MAXIMUM POWER POINT TRACKING CONTROL OF PHOTOVOLTAIC ARRAY USING FUZZY NEURAL NETWORK

Tomonobu Senjyu*, Yasuyuki Arashiro*, Katsumi Uezato*, and Han Kyung Hee**

*University of the Ryukyus
1 Senbaru Nishihara-cho Nakagami Okinawa
903-0213 JAPAN
FAX: +81-98-895-8708
Phone: +81-98-895-8686
E-mail: b985542@tec.u-ryukyu.ac.jp

**Myong Ji University
San 38-2 Nam-Dong Yong-In
Kyunggi-Do 449-728 Korea
FAX: +82-335-321-0271
Phone: +82-335-330-6359
E-mail: hkh@wh.myongji.ac.kr

ABSTRACT – Solar cell has an optimum operating point to extract maximum power. To control operating point of the solar cell, a fuzzy controller has already been proposed by our research group. However, several parameters are determined by trial and error. To overcome this problem, this paper adopts Fuzzy Neural Network (FNN) for maximum power point tracking control for photovoltaic array. The FNN can be trained to perfect fuzzy rules and to find an optimum membership functions on-line.

1 . INTRODUCTION

The fossil fuel is used as a source of energy for long time, therefore the environmental pollution is getting more and more serious. In recent years, the research and development for a renewable energy are making rapidly progress around the world. As a clean energy, the solar energy attracts lots of attention. In particular, the photovoltaic(PV) energy system is very expected as an important energy source for the future.

Solar cell has an optimum operating point to extract maximum power. However, as an optimum operating point of solar cell varies with load, solar insolation, temperature and so on, maximum power point tracking (MPPT) control is required to get maximum power efficiently.

To achieve MPPT control of the PV array, several methods have been proposed[1][2]. As one method, a fuzzy controller has already been proposed by our research group [3][4]. This method models characteristic of solar cell and extracts maximum power point of PV array. However, the several fuzzy parameters are determined by trial and error.

To overcome this problem, this paper adopts Fuzzy Neural Network (FNN) for maximum power point tracking control for PV array. The FNN combines the fuzzy inference principles with the neural network structure and can be trained to perfect the fuzzy rule and to find optimum membership functions on-line. This method is able to extract the maximum power point quickly than conventional fuzzy method.

The usefulness and validity of the proposed control method are illustrated through experiments on MPPT control of PV array.

2. MPPT CONTROL OF PHOTOVOLTAIC ARRAY

System configuration

The MPPT control uses a DC-DC step-down converter so as to make PV array work at maximum power point. Fig. 1 shows the MPPT control system using the DC-DC converter. Switching device is a MOS-FET and its switching frequency is 25 kHz. In Fig. 1, secondary voltage E_2 and current I_2 are detected through A/D converter. I_2 is measured through a current sensor, and E_2 is measured through a low-pass filter to restrain voltage pulsation. Output power of PV array is multiplying by E_2 and I_2. Next, the modulation signal M which is calculated by computer using output power information is transmitted to pulse generator through D/A converter, and it makes switching signal. The switching signal drives gate of the MOS-FET as a duty-factor α through firing circuit. The MOS-FET works as a switch and changes load condition of PV array equivalently, and MPPT control is carried out.

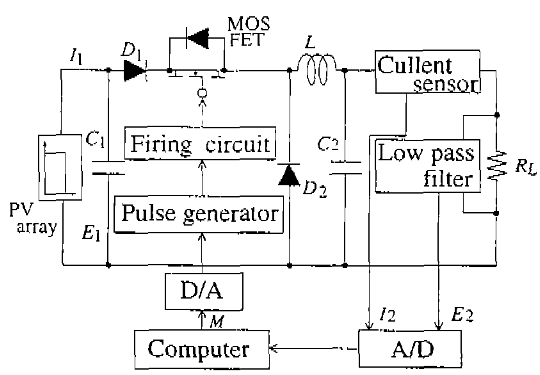


Fig. 1. Configuration of control circuit.

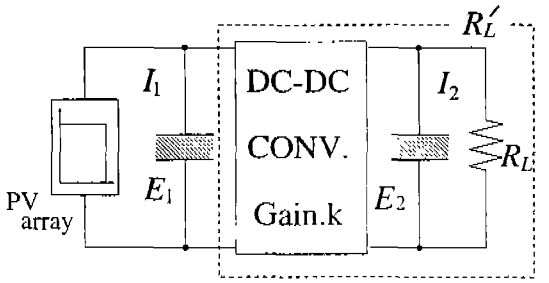


Fig. 2. DC-DC converter.

