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Development of FPGA-based Dual Axis Solar Tracking System

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ABSTRACT

Field Programmable Gate Arrays (FPGAs) meet critical timing and performance requirements with parallel processing and real-time control application performance, allowing greater system integration and lower development cost. This paper describes a dual axis solar tracking system based on astronomical equations. The position of sun at any time is a function of azimuth and altitude angle values. Azimuth and altitude angle values are collected off line. The prototype of dual axis solar tracking system is developed on FPGA to implement the proposed idea. The system comprises of digital clock module, rise time module and two pulses generator modules. Pulse generator modules employ Pulse Width Modulation (PWM) technique for controlling two stepper motors for tracking the azimuth and altitude angles. The functionality of various blocks of the system is described in Very High Speed Integrated Circuit (VHSIC) Hardware Description Language (VHDL). The control logic has been successfully implemented on Spartan 3E FPGA device. Xilinx ISE 14.1 suit is used for design entry, synthesis and burning the bit stream file into FPGA device. The functional verification has been performed using Xilinx simulator.

1. Introduction

Solar energy research and application have been receiving increasing attention throughout the

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world because solar energy is a renewable, pollution free and freely available energy resource. Solar energy is the way of the future and is an effective and reliable source of alternative energy (Garg, 2000).

Solar energy can also be used to meet our electricity requirement through solar photovoltaic cells (SPV) or solar cell. Solar cells convert solar radiations into DC voltage. The generated electricity can be used directly or can be stored in the battery. There is variety of applications of solar energy ranging from simple solar cooker to huge power generation plants. The solar collector collects the incident radiations from the sun. The photons strike the surface of these solar cells and generate an electrical current. The collection of light-generated carriers by the *p-n* junction causes a movement of electrons to the *n*-type side and holes to the *p*-type side of the junction. The figure 1 shows generation of charge carriers as sun light falls on photovoltaic cell.

Incident solar radiation is the most important parameter for the power generated by the solar energy system. The sun position in the sky varies both with the seasons and time of the day. To design and monitor a solar system, critical parameters are sun's rise time, set time, azimuth and altitude angles. There are numerous equations developed to predict the exact position of the sun in the sky at a given date, a given hour and given latitude (Masters, 2004; Patel, 2006).

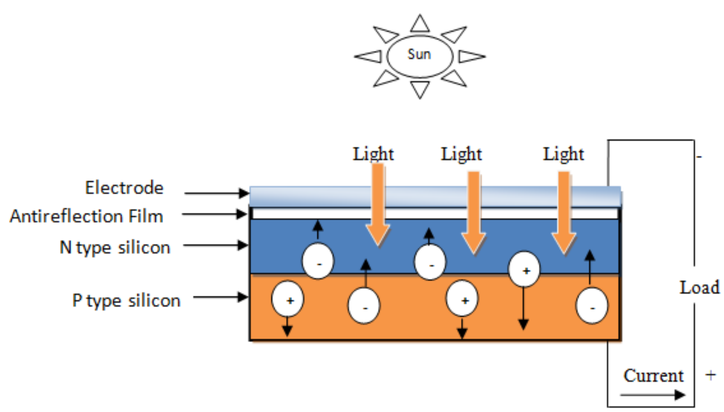

Figure1: Charge generation in a photovoltaic cell

Field Programmable Gate Arrays (FPGA) is widely used for rapid prototyping. FPGAs are programmable digital logic chips that are based up on a matrix of configurable logic blocks (CLBs). These CLBs are connected via programmable interconnects.

We can reprogram the FPGA to desired application or functionality requirements after manufacturing. Additional functionality and user interface controls can be included into the FPGA minimizing the requirement for additional peripheral components due to its flexibility.

2. Solar System Tracking Mechanisms

Solar tracking system is an electromechanical device that is used to turn the solar devices to face the sun as it moves across the sky. Solar radiations are absorbed most efficiently when it strikes the photovoltaic cells at 90° angles. It becomes very essential that the solar panel should be correctly positioned to collect the maximum energy. By accurately tracking the sun, the incident solar irradiance can be effectively increased. There are two different types of mechanisms that are most commonly used to track the sun i.e. active trackers and passive trackers (Balfour, 2013).

Active tracking mechanism directed the solar collecting device towards the sun by electric circuitry in the form of light sensing Photo sensors. Motors and gears are employed to direct the tracker to the sun's direction.

