Design of Photovoltaic Chargers Using the Maximum Power Point Tracking Method Based on the Adaptive Fuzzy Control

Xinglong Zhao [1, 2] and Jinyan Li [3]

[1] College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou 730070, China

[2] College of physics and Electronic Information Engineering, NingXia Normal University, Guyuan 756000, China

[3] Department of Mechanical and Electrical Engineering, NingXia Vocational Technical College of Industry and Commerce, Yinchuan, 750021 China

Abstract

In view of the non-linearility, complexity and instability of photovoltaic chargers, this study proposes an adaptive fuzzy logic control (AFLC) algorithm. By analyzing the output volt-ampere (VA) characteristics and power model of solar photovoltaic cell modules and combining with the properties of the optimal charge curve of batteries, the maximum power point tracking (MPPT) method is put forward based on the adaptive fuzzy logic controllers. By using the voltage between the two ends of a battery and loop current as the core feedback parameters, the duty cycle of pulse-width modulation (PWM) is adjusted to fit the optimal charge curve of batteries. By using the method, the service life of batteries is extended while maintaining the system efficiency. The hardware circuit with the TMS3713B digital processor as the core was designed for verification and the experimental results show that this algorithm can realize the optimal charging efficiency.

Keywords

Adaptive Fuzzy Logic Control, Maximum Power Point Tracking, Duty Cycle, Charge Curve.

1. Introduction

Photovoltaic power generation, as an effective way to develop renewable energies, has risen to the national strategic level. If China can effectively utilize 1/10 of the vast desert areas in the northwest areas of China, the generated power is equivalent to that produced by 128 Three Gorges hydropower stations [1, 2]. Statistics demonstrate that in solar photovoltaic power generation systems, photovoltaic arrays, batteries, controllers or the maximum power point trackers, and others account for 57%, 30%, 7%, and 6% respectively in the total costs for the whole system. Obviously, photovoltaic array plays an important role with respect to the costs for solar photovoltaic power generation systems. However, under existing technologies, it is unrealistic to seek for economic and practical solar cell arrays. Therefore, researching new controllers to improve the conversion efficiency of photovoltaic arrays, strengthen the protections on the charge of batteries and prolong the service life of batteries is significant to reduce the costs and enhance the popularity of solar photovoltaic power generation.

Photovoltaic cell panels collect heat and light energies to generate photo-current and form an open-circuit voltage between both ends of a battery. The output power of photovoltaic arrays is a function of the solar light intensity and ambient temperature, showing non-linear characteristics. Owing to power points fluctuate greatly with sunshine time, if the chargers are designed unreasonably, photovoltaic cells are probably not matched with batteries and loads. This, on the one hand, is likely to lead to the ineffective conversion from light energy to electrical energy. On the other hand, the batteries are damaged with reducing service life. The maximum power point tracking (MPPT) method [3-5] is widely used in studying the control methods of chargers. Therefore, based on the MPPT method, this research analyzes the properties of charge curve of batteries and designs chargers based on the adaptive fuzzy logic control (AFLC). Furthermore, this study theoretically analyzes the variable universe to charge batteries through maximum power output and prolong the service life of batteries. By utilizing TMS320C6713B as a main control chip, a hardware circuit was designed to verify the feasibility of the control algorithm.

2. Theoretical research on chargers

2.1 Mathematical model of photovoltaic cell modules

By using the photoelectric effects of semiconductors, photovoltaic cells directly change solar energies into electric energies through PN junction method. Cell panels are the basic units of photovoltaic cell modules and each cell panel only output 0.45 V~0.6 V voltage. In the practical applications of industry, a plurality of single solar cell panels is connected in series and parallel to obtain specific output voltage and current. They are packed by using certain process to form photovoltaic cell modules [6].

