# Solar Tracking Fuzzy Control System Design using FPGA

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***Abstract*—A solar tracking generating power system is designed and implemented. An expert controller, sensors and input/output interface are integrated with a tracking mechanism to increase the energy generation efficiency of solar cells. In order to track the sun, cadmium sulfide light sensitive resistors are used. To achieve optimal solar tracking, a fuzzy algorithm is developed. A field programmable gate array is applied to design the controller such that the solar cells always face the sun in most of the day time.**

***Index Terms*—solar tracking, two-axis tracking, field programmable gate array, fuzzy control.**

## I. Introduction

The green energy also called the regeneration energy, has gained much attention nowadays. The green energy can be recycled, such as solar energy, water power, wind power, biomass energy, terrestrial heat, temperature difference of sea, sea waves, morning and evening tides, etc [1, 2]. Among them, solar energy is the most powerful resource that can be used to generate power. So far the efficiency of generating power of solar energy is relatively low. Thus, how to increase the efficiency of generating power of solar energy is very important.

In the past, solar cells are hooked with fixed elevating angles. It dose not track the sun. Therefore, the efficiency of power generation is low. For example, the elevating angle of a solar cell for the largest volume of illumination in daytime is 23.5$^\circ$ in southern Taiwan. Since the fixed-type solar panel can not obtain the optimal solar energy, the transformation efficiency of solar energy is limited. Many scholars proposed different methods for tracking the sun [3-9]. Many different light source sensors, light intensity sensors, intelligent vision techniques, and CCD equipments were applied to compute the absorbed time of the sun radiation in everyday for measuring the volume of solar energy. So far the majority of solar cell panels worldwide are hooked with fixed angles. Thus, it is clear that the method of tracking the sun is a worthy technique to be developed.

In this paper, the main goal is to design and implement a solar tracking control system using field programmable gate array (FPGA). The CdS light sensitive resistors are used. Feedback signals are delivered to the assigned chip through an A/D converter. Then we developed a fuzzy controller and implement it on the FPGA platform. A Cyclone II chip of the Altera Company is adopted as the control kernel [10]. Finally, a comparison between the tracking system and the fixed system is made. From the experimental results, the proposed tracking system is verified more efficiently in generating energy than the fixed system.

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## II. Solar Cell Description

The solar cell is composed by the semiconductors of the P-N junctions [11-12]. It can convert light into electric energy. Therefore we can assume that through the sunlight shining on the solar cell, the electricity produced by it can be used like common electricity. The equivalent circuit of the solar cell is shown in Fig. 1.

The current supply $I_{ph}$ represents the electric current generated from the sun beaming on the solar cell. $R_j$ is the non-linear impedance of the P-N junction. $D_j$ is a P-N junction diode, $R_{sh}$ and $R_s$ represent the equivalent lineup with the interior of the materials and connecting resistances in series. Usually in general analysis, $R_{sh}$ is large, and the value of $R_s$ is small. Therefore in order to simplify the process of analysis, one can ignore $R_{sh}$ and $R_s$. The symbol $R_o$ represents the external load. $I$ and $V$ represent the output current and the voltage of the solar cell, respectively.

From the equivalent circuit, and based on the characteristics of the P-N junction, (1) presents the connection between the output current $I$ and the output voltage $V$ :

$$I = n_p I_{ph} - n_p I_{sat}\left[\exp\left(\frac{q}{kTA}\frac{V}{n_s}\right) - 1]\right], \qquad (1)$$

where $n_p$ represents the parallel integer of the solar cell; $n_s$ represents the series connected integer of the solar cell; $q$ represents the contained electricity in an electro ($1.6\times10^{-19}$ Columbic); $k$ is boltzmann constant($1.38\times10^{-23} J/^\circ K$); $T$ is the temperature of the solar cell (absolute temperature $^\circ K$); and $A$ is the ideal factor of the solar cell ($A = 1 \sim 5$). The current $I_{sat}$ in (1) represents the reversion saturation current of the solar power. Further, $I_{sat}$ can be determined by using the following formula:

