New solar cell charging system for green energy through the use of fuzzy logic design

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A new solar cell charging system with fuzzy logic design is proposed in this study. This kind of solar energy storage system is composed of a solar cell, a charger, batteries, a buck converter and a digital signal processor. In other words, it mainly applies a low-voltage level translator to control the pulse charging current of a lead-acid battery and also combines the fuzzy control method to improve the charging efficiency, suppress the abnormal temperature rise in the battery, lengthen the battery life-time, reduce the additional waste, etc. Finally, the experimental and simulated results are shown to demonstrate the validity of the system and verify the effectiveness with each other.

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1. Introduction

Due to the lack of energy source and the getting worse in environmental pollution, how to create and find a clean and never exhausted energy is becoming very important. The threat of energy shortage in the next few decades, for Taiwan as an example which is a small island highly clustered with a large density of people, has to find out a way to treat this pressing need for emergency. Because Taiwan island has almost no natural resources, in fact, the consumed 95% energy is relied on the abroad imports. This makes Taiwan even more vulnerable. To make the matter worse is the introduction of Kyoto Protocol [1], whose main objective is to stabilize and reduce greenhouse gas (GHG) emissions, mitigate climate change, and promote sustainable development. Specifically, if one country is not in compliance with its emissions limitation, then that country is required to make up the difference plus an additional 30%. In addition, that country will be suspended from making transfers under an emissions trading program. As a result, finding another sort of energy which will not cause greenhouse effect is very critical and essential. Without reliable sources of energy, the economy of Taiwan will be detrimental. This is not just for the sake of economy but also the sustainable environment for our future generations, including all the other animals and plants. In the foreseeable future, we not only have to develop more energy such as nuclear plants or power plants but also sustainable green energy such as solar, wind, windmill.

The problem with windmill method is that it has a noise concern and it will destroy the landscape. Furthermore, the wind is not easy to be controlled to meet the need of people. For such a highly density country like Taiwan, it is not a good option. On the contrary, the solar energy seems to be a much better option because Taiwan is located at the subtropical area which provides abundant sunlight. As shown in Table 1, it is found that the average of sunlight radiation in Tainan, south of Taiwan, is 58.34 kWh/m^2, and Hengchung even as high as 65.54 kWh/m^2.

With the rapid development of technology, the solar energy battery manufacturers are able to produce highly efficient and affordable solar batteries. Some obvious advantages of using solar energy are that it is clean, quiet and abundant. People can get the energy almost for free and maintain the corresponding facilities cheaply and easily. However, there are still some important concerns involved. First, some technological issues need tackling such as the cost to produce a solar cell, the density of energy, the time to charge the cell as well as the rising temperature of cell when charged. All of these in some ways will shorten the lifetime of the cell. This is mainly attributed to the traditional approach of charging control, and its efficiency.

Table 1. List of average sunlight radiation energy in some places of the world.

Country	City	Average sunlight radiation (kWh/m^2)
Taiwan	Taipei	46.25
Taiwan	Tainan	58.34
Taiwan	Hengchung	65.54
American	Miami	65.54
Australia	Canberra	63.74
Japan	Tokyo	39.25

To improve the performance of solar cell, there is quite a lot of charging technology proposed [2,3], for example, the mitigation of battery temperature, spread up charging design, fast charging technology, the prediction of voltages and current of acid-lead batteries, and searching the best charging parameter etc. In this paper, we will focus on the improvement of solar cell to get the best performance. A low-voltage converter is used to produce pulse current and charges lead-acid batteries. In addition, a digital signal processor is used to get the feedback of the voltages, temperature and current of the batteries. With the feedback, we can apply fuzzy control theory to charge the batteries more efficiently, mitigate the temperature increase as well as improve the charging performance.

