

Design of Digital Battery Charger System Based on PV-Module

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Abstract—This paper aims at to realize the solar cell charged systems of 120W PV module with the dsPIC30F4011 control chip. All of the control schemes are written and accomplished with the C language. In the power converter, a single-ended primary inductance converter (SEPIC) is adopted which has the features including the buck-boost operating mode, no polarity inversion, low input current pulsation, and wide input voltage range, so, it is very suitable for the conversion of solar cell. In order to obtain the high efficient solar cell energy conversion, a fuzzy maximum power point tracking (MPPT) control is activated if the solarization is insufficient. The fuzzy controller is to maintain a charged current so as that the battery voltage can reach to desired value. The effectiveness of the proposed methods is demonstrated with the experimental results.

Keywords—PV module; MPPT; SEPIC converter;

I. INTRODUCTION

Solar energy from the sun is fruitful without environmental pollution. It does not consume the earth's resources and cause global warming. A solar panel is a device comprised of a number of solar cells connected series/parallel units which are used to convert solar energy into electricity. Solar panels have been used more and more each day. As the solar panel has been constructed, the only need is sunlight to create energy. The economic value of the solar panel is a popular choice to battle the rising cost of electricity. The solar energy technology has been developed for many years, but it is utilized today more than ever. One main reason for its rising usage is its renewable capability. The sun will always provide the Earth with more energy continuously than human being can consume.

The output voltage, current, and power of the solar panel are highly nonlinear and closely related to effects, such as: the sunlight intensity, working temperature, aging of components, and types of optical materials. The solar panels have their own inherent unique working curve with a corresponding maximum power point only, namely, the optimal working point of solar panels, therefore, to fully utilize solar energy, we need to enable the design of appropriate control algorithms in a variety of different working environments to obtain the maximum power from solar panels. This control method is called the maximum power tracking method. Maximum power point

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tracking methods are discussed in many literatures with different tracking ways to obtain the overall efficiency; so, we need to select the appropriate maximum power tracking method according to the actual environmental conditions. To select the maximum power tracking methods, one must understand the characteristics of solar panels, such as, output power, temperature, sunlight intensity, and the relationship between the loads. It is almost impossible to utilize all the available solar energy in varying load and atmospheric conditions with an uncontrolled system; so, there are several maximum power point extraction solutions via different type DC-DC converters presented in the literature [1-9]. The perturbation and observation method is the most often used algorithm which is based on periodically changing the operating point and observing the resultant change in power. Although, it is well established algorithm, some confusions and instabilities may occur when the irradiation and/or load changes rapidly and randomly. In this paper a fuzzy method is adopted for MPPT. The fuzzy MPPT method is simple and easy to be implemented which is based on the relationship that exists between the PV panel current and voltage. The charged system is implemented with the single-ended primary inductance converter (SEPIC). The SEPIC converter is very effective to charge a battery by PV panel, because the battery voltage could be higher or lower than the PV module voltage, and also the buck boost feature of the SEPIC widens the applicable PV voltage and thus increases the adopted PV module flexibility. Single-ended primary-inductor converter (SEPIC) is a type of DC-DC converter that allows its output voltage to be greater than or less than its input voltage; the output of the SEPIC is controlled by the duty cycle of the control transistor. Figure 1 shows the circuit diagram of the SEPIC converter with two inductors.

There are several advantages by using SEPIC in the charging system of PV module. For instance, the buck-boost

