

A Fuzzy Control Maximum Power Point Tracking Photovoltaic System

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Abstract -- Conventional maximum power point tracking (MPPT) method, e.g. perturbation and observation (P&O) and incremental conductance (INC), have the drawbacks such as oscillation at the MPP during power fast tracking and power divergence under rapidly changing atmospheric condition. Thus, a fuzzy logic controller (FLC) is implemented in the PV system to avoid the conventional problem. FLC method has not only fast response under rapidly changing atmospheric conditions but also small oscillation at the maximum power point (MPP). However, FLC presents tuning difficulty of membership function, scaling factor and control rules. The FLC disadvantages can be reduced using single-fuzzy logic controller (S-FLC) without degrading its performance. The experiment results are shown to verify the studied S-FLC MPPT method.

Keywords: *Maximum Power Point Tracking, Photovoltaic Module, Single-Fuzzy Logic Control*

I. INTRODUCTION

Worldwide energy consumption has increased rapidly due to world population growth. Since amount of fossil energy source has no longer enough, renewable energy sources such as solar power, wind power, geothermal power, and fuel cell are considered to meet the global demand for energy. Aside from the unlimited amount of the sources, renewable energy has advantages such as no or low pollution emissions compared with fossil energy. Among these renewable energy sources, solar energy is one of the most appropriate and primary renewable energy [1, 2]. Although the first PV cell was developed in 1954 [3], the researcher began to conduct its further development in the 1970s. They have improved device efficiency and reliability with lowered cost by using new material and fabrication process [4]. Currently, improvement of PV system performance is the goal of the development.

Development of PV system is generally focused on two areas: the PV cell manufacturing process and materials and the PV power management strategy. Techniques in manufacturing have had significant progress in terms of higher efficiency with lower cost. Regarding to PV power management, implementation of PV system with inappropriate strategy will result in low efficiency. Thus, PV power management strategy including energy conversion system is a very important part in efficiency improvement. One of the energy conversion strategies being developed is method to find maximum power of the PV module that known as maximum power point tracking (MPPT) method. The MPPT method automatically finds the maximum voltage or maximum current of a PV module at which it will operate to reach the maximum power

output under certain temperature and irradiance. To obtain good performance, numerous methods are proposed to be implemented in the PV system. Based on the control algorithm, these proposed MPPT methods can be categorized into conventional and intelligent methods. The conventional MPPT method includes perturbation and observation (P&O), incremental conductance (INC), voltage-feedback methods, and so on. Fuzzy logic control (FLC), neural network, genetic algorithm, and so on is based on intelligent algorithm, thus it categorized into intelligent method.

The P&O and INC method are commonly used in the MPPT system because of their simple implementation. However, the P&O method has two drawbacks regarding its performance. The first is power oscillation at the maximum power point (MPP) and the other one is divergence of the MPP under rapid atmospheric change [5, 6, 7, 8]. The problem of power oscillation at the MPP also occurs in the INC method when fast tracking of the maximum power is desired. In the case of solar vehicle which its load consist mainly of batteries, these two methods are not suitable to be implemented. Therefore, an appropriate MPPT method that can quickly converge to MPP without oscillation problem is needed to maximize load current or voltage. One of alternative method to be implemented in this case is FLC MPPT method [8]. The implementation of FLC method in the MPPT system is referred to [9, 10, 11]. Some Improvements of FLC MPPT method has been proposed but it still with complex control rules [10, 11]. Consequently, FLC presents difficulty of modification and tuning of control rules. Due to this reason, B.J. Choi et. al. [12, 13] simplified the inputs of FLC to only one input that known as single-fuzzy logic controller (S-FLC). Besides simplicity of tuning of membership function, scaling factor and control rules, S-FLC present some other advantages such as the control rule table is built in one-dimensional space, the computational complexity is reduced, it is equivalent to the sliding mode control with a boundary layer and so on [13].

II. PV MODULE CHARACTERISTIC

A PV module is composed of PV cells connected in series to achieve required output voltage within a certain range of the system voltage under condition of average irradiance and temperature. The simplest circuit model of PV cell is represented by a current source paralleled with an ideal diode as shown in Fig.1. The current source I_p represents a current source generated by solar radiation. This current source is also called as the photo generated current.

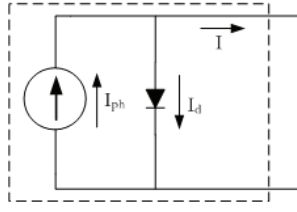


Fig.1. The equivalent circuit of ideal PV cell

The corresponding I - V characteristic can be described by the Kirchhoff's Current Law (KCL) where the output current I is the subtraction result of the current source I_p and the diode saturation current I_d . This characteristic can be written as:

$$I = I_p - I_d \left(e^{\frac{qV}{k_B T}} - 1 \right) \quad (1)$$

where k_B is the Boltzman constant (1.381×10^{-23} J/K), T is the absolute temperature (in Kelvin), $q(>0)$ is the electron charge (1.602×10^{-19} C), and V is the voltage at the terminal of the cell (in Volt).

