LOW COST AUTOMATIC SUN PATH TRACKING SYSTEM

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ABSTRACT
Solar tracking systems used are to increase the efficiency of the solar cells have attracted the attention of researchers recently due to the fact that the attention has been directed to the renewable energy sources. Solar tracking systems are of two types, Maximum Power Point Tracking (MPPT) and sun path tracking. Both types are studied briefly in this paper and a simple low cost sun path tracking system is designed using simple commercially available component. Measurements have been made for comparison between fixed and tracking system. The results have shown that the tracking system is effective in the sense of relatively high output power increase and low cost.

الخلاصة
لقد جذبت انظمة المتابعة الشمسية المستخدمة لزيادة كفاءة الخلايا الشمسية انتباه الباحثين مؤخراً بسبب كون الاهتمام قد توجه نحو مصادر الطاقة المتجددة. ان انظمة المتابعة الشمسية هي على نوعين، متابعة نقطة القدرة العظمى (MPPT) ومتابعة طريق الشمس. تم دراسة كلا النوعين في هذا البحث بصورة مختصرة وتم تصميم منظومة مبسطة لمتابعة طريق الشمس باستعمال مواد بسيطة متوفرة في السوق التجارية. تم اخذ قياسات لاجل المقارنة بين المنظومات الثابتة والمتحركة (المتابعة). اظهرت النتائج ان المنظومة المتحركة هي فعالة من حيث الزيادة العالية لقدرة الاخارج وانخفاض الكلفة.

KEY WORDS: solar tracking, MPPT, sun path tracking, solar cell, photovoltaic cell

INTRODUCTION

The resources of most of the energy consumption were and still in the form of fossil fuel, which is either oil, coal or gas. The other source of energy is the nuclear energy. Each one of these types has its own major downside. The increasing consumption of fossil fuel and especially oil has caused the continuing depletion of the world reserve of oil and the lack of new explorations of new reserves that would balance the consumption has led to increase in oil prices for record highs that reached over 140 $/barrel in 2008 until the global recession brought the prices down to about 80 $/barrel. Another negative aspect with the fossil fuel is the environmental considerations in regards to carbon dioxide emission that is causing the global warming and climate change that is raising horrible concerns about the future of our planet.
For the nuclear energy, although it does not involve carbon dioxide emission but it is still considered a dangerous source of energy because of the risk of nuclear radiation and on the other hand the nuclear waste that needs to be looked after for several thousand years (10'000 years according to United States Environmental Protection Agency standards). Also, nuclear energy is highly controversial and politics plays a big roll that even if the technical and economical facilities were available, politics can cause agonizing troubles for the developing countries.

For the reasons summarized above, the world has turned to other form of energy sources namely the green energy sources. Green energy is clean in the sense that it does not have a bad impact on the environment, and also it is renewable. Types of green energy sources are:

- Hydropower
- Wind power
- Solar power
- Biofuel
- Wave power
- Geothermal power
- Tidal power

Many developed countries have set strategic goals to explore such types of energy sources to minimize their dependence on the fossil fuel as it is mostly an imported product from the developing countries.
The solar power conversion is one of the most addressed in the field of the renewable energy systems. The available techniques allow converting the solar radiation into two forms of energy: thermal and electrical [1]. The conversion of the solar energy into electrical is done by the photovoltaic (PV) cells or panels. The power supplied by PV panels depend on many extrinsic factors [2], such as irradiation levels affected by weather conditions which limits the amount of the incident solar radiation, temperature, angle of incident radiation and load conditions.
Solar tracking is mainly about achieving the maximum power and hence increasing the efficiency of the PV panels, this is important from the economical point of view, because in total the overall cost should give higher output power. The average solar energy obtained by conventional PV panels during the course of the day is not always maximized [2]. This is due to the static placement of the panels which limit their exposure to the sun. Solar tracking systems usually deal with the two factors namely the load condition and the angle of incidence. The system that adjusts the load condition in order to track the maximum power operating point is called maximum power point tracking (MPPT), these are electronic systems in which high efficiency DC-DC converters are used to control the load current and voltage in order to extract maximum power for a certain PV panels placement and radiation conditions, more explanation about this technique will be presented later. The other type is an electro-mechanical system intended to track the sun path using rotary motors and/or linear actuators to ensure normal incidence of solar radiation on the PV panels and hence maximizing the amount of converted solar irradiation into electrical energy. A combination of both systems can be used to achieve even higher output power.
Many researches have been made about solar tracking with various approaches. Simulations of sun path tracking are presented in [1] that showed efficiency improvement over fixed systems, and in [2] where maximum power is obtained for different environmental conditions. Studies and simulations of the MPPT techniques were presented in [3] and [4] where different algorithms are compared. Analytical calculations for both sun tracking and