The rotation mechanism of a passive tracker uses a hydraulic mechanism that respond to the heat of sun. The incident sun radiations causes a low boiling point compressed gas fluid to be driven to one side or the other, creating gas pressure and thereby moving the mechanism along.

3. Types of Solar Trackers

The types of trackers are defined by several factors. Probably the most important factors are the number and orientation of their axis. Trackers are described being as single axis tracker and dual axis trackers.

A mechanism rotates the single axis tracker only in one plane around a single axis. Single axis tracking system increases the power production by 20 to 25 percent as compared to fixed PV cell panel. The advantages of single-axis trackers are that they are less complicated, and thus less expensive.

Dual axis tracker follows the sun properly. Dual axis tracker tracks the sun both in azimuth

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and altitude angles. Dual-axis trackers capture the full extent of the sun, but they are slightly more complex and hence a little more expensive.

Dual axis tracking system increases the performance up to 34 to 37 percent as compared to stationary PV panel (Gesellschaft, 2008).

4. Movement of Sun

In northern hemisphere of the earth, the sun rises in the east moves across the southern sky and sets in the west. The position of the sun can be described at any time by two angles, the altitude and azimuth angle. The solar altitude angle (α) is the angle between a line collinear with the sun's ray and the horizontal plane. The solar azimuth angle (ψ) is the angle between a due south line and the projection of the site to the sun line (Al-Naima and Al-Taee, 2010).

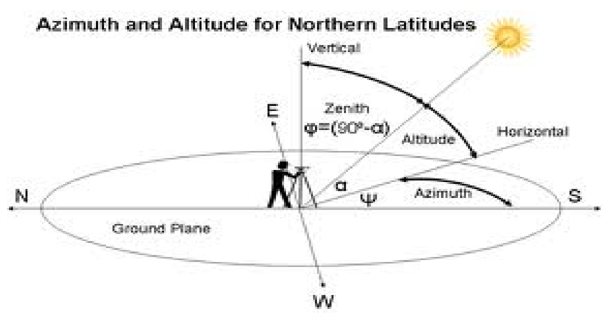

Figure 2: The sun position depicted by Azimuth and Altitude angles.

The following mathematical equations (1) and (2) are used to calculate azimuth and altitude angle of the sun respectively (Fawzi and Bilal, 2011).

$$\text{Azimuth angle} = \frac{cos^{-1}[\, sin\delta cos\emptyset - cos\delta sin\emptyset \cos(HRA)]}{cos\alpha} \quad (1)$$

$$\text{Altitude angle} = sin^{-1}[\, sin\delta cos\emptyset + cos\delta cos\emptyset \cos(HRA)] \quad (2)$$

Where, δ is declination angle, $\emptyset$ is latitude of location of interest. HRA is hour angle and α is the elevation angle.

The Hour Angle converts the local solar time (LST) into the number of degrees by which the location of the sun moving across the sky is measured. It is calculated using following relationship:

$$HRA = 15°(LST - 12) \quad (3)$$

The declination angle is given as:

$$\text{Declination angle} = 23.45^{\circ} \sin[\frac{360}{365}(d - 81)] \quad (4)$$

Where, *d* is the number of the day since the start of the year.

5. Design of Tracking System

Our design contain four modules which have been implemented and synthesized on FPGA board: Digital Clock, Module for rise time of sun and two pulse generators for azimuth and altitude angles. In the developing countries where cost is one of the main issues to integrate technologies, solar tracking system prototype proposed in this paper can provide an effective solution. FPGAs can be used to implement any logical function that an Application Specified Integrated Circuit (ASIC) could perform. The Spartan XC3S1600E FPGA as controller has been used in this project. The quick and easy programming is the main advantage of FPGA.

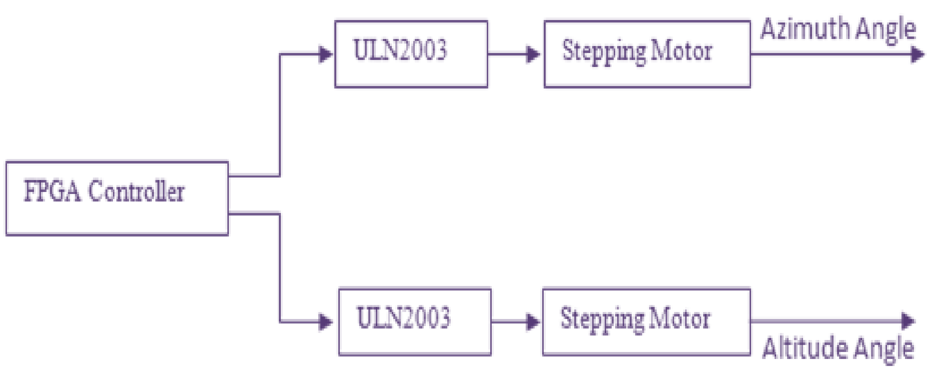

Figure 3: Block Diagram of Tracking System.