In an ideal case, the open circuit voltage V_{oc} is calculated where the short circuit current I_{sc} is equal to the current source I_p . It can be written as:

$$V_{oc} = \frac{k_B T}{q} \ln \left(1 + \frac{I_p}{I_d} \right) \quad (2)$$

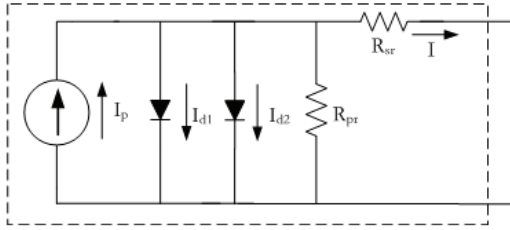
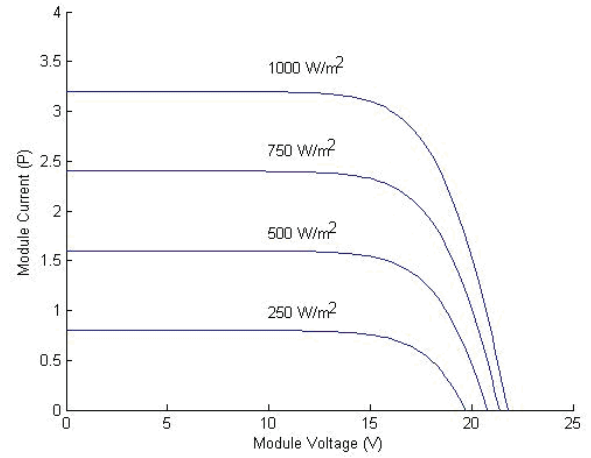


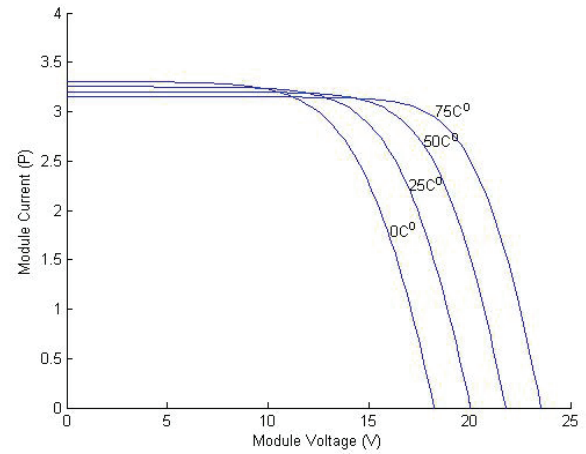
Fig.2. The equivalent circuit of non-ideal PV cell

In practice, a non-ideal circuit is used to model the PV cell represented by a two-diode, shunt resistance R_{pr} , and series resistance R_{sr} as shown in Fig. 2. These components relates to the maximum power which can be generated by the PV cell. In details, the two-diode is used to correct an ideal characteristic curve and the two-resistor is leading to a characteristic of the form where the photo generated current may depend on the voltage. Instead of the equation (1), the characteristic equation is now written by incorporating ideality factor of two which appeared in the exponential term of the second diode. The equation becomes [14]:

$$I = I_p - I_{d1} \left\{ \exp \left(\frac{V + IR_{sr}}{k_B T} \right) - 1 \right\} - I_{d2} \left\{ \exp \left(\frac{V + IR_{sr}}{2k_B T} \right) - 1 \right\} - \frac{V + IR_{sr}}{R_{pr}} \quad (3)$$



(a)



(b)

Fig.3. The I - V characteristic of BP350 PV module (a) under different levels of irradiance and (b) under different levels of temperature

The relationship among power P , current I and voltage V produced by the PV module is shown in Fig. 3. The figure shows if the PV module generates power maximum P_{max} at the maximum voltage V_{max} and the maximum current I_{max} and it is varying with present temperature and irradiance.

III. FUZZY-LOGIC MPPT CONTROLLER

A. Conventional Fuzzy-Logic Controller

Based on fuzzy-logic system (FLS) as shown in Fig.4, fuzzy logic controller (FLC) MPPT method consists of four components: fuzzification, rules and inference engine, and defuzzifier [15, 16, 17]. The input signal is measured from the output of PV power and then processed to generate signal control in the FLS. In the process, each of these signal, either input signal or output signal, are defined by one or more variable (s).