MPPT were presented in [5] and the results are compared to fixed system. Hardware implementations were presented in [6-10] using PIC controller or PC-based controllers.

BASICS OF PV CELLS

The solar cell is a non-linear device and can be represented as a current source model as shown in Fig. 1 [4]. The current source generates the photocurrent I_{ph}, which is directly proportional to the solar irradiation or solar insolation (not insulation) in W/m^2 that measures the radiation power from the sun per unit area, which is also equivalent to the light intensity or illumination measured in lux. The two resistances R_s and R_p represent the solar cell internal losses. The series resistance R_s represents the ohmic losses in the surface of the solar cell. The parallel shunt resistance R_p represents the losses due to leakage current.

The I-V characteristics of a solar cell, when neglecting the internal shunt resistance, is given by the equation [3] [4]

$$I_o = I_{ph} - I_{sat}\left[\exp\left(\frac{q}{AKT}(V_o + I_o R_s)\right) - 1\right] \qquad (1)$$

Where I_{ph} is the light generated current, I_{sat} is the reverse saturation current, q is the electron charge, A is the p-n junction ideality factor (a dimensionless factor), K is Boltzmann constant, T is the absolute temperature in Kelvin and R_s is the series resistance of the cell.

The graph of the I-V and P-V characteristics of the solar cell is shown in Fig. 2 [3]. It is clear that the solar cell has non-linear characteristics and these characteristics are affected by the temperature and irradiation level, while the operating point is affected by the load condition. It is also clear from the P-V characteristics that there is only one point of operation where the output power has a maximum value which is desirable operating point for the MPPT techniques that will be discussed next.

As has been mentioned earlier, the term solar tracking means two different techniques; the maximum power point tracking and the sun path tracking. A brief description of both techniques is given bellow

THE MAXIMUM POWER POINT TRACKING (MPPT)

As can be seen from the curves in Fig. 2, the power curve exhibits a maximum point, i.e. there is an optimum operating point of cell voltage and current at which the load will receive maximum power from the solar cell. The problem is that the load can not be guaranteed to operate at this point for two main reasons. The first reason is that the load condition may not allow to be operated at exactly the desired MPP, and the second reason is that the weather condition and other factor will affect the irradiation level that generates the photocurrent I_{ph} and hence affecting the characteristics curve which in turn will change the MPPT, so, the MPP is virtually unknown. The MPPT is about searching for (or tracking) the values of current and voltage that would produce the maximum power to be extracted from the solar cell. Therefore; high efficiency DC-DC converters are used between the solar array and the load where the switching element is controlled to change the duty cycle that in turn will affect the output voltage and hence the current. Fig. 3 shows a block diagram describing the general idea of MPPT. By using an appropriate algorithm, the MPPT should be achieved under any conditions affecting the solar cell or the load. Different algorithms are used in MPPT, The most widely used are the Perturbation and Observation (P&O) method and the Incremental Conductance (IncCond) method [3] [4]. Below is a brief description of each method.