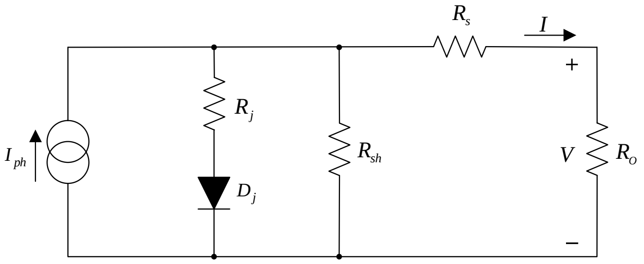


Fig. 1. Solar cell equivalent circuit.

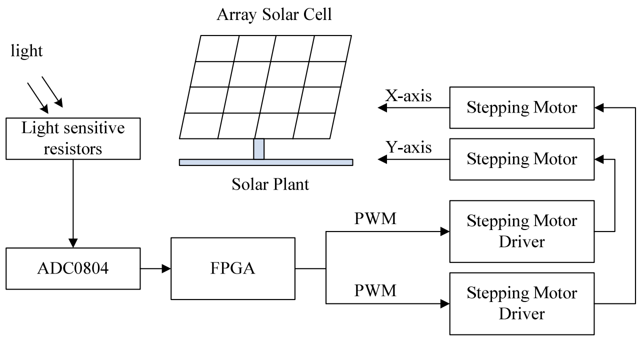


Fig. 2. System architecture of the solar tracking system.

$$I_{sat} = I_{rr}\left[\frac{T}{T_r}\right]^3 \exp\left[\frac{qE_{Gap}}{kA}\left(\frac{1}{T_r}-\frac{1}{T}\right)\right], \qquad (2)$$

where $T_r$ represents the reference temperature of the solar cell; $I_{rr}$ is the reversion saturation current at the time when the solar cell reaches its temperature $T_r$; and $E_{Gap}$ is the energy needed for crossing the energy band gap for the semiconductor materials. (the crystalline $E_{Gap} \cong 1.1eV$ ).

From the study we are able to know when the temperature is fixed, the stronger the sunlight is, the higher the open-circuit voltage and the short-circuit current are. Here we can see the obvious affects of the short-circuit current by the illumination rather than the open-circuit current. Therefore the solar cell can provide higher output rate as the sunlight becomes stronger, i.e. solar cell facing the sun.

## III. Architecture of System Hardware

The system architecture of the proposed solar tracking control system using FPGA is shown in Fig. 2. A feedback signal is produced from the CdS light sensitive resistors since the sun shines and is inputted to the FPGA through an analog/digital converter. Then, the controller in the chip delivers an output, the corresponding PWM signals, to drive the stepping motors. Thus, the directions of the two dimensional solar platform can be tuned to achieve optimal control, respectively.

There are three modes in the controller as follows:

(1) Balancing mode

To set the initial position of the solar platform, we use mercury switches for balancing position. The goal is to set boundary problems around for preventing too large elevating angles, which may make the solar panels crash the mechanism platform. Thus, the motors and the platform may be broken.

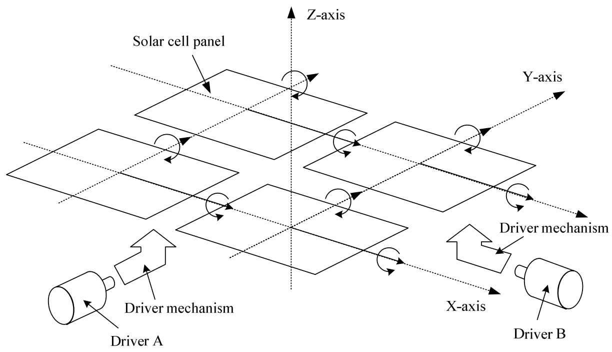


Fig. 3. Sketch of the two-axis array solar cells.

