Efficient and Low Cost Implementation of a Single Axis Solar Tracking System

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Abstract— **Photovoltaic system utilizes the naturally available solar energy without creating any negative effect on the environment. Solar energy is relatively available in different regions of the world and this makes it a very vital source of renewable energy. The exposure of the earth's surface to the sun rays varies with the earth's revolution and rotation and to get maximum energy from the sun, the incident solar beam must always be at 90^o to the solar cells at all times. To achieve this, a solar tracker is required which senses the direction of the solar rays and adjusts the position of the solar panel accordingly. This paper is based on the design and implementation of an effective and low cost sensor-enabled solar tracking device which uses photo-sensors to detect sunlight and the measured intensity is read as input by a microcontroller which commands an actuator to change the position of the solar panel for maximum energy reception. The test results after design implementation shows an improved solar energy capture-efficiency as compared with that of a fixed solar panel and this was achieved at a low cost.**

Index Terms— **Linear actuator, Photovoltaic (PV) System, Renewable energy, Single-axis solar tracker, Solar energy efficiency**

1. INTRODUCTION

Energy is a daily human need and with a constant desire for societal development, better living conditions for humanity and industrialization of the developing countries coupled with an ever-growing population, the global demand for energy increases day by day [1]. Energy is an essential element for industrial and socio economic development of a country. In the world today fossil fuels is the highest generator of electricity; with its shortcomings it has become necessary to develop other alternative sources of electricity, in this case renewable energy. Renewable energy sources like solar energy, waterpower, wind power, biomass energy, terrestrial heat etc. can be recycled.

Solar energy provides heat, light and electricity and due to the massive energy output and free availability of the sun [2] many homes and office blocks all over the world use electric solar system as a source of power. Globally, the major source of conventional energy e.g. coal, crude oil and natural gas are depleted daily at a very high rate and the impact becomes very significant considering the attendant environmental effects e.g. global warming [3] as a result of the exploration process of these non-renewable energy sources, and this makes it imperative to invest in renewable energy sources as a dependable energy source of the future.

Globally, the role of fossil fuel in the energy mix continues to drop with daily growth in the application of renewable energy alternatives. Solar energy is a vital source of renewable energy which has found application in many areas such as solar heating of buildings, solar distillation, solar street lighting, solar green buildings, electric power generation, solar car designs etc. [4] and in the past decade the world has witnessed a sporadic growth of the solar energy industry [5, 6].

Solar energy is harvested using Photovoltaic (PV) cells for generating electricity [4, 7, 8]; the solar PV cell converts solar energy to electrical energy. The power output of a solar cell is a function of the quantity of light rays incident on the cell [9] and due to the conversion property of the solar PV cell, constant electrical energy can only be realized when the solar panel receives constant energy from the sun which is ordinarily not realizable due to the natural daily variation of the direction and intensity of the sun rays which results in solar electric power fluctuations. To increase energy captured by the PV system, users of solar energy often purchase more than the needed solar panel to enable redundancy and increase total PV array cell coverage area, and at times some users manually adjust the pivoted solar panel each time the sun direction changes significantly. Buying extra PV cells is costly and manual adjustment of the solar panel is also inefficient and hence to address this challenge a Solar Tracking Device is required [10, 11].

A solar tracker is a purpose specific electromechanical system which tracks the current direction of the solar rays and constantly aligns the solar panel module to face the sun directly thereby ensuring maximum power delivery [12, 13]. Solar trackers available in the market are costly [9] and this calls for low cost alternatives. This paper is based on the design and implementation of an effective and low cost sensor-enabled solar tracking device which gives guiding information that directs a drive system to track the sun as it moves across the skyline in real time and by doing so, it positions the solar panel to directly face the sun at all times thereby ensuring maximum energy capture.

2. THEORETICAL BACKGROUND OF THE DESIGN

Solar Irradiation: Sunlight and the Solar Constant

The sun generates its energy through solar fusion as a result of the high temperature and pressure and availability of nuclear materials at the core of the sun. Solar fusion generates a lot of energy in the form of gamma rays. The gamma rays are absorbed by solar particles followed by a re-emission of the energy by the particles and the cycle continues. The sun radiates this energy by means of electromagnetic radiation.

An estimation of the total power of the sun can be determined using the law of Stefan and Boltzmann [14].

$$P = 4\pi r^2 \sigma \varepsilon T^4 \quad (1)$$

Where,
T is the temperature = 5800K,
The radius (r) of the sun = 695800 km
Boltzmann constant (σ) = $1.3806488 \times 10^{-23}$ $m^2\,kg\,s^{-2}\,K^{-1}$.
ϵ is the emissivity of the solar surface

According to Einstein's $E=mc^2$ law, millions of tons of solar particles are transformed to energy per second. Yearly, about 5.1024 Joules of solar energy is irradiated to the earth.