PERTURBATION AND OBSERVATION METHOD

In P&O method is widely used because of the simple feedback structure and fewer measurements. The tracking algorithm operates by periodically incrementing or decrementing the output voltage, if a given perturbation leads to an increase in the PV array power the subsequent perturbation is made in the same direction, otherwise the subsequent perturbation is made in the opposite direction. In this manner the successive change in the voltage will lead to the MPPT where the voltage will oscillate around the maximum power point. If the irradiation level changes and hence the characteristics curve changes accordingly, the MPPT will be different than the current operating point but since the perturbation and observation is being done in a continuous manner the P&O algorithm will be able to track the new MPP to be the new operating point.

INCREMENTAL CONDUCTANCE METHOD

The IncCond method is basically a computational method that is based on the fact that maximum power is where the derivative of power with respect to PV array voltage is zero, i.e.

$$P = IV$$

$$\frac{dP}{dV} = I + V\frac{dI}{dV} = 0$$

From which

$$\frac{dI}{dV} = -\frac{I}{V} \tag{2}$$

Equation 2 says that the peek power point is obtained by adjusting the PV array voltage such that the incremental conductance ($\Delta I/\Delta V$) equals the negative of the conductance ($-I/V$). So the role of the algorithm is to increase or decrease the duty cycle of the DC-DC converter until the above condition is satisfied which is equivalent to ($dP/dV=0$). The IncCond method offer good performance under rapidly changing atmospheric conditions (that affect the irradiation level) but it requires more measurements than the P&O method. There are other methods suggested in literature for MPPT [4], but these are beyond the scope of this paper.

SUN PATH TRACKING

Due to the relative motion between the earth and the sun, the incident solar irradiation cannot always be normal to the PV panel that has a fixed placement. Therefore, the intensity of the sunlight falling on the PV panel is greatly reduced. Sun path systems are used to move the PV panel with the sun movement so that the incident sunlight is always normal to the surface of the PV panel.

Before having further discussion of the sun tracking systems, it is useful to define the basic terms associated with the position and motion of the sun.

Zenith: The point directly overhead of the observer. The zenith is used with the west and east as a three-dimensional orthogonal coordinate system to define the sun position.

Solar altitude angle: The angle measured between an imaginary line between the observer and the sun and the horizontal plane the observer is standing on, see Fig. 4a. This angle is positive during day time and negative at night, therefore, the zero value of the altitude angle defines the time of sunrise and sunset. The maximum value of the altitude angle is at solar noon, and the maximum value of the altitude changes with the season for a given location. If the altitude angle is 90^o, which usually occurs near the equator, it means that the sun is at the zenith.

Solar azimuth angle: The solar azimuth angle is the angular distance between south (in some literature north) and the projection of the line of sight to the sun on the ground. A positive solar azimuth angle indicates a position east of south, and a negative azimuth angle indicates west of south, see Fig. 4b. The sunrise and sunset do not occur at azimuth angles $\pm 90^o$.

Angle of incidence: It is the angle between the sun's rays irradiated on the PV panel surface and the line normal to the PV panel. The objective of the sun path tracking systems is to make this angle zero.

For a fixed point on the surface of earth, the sun position is described by the altitude and the azimuth angles. In sun path tracking systems there can be either a dual axis tracking technique, where the tracking for the azimuth angle or the east-west motion which is due to the daily change of sun position in addition to tracking the altitude angle of the sun due to the seasonal motion. Sometimes, single axis system is sufficient to track the daily east-west motion of the sun because the span of this motion is wider than the span of the seasonal motion.

On the other hand the sun tracking systems are divided into two types according to the way of controlling the alignment of the PV panel to the incident sunlight. They can be either open loop control systems or closed loop control systems.

OPEN LOOP CONTROL SYSTEMS

In this type the controller calculates the tilt angle of the PV panel using special equations or lookup tables for the sun trajectories. Although these systems do not require any measurements but they have the drawback that they require adjustment to a reference point that defines the angles produced by the mechanical system. If that reference point is disturbed, the control system would not sense the resulting error and eventually the alignment of the PV panel will be shifted from its desired location. This type of systems is best suited for theoretical research that calculate the extracted power of the tracking system using mathematical models as used by Armstrong [5].

CLOSED LOOP CONTROL SYSTEMS

This type is a photo sensor based systems, in which the sun position in the sky is detected by photo sensors and the measurements from the photo sensors are fed to the control system, as in Fig. 5. Two photo sensors (for each axis) are positioned in a way that the correct alignment of the PV panel makes equal angles of incidence of the sunlight at two sensors. This produces zero difference (or error) between the measurements of the sensors. When the sun moves, the error will not be zero because the angles are not equal, and the control system will rotate the PV panel to be adjusted in the direction that will make the angles equal and hence eliminating the error as explained in Fig. 6. Although the closed loop systems share the same concept, but the control algorithm can differ widely, they can be simple difference calculating algorithms that can be implemented using PIC controllers [6] or they can be more complex algorithms like genetic [2] algorithms or fuzzy logic control [7] that can only be implemented on a PC. Such systems are able to track the sun path without the need to calculate the sun trajectories.

The sensor based closed loop systems more commonly used than the open loop systems mostly because they are easier to orient and install than the open loop systems in the sense that there is no need for precise adjustment of the mechanical system and if the adjustment is disturbed in the future by external factors, the control system is still able to track the sun path as long as the sun path is within the limits of movement of the mechanical system. This feature has been tested practically in our proposed system by putting the moving base in an arbitrary orientation, and then the control system starts to adjust the moving base in the direction of the sun until the angle of incidence of sun light is zero without any outside adjustments. The system can then be left to automatically track the sun.

A combination of both the open loop and the closed loop control systems can be used in a way that the angles are calculated first and the PV panel is moved accordingly, then the sensors would detect more accurately the sun position and the PV panel is further adjusted. When the there is a cloudy weather condition, the sensors would not be able to accurately locate the sun, therefore, the open loop system takes over the control of the PV panel. This approach is used by Xu [9].

SYSTEM DESCRIPTION

The objective of solar tracking is to increase the efficiency of the PV Panel and hence obtaining higher output power. The overall system is equivalent to having a larger fixed PV panel with output power equals to the smaller PV panel with the tracking system. From the engineering point of view the tracking system must be cost effective in order to justify the cost of the extra equipment required for the tracking system. Therefore, in the design of the proposed tracking system, the cost is considered as a primary factor. Therefore a single-axis tracking system is adopted and since the control and the mechanical parts are the most cost affecting parts of the system, the control part is made using electronic circuit that have the opamp LM324 as the main component. While for the mechanical part, the moving base of the reflector of the satellite receiver antenna is used because of its availability and low cost, in addition to that it well suits the purpose of sun path tracking. For the motor drive part, the H-type drive is used to reverse the direction of the motor motion. Bellow is a detailed description of the three parts of the system

THE CONTROL PART

The circuit diagram of the controller is shown in Fig 7. It is basically a difference amplifier implemented using the low offset quad opamp LM324. The photo sensor is the 1KLB3B phototransistor that is used to detect the sunlight intensity. Two photo transistor are positioned on opposite side on the moving base (that carries the PV cell) one to the east side (QE) and one to the west side (QW). With the appropriate choice of the values of the resistors the output of difference amplifiers of opamp A and opanp B are given by [11]

$V_A = 10(V_{QE}–V_{QW})$ (3a)
$V_B = 10(V_{QW}–V_{QE})$ (3b)

Looking at the characteristics of the phototransistor shown in Fig. 8, it can be seen that this characteristics is different than the characteristics of the normal transistor in the way that the collector current curve is drawn for deferent values of illumination while for the normal transistor the collector current is drawn for different values of base current. Therefore the illumination will represent the biasing of the phototransistor. Instead of the current gain β which is defined as the ratio between the collector current and the base current I_C