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A Sun Tracking System Design for a Large Dish Solar Concentrator

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ABSTRACT

Energy crisis promotes the development of renewable energy, especially the solar energy. Sun tracking system proposed in this paper is such a device for efficiency improvement. This closed loop tracking system with two axis sun tracking method is controlled by a programmable logic controller (PLC) and is used for a large dish solar collector. A combination tracking mode combined active and passive tracking methods used in the design make the tracker efficient whatever the circumstances. Two stepper motors and two reduction boxes move the device towards the sun with chain transmission. Besides sun tracking, the system also has functions of overheat monitoring, wind speed monitoring and measurement of illumination.

Keywords: Renewable Energy; Solar Energy; Sun tracking; PLC; Combination Tracking Mode

1. Introduction

International energy structure adjustment and the energy crisis promote the development of renewable energy. Solar energy has gained much more focus because of its endless and eco-friendly features. In 2012, the International Energy Agency(IEA) point out in its report "World energy outlook 2012" [1] that renewable energy has become an integral part of the global energy structure and it will be the world's second largest power source in 2015. In 2035, power generation of renewable energy will account for about one-third of electricity output, and the solar energy will be the fastest one among it.

Solar thermal power generation is one of the main ways of solar energy utilization which has been widely used throughout the world. The dish solar thermal power generation usually uses a two axis sun tracker having high tracking accuracy and thermoelectric conversion efficiency. Thermal solar tracking needs higher tracking precision compared with photovoltaic. Through simulation of light incidence by TRACEPRO software, the collector will lose half of total energy in 1.25° light deflection and will lose all energy in 1.5° deflection. While the value is 0.35° , the light loss less than 5%. Photovoltaic tracking losses only 1.5% in 10° deviation of light.

This paper introduces a solar tracking system which controlled by the programmable logic controller (PLC) to improve solar energy efficiency. Active and passive tracking control methods with a closed loop system could accommodate different weather conditions. Two stepper motors and two reduction boxes are used to control the rotation of the collector with chain transmission. The goal in this system is to achieve a tracking precision within 0.1° . In this case, the light energy loss would be negligible.

2. Sun Tracking System Design

2.1. Tracking Mode Selection

There is different automatic sun tracking methods according to different solar concentrator. These methods are usually sorted into three categories: active tracking methods, passive tracking method and combination of both[2-4].

Active tracking method can calculate the altitude angle and azimuth of the sun by preset program in PLC. The system can determine the position of the sun as long as the latitude-longitude and date-time information has been input. The upside to this method is that the system can't be affected by outside factors such as cloud and dust. The downside is that this mode has a low tracking precision while it has a high cost. So it is difficult to design such a structure at the same time.

Passive tracking method is based on electoral-optical sensors which can indicate the deflection of light. Imbalance light make these sensors product control signal on motors. To utilize such a tracking method is not only economical but also efficient, but the device will lose effectiveness if the sensor is shielded by cloud.

There are advantages and disadvantages for both methods mentioned above. To complement the weakness of each other, a hybrid tracking mode combined active and passive tracking methods is adopted in this article. Adopting such a scheme can greatly improve the tracking accuracy and stability of the system.

2.2. General Structure Design

The mechanical structure of this design consists of a bottom bracket rotated around vertical axis and a mirror array rotated around horizontal axis with a height of 15 m, shown as in **Figure 1**. The mirror array has an area of 120 m^2 and the power system generate about 20 KW of clean electricity.

Figure 2 shows the components of the sun tracking system. PLC acts as a control center which can calculate sun position to make sure every instruction is executed precisely and quickly. Drive system which is made up of stepper motors and matched reduction gearbox receives control signals from PLC and make the solar collector move toward the sun. A closed loop control method is employed where two angle encoders are acted as feedback components. Direction signals created by a four quadrant detector are sent to PLC to active the motors in passive tracking mode.

In order to meet different function demand, several auxiliary function units are designed. A temperature sensor as one part of temperature monitoring system can avoid high temperature damage to the collector while a wind sensor can decide a suitable wind speed working environment. During the experiment the changing intensity of the sun can be detected by a pyroheliometer and a pyranometer.

