A New Maximum Power Point Tracker of Photovoltaic Arrays Using Fuzzy Controller

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ABSTRACT

The studies on the photovoltaic system are extensively increasing because of a large, secure, essentially exhaustible and broadly available resource as a future energy supply.

However, the output power induced in the photovoltaic modules is influenced by an intensity of solar cell radiation, temperature of the solar cells and so on. Therefore, to maximize the efficiency of the renewable energy system, it is necessary to track the maximum power point of the input source.

In this paper, a new maximum power point tracker (MPPT) using fuzzy set theory is proposed to improve energy conversion efficiency. Fuzzy algorithm based on linguistic rules describing the operator's control strategy is applied to control step-up converter for MPPT. Fuzzy logic control based on coarse and fine mode has been incorporated in order to reduce not only the time required to track the maximum power point but also fluctuation of power. MPPT algorithm is implemented by 16 bit single chip 80C196KB microcontroller.

Simulation and experimental results show that performance of fuzzy controller in maximum power tracking of photovoltaic array is better than that of controller based upon hill climbing method.

I. INTRODUCTION

According to the realization of high efficiency and low cost photovoltaic(PV) modules, interest in photovoltaic power generation system has increased over the past decade as a clean and infinite energy.

The PV modules have maximum operating points corresponding to the surrounding condition such as intensity of the sunlight, the temperature of the PV modules, cell area, and load. When solar energy is used as a power source, the output power has to be maximized by improving the efficiency of the power conditioning equipment used and implementing an adaptive power controller that automatically tracks the system to the point of maximum power delivered from the solar panel under all conditions.

Generally, a hill climbing method demonstrated by Boehringer (1971), Harashima(1987) is used to determine the maximum power point. The instantaneous current and voltage are sampled and multiplied to obtain the power. Futhermore, the input source voltage is sampled to help the controller determine whether the operating point is to the left or right side of maximum power point of the solar array [1],[2].

On the other hand, fuzzy logic or fuzzy set theory has received attention of a number of researchers in the area of power electronics. The fuzzy logic control is somewhat easy to implement because it does not need the mathematical model of a system. Since it gives robust performance, the interest in practical application of fuzzy logic is growing rapidly [3][4].

In this paper, a new method using fuzzy logic has been applied to step-up maximum power point tracker for PV arrays [5].

Particularly, input variables of fuzzy controller are dP_{ph}/di_{ph}(where P_{ph} is PV array output power and i_{ph} is PV array output current) and change of it. To reduce the transient response time for tracking maximum power point and force fluctuation of PV array output power to minimize, fuzzy controller has two modes - coarse and fine modes.

Proposed step-up MPPT system is studied by simulation and is implemented by using a microcontroller which controls duty ratio of MOSFET boost converter. Comparisons of proposed MPPT with conventional hill climbing MPPT indicate that the proposed method overcomes the trade-off problem that the smaller change of duty ratio is, the closer maximum power point, however there will be an increase in the time required be the system to reach equilibrium in the hill climbing method.

II. STEP-UP (BOOST) CONVERTER FOR MPPT

In order to minimize the long-term system losses, it is required that converter input current has very small ripple and conversion efficiency is very high even at part load. Therefore the installation of a boost type converter or Cük converter will be advised [5]. In this paper, a step-up converter is used as MPPT.

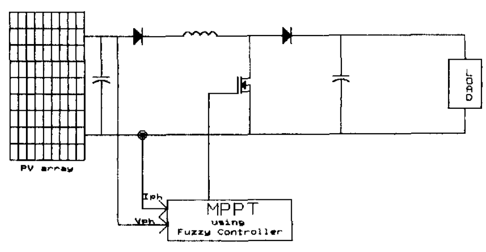

Fig.1 The STEP-UP converter for MPPT.

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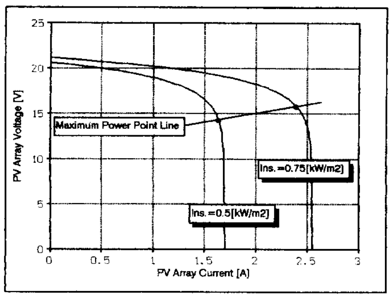
The basic circuit for a step-up chopper shown in Fig.1, where the power MOSFET is used as a switching device since it is easy to control and can be operated at higher frequencies as compared to BJTs. The MOSFET is controlled using a PWM signal generated by 80C196KB Microcontroller.

III. MAXIMUM POWER POINT TRACKING BY FUZZY LOGIC CONTROLLER

The control objective is to track and extract maximum power from the PV arrays for a given solar insolation level. The maximum power corresponding to the optimum operating point is determined for different solar insolation level. Fig.2 shows the typical current, voltage relationships of a PV panel as well as the corresponding output power.

Normally a DC-DC converter is utilized between the input source and the load for the purpose of MPPT.



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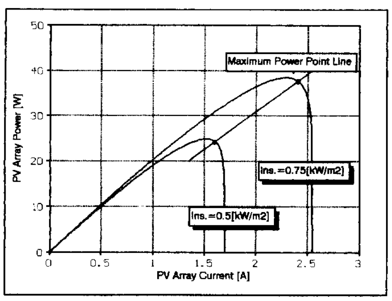


(b)

Fig.2 Typical characteristics of a photovoltaic module.
(a) voltage-current curve (b) power-current curve

A. Fuzzification

The actual voltage and current of PV array can be measured continuously via on chip A/D converter of 80C196KB microcontroller and the power can be calculated. We have focused on single input-single output plant in which control is determined on the basis of satisfaction of two criteria relating to two input variables of proposed controller, namely error (E) and change of error (CE), at a sampling instant k.

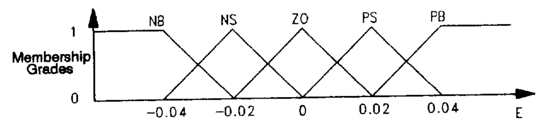
The variable E and CE are expressed as follows :

$$E(k) = \frac{P_{ph}(k) - P_{ph}(k-1)}{i_{ph}(k) - i_{ph}(k-1)} \quad (1)$$

$$CE(k) = E(k) - E(k-1) \quad (2)$$

where $P_{pv}(k)$ and $i_{pv}(k)$ are the power and current of the PV array, respectively. Therefore, $E(k)$ is zero at the maximum power point of a PV array.

These input variables are expressed in terms of linguistic variables or labels such as PB (positive big), PS (positive small), ZO (zero), NS (negative small), NB (negative big) using basic fuzzy subset. Fig.3 shows the membership grades of five basic fuzzy subset for input and output variable.



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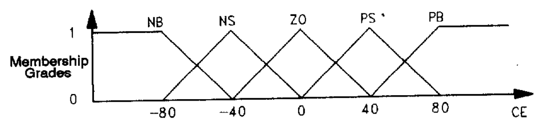

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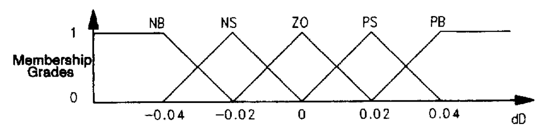


(c)

Fig.3 Membership function for
(a) input E (b) input CE (c) output dD

B. Inference Method

Table 1. shows the rule table of fuzzy controller, where all the entries of the matrix are fuzzy sets of error (E), change of error (CE) and change of duty ratio (dD) to the boost converter. In the case of fuzzy control, the control rule must be designed in order that *input variable E has to always be zero.*

Table 1. Fuzzy rule table.

E \ CE	NB	NS	ZO	PS	PB
NB	ZO	ZO	NB	NB	NB
NS	ZO	ZO	NS	NS	NS
ZO	NS	ZO	ZO	ZO	PS
PS	PS	PS	PS	ZO	ZO
PB	PB	PB	PB	ZO	ZO

As an example control rule in Table 1 :

IF E is PB AND CE is ZO THEN dD is PB.

This implies that *"If operating point is distant from maximum power point towards left hand side and the change of slope in P_{ph}-I_{ph} curve is about zero, increase duty ratio largely"*.

As a fuzzy inference method, Mamdani's method is used with max-min operation fuzzy combination law. Fig.4 illustrates MAX-MIN composition.

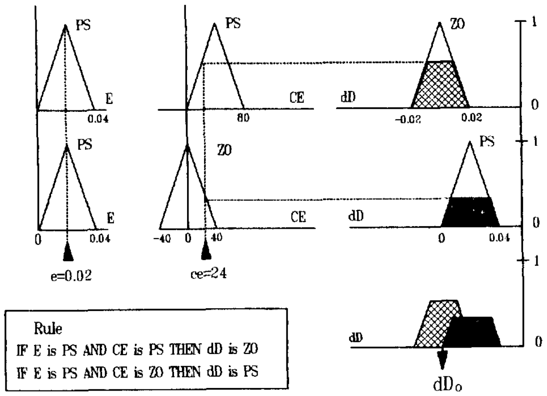


Fig.4 MAX-MIN composition.

C. Defuzzification

The output of fuzzy controller is a fuzzy subset of control. As the plant usually requires a nonfuzzy value of control, a defuzzification stage is needed. Defuzzification can be performed normally by two algorithms : Center of Area (COA) and the Max Criterion Method (MCM). The COA is a combine-then-defuzzification algorithm that determines the crisp controller output as the center of gravity of the final combined fuzzy set. The final combined fuzzy set is defined by the union of all rule output fuzzy set using the maximum aggregation method. For a sampled data representation, the center of gravity dD_o is computed point-wise by

$$dD_o = \frac{\sum_{j=1}^{n} \mu(D_j) \cdot D_j}{\sum_{j=1}^{n} \mu(D_j)} \qquad (3)$$

Fig.5 shows the configuration of fuzzy controller, which consists of input-output scaling, fuzzification, fuzzy decision, and defuzzification, The scale factors, *SE, SCE* and *SdD*, change the inputs and output of the controller proprotionally. The output *dD* is inferred from the two state variables *E* and *CE* where each is derived from the actual signal by dividing with the respective scale factor. The output variables are defuzzified and multiplied by the scale factor to construct the actual control signal. Their role is to tune the fuzzy controller to obtain the maximum power point tracking [6].

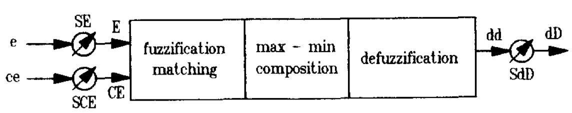


Fig.5 Configuration of fuzzy controller.

IV. SIMULATION RESULTS

A common practice in science and engineering is to make an equivalent model of a device or system so as to better analyze and predict its performance. Solar cell can be represented as an ideal current source. A diode wired across an ideal current source as in Fig.2 exhibits a voltage-versus-current response curve that perfectly mimics a photovoltaic cell's I/V characteristics [7].

From Fig.6, we can infer following equation :

$$\begin{aligned} I &= I_{ph} - I_D \\ &= I_{ph} - I_o - I_o \exp\left[\frac{q}{ATK}(V + I \cdot R_s)\right] - \frac{V + I \cdot R_s}{R_{sh}} \end{aligned} \qquad (4)$$

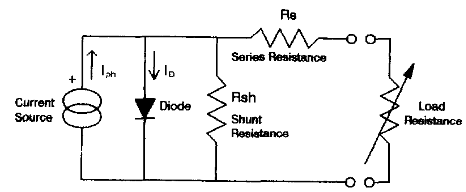
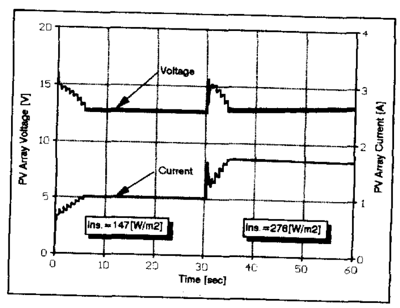


Fig.6 A solar cell equvalent circuit modeling.

For simulation of photovoltaic arrays, Eq.(4) is used and all devices of boost converter (MOSFET, diode, inductor, capacitor) is assumed to be ideal.

In order to verify the control strategy as discussed above, the simulation study of the total system was made using the C language.

Fig.7~Fig.16 show the simulation results of the conventional hill climbing method and the proposed fuzzy algorithm method. Fig.7~Fig.11 is the simulation results of PV generation in the laboratory using halogen lamp and Fig.12~Fig.16 in the field. Each PV array characteristic is next section.



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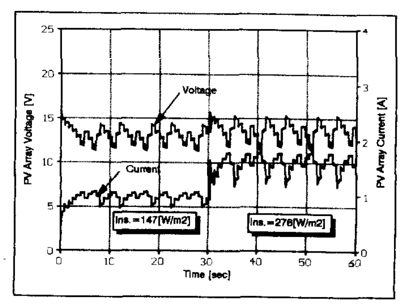

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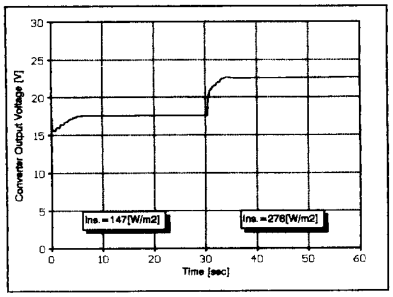
Fig.7 Time-PV array current & voltage relation in the laboratory.
(a) Fuzzy logic control (b) Hill climbing method



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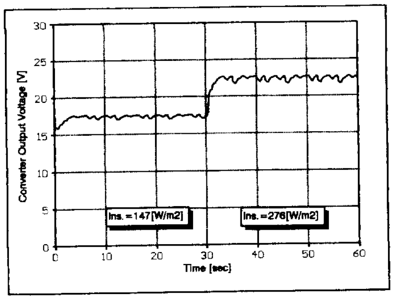

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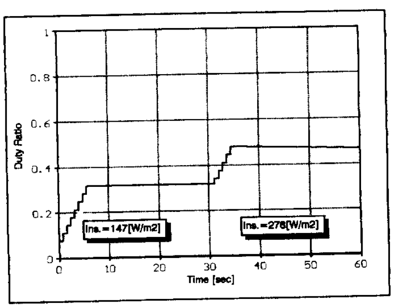
Fig.8 Converter output voltage in the laboratory.
(a) Fuzzy logic control (b) Hill climbing method



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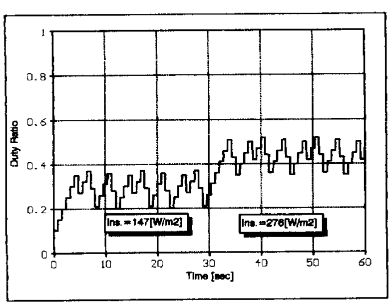

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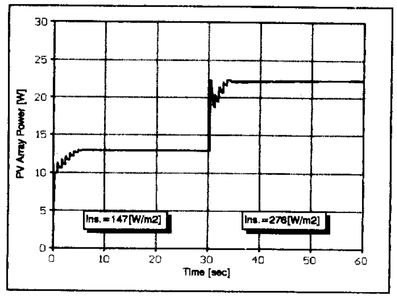
Fig.9 Converter duty ratio in the laboratory.
(a) Fuzzy logic control (b) Hill climbing method



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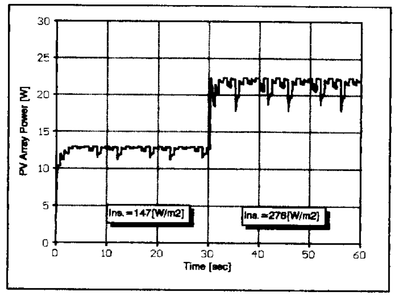

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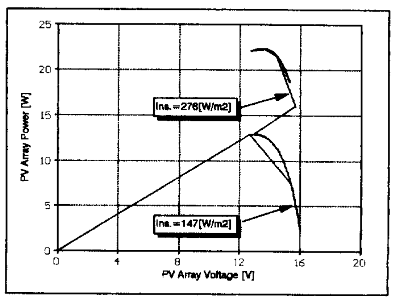
Fig.10 PV array power in the laboratory.
(a) Fuzzy logic control (b) Hill climbing method



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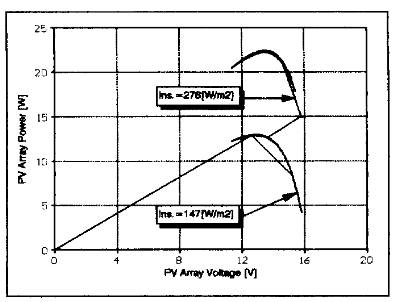

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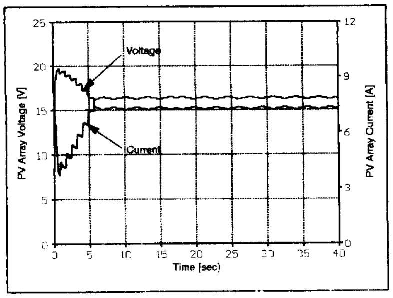
Fig.11 The power versus voltage loci in the laboratory for MPPT.
(a) Fuzzy logic control (b) Hill climbing method



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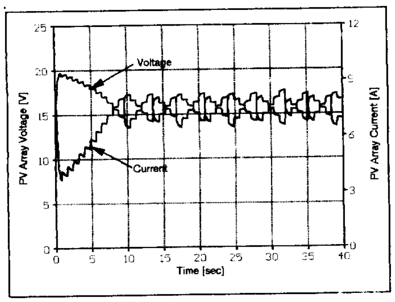

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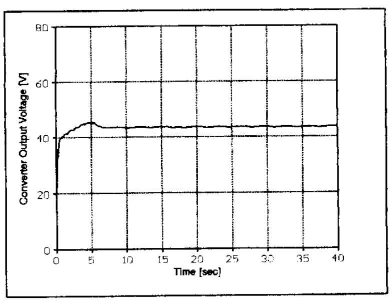
Fig.12 Time-PV array current & voltage relation in the field. (Ins.=1016W/m^2)
(a) Fuzzy logic control (b) Hill climbing method



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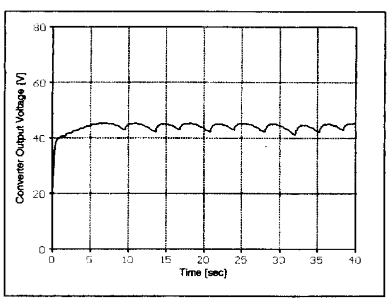

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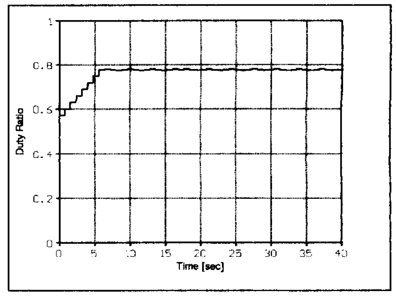
Fig.13 Converter output voltage in the field. (Ins.=1016W/m^2)
(a) Fuzzy logic control (b) Hill climbing method



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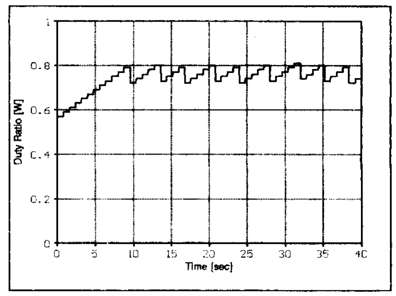

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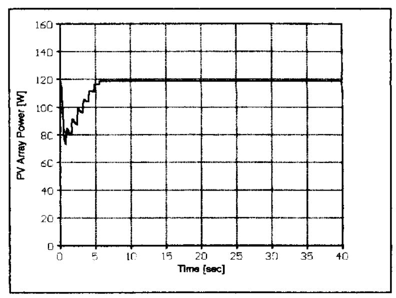
Fig.14 Converter duty ratio in the field. (Ins.=1016W/m^2)
(a) Fuzzy logic control (b) Hill climbing method



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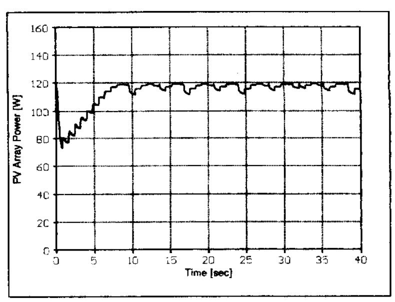

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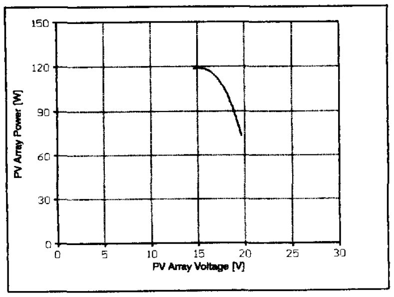
Fig.15 PV array power in the field. (Ins.=1016W/m^2)
(a) Fuzzy logic control (b) Hill climbing method



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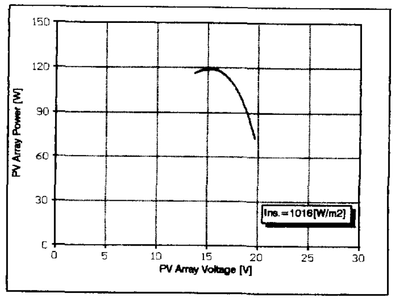


(b)

Fig.16 The power versus voltage loci in the field for MPPT. (Ins.=1016W/m^2)
(a) Fuzzy logic control (b) Hill climbing method

V. EXPERIMENTAL RESULTS

A hill climbing algorithm, demonstrated by Boehringer (1971), Harashima (1987) and Van Wyk (1983) is used to determine the maximum power point. The converter being of high efficiency, enables us to sample the photovoltaic current, I_{ph} , and voltage, V_{ph}. This instantaneous current and voltage are sampled and multiplied to obtain power.

Fig.17 shows the control routine flow chart. Initially on startup, the duty ratio is set to 0.1 and gradually increased. From Fig.2 the sign of E(error) is positive on the left hand side of maximum power

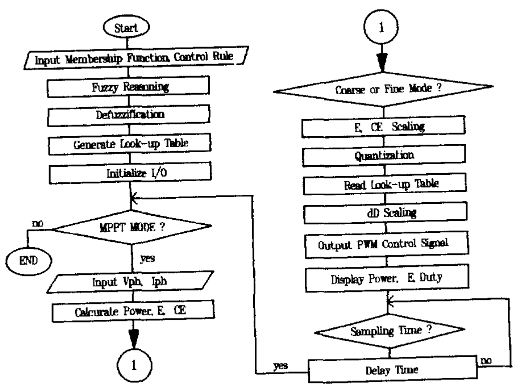


Fig.17. Control routine flow chart

point while negative on the right hand side and zero at maximum power point. For a boost converter, threrfore, duty ratio should be decreased for negative E and duty ratio should be increase for positive E so as to shift the operating point towards the maximum power point.

Fig.18 shows block diagram of proposed PV energy conversion scheme with fuzzy rule based controller. The control program is down-loaded from host computer(IBM-PC) to 80C196KB via RS-232C port. The experimental results using a photovoltaic modules as a input power source are shown in Fig.19~Fig.22 The on chip 10 bit A/D converter of 80C196KB is used to convert photovoltaic current and voltage into digital signals. Microcontroller 80C196KB calculates E (error), CE (change of error) from these two signals and generates duty ratio for maximum power. A 12 bit D/A converter (AD667) with conversion time of 4 µs, is used to display power [8].

In this paper, experiments are implemented in laboratory using 2 photovoltaic modules and in the field 5 photovoltaic modules in parallel. Hall sensor (100A/10V) is used to measure the PV array current and 19.6 [kHz] PWM output of 80C196KB provides controlled duty rario for maximum power tracking. The duty ratio is limited from 0.1 to 0.9 for MPPT.

The main characteristics of a photovoltaic module used in the laboratory are as indicated below :

Open circuit voltage :	18.0 [V]
Short circuit current :	5.0 [A]
Peak power :	40.0 [W]

The main characteristics of a photovoltaic module used in the field are as indicated below :

Open circuit voltage :	21.7 [V]
Short circuit current :	3.4 [A]
Maximum power voltage :	17.4 [V]
Maximum power current :	3.05 [A]
Peak power :	53.0 [W]

Fig.20 and 22 present power versus voltage loci of PV array. It confirms that the new maximum power point tracking algorithm shows a good performances compared with conventional method.

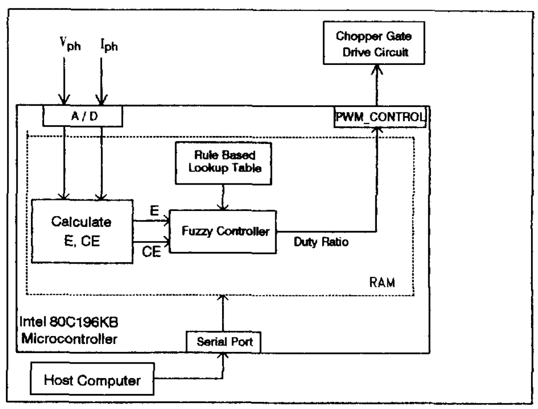
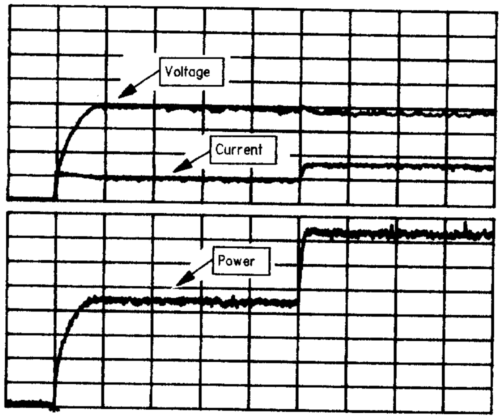


Fig.18 Block diagram of proposed PV energy conversion scheme with fuzzy rule based controller.



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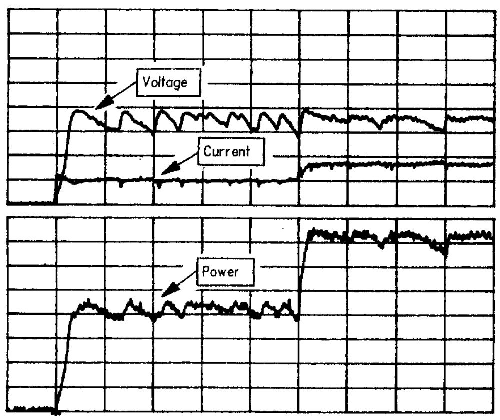
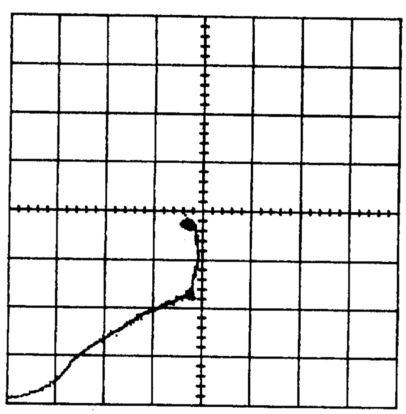


(b)

Fig.19 Experimental results of V_{ph}, I_{ph} and P_{ph} in the laboratory for step change in insolation.
(Ins.1=147W/m^2, Ins.2=276W/m^2, 3.4V/div, 1A/div, 3W/div, 10s/div)
(a) Fuzzy logic control (b) Hill climbing method



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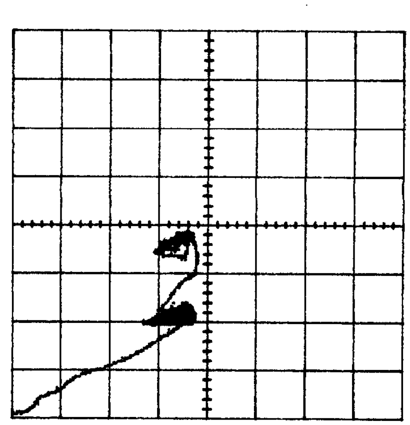
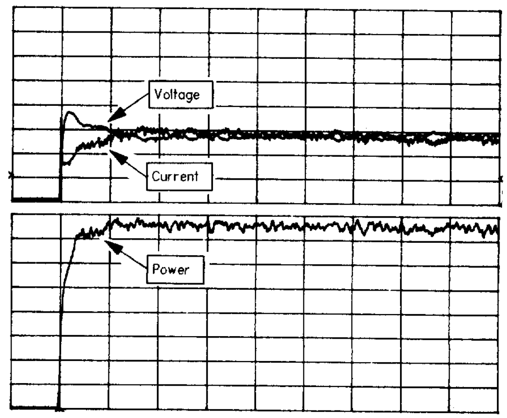


(b)

Fig.20 The power versus voltage loci in the laboratory for MPPT.
(X:3.4V/div, Y:6W/div)
(a) Fuzzy logic control (b) Hill climbing method



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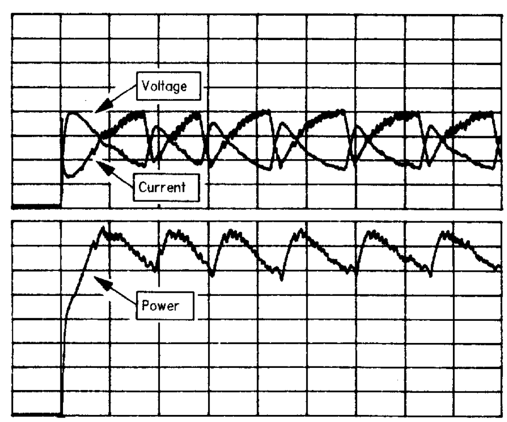

(b)

Fig.21 Experimental results of V_{ph}, I_{ph} and P_{ph} in the field.
(Ins.=1016W/m^2, 5V/div, 3A/div, 15W/div, 10s/div)
(a) Fuzzy logic control (b) Hill climbig method

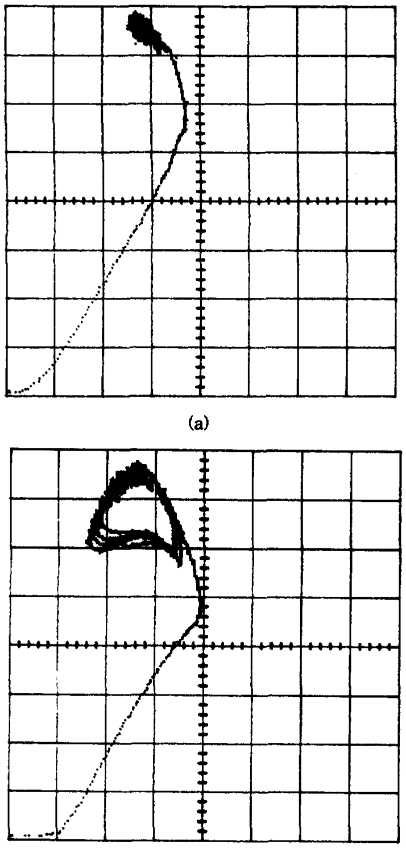

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Fig.22 The power versus voltage loci in the field for MPPT.
(X:5V/div, Y:15W/div)
(a) Fuzzy logic control (b) Hill climbing method

Ⅵ. CONCLUSION

In this paper, a new Maximum Power Point Tracker using fuzzy logic is proposed and applied to boost converter. The photovoltaic array conversion system in the laboratory and field is studied with proposed algorithm by simulation and experiment. From the simulation results, we are confirmed to superiority of a new control method compared to the hill climbing method. Fuzzy logic based on coarse and fine mode controls reduces not only the time required to track the maximum power point but also fluctuation of power.

Simulation is studied for maximum power point tracking performances and then to certify the simulation results. The experiment is implemented by using 16 bit microcontroller 80C196KB.

As a result, the proposed maximum power point tracking method improves the energy conversion efficiency since more power is generated by photovoltaic array than hill climbing method.

ACKNOWLEDGEMENT

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