The figure 3 shows the block diagram of the developed solar tracking system. The major components of this block diagram are FPGA controller, stepper motor driver ICs ULN2003, stepper motors for azimuth and altitude angles.

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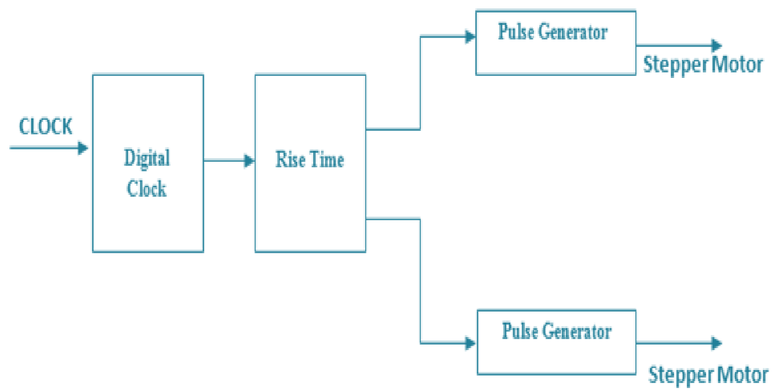

Figure4: Control logic modules of the proposed solar tracking system.

Figure 4 shows the control logic modules of this solar tracking system implemented on FPGA. All the modules are described in VHDL.

5.1 Digital Clock Module

The digital clock starts when we turn on the tracking control circuit. The operation principal of this module is based on the time control method. Digital clock used in the solar tracker provides the outputs in minutes, hours, day, and day5. The day5 output is the special output which contains 5 days. So we have grouped the 365 days of a year into 73 groups thus having 5 days in each group (Day5 is set as output).

5.2 Rise Time Module

This module is utilized to create rise time for each group. Internal rise time control signal is fed by this module. This control signal will control the forward and reverse direction of motors.

When rise time signal becomes HIGH, motor set for azimuth angle will start rotating from east to west and west to east when signal become LOW. Same thing happens for tilt angle which will rotate the motor anticlockwise when signal become high.

5.3 Pulse Generator Modules

Pulse generator modules send the stepping pulses to stepper motor, for movement of motor in azimuth and altitude direction. During start position tracker will wait for 15 minutes and generates pulses for stepper motor.

5.4 Stepper Motor and Driver

Stepper motors are widely used in the robotics industry & position control applications. Stepper motors move a known interval for each pulse. These pulses are provided by Pulse generator and given to a ULN driver chip (ULN 2003) for current amplification and are referred to as a step. As each step moves the motor a known distance it makes the handy devices for repeatable positioning (Meshram *et al*., 2009).

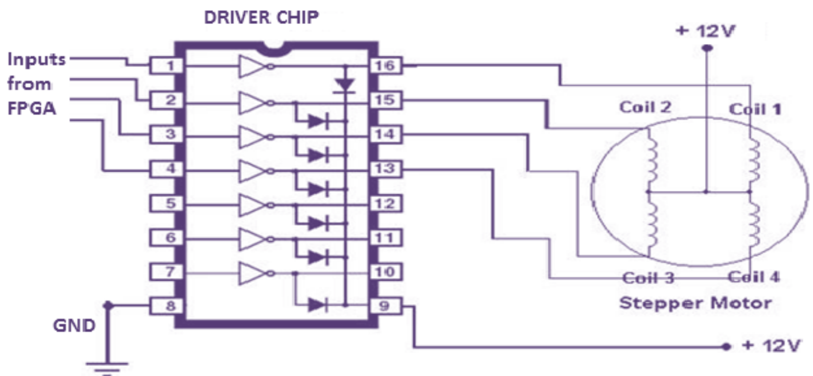

Figure 5: Stepper motor with driver circuit.