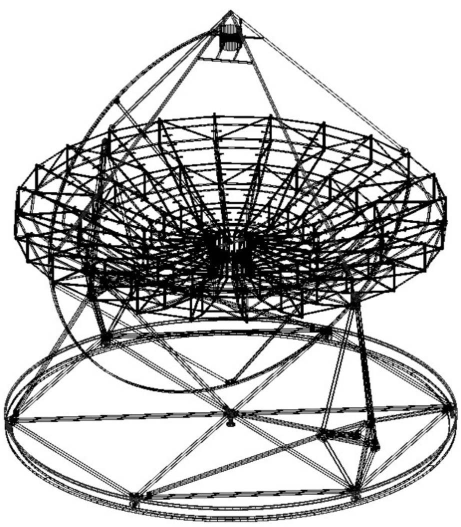

Figure 1. Mechanical structure of the design.

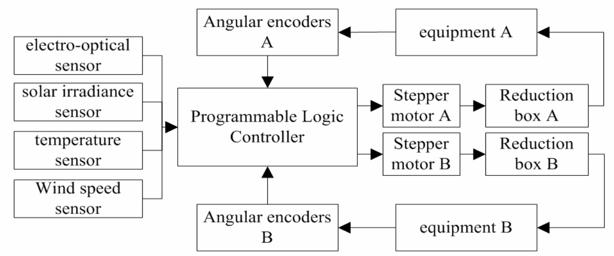

Figure 2. Electromechanical components of the design.

2.3. Active Tracking Method

There are many different active tracking algorithms with different tracking accuracy. Comparisons of different tracking precision results of several papers (cooper, 1969; Lamm, 1981; Spencer, 1971; Swift, 1976; Walraven, 1978; Pitman and Vant-Hull, 1978; Michalsky, 1988; Blanco, 2001; Ibrahim Reda, 2004; A. B. Sproul, 2007; Roberto Grena, 2008) prove that algorithm proposed by Reda displays the highest accuracy [5].

It is necessary to calculate the altitude angle α and azimuth angle γ to determine the position of the sun. The altitude angle (sometimes referred to as the "solar elevation angle") describes the angular height of the sun in the sky measured from the horizontal. The altitude angle is positive when the sun rises above horizon and become negative after sunset. The azimuth angle is the horizontal angle between exact south and the projections of sun rays onto ground. It's a positive before noon and negative afternoon. The steps of common algorithm are listed below [6]:

$$\sin\alpha = sin\varphi sin\delta + cos\varphi cos\delta cos\omega \quad (1)$$

$$\cos\gamma = (\sin\alpha sin\varphi - sin\delta) / \cos\alpha cos\varphi \quad (2)$$

The latitude φ can be determined by GPS service. The hour angle ω is the local time (LT) shown by angle. The local time is also known as solar time. Earth rotates on its axis once every 24 hours and 15˚ every hour on average.

$$\omega = (LT - 12) \times 15^{\circ} \quad (3)$$

Declination angle of the solar declination angle δ is the angle between the earth-sun line and the equatorial plane. It varies between –23.45˚ on winner solstice and 23.45˚ on summer solstice. Equation (4) was put forward by cooper in 1969.

$$\delta = 23.45^{\circ} \times \sin[360 / 365 \times (284 + n)] \quad (4)$$

The symbol n is the sequence number of the date in a year.

In order to describe the solar time we need to make connection between local time (LT) and standard time (SDT). The symbol λs and λl mean standard meridian longitude of time zone and local longitude. We will use the method of subtraction in Equation (5) for the eastern hemisphere uses.

$$LT = SDT - 4(\lambda s - \lambda l) + E \quad (5)$$

Time difference E is the functions of solar angle Γ.

$$E = (0.000075 + 0.001868\cos\Gamma - 0.032077\sin\Gamma - 0.014615\cos 2\Gamma - 0.04089\sin 2\Gamma) \times 229.18 \quad (6)$$

Solar angle Γ can be obtained by the equation below.

$$\Gamma = 2\pi(n-1)/365 \quad (7)$$

From the equations above we can easily calculate the position of the sun.

2.4. Driving Strategy

Radius of the mechanical structure rotated vertical and horizontal axis is 6.5 m and 6 m respectively. The equipment is so large that it moves at a slow speed with high resistance. Reducer gearboxes are used in this project to get a higher driving force. Stepper motors matched with gearboxes receive impulses signal from PLC to control the motion of the solar concentrator. Rotating Angle of stepper motor can be proportionally adjustable with impulse frequency input. Such a driving strategy with stepper motor and gearbox can ensure the collector to turn to desired position accurately.

Several transmission methods such as gear drive, rope drive, belt drive were taken into account at the beginning of the design. But they don't suit this design because of economical or stable reasons. At last, chain transmission device composed of drive wheel, driven wheel and chains becomes the preferred solution in this design. The driven wheel is a circle of channel steel fixed on the solar collector chains sliding in it. For the high tension chain transmission, additional bearings and shafts were connected to output shafts of reducer gearboxes by flexible coupling which could avoid gearboxes' damage.