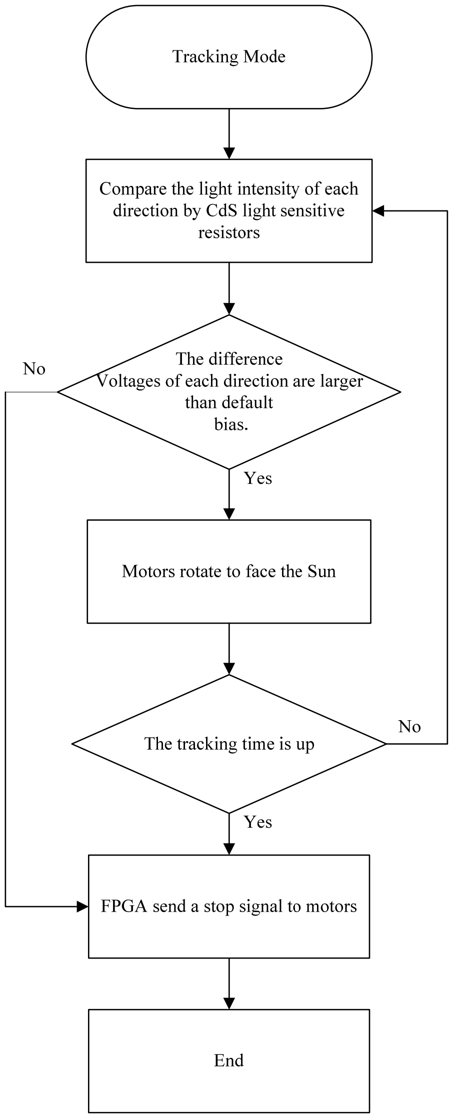


Fig. 4. Flow diagram of the tracking control.

(2) Automatic mode

The tracking light sensors are based the intensity of receiving light of the CdS light sensitive resistors. The sensors can deliver different signals to the FPGA controller through an analog/digital converter according to the different sunlight intensity. The NiosII CPU is the main control kernel

[13]. By tuning the two-dimensional solar platform, the optimal efficiency of generating power can be achieved.

(3) Manual mode

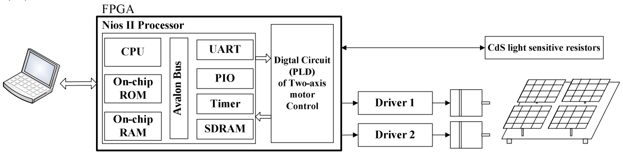


Fig. 5. System architecture with FPGA.

When the tracking control system is in a trouble or a maintaining process, the manual mode of the system can be chosen. Then, engineers can tune the position of the solar panel arbitrarily and overhaul it.

The array solar tracking system architecture contains two motors to drive the platform, conducting an approximate hemispheroidal three-dimensional rotation on the array solar generating power system as shown in Fig. 3. The two motors are decoupled, i.e., the rotation angle of one motor does not influence that of the other motor, reducing control problems. This implementation minimizes the system's power consumption during operation and increases efficiency and the total amount of electricity generated. The flow chart of the tracking is shown in Fig. 4. The system architecture with FPGA Nios II is shown in Fig. 5.

There are two important advantages in the array type mechanism as follows:

(1) High efficiency of light-electricity transformation.

Since the array solar tracking mechanism has a function of rotating like three-dimensional, the array solar tracking mechanism can track the sun in real time. Therefore, the system has high efficiency of light-electricity transformation and has an advantage of large production.

(2) The mechanism is simple and saving power.

The two rotating dimensions of the array solar tracking mechanism are controlled by the two independent driving sources, which do not have the coupling problem and bear the weight of the other driving source. At the same time, the rotating inertia of the rotating panels can be reduced.