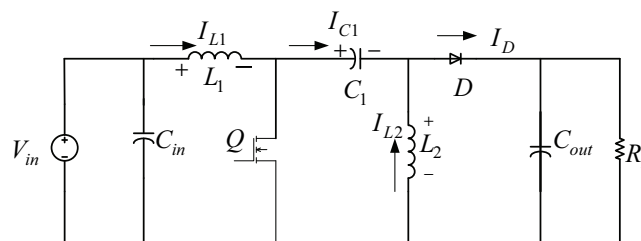


Figure 1. The SEPIC converter diagram

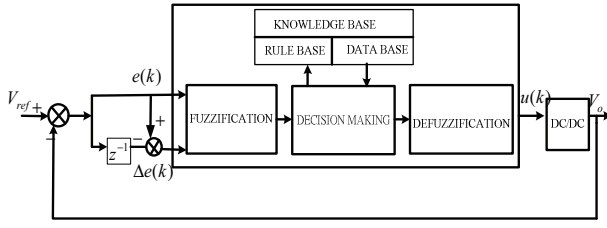


Figure 2. Block diagram of the FLC for DC-DC converters

converter operating voltage can be used to increasing the PV cells voltage range, and SEPIC converter output voltage does not reverse polarity problem. SEPIC converter inductively coupled inductor technology can be used to reduce the size of inductor. The input circuit has inductor can reduce the input current ripple and thus increase the precision of the maximum power point tracking [10, 11].

The fuzzy logic control (FLC) has been successfully applied to many control problems that the conventional one has difficulties to deal with when the controlled systems are complex, not well defined and/or model-free and can be controlled by a skilled human operator with the knowledge of their underlying dynamics. There are many papers pointed a way for an effective utilization of fuzzy control for both practical situations [14-23]. The block diagram of the FLC for DC-DC converters is shown in Figure 2. The fuzzy logic controller can be divided into four part: fuzzification is the input variable partition into suitable fuzzy sets; knowledge base includes fuzzy rule base and data base, they contain knowledge of the control rules and linguistic labels; decision making is inferring control action from rule base; defuzzification is the conversion from the inferred fuzzy value to real control crisp value [13].

The main work of this paper is to integrate fuzzy methodology and SEPIC DC-DC converter so as to realize a charged system of 120W PV module. The control chip is adopted dsPIC30F4011 in the circuit, and all of the control actions are written and completed with the software C program. In the DC-DC power converter, a single-ended primary inductance converter (SEPIC) is adopted. The SEPIC has the features of the buck-boost operating mode, no polarity inversion, low input current pulsation, and wide input voltage range, it is very suitable for the conversion of solar cell. In order to obtain the highest efficient solar cell energy, a fuzzy maximum power point tracking (MPPT) control is adopted, in the hope of reaching steady charging. Three stages of charging

process are taken in this work. While the battery voltage is not full and the solarization is insufficient such that available power of the PV module is not enough to produce the charged current between 0.1C and 0.01C to battery, then fuzzy maximum power point tracking (MPPT) control is activated. As the battery voltage is not full, the solarization is sufficient, and the available peak power of the PV module is enough to produce 0.1C charged current to battery, then, 0.1C charged current is set as command and a fuzzy controller is taken to maintain 0.1C charged current of battery. No matter what the solarization is sufficient or not, once the battery voltage reaches a predefined value, the current command will be shifted to 0.01C, then, the fuzzy controller is activated to maintain a litter charged current so as the battery voltage can reach the desired value. The effectiveness of the proposed methods will be demonstrated by the experimental results.

This paper is organized as follows. In Section II, the circuit characteristics of the SEPIC are described. The fuzzy maximum power point tracking and fuzzy control strategy is addressed in Section III. The experimental results are given in Section IV. Finally, the conclusions are drawn in Section V.

II. SEPIC CIRCUIT CHARACTERISTICS

Roberto *et al* [12] presented a simple method to properly choose the better DC-DC converter to be applied as MPPT in photovoltaic systems, as a function of the radiation, temperature operation range, and load connected at the photovoltaic module. The theory shows that buck and boost converters, although widely used on the literature, might not be the better option to work as MPPT, once they have tracking problems under different radiation and temperature combinations. Before to evaluate parameters of each component, there are some assumptions should be made first: (a) SEPIC operating in continuous conduction mode (CCM); (b) Circuit is at the steady state; (c) All semiconductor components are at ideal case; (d) The energy storage element is not considered. The parameters are listed in Table I.