At the end of rotate strokes, four limit switches are used to supply signals that the cycle has been completed.

2.5. Electro-optical Sensor

The electro-optical sensor used in this design is a four quadrants detector which is composed of four identical photodiodes distributed in a small circuit board. There is a cross isolation zone among them. The sun light images on different portions of the four quadrants detector pass through an optical lens. As shown in **Figure 3**, four symbols represent four directions.

Diodes produce different currents under different light illumination. There will be no voltage signal sent out from the detector under equal intensity of illumination on every photodiodes. An imbalanced illumination will cause control signals to yield a driving motor.

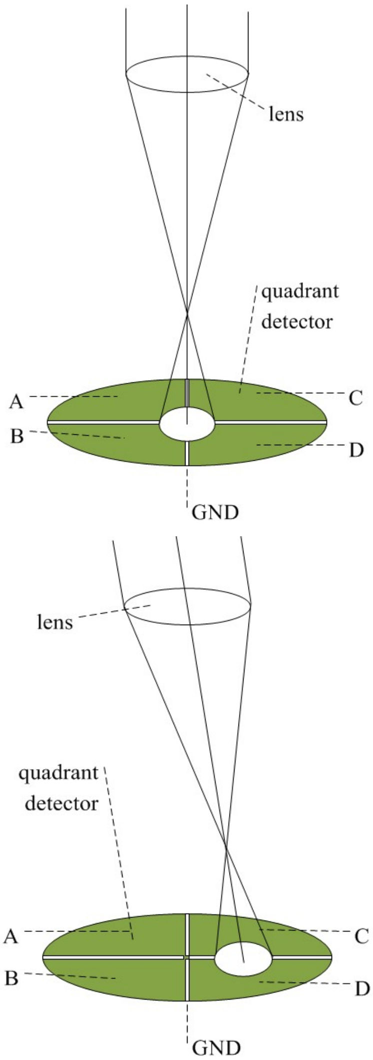

Figure 3. Illumination of different situations.

For diodes in every quadrant are the same, luminous power of diodes generate in proportion to facular area. The detector would send out negligible voltages to a circuit where the voltages are compared and magnified. After that the magnified signals are sent to PLC as motor motion control signals.

3. System Software Design

3.1. Working Time Intervals

The solar altitude angle and azimuth angle are not constant, and they change with alternation of day and night and seasonal shifts. In this design, motors work for a few seconds and then idle for dozens of seconds.

There was a time interval during drive system working process. It will waste resource in a short time interval because the frequent start and stop of motors, but a long time interval will lead a low tracking accuracy. The time interval is important for sun tracking system. Abdallah

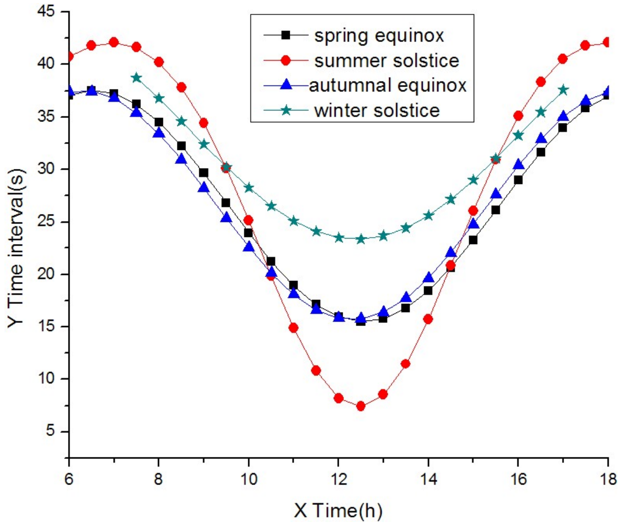

Figure 4. Interval of azimuth rotation.

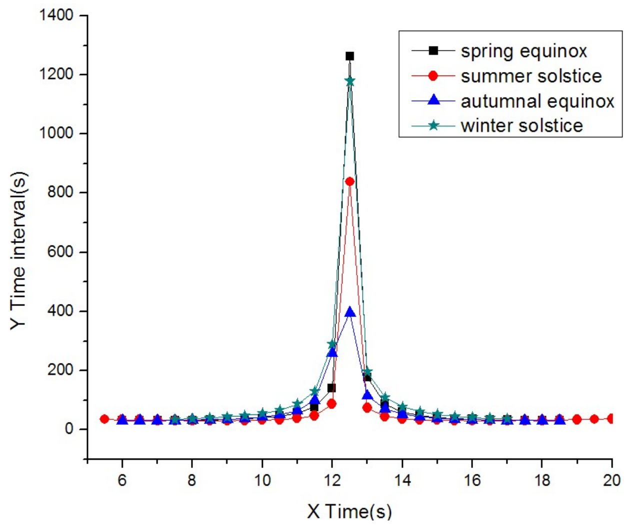

Figure 5. Interval of altitude rotation.