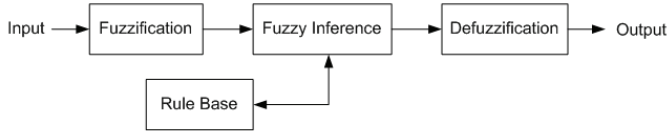


Fig.4. Fuzzy logic system (FLS)

Generally, FLC MPPT method has two input variables, error e and change in error Δe , and an output variable. The two input variables are described by:

$$e(k) = \frac{P_p(k) - P_p(k-1)}{I_p(k) - I_p(k-1)} \quad (4)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (5)$$

where $P_{pk}(k)$ and $I_{pk}(k)$ are the power and current of the PV module, respectively [9]. Therefore, a fast convergence with a small oscillation at the steady state can be achieved. As for the output variable, the output of duty cycle step is expressed by dD .

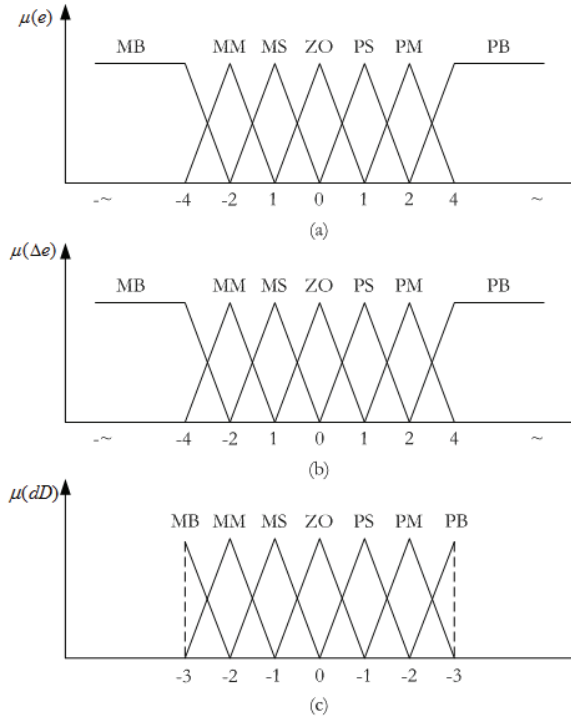


Fig.5. Membership function for (a) input, (b) input Δe and (c) output dD

These two input and output variables are represented by fuzzy subsets. As shown in Fig.5, each fuzzy set has seven basic fuzzy subsets for variables of input and output which declared in terms of linguistic variables such as PB (plus big), PM (plus medium), PS (plus small), ZO (zero), MS (minus small), MM (minus medium), NB (minus big).

Fuzzy rules are designed to achieve zero error at the steady state of the MPP. As shown in the Table 1, the main idea of the rule is to bring operating point to the MPP by increasing or decreasing the duty ratio depending on the position of the operating point from the MPP. If the operating point is distant

from the MPP, the duty ratio will be increased or decreased largely.

TABLE 1. FUZZY RULES BASE

$\Delta e \backslash e$	ML	MM	MS	ZO	PS	PM	PB
MB	MB	MB	MB	MB	MM	MS	ZO
MM	MB	MB	MB	NM	MS	ZO	PS
MS	MB	MB	MM	MS	ZO	PS	PM
ZO	MB	MM	MS	ZO	PS	PM	PB
PS	MM	MS	ZO	PS	PM	PB	PB
PM	MS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

Since the rules table has seven linguistic variables of error e and change in error Δe respectively. The fuzzy-logic system has 49 rules as follows:

Rule¹: IF e is MB and Δe is MB THEN dD is MB

Rule²: IF e is MM and Δe is MB THEN dD is MB

...

Rule⁴⁹: IF e is PB and Δe is PB THEN dD is PB

To get the output of inference, many methods are proposed by the researchers. There are some known methods such as Mandani, Sugeno, Larsen, and so on but the Mandani's method is commonly used. Its description is shown in Fig.6.