Photovoltaic cell modules are the devices for transforming solar and electric energies. Based on the internal compositions and volt-ampere (U-I) characteristics, the engineering current formulas of photovoltaic cell modules are shown as follows [7].

$$I = I_{SC}(1-K_1\{\exp[V/(K_2V_{OC})]-1\}) \tag{1}$$

$$K_1 = (1-I_m/I_{SC})\exp\left[-V_m(K_2V_{OC})\right] \tag{2}$$

$$K_2 = (V_m/V_{OC}-1)\left[\mathrm{In}(1-I_m/I_{SC})\right]^{-1} \tag{3}$$

Where, I_{SC} and V_{OC} represent the short-circuit current and the open-circuit voltage, respectively. I_m and V_m indicate the maximum current and voltage, respectively and they have unique values when sunshine and battery temperature are fixed. In the engineering, the following formulas are generally used to simplify the function relationship of I_{stm} and V_{stm} with the photovoltaic cell temperature T and illumination coefficient S.

$$I_{stm} = I_m \times S/S_{ref} \times (1+\alpha\Delta T) \tag{4}$$

$$V_{stm} = V_m \times (1-\mathrm{c}\Delta T)\times(1+\mathrm{b}\Delta S) \tag{5}$$

Where,

$$\Delta T = T + 0.3\times S - 25 \tag{6}$$

$$\Delta S = S/1000-1 \tag{7}$$

It can be seen from the above formulas that the current and voltage of output points are related to the photovoltaic cell temperature T and illumination coefficient S. Three constants including α, b and c value 0.0025, 0.5 and 0.00288, respectively.

2.2 Mathematical model of batteries

A photovoltaic system has to be equipped with batteries for storing energy whose service life influences the stability of the photovoltaic system and determines the maintenance costs in the late stage after establishing the system. Therefore, it is very necessary to effectively prolong the service life of batteries by adopting a correct charging method.

Previous researches demonstrate that in the two processes (charge and discharge) influencing the service life of batteries, charge plays a decisive role. Batteries of photovoltaic systems are charged by photovoltaic cell modules, showing randomness, discontinuity and finiteness [8]. Therefore, the designs of chargers not only need to consider the efficiency of photovoltaic systems to maximally utilize solar energies, but also should take the service life of batteries and the orientation of charge curve into account.

After deeply discharging batteries, at any moment in the charge process, the acceptable current for batteries is [5].

$$I = I_0 \times \exp(-\alpha t) \quad (8)$$

Where, I, I_0 and α represent the acceptable maximum current at any moment, the current when t equals 0 and the attenuation factor, respectively. According to Formula 8, the optimal charge curve of batteries is demonstrated in Figure 1.

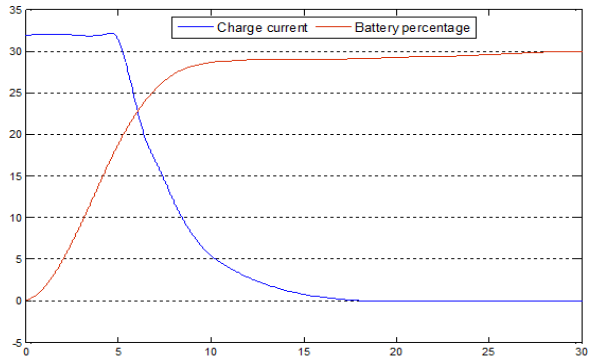

Figure 1. The relationship between optimal charge current and battery charge

As shown in the figure, the ideal charge curve is divided into three stages consisting of constant current, constant voltage and floating charge stages. In the stage of constant current, the current is limited to prevent impacts of excessive initial currents on batteries in the charge. In the stage of constant voltage, the current decreases in the form of a negative exponent to reduce the polarization of batteries. In addition, in the stage of floating charge, the charge is maintained to supplement the energies consumed by internal resistance of batteries. Batteries as a device for storing energies in solar photovoltaic power generation systems, the floating charge is essential.