Solar radiation reaches the earth in three major ways and these are:

Direct radiation: this is the solar irradiation that advances on a straight line as it moves from the sun down to the earth's surface and it is also called the beam radiation.

Diffuse radiation: refers to the solar radiation that is scattered by atmospheric particles before reaching the earth. Diffuse radiation does not have a definite travel path, unlike direct radiation.

Reflected radiation: this refers to sunlight rays that is reflected off from non-atmospheric surfaces e.g. the earth surface[15].

Single Axis Trackers

Single axis trackers can only move along one axis of rotation and the rotational axis is along the meridian of the true North. Solar trackers that are controlled by advance programs can be aligned in any cardinal direction. Single axis trackers comes in unique designs and configurations and these are the Horizontal Single Axis Tracker with Tilted Modules (HTSAT), Tilted Single Axis Trackers (TSAT), Horizontal Single Axis Trackers (HSAT), Vertical Single Axis Trackers (VSAT) and Polar Aligned Single Axis [15].

Fixed Collectors

Fixed collectors are mounted in places with a good angular view of the sun; this includes rooftops. This is to ensure that without using solar trackers, the solar panel will be exposed to the sun for the maximum possible hours daily. As a result of this simple positioning and installation requirement there is a drastic reduction in installation and maintenance cost. A large percentage of collectors are of the fixed type and as such when using these collectors, it is vital to note the seasonal position and orientation of the sun so that the collectors can be positioned accordingly with this variation. This ensures maximum solar power output throughout the year.

For fixed solar collectors, the projection area is the area that is perpendicularly oriented to the direction of the solar rays and it is given by:

$$S = S_o \cos\theta \quad (2)$$

Where θ varies from $-\pi/2$ to $+\pi/2$ during the day
As the sun moves across the sky, its angular velocity is given by

$$\omega = \frac{2\pi}{T} = 7.27 \times 10^{-5}\ \text{rad/s} \quad (3)$$

For the incident solar energy the differential is defined as

$$dW = ISdt$$

Neglecting any effect of atmospheric conditions, the energy collected per unit solar panel area for each day is given by:

$$W = \int_{-21600}^{+21600} IS_o \cos\omega t\, dt = I\, S_o \left[\frac{\sin\omega t}{\omega}\right]_{-21600}^{+21600} = \frac{2IS}{\omega} \quad (4)$$

$$= 3.03 \times 10^7\ \text{W/m}^2\ \text{day}$$

Tracking Collectors: Improvement of efficiency

For tracking collectors, theoretical extracted energy is calculated assuming that maximum intensity of the radiation $I=1100\ \text{W/m}^2$ falls on the solar panel area that is perpendicularly to the path of the solar rays.

For tracking collectors, if atmospheric influence is neglected, the captured energy per unit area of the solar panel per day is given by

$$W = IS_o t = 4.75 \times 10^7 \text{Ws} \quad (5)$$
$$= 13.2\ \text{kWh/m}^2\ \text{day}.$$

The theoretical analysis for the fixed and tracking solar system shows that the tracking system captures more energy from the sun rays though this is subject no environmental factors. That notwithstanding, the tracking collector has more exposure to the sun's energy at any given time.

The parameters of a solar cell like the short circuit current, the efficiency, the open circuit voltage and the fill factor are affected by the amount of incident light rays. Consequently, variations in the level of the incident light have a corresponding effect on the output power of the solar panel.

The efficiency of a solar cell can be obtained as the percentage of the incident solar power that is transformed into electrical energy. Given the maximum power, the efficiency is defined as follows:

$$P_{max} = V_{oc} I_{sc} FF \quad (6)$$

As defined by [16]

$$\eta = \frac{V_{oc}\, I_{sc}\, FF}{P_{in}} \quad (7)$$

Where, Isc is the short circuit current
Voc is defined as the open circuit voltage
η is the efficiency
FF is the fill factor

3. THE DESIGN

Solar tracking designs are often structured to suit the seasonal solar energy variation of the target environment. A number of studies came up with unique designs such as the Azimuth Altitude Dual Axis Solar Tracker which incorporates four photovoltaic sensors that provides inputs for the microcontroller. The microcontroller reads the sensor output and based on the read data the microcontroller gives an output to two H-Bridges and four LED indicators. The H-bridge controls the direction of rotation of the DC motors. Later designs have improved the efficiency of this model through design modifications like using various types of solar sensors and sensor configurations, application of pulse width modulation (PWM) for accurate motor control, replacement of the analog comparator circuit with a digital microcontroller for enhanced performance.