Referring to the equivalent circuit of SEPIC converter at ON and OFF states as shown in Figure 3 and 4, respectively, when Q turns ON, the energy is stored in the inductor L1. At this time the inductor voltage equals to input voltage, and the energy stored in capacitor C1 will be transferred to inductor L2. The load is supplied by capacitor C2. Similarly, when Q turns OFF, the energy stored in inductor L1 is transferred to C1. The energy stored in L2 is transferred to C2 through D1 and supplying the energy to load. Figure 5 shows the corresponding switching waveforms of the SEPIC converter [23].

The relationship of SEPIC output and input voltage conversion in the static state can be expressed as

$$\frac{V_{in}}{V_{out}} = \frac{D}{1-D} \quad (1)$$

where V_{in} and V_{out} are the input and output voltage, respectively, and D is the duty cycle. Considering the diode forward bias voltage with the input maximum value, the maximum duty cycle D_{max} can be expressed as follow

TABLE I. SPECIFICATIONS AND PARAMETERS OF THE SEPIC.

Input voltage range 5-40V	Charge voltage range 12V-14.4V	Input current range 0.1-10A
Charge current range 0.1A-10A	Switching frequency 100 kHz	Output power range 1W-120W
Coupled Inductor 63 mh	Switch components IRFP048NI	Coupling capacitor 490uf/150V
Output diode B20100 (20A/100V)	Duty cycle range 10%-70%	I/O filter capacitor 4700uF 53V