3. The MPPT control algorithm based on adaptive fuzzy controllers

In a photovoltaic system, it is hard to obtain the ideal charge curve of batteries. Because the output characteristics of photovoltaic cell modules significantly change with the environment, the charge stage is different from traditional methods. Considering the influences of environment temperature and illumination intensity on output current and voltage of photovoltaic systems and the performances of batteries, the charge process is divided into three stages, namely, constant current, constant voltage and floating charge stages. As shown in Figure 1, in the constant current stage, the charging capacity of batteries can reach 80% of the maximum capacity. When the voltage between the two ends of a battery increases to the set threshold, it changes to the constant voltage charge stage. In order to maintain the charging voltage between the two ends of a battery at a constant value, a constant pressure ring needs to be established. PI controllers can improve the performances at dynamic and steady states, adjust the duty cycle of the power switch tubes and ensure the constant charging voltage. When the voltage is 1.2 times that of the rated voltage, the charge is completed and the floating charge begins. Based on the three stages of charge, the key to improving charge efficiency is the constant current charge stage, so it is necessary to introduce the maximum power tracking technology, so as to improve the efficiency of photoelectric conversion [9].

3.1 MPPT algorithm

According to Formulas (4) and (5), when the environment temperature and illumination coefficient are unchanged, the maximum output power is unique. By adjusting and transferring the working states of the transfer circuit and measuring the voltage, current or power, the MPPT technology determines the position relationship between the current working point and the maximum power point and impels the current (or voltage) to approach to the maximum power point until reaching it. The aim is to make photovoltaic cell modules output more electricity, so that electricity is effectively stored in batteries [10]. The matching between the load impedance and power resistance impedance is the condition for photovoltaic cells outputting the maximum power. As the external environment changes, the equivalent internal resistance impedance of photovoltaic cells varies as well, so the load impedance needs to match with the changing resistance impedance.

MPPT technology is an optimization process essentially that realizes optimization by constantly changing the setting values of controllable parameters in the operation. Two algorithms including exact optimization and fuzzy optimization are generally used. The former consists of the incremental conductance algorithm and open circuit voltage function method, while the latter comprises the disturbance observation method and fuzzy control method [11, 12]. This study designed an adaptive fuzzy controller to track the maximum power point.

3.2 Adaptive fuzzy controller

Controlling non-linear systems using fuzzy logic can obtain better effects than utilizing traditional control methods.

3.2.1 Fuzzy logic design

(1) Defining input and output variables

When tracking the maximum power point of a solar photovoltaic system by using the fuzzy control, the difference *E* between the change value of output conductance and instantaneous conductance value of solar cells and the change Δ*E* of this difference are used as the inputs of fuzzy control, namely,

$$E(m)=\frac{P(m)-P(m-1)}{U(m)-U(m-1)} \tag{9}$$

$$\Delta E(m)=E(m)-E(m-1) \tag{10}$$

Where, $P(m)$, $P(m-1)$, $U(m)$ and $U(m-1)$ indicate the output powers and voltages of photovoltaic cell modules collected at *m* and *m-1* moments, respectively. The essential condition of the maximum power point is to make $E(m)$ be 0.

In accordance with the basic principles of MPPT of solar cells, the change dD of duty cycle of power switch tubes of controllers is selected as the output of fuzzy controllers.

(2) Determining fuzzy sets and membership function

The inputs and output are fuzzified into 5 sub-sets that are represented as PB (positive big), PS (positive small), ZO (zero), NS (negative small) and NB (negative big). The fuzzy domains of *E*, Δ*E* and *D* are [-20, 20], [-10, 10] and [-4, 4], respectively. The membership function is shown in Figure 2.

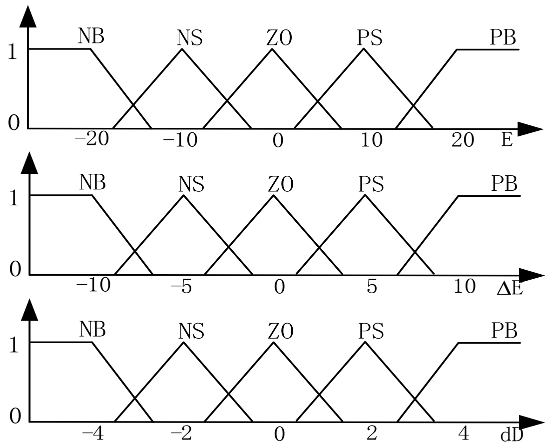

Figure 2. Input / output membership functions

A linear function is used for the membership function to reduce the loads of processors. Furthermore, each membership range is determined according to the actual experiment.

