
C.S.Chin*, A. Babu*, W. McBride*

*School of Marine Science and Technology, University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU, United Kingdom
cheng.chin@ncl.ac.uk

*School of Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan NSW 2308, Australia

Abstract

This paper presents the design, modeling and testing of an active single axis solar tracker. The compactness of the proposed solar tracker enables it to be mounted onto the wall. The solar irradiance is detected by two light-dependent resistor (LDR) sensors that are located on the surface of the photovoltaic (PV) panel. The smart tracker system operates at different modes to provide flexibility to accommodate different weather conditions and preference for different users. The PV panel rotates automatically based on the sun irradiance during the day while at night; the system is in 'sleep' mode in order to reduce the energy consumption. A computer model of the standalone solar tracker system is first modeled using MATLAB™/Simulink™. The efficiency over the fixed solar panel, the power generated and the types of PV systems to achieve the required level of efficiency can be determined before actual implementation. The experimental testing shows some agreement with the simulation results.

Keywords: solar tracker, MATLAB™, PV panel, microcontroller, modeling.
1. Introduction

Renewable energy resources will be an increasingly important part of power generation in the new millennium. Besides assisting in the reduction of the emission of greenhouse gases, they add the much-needed flexibility to the energy resource mix by decreasing the dependence on fossil fuels [1]. Among the renewable energy resources, solar energy is the most essential and prerequisite resource of sustainable energy because of its ubiquity, abundance, and sustainability. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost. Recently, photovoltaic (PV) system is well recognized and widely utilized to convert the solar energy for electric power applications. It can generate direct current (DC) electricity without environmental impact and emission by way of solar radiation. The DC power is converted to AC power with an inverter, to power local loads or fed back to the utility [2]. Being a semiconductor device, the PV systems are suitable for most operation at a lower maintenance costs.

The PV application can be grouped according to the scheme of interaction with utility grid: grid connected, stand alone, and hybrid. PV systems consist of a PV generator (cell, module, and array), energy storage devices (such as batteries), AC and DC consumers and elements for power conditioning. The most common method uses the PV cells in grid network. However, to understand the performance and to maximize the efficiency of the irradiation on the PV cells, the standalone PV cells have spurred some interest especially, in the area of solar tracker system.

Over the years, test and researches had proved that development of smart solar tracker maximizes the energy generation. In this competitive world of advanced scientific discoveries, the introductions of automated systems improve existing power generation methods. Before the introduction of solar tracking methods, fixed solar panels were positioned within a reasonable tilted direction based on the location. The tilt angle depending on whether a slight winter or summer bias is preferred in the system. The PV systems would face “true north” in the northern hemisphere and “true south” in the southern hemisphere. Solar tracking is best achieved when the tilt angle of the tracking PV systems is synchronized with the seasonal changes of the sun’s altitude.

Several methods of sun tracking systems have been surveyed and evaluated to keep the PV cells perpendicular to the sun beam. An ideal tracker would allow the PV cells to accurately point towards the sun, compensating for both changes in the altitude angle of the sun (throughout the day), latitudinal offset of the sun (during seasonal changes) and changes in azimuth angle. In the light of this, two main types of sun trackers exist: passive (mechanical) and active (electrical) trackers. The detailed literatures review can be found in [3].

One class of the passive solar trackers is the fixed solar panel. It is placed horizontally on the fixed ground and face upwards to the sky. But most of the passive solar trackers are based on manual adjustment of the panel[4], thermal expansion of a shape memory
alloys[5] or two bimetallic strips made of aluminum and steel[6]. Usually this kind of tracker is composed of couple of actuators working against each other which are, by equal illumination, balanced. Another passive tracking technology is based on the mass imbalance [6] between both ends of the panel. This group of trackers does not use any kind of electronic control or motor. The sun heats the fluid inside the cylindrical tubes causing evaporation and transfer from one cylinder to another which creates the mass imbalance. Passive solar trackers, compared to active trackers, are less complex but work in low efficiency. Although passive trackers are often less expensive, they have not yet been widely accepted by consumers.

On the other hands, major active trackers can be categorized as microprocessor based, computer controlled date and time based, auxiliary bifacial solar cell based and a combination of these three systems. In the microprocessor based solar tracker systems [7-11], a controller is connected to DC motors. Once the location is selected, the azimuth elevation range is determined and the angular steps are calculated. In this solar tracker design, sensors were often used. For example, a photo-resistor [12-13] was put in a dark box with small hole on the top to detect the illumination or Photosensors called light-dependent resistor (LDR) [11,14] to indicate the intensity of the radiation. The signals were then captured by the microcontroller that provide signal to the motors to rotate the panel.