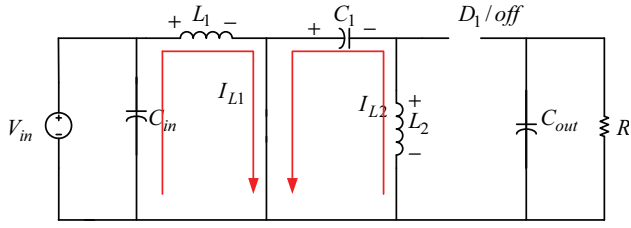


Figure 3. SW on

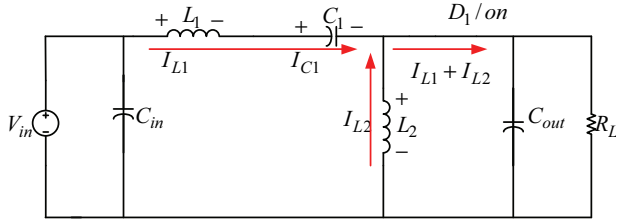


Figure 4. SW off

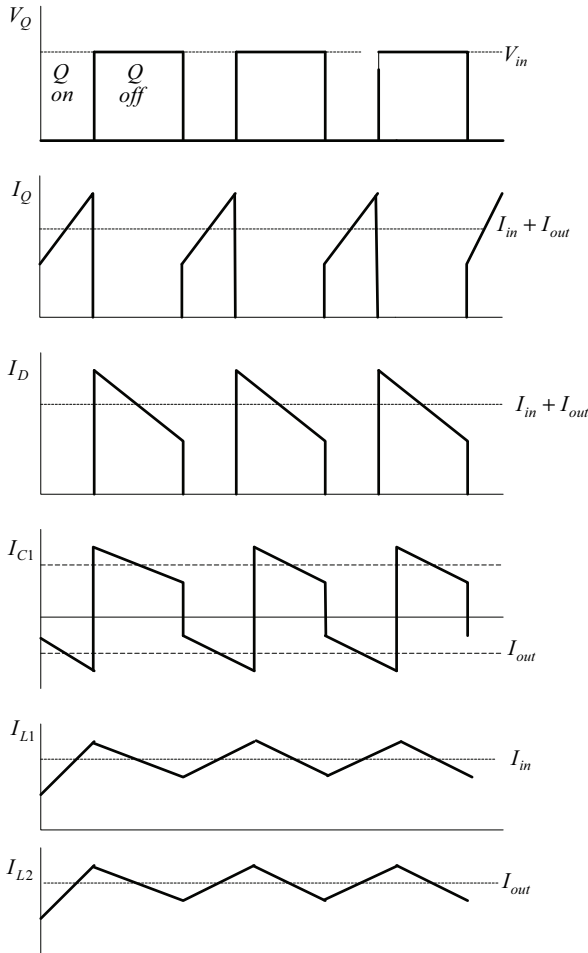


Figure 5. SEPIC Converter Switching Waveforms

$$D_{\max} = \frac{V_{out} + V_D}{V_{in(\max)} + V_{out} + V_D} \quad (2)$$

where V_D is the diode voltage. Because inductor L1 is in the input, the inductor peak to peak ripple current for the maximum input current of 40% is selected, so the L1 inductor ripple current is:

$$\Delta L_1 = I_{in} \times 40\% = \frac{I_{out}}{V_{in(\min)}} \times 40\% \quad (3)$$

Operating under the CCM, L1 must be equal to L2, the inductor value can be calculated as:

$$L_1 = L_2 \quad (4)$$

In order to ensure that the inductor saturation does not occur, the peak inductor current to be met is as follows

$$I_{L1(\text{peak})} = \frac{V_{out} I_{out}}{V_{in(\min)}} \times \left(1 + \frac{40\%}{2}\right) \quad (5)$$

$$I_{L2(\text{peak})} = I_{out} \times \left(1 + \frac{40\%}{2}\right) \quad (6)$$

where the inductor L1 and L2 are wound on the same core and the inductance value is half of L, then

$$L_1 = L_2 = \frac{L}{2} = D_{\max} \times \frac{V_{in(\min)}}{2 \times \Delta I_{L1} \times f_{SW}} \quad (7)$$

where f_{SW} is the switching frequency. According to the switching modes shown in Figure 3 and 4, the switch maximum voltage stress and the switch maximum current stress can be obtained, and then, the selected MOSFET switch specification will be as (8) and (9).

$$I_{SW} = I_{L1(\text{peak})} + I_{L2(\text{peak})} \quad (8)$$

$$V_{SW} = V_{out(\max)} + V_{in(\max)} \quad (9)$$

In the SEPIC converter circuit, the output diode D1 should withstand the reverse bias and peak output voltage.

$$V_{D(\max)} = V_{out(\max)} + V_{in(\max)} \quad (10)$$

At a fixed switching frequency and maximum duty cycle, the SEPIC coupling capacitor voltage must be greater than the maximum input voltage. The voltage ripple can be determined by the coupling capacitor, so the peak ripple voltage can approach to the input voltage as

$$\Delta V_C = \frac{I_{out} \times D_{\max}}{C_S \times f_{SW}} \times 40\% \quad (11)$$

where C is the battery capacitance. The battery capacity, adopted at the experiment, is 12V45AH with the maximum charging current limit set to 0.1C. When the battery voltage reaches to 14.4V, the minimum charge current command will be activated, and then the floating charge current command is shifted to 0.01C. Table I is SEPIC power converter implementation specifications and parameters list.

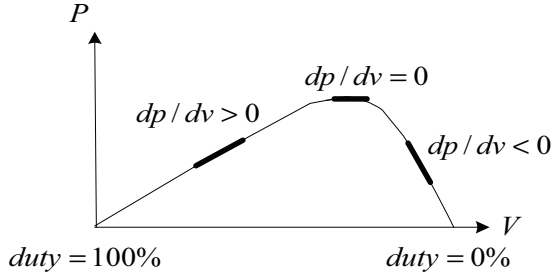


Figure 6. The PV panel power and voltage curve

III. FUZZY MAXIMUM POWER POINT TRACKING AND FUZZY CONTROL STRATEGY

In general, there are many different implementation methods for solar power systems to achieve maximum power point tracking control. One of the most popular methods used is P&O one which can be easy to be implemented, but, there are some disadvantages, for example: power will oscillates near the maximum point resulting to reduce energy efficiency of solar panels. Here, we use the fuzzy controller method for MPPT instead of the simple P&O one [1-3]. The fuzzy controller not only can reduce the time required to track the MPPT but also can reduce the fluctuation of power output. A simple fuzzy maximum power tracking control law is proposed here only with three fuzzy if-then control rules to complete the maximum power tracking work.