The performance of stepper motor is strongly dependent on the drive circuitry. The stepper motor driver circuitry regulates the current and flux direction in the phase windings and makes a convenient amount of current to flow through the windings. It also allows short current rise and fall times as feasible for better high speed performance.

6. Principle of Solar Tracking System

The recognition of position of sun goes through several steps. The astronomical equations for calculating the azimuth and altitude angle contain trigonometric functions, so implementation of these equations in hardware is both time consuming and difficult. To overcome this problem, we have used PHP language based solar position calculator to calculate the values of azimuth and altitude angles of sun for year 2013. We have prepared the database containing values of azimuth and altitude angles for location Chandigarh city in India for year 2013. The database contains values of azimuth and altitude angle updated after a delay of every 1 hour. To drive the stepper motor for controlling azimuth and altitude angles, we have adopted Pulse Width Modulation approach. A two pulse generator modules one for altitude angle and other for azimuth angle

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generate pulses, according to movement of the sun in the sky during a complete day. The whole problem is formulated into three parts.

I. Since almost negligible variations are there in azimuth and altitude angle for a group of 5 days, grouping of days in a year is done by combining 5 days thus a year contains a total of 73 groups. 1^{st} day to 5^{th} day of year become 1^{st} group and 361^{th} to 365^{th} day of year become 73^{rd} group.

II. The database contains values for azimuth and altitude angle for each group with 1 hour delay.

III. Calculate the change in the angles after every 1 hour delay from rise time to set time of the sun for each group of the year.

Table 1 lists values of variations in azimuth and altitude angles for the 1^{st} group of days after a delay of every 1 hour. For example from 7:30 to 8:30 the change in the value of azimuth and altitude angle varies by 8° and 10° respectively after every 1 hour.

Table 1: Angles of rotation of sun with 1 hour delay.

Time	Azimuth	Altitude
7:30 to 8:30	8^{o}	$+10^{o}$
8:30 to 9:30	10^{o}	$+10^{o}$
9:30 to 10:30	14^{o}	$+8^{o}$
10:30 to 11:30	15^{o}	$+5^{o}$
11:30 to 12:30	17^{o}	$+3^{o}$
12:30 to 13:30	17^{o}	-2^{o}
13:30 to 14:30	15^{o}	-5^{o}
14:30 to 15:30	13^{o}	-7^{o}
15:30 to 16:30	10^{o}	-10^{o}
16:30 to 17:30	9^{o}	-12^{o}

The "+" sign indicating the upward trajectory of the sun from morning till noon i.e. 0° to 90° whereas "–" sign indicating the downward trajectory of the sun from noon to evening i.e. 90^{o} to 0^{o} for altitude angle. The grouping of the days reduces the complexity. The variations in both angles from its previous day's value are ignorable as depicted in Tables 2 and 3. Both tables represent azimuth and altitude angles for Chandigarh, city in India.

The designed tracking system will start tracking the sun angles for each group of 5 days and will change its rotation in next group of the day.

Table 2: Azimuth angle values for Group 1.

Time	Day1	Day2	Day3	Day4	Day5
7:30	114^o	114^o	114^o	114^o	114^o
8:30	123^o	122^o	122^o	122^o	122^o
9:30	133^o	133^o	132^o	132^o	132^o
10:30	145^o	145^o	145^o	145^o	144^o
11:30	160^o	160^o	159^o	159^o	159^o
12:30	176^o	176^o	176^o	176^o	176^o
13:30	193^o	193^o	193^o	193^o	193^o
14:30	208^o	208^o	208^o	208^o	208^o
15:30	221^o	221^o	221^o	221^o	221^o
16:30	231^o	231^o	231^o	231^o	231^o
17:30	240^o	240^o	240^o	240^o	240^o

Table 3: Altitude angle values for Group 1.