Whilst in the auxiliary bifacial solar cell [15] systems, the bifacial solar cell senses and drives the tracker system to the desired position. In the design, components such as batteries and driving electronics were eliminated. Hence, it is very simple solar tracker for space and terrestrial applications. In the solar tracking system using the Programmable Logic Control (PLC) [16-17], the required position was calculated and later programmed into the PLC to adjust the PV panel to the sun direction. In another method that uses the combination of microprocessor with sensor and date/time based system [18-19], the sensors such as pyrheliometers (that measure the direct beam of sun irradiance) send signal to the microcontroller. Using the real-time clock, the data gathered during the day are analyzed, and a new improved set of parameters are used in the next day to compute the sun positions and the cycle continues.

In summary, the main difference among the active tracker is the ability to reduce the pointing error using external sensors, thereby increasing the daily irradiation the solar cells receive and the electric energy that they produced. A comparative study[3] shows that, the power consumption by the tracking device is only 2-3 % of the increased energy. The annual energy available to the two axis tracker was 72% higher than a fixed surface and 30% for single axis East-to-West tracker. However, the two or more axes trackers are more complex and costly to maintain as compared to the single-axis tracker. Furthermore, as Singapore is near to the equinoxes, the sun rises directly East and set directly West regardless of the latitude, the single axis solar tracker becomes more favorable in this region. Based on the above-mentioned tracking systems, we have suggested that the active based single-axis tracker system is less complex to design and maintain. Additionally, for the system to work solely based on light-sensor tracking technology is not practical due to Singapore’s unexpected changes in weather conditions. We have
therefore come about with the idea to integrate a time-based tracking technology with the light-sensor tracking technology in the tracker system. With high numbers of high-rise buildings in Singapore, the ideas of having a wall mounted design for each household usage become an attractive option.

In the new solar tracking system installed with sensor feedback and real-time clock control was capable of performing both automatic and preset mode of operation. The system’s ability to switch between the modes proves to be an important feature. The position and "status" of the sun are detected by two light-dependent resistor (LDR) sensors that are located at the both ends of the surface of the photovoltaic panel. In the automatic modes, the resultant signals from the sensors are fed into an electronic control system that operates a low- speed DC motor to rotate the panel via a speed-reduction system. In this mode, the Sun is not constantly tracked to prevent energy consumed by the motor, and the system will be in 'sleep' mode when the night falls. In the preset mode, the solar tracker rotates at a pre-determined angle from the sunrise to the sunset. Whilst in the manual mode, the solar tracker is set to a desired angle by manually increasing or decreasing the angle via the input to the PIC microcontroller. In all modes, a night return algorithm repositioned the panel to its initial home position facing the East (at sunrise).

Besides, the ability to operate as a solar tracker, computer models of the PV panel and the electro-mechanical systems are modeled using MATLAB™ and Simulink™ software. In literature [20], a simple visual C++ program was used to provide an excellent graphic user interface (GUI) and control normal DC power supply output using computer printer port to exactly simulate solar panel characteristics. As seen in [21-23], MATLAB™ and Simulink™ was used to model and analyze the PV model characteristics. However, there are no attempts to model the entire PV standalone system including the electro-mechanical subsystem such as DC motor, drive transmission, microcontroller output, battery and charging module. Whether like or not, this is essential as they are parts of the PV systems and the influence on the overall performance such as efficiency and power output can be compromise if the electro-mechanical system is poorly design for the active solar tracker. With that in mind, the PV standalone system model consists of a PV panel, a servo motor, a battery, a charger, two LDR sensors, an external load and a microcontroller are modeled using the software, MATLAB™ and Simulink™.

This paper presents the modeling and simulation of the solar tracker system consisting of the photovoltaic system under a constant load using MATLAB™ and Simulink™. The paper is organized as follows. The overview of the electro-mechanical design of the single-axis solar tracker is described in Section 2. This is followed by the description of the proposed MATLAB™ and Simulink™ models in Section 3. The experiments and testing are described in Section 4. Conclusions are drawn in Section 5.
2. Solar Tracker System Descriptions

2.1. Mechanical Structure

After the solar panels and other components were selected, the overall structural design of the solar tracker as seen in Fig.1 was modeled using mechanical design software, SolidWorks. The solar tracker weight 3 kg and has an overall dimension of 340mm x 270mm x 500mm. The compactness of the proposed solar tracker enables it to be mounted onto the wall. It consists of the PV panel, the pulley-chain transmission system, the motor and electronics boards support and the vertical pillar with base plate support. The entire structure was fabricated using the aluminum rods and plates. The pillar holding panel is aligned to the centre of panel for better flexibility during the panel rotation. The tracker is designed to have a single axis rotation (East to West) and the motor is mounted in such a way that the tracker systems have only a single-axis freedom of rotation. The fixture to hold the sensors are then assembled and aligned at both ends of the PV panel to obtain the sun irradiance.