2. Solar cell and lead-acid battery

Solar cell, also known as photovoltaic cell (PV), uses a solar panel to absorb solar energy and converts it into direct current. After that, through electrical and electronic technology, this direct current can be transformed into either an alternate or direct output current. Since the solar cell output voltage is very low about 0.5-0.6V per cell, normally it has to be connected series with other cells such as 36 or 72 cells in a set. Then people will arrange different sets of cells to produce the output voltages that a solar panel needs. Therefore, producing solar energy needs a lot of space. There are two main reasons that should be considered before solar energy can be really practical, i.e. the space and the efficiency. However, once a solar panel is set up, all it needs to be taken into account is the cost of electronic converter. In general, there are two basic types of solar cells, i.e. bulk type and thin film type, respectively. Bulk type solar cell can be further classified into three subtypes, i.e. single crystal silicon, poly-silicon and III-V compound semiconductor. Single crystal silicon has the efficiency between 15% and 17%, the highest efficient silicon solar cell. Poly-silicon solar cell has the efficiency from 10% to 14%. On the other hand, thin film type solar cell needs rare materials to produce and has lower price and output efficiency. It also can be classified into three subtypes, i.e. amorphous silicon, $CuInSe_2$ and CdTe solar cells. In equivalent circuit, a solar cell diode is consisted of a stable current source I_{sc}, rectified diode current I_{pv}, shunt resistance R_{sh} and series resistance R_s as shown in Fig.1. The charging efficiency depends on the insulation, materials of cells, surroundings, the place, direction, and latitude of the installation as well as the internal circuit design of the solar panel.

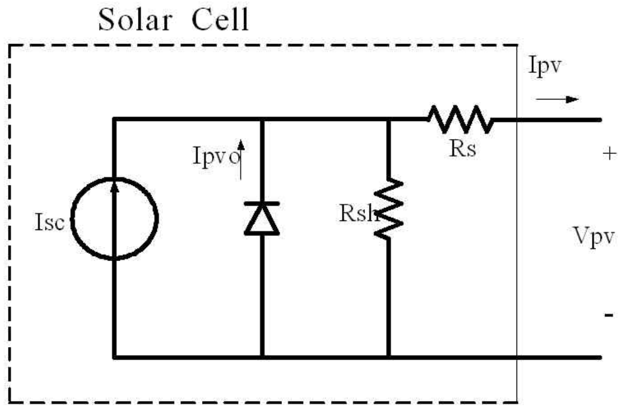

Fig. 1. Equivalent circuit of a solar cell.

Its current output I_{pv} is derived and given as [4]:

$$Ipv = Isc - Ipvo\left[\exp\left(\frac{q\left(Vpv + IscRs\right)}{nKT}\right) - 1\right] \tag{1}$$

where

I_{PV}	cell output current
I_{SC}	electron-hole current from light illumination
I_{PVO}	cell saturation current
q	electron charge (1.602 X 10^{-19} coul)
V_{PV}	cell output voltage
R_S	series resistance
n	ideality factor of solar cell diode
K	Boltzmann constant (8.63 × 10^{-5}ev/K)
T	cell temperature

In additional, lead-acid batteries belong to second batteries. When the energy of them is gone, they can be recharged. They can be classified into sealed and non-sealed lead-acid batteries. Because they are mostly used in offices, automatic factory, or energy back-up places, they are required to be efficient and last longer. To accomplish this, they also need to have more efficient charging circuits. A basic structure of a lead-acid battery is shown in Figure 2. By inserting two pieces of metal in the H_2SO_4, one of which is the positive node (PbO_2) and the other negative node (Pb), a sifter locates between these two pieces of metal to separate them from contacting each other. On the top of the battery is a valve to release the internal pressure caused by the process of charging and recharging. However, in a sealed lead-acid battery, the negative node will not be fully charged, resulting in no extra hydrogen. The positive node, on the contrary, is designed to be fully charged so it will not produce any oxygen. The reason for no oxygen produced is that whenever there is oxygen, it will be combined with the sponge lead at the negative node. This combination will produce PbO which consequently will react with the H_2SO_4 from the liquid and become $PbSO_4$ [5].

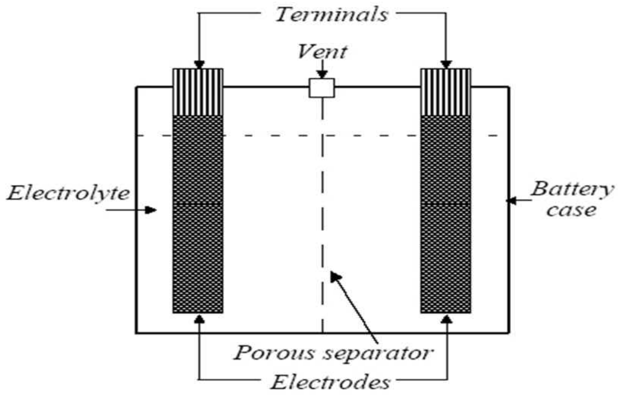

Fig. 2. Structure of a lead-acid battery.

