8. Table 2 lists up steady-state value (SSV) and slope value (SV) of each solar irradiance condition. Figure 9 shows the corresponding simulation results. From visual observation, it is obvious that the proposed method can track maximum power points under varying solar irradiance and can regulate it in steady-state condition.

Percentage of power drop, $RP(\%)$, is used for quantitative assessment of robustness performance against DC link voltage disturbance. The smaller value indicates better robustness performance.

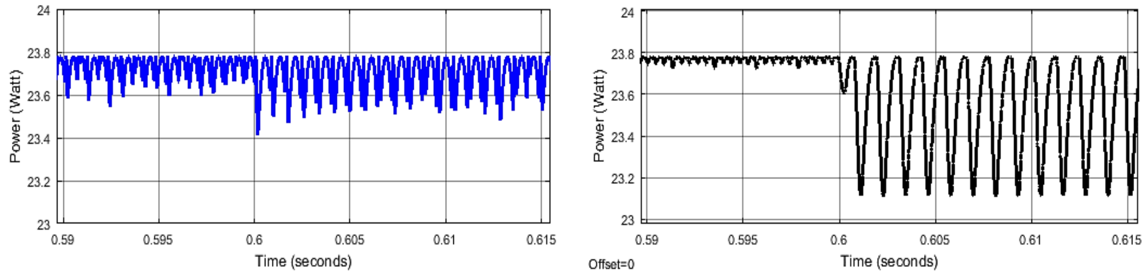
$$RP(\%) = \frac{(P_n - P_d)}{P_n}(100) \quad (15)$$

where P_n is the average of maximum power under normal operation, P_d is the average of minimum power under disturbance. On the other hand, the amount of energy is used for the quantitative evaluation of tracking performance and regulation performance of the MPPT methods. The amount of energy (Joule) is calculated as follows:

$$E(t) = \int_0^t P_{pv}(\tau)d\tau \quad (16)$$

The larger value indicates better tracking and regulation performance.

Table 3 summarizes robustness performance under testing 1, and tracking as well as regulation performance under testing 2. From this table, it can be said that the proposed MPPT control method has better robustness performance but worse tracking and regulation performance compared to the direct FLC. From Table 3, we can calculate (2.86-1.68)/2.86 = 0.412. Thus, the robust performance of the proposed indirect adaptive PI-FLC is 41.2 % better than that of the direct FLC. On the other hand, the regulation and tracking performance degradation of the proposed method in testing 2 is 2.1%. However, it can be observed from Figure 9 (a) and Figure 9 (b) that regulation performance degradation of the proposed method happens when solar irradiance is at around 200 ($W/m^2/s$) and 1000 ($W/m^2/s$). From real measurement, it is known that most of the time when solar irradiance is available at the location of the experiment it is between 300 ($W/m^2/s$) and 930 ($W/m^2/s$). Thus, the tracking and regulation performance of the proposed MPPT control method is still acceptable.



(a) (b)

Figure 7. Robustness performance tesing (Testing 1): (a) adaptive PI-FLC, (b) direct FLC

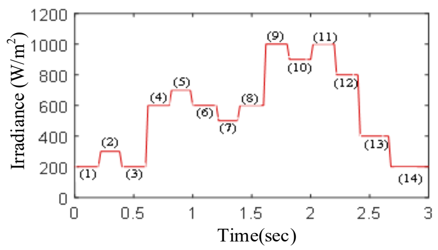
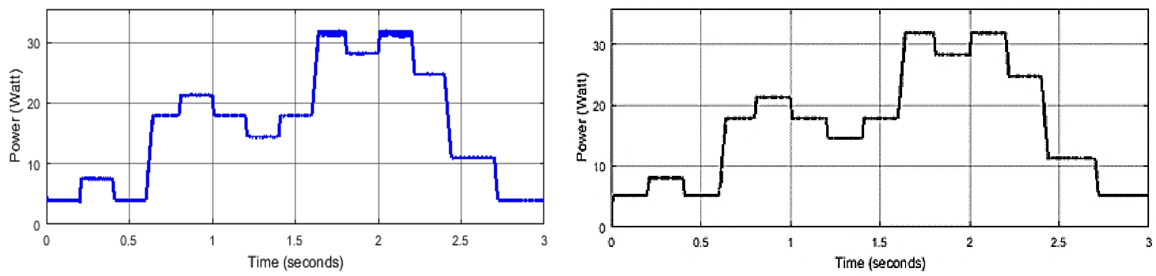


Figure 8. Irradiance profile for step like rapid changes and steady-state testing (Testing 2)