The Solar Evaluation Laboratory of the Technical University Federico Santa Maria (UTFSM) came up with a design that suits the climatic conditions of Valparaiso City in Chile. The system automatically measures the solar radiation directly using a pyrheliometer. The solar panel is positioned by a closed loop servo system. Similar works have also been done by [17, 18] using LDR sensors, [4] using PLC for system monitoring and by [19, 20] that utilized photodiode sensors and DC motor for panel positioning.

After a detailed study of the types, configurations and the implementation methods of the various tracking systems available, the general conclusion is that the most effective and ideal tracking system is one built using a microcontroller system for dynamic and real time tracking capability similar to the works of [21, 22] which used stepper motors for alignment. The proposed solar tracker has a unique design that differentiates it from previous works; it is a low cost version that utilizes a PIC18F2620 microcontroller, a low cost, simple and easy to interface Light Dependent Resistor (LDR) and a linear actuator for positioning the solar panel.

Two LDR sensors are used in this design and the resistance of the LDR drops with increasing incident light intensity. Using the luminous light intensity, the resistance of the LDR can be determined by

$$R_L = \frac{500}{Lux} \qquad (8)$$

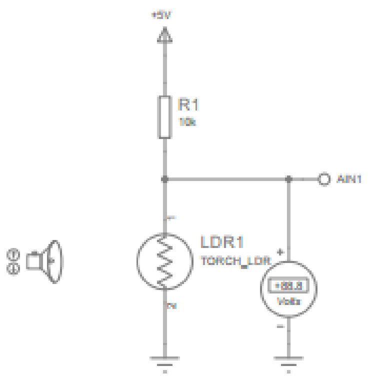

Figure 1: LDR-Resistor potential divider network

Each LDR is positioned in a voltage divider network such that the voltage V_o across the LDR per time is given by

$$V_o = \frac{R_L}{10k + R_L} \times 5V \qquad (9)$$

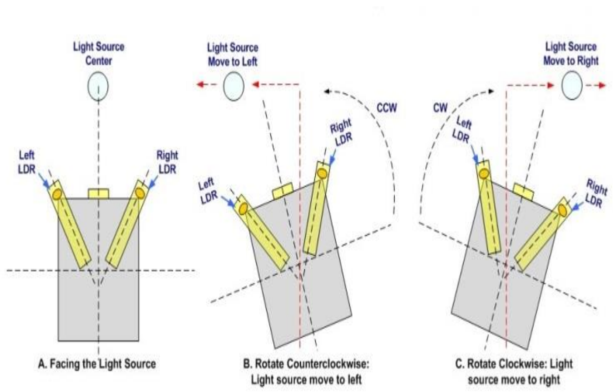

Figure 2: Working Principle of the two LDRs [23]

The microcontroller was programmed with C codes using MikroC PRO for PIC. The microcontroller uses the ADC to convert the LDR voltage values V_o to digital values, the difference of the two LDRs indicates the axis that the solar panel should face and the desired change in direction is effected by the linear actuator. The LDRs are positioned such that the light intensity incident on each one varies depending on the position of the sun; this principle is shown in figure 2. The solar panel is stabilized at a fixed position when the two LDRs are exposed to equal light intensity. When the sun moves from east to west and the direction of the solar rays changes the amount of light incident on the two LDRs will vary. The resultant change in the received light intensity is converted to voltage by the potential divider network and the difference is compared by the in-built comparator circuit of the microcontroller which generates an error signal for its decision making algorithm. The microcontroller performs a computation and gives a corresponding output to the mechanical system to position the solar panel for maximum light reception. The two light dependent resistors are placed side by side separated by a thin wall. The concept of the thin wall is to allow shadow to be casted on one side and light to reflect on the other side so as to determine where the light source is coming from so that the solar panel can be turned in the direction of the light source. The four relays present serves as the H-bridge motor drive for bi-directional movement. The relays are connected to the high current driver array which is called the ULN2003A, both the relays and the high current driver array also powered by a 12V battery source.