3. Brief introduction of the proposed structure

This study is based on a micro-processor to design a modified solar energy storage system (see Fig. 3). Some traditional rules for tracking maximum power have been proposed including interference observation method [6] and increase conduction method [7]. With interference observation method by observing the output voltage differences before and after the change of load as well as the variations of output power, the solar cell will decide whether to increase or decrease input. This process will continue in sequence forever to get the best power point. The basic philosophy of increase conduction method starts from the logic formula dP/dV = 0. The power P can then be expressed by voltage V and current I. Thus dP/dV = 0 can be expressed as:

$$\frac{dP}{dV} = \frac{VdI}{dV} + I \quad (2)$$

$$-\frac{I}{V} = \frac{dI}{dV} \quad (3)$$

where dI represents the differences of current measured, and dV for the differences of voltage. By comparing the increased value (dI/dV)and the conducting value (I/V), we can determine the next variation of responsible cycle. When the increased value and the conducting value are fit into the equation (3), the maximum power point is reached. The basic principle of this study is using a solar cell as the system power source and a low-voltage converter to actualize the pulse charging process on a lead-acid battery. Specifically, the DSP, the core of controller, detects the signal from the circuit in order to monitor the situations in the battery. The feedback values of the voltage, current and temperature of the battery can determine the responsible cycle of PWM. By doing this, it will be possible to avoid overcharging in the lead-acid battery, control the temperature of charging and voltage of output, and prolongs the lifetime of the battery.

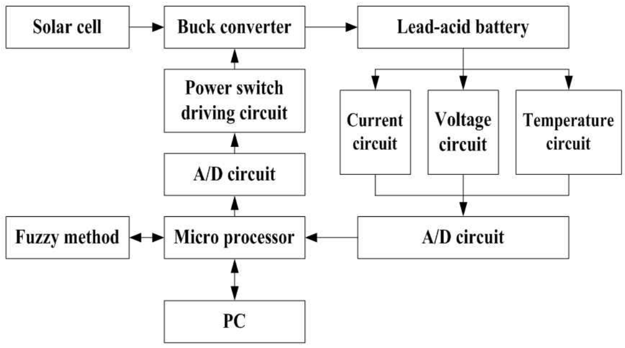

Fig. 3. The hardware of the proposed structure.

3.1 DSP and its related detecting facilities

TMS320F240 produced by TI is a fixed point conductor which has very powerful perimeter facilities (64k I/O mode, A/D interface and Digital I/O). Inside the conductor is a modified Harvard structure. What is incredible is that it separates the paths of information flow and programming flow. This has the following benefits:

1. The executing time and efficiency of the whole system are improved. This makes real time control possible.
2. The special hardware and programming result in high performance control.
3. Due to the ease of expanded functions. Thus the facilities can be expanded without difficulties;
4. It provides with Watchdog, thus monitoring of the programming is accessible.
5. The programming and the design of the 4^{th} Pipeline have the delaying instruction function.

3.2 The structure of buck converter

The main function of power source converter is to transport energy so as to isolate and regulate voltages. When the energy is being transported, there will be a complex problem that needs to deal with: how to transport and store energy. This paper proposes the use of induction current to charge lead-acid batteries. This can be done through the function that an inductor can storage and release energy. Specifically, the continuous releasing energy from the inductor to the batteries can produce pulse charging current and avoid the saturation of induction. Also the signal of counter PWM from the responsible cycle designed by the DSP can help pick the maximum value, increase feedback frequency and reach stable current rapidly.

4. Brief introduction of charging method with fuzzy theory

In general, there are three charging methods, i.e. fixed current charging method, pulse charging method and multi-step charging method. For the fixed current charging method, it is achieved by connecting many batteries in serial, resulting in having the same charging current in each battery. One of the setbacks of using this method is the lifetime will be shortened when overcharging whereas when charging current is too low, it will take a long time to charge the batteries. Another setback is that because of charging cycle which leads to no time to rest, the efficiency is usually very low. For the pulse charging method, it is used cycling method to charge batteries. Unlike fixed current method, it is more time for the liquid in the batteries to rest, mitigating the polarization phenomenon during charging process. This also prolongs the lifetime of the batteries. In fact, when greater pulse current is applied, the charging time will be shortened. Just as its name, multi-step charging method uses different types of charging currents. It uses lab's figures as the foundation to set up the different states of charging regulations and strategies. In the beginning of the charging process, it applies certain state of current to charge the batteries. Once batteries reach the setting voltages, it continues using different charging process--the charging currents will decrease as time goes on. Thus, it will take a long time to charge the batteries. For example, two-step charging method is one of these kinds.