Table 2. Steady-state value (SSV) and slope value (SV) of irradiance

No	Parameter	Value						
1	SSV (rise to)	(1)	(2)	(4)	(5)	(9)	-	
	(W/m^2)	200	300	600	700	1000		
2	SSV (fall to)	(3)	(6)	(7)	(10)	(12)	(13)	(14)
	(W/m^2)	200	600	500	900	800	400	200
3	SV (rise)	(1)	(1-2)	(3-4)	(4-5)	(8-9)	-	-
	($kW/m^2/s$)		5	20	5	20		
4	SV (fall)	(2-3)	(5-6)	(6-7)	(9-10)	(11-12)	(12-13)	(13-14)
	($kW/m^2/s$)	-5	-10	-20	- 5	-10	-20	-10



(a) (b)

Figure 9. PV power in testing 2; (a) indirect adaptive PI-FLC, (b) direct FLC

Table 3. Performance indicator values

No	Performance	Value	
		Indirect API-FLC	Direct FLC
1	Robustness (Testing 1), (%)	1.68	2.86
2	Tracking and regulation (Testing 2), (Joule)	48.64	49.69

3.2. Experiment

To evaluate the effectiveness of the proposed MPPT control method, experiments have been carried out in real natural climate conditions. The experimental set up mainly consists of a PV panel, a dc-dc boost converter, a single-phase inverter, a bulb lamp as the load, a data logger, and a computer for Human Machine Interface as shown in Figure 10. A pyranometer is fixed at the experimental set up only for solar irradiance monitoring. The controller algorithm is implemented in a Texas Instrument's TMS320F28035 DSP which controls the switching of the boost DC-DC converter at a switching rate of 100 kHz. The topology of the boost DC-DC converter is the same as that in the previous publication [45]. It has the maximum power of 50 watts, and the switch uses IRFR3607TRPBFCT ND-channel MOSFET. In the experiment, two performance indicators are adopted i.e. regulation performance under steady-state condition of solar irradiance and tracking performance towards solar irradiance change. A large amount of experiments under various solar irradiance conditions have been done, but only selected results of three experiment scenarios are reported. These scenarios are believed to represent well other conditions. During experiment parameters values of the internal PI controller were kept constant. Its sampling rate is 50 kHz. The initial values of the external adaptive PI controller parameters were first determined through the tuning process under the solar radiance of around 634 (W/m^2). Their values are $K_{pen} = 0.16$, and $K_{ien} = 0.07$. It works at a sampling rate of 10 Hz. The real values of external PI controller gains are adaptively tuned by the fuzzy logic. The values of characteristic coordinates of the fuzzy logic variables used in experiments are listed in Table 4.

(a)

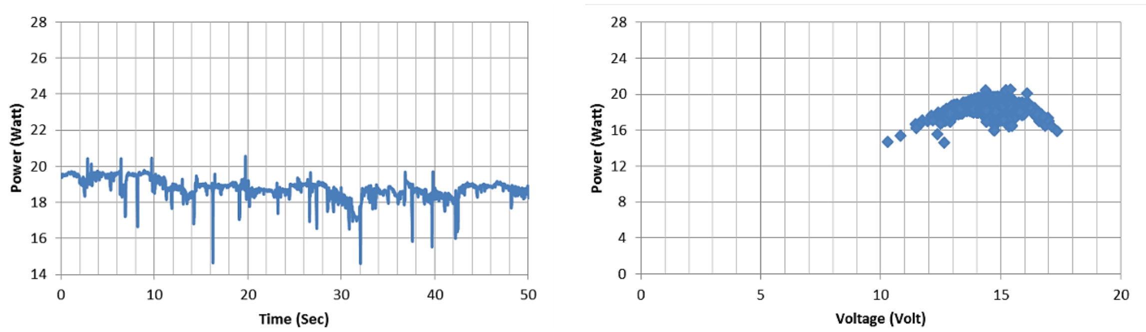
(b)

Figure 10. Experimental set up; (a) PV panel, (b) instruments and HMI computer

Table 4. Characteristics coordinates of the fuzzy logic variables (e, ΔK_{pe}, ΔK_{ie})

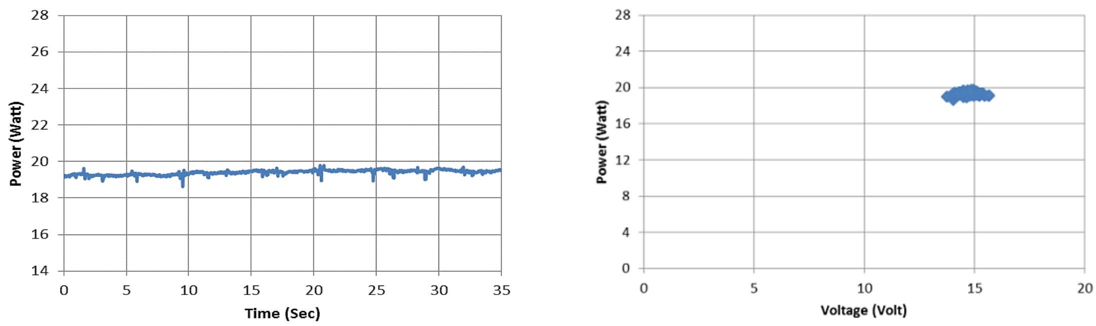
Output	Input: e				
	-5.0	-0.25	0.0	0.25	5.0
ΔK_{pe}	-0.05	-0.025	0.0	0.025	0.05
ΔK_{ie}	-0.05	-0.025	0.0	0.25	0.5