The tracking device is composed of four same CdS (Cadmium Sulfide) light sensitive resistors, which detect light intensity from eastern, western, southern, and northern directions, respectively. In every direction, there is a CdS light sensitive resistor with an elevating angle $45^{o}$ to face a light source. The four sensors are separated as two groups. One is using two CdS light sensitive resistors to be an eastward-westward direction sensor for comparing the light intensity of eastward and westward directions. When the eastward-westward direction sensor receives different light intensity, the system will obtain the signal according to the output voltages of the eastward-westward direction sensors. A voltage type analog/digital converter (ADC0804) can read different output voltages of the sensor and decide which direction has larger light intensity than the other direction. Then, the system will drive the stepping motors to make the solar panel turn to the decided direction. When the output voltages of the eastward-westward direction sensor are equal, i.e., the difference between the outputs of the eastward-westward direction sensors is zero. Then, the motor voltage is also zero. This means that the tracking process is completed in the eastward-westward direction. Similarly for another southern-northern direction sensor, it can be analyzed by the same methodology to track the sun in the southern-northern direction.

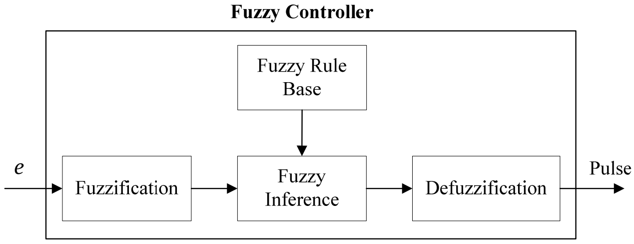


Fig. 6. Block diagram of the fuzzy control.

## IV. Fuzzy Controller Design

The fuzzy sets concept was proposed by Zadeh in 1965 [14-16]. The fuzzy algorithm can make human knowledge into the rule base to control a plant with linguistic descriptions. It relies on expert experience instead of mathematical models. The advantages of fuzzy control include good popularization, high faults tolerance, and suitable for nonlinear control systems.

A fuzzy controller design has four parts, fuzzification, control rule base, fuzzy inference, and defuzzification. The block diagram of the fuzzy control system is shown in Fig. 6.

At first, the sun light illuminates on a CdS light sensitive resistor of the solar tracking device. Then a feedback analog signal will be produced and transformed into a digital signal through an analog/digital converter. When the voltage on the eastward-westward direction or the southward-northward direction is different, the differences will be delivered into the fuzzy controller. Then, the fuzzy controller produces pulses to motor drivers and the motor drivers produce PWM signals to control step motors for tuning desired angles. Note that if the differences of sensors are zero, i.e., the sun is vertical to the solar panel, so the fuzzy controller does not work. Since the sun moves very slow, the fast rotating speed of the solar tacking device is with high speed rotation not necessary. By fuzzy control, some advantages such as reducing consumption power of step motors and fast and smooth fixed position can be achieved. Therefore, the fuzzy control algorithm has enough ability to complete this goal.

Since the corresponding CdS light sensitive resistors can operate independently, it can be seen as independent control. For one motor control, the error of output voltages of corresponding sensors can be set as input variables. The rotation time of the stepping motors for clockwise and counterclockwise are output variables. The membership functions are shown in Figs. 7 and 8. Five fuzzy control rules are used, as shown in the following.

$$\text{Rule 1: If } e \text{ is PB, then } U_f \text{ is PB.}$$

$$\text{Rule 2: If } e \text{ is PS, then } U_f \text{ is PS.}$$

$$\text{Rule 3: If } e \text{ is ZE, then } U_f \text{ is ZE.}$$

$$\text{Rule 4: If } e \text{ is NB, then } U_f \text{ is NB.}$$

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Rule 5: If $e$ is NS, then $U_f$ is NS.

In this paper, product inference is applied for fuzzy inference. The center of gravity method is adopted for

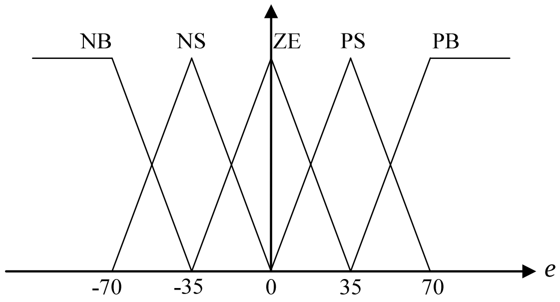


Fig. 7. Input membership function of the fuzzy control system.