Time	Day1	Day2	Day3	Day4	Day5
7:30	0^o	0^o	0^o	0^o	0^o
8:30	10^o	10^o	10^o	10^o	10^o
9:30	20^o	20^o	20^o	20^o	20^o
10:30	28^o	28^o	28^o	28^o	28^o
11:30	33^o	33^o	33^o	33^o	33^o
12:30	35^o	35^o	35^o	35^o	35^o
13:30	34^o	34^o	34^o	34^o	34^o
14:30	29^o	29^o	29^o	29^o	29^o
15:30	21^o	21^o	21^o	21^o	22^o
16:30	16^o	17^o	17^o	17^o	17^o
17:30	1^o	1^o	1^o	1^o	1^o

Due to this small change in the angles, variation of solar insolation will be very less and would not greatly affect on the efficiency of the photovoltaic cells. Solar insolation is the rate at which direct solar radiation is incident upon a horizontal surface at any point on or above the surface. The solar insolation is calculated using following mathematical relationship.

$$I = S\cos(Z) \quad (5)$$

Where, I is Solar Insolation, S = 1000w/m^2 (clear day solar insolation on a surface perpendicular to incoming solar radiation, Z is Zenith angle dependent upon latitude, solar declination angle and time of the day. The solar insolation value at sunrise and sunset are 0 W/m^2.

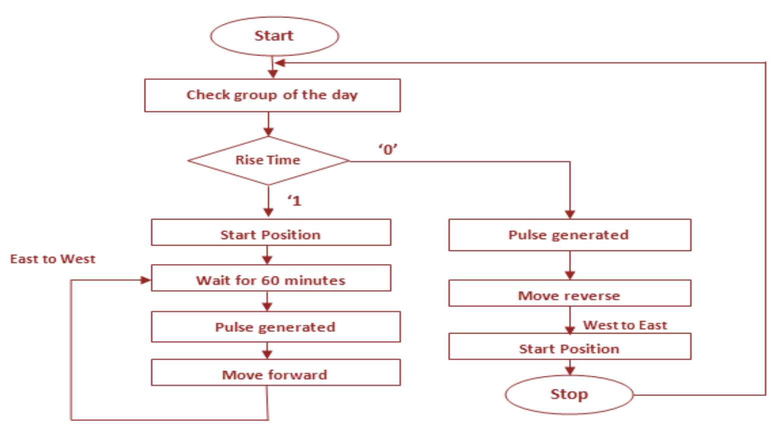

Figure 6: Flow chart for azimuth angle movement.

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6.1 Tracking Method

The range of the motion of proposed tracking system is 0^{o} to the sun set time and 90^{o} for tilt angle. The system function starts from the first day of the year. The system is designed for continuous operation in the next year when the tracker reaches the last day of the year (31 December).

Two pulse generators are used to locate the tracker to the approximated value of the sun after every 1 hour. As for the first running in the day, the system has to wait for rise time, for this reason digital clock is used. The flow charts for both angles are shown in Figures 6 and 7.

As mentioned in the flow charts, both angles have to wait for rise time. Pulse generation depends up on the value of the rise time. After starting, the tracker will check group of the day. 'HIGH' value of the rise time will be the start position of the tracker. The rise time signal will rotate the tracker in forward and backward direction.