Figure 1: SolidWork design model

The PV panel frame support (as seen in Fig. 2) has a support rod that runs across the PV panel width. The gear on the rod supported by two bearings is directly connected to the motor shaft via the pulley-chain transmission system. The two mechanical stoppers at each ends were incorporated to limit the rotation of panel. As shown in Fig. 1, the components were arranged along the vertical pillar mounted on the base plate support. The SolidWork assembly design was finally assembled as shown in Fig. 3.

Figure 2: Transmission system between motor and PV panel holder
Figure 3: Actual fabricated design

2.2. Electrical System

The overall mechanical and electrical subsystems were integrated into the solar tracker system as shown in Fig. 4. The block diagram of the solar tracker system consists of mostly electrical components. The solar tracker consists of the PV cells, the charge controller and the lead-acid battery. Other subsystems such as the LDR sensors, the voltage regulator, the microcontroller-PIC18F4520 target board were also used. The LDR sensors sense the sunlight intensity and send the signal to the microcontroller to rotate the PV panel via the servo motor. The electrical energy is then stored in the lead-acid battery that is later used for powering the respective components.

Figure 4: Schematic diagram of the standalone solar tracker system
The PV cells are a device that helps to convert the solar energy into electrical energy. The solar panel selected is capable of generating 10W power. As per the vendor specification, it weight about 1.3kg with a dimension of 341mm x 269 mm x 28mm. Charge controller was supplied together with the solar panels units. It requires 12V supply and is capable of handling a maximum of 5A. The charge controller prevents the over-charging of the battery that provides the voltage supply to the respective electronics components such as the microcontroller-PIC18F4520 target board, the charge controller and the voltage regulator circuit.

The LDR sensors (NORPS-12) were used to sense the sun irradiance. LDR sensors are resistors that would vary their resistance according to the sunlight intensity exposed onto its surface. The LDR sensor circuitry is designed as a voltage divider circuit as shown in Fig. 5. The output of the sensor circuit is an analogue voltage that is used as an input to the PIC microcontroller.

The sensor circuitry was tested under the sun using the circuit as shown in Fig. 5. To determine the appropriate value of resistor R, various values of different resistors were examined to finalize an appropriate resistor. The desired resistor value should provide a voltage that covers the sunny and cloudy conditions. The following resistor values as shown in Table 1 were tested. From the test result, it was found that varying the value of resistors in the voltage divider circuit helps to improve the sensitivity of the output. The resistor of $100\Omega$ was found to be suitable to differentiate between the sunny and cloudy day.

<table>
<thead>
<tr>
<th>Table 1: Recorded Voltage variation at different resistance</th>
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The driving mechanism includes the servo motor and the pulley-chain system. The servo motor (HS-805BB) was controlled using the microcontroller. The controller uses the PWM (Pulse Width Modulation) signal to drive the servo motor at a controlled speed correspond to a maximum voltage of 6V. The PWM wave is a continuous square wave signal that changes between 0V and 6V. The duration or width of the pulse determines the angle of the shaft’s rotation.

A voltage regulator circuit was used to bring the supply voltage down to a level suitable for use in the microcontroller, the charge controller and the LDR sensors. The voltage regulator circuit (using the IC UA723chip) is shown in Fig. 6. The input supply of 12V from the battery source is lowered to 6V as the result of the circuitry. The circuit has a heat sink to dissipate the heat generated by the long duration used.

The microcontroller target board was used to control the servo motor. It receives the signals from the LDR sensors. The analogue voltage is converted into digital signal (logic 1 or 0) for processing. The processor used was a PIC18F4520 from Microchip Inc. As shown in Fig. 7, the PICKIT2 programmer was used to interface the MPLAB-Integrated
Development Environment (IDE) to the target board. To program the microcontroller-PIC18F4520 target board, the MPLAB-IDE using the MPLAB C18 Compiler software was used. The C program can be written onto the MPLAB and is then compiled before downloading into the target board as shown in Fig. 7. The figure illustrates a PC connection to microcontroller-PIC18F4520 target board using PICkit2 programmer kit.

Figure 7: Process of downloading C program to PIC using PICKit2 programmer

The complete schematic diagram showing the wiring connections of the above-mentioned LDR sensors, the servo motor, the charge controller and the voltage regulator to the microcontroller is shown in Fig. 8. All electronics components were soldered on-board and tested before they were mounted onto the solar tracker platform.

Figure 8: Schematic diagram of electronics integration of sensors

Recalled, there are three modes of operation in the solar tracker. They are namely: automatic, preset and manual mode. In the automatic mode, the PIC microcontroller rotates the PV panel to balance the light intensity at both LDR sensors. In the case when both sensors receive a low voltage due to cloudy conditions, the PV panel is programmed to wait for 15min and automatically switched to preset mode (using internal real-time clock). In this mode, the PV panel is programmed to rotate 2° towards west in every 15 min. If the extreme position towards the west is sensed (at sunset), the night return algorithm repositioned the panel to its initial home position facing the East (at sunrise). In the manual mode, it allows the panel to rotate to the desired angle by manually increasing or decreasing the angle via the input to the PIC microcontroller. Once the PV panel is positioned to the desired angle, it switches back to the automatic mode.