(3) Fuzzy inference rule

Whether the output power of a solar photovoltaic array can rapidly reach the maximum is regarded as the basic inference rule. Specifically, when $E > 0$ and $\Delta E > 0$, the maximum power point is in the left of the sampling point, so the working voltage needs to be increased by a large step size to move the power point to the right, so as to approach to the maximum power point. If $E < 0$ and $\Delta E < 0$, the maximum power point lies in the right of the sampling point. Under such condition, the working voltage requires to be reduced by a large step size to move the power point to the left, making it close to the maximum power point. In addition, when $E = 0$, the power is the largest and there is no need to change working voltage. Based on this, the fuzzy rule is established, as demonstrated in Table 1.

Table 1. Fuzzy inference rule

ΔE	E				
NB	NB	NS	ZO	PS	PB
NS	ZO	ZO	NB	NB	NB
Z0	ZO	ZO	NS	NS	NS
PS	NS	ZO	ZO	ZO	PS
PB	PS	PS	PS	ZO	ZO

(4) Defuzzification

The output deduced based on the fuzzy rule and its degree of membership are fuzzy quantities, while the outputs for control systems are exact quantities. Therefore, the fuzzy output obtained from the fuzzy inference and the corresponding degree of membership need to be transferred into exact values, which is known as defuzzification. The centroid method is used for defuzzification in this research and the calculation formula is shown as follows.

$$dD = \frac{\sum_{i=1}^{n} u(D_i) D_i}{\sum_{i=1}^{n} u(D_i)} \tag{11}$$

3.2.2 Adaptive algorithm

Fuzzy control method can obtain high precision and response speed under general conditions, but when the output of photovoltaic cell modules changes suddenly, this method cannot converge in time. Owing to photovoltaic cell modules work in complex outdoor environment, it is necessary to introduce the adaptive algorithm. As for the fuzzy control, the adaptive algorithm is the most effective in adjusting the shape and range of membership function. According to the evaluations using the control rules in the working state at the last moment, the boundary of input membership function is shifted to correct the parameters, so as to improve the performances of control systems.

Adaptive fuzzy control adopts measured values as the standard to evaluate membership function. By constantly measuring the input, state and output of a controlled system, the performances of fuzzy controllers are determined. The measured power and theoretical values are compared and calculated, and then the fuzzily input membership function is corrected using adaptive mechanism.

The membership function of the AFLC is demonstrated in Figure 3.

Boundary variables are added in the membership function.

For the input variable E, three parameters including X0, X1 and X2 are added and their relationship is shown as 0<X1<X0<10<X2<20-X1.

As to the input variable ΔE, three parameters–Y0, Y1 and Y2 are added and their relationship is demonstrated as 0<Y1<Y0<10<Y2<20-Y1.

With the changes of variable parameters, the membership of the function changes. By using the fuzzy control rule, the output changes correspondingly.

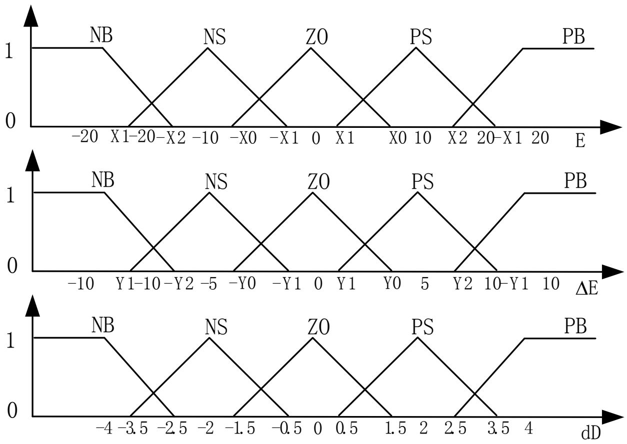

Figure 3. Membership function of increasing variables

3.2.3 Algorithm flowchart

The flowchart of AFLC is displayed in Figure 4.