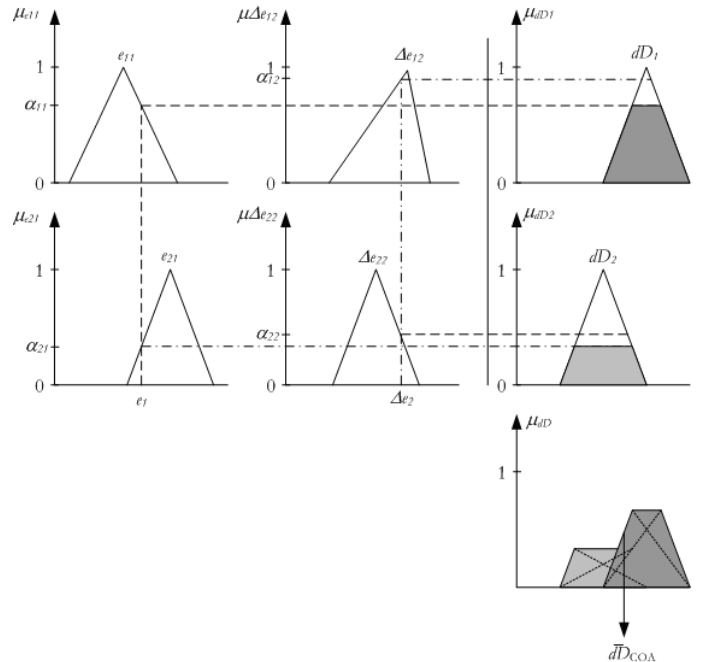


Fig.6. Mandani's inference method with COA defuzzification [17]

The output of fuzzy inference is a fuzzy control subset, such that it must be converted to the crisp value. By using the centroid (COA) defuzzifier, the output control dD can be calculated by:

$$dD = \frac{\sum_{k=1}^I dD_k \mu_{dD}(dD_k)}{\sum_{k=1}^I \mu_{dD}(dD_k)} \quad (6)$$

The value of dD is the duty step added to the previous duty cycle of PWM control signals.

B. Single Fuzzy-Logic Controller

S-FLC was published in [12, 13] as the controller of the inverted pendulum system tracking. The experiment proves that the performance and stability of S-FLC are similarly to that of FLC. The standalone MPPT system with S-FLC MPPT method is shown in Fig.7.

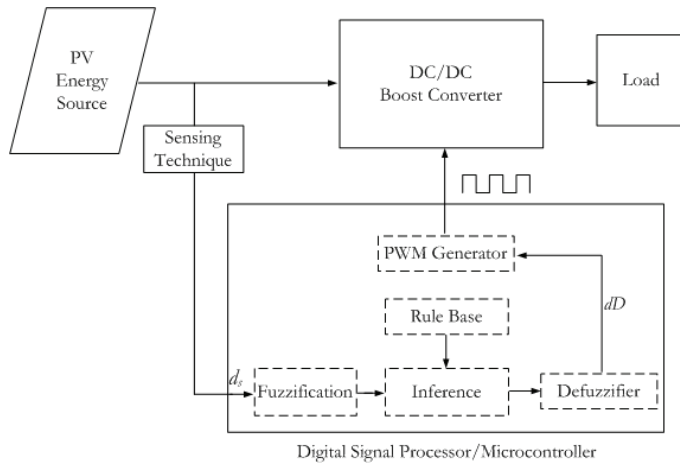


Fig.7. Stand-alone MPPT system with S-FLC MPPT method

As shown in Table 1, The FLC rules have a skew-symmetric property, thus the diagonal lines can be drawn following output variable shapes. The quantization level of the independent variables can be divided into two parts, such that the number of boundaries of control region is two times the numbers of output variables. Because the quantization level of the independent variables becomes infinitesimal, the boundaries become straight lines. Also the absolute magnitude of the input variables is proportional to the distance from the main diagonal line called the switching line s . It is written by [12, 13]:

$$s: \Delta e + e = 0 \quad (7)$$

The value of the control input is measured as the distance from the main diagonal line or the distance between $H(e, \Delta e)$ and $P(e, \Delta e)$ called as the signed distance. It is described clearly in Fig. 8. This signed distance is written by:

$$d_s = \text{sgn}(s) \frac{|\Delta e + \lambda e|}{\sqrt{1 + \lambda^2}} = \frac{|\Delta e + \lambda e|}{\sqrt{1 + \lambda^2}} \quad (8)$$

where:

$$\text{sgn}(s) = \begin{cases} 1 & \text{for } s > 0 \\ -1 & \text{for } s < 0 \end{cases} \quad (9)$$

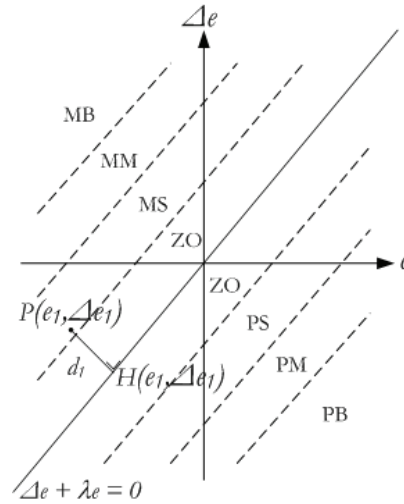


Fig.8. Derivation of a signed distance [12, 13]

Since the sign of a control input depends on the value of switching line s as described by equation (9), the absolute magnitude of control input is proportional to the distance from main diagonal line ($s=0$). It can be concluded that:

$$dD \sim -d_s \quad (10)$$

Instead of the fuzzy rules in Table 1, the single-fuzzy rules can be constructed to one dimensional space of d_s as shown in Table 2.