When fuzzy control theory is used in the design of battery charging, its main objective is to have self-modifying ability to achieve the best charging phenomenon. This involves mitigating the unusual temperature rise in the batteries so as to avoid overcharging and over discharging, and eventually extend the lifetime of the batteries. Therefore, it will limit the wastes, an environment-friendly approach. Fuzzy control theory consists of four parts: fuzzifier, decision logic, fuzzy data and defuzzifier. Among all of these parts, decision logic is the nuclear part. It is acquired through the experience of controlling system done by experts and the fuzzy regulation data of language expressions.

4.1 Two logic values

Definite set belongs to two logic values. In definite set, each subset has a clear set. If a subset belongs to a specific set, it will have a value: 1, otherwise a value: 0. This is what is called 'Dichotomy'. Traditionally, in definite set, we can define X as the expressed area. X is the members of expressed area. A is a definite set of the expressed area. Then this specific function A can be defined as $\mu_A(x)$ shown as followed:

$$\mu_A(x) = \begin{cases} 1 & x \in A, \\ 0 & x \notin A. \end{cases} \quad (4)$$

4.2 Fuzzy set

The main difference between fuzzy set and definite set is that fuzzy set does not belong to dual logic. Thus, it does not have a clear subset. When considering a fuzzy set $\tilde{A}$, we can only give the value $\mu_{\tilde{A}}(x)$ between 0 and 1, depending on how fuzzy the set is. For example, when $\mu_{\tilde{A}}(x_1) < \mu_{\tilde{A}}(x_2)$, we define that the relationship (closeness) between x1 and $\tilde{A}$ ($x_1 \in \tilde{A}$) is less than that of x2 and $\tilde{A}$ ($x_2 \in \tilde{A}$). When a set $\tilde{A}$ does not have clear relationship, we call this set a fuzzy Set. The function of describing fuzzy characteristics is commonly called Belonging function $\mu_{\tilde{A}}(x)$. When $\mu_{\tilde{A}}(x)$ close to 1, it means that *x* very close to $\tilde{A}$. The definition of fuzzy set can be defined as followed:

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \mid x \in X\}, \mu_{\tilde{A}}(x) = [0,1] \quad (5)$$

4.3 Membership function

Membership function fuzzilizes the feedback signals of the voltage and current of a battery in order to be as the input value of fuzzy inference engine. (Figure 4 is the floating chart of fuzzy controller whereas Figure 5 is the basic block of feedback controlling system). By using the triangle serial membership function to describe the value of fuzzy set, we can minimize the variances.

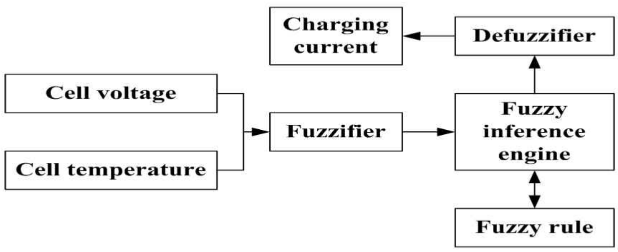

Fig. 4. Flowchart of fuzzy controller.

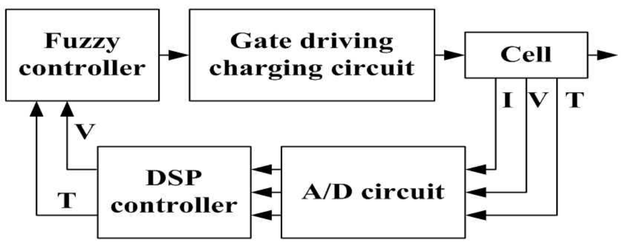

Fig. 5. Block diagram of loop control system.