From PV panel power and voltage curve in Figure 6, one can see that the slope of PV curve can be partition into three parts, i.e. slope of $\Delta p / \Delta v > 0$, slope of $\Delta p / \Delta v = 0$, and slope of $\Delta p / \Delta v < 0$. Therefore; according to the slope of PV located in which part, the rate of increase of $\Delta u(k)$ is selected as one of the P, Z, or N, which denote positive, zero, and negative, respectively. The input of the proposed fuzzy logic controller is the slope $\Delta p / \Delta v$ and the output is rate change in duty ratio $\Delta u(k)$. The slope of $\Delta p / \Delta v$ is fuzzified into three partitions with triangular membership function labeled with P, Z, and N as shown in Figure 7(a). Similarly, the rate of increase of $\Delta u(k)$ is also fuzzified into three partitions with triangular membership function labeled with P, Z, and N as shown in Figure 7(b).

Thus; the fuzzy maximum power tracking control rules are given by

If $\Delta p / \Delta v$ is P Then Δu is N

If $\Delta p / \Delta v$ is Z Then Δu is Z

If $\Delta p / \Delta v$ is N Then Δu is P

The rate of increase of Δp and Δu are defined as follows:

$$\Delta p = p(k) - p(k-1) \quad (12)$$

$$\Delta v = v(k) - v(k-1) \quad (13)$$

The final control output is given by

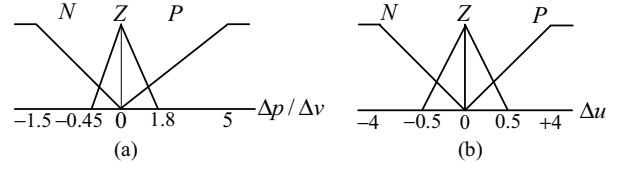


Figure 7. The membership functions of $\Delta p / \Delta v$ and Δu

$$u(k) = u(k-1) + \Delta u(k) \quad (14)$$

The actual control command $u(k)$ which is used to control the duty ratio of the switching pulse is calculated by the center weighted average defuzzification method, i.e.,

$$\Delta u = \frac{\sum_{i=1}^3 w_i C_{R_i}}{\sum_{i=1}^3 w_i} \quad (15)$$

where w_i is the antecedent part's membership function value of the i th-rule, C_{R_i} is the center of Consequent parts of the i th-rule.

When the charged current command is shifted to 0.1C or 0.01C, the fuzzy controller is activated to maintain the charged current reach to desired command value. In this situation, for precision control goal, the input variable $e(k)$, $\Delta e(k)$ and output variable $\Delta u(k)$ are fuzzified into seven fuzzy sets which are labeled as negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive big (PB). The fuzzy sets used in input and output are triangular membership functions as shown in Figure 8 and Figure 9, respectively. The error e and difference of error Δe are defined as

$$e = I_{ref} - I_{BAT} \quad (16)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (17)$$