TABLE 2. SINGLE-FUZZY RULES BASE

d_s	MB	MM	MS	ZO	PS	PM	PB
dD	PB	PM	PS	ZO	MS	MM	MB

As shown in Table 2, the fuzzy-logic system has only 7 rules instead of 49 rules of Table 1. These 7 rules of S-FLC is shown as follows:

Rule¹: IF d_s is MB THEN dD is PB

Rule²: IF d_s is MM THEN dD is PM

...

Rule⁷: IF d_s is PB THEN dD is MB

Now, each of input variable d_s and output variable dD is represented by seven basic fuzzy subsets as shown in Fig.9.

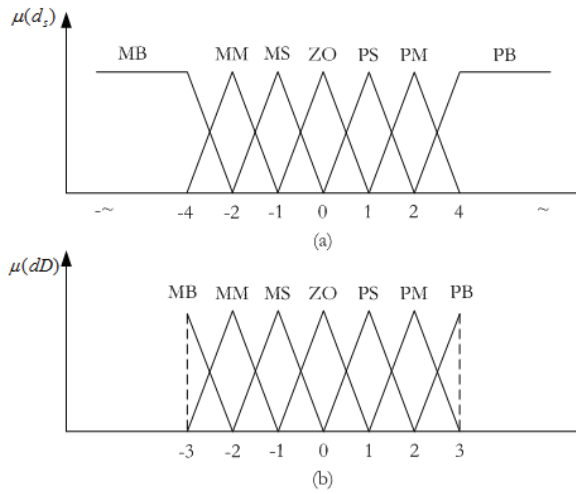


Fig.9. Membership functions for (a) input d_s and (b) output dD

IV. SYSTEM DESIGN

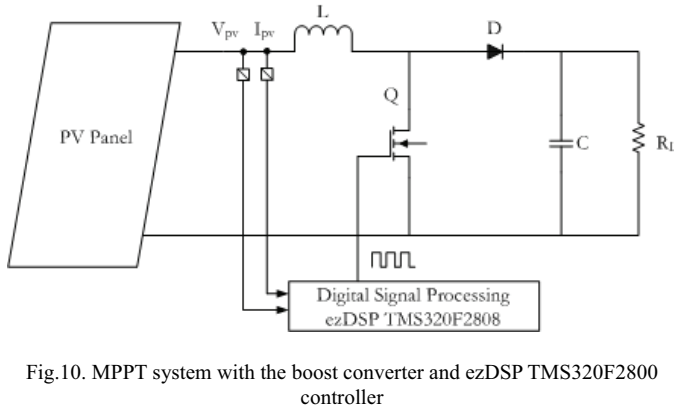


Fig.10. MPPT system with the boost converter and ezDSP TMS320F2800 controller

A design example of the studied MPPT PV system is shown in Fig.10. The design of standalone PV system consists of a PV panel, DC/DC boost converter and DSP controller. The design includes the boost converter which its component selection following the specification in Table 3. As the controller, DSP TMS320F2808 is used where a MPPT algorithm is implemented.

TABLE 3. DESIGN SPECIFICATIONS OF THE BOOST CONVERTER

Specifications	
Nominal input voltage	17.5V
Maximum input voltage	21.8V
Nominal output voltage	24V
Maximum output voltage	50V
Maximum solar power	50Watt
Switching frequency	50kHz

Maximum inductor current ripple	10%
Maximum output voltage ripple	0.50%
Efficiency	>90%

To meet the specification required in Table 3, inductance L and output capacitance value C follows the calculation in Table 4 [18].

TABLE 4. LIST OF THE SELECTION COMPONENTS: INDUCTANCE AND CAPACITANCE

Description	Values
Inductance L	$L = \frac{V_{pv} D}{2 \Delta i_L f_s} = 165.885 \mu H$
Output capacitance C	$C = \frac{I_o D}{2 \Delta v_o f_s} = 47.02 \mu F$

Regarding to diode selection, diode reverse voltage rating is one of the considerations. The diode is used as a current path for the inductor to the output at the off-state power switch and its forward current rating is calculated from the maximum output current. Therefore, a Schottky diode is chosen because it has fast switching characteristics, low reverse-recovery, and low forward voltage drop. The super fast recovery diode rectifier D10LC20U, with 200V maximum off-state voltage stresses and 10A average current handling, meets the requirement.