4.4 Fuzzy inference engine

The minimum inference engine application of DSP could be used for fuzzy inference engine [8-9]. From Fig. 6, the charging current would be solved by defuzzifier. The input fitness is

$$W_i = Min\{\max[\min(Ti, Vi)], \max[\min(T_{i2}, V_{i2})]\} \quad (6)$$

and the output fitness is

$$B_i = \min\left(W_i \mu(y)\right) \tag{7}$$

and the integration of all rules is

$$B^* = \underset{i=1}{\overset{r}{Max}}\, B_i \tag{8}$$

where r is the numbers of trigged rules.

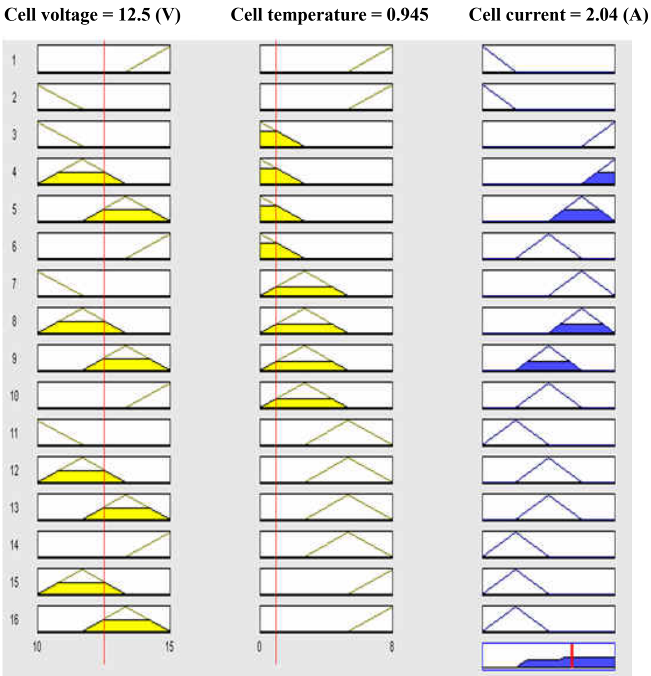

Fig. 6. Process of fuzzy inference.

4.5 Defuzzifier

This paper uses focus-center method to defuzzifier, whose serial values can be shown below:

$$U^* = \frac{\int \mu(y) \times y dy}{\int \mu(y) dy}. \tag{9}$$

When topology method is used, the calculation time can be shortened. The output area Y is classified into p numbers of discrete values, which can be expressed as $Y=\{y_1,y_2,y_3,\ldots,y_p\}$. Thus, the focus-center method can be shown as followed:

$$U^* = \frac{\sum_{j=1}^{p} y_i \times \mu(y_i)}{\sum_{j=1}^{p} \mu(y_i)} \tag{10}$$

Because TMS320F240 fuzzy controller does not have the function of floating calculation, this paper uses digitalized tables to set up the data system of the results of fuzzy theory in order to save time and complexity of calculation. When the controller finds out the input values of the fuzzy theory, the value of charging current can be known by checking the tables. Applying fuzzy controlling theory in the design of charging controller not only can mitigate the unusual rising temperature but also avoid overcharging and over discharging. This in return can prolong the lifetime of the batteries.

5. Experiment and results

5.1 Fuzzy control charging method

This paper uses DSP as the central controlling system and other related facilities. With these facilities, it can produce 10Hz charging current. The brand of the lead-acid battery is CSB 4AH. The internal time pulse in DSK is 20M with a counter to set cycling breakpoint defined by upper and lower counts. The output model is comparative output and its hardware is shown in Fig. 7.

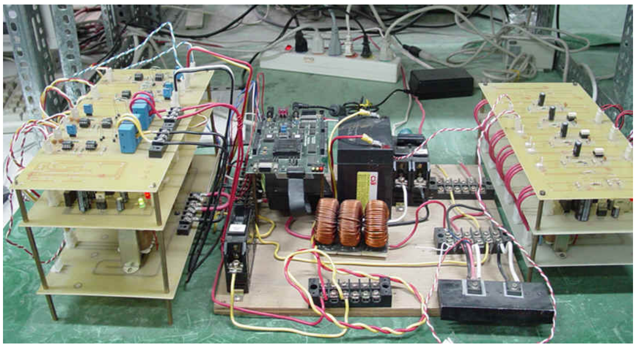

Fig. 7. The overall hardware structure.

With the feedback voltage and temperature of the batteries, this method can apply the input fuzzy controlling theory to calculate the new responsible cycle in order to control the charging current. For example, when the duty cycle is 0.08, it will match with the DSP data bank to export next responsible cycle. The initial voltage is 10.8V and the breakpoint voltage is 14.2V. To prove the feasibility of this method, we present the charging waves, charging voltage and charging temperature in Figs. 8-10. Experimental results can be listed as below:

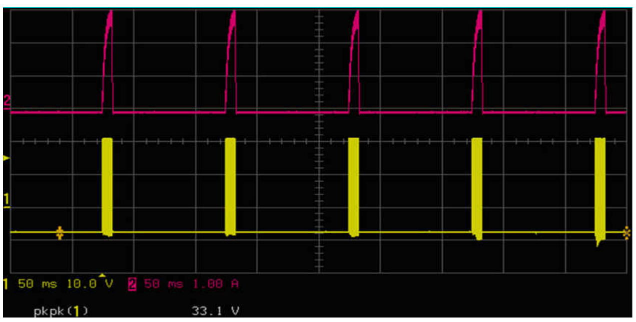

Fig. 8. Charging waveforms with fuzzy theory.

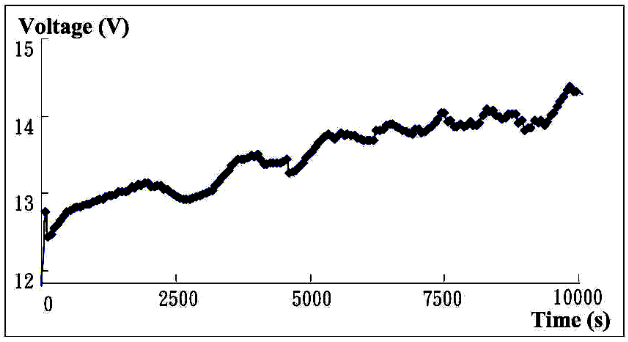

Fig. 9. Waveform of charging voltage with fuzzy theory.

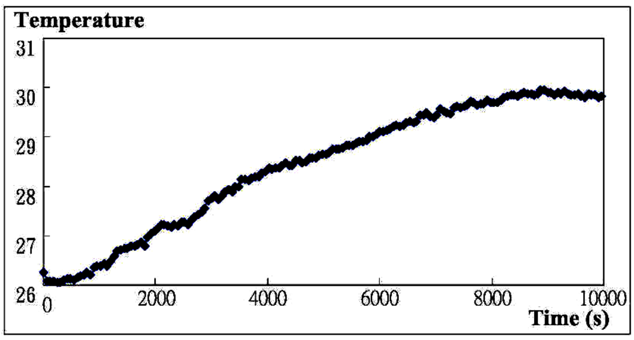

Fig. 10. Waveform of charging temperature with fuzzy theory.

1. The charging capacity can be estimated according to the statistics of the internal programming of DSP.
2. The charging time is roughly 3 hours with the average of 2.95AH.
3. The output capacity can be estimated according to the statistics of the discharging of the electronic load.
4. The discharging process will not be carried out until an hour after the charging process has been accomplished. We set the fixed current model and discharge 1 amber of current to lead-acid batteries until the voltage reaches 10.8V, resulting in discharging 2.65AH.
5. Attained efficiency = output capacity/input capacity = 89.8%.

5.1 Comparison with different charging methods

We also try to compare with different methods of charging a battery in terms of charging waves, charging voltage waves, and charging temperature figures by actually testing them. In fact, the charging time, the rising temperature of the batteries, charging capacity and efficiency are analyzed as followed:

1. The relation of battery rising temperature vs. charging voltage (see Fig. 11): Three-step and fuzzy control methods can effectively control charging and are quite efficient but both methods need a long time to charge.
2. The relation of charging voltage vs. charging time (see Fig. 12): Fixed current method needs the least time to charge but it causes the rising temperature, which affects the charging efficiency lower to only 76%. This makes it the least charging capacity of all.
3. The relations of charging capacity and efficiency vs. charging method (see Figs. 13-14): Among all of four tested methods, it is found that fuzzy control theory method is the most appropriate method of charging a battery no mater in capacity or efficiency.

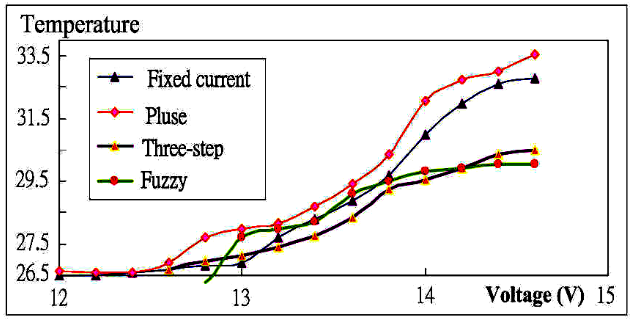

Fig. 11. Comparison with the rising temperature.

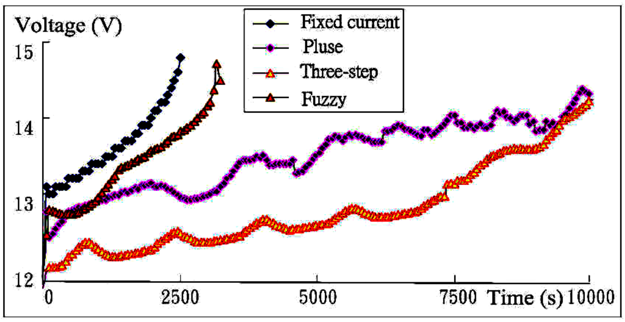

Fig. 12. Comparison with the charging time.

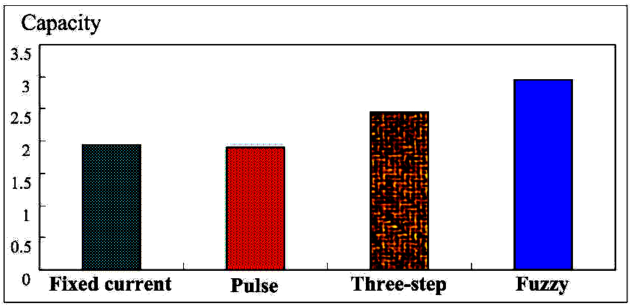

Fig. 13. Comparison with the charging capacity.

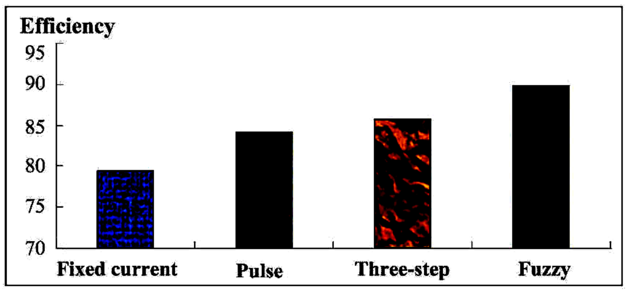

Fig. 14. Comparison with the charging efficiency.

After comparing the four methods, we can understand that fuzzy control method is a feasible way of charging a battery. It is efficient and has a large capacity in charging. Also it can effectively mitigate the temperature around 4 degree. In fact, the chemical reaction in the battery is very stable and slow, which can slow down the polarization process as well as prolong the lifetime of the battery. Nevertheless, it needs longer time to charge a battery. This may seem a disadvantage but from the perspective of the solar energy storage system, this lower temperature method can actually avoid damage caused by heat in the facilities. In the long run, it is more economical and friendly.

6. Conclusions

This study has successfully proved that the proposed fuzzy controlling system is the best method during testing different charging methods. It uses the single chip processor as the basic controller to design a smart charging system for solar batteries. Through digitalized signal processor and perimeter facilities, we can not only save the cost of the circuit installation but also monitor the charging situations in real time. With the monitoring information, this fuzzy controlling system can adjust the most appropriate current to charge and mitigate the abnormal rising temperature. In summary, this new charging system with fuzzy controlling system has the following benefits:

A) Using digitalized signal processor and perimeter facilities can save the cost of circuit installation.
B) Monitoring the charging situation in real time and adjusting appropriate charging current
C) Using lower voltage converter to produce a pulse charging method can effectively improve polarization phenomenon.
D) Using fuzzy theory controller can effectively mitigate the rising temperature during charging process.
E) This system can be easily applied in automobile electronics.

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