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Microcontroller-based sun tracking system for PV module

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Abstract

This paper presents the proposed experimental implementation of a single-axis sun tracking system for photovoltaic (PV) module. The sun tracking system is implemented experimentally by using advanced virtual RISC (AVR) ATmega microcontroller and an H-bridge. The control system of the implemented system is designed based on utilizing the optical tracking technique, which is chosen, in this work, due to its simplicity and independence on the geographical location. Experimental results indicate that the use of the implemented system gives good results for the proposed sun tracking technique.

Keywords: Single-axis sun tracking, PV module, H-bridge, on-off control, experimental system

1. Introduction

Renewable energy resources have enormous potential and can satisfy the present world energy demand. They can enhance diversity in energy supply markets, secure long-term sustainable energy supply, and reduce local and global atmospheric emissions. One of the important renewable energy is the solar energy which can be captured anywhere and can be directly converted into electric power through photovoltaic (PV) panels which allow the production of electricity using solar cells that convert solar irradiation into useable electricity and, as a result, have become one of the most reliable sources of low pollutant energy. Besides, PV energy production represents an environmentally advantageous and sustainable method of maintaining an energy intensive standard of living [1]. Covering 0.16% of the land on earth with 10% efficient solar conversion systems would provide 20 TW of power, nearly twice the world's consumption rate of fossil energy [2].

The most important factor in the performance of a flat plate solar panel is the amount of solar radiation that reaches it [3, 4]. Higher efficiency of such system can be achieved when the sunlight is perpendicular to the surface of the PV solar panel, consequently maximum possible electrical energy can be produced [5].

Solar irradiance on a panel varies with geographic location, time, and the orientation of the panel relative to both the sun and the sky. For a given geographic location, the amount of radiation incident on a surface can be increased by utilizing a sun tracking system that mechanically changes the orientation of the panel so that it more closely points towards the position of the sun as it moves across the sky [3].

Sun tracking techniques can be used to optimize the efficiency of PV systems. Physical sun tracking involves aligning the PV panels to be perpendicular to the sun’s rays throughout the day in order to receive maximum solar radiation. This tracking can be done manually or automatically [6].

In manual tracking, the PV panel orientation is changed manually at the beginning of each season to a predetermined angle. In the case of automatic tracking, the PV panel is mounted on a tracking mechanism, which is controlled to follow the trajectory of the sun throughout the day. The tracking control techniques

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of these mechanisms can be classified, in literature, according to the drive method into two types namely, passive method and active method [7, 8, 9].

Passive sun tracking is based on the heating properties of gas matters such as Freon [6, 7, 10]. The tracker, in this case, is composed of two cylindrical tubes fitted on the edges of the tracking surface; these tubes are filled with a fluid under partial pressure. Sun heating will increase the gas pressure of the sun side cylinder causing an unbalance in the tracker. As a result, the tracker will tilt towards the sun. This type of system is cheap and simple (i.e., it does not use any gear or motor) and consumes no power for rotation. But, it has lower efficiency due to the non-precise orientation compared to other tracking methods, especially at low temperatures. Moreover, it has not yet been widely accepted by consumers [6].

In active sun trackers, gears and motors are used to drive the PV holding structure. The control circuit, in these trackers, sends a command signal to the driving motor to rotate in the direction that makes the PV panel tracking the sun. Since the motors consume energy, in this case, they could be utilized only once required [10].

The first method of active sun tracking is the optical or electro-optic trackers. This method uses feedback sensors such as photo-sensors, current or voltage sensors or auxiliary cells to determine the panel reference position [6, 7]. A closed loop position control system based on PID or FLC is next used to produce the actuators control commands. The drawback for such a system is that it is a very sensitive to atmospheric conditions (clouds shading). Although, this method is not able to continue tracking the position of the sun in a cloudy day, it can collect the most available solar radiation that is incident throughout that day. Also, it can be implemented easily in practical work.

The second method of active sun tracking is the astronomical method, which employs the longitude and latitude data of a given location to determine the current position of the sun. The main advantages of this method are that it can be simulated easily, involves simpler programming, reduced implementation cost, and lower power consumption as the need for additional sensors is eliminated. This method also provides a high degree of accuracy and is not sensitive to atmospheric conditions. But, the main drawback of this method is that it depends on the information of the site [6, 7].

In addition, in literature also, sun tracking mechanisms can be classified based on the rotation axis to single-axis and dual-axis. The general features that characterize an efficient tracking mechanism are its ability to cover a wide range of space, its robustness against wind disturbances, and its low power consumption [7, 8, 9]. Single-axis trackers have one degree of freedom as an axis of rotation. Three orientations of single-axis solar trackers are common: horizontal, vertical, and tilted [11]. Also, the dual-axis trackers have two degrees of freedom that act as axes of rotation. These axes are typically normal to each other. The primary axis is the one that is fixed with respect to the ground. The secondary axis is the one referenced to the primary axis. There are various common implementations of dual trackers. Their classification is based on orientation of their primary axes with respect to the ground [11, 12].

In this paper, the experimental implementation of a single-axis sun tracking system for PV module is carried out. The proposed sun tracking system is implemented, in this case, by designing the appropriate H-bridge, which is controlled by using an inexpensive advanced virtual RISC (AVR) ATmega16 microcontroller.

The rest of the paper is organized as follows. Section 2 clarifies the proposed sun tracking system. Section 3 presents the experimental implementation of the proposed single-axis sun tracking system. Section 4 is dedicated for the required software development. Section 5 illustrates the obtained experimental results of this work. Finally, the concluding remarks are presented in Section 6.

2. The Proposed Sun Tracking System

The block diagram of the proposed sun tracking system that is required to be implemented and utilized for tracking the sun is shown in Fig. 1(a). This block diagram includes four main components: the PV tracker structure, the DC motor and gear box unit, the H-bridge, and the sun tracker controller, which is implemented, in this work, by using a microcontroller. Also, a more detailed diagram of the implemented system is illustrated in Fig. 1(b), which is composed of the following detailed components:

- The tracker structure that holds the PV module
- The DC motor and gear box that rotates the solar tracker
- The high power H-bridge that can supply the DC motor with the suitable voltage polarity; to rotate it in a certain direction or to reverse its rotation.
- The dead time generator and the driving circuits that is necessary to drive the four power MOSFETs of the H-bridge and at the same time protects each of two MOSFETs on the same arm of the H-bridge from being short-circuited i.e., to be not conducted at the same time.
- The microcontroller that is responsible for controlling the overall tracking system, by receiving the measured sensors' signals, processing them, and finally outputting two digital control signals that are responsible for rotating the solar-tracker motor in the direction that tracks the sun.

The proposed solar tracking system is designed, in this work, to rotate the used PV module to track the sun in the East-West direction only (i.e., single-axis tracking). Noting that the used PV module has a fixed tilt angle to the horizontal that equals the site latitude angle ϕ of the considered site. LDR1 and LDR2 are two light dependant resistors or sensors for light intensity detecting. If one of the two LDRs gets more light intensity than the other, an error signal will occur in node voltages that are sent to the appropriate ADC channels of the microcontroller. The microcontroller then calculates this error signal and compensates for it by rotating the tracker motor in one direction, otherwise the microcontroller will reverse the direction of the rotation till the generated error signal is vanished. At this instant, the light intensities on both LDRs will be equal. If the two LDRs are illuminated equally by the sun, the error signal calculated by the microcontroller will equal to zero and consequently the microcontroller will not generate any logic signal to rotate the motor. Therefore, the main purpose of the proposed sun tracking system is to use the microcontroller to control the H-bridge that can rotate the motor of the sun tracker in a certain direction or to reverse its rotation according to the position of the sun in the sky.

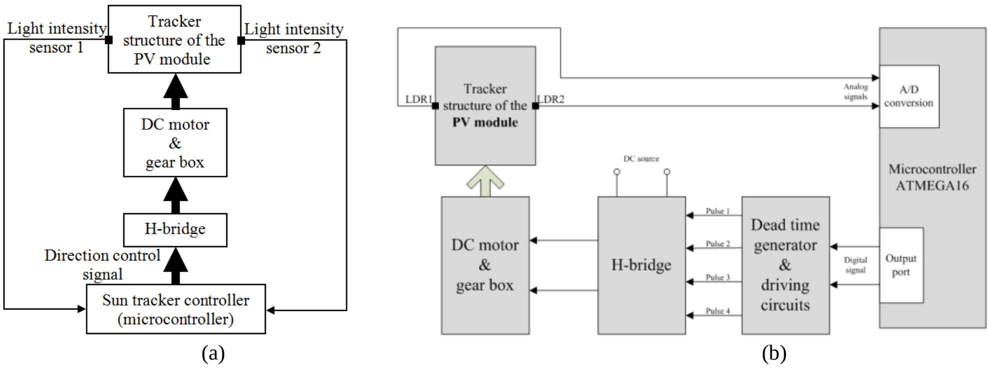

Fig. 1 Proposed sun tracking experimental system: (a) block diagram (b) detailed diagram.

It is necessary to note here that each of the used LDRs is connected in the circuit in series with another limiting resistor to form a voltage divider as shown in Fig. 2, for detecting the light intensity voltage signal (V_{LI}).

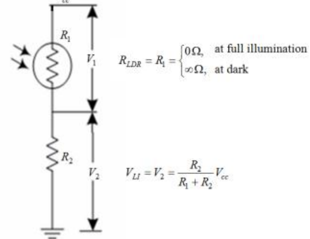

Fig. 2 Connection of the LDRs in the circuit.

2.1. The H bridge

Figure 3 shows the high power H-bridge circuit. Q1, Q2, Q3, Q4 are four N-channel MOSFETs. In order to rotate the motor in the forward direction, switches Q1 and Q4 must be closed to power the motor as shown in Fig. 4. On the other hand, to rotate the motor in the reverse direction, switches Q2 and Q3 must be closed to power the motor as shown in Fig. 5.

The dead time generator circuit, that is shown in Fig. 6, is necessary in this case to protect each of the two MOSFETs on the same arm of the H-bridge from being short-circuited i.e., to be not conducted at the same time. Thus, to achieve this, it is necessary to delay the turn on of the low-side MOSFET by at least as much as the turn-off time of the high-side MOSFET. The same should be satisfied for the other transition, i.e., when the switching process is reversed and to be from the low-side to the high-side MOSFETs.

Figure 7 shows a photo of the experimental setup of the driving circuit of the H-bridge that was implemented in this work. Noting here that Each MOSFET of the H-bridge should has a separate driving circuit to drive it, which requires a separate isolated power supply. Thus, in this case, it is necessary to have four driving circuits with three isolated power supplies, to drive the four MOSFETs of the considered H-bridge.

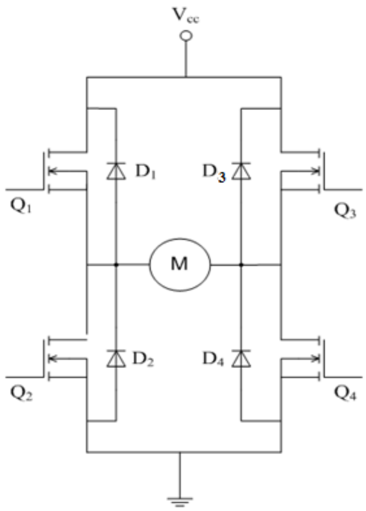

Fig. 3 H-bridge circuit using power MOSFET.

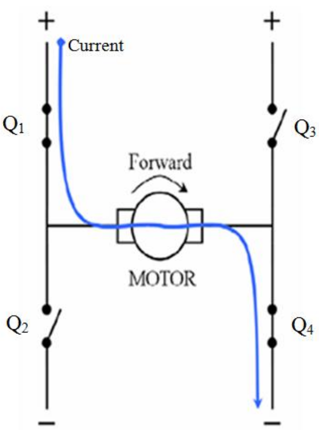

Fig. 4 H-bridge topology - forward direction.

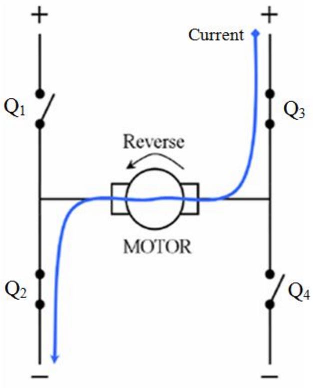

Fig. 5 H-bridge topology - reverse direction.

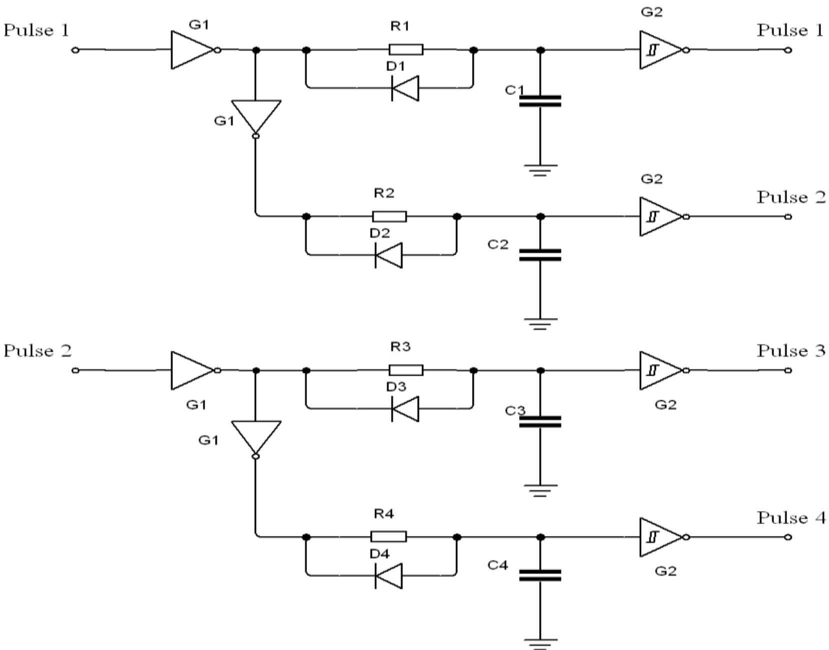

Fig. 6 The dead time generator.

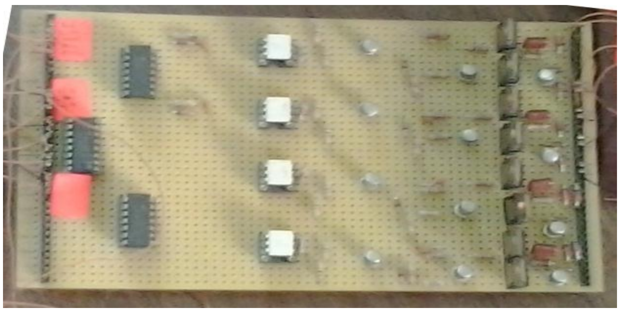

Fig. 7 Experimental setup of the driving circuit of the H-bridge.

2.2. The microcontroller

The microcontroller that is used in this system is an 8-bit AVR ATmega16 microcontroller from ATMEL. On it a program can run to govern the control of the sun tracking system. Where, it is used to read the two measured voltage signals of the LDRs, that are proportional to the corresponding incident light intensity on each of them, to yield the on-off switching control signal of the H-bridge that is suitable for directing the PV module towards the sun position in the East-West direction. This microcontroller has an A/D converter features that are 10-bit, eight channels, successive approximation A/D converter, that can be used by the control program to read the signals required for the control purposes. The 8-bit resolution is chosen to be adequate for the present application. Also, the used microcontroller has 32 programmable I/O lines for digital data inputting and outputting. In addition, it has three timers with PWM outputs and program-controlled duty cycle of maximum frequency of 31.2 kHz when driven by a crystal that generates a clock frequency of 8 MHz. This microcontroller was chosen, in this case, because it has the necessary features for the proposed system, such as an on-chip A/D converter, 32 programmable I/O lines, 8-bit architecture, high clock rate, low-power consumption and low cost [13].

3. Experimental Setup of the Sun Tracking System

The experimental setup of the sun tracking system is divided, in this work, into two parts: the electronic-part and the mechanical-part. Figure 8 shows a photo of the sun tracking mechanical structure, together with the DC motor and gear box that rotates the shown tracker structure. It is to be noted here that Fig. 8 contains also the utilized PV module, which is the LORENTZ LC80-12M PV module type. This module consists of 36 mono-crystalline silicon solar cells connected in series and provides 80Wp of maximum power at standard test conditions (STCs) of temperature and solar insolation (i.e., 25 ^{o}C and 1000 W/m^2). The complete details of this module, which include its datasheet characteristics, accurate modeling, and MATLAB-Simulink simulation, are given by the authors in another paper [14]. In this work, the utilized PV module is connected directly to the available DC load, which is a DC programmable electronic load that can be adjusted at any constant resistance value as shown in Fig. 9.

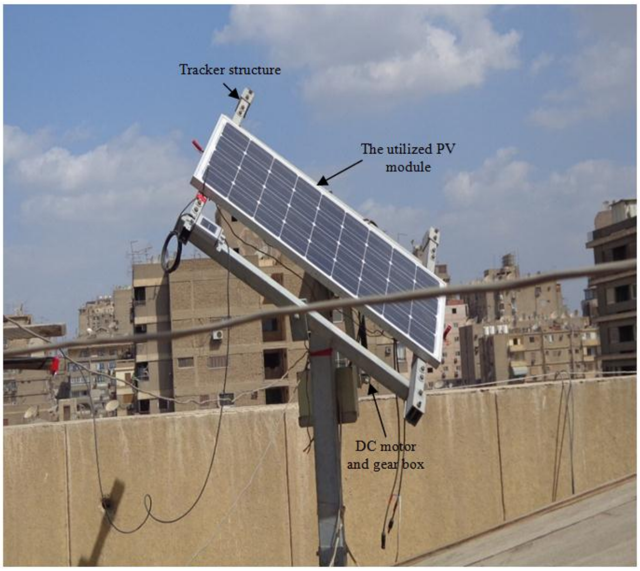

Fig. 8 Solar tracking mechanical structure.

Fig. 9 DC Programmable electronic load.

In addition, Fig. 10 shows a photo of the experimental setup of the electronic-part of the sun tracking system that was designed and carried out, in this work. This figure includes the used ATmega16 microcontroller, the H-bridge, the dead time generator and the driving circuits of the four power MOSFETs of the H-bridge, and the designed power supply that is required for operating the overall system from the utilized PV module.

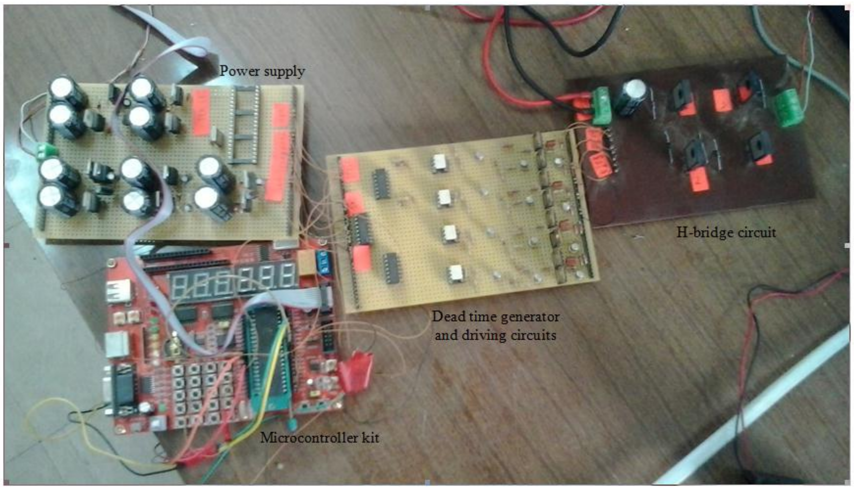

Fig. 10 Experimental setup of the electronic-part of the solar tracking system.

4. Software Development

The software design, in this work, includes the flowchart of the sun tracking control system, which is shown in Fig. 11. This flowchart starts with initialization of the data, variables, ADC converter, and ports of the ATmega16 microcontroller. Afterwards, the program starts to read two signals that are the output voltage signals of the LDR1 and LDR2 voltage dividers (i.e., the light intensity voltage signals). Then, the program calculates the error signal e(k), as the difference between these two voltage signals. After that the error sign is checked, whether it is positive or negative. If it is a positive sign CX register is filled with 0, otherwise it is filled with 1 to indicate a negative sign and in this case the error is negated. The next decision is to show that if the absolute error is greater than or equals certain error value ε, then the program will output signals to rotate the tracking motor in one direction or reverses its rotation depending upon the sign of the error that is stored in the CX register. Otherwise, if the absolute error is lower than ε, then the program will stop the motor rotation. Afterwards, the program returns to read new values of the light intensity voltage signals and continues again to do the previous same steps, to track the sun in the East-West direction.

The code of the sun tracking control program is written in assembly language (that is suitable with 8-

bit AVR ATmega16 microcontroller), debugged, and run with the help of the STK500 starter kit evaluation board, AVR Studio software.

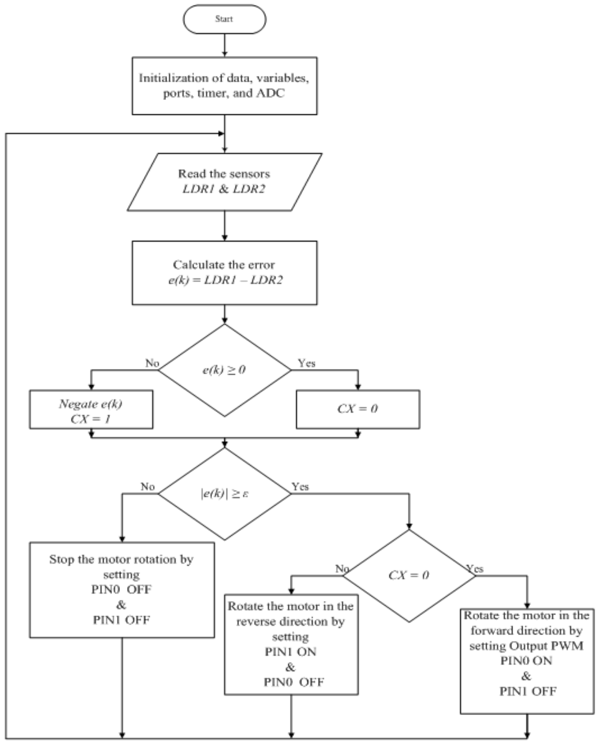

Fig. 11 Flowchart of the sun tracking control system.

5. Experimental Results

The experimental results of the suggested sun tracking system indicate the results of the implemented system hardware using the developed software. In this work, the implemented sun tracking system is tested at the roof top of the Electronics Research Institute (ERI), Dokki, Cairo, Egypt. The latitude and longitude of the considered site are 30 °06' N and 31 °25' E, respectively.

The global experimental system is divided, in this work, into two similar PV modules connected to two similar loads, such that one PV module is mounted on a fixed structure facing the south direction and the other module is mounted on the implemented single-axis sun tracking system. In this case, the two modules are tilted to the horizontal with equal and fixed tilt angles, which are equal to the site latitude angle. Here, it is necessary to note that the implemented single-axis sun tracking system is the actual experimental system, whereas the other fixed system is a fictitious system designed by using MATLAB-simulation; for simplicity and due to the availability of only one PV module at hand.

In this work, the incident global solar insolations on the PV modules of the sun tracking and fixed systems are measured, respectively in this work, by using two pyranometers. One of these pyranometers is mounted on the surface of the actual sun tracking PV module and the other is mounted on a fixed structure facing the south direction with a tilt angle equals the site latitude angle. At the same time, the ambient temperature is measured by using a thermistor temperature sensor element that is mounted also on the fixed structure. The considered two pyranometers and temperature sensor are connected directly to the data logger of a WMS-16 weather station that was installed on the rooftop of the Electronics Research Institute (ERI), Cairo, Egypt. Noting here that the PV module temperature, in each case, can be estimated from the relation [15]: $T_{PV} = T_{ambient} + 0.03G$, where G is the corresponding global insolation incident on the considered PV module.

Figures 12 to 14 show different comparisons between the sun tracking and fixed PV systems. Such that Fig. 12 is dedicated for the hourly incident global solar insolation, Fig. 13 is for the hourly PV module temperature, and Fig. 14 is for the hourly output power of the used PV module. Thus, these three figures indicate that the collected global solar insolation and consequently the corresponding PV output power of the sun tracking PV system are higher than those of the fixed PV system during the daylight hours of the considered testing day (i.e., April 2, 2015).

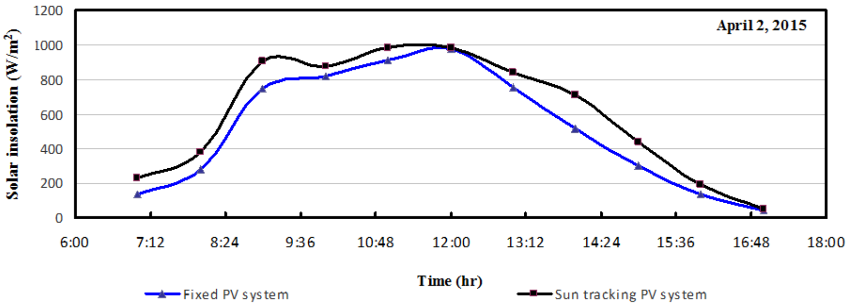

Fig. 12 Global insolation incident on the PV module during the daylight hours of the testing day.

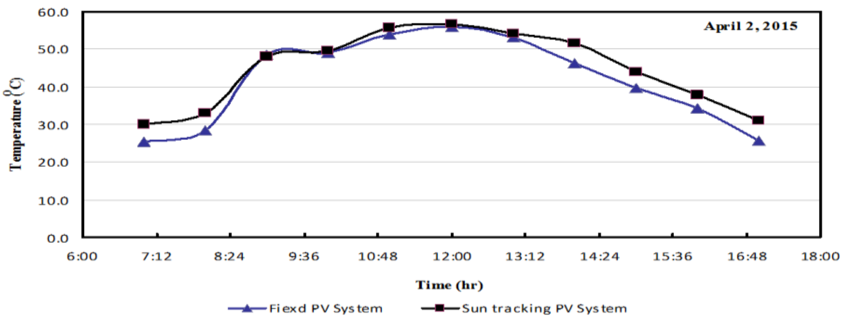

Fig. 13 PV module temperature during the daylight hours of the testing day.

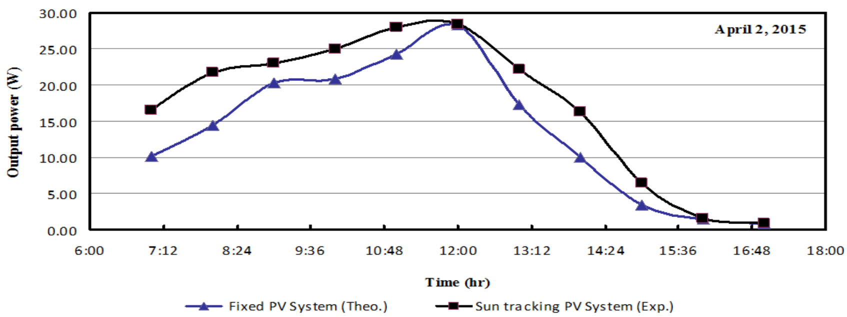

Fig. 14 PV output power during the daylight hours of the testing day.

Table 1 shows a comparison between the collected daily irradiations by the fixed and sun tracking PV systems. Thus, this table indicates that the designed single-axis sun tracking system can boost the daily collected irradiation with 17.5% over that collected by the fixed PV system.

Also, Table 2 shows a comparison between the daily generated energies from the fixed and sun tracking PV systems. Therefore, this table illustrates that the designed single-axis sun tracking system can boost the daily generated energy with 25.62% over that generated by the fixed PV system.

Table 1. The collected daily irradiation during the testing day

Type of system	Fixed PV system	Sun tracking PV system
Daily irradiation (Wh/m^2/day)	5621.53	6607.97
Increase in daily irradiation due to using sun tracker (%)	-	17.5

Table 2. The generated PV energy during the testing day

Type of system	Fixed PV system	Sun tracking PV system
Daily generated energy (Wh/day)	151.34	190.11
Increase in daily generated energy due to using sun tracker (%)	-	25.62

6. Conclusions

The utilization efficiency of the PV modules can be enhanced by continuously maximizing the incident solar insolation on their surfaces. An appropriate stand-alone PV system that includes the single-axis sun tracking system has been suggested and implemented experimentally in this work. The control of the suggested sun tracking system was implemented experimentally based on utilizing the low cost 8-bit AVR ATmega microcontroller, such that the control technique was implemented by designing the suitable assembly language code. The design of the sun tracking system was mainly based on utilizing the optical method, due to its ease of implementation and independence on the geographical location. Experimental results of the sun tracking system indicated that the designed single-axis sun tracking system was capable of maximizing the daily collected irradiation of the tracking PV module by about 17.5% compared to the fixed module during the daylight hours of the testing day. Also, the experimental results, in this regard, showed that the daily collected output PV energy during the daylight hours of the testing day was greatly enhanced by about 25.62%, if the designed sun tracking system was utilized. Consequently, it is recommended to use the designed sun tracking system in all large-scale applications of the photovoltaic (e.g., large-scale PV power stations), and to not use it in small-scale applications because of the associated energy losses and incurred cost of the sun tracking system.

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