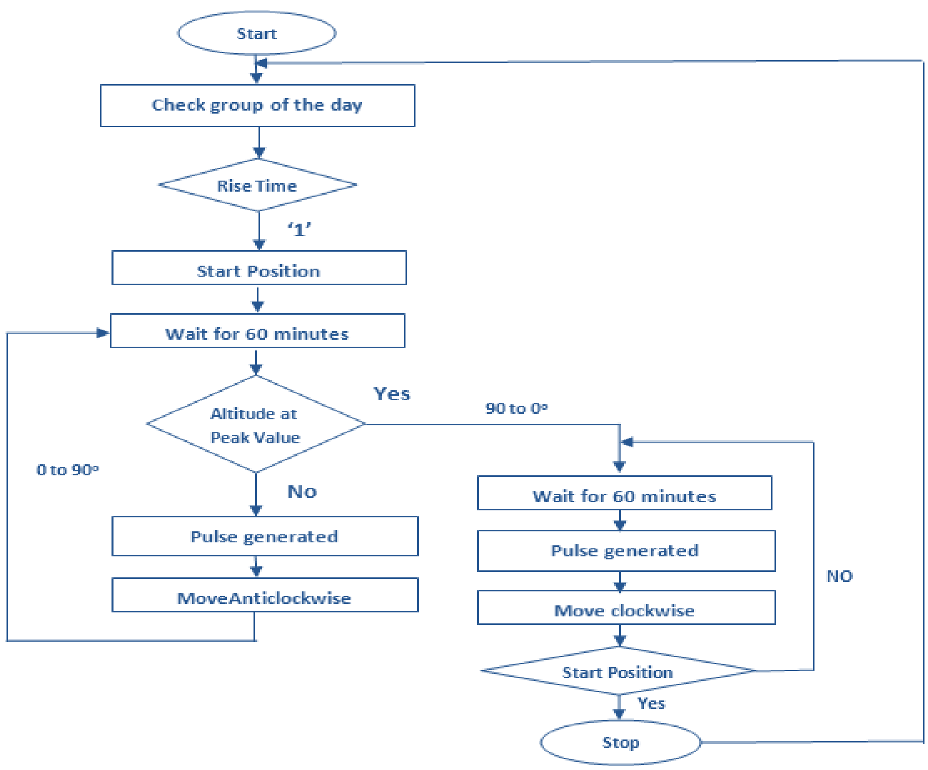

Figure7: Flow chart for altitude angle movement.

The stepper motor to control the azimuth angle will rotate east to west when rise time is 'HIGH' and west to east when rise time is 'LOW'.

However, for altitude angle scenario the operation principal is different. The Altitude angle motor rotate anticlockwise, when rise time become ‘HIGH’, up to peak sun hours. After peak sun hour the motor will rotate clockwise and stopped at start position.

7. Results and prototype of proposed idea

The control logic of solar tracking system comprises of the digital clock module, the rise time module and two pulse generator modules. All the modules are designed, verified, synthesized and implemented on FPGA. The design of the solar tracking system combines the FPGA solar tracking system with two stepping motors and stepping motor drivers.

Solar tracking system is synthesized and simulated using Xilinx ISE design suit 14.3 and ISIM simulator. Figure 8 shows the RTL schematic of the solar tracking system. Figure 9 shows the simulation results of the tracker. After *rise* signal is activated at 7:30 for the 1st group, two different set of pulses are generated with some delay for driving the stepper motors to track the altitude and azimuth angles. Figure 10 shows the reverse direction of the azimuth angle when rise time is ‘LOW’ at 17:32.

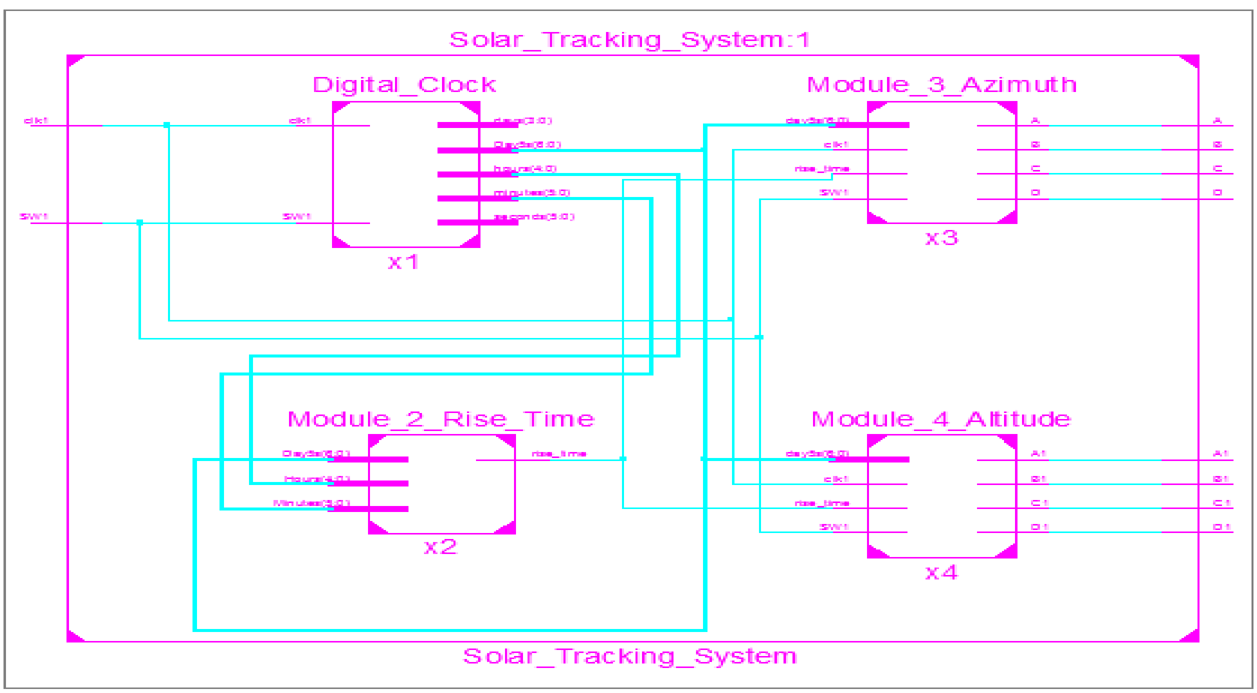

Figure 8: RTL View of Architecture of Solar Tracking System.