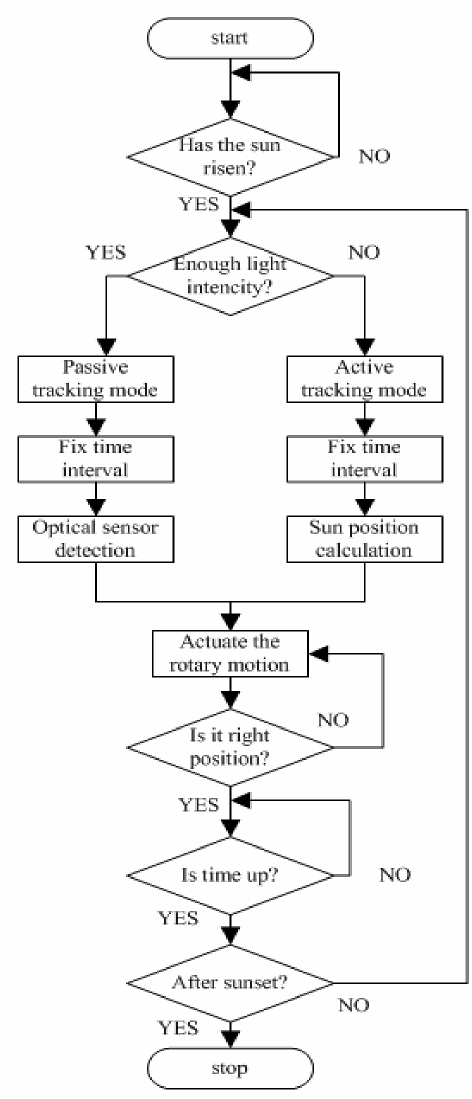

Figure 6. Flow diagram of tracking strategy.

divided the daytime into four identical time intervals during which the motor speed were determined [7].

The equipment of sun tracking system is put in a factory in Tianjin (39.72° N, 117.31° E), China. The accuracy requirement is no more than 0.1°. A simulation about the interval time in which the device rotate is 0.1° has been carried out. **Figure 4** and **Figure 5** show the relationship between interval time and daytime. In the simulation, angle change in four representative dates was discussed. The four dates were spring equinox, summer solstice, autumnal equinox and winter solstice.

The azimuth angle turns fast around noon, the shortest time interval for 0.1° angle rotation only 7.4 s in summer solstice. At the beginning of each day, it takes about 40 s to get a 0.1° angle rotation. The variation of angle change curve is so great that a time interval division is needed. The altitude angle has a small change around noon. Most of the angle change curve is very gentle except noon. It takes about 40 s at the beginning of the day for 0.1° angle rotation.

Day time was divided into 5 time buckets: the time before 10:00, 10:00 - 11:00, 11:00 - 14:00, 14:00 - 15:00, and the time after 15:00. The PLC will calculate the time interval of every time bucket separately. Such a division method can save power resource and improve tracking efficiency.

3.2. Programming of the System

After the system is initialized at startup, PLC will calculate the sunrise time and sunset time of day through automatic tracking program written in program. Electro-optical sensor detects light intensity to distinguish cloudy weather or sunny weather at daytime. If light intensity meets the requirements, the program will turn to passive tracking mode. If not, the program will turn to active tracking mode. In different time buckets men- tioned before, motors move at a given speed calculated by PLC. Angular encoders detect the angle that the col- lector rotated and send corresponding signals to PLC as a feedback. At the end of every time interval, time will be checked to ensure it is daytime. If it doesn't arrive at sunset, the tracking system will turn to the next interval and repeat this course until sunset. After sunset, the PLC will calculate position of the next day and make the col- lector to move to this new initial position. The progress of the program is shown as the flow diagram in **Figure 6**.

4. Conclusions

In this study, a two-axis sun tracking system with PLC controlled is described and a combinative tracking method is used to control the motion of the solar collector. The hardware and software of the system are design and constructed. The designed accuracy of the tracking system is 0.1° . It is certain that the device can operate under many circumstances without manual operation. Stepper motors and reducer gearboxes are employed in this design for the high driving force and accuracy demand.

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