In selecting a power MOSFET and driver, the requirements is related to the ability to handle the maximum current and voltage stresses. This maximum voltage stress and the maximum current stress is considered from the maximal PV output voltage, and the maximum output current of PV module with its ripple, respectively. MOSFET IRFZ44N with 55V maximum drain-source voltage and 49A maximum drain current is selected in this design.

V. EXPERIMENTAL RESULT

A laboratory prototype of MPPT system is built to validate the performance of the S-FLC MPPT method. The prototype setup consists of a boost DC/DC converter, DSP controller, resistive load and a solar array simulator SAS Agilent E4360 (instead of PV module). The SAS Agilent E4360 simulates PV power source following the specification of BP350 solar module as shown in Table 5.

TABLE 5. THE SPECIFICATION OF BP350 SOLAR MODULE [19]

Specifications	
Maximum Power (P_{max})	50W
Voltage at P_{max} (V_{mp})	17.5V
Current at P_{max} (I_{mp})	2.9A
Short-circuit current (I_{sc})	3.17A
Open-circuit voltage (V_{oc})	21.8V

The experimental results include not only comparison between S-FLC MPPT method and FLC MPPT method, but also comparison between P&O methods and INC MPPT method. In detail, the results of measurement are described as follows:

a) No MPPT controller

The characteristics of MPPT system when the controller is not activated are shown in Fig. 11. A load of $50\ \Omega$ is connected to the system. The SAS voltage and current delivered to the converter is around 21.3V and 0.4A , respectively. Consequently, the SAS power reached by the system is only 8.7W or in the other hand 83% of PV maximum power is lost.

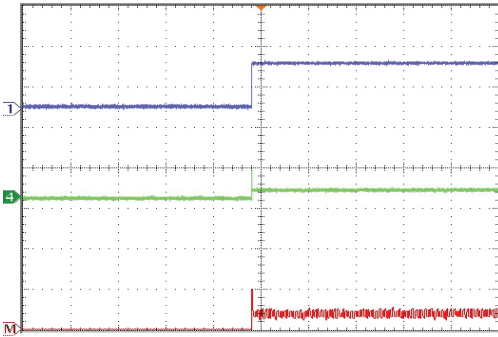


Fig.11. Maximum power reached by the system without any MPPT controller; Scale: [1]-Voltage (20V/div), [4] - Current (2A/div), [M]-Power (20W/div), Time 2s/div.

b) MPPT response time to the steady state

The characteristic of system response to the steady state (MPP) is shown in Fig. 12 when the controller is activated. The initial PWM duty cycle of 50% is set in the controller and a resistive load of $50\ \Omega$ is connected to the system. It shows that the P&O and INC with 0.2% duty step are slower to reach the MPP than the others. The time required by the S-FLC method to reach the steady state of the MPP is close to the time needed by the P&O and INC with 0.9% duty step.

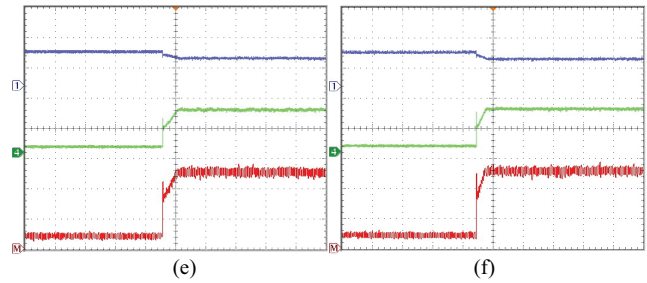
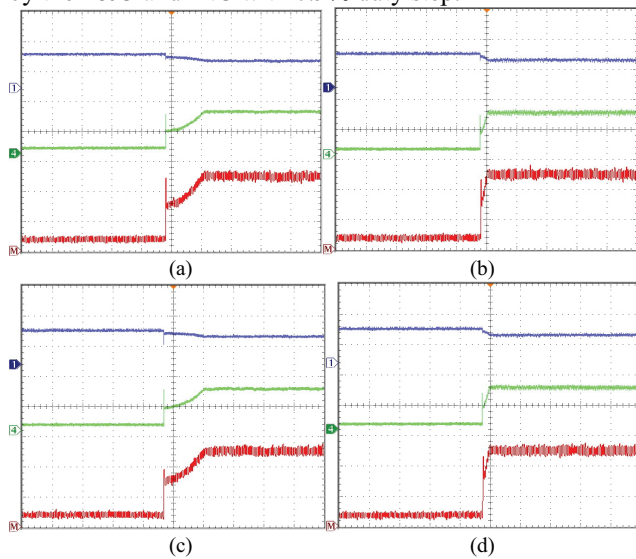