Experiment 1 and experiment 2 were conducted to evaluate the effect of the fuzzy logic in adaptively controlling the external PI controller parameter values. The PV panel was experiencing real natural solar radiation of around 634 (W/m^2) in almost steady-state conditions. Regulation and robustness performance of the adaptive PI-FLC is compared with that of the nominal PI controller. Figure 11 shows the results of experiment 1 using the indirect MPPT nominal PI controller while Figure 12 shows those of experiment 2 using the indirect MPPT adaptive PI FLC. Each time histories of the PV panel power is shown on the left side. On the right side is the plot of the P-V curve. Notice that the PV power in Figure 12 is better regulated with smaller swing compared to that in Figure 11. From the experiments, the following quantitative results were obtained. The nominal PI controller provides average power of the PV panel of 18.86 W with standard deviation value of 0.60 W. On the other hand, the adaptive PI-FLC provides average power of 19.4 W with standard deviation value of 0.13 W. Thus, the adaptive PI-FLC gives larger power with smaller standard deviation value than the PI controller. These experiment results validate that proposed MPPT control effectively provide good regulation and robustness performance.



(a) (b)

Figure 11. Experiment results using PI controller: (a) PV panel power, (b) P-V curve

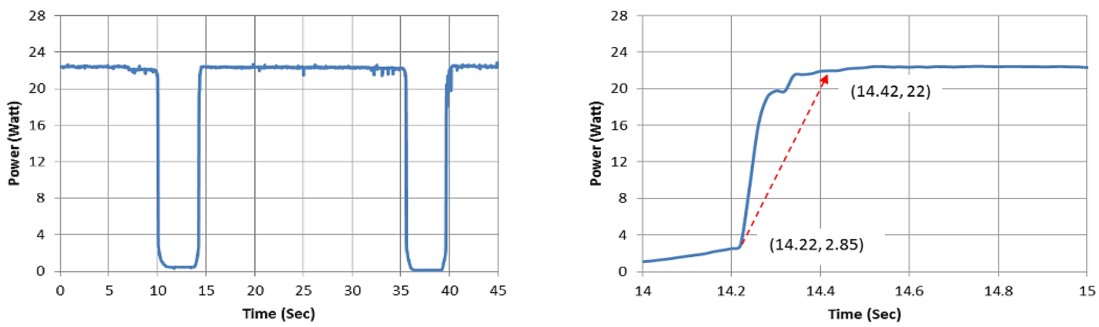


(a) (b)

Figure 12. Experiment results using adaptive PI-LFC: (a) PV panel power; (b) P-V curve

In experiment 3, the tracking performance of the adaptive PI-FLC was evaluated by manually opening and closing the PV panel under solar irradiance of 708 (W/m^2). Closing the PV panel surface with a thick carton shuts off the solar radiation into the panel. The measured PV power is plotted in Figure 13. These results demonstrate that the controller can track the MPP when the solar irradiance changes drastically, from 708 (W/m^2) decreases to almost zero, and then increases back to 708 (W/m^2).

A deeper analysis of the repetition tracking responses in Figure 13 (a) and the closed up of the tracking response in Figure 13 (b) reveals two satisfactory results. First, from Figure 13 (a) the PV panel MPPT control responses consistently well towards solar irradiance fast changes repeatedly. Secondly, from Figure 13 (b) the PV power rises fastly from 2.85 W at time 14.22 s to its MPP of 22 W at time 14.42 s. Thus, the average speed of the PV power tracking is 95.75 W/s. These experimental results validate the satisfactory tracking performance of the proposed MPPT control method. This research is being expanded into parameter values optimization of the internal controller and the external adaptive PI-FLC of the proposed MPPT control method in order to obtain better performance of both performance indicators.



(a) (b)

Figure 13. Tracking performance of the PV power: (a) tracking repetition, (b) closed up

4. CONCLUSION

The simulation results indicate that the proposed MPPT control method provides 41.2 % better robust performance than the direct FLC, with acceptable tracking performance and regulation performance. Through experiments under natural climate conditions with real solar radiation, the proposed MPPT control method has been evaluated in terms of regulation performance and tracking performance. The experiment results validate that the proposed MPPT control method works well in regulating the PV panel system at maximum power points. It also tracks maximum power points towards fast irradiance changes yielding the PV power tracking speed of 95.75 W/s.

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