where I_{ref} is the reference charged current of battery, which

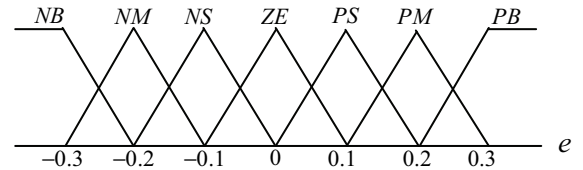


Figure 8. The the membership function of e

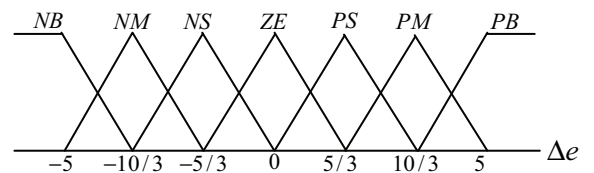


Figure 9. The the membership function of Δe

depended on how sufficiency is the solarization such that PV panel can provide either 0.1C or 0.01C current command. To simplify the design scheme of the fuzzy control, the discourse of universe of $e(k)$ is taken the same value for both 0.1C and 0.01C. and also as $\Delta e(k)$. The crisp output of the duty ratio of the switching pulse is calculated by the center weighted average defuzzification method that the same as (15). The output of the FLC is changed in duty ratio $\Delta u(k)$. The duty cycle $u(k)$ at the k th sampling time is defined as

$$u(k) = u(k-1) + \Delta u(k) \quad (18)$$

Then, it is sent through the PWM to DC-DC converter to generate desired switching action. The control rule must be designed in order that input variable $e(k)$ has to always be zero. The rule table of the FLC is listed in Table 2.

TABLE II. THE CONTROL RULE BASE

e/de	NB	NM	NS	ZE	PS	PM	PB
PB	ZE	NS	NM	NB	NB	NB	NB
PM	PS	ZE	NS	NM	NB	NB	NB
PS	PM	PS	ZE	NS	NM	NB	NB
ZE	PB	PM	PS	ZE	NS	NM	NB
NS	PB	PB	PM	PS	ZE	NS	NM
NM	PB	PB	PB	PM	PS	ZE	NS
NB	PB	PB	PB	PB	PM	PS	ZE

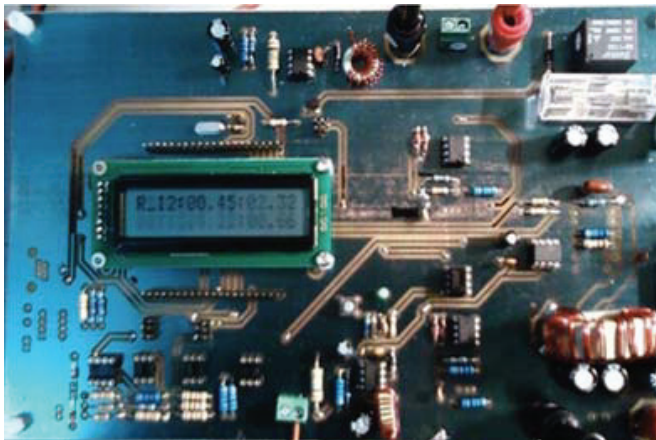


Figure 10. digital charged system circuit board.

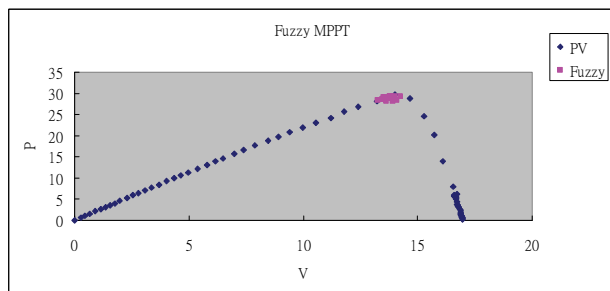


Figure 11. The fuzzy MPPT record curve and solar cell P-V curve

IV. EXPERIMENTS AND RESULTS

A. Halogen irradiation experiments:

The completed digital charged system circuit board is shown as Figure 10. Because of the sunlight is lack in winter, so that the experiment environment is emulated by using four 500W halogen lamps to irradiate the 120W solar cell instead. The wavelength between halogen lamp and sunlight is different, so the power generated by using halogen lamps is smaller than that from sunlight. In Figure 11, the red graph is the record for the fuzzy MPPT method, the blue curve graph is

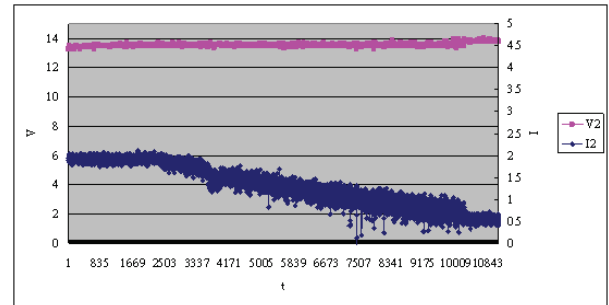


Figure 12. The battery charge voltage (red) and charge current (blue).