Fig.12. Time response from no-MPPT to Load $R=50\ \Omega$ (a) P&O with duty step 0.2% (b) P&O with duty step 0.9% (c) INC with duty step 0.2% (d) INC with duty step 0.9% (e) FLC with duty step 0%-0.9% (f) S-FLC with duty step 0%-0.9%; Scale: [1]-Voltage (20V/div), [4]- Current (2A/div), [M]-Power (20W/div), Time 2s/div.

c) MPPT response time to load changing at the steady state

To validate the MPPT system response to the changing atmospheric condition, the system is tested by changing the loads. The value of load changing is $50\ \Omega$ to $100\ \Omega$ and then $100\ \Omega$ to $50\ \Omega$. Both FLC and S-FLC method have a fast response to reach the steady state condition. Fig. 13 shows the characteristics of the response time.

The response time of the MPPT system with respect to big load changing is shown in Fig. 14. The load changing of $25\text{-}110\ \Omega$ is connected to the system. As shown in the Fig. 14, FLC and S-FLC methods are robust to handle big load changing that it means an extreme change in atmospheric conditions can be handled by the system.

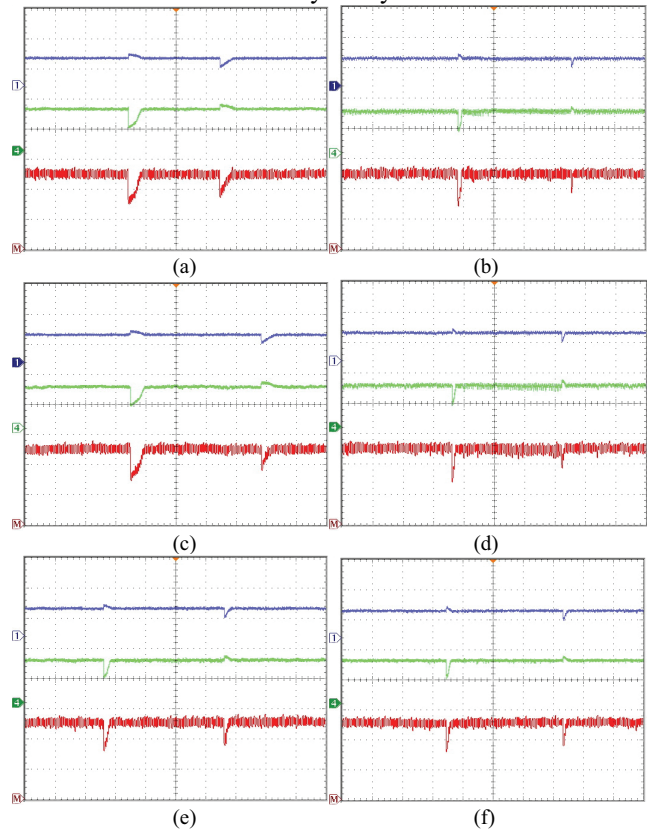


Fig.13. Time response to small load change $R=50\ \Omega \rightarrow 100\ \Omega \rightarrow 50\ \Omega$ (a) P&O with duty step 0.2% (b) P&O with duty step 0.9% (c) INC with duty step 0.2% (d) INC with duty step 0.9% (e) FLC with duty step 0%-0.9% (f) S-FLC with duty step 0%-0.9%; Scale: [1]-Voltage (20V/div), [4]- Current (2A/div), [M]-Power (20W/div), Time 2s/div.