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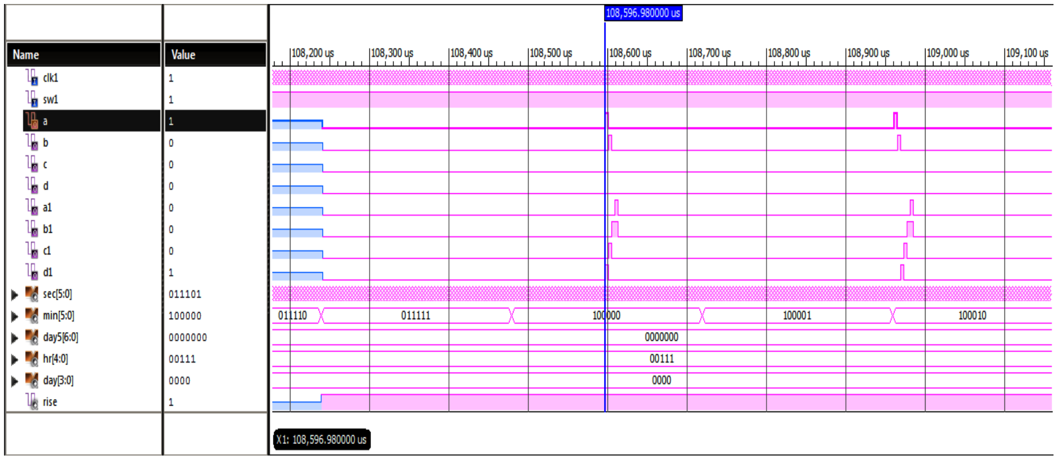

Figure 9: Pulse geneartion for azimuth and altitude angle.

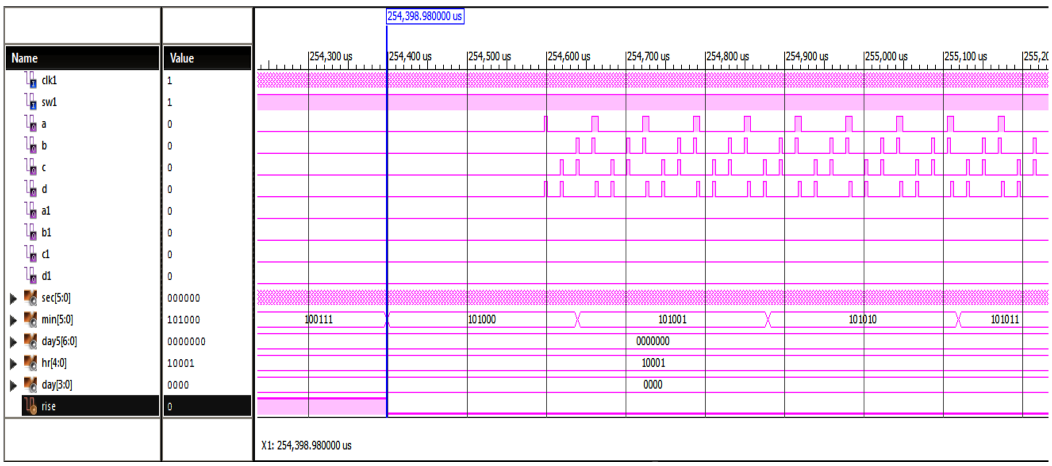

Figure 10: Reverse direction of azimuth angle stepper motor.

Figure 10 shows the initial stage interfacing of two stepper motors with Spartan 3E FPGA board. A diminutive scale prototype of the solar tracker has been made for checking the practicability of the design methodology. Figures 11 and 12 show the initial stage and the actual prototype implemented.