In the initialization, the duty cycle D values 35%, and photovoltaic cell modules have 80% open-circuit voltage and work in the range of the maximum working point. According to the fuzzy controllers, the changes of D are obtained to conduct superposition with the original duty cycle. The calculated duty cycle controls the voltage output from the circuits and then the power is calculated constantly to obtain the maximum power.

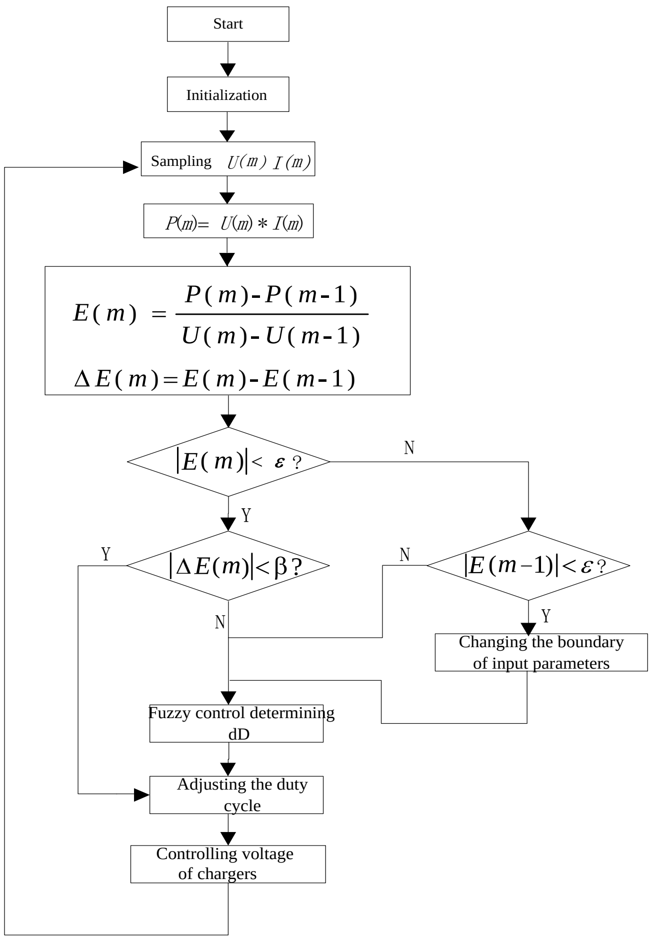

Figure 4. Adaptive fuzzy control algorithm

4. Designs of charger

Photovoltaic cells output direct-current (DC) power and battery charging also requires DC power, so the hardware used for realizing the MPPT is a DC-DC converter. By changing the duty cycle of drive MOS tubes, the output duty cycle is adjusted in real time. In order to verify the validity of the control algorithm, a charger for batteries of a photovoltaic system is designed. Owing to the fuzzy control was used in the whole control strategy which requires high real-time, the DSPTMS320C6713B digital processor was utilized as a master chip. Shangde's STP205-18/UD in Wuxi was used as solar cell modules with the open-circuit voltage, short-circuit current and the maximum power being 26.3 V, 7.8 A and 205 W. Furthermore, LC-P12100 batteries with 12 V of voltage and 100 Ah of capacity produced by Shenyang Northeast Storage Battery Ltd. Co., China were used. The charger is designed with a main circuit, a drive circuit, a sampling circuit and a power supply circuit.

4.1 DC-DC converter

The main circuit is shown in Figure 5. By using BUCK topology, a DC-DC buck chopper circuit, the voltage of 26 V is converted into DC voltage of 13 V to charge the battery. When MOS2 is connected, C2 is charged by PV passing through the inductor L. When MOS2 is unconnected, C2 discharges and the battery is charged through the D2 freewheeling diode. Due to the damping effects of inductance elements, the terminal voltage of the battery is smaller than that of solar cell panels. When the battery is full and does not need floating charge, MOS2 is unconnected. With the connection of MOS1, the electricity of solar cell panels is discharged.