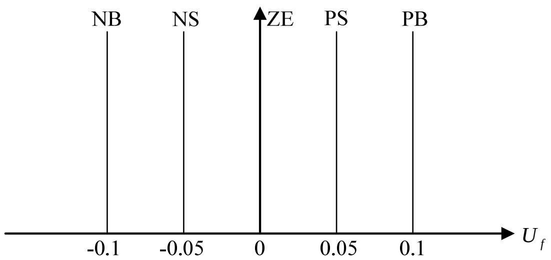


Fig. 8. Output membership function of the fuzzy control system.

defuzzification to achieve a practical operation value. The defuzzification is shown in (3).

$$\hat{U}_f = \frac{\sum_{i=1}^{5} w_i r_i}{\sum_{i=1}^{5} w_i} = w_1 r_1 + w_2 r_2 + w_3 r_3 + w_4 r_4 + w_5 r_5 \qquad (3)$$

This defuzzification method is implemented by digital circuits.

## V. Experimental Results

This experiment applies four solar cell panels. Every two panels are connected in series as a set. There are four panels; this means there will be two sets. Then, we connect these two sets in a parallel configuration. Solar cell array can be composed of many small sets by series connection and parallel connection. While sets are in a series connection, the output DC voltage of the solar generating power system will be raised. While sets are in a parallel connection, the output DC current of the solar generating power system will be raised. Therefore, series and parallel connections can be used suitably to produce desired output DC voltage and current. Since solar cells are difficult to be produced, every solar cell panel has its own characteristics. In addition, environmental factors such as dust, clouds, etc., may cause different voltages and currents in different sets. Another problem is that some sets may be loads for other sets. In this case, the temperature of set will be risen because of power consumption. When the internal temperature of a solar cell panel is over 85 °C ~100 °C , the set will be broken. Furthermore, all voltage will be applied in the set, when there are some broken sets in the solar cell array. Therefore, a bypass diode is in a parallel connection to a set for solving the above problem. Thus, a low impedance path of energy dissipation can be provided for each set to overcome a problem of many sets connection.

Fig. 9. The picture of proposed solar tracking system placed by a large-scale fixed angle type system.

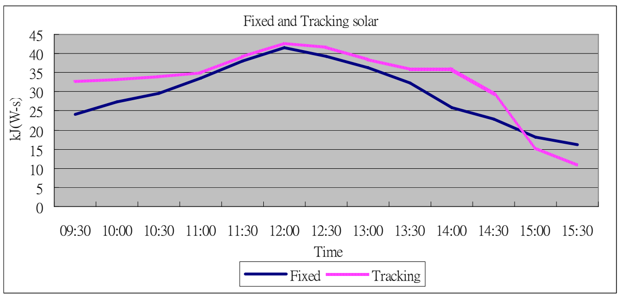


Fig. 10. The power generation comparison of fixed angle type and tracking systems

The experimental data of the solar generating power system are measured outdoors as shown in Fig. 9. We select the roof of the third building in Yuan Ze University as the outdoor place. Each battery is 12 volt and 7Ah, so we combine two batteries together as the power supply which is 24 volt and 14Ah. Fig. 10 shows that the efficiency with solar tracking methodology is 6.7 percentages higher than that with fixed angle.

## VI. Conclusion

The paper presents a solar tracking power generation system. The tracking controller based on the fuzzy algorithm is designed and implemented on FPGA with NiosII embedded system. Set up on the solar tracking system, the CdS light sensitivity resistors are used to determine the solar light intensity. The proposed solar tracking power generation system can track the sun light automatically. Thus, the efficiency of solar energy generation can be increased. Experimental work has been carried out carefully. The result shows that higher generating power efficiency is indeed achieved using the solar tracking system. The proposed method is verified highly beneficial to the solar power generation.

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