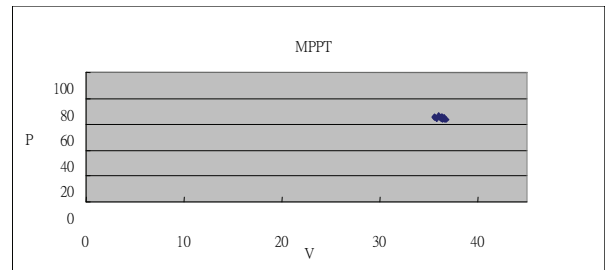


Figure 13. The maximum power graph.

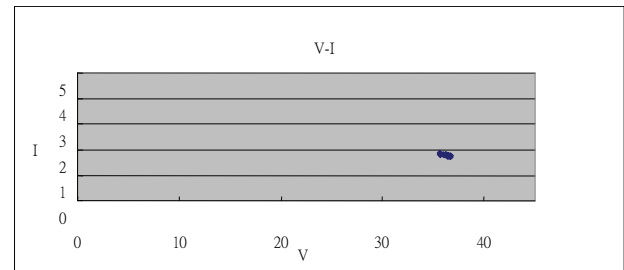


Figure 14. The solar cell V-I curve

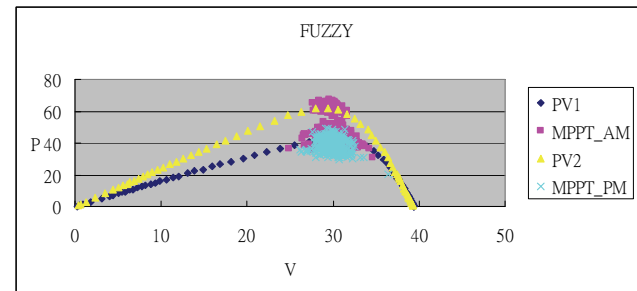


Figure 15. the Maximum power tracking graph in the insufficient light case in the morning and afternoon.

the record of solar cell power versus voltage data.

The battery charged voltage (red) and charge current (blue) are shown in Figure 12. When the battery voltage is close to the setpoint voltage 14.3V, then controller reduce the charge current command limit to 0.01C to float charge state to keep the battery maintain full voltage state, and ultimately battery voltage will maintain at the setpoint value 14.3V.

B. solar irradiation experiments: Cloudy 12:35

At this condition, the sun illumination is 714W/m² and the solar cells temperature is 60 degrees, Figure 13 is the maximum power point tracking record graph. At this time, because the sun illumination not enough to make controller to set the charge current command limit to 0.1C, therefore; controller is set to MPPT charge mode, Figure 14 is the solar cell V-I curve.

Due to insufficient light in the morning and afternoon, he battery voltage is less than 14.3, the controller is set to MPPT charge mode automatically, and therefore maximum power tracking is activated. Figure 15 is the Maximum power tracking record plots in a long period of time.

V. CONCLUSIONS

This paper have completed SEPIC converter circuit board and implemented the fuzzy control strategy. In order to obtain the high efficient solar cell energy conversion, a FMPPT control is activated if the solarization is insufficient. The fuzzy controller has been successfully to maintain a charged current so as that the battery voltage can reach to desired value, 0.1C charged current command and 0.01C floating charged current command. Three cases of the experimental results show that the circuit design and the proposed charge strategy are effective and feasible.

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