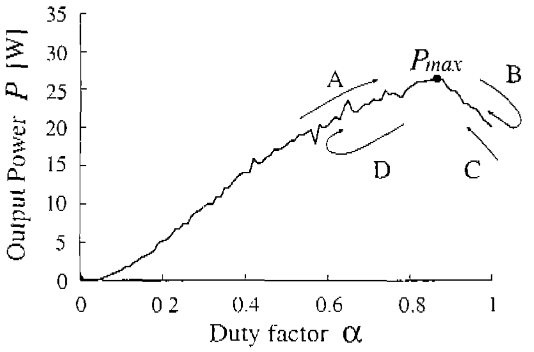


Fig. 3. Duty factor α versus Output Power P.

MPPT control scheme

This section explains the maximum power point tracking control of PV array. The control circuit as shown Fig. 1 is regarded as a DC-DC converter as shown in Fig. 2. In Fig. 2, we regulate the duty-factor of this converter and the load resistance R_L is changed to R'_L equivalently.

Fig. 3 shows the output characteristic of PV array for duty factor α. From Fig. 3, we find that the PV array can work on the maximum power point P_{max} by controlling α.

In MPPT control, to extract the maximum power, we adjust the duty-factor of the converter based on the following equation

$$\alpha_{n+1} = \alpha_n + \Delta\alpha_{n+1}. \tag{1}$$

In above equation, $\Delta\alpha$ is increased (or decreased) in order to increase output power P as representing in Fig. 3. For example, if P increases with increasing $\Delta\alpha$, then α is increasing until the PV array generates the maximum power P_{max}. Based on above algorithm, we tracks maximum power point by comparing output power only.

Fuzzy control

In MPPT control, to obtain a good tracking performance, the duty factor increment (or decrement) $\Delta\alpha$ should be estimated based on fuzzy inference, so that the operating point of solar array come to maximum power point quickly and generated power does not pulsate.

This section describes the scheme how to control $\Delta\alpha$ using the fuzzy control. The fuzzy rules and membership functions in this control are shown in Table. 1 and Fig. 4, respectively.

Fig. 4(a) shows the membership functions inferring $\Delta\alpha$ so as to extract maximum power point quickly and to prevent generating power. $\Delta\alpha$ is inferred by the following power information

$$\Delta P_n = P_n - P_{n-1}. \tag{2}$$

Fig. 4(b) shows the membership functions which prevent big change of duty factor due to the insolation change. This membership functions use a $|\Delta P/\Delta\alpha|$ as a input information representing solar insolation change.

Thus, the fuzzy rules are expressed as follows

$$R^i \;:\; \text{if } \Delta P \text{ is } Q_j \text{ and } |\Delta P/\Delta\alpha_n| \text{ is } R_k,$$
$$\text{then } \Delta\alpha_{n+1} = f_i(\alpha_n) = c^i(1-\alpha_n). \tag{3}$$

In above consequence, the parameter c^i is coefficient in the operation part. $\Delta\alpha$ is determined by

$$\Delta\alpha_{n+1} = \sum_{i=1}^{6} w^i f_i(\alpha_n) \Big/ \sum_{i=1}^{6} w^i \tag{4}$$

where w^i represents the product of fitness of membership functions as

$$w^i = Q_j(\Delta P) R_k(|\Delta P/\Delta\alpha|). \tag{5}$$

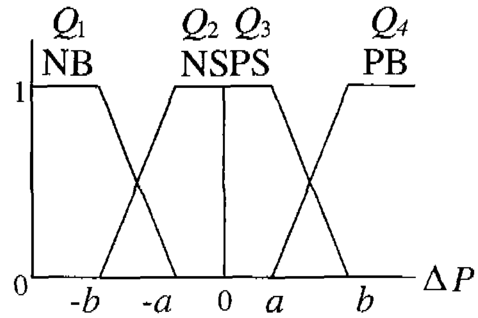
Control signal α_{n+1} is determined from (1), adding $\Delta\alpha_{n+1}$ to α_n.

However, in the fuzzy control, several fuzzy parameters are determined by trial and error. To overcome this problem, we adopt Fuzzy Neural Network (FNN) instead of fuzzy controller for MPPT control. The FNN represents the fuzzy inference by the neural network and can be trained by the back propagation algorithm on-line.

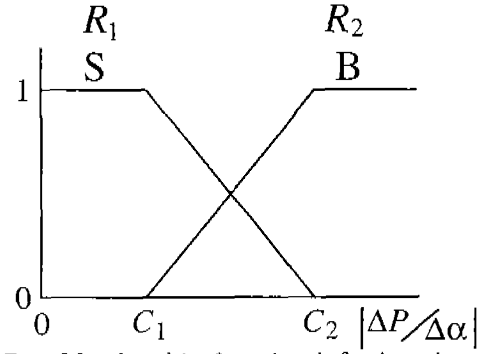
Table 1. Fuzzy rules.

Rule	ΔP	$\lvert\Delta P/\Delta\alpha_n\rvert$	c^i
R^1	PB	B	PS
R^2	PB	S	PB
R^3	PS	–	PS
R^4	NS	–	NS
R^5	NB	S	NB
R^6	NB	B	NS

P : Positive, N : Negative, B : Big, S : Small, – : Any



(a) Q_J : Membership functions inferring $\Delta\alpha$ $(j = 1,2,3,4)$



(b) R_k : Membership function inferring change of insolation $(k = 1, 2)$

Fig. 4. Membership functions.

3. MPPT CONTROL USING FUZZY NEURAL NETWORK

In this section, we provide the MPPT control using FNN. The FNN can tune fuzzy parameters through a training process on-line, with using the back propagation (BP) algorithm.

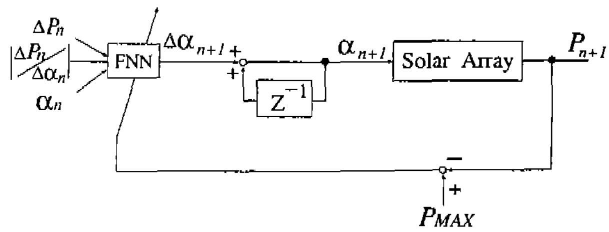
System configuration

Fig. 5 shows a system configuration of MPPT control using FNN. In Fig. 5, the FNN estimates $\Delta\alpha_{n+1}$ and the duty factor α_{n+1} is calculated from (1). And then the control system tracks the maximum power points of PV array. In the FNN training, we use the learning algorithm[5] which changes the learning rate.

FNN model

We use the FNN as shown in Fig. 6. In Fig. 6, the premise and conclusion of fuzzy system are represented by neural net at layers from (A) to (I) and from (J) to (P), respectively. In the premise, the f and Σ calculate the following function

$$\Sigma : \begin{cases} I_j^{(n)} = \sum_k w_{jk}^{(n)} O_k^{(n-1)} \\ O_j^{(n)} = I_j^{(n)} \end{cases} \quad (6)$$



$\alpha_{n+1} = \alpha_n + \Delta\alpha_{n+1}$, $\Delta P_n = P_n - P_{n-1}$

Fig. 5. FNN system configuration.

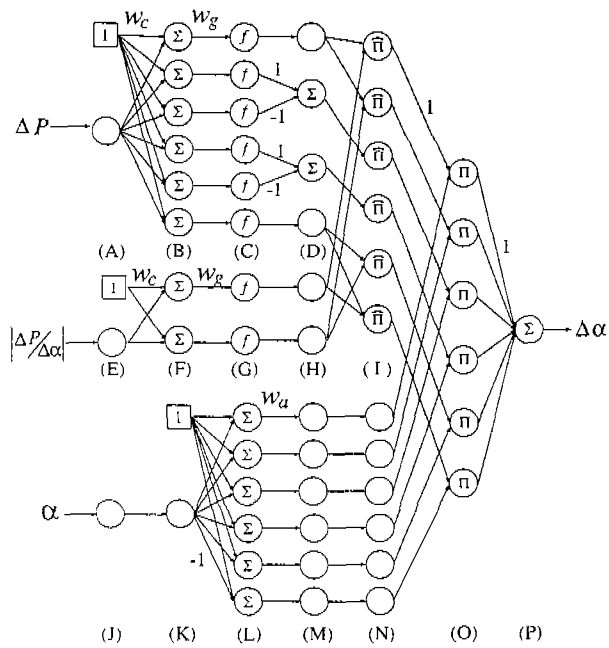


Fig. 6. Fuzzy Neural Network model.

$$f : \begin{cases} I_j^{(n)} = \sum_k w_{jk}^{(n)} O_k^{(n-1)} \\ O_j^{(n)} = 1/\{1 + \exp(-I_j^{(n)})\} \end{cases} \quad (7)$$

where, I and O are input and output respectively, and (7) is the sigmoid function. And w is weight and n is number of layers. From (6) and (7), the outputs of (C) and (G) layers are expressed as

$$O^{(C),(G)} = \frac{1}{1 + \exp\{-w_g(x_j + w_c)\}} \quad (8)$$

where, w_c and w_g express the center and gradient of sigmoid function. $\widehat{\prod}$ calculate the following functions

$$\widehat{\prod}:\begin{cases} I_j^{(n)} = \prod_k w_{jk}^{(n)} O_k^{(n-1)} \\ O_j^{(n)} = I_j^{(n)} \Big/ \sum_k I_k^{(n)}. \end{cases} \tag{9}$$

In the layer (O), $\prod$ represents the following calculations

$$\prod:\begin{cases} I_j^{(n)} = \prod_k w_{jk}^{(n)} O_k^{(n-1)} \\ O_j^{(n)} = I_j^{(n)} \end{cases} \tag{10}$$

and, in the layer (P), $\Delta\alpha$ is obtained. These parameters w_c, w_g, and w_a which are coefficients of conclusion part are used to adjust the premise membership functions and coefficients, respectively.

Learning algorithm

Optimization of membership functions are accomplished by adjusting weights which has a very important role in the shaping of the fuzzy membership functions. The back propagation algorithm is used in the learning process. As for back propagation algorithm, we use the following performance index

$$E_{n+1} = (P_{MAX} - P_{n+1})^2 \Big/ 2 \tag{11}$$

where P_{MAX} and P_{n+1} are the rated maximum power and the output power of the PV array, respectively. This equation means that the performance index is minimum when the PV array is working at maximum power point. power P_{n+1} controlled by MPPT tracks maximum power point quickly. In learning process, if $|E_{n+1} - E_n|$ is small, the learning is stopped so as to prevent over-learning after the output power is maximum power.

4. EXPERIMENTAL RESULTS

In this section, to verify the effectiveness of the proposed control, we experimented on the MPPT control in the constant and stepwise insolation, respectively. And in the experiment, we compared with following the three control schemes:

(a) FNN(proposed method)
The MPPT control adjusting FNN parameters on-line.

(b) Fuzzy
The conventional fuzzy control that parameters are decided by trail and error.

(c) No control
Without MPPT control.

Table 2 shows the fuzzy parameters.

Table 2. Fuzzy parameters for conventional fuzzy controller.

a	b	c_1	c_2
0.1	5.0	200	400

c^1	c^2	c^3	c^4	c^5	c^6
0.1	0.2	0.1	-0.1	-0.2	-0.1

Experimental results in constant insolation

Fig. 7 shows the experimental results in constant insolation. In Fig. 7(a) and (b), we find that the output power with using FNN and Fuzzy is higher than that of No control, and that the FNN tracks maximum power point quickly than Fuzzy. And in Fig. 7(c), the parameters which represent coefficients of PB and PS are adjusted in right after starting. In Fig. 7(d), we can see that the premise membership function are modified.

Thus, FNN control scheme can shorten the tracking time of MPPT control by adjusting parameters on-line.

Experimental results in stepwise insolation

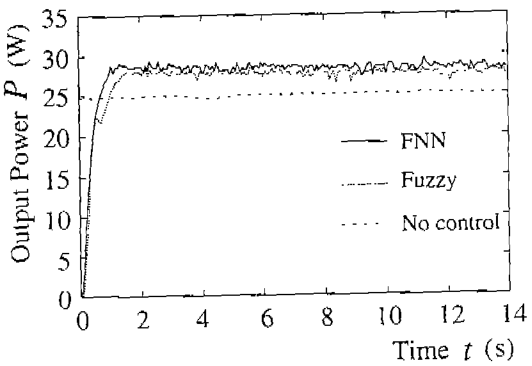
Next, Fig. 8 shows the experimental results in which the solar insolation is rapidly changed. From Fig. 8 (a) and (b), it is seen that the FNN tracks maximum power point quickly than the fuzzy controller in particularly when the solar insolation is changed at 6 sec. In Fig. 8(c), when the experiment starts and output power changes rapidly because of insolation change, the parameters are adjusted. In Fig. 8(d), we can see that the premise membership functions are modified.

From these experiments, it is seen that the FNN adjusts the parameters so that it can extract maximum power quickly even if insolation changes.

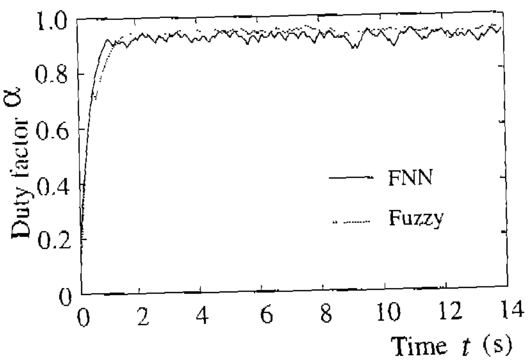
Effectiveness MPPT control

To confirm the validity and usefulness of the proposed MPPT. Fig. 9 shows the FNN control results when solar insolation is changed in stepwise. Fig. 9(a) shows the short-circuited current of PV array as a measured of solar insolation. In Fig. 9(b), sector A to F corresponds to the sectors in Fig. 9(c), and Fig. 9(c) shows the output characteristic of short-circuited current versus output power of PV array. Generally, the maximum power points of PV array are proportional to short-circuited currents. In Fig. 9(c), since the output power is proportional to short-circuited current, it is confirmed that the output power is at maximum power point for PV array.

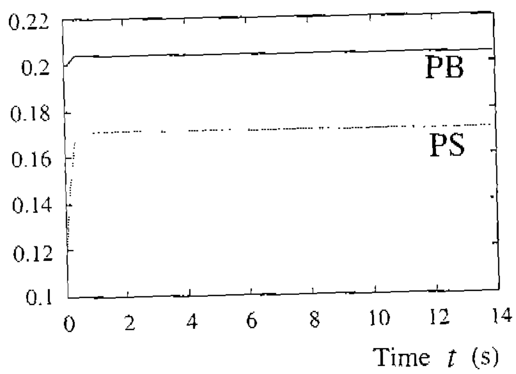
From the above experimental results, it is demonstrated that the MPPT control using FNN can track the maximum power point quickly than fuzzy control by adjusting the parameters through on-line learning process.



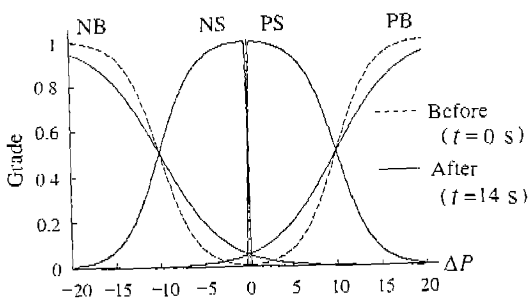
(a) Output power P



(b) Duty factor α

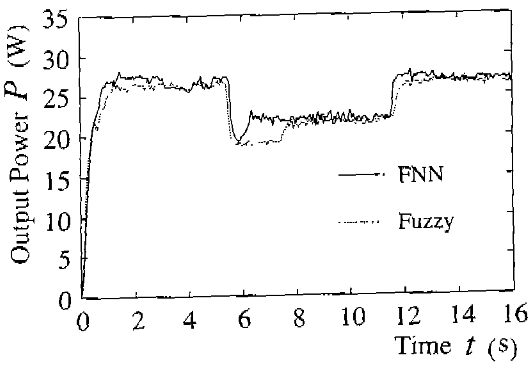


(c) Coefficients

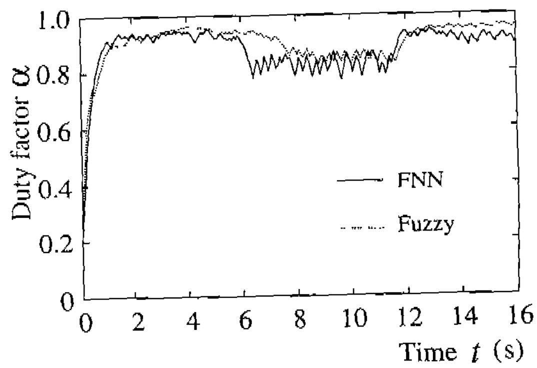


(d) Premise membership functions

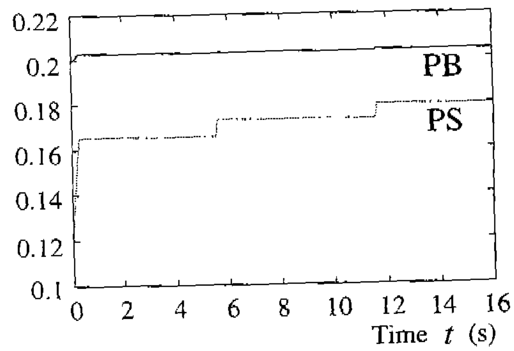
Fig. 7. Performance of maximum power point tracking control for constant solar insolation.



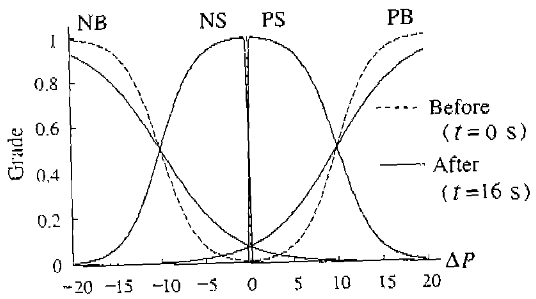
(a) Output Power P



(b) Duty factor α

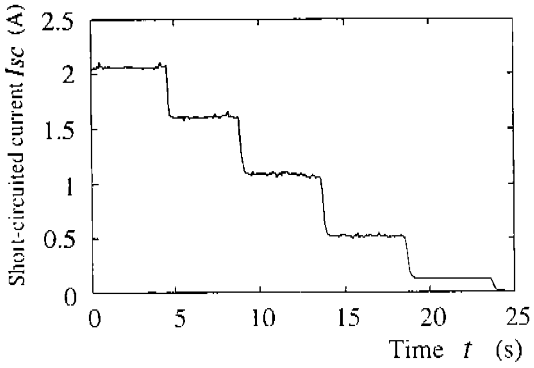


(c) Coefficients

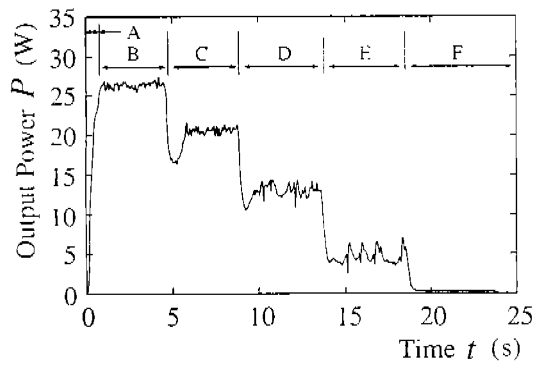


(d) Premise membership functions

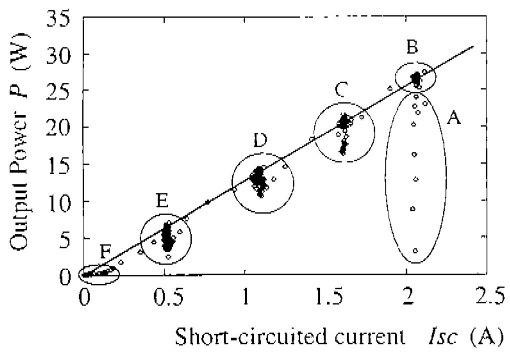
Fig. 8. Performance of maximum power point tracking control for stepwise solar insolation.



(a) Short-circuited current I_{SC}



(b) Output Power P



(c) Short circuited current I_{SC} vs. output power P

Fig. 9. Performance of maximum power point tracking control for stepwise solar insolation.

5. CONCLUSIONS

This paper presents a MPPT control scheme on PV array using a FNN. This scheme can extract maximum power quickly than conventional fuzzy control, because the FNN can be trained to perfect fuzzy rules and to find an optimum membership functions on-line. The usefulness and validity of the proposed method are illustrated through experiments on MPPT control of PV array. And more, since this scheme uses output power information only, the inexpensive and high efficient system would be constructed.

6. REFERENCES

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