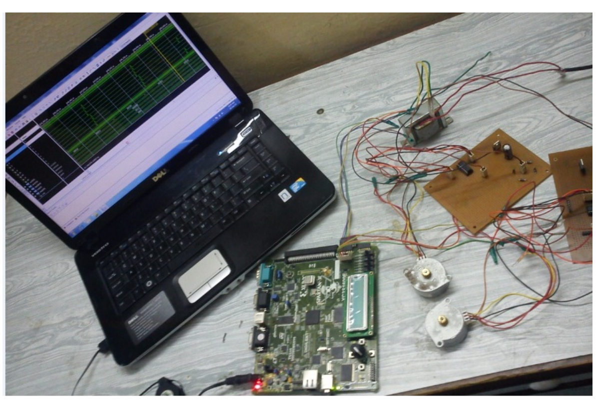

Figure 11: FPGA Interfacing with Stepper Motors.

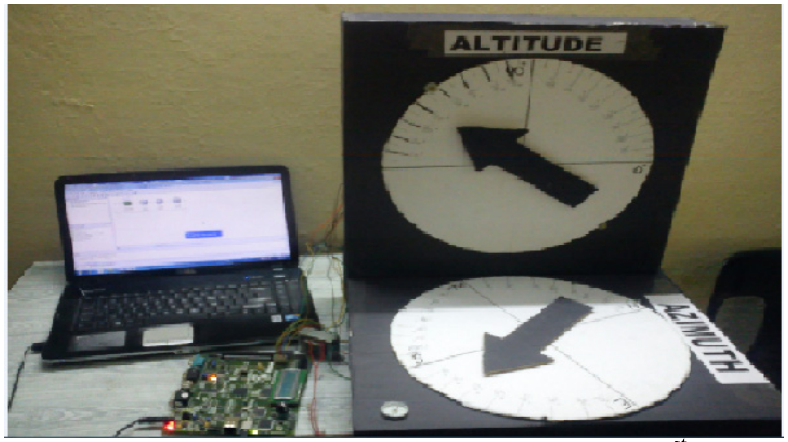

Figure 12: Prototype of Solar tracking system for 1st group.

Two 7.5^0 stepper motors are used in this tracker system. Table 4 shows the tracking error for the 1st group of days. At the end of day the tracking error is 0.5°.

Tabel 4: Tracking error for 1st group of days.

Time	Change in Azimuth Angle	No. of steps	Total angle taken by stepper motor	Tracking Error	Error Compensation by 7.5° stepper motor
7:30 to 8:30	8°	1 step	7.5°	-0.5°	-0.5°
8:30 to 9:30	10°	1.5 steps	11.75°	1.75°	1.25°
9:30 to 10:30	14°	2 steps	15°	1°	2.25°
10:30 to 11:30	15°	2 steps	15°	0°	2.75°
11:30 to 12:30	17°	2 steps	15°	-2°	0.25°
12:30 to 13:30	17°	2 steps	15°	-2°	-1.75°
13:30 to 14:30	15°	2 steps	15°	0°	-1.75°
14:30 to 15:30	13°	2 steps	15°	2°	0.25°
15:30 to 16:30	10°	1.5 steps	11.75°	1.75°	2°
16:30 to 17:30	09°	1 step	7.5°	-1.5°	0.5°

Tracking Error = Total Angle taken by stepper motor – change in azimuth/altitude angle

Error Compensation by 7.5° stepper motor = Tracking Error + Error Compensation by stepper motor.

The photovoltaic cell module generates the maximum electrcity when directly facing the sun. However, due to step size, error is existing but this error will not significantly affect the efficiency of the PV cells. The relation between the tracking error and output of the PV cells is given in Table 5.

Table 5: Relation between tracking error and PV cell output.

Tracking Error	Relative Photovoltaic Cell Output
0^o	100%
5^o	99.6%
10^o	98.5%
15^o	96.6%
20^o	94.0%
25^o	90.6%

8. Conclusion and Future Work

Time based controlling is an attractive feature of this solar tracking system. In the proposed two axis tracker, we have not used light sensor, instead, control logic implemented on FPGA chip is controlling all the modules. The light sensors based tracking systems lead to error in partially cloudy weather, since there will be less or no striking of light on light sensors so satisfactory voltages may not be available at junction point. Therefore these light sensors are avoided, and the proposed tracking system is facing the sun even in very cloudy day and will be ready at the beginning of the next day. The proposed and developed practically comprehensible solar tracking system is relatively simple and with minimal cost.

This prototype has some limitations which can be improved through future developments. We can easily implement micro stepping module to reduce the tracking error. The micro stepping module can also reduce the oscillations and resonance when the motor and load are driven at the usual resonance frequency or sub harmonic (Astarloa et al., 2003).

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