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MEDIUM SIZE DUAL-AXIS SOLAR TRACKING SYSTEM WITH SUNLIGHT INTENSITY COMPARISON METHOD AND FUZZY LOGIC IMPLEMENTATION

Azwaan Zakariah[a], Mahdi Faramarzi[a], Jasrul Jamani Jamian[b], Mohd Amri Md Yunus[a*]

[a]Protom-i Research Group, Innovative Engineering Research Alliance, Control and Mechatronic Engineering Department,
[b]Resource Sustainability Research Alliance,
Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia

Graphical abstract

Abstract

Nowadays, renewable energy such as solar power has become important for electricity generation, and solar power systems have been installed in homes. Furthermore, solar tracking systems are being continuously improved by researchers around the world, who focus on achieving the best design and thus maximizing the efficiency of the solar power system. In this project, a fuzzy logic controller has been integrated and implemented in a medium-scale solar tracking system to achieve the best real-time orientation of a solar PV panel toward the sun. This project utilized dual-axis solar tracking with a fuzzy logic intelligent method. The hardware system consists of an Arduino UNO microcontroller as the main controller and Light Dependent Resistor (LDR) sensors for sensing the maximum incident intensity of solar irradiance. Initially, two power window motors (one for the horizontal axis and the other for the vertical axis) coordinate and alternately rotate to scan the position of the sun. Since the sun changes its position all the time, the LDR sensors detect its position at five-minute intervals through the level of incident solar irradiance intensity measured by them. The fuzzy logic controller helps the microcontroller to give the best inference concerning the direction to which the solar PV panel should rotate and the position in which it should stay. In conclusion, the solar tracking system delivers high efficiency of output power with a low power intake while it operates.

Keywords: Dual-axis tracker; solar renewable energy; sunlight intensity comparison method, fuzzy logic

1.0 INTRODUCTION

Nowadays, fossil fuel energy, such as coal energy, natural gas energy, and so on, contributes significantly to the utilization and development of industrial society. Electric power generation using renewable energy sources has begun to take on a dominant role in fulfilling the demand for electric energy. The diminishing fossil fuel resources are expected to be exhausted within the next hundred years [1]. Renewable energy is energy that is generated from natural surroundings and is continuously replenished. Wind, sunlight, water, geothermal heat, and biomass are sources of energy that are constantly renewed.

Among the different types of renewable energy, solar energy is the most effective and efficient for

producing electricity. In countries where a warm climate is dominant, solar energy is examined as one of the predominant energy resources [2].

Moreover, solar technology is also the fastest growing type of renewable energy technology, because the primary source is always costless, accessible, plentiful, non-polluting, safe, and clean. Solar radiation is the quantity of solar energy that falls on a solar PV panel over a period of time, and is called solar irradiation. Solar radiation is made up of a combination of three types of radiation: direct, diffuse, and reflected, as shown in Figure 1. The limitation of solar energy is that when the weather is cloudy and/or wet, solar photovoltaic (PV) panels cannot capture enough solar radiation to produce electricity.

In addition, a problem of solar PV is that it has low efficiency in producing the maximum output power from sunlight. To solve this problem, many research works have been carried out to increase the efficiency of output power by using solar-tracking systems. The solar-tracking system is used to keep the solar PV panels perpendicular to the direction of solar radiation. Solar-tracking systems are also considered as mechatronics systems, which merge elements of mechanics, electronics, and information technology [3]. Increases in the efficiency of energy production of 35% per year have been achieved by solar-tracking systems [4].

Thus, solar energy efficiency can be increased by applying a tracking system or a maximum power point tracking (MPPT) system for solar PV. A combination of both systems will improve the efficiency of the output power.

1.1 Sun Azimuth and Altitude Angle

The sun's position is determined by the azimuth and altitude angles of the solar PV panels. The azimuth is the angle along the horizon, where zero degrees is equivalent to north, and increases in a clockwise fashion, while the altitude angle is the angle measured upwards from the horizon [5]. Figure 2 illustrates the azimuth and altitude angles of the sun.

Hence, the direction of the sun can be calculated from these angles. The azimuth angle, θz, depends on its declination, D, (negative for the Southern Hemisphere), its altitude angle, θ_L, and on the latitude, L, of the observer:
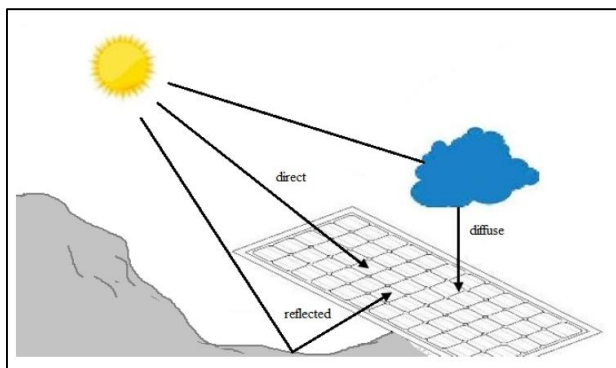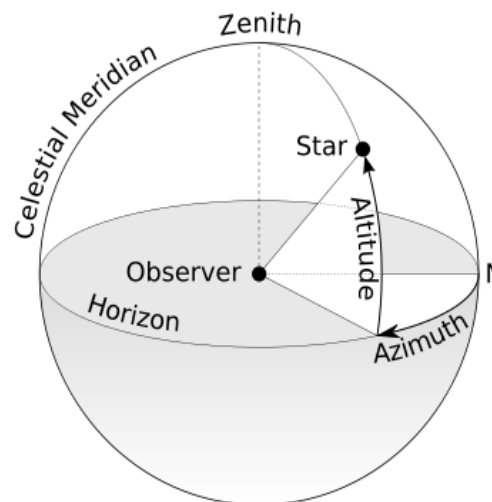

Figure 1 Components of solar radiation

Figure 2 Azimuth and Altitude Angle of the Sun

$$cos\,\theta z = \frac{(\text{Sin}\,D - \text{Sin}\,L\,\text{Cos}\,H * \text{Sin}\,\theta_L)}{cos\,L * cos\,\theta_L} \qquad (1)$$

The altitude angle, θ_L, is calculated based on Equation 2 and depending on the latitude, L (negative for the Southern Hemisphere), declination, D (negative for the Southern Hemisphere), and hour angle, H.

$$\sin\theta_L = [\cos L * \cos D * \cos H] + [\sin L * \sin D] \qquad (2)$$

1.2 Problem Statement

Not all of the countries in the world possess natural oil and gas that can be used to produce electricity. It is estimated that fossil fuel resources will be exhausted after one hundred years or so. Because of this problem, renewable energy was introduced to the world due to its availability and unlimited sources for producing electricity. Basically, solar energy is a renewable energy that is frequently favoured by consumers as a point of supply to produce electrical energy, particularly for small and portable appliances [6].

At present, the efficiency of the generating power of solar energy is comparatively low [7]. However, there is a lack of efficiency and accuracy and also a problem of an increase in the operating energy consumption when the solar system is operated. Thus, the question of how to boost or advance the utilization of solar energy has evolved into a hot issue in domestic and foreign studies [8]. To solve this issue, solar tracking systems have been introduced. Generally, a solar tracker is a device for orienting a solar PV panel toward the sun, by reducing the angle between the lines so that the solar PV panels face perpendicular to the solar radiation. This solar-tracking system tracks the maximum solar irradiance. It changes direction when there is a decrement of solar irradiance intensity.

As compared to the other types of power generation systems, a solar-tracking system is more cost-effective since it does not require a large-scale area and can yield an abundant amount of power [9]. There are two types of solar-tracking systems: fixed and dynamic. The dynamic type is the most preferred and reliable. Dynamic solar trackers include both active and passive trackers, of which the active or electronic trackers have higher efficiency and reliability than passive or mechanical trackers, which depend on the weather.

There are three common methods that can be used to implement a solar-tracking system: time-based control, sunlight intensity comparison, and space-time synchronization. In the first method, an electronic tracker utilizes an electronic sensor or transducer that is able to detect the intensity, such as a light-dependent resistor (LDR) or a photo diode linked to motors for pivoting the position of the solar PV panels.

There are two types of axis tracking of electronic trackers: single-axis and dual-axis tracking. Basically, dual-axis trackers are more accurate for pointing directly at the sun. However, the dual-axis tracker design is more complex and expensive because of the electronic parts of the system such as sensors, microcontroller, drivers, motor, and so on.

A maximum power point tracker (MPPT) is an electronic DC to DC converter that optimizes the match between the solar array (PV panels), and the battery bank or utility grid [10]. In order to further improve the utilization efficiency of solar energy, the MPPT technique for PV systems has been adopted in this project. MPPT is used to control the voltage and current output of the solar PV panel to deliver maximum power. In addition, intelligent control using fuzzy logic is also introduced. The fuzzy logic approach can increase the system performance and simplify application. The fuzzy logic controller is designed "to determine the required position of the solar panel and the direction in which the tracking system should move. The main function of this MPPT enhanced with a fuzzy logic controller is to obtain as much power as possible from the solar PV panel.

Therefore, the main question is how to reduce the operating energy consumption and increase the output power efficiency of the dual-axis solar tracker through improvement of the hardware system. The goal of this project is to design an active and dual-axis solar tracker integrated with a fuzzy logic control system to deliver maximum output power and low power consumption when the solar tracker is operated and also to make the system compact and able to withstand the outdoor conditions.

2.0 INTRODUCTION OF A SOLAR TRACKING SYSTEM

Generally, a solar-tracking system is a mechanism or device that is used for orienting a solar PV panel towards the sun to minimize the incident angle between the sun and the surface of the solar PV panel

throughout the day. It works best when pointed directly at the sun, so the effectiveness of the output power of the solar PV panel can be increased, but it will contribute to the complexity and thus incur additional cost. In practice, this system should track the maximum intensity of solar radiation. When the intensity of solar radiation it receives decreases, this system automatically rotates the solar PV panel to face the sun to acquire the maximum intensity of solar radiation. There are many advantages to this system, but the most important is that it can maximize the efficiency of output power from the solar energy. One downside of this system is the high operating energy consumption when the system is operated, making the system unable to produce more power generated than expected due to high power consumption when system operate. Basically, an efficient solar-tracking system must be able to produce maximum output power and operate with low energy consumption at the same time.

2.1 Types of Solar Tracker Axis

Generally, there are two main types of solar tracker axes: single-axis and dual-axis trackers.

2.1.1 Single Axis Tracker

Figures 3 and 4 show the types of single-axis trackers. Single-axis trackers have a single degree of freedom (DOF) which operates as an axis [11]. The movement and direction of a single-axis tracker system can be around either a horizontal or a vertical axis. The appropriate movement among these systems relies on the technology adopted in the tracker and also the
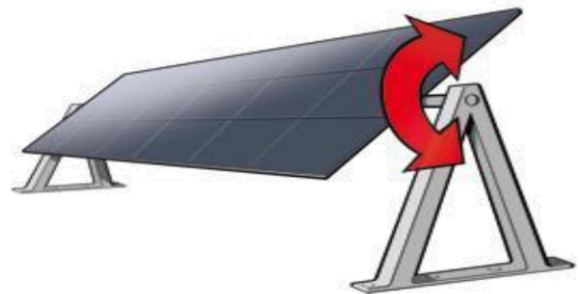

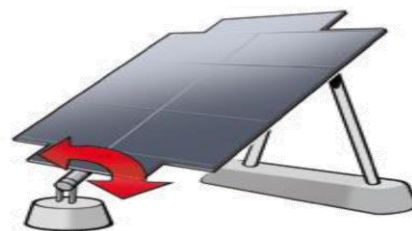**Figure 3** Horizontal Single Axis Solar Tracking System

Figure 4 Vertical Single Axis Solar Tracking System

amount of space in which it is mounted [11]. As the sun is usually located at the highest point in the sky in the tropical region, it is suggested that countries in this region set up the horizontal type of tracker. On the other hand, countries where the sun is usually at the lowest point most of the time, including high latitudes, or where the period of the summer day is long may adopt the vertical type of single-axis tracker [6]. A single-axis tracker only pivots in one plane and rotates either horizontally or vertically. Generally, it is less difficult to control and cheaper than the dual-axis tracker but less effective in collecting the solar irradiance [11].

2.1.1 Dual Axis Tracker

With two DOF, a dual axis or double axis tracker, rotates horizontal and vertical axes [6]. Normally, vertical axis pivots the solar PV panel to rotate from east to west or west to east, while the horizontal axis rotates and move from north to south or south to north depend on the position of the sun. As compared to a single axis tracker, a dual axis tracker naturally gives a better performance, reliability, and accuracy. A micro controller or computer control is used to control the solar PV panel according to the expected the sun position. The sensor that placed on solar PV panel will give the value of current or voltage generated by the solar radiation to control the motors that orient the solar PV panel towards the sun. Instead of using the fixed panels, a dual axis tracker increases the output power around 40% [12, 13]. Figure 5 shows an example of dual axis tracker that have two DOF.

2.2 An Overview of Solar PV Panel

A solar PV panel is also known as a solar module, PV module, or PV panel. A solar PV panel is actually an assembly of PV cells. On communications satellites, the solar PV panels occupy a large amount of the total surface, providing large flat surfaces over which antennas can be mounted or printed. A larger PV system to generate and supply electricity for commercial and residential usage is another application of solar PV panels. Generally, all panels produce DC output power under a controlled testing environment. The output power yielded can be within the minimum range of 0 to 100 W and maximum range of 0 to 320 W. The efficiency of the solar PV panel will determine its total area and thus determine the total output power; for example, a 16%-efficient 230-W panel will have twice the area of a 32%-efficient 230-W panel. A larger amount of power can be harvested if many solar PV panels are used in a single connection (array). A PV system often consists of an array of solar PV panels, an inverter, sometimes a battery and/or solar tracker, and wiring connections.

2.2.1 Type of Solar PV Panel

In general, the types of solar PV panel can be listed as:
  i.   Poly-crystalline (p-Si)

Figure 5 Dual Axis Solar Tracker

  ii.   Mono-crystalline (m-Si)
  iii. Amorphous Silicon (a-Si)
  iv.   Ribbon Silicon
  v.   Chalcogenide films of Cu (CIS)

Technologies (i), (ii), and (iv) are fabricated by wafer-based manufacturing. In other words, in these approaches, self-supporting wafers of approximately 300 μm thick are fabricated and then soldered together to form a module. Thin-film approaches are module based. However, for (iii) and (v), the whole of the panel's module substrate is coated with the desired layers and a laser scribe is then used to delineate individual cells.   Polycrystalline panels produce the highest power output compared to amorphous silicon and monocrystalline panels.

2.3 Fuzzy Logic Controller (FLC)

In solar-tracking systems, intelligent control is desired to pivot the PV panel subsequent to the sensor output [14]. Thus, for solar tracking, an intelligent controller like a proportional integral derivative (PID) controller and a fuzzy logic controller (FLC) can be used. The advantages acquired by using an FLC rather than a PID controller are that a mathematical model of the control system is unnecessary, there is complete reliance upon the operator's experience, it can deal with the nonlinearities of the system, and lastly, linguistic system definitions can be transformed into a control rule base or control algorithm [14]. FLC can be implemented in the microcontroller, microprocessor, and field-programmable gate array (FPGA). Mainly microcontrollers are used because of their flexibility and faster speed of execution.

2.3.1 FLC for Solar Tracking System

Generally, an FLC has three parts: fuzzification, rule base, and defuzzification [14]. Error and changes in the error are the inputs to the FLC, and the output of the FLC is fed to the motor driver. Figure 6 shows that the FLC elements. A sensor fixed on a solar PV panel
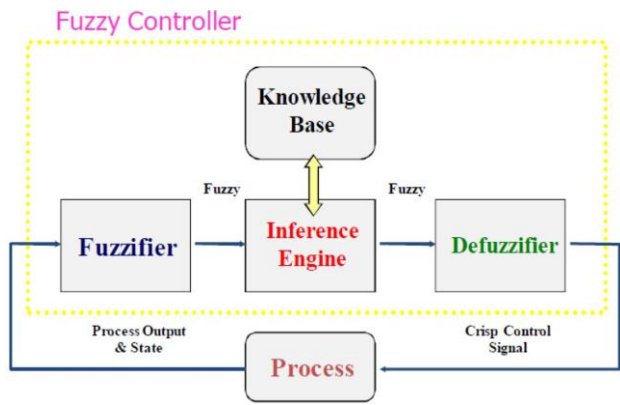
Figure 6 Block Diagram of Fuzzy Logic Controller

assigns the input error and error difference. Then, the output is fed to the motor to control it.

2.3.1.1 Fuzzification

A process that transforms numerical values into a class of membership of fuzzy set members is called fuzzification. Thus, to decide how mutually the condition of each rule suits that specific input case, the fuzzification block must suit the input data with the condition of the rule Membership function values can be set depending on the application [15]. The number of fuzzy subsets increases when there are many possibilities regarding the movement of the sun.

It is believed that for any specific input there is only one principal fuzzy subset adapted from the triangular form of the membership function. The input error (e) for the FLC can be calculated from the maximum power point as follows:

$$E(k) = \frac{\Delta I}{\Delta V} + \frac{I}{V} = \frac{\Delta P}{\Delta V} = \frac{\Delta P}{\Delta I} \qquad (3)$$

where I is the output current from a PV panel, ΔI is the change of output current, $I(k)$-$I(k-1)$, V is the output voltage of PV panel, ΔV is a change of output voltage, $V(k)$-$V(k-1)$.

2.3.1.2 Control Rule Base

The control rule base depends on the operator's experience. Authorize relationship, both input and output changeable based on membership function is developed to count on that experience knowledge base. The structure of the control rule base is based on IF-THEN rules, where NB stands for negative big, NM stands for negative medium, NS stands for negative small, ZE stands for zero, PS stands for positive small, PM stands for positive medium, and PB stand for positive big.

2.3.1.3 Defuzzification

The reverse of fuzzification is defuzzification. The transformation of fuzzified output into the normal crisp output is called defuzzification [14]. Defuzzification is a simple and fast method and can be calculated as shown in Equation 4.

$$du = \left(\frac{\sum_{k=1}^{m} c(k) * w_k}{\sum_{k=1}^{n} w_k} \right) \qquad (4)$$

where du is the change of control output, $c(k)$ is the peak value of each output and w_k is the weight of rule k.

3.0 OVERALL SYSTEM DESIGN

The solar-tracking system with an intelligent method consists of an Arduino UNO microcontroller board, four LDR sensors, two power window motors, a motor driver board, and an MPPT charger module. An FLC is applied in the system through Arduino programming. The overall system is illustrated in Figure 7. The aim of this circuit design is to minimize the power
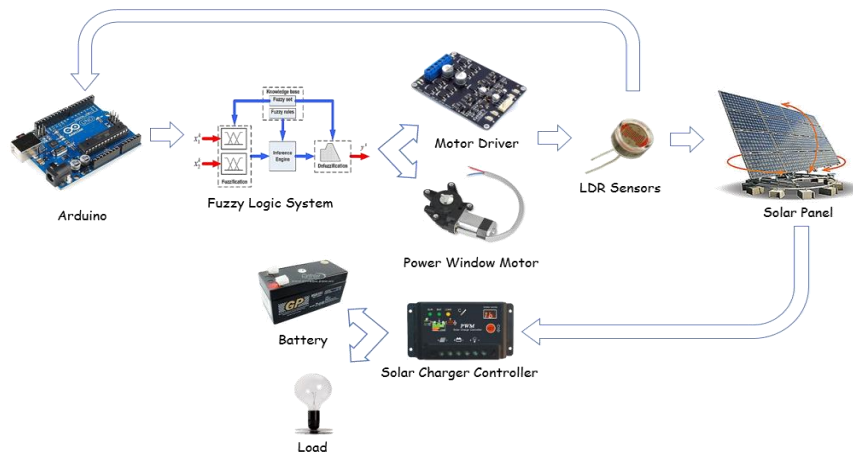

Figure 7 A Diagram of the Overall System

consumption and maximize the solar energy generation.

The Arduino UNO microcontroller board which controls the overall performance of the systems also controls all the subsystems and feedback operation. The MPPT charger adjusts the current and voltage outputs of the solar PV panel, and then the FLC supplies the leading inference and decision to an Arduino UNO board concerning the position to which the solar PV panel should rotate and the direction of rotation.

Four LDRs sensors are placed on the solar PV panel, one on each side. These sensors are used for sensing the positional change of the sun, thus tracking the movement of the sun. The outputs of the LDR sensors are inputted into the Arduino and subsequently used as the input variable for the FLC. Then the FLC makes decisions based on its approximate reasoning and sends the outputs to the motor drivers. Two power window motors pivot the solar PV panel horizontally and vertically to the position in which the panel is perpendicular to the sun and the intensity of solar irradiance is maximized. The sensors continuously monitor the solar radiation and these data are transferred to the power window motor via the Arduino UNO microcontroller.

3.1 System Block Diagram

In most cases, the solar-tracking systems that have been developed by researchers are closed-loop systems and employ many kinds of tracking techniques to track the sun's position. Most previous researches combined the system with a microcontroller or programmable logic controller with sensors, a real-time clock (RTC), or a combination of an RTC with sensors. Nevertheless, only a simple system will be applied to this project in order to make sure the system is ready to harvest the maximum output power and reduce the operating energy consumption. The angles and fuzzy logic control will be implemented to reduce the time taken by the system to make the decision to rotate the solar PV panel.

In this circuit and model, two power window motors are operated separately at any time. Since the sun changes its position, after every five minutes the sensor detects the position of the sun. If the sun moves from east to west, the second power window motor, which is responsible for vertical movement of the solar tracker, will stop working. The second power window motor will start running only after the sun moves to a northward or southward position. Thus, this system will result in low power consumption. The vertical and horizontal movements of the solar PV panel on the azimuth and altitude angles are taken as a reference. The exact position of the sun is estimated from these two angles.

3.2 Controller Circuit Design

Basically, the circuit design comprises the solar controller (DC to DC converter), MPPT charger

module, tracker controller, and inverter (DC to AC inverter), but this project focuses only on the tracker controller circuit design. The solar controller, MPPT charge controller, and inverter were used for the current generator. In this project, an Arduino UNO microcontroller is integrated with LDR sensors, motor driver board, power window motors, and MPPT charger.

3.2.1 Solar PV Panel

This project utilizes a mono-crystalline (m-Si) solar PV panel, as shown in Figure 8, which was chosen because of its good longevity, efficiency, lower installation cost, embodied energy, the fact that monocrystalline solar PV panels are not hazardous to the environment, greater heat resistance, and higher electricity generation. This 10-W solar panel is a combination of a solar cell which generates a maximum of 10 W of electricity when exposed to sunlight. It outputs from 2 to 20 V depending on the sunlight intensity and comes ready with two cables terminated with crocodile clips (black and red). With a medium size (78 mm × 26 mm) and light weight (1.2 kg), it is suitable for a variety of applications.

3.2.2 Motor Driver Module

Figure 9 shows the MD30C motor driver used in the project. A motor driver was used to drive the motor in this project. By controlling the pulse width modulation

Figure 8 10W Polycrystalline (m-Si) solar PV panel

Figure 9 MD30C DC Motor Driver

(PWM) duty cycle, the motor speed can be controlled. The motor driver model is MD30C. It is designed to drive a medium- to high-power brushed DC motor. Its current capacity is up to 80 A peak for 1 second and 30 A continuously. It has reverse polarity protection. Its PWM generator enables it to operate without a host controller. This motor driver has bidirectional control of one brushed DC motor and the voltage of the motor is 5 to 25 V. Its logic level input is 3.3 and 5 V. It has better efficiency due to its full NMOS H-bridge, and no heat sink is needed. The PWM frequency of speed control can go up to 20 kHz. It can support both locked-antiphase and sign-magnitude of external PWM operation.

3.2.3 Power Window Motor

The power window motor was chosen in this project because of its high torque, availability, and cheap price. The power window motor functions or is used like a brushless DC motor. It can rotate clockwise (CW) or counter clockwise (CCW) by using the motor driver. The specifications of the power window motor are as follows: the rated voltage is 12 VDC, the no-load speed is 85 rpm, the no-load current is less than 3 A, the load current is not more than 7 A, the lock current is less than 20 A, and the torque is 30 kg.cm. Figure 10 shows the waterproof power window motor.

In general, a DC motor has two wires which are known as the positive and negative terminals to distinguish between them. The motor rotates clockwise when the positive wire of the motor is connected to the positive terminal of the power supply while the negative wire is connected to the negative terminal of the power supply. The motor rotates anticlockwise if the wire polarity is reversed.

The DC motor consists of two main parts: a stator and a rotor (armature). The armature rotates due to the electromagnetic interaction between the stator and the rotor. The rotation speed is proportional to the voltage applied to the armature. The speed of the motor can be controlled by regulating the amount of voltage across the motor terminals. One popular way to achieve voltage regulation is by PWM.

The idea behind PWM speed control is to drive the DC motor using a series of ON and OFF pulses of voltage level and varying the duty cycle while keeping the frequency constant. When the duty cycle is small the average voltage is low, and therefore the motor speed is small. When the duty cycle is big the average voltage is high, and therefore the motor speed is high.

### 3.2.4 Light Dependent Resistor

Next, four LDR sensors are fixed on top of the solar PV panel. It is connected to the Arduino UNO analogue pins. The sensors are placed on the north, south, east and west sides of the solar PV panel. Figure 11 shows the type of LDR sensor and the voltage divider circuit where the sensor is connected in series with a variable resistor. This sensor detects the intensity of the sunlight


Figure 10 Power Window Motor

and compares the intensity analogue value with a 10-kΩ variable resistor which acts as a proportional controller. The configuration of the LDR sensors is located on the voltage divider circuit, where the sensor is fixed in series with a resistor.

The difference in voltage appears at their junction for different levels of light, where the LDR changes its resistive value depends on the light intensity, and the output voltage, Vout, is determined by the voltage divider formula. The resistance of the LDR can vary
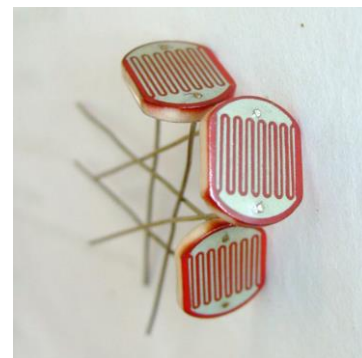
(a)
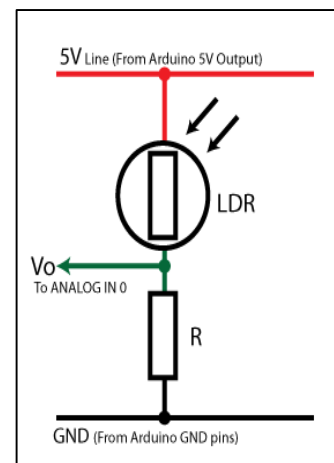
(b)

Figure 11 (a) LDR Sensor (b) LDR Sensor Voltage Divider Circuit

from about 100 Ω in the sunlight to over 100 M Ω in absolute darkness. Based on the LDR configuration in Figure 11, when the incident sunlight intensity increases, V_{out} also rises to a bigger value. The output voltage of the LDR is calculated according to the voltage divider equation:

$$V_{out} = V_{in} \times R_2 \big/ \big(R_{LDR} + R_2 \big) \qquad (5)$$

The feedback input from the LDR sensor is calculated according to the equation:

$$\text{Illumination}, (Lux) = \left(\frac{2500}{V_{out}} - 500 \right) \bigg/ 3.3 \qquad (6)$$

3.2.5 Micro Limit Switch

A micro-switch is an electrical switch which can be operated using a very small force and also possibly using a small movement. "Micro-switch" is a general term and not all micro-switches use the same principle, but most of them use a stiff metal strip supported by a spring which suddenly flips when a certain force is applied on the switch button. It flips back with a high speed too when the force decreases under a certain limit. The switches use hysteresis, so the activation force is higher than the deactivation force. Also the quick movement of the metal strip produces the typical clicking sound.

The function of the micro-switch in this project is to limit the rotation of the power window motor on each axis. The micro-switch can give a signal of 0 or 1 to the Arduino, which can be used as a condition in programming.

3.3 Hardware Development

The development of the hardware and mechanism is quite important in order to make the solar-tracking system robust against the weather's elements. Firstly, for the mechanism of this project, the size of the solar-tracker mechanism was considered; it should be portable and easy to relocate to other locations.

The tower consists of three main subparts: the base, the vertical axis motor connecter and the shaft holder, and the rotating shaft mounted with the horizontal motor and the solar PV panel on the top, as shown in Figure 12.

The placement of the LDRs sensors on the solar PV panel is shown in Figure 13. Each LDR sensor was confined inside a rectangular pipe to help the collimation of direct solar irradiance and to reduce the effect of reflected and diffuse solar irradiances. The S1 (west side) and S2 (east side) LDR sensors were placed on the sides of the solar PV panel to control the vertical rotation, and the S3 (north side) and S4 (south side) LDR sensors were placed on the solar PV panel to control the horizontal rotation. Each LDR sensor was placed exactly at the midpoint of each

side. Furthermore, three limit switches were placed below the solar PV panel. The function of the limit switches was to limit the horizontal rotation of the solar PV panel.

An Arduino UNO R3 micro-controller, motor driver, four LDR sensors, power window motor, and the solar tracker mechanism were implemented on the solar tracker. The Arduino UNO is used as the microcontroller unit in this project. The Arduino UNO is a microcontroller that is based on the ATmega328. The Arduino UNO is a perfect microcontroller for this project because it performs the task efficiently in term of speed, power consumption, number of inputs/outputs, and so on. For the input system, four LDR sensors were selected because of their capability to detect the intensity of sunlight accurately. The motor driver and power window motor were used to control the direction and position of the solar tracker. The power window motor has low power consumption, a higher torque to rotate the solar PV panel, and a low price. Figure 14 shows the whole solar-tracker tower.

3.4 Implementation of Fuzzy Logic Controller

Generally, there is a design procedure for designing an FLC. There are five principal components that must

Figure 12 Mechanisms of Solar Tracker

Figure 13 LDR Sensor Position on Solar PV Panel

Figure 14 Different Angle View of the Solar Tracker Tower

be considered in order to design and implement an FLC in an executable program. The five principal components can be listed as:

   i.   Inputs and Output(s)
   ii.   Fuzzification
   iii.   Knowledge Base
   iv.   Inference Engine
   v.   Defuzzification

3.4.1 Inputs and Outputs

To execute the fuzzy logic controller in a program, first step is to identify the input and output variables for the FLC. In this project, there are two sets of inputs and outputs, where each output is controlled by one input. Each input comes from the difference output value between two LDR sensors to control one output, which is the motor rotations. Hence, each input will control one output, either vertical or horizontal rotation.

3.4.2 Fuzzification

Basically, fuzzification involves the conversion of the input or output signals into a number of fuzzy values or fuzzy sets. This project used two inputs of membership functions and two outputs of membership function to represent each fuzzy set. On the other hand, each membership functions that represents the degree of difference of the first LDR sensor from the other LDR sensor has seven fuzzy sets and needs to be quantized, as shown in Table 1. For example, when S2 detects higher intensity than S1, then the fuzzy set is determined as negative big (NB).

Table 1 Quantization of Fuzzy Set

Linguistic Term	Label
Negative Big	NB
Negative Medium	NM
Negative Small	NS
Zero	ZE
Positive Small	PS
Positive Medium	PM
Positive Big	PB

Then, all the fuzzification components are translated into C++ codes. Figure 15 shows the fuzzification codes for the fuzzy component of NB.

3.4.3 Knowledge Base

The knowledge base of a fuzzy logic controller consists of a database and a rule base. The fuzzy control rules in this project are based on a fuzzy model of the process, which means that the IF-THEN fuzzy control rules were generated in order to track the maximum intensity of sunlight. This method is somewhat more complicated than other approaches, but it yields better performance and reliability for dealing with nonlinearities of the sun's movement. Figure 16 shows a part of the fuzzy control rules' C++ codes for the vertical rotation. Below are some examples from 15 rules for the tracking system:

IF *input for vertical rotation is PB,* **THEN** *time duration of vertical motor is PB*

*IF input for vertical rotation is ZE, **THEN** time duration of vertical motor is ZE*

.
.
.

*IF input for horizontal rotation is NM, **THEN** time duration of vertical motor is NM*

3.4.4 Inference Engine

From the rule base, the fuzzy values determine which rules are to be fired through an inferencing algorithm in programming as shown in Figure 17. For this work, the max-min inferencing method was selected because it is easier to write the codes for the algorithm. The aggregation operation max results in an aggregated membership function comprised of the outer envelope of the individual truncated membership forms from each rule. Then, a crisp value can be obtained from this aggregation process through the defuzzification technique, as discussed in the next section.

3.4.4 Defuzzification

Generally, this technique converts the fuzzy value into a crisp value that is required to actuate the motor to rotate the solar PV panel. There are many methods of defuzzification; in this project the centre of gravity method, also known as the centroid method, is used because it is the most prevalent and physically appealing of all the defuzzification methods. Figure 18 shows an excerpt of the C++ code of the defuzzification technique for the vertical rotation. The equation of the centroid method can be calculated according to the equation:

$$x* = \frac{\sum_{ux}(x).x}{\sum_{ux}(x)} \qquad (7)$$

where $x*$ is the defuzzified output, $u_x(x)$ is the aggregated membership function and x is the output variable.

3.5 Experiment Setup

One of the objectives to be achieved in this project was to increase the efficiency and reduce operating power of the solar tracker. Thus, several experiments were set up to fulfill the objectives of the project. Firstly, all the connections must be connected to the terminal of the controller box as shown in Figure 19. The LED indicators on the solar controller turn on if the connections to the terminal are wired correctly.

Then, tracking and non-tracking experiments were conducted successively at intervals of one hour between 8.00 am and 6.00 pm; in total, almost 10 hours of operation of harvesting solar energy were observed. To calculate the input power from the solar energy, a 0.1-Ω resistor is connected in series with the

```
float fuzzification(int x, int i) {
  float mu = 0;

  switch (i) {
    case 0:
      mu = trapizoidal(x, -1000, -1000, -300, -200);
      return mu;
      break;
    case 1:
      mu = triangular(x, -300, -200, -100);
      return mu;
      break;
```

Figure 15 C++ codes to execute the Fuzzification

```
if (X_out2 == 1 && switch1 == HIGH && switch2 == HIGH )
{
  digitalWrite(M1_dir, HIGH);
  digitalWrite(M1_pwm, m_speed_x);
  delay(X_out1);
  digitalWrite(M1_pwm, 0);
}

else if (X_out2 == 0 && switch1 == HIGH && switch2 == HIGH)
{
  digitalWrite(M1_dir, LOW);
  digitalWrite(M1_pwm, m_speed_x);
}
```

Figure 16 C++ codes for the Fuzzy Rules for the Vertical Rotation

```
float Rule_evaluation_1(float mu[])
{
  int i = 0;
  float Out = 0;
  float MF = 0 ;

  for (i == 0; i < 7; i++)
  {
    if (MF < mu[i])
    {
      MF = mu[i];
```

Figure 17 C++ codes for the Rule Evaluation of the Vertical Rotation

```
float Defuzzification_1(int rr_2)
{
  int time_of_rotation[4];
  int Out = 0;
  time_of_rotation[0] = 15; // for NB and PB
  time_of_rotation[1] = 15; // for NM and PM
  time_of_rotation[2] = 15; // for NS and PS
  time_of_rotation[3] = 0; // for zero
```

Figure 18 C++ codes for the Defuzzification for the Vertical Rotation

battery to calculate the current flows by using Ohm's Law, and the input power can be calculated according to the equation:

$$I_R = \frac{V_R}{R} \qquad (8)$$

$$Power, P(W) = I_R V_{Load} \qquad (9)$$

where I_R is the input current from the solar PV panel, V_R is the voltage drop across the 0.1 Ω resistor and P is the input power in Watts collected from the solar PV panel.

Figure 19 Controller Box Connection, Batteries, and Inverter

4.0 RESULT AND DISCUSSION

In this section, some important findings of the experimental works are provided. The input power collected from a stationary panel (non-tracking mode) and also from a solar tracking system with the intelligent method was analysed. Then, the results of the two systems were compared to identify whether or not the efficiency of collection of solar energy increased when the solar tracking system with the intelligent method was used.

The data of the project were collected by using an oscilloscope. Figures 20 and 21 show the graphs of the relationship between the inputs and outputs of the horizontal and vertical axes, respectively. LDR sensors were used as the input and power window motors were used as output. In Figure 20, the purple colour line represents the output value of the LDR on the north side of the solar PV panel S3 and the green colour line represents the output value of LDR on the south side of the solar PV panel S4. If the output value of the LDR on the north side is larger than the LDR value on the south side, the motor rotates clockwise (CW) when the motor receives a train of positive PWM pulses (yellow colour line). The PWM duty cycle increases when the intensity difference increases.

On the other hand, if the output value of the LDR on the south side is larger than the output value of LDR on the west side, the motor rotates counter-clockwise (CCW) when the motor receives a train of negative PWM pulses (light blue colour line). The duration of motor rotation depends on the difference in intensity between the two LDR sensors. If the difference between the LDR sensors is smaller, the motor rotates for a short period of time. Inversely, when the difference is larger, the motor rotates for a long period

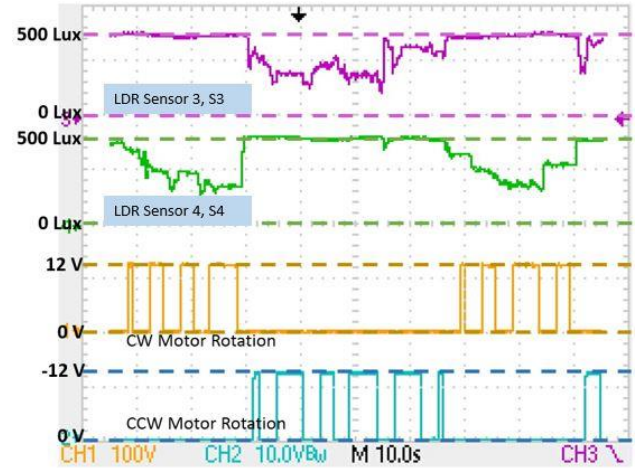of time. This concept is also the same and relevant for

Figure 20 Relationship between Input and Output on Horizontal Axis
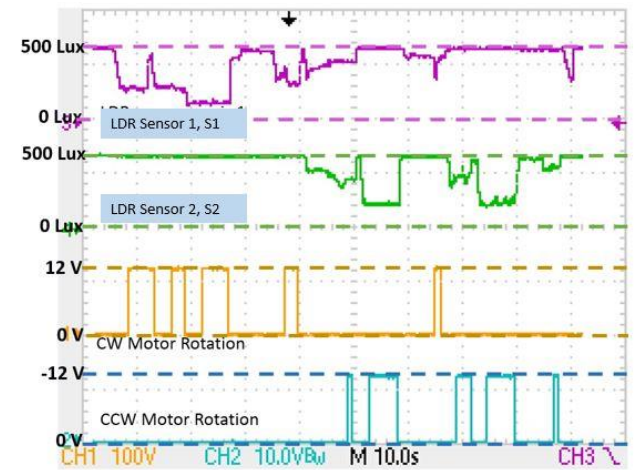

Figure 21 Relationship between Input and Output on Vertical Axis

the vertical axis.

The next experiments were carried out by comparing the input power collected from solar energy using the tracking and non-tracking systems for seven days between 8.00 am and 6.00 pm. All the data were recorded and are tabulated in Figure 22. The main parameters for this experiment to calculate the input power were the voltage across the battery terminal and the current flow through the battery terminal. From the data collected, the input power from the solar PV panel with the tracking mode is almost always more than the input power with the non-tracking mode. For one week, the input power from the tracking mode gradually increased from 7.5 to 9 W between 8.00 am and 5.00 pm. The input power decreased dramatically after 5 pm. The input power harvested from the non-tracking mode showed a less significant peak at around 12.00 pm.

Figure 23 shows the graph of input power in watt-hours collected by the non-tracking mode and by the solar tracking system with the intelligent method (tracking mode) during a one-week operation period.
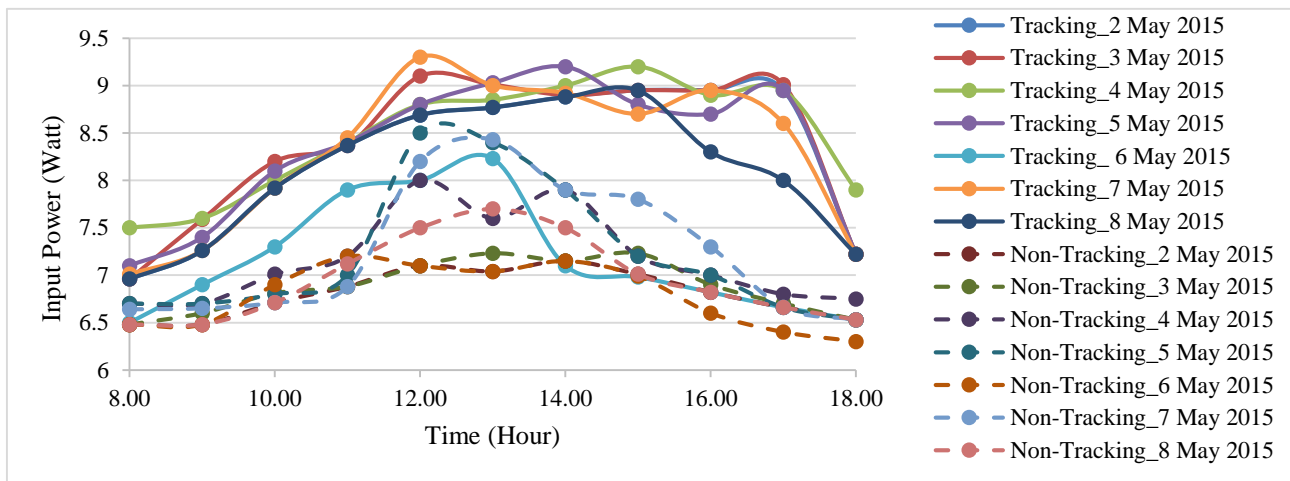
Figure 22 Input Power Collected in Seven Days between 8.00 a.m. and 6.00 p.m.

The expected maximum input power in watt-hours is 100 Wh. The graph shows that the efficiency of the solar tracking system with the intelligent method increased compared to the stationary panel (non-tracking) between day one and day seven. The input power collected in one week is not constant, but always varies depending on the weather. On 4 May 2015, the input power collected showed almost 90% efficiency because the weather on that day was quite sunny and hot, and as a result the highest input was collected compared to the other days. On 6 May 2015, the graph demonstrates that the total input power collected showed around 75% efficiency, which was somewhat lower than on other days. The reason is that on that day the weather was cloudy in the morning and rainy in the afternoon, and only in the evening was the system able to track the maximum intensity of sunlight.

The efficiency for the tracking and non-tracking modes can be calculated by using the following equation:

Figure 23 Total Input Power in Watt-hour Collected on Different Days

$$\eta = \frac{P_t(total)}{P_t(expected)} \times 100\% \qquad (10)$$

where $P_t(total)$ is the sum of the total input power collected and $P_t(expected)$ is the expected sum of the total input power which is equal to 100 Wh.

Hence, the percentage of efficiency improvement as compared to the non-tracking mode is:

$$\text{Improvement, \%} = \frac{\eta' - \eta''}{\eta'} \times 100\%$$

$$= \frac{85.54 - 70.03}{85.54} \times 100 = 18.13\%$$

where η' is the efficiency of the tracking mode and η'' is the efficiency of the non-tracking mode. Therefore, it is seen that a solar tracking system with intelligent method is not only able to collect more sunlight, but can increase the efficiency of harvesting of the solar energy by 18.13 %.

5.0 CONCLUSION

A solar-tracking system with an intelligent method aims to track the maximum intensity of solar irradiance. Solar energy has become one of the most effective types of alternative energy because of its availability and cost effectiveness. One of the challenges of solar energy technology is to increase the maximum output power by collecting as much direct solar irradiance as possible. Therefore, this system demonstrates a good platform for contributing to the solution to the problem.

This system utilizes a fuzzy logic controller to give the best inference regarding the position to which the solar PV panel should rotate and the direction of
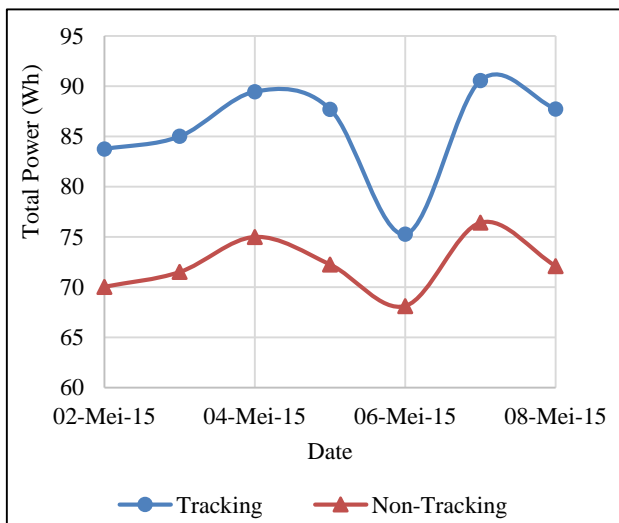
rotation. Implementing this fuzzy logic ensures that the maximum power point is easily found. In order to detect the solar irradiance, an LDR sensor was used to sense the positional change of the sun. This sensor continuously monitors the solar radiation and these data are transferred to the power window motor via the Arduino UNO microcontroller.

The power window motors pivot the solar PV panel horizontally and vertically to the position in which the panel is perpendicular to the sun, where the intensity of solar irradiance is maximized. Initially, two power window motors start running in turn. Since the sun changes position, the LDR sensors measure the sunlight intensity every five minutes and the system locates the position of the sun based on the sunlight intensity measured by the LDR sensors. If the sun moves from east to west, the first power window motor, which is responsible for horizontal movement of the solar tracker, will be working. On the other hand, when the sun moves to the north or south, the second power window motor will be working.

Lastly, it is clearly seen that this system is able to provide a small improvement of output power efficiency of 18.13% as compared to the stationary panel system.

Acknowledgement

References

[1] Stamatescu, I., G. Stamatescu, N. Arghira, I. Fagarasan, *et al*. 2014. Fuzzy Decision Support System for Solar Tracking Optimization. *2014 IEEE International Conference on Development and Application Systems (DAS)*. Suceava, Romania. IEEE. 16-20.

[2] Ahmad, S., Shafie, S., Kadir, M. Z. A. A. 2012. A High Power Generation, Low Power Consumption Solar Tracker. *2012 IEEE International Conference on Power and Energy (PECon)*. Kota Kinabalu, Sabah. IEEE. 366-371.

[3] Alexandru, C. 2009. The Design and Optimization of a Photovoltaic Tracking Mechanism. *2009 International Conference on Power Engineering, Energy and Electrical Drives*. Lisbon, Portugal. IEEE. 436-441.

[4] Usta, M. A., Akyazi, O., Altas, I. H. 2011. Design and Performance of Solar Tracking System with Fuzzy Logic Controller Used Different Membership Functions. *2011 7th International Conference on Electrical and Electronics Engineering (ELECO)*. Bursa, Turkey. IEEE. 381-385.

[5] Zhang, X., Li, X. and Lu, K. 2012. Research on an Intelligent Solar Tracking System Based On LPC2131. *2012 3rd IEEE International Conference on Network Infrastructure and Digital Content (IC-NIDC)*. Beijing, China. IEEE. 429-432.

[6] Ahmad Amsyar bin Azman. 2014. A Solar Tracking System With Multiple Parameter Input For Maximize Efficiency. B. Degree Thesis. Universiti Teknologi Malaysia.

[7] Bader, S. and Oelmann, B. 2010. Enabling BatteryLess Wireless Sensor Operation Using Solar Energy Harvesting at Locations with Limited Solar Radiation. *2010 Fourth International Conference on Sensor Technologies and Applications*. Venice, Italy. IEEE. 602-608.

[8] Huang, Y. J., Wu, B. C., Chen, C. Y., Chang, C. H., and Kuo, T. C. 2009. Solar Tracking Fuzzy Control System Design Using FPGA. *In Proceedings of the World Congress on Engineering (WCE '09)*, vol. 1, London, UK, July. 1-5.

[9] Sefa, I., Demirtas, M., & Çolak, İ. 2009. Application of one-Axis Sun Tracking System. *Energy Conversion and Management*. 50(11): 2709-2718.

[10] Chin, C. S., Neelakantan, P., Yoong, H. P., & Teo, K. T. K. 2011. Optimisation of Fuzzy Based Maximum Power Point Tracking In PV System For Rapidly Changing Solar Irradiance. *Transaction on Solar Energy and Planning*. 2: 130-137.

[11] Shrivastava, S. M. 2013. *Dual Axis Solar Tracker*. B. Degree Thesis. Gautam Budh Technical University;

[12] Clifford, M. J. and Eastwood, D. 2004. Design of a Novel Passive Solar Tracker. *Solar Energy*. 77(33): 269-280.

[13] Beltran, J. A., Gonzalez Rubio, J. L. S., and Garcia-Beltran, C. D. Design, Manufacturing and Performance Test of a Solar Tracker Made by an Embedded Control. *2007 IEEE Electronics, Robotics and Automotive Mechanics Conference*. Morelos, Mexico. Sept. 2007:IEEE. 2007. 129-134.

[14] Hon, S. P., Kolte, M. T. and A, R. S. 2013. FPGA Based Sun Tracking System Using Fuzzy Logic. *International Journal of Scientific and Technology Research*. 2(9): 217-220.

[15] Patcharaprakiti, N., Premrudeepreechacharn, S., and Sriuthaisiriwong, Y. 2005. Maximum Power Point Tracking Using Adaptive Fuzzy Logic Control for Grid-Connected Photovoltaic System. *Renewable Energy*. 30(11): 1771-1788.