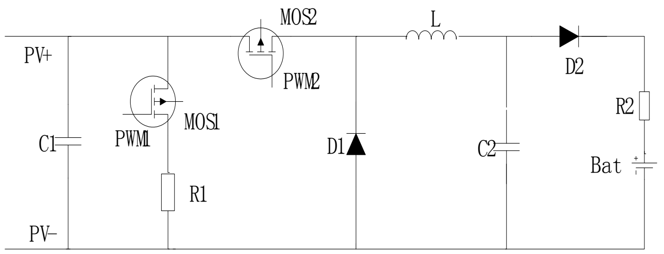

Figure 5. Main circuit of DC-DC conversion

4.2 Drive circuit

Because the PWM waveform amplitude output by DSP is only 3.3 V, signals are bound to be amplified. IRF840 was used as MOS tubes in the main circuit and the TLP250 chip was utilized for designing the drive circuit, as shown in Figure 6. The performance of the drive circuit determines the efficiency and performance of power conversion.

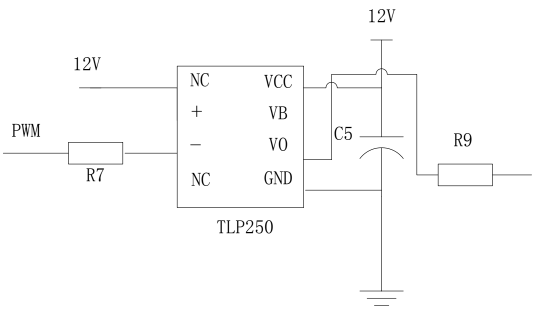

Figure 6. Drive circuit

4.3 Sampling circuit

Circuit feedback involves three parameters including DC voltage, DC current and temperature.

The DC voltage was adopted to feed back 0~3.3 V of voltages to A/D port of the DSP through resistive subdivision in two ends of C2. The MIK-DZI0-1A0 produced by Amico Company was used as the DC current sensor with the supply voltage, measuring current, output and sampling resistance of 24 V, 20 A, 4–20 mA, and 150 Ω, respectively. The Songye high-precision temperature transmitter SY-DFC was utilized as the temperature sensor, showing 12 V of supply voltage, 4~20 mA of output current and 150 Ω of sampling resistance at -20~70 ℃ of input temperature.

4.4 Algorithm comparison

Figure 7 displays the charging current curves recorded by prototype tests. The horizontal ordinate is time axis and each point is recorded every 10 min for 5 h in total. The vertical ordinate represents charging current. It can be seen from the figure that the AFLC algorithm is used to track the maximum power in the first one hour during which 80% charging capacity are completed.

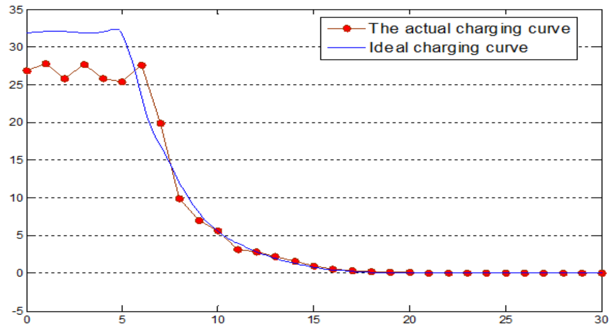

Figure 7. Ideal charging and actual charging current curves

5. Conclusion

This study researches the chargers of photovoltaic power generation systems by using the MPPT control algorithm based on adaptive fuzzy controllers. According to the working state of the prototype tested at 200 W, the actual charging curve of batteries can well simulate the ideal charging curve and the AFLC algorithm can preferably track the maximum power. The prototype test basically reaches the expected effects. The study makes an attempt for the development and application of chargers of high-power photovoltaic power systems.

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