The solar Tracking system has the following three sub systems which performs unique roles:

1. An input sensor stage that converts received solar energy to a voltage
2. A control stage which makes decision and determines the extent and direction of the solar panel movement
3. The driving mechanism performs the physical solar panel movement

The functional flow of the components of the solar tracking system is shown in figure 3

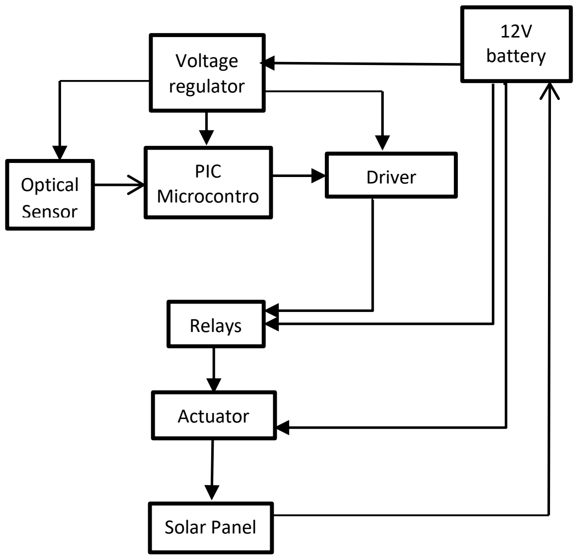

Figure 3: Block diagram of the solar tracking device

4. The Control Algorithm

The algorithm for achieving the solar tracking is summarized below in figure 4

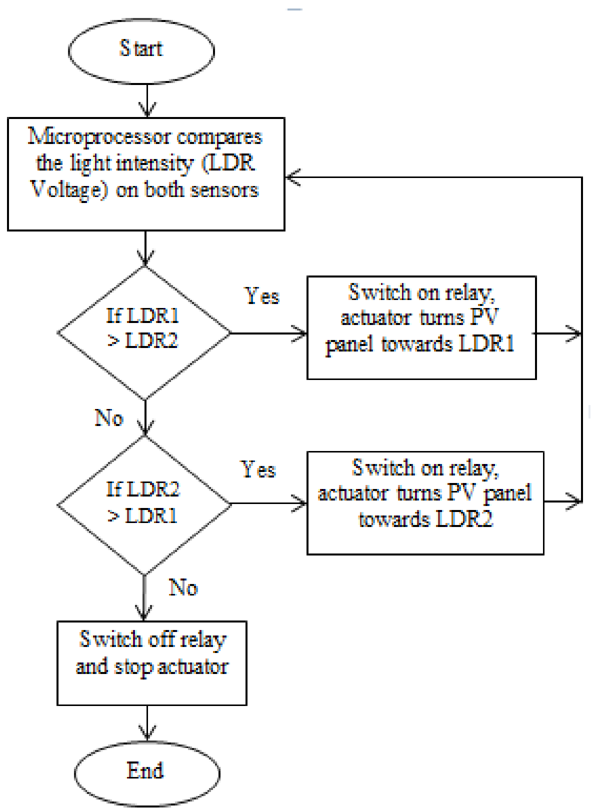

Figure 4: Decision Process Flow Chart

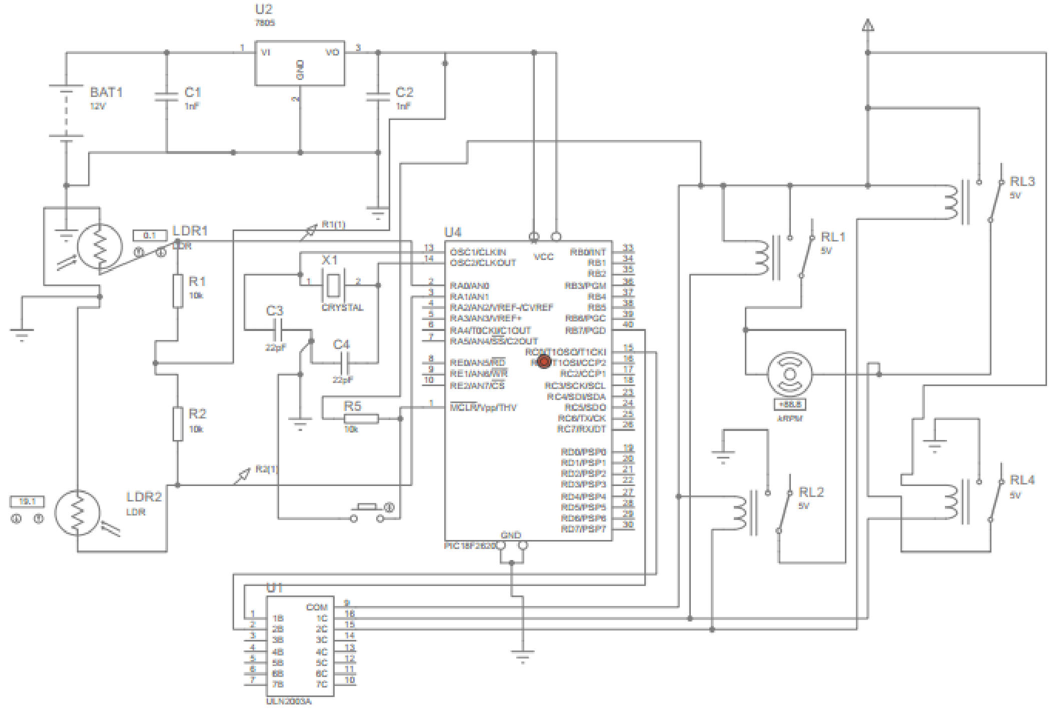

Figure 5: The schematic diagram of the Solar Tracker

5. TESTING AND RESULTS

For direct performance comparison, the solar tracking PV system was setup together with a fixed PV array at the same spot. Experimental results were obtained from the setup at hourly intervals. From the test results, the maximum light reception occurred at midday. The top values of the output voltage and power were acquired between 1230 to 1430 hours respectively when the light intensity was at its peak. The value acquired in the morning and late in the evening is lower due to the fact that we have less sunlight intensity during this period unlike what we have in the day time. After sunset the effect of the solar tracker on system performance is no longer significant and as such, the controller automatically turns the tracker off in the night to save energy and it is switched on, in the morning.

The measured output in terms of voltage and power was greater for the solar tracking system during the day but when the sky is dark with reduced solar intensity, the output values from the fixed system and the tracking system are very close and this is because the light intensity at those times is almost the same. A similar scenario occurred during the mid-day when the solar intensity is maximum, the output from both the fixed and solar tracking system were quite close because both panels were almost equally perpendicular to the sun.

The output voltage and power of the solar system for the study period was measured and is plotted in figure 6 and 7. The maximum output power and voltage for the solar tracking system is 8.528W and 16.40v as compared with 8.359W and 16.39V for the fixed solar panel.

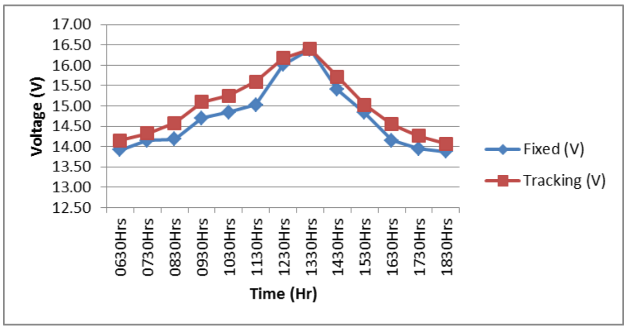

Figure 6: A plot showing Output Voltage Variation for Fixed and Tracking PV Module with Time

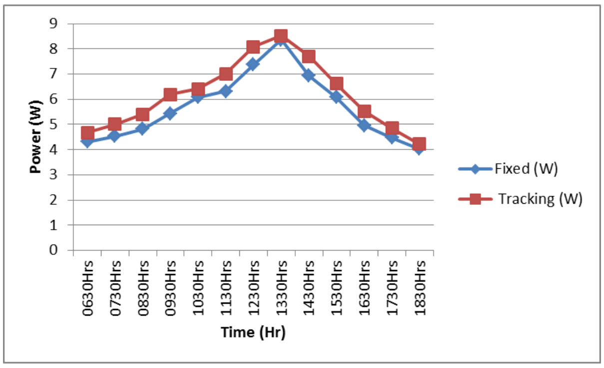

Figure 7: A plot showing Output Power Variation for Fixed and Tracking PV Module with Time

To calculate the translated efficiency, the cumulative output power of both systems were taken and the difference in power was computed, the calculation shows that the tracking system has better light reception capacity.

The overall output power of the solar tracker is 80.21W and that of the fixed panel is 73.68W.

The percentage change in output power =

$$\frac{Diffrence\ in\ Output\ Power(W)}{Overall\ Fixed\ Panel\ Output(W)} = \frac{6.54W}{73.67W} \times 100\% \\ = 8.87\% \tag{9}$$

Due to the application of the solar tracker system, there is an 8.87% increase in the output power of the solar system.

6. CONCLUSION

The solar tracker is a system with lots of beneficial attributes. This research work presented the design and implementation of a low cost, effective and easy to implement solar tracking system. The tracker is also more effective due to the fact that Nigeria is a tropical country where we do not have notable solar changes in the different seasons. This eliminated the need for the extra circuitry and complexity of a dual axis tracker and it further reduced the implementation cost. The single axis tracker system designed is more efficient in tracking the sun than the fixed system.

This project was implemented with minimum resources and the design achieved an improved efficiency of 8.87% even though the circuitry was kept simple.

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