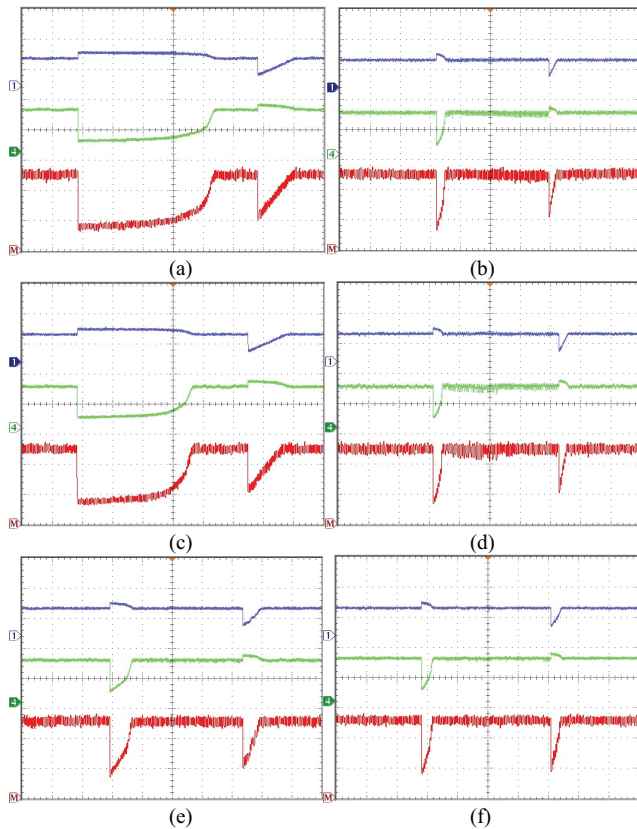


Fig.14. Time response to big load change $R=25\Omega \rightarrow 110\Omega \rightarrow 25\Omega$ (a) P&O with duty step 0.2% (b) P&O with duty step 0.9% (c) INC with duty step 0.2% (d) INC with duty step 0.9% (e) FLC with duty step 0%-0.9% (f) S-FLC with duty step 0%-0.9%; Scale: [1]-Voltage (20V/div), [4]- Current (2A/div), [M]-Power (20W/div), Time 2s/div.

d) MPPT oscillation at the steady state

Small oscillation at the steady state of the MPP is one of the criterions of the MPPT method. Regarding to this criteria, experimental comparison of all methods is shown in Fig.15. The system is connected to resistance load of 50Ω , and then the oscillation is measured at the MPP. It can be seen in the figure, similar to P&O and INC method with 0.2% duty step, the FLC and S-FLC method has a small power oscillation at the MPP. However, a big power oscillation at the MPP cannot be avoided by the P&O and INC method with 0.9% duty step.

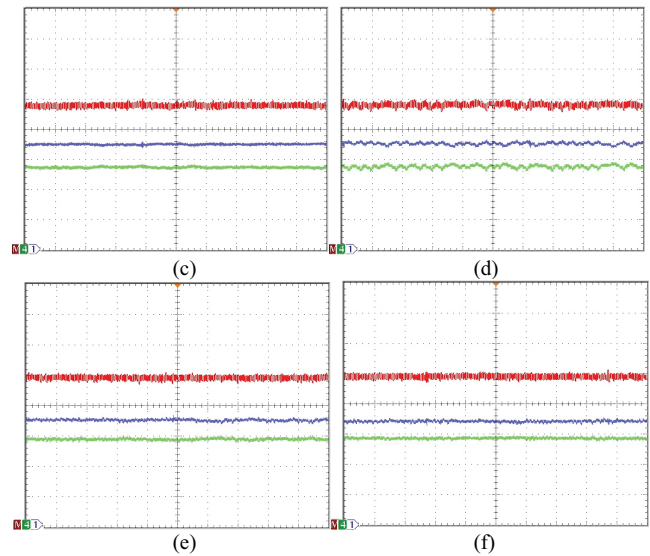
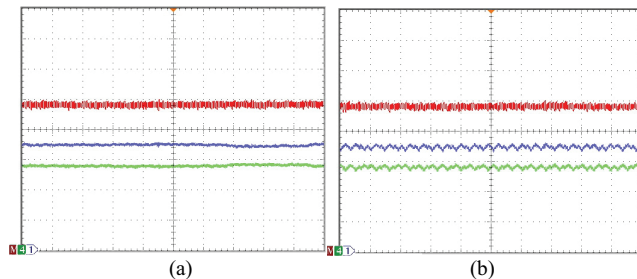


Fig.15. Power oscillation at the MPP (a) P&O with duty step 0.002% (b) P&O with duty step 0.009% (c) INC with duty step 0.2% (d) INC with duty step 0.9% (e) FLC with duty step 0%-0.9% (f) S-FLC with duty step 0%-0.9%; Scale: [1]-Voltage (5V/div), [4]- Current (1A/div), [M]-Power (10W/div), Time 400ms/div.

VI. CONCLUSION

A single-fuzzy logic controller (S-FLC) MPPT method is successfully implemented in a MPPT PV system. Due to control algorithm simplicity, it is easier to implement, modify and tune the control rules. The performance of S-FLC method has been validated in the MPPT system with a boost DC/DC converter and resistive load. A fast convergence with small oscillation at the MPP can be achieved by this method such that it has similar performance to FLC MPPT method. At the MPP tracking, both S-FLC and FLC, has a characteristic which similar to the conventional method, P&O and INC, with a high duty step and at the steady state of the MPP, they have a characteristic which similar to the conventional method with a low duty step.

To achieve more robust performance of S-FLC MPPT method, it is necessary to find appropriate membership function and sampling strategy without avoiding computation simplicity. Therefore, it is the most difficult part in the S-FLC design as well as the FLC design.

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