3. Standalone Solar Tracker System Modeling

The main focus in this section is to simulate the single axis solar tracking system during the automatic mode using MATLAB™/Simulink™. All the data for building the simulation models were obtained from either the components datasheets or the experiments conducted. The simulation run was performed in every second of the entire 10 hours or 36000 seconds of experimental set up. The rapid accelerator mode has been chosen to reduce the simulation time to about 180 seconds real time (one second simulation time is equivalent to 180 seconds real time). The rapid accelerator mode gives the best speed improvement compared to normal mode when simulation execution time exceeds the time required for code generation. The ODE45 solver type of variable step size was used throughout the simulations.

As seen in Fig. 9, the simulation model is implemented in a way that when the sun irradiance falls on the sensors, the servo motor moves the PV panel in an incremental way till the sunset. The LDR sensors signal provide the input to the microcontroller for the servo motor to rotate the PV panel. The charging and discharging mechanism of the
battery uses the charger subsystem. The PV tracking panel with the two LDR sensors generates the voltage outputs (i.e. V\_LDR\_B and V\_LDR\_T) based on the corresponding sun irradiance data used in the simulation. The irradiance from the sun model was obtained by dividing the power obtained from the tracker by the surface area of the PV cells. The servo motor rotates the panel at an angle based on the microcontroller PWM signal. This process repeats again until the sunset. During the process, the PV panel generates direct current that keeps the 12V battery charged. The battery gets charged or discharged depending on the state of the charger. The external load was modeled by a pure resistor to simulate the loading on the motor shaft. As observed in Fig. 9, the solar tracker model developed in Simulink provides a means to compare the experiment data (e.g. power, current and sun irradiance) with the simulated results and to compute the efficiency of the proposed solar tracking system over the fixed panel.

Figure 9: Overall tracking system block diagrams in Simulink

### 3.1 PV Panel Model

The simplest equivalent circuit of a solar cell is a current source in parallel with a diode as shown in Fig. 10. The current source represents the current generated by the PV cell due to the photons received by it, and is constant under constant sun irradiance and temperature. During darkness, the solar cell is not an active device; it works as a diode. It produces neither a current nor a voltage. However, if it is connected to an external supply (large voltage) it generates a saturation current or dark current. The key parameters for a PV cell are short circuit current ($I_{\text{sc}}$ or the current from the solar cell when the voltage across the cell is zero), open circuit voltage ($V_{\text{oc}}$) and sun irradiance value. Usually these values are given by the manufacturer in the data sheet.

Figure 10: Circuit diagram of a PV cell model

Normally a single PV cell produces a rather small voltage that have less practical use. The real PV panel always uses many cells to generate a large voltage. For example the Kamtex-10W PV module used for our project comprises of 36 cells to generate a large enough voltage to charge a 12 volt battery. The data sheet for Kamtex-10W is given in Table 2.

Table 2: Electrical characteristics of PV Module-Kamtex (KMX-10W)

The following parameters were used in the calculation of the net current of a PV cell.
- Saturation current of the diode, $I_0$.
- Net current from the PV panel $I$.
- Light-generated current inside the cell $I_L$.
- Series resistance $R_s$, which is internal resistance of the PV panel;
- Shunt resistance $R_{sh}$ in parallel with the diode, $R_{sh}$ is very large unless many PV modules are connected in a large system;
- Diode quality factor, $n$;
In an ideal cell, $R_s$ is 0 and $R_{sh}$ is infinite. The net current of the PV cells is the difference between the output current [27-28] from the PV cells and the diode current is given by,

$$I = I_L - I_n \left[ e^{\frac{q(V + R_s)}{nkT}} - 1 \right]$$

where $V$ is the voltage across the PV cell, $k$ is the Boltzmann’s constant (=1.381×10^{-23} J/K), $T$ is the junction temperature in Kelvin, $q$ is the electron charge (=1.602×10^{-19} C), $n$ is the diode ideality factor (=1.62).

$$I_L = I_L(T_1) + K_0(T_{ref} - T_1)$$

(2)

$$I_L(T_1) = I_{oc}(T_1).G(T_{ref})$$

(3)

$$K_0 = \frac{I_{oc}(T_2) - I_{oc}(T_1)}{T_2 - T_1}$$

(4)

Here, $T_{ref}$ equals to 298K is the reference temperature of the PV cell, $G(T_{ref})$ equals to 1000W/m^2. $K_0$ is the temperature coefficient are used. Then,

$$I_0 = I_0(T_{ref})\left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}} e^{-\frac{qV_e}{nkT_{ref}}}$$

(5)

$$I_0(T_{ref}) = \frac{I_{oc}(T_1)}{\left(e^{\frac{qV_e(T_1)}{nkT_1}} - 1\right)}; \quad V_0(T_1) = \frac{nkt}{q}\ln\left(\frac{I_L}{I_0}\right)$$

(6)

where $V_e$ is the band gap energy (=1.12eV). It is the energy needed to break a bond in the crystal, $V_{oc}$ is the open circuit voltage corresponds to the photocurrent $I_L$. The resistance within each cell in the connection between cells is the series resistance, $R_s$

$$R_s = \frac{dV}{dI_{oc}} - \frac{1}{X_v}$$

(7)

$$X_v = I_0(T_1) \frac{q}{nkT_1} e^{\frac{qV_e(T_1)}{nkT_1}} - \frac{1}{X_v}$$

(8)

By Newton’s method,

$$x_{n+1} = x_n - f(x_n) / f'(x_n)$$

(9)

where $f'(x)$ is the derivative of the function $f(x) = 0$, $x_n$ is a present value, and $x_{n+1}$ is the next value. So,
Then using Newton’s equation:

\[
f(I) = I_L - I - I_o \left[ e^{\frac{q(V+IR_v)}{nkT}} - 1 \right] = 0
\]

(10)

By using MATLAB\textsuperscript{TM}, the above function can be computed numerically to obtain the net output current from the PV cells.

The fixed PV panel was modeled as shown in Fig.11 using the equations as seen in (11). The output voltage of the battery is 12V. The temperature (\(T_{AC}\)) obtained during the experiment and the sun irradiance data (\(G\)) that represents the intensity (or the power of sunlight falling per unit area) were used. The solar irradiance data were taken hourly and the averages in each hour were then tabulated. The PV Cells Array block diagram computes the net current from the PV cells using the embedded MATLAB function. The plot for the actual and simulated net output current is shown in Fig. 12. The deviation in the plot maybe due to the averaging done during each hours and the power consumed before noon was actually higher than expected. This is reasonable as the sunlight is stronger during the day. Errors due to unmodelled external disturbances such as mechanical friction and wind loading may contribute to the differences.

Figure 11: Fixed PV panel model

Figure 12: Actual and simulated net output current value of fixed panel

To simulate the sun irradiance at different PV panel’s angle, the effective irradiance was used. Details of the effective irradiance block diagram can be seen in Fig. 13. The block diagram basically defined the angle between sun’s incident ray and PV panel. For a static panel, it is always parallel to the ground that is at 90 degrees (0 degree for sunrise and 180 degrees for sunset). A simple program was written to obtain the relationship of the effective sun irradiance when the difference between the sun angle and panel angle is more than +/-90 degrees. To limit the angle to 90 degrees, the cosine trigonometric function was introduced in the model to create the zero sun irradiance when such a situation occurs.

Figure 13: Effective sun irradiance model

3.1.1 Smart Tracker PV panel

The smart tracker panel was installed with two LDR sensors. Assuming both sensors are placed in parallel with the PV panel, the effective irradiance is similar. As the results, the
smart tracker is unable to perform the proposed sun tracking algorithm. To circumvent this, the top and bottom sensors were positioned at 45 degrees and 135 degrees respectively as seen in Fig. 14. When the sunlight falls onto the PV panel, the LDR sensors generate different voltages (that is V_LDR_B and V_LDR_T according to the changes in the sun irradiance) to move the PV panel.

Figure 14: PV panel and LDR sensor angle position
Figure 15: Smart tracker PV panel Model

3.2. Sun Model

At each time instant, the actual sun irradiance data obtained from the experiment was used. In the sun model, the sun is assumed to travel from 0 degree (sunrise) to 180 degree (sunset) from 7am to 5pm. During these 10 hours, the PV panel rotates 180 degrees. As shown in Fig. 16, the initial sun’s angle is at 30 degrees and with the angle changes at 15 degrees per hour or 0.004147 per simulated time in second; the corresponding sun angle (with respect to the base) is obtained.

Figure 16: Sun’s model

3.3. LDR Sensor Model

The LDR sensor is a variable resistor that changes the resistance according to the intensity of incident ray illuminated onto it. As the intensity of sunlight changes, the resistance and the voltage of LDR sensors change. The output voltage across the resistor (resistance value of 100Ω) is converted into digital signal at the input of the microcontroller. Based on the TTL input, the servo motor rotates clockwise (CW) or anticlockwise (CCW). In the LDR sensor model as shown in Fig. 17, the difference between the panel angle and the assumed sun position was calculated. The angles were limited to +/- 90 degrees. When 90 degrees is reached, the LDR sensor output a zero irradiance that corresponds to a certain voltage as shown in Table 1. Recalled, V_LDR_B and V_LDR_T are the voltage output from the bottom and top sensors.

Figure 17: LDR sensor model

3.4 Microcontroller model

Figure 18: Microcontroller model

As shown in Fig. 18, the microcontroller model is modeled using the embedded MATLAB™ function. The inputs to this function are LDR_B and LDR_T, a real time clock and initial buffer value of 1.5. One of the inputs (named Extime) is used to compare the current time with the previous time when the PWM value changes. The
microcontroller generates output duration of 1.5ms to rotate the PV panel if the voltage difference of the LDR sensors is less than 0.07V and are both less than 0.75V (very low irradiance). If LDR sensors voltages are both greater than 0.75V but the voltage difference is less than 0.07V, the PV panel remains in the current position. In the case when the LDR sensor values is greater than 0.07V, the motor turns the PV panel by adjusting its PWM value until the sensors’ voltages are equal. The delay time of 0.7 seconds and increment steps were found using trial and error method during the simulation. The process flow chart for the microcontroller operation is illustrated in Fig. 19.

Figure 19: Process flow chart for the microcontroller operation

3.5. Charger Model

A charger is essential to protect the battery from over-charged and fully drained. In an ideal case, the battery charge remains between 20% and 100% based on a PSpice photovoltaic model [25]. This model includes two switches namely: Switch A and B to control the battery voltage flow. Switch A remains deactivated for any value of battery charge above 12.95V (100% charged). Switch B deactivates once the battery charge drops to 11.6V (20% charge left). The truth table for the charge control is given in Table 3.

Figure 20: Block diagram of charge control

The Switch A is connected to the PV module on one side and the battery on the other side. When the net output current from the PV panel is positive, it begins to charge the battery until the maximum charge of 12.95V is reached. When there is no current from PV panel the switch remains activated, the current required is obtained from the battery. After the battery is fully charged, the switch disconnects. The switch is activated again if the battery voltage drops below to 12.2 V.

The Switch B is connected when the battery is in charging mode (greater than 12.25V). When the battery voltage drops below 11.6 V, the battery is draining and hence it is important to cut off the loads in order not to damage the motor. The conditions for the switching are given in Table 3 and the corresponding values of Switch A and Switch B (previous states and current states) are given by X, Y, M and N respectively. The value ‘1’ represents the closed switch and ‘0’ represents the open switch.

Table 3: Truth table used for discharging (left) and charging (right) condition.

The Simulink model of the charger can be seen in Fig. 21. The Compare block diagrams were used to compare the various conditions as shown in Table 3. The logic gate after the comparisons serves as the truth table for operating the Switch A and B.

Figure 21: Charger model in Simulink
3.6. Battery Model

The lead-acid battery model was implemented based on a PSpice model [25] for a lead acid battery. It has two modes of operation – charging and discharging modes. When the current to the battery is positive (negative), the battery is in the charging (discharging) mode. The following parameters were used for modeling the battery.

- \( SOC_i \) is the initial state of charge,
- \( SOC(\%) \) is the available charge.
- \( SOC_m \) is the maximum state of charge.
- \( n_s \) is the number of 2V cells in series.
- \( D \) (h\(^{-1}\)) is the self discharge rate of battery.
- \( K_b \) (no unit) is the charging and discharging battery efficiency.

As \( SOC \) varies linearly with \( V_{ocb} \) (open circuit voltage of the battery), the relationship between open circuit battery voltage and state of charge can be determined using the Table 4.

**Table 4: State of charge with respect to Voc.**

As shown in Fig. 22, the terminal voltage for the battery is given by:

\[
V_{bat} = V_t + I_{bat}R_t
\]  

(12)

Here \( V_t \) and \( R_t \) both depend on the mode of battery operation and have different equations. Battery current; \( I_{bat} \) is positive when battery is in charge (ch) mode and negative when in discharge (dch) mode.

**Figure 22: Battery circuit**

In charging mode, we can write the resistance and voltage as follows:

\[
R_t = R_{ch} = \left( 0.758 + \frac{0.139}{[1.06 - SOC(t)]n_s} \right) \frac{1}{SOC_m}
\]  

(13)

\[
V_t = V_{ch} = [2 + 0.148 \times SOC(t)]n_s
\]  

(14)

where \( SOC(t) \) represents the current state of charge (%), \( SOC(t) \) is defined by a set of equations later. In discharging mode, the resistance and voltage are written as follows:

\[
R_t = R_{dch} = \left( 0.19 + \frac{0.1037}{[SOC(t) - 0.14]n_s} \right) \frac{1}{SOC_m}
\]  

(15)

\[
V_t = V_{dch} = [1.926 + 0.124 \times SOC(t)]n_s
\]  

(16)
To estimate the value of $SOC(t)$, the following equations have been used to describe them in the PSpice model[25].

$$SOC(t + dt) = SOC(t) \left(1 - \frac{D}{3600} + \frac{K_b(V_{bat}I_{bat} - R_l I_{bat}^2)}{3600}\right) dt$$  \hspace{1cm} (17)

In equation (17), the time is assumed in seconds, so some terms must be divided by 3600 such that $SOC$ is in Wh. By substituting $V_{bat}$ as a function of $V_1$, the value of $SOC(t)$ can be determined as shown.

$$SOC(t) = SOC(t - 1) + \frac{1}{3600} \int_{t-1}^{t} \left[ \frac{K_b V_1 I_{bat}}{SOC_m} - SOC(t - 1)D \right] dt$$ \hspace{1cm} (18)

The Simulink model in Fig. 23 is used to model the charging and discharging conditions during the process. The left-hand side of the Fig. 23 shows the respective functions used. There are namely: $V_{ch}$, $V_{dch}$, $R_{ch}$ and $R_{dch}$. The input to the battery is the net current output from the PV panel and the output is the battery voltage, $V_{bat}$. In order to obtain 12V, six 2V cells denoted by $n_c$ were used. The maximum state of charge, $SOC_m$ was set to 84. The discharge rate, $D$ and the efficiency, $K_b$ are set as $1.5 \times 10^{-5}$ and 0.8 respectively. As the battery is in charging or discharging mode, it allows only one value for $R_1$ and $V_1$ to the equations.

Figure 23: Battery model in Simulink

3.7. Motor Model

The solar panel is designed to drive the PV panel in a small angle, between 0 to 180 degrees at a low speed. PWM is used to control the motor. The PWM is a continuous square wave with a period of 20ms. With the PWM signal, the output shaft of the servo motor changes the angular position of the PV panel. The following parameters are used to model the DC motor.

- Moment of inertia ($J$) = 0.01 kg.m²/s²;
- Damping ratio ($b$) = 0.1 Nms;
- Electromotive force constant ($K_t$) = 0.01 Nm/Amp;
- Back electromotive force constant ($K_e$) = 0.01 s.s/rad;
- Electric resistance ($R_m$) = 1 ohm;
- Electric inductance ($L_m$) = 0.5H;
- Input Voltage ($V_m$);
- Output angle ($\theta$);

As the modeling of the DC motor is common, we write the following open-loop transfer function without any derivation. Here, the transfer function between the output rotational angle and the input voltage is written as follows.
\[
\frac{\theta(s)}{V_m(s)} = \frac{1}{s} \left[ \frac{K_i}{(J s + K_p)(L_m s + R_m) + K_i K_p} \right]
\] (19)

Based on this transfer function, the DC motor model can be modeled in Simulink (as seen in Fig. 24) using the look-up tables. The look-up table uses the PWM as an input to rotate the motor to a pre-determined angle. When pulse width changes from 1.25ms to 1.75ms, the panel angle changes from 0 degree to 180 degree in a linear manner. The second look-up table on the feedback path provides the actual pulse width results. The actual and the desired pulse-width are then compared to obtain the error signal for the Proportional-Integral-Derivative (PID) controller (using the controller gains: \(K_p = 60, K_i = 30, K_D = 3\)) to drive the motor to the desired angle. The embedded MATLAB\textsuperscript{TM} function block is used to deactivate the motor load when it is not turning. An external load was added to show whether the motor is able to drive the PV panel. The weight could vary due to the modeling error and the wind disturbance during the windy day. In this case, the external load is modeled as a pure resistance value (\(\approx 40\Omega\)).

*Figure 24: DC motor model in Simulink*

### 4. Experimental and Simulation Results

In order to validate the proposed modeling, it was necessary to compare the experiment results for the fixed panel with the smart solar tracker system. To obtain this data, simple experiments were performed. The experiment setup for both fixed and tracker system can be seen in Fig. 25. The setups were installed on building roof top that was 40m above the ground. The temperatures during the experiment were recorded using the Type-K thermocouple sensor. The open circuit voltage and the current readings were recorded using a multi-meter connected to the solar cells. The climatic condition considered for experimental was a quite sunny during the entire test period. The average temperature recorded was around 30°C.

*Figure 25: Experiment Setup for fixed (left) and smart tracker (right) system*

The simulation results of the solar tracker using Simulink are shown in Fig. 26. As observed from the plots, the solar tracker is able to follow the sun angle. The other part of the graph shows the state of the charge during the simulation. As seen in the battery voltage, the Switch A was deactivated when the maximum allowable voltage of 12.95V had reached. The switch B was always connected during the entire duration (in charging mode).

*Figure 26: Simulation results of the standalone smart solar tracker*
In Fig. 27, the simulated power and net current output over the day was quite close to the actual results obtained. There was some slight deviation during the noon and evening period due to the modeling of the actual irradiance obtained from the experiment. Furthermore, the current consumed during the actual test was different as the wind loading and other disturbances were not modeled in the simulation.

Figure 27: Simulated and actual power generated by smart solar tracker
Figure 28: Simulated and actual current generated by smart solar tracker

The output power of the smart tracker was compared with the fixed panel design in order to determine the efficiency of the solar tracker system. As expected the overall power (or the efficiency) generated by the tracking panel is higher than that of static panel. Here, the efficiency refers to the ratio of difference between the sum of smart tracker and the fixed panel power to the sum of fixed panel power over the period of interest. From Fig. 29, the efficiency (obtain from experiment results) is around 20%. As compared to various the solar trackers as seen in [3], the average efficiency is around 12-15% and hence, the proposed design is slightly higher and comparable to the existing design.

As seen in Fig. 28, the solar tracker was efficient during most of the day except during the noon time where the sun irradiance was found to be the highest. The fixed panel that lies horizontally on the ground is therefore quite comparable to the solar tracker system and hence zero efficiency was obtained. This explained why it is common to use a fixed panel in a sunny day where it experienced the maximum sun irradiance during the noon time.

Figure 29: Simulated and actual efficiency

For the cost and benefit of the proposed solar tracker system, it has some special features such as the initial expenditure on the equipment is usually high but there is no fuel cost involved and the maintenance cost is low. The accumulated data [24] show that at present a PV system is competitive where small amounts of energy are required at a place that is far away from an electric grid or any other source of energy. For the economic evaluation of a system, the parameters that are usually considered are the life-cycle cost (LCC), payback period (PP) and rate of return (RR). LCC is the sum of all the costs of a system over its lifetime, expressed in today’s money. In case of the analysis of a PV system, the lifetime of the modules is usually taken as 20 years. The calculations were made on the basis of the approach described in [24,26] and the results are shown in Table 5.

Our estimates of the electricity cost matched with those reported in [24] for the PV, diesel generator and grid-extension systems. Our analysis shows that the cost of electricity from a PV system is approximately equal to that from a diesel generator and cheaper than a grid extension. This PV system may be used for domestic applications especially in remote areas. Keeping in view the environmental impact and economical assessments of the designed PV system it is evident from the listed data that the PV system even at present is a competitive choice for small power requirements. With the expectation that the cost of a solar module will reduce from around $ 3/Wp to below $2/Wp in the near
future (see one of the quarterly report from Solarbuzz.com on Jan 2011), a PV system may as well become an economic and more attractive option for higher loads.

Table 5: Life-cycle costing analysis sheet for a standalone PV system

5. Conclusions

The design, modeling and testing of an active single axis solar tracker were presented. In the proposed design and operation of the solar tracker system, the sun was not constantly tracked based on the simulated irradiation. This helps to prevent unnecessary energy to be consumed by the devices, and the system will be in 'sleep' mode when the night falls. Hence, the proposed control structure provides the flexibility to accommodate different weather conditions, and also different user preference. The completed MATLAB™/Simulink™ model of the solar tracker’s is first used to provide a computer-aided design tool to determine the efficiency over the fixed solar panel, net current output, power generated and the types of PV systems that can be combined to give a required level of efficiency before actual implementation. The experimental results show a similar behavior in the power, the efficiency and the current output over the fixed solar panel when compared them with the simulation results. However, due to the unmodelled external disturbances such as mechanical friction, wind loading and the results averaging performed in each hour; the simulated outputs deviate from the experiment results. Hence, the future works will cover the modeling of the external disturbances, the sensitivity of the model parameters to the output responses and the design of a smart grid solar cells system to achieve a higher efficiency. Lastly, a large-scale integration of the smart grid solar cells system can be considered in Singapore’s public housing estate.

Acknowledgments

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Fixed Resistor (Ω) | $V_{out}$ on sunny day | $V_{out}$ on cloudy day | $\Delta V_{out}$
---|---|---|---
50 | 2.14 | 0.82 | 1.32
100 | 3.95 | 0.90 | 3.05
200 | 4.56 | 1.35 | 3.21
500 | 4.78 | 1.41 | 3.37
1000 | 5.02 | 1.9 | 3.12

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<td>Current at $P_{\text{max}}$</td>
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<td>Open-circuit voltage ($V_{\text{oc}}$)</td>
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<td>Temperature coefficient of short-circuit current</td>
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<td>Nominal Operating Cell Temperature (NOCT)</td>
<td>30 +/- 3 degree Celsius</td>
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Figure 21: Charger model in Simulink
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Figure 25: Experiment Setup for fixed (left) and smart tracker (right) system

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System description: 10 W stand-alone PV supply

Parameters:
Period of analysis = 20 yr; Excess inflation, \( I = 0 \); Discount rate, \( d = 10\% \)

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Table 5: Life-cycle costing analysis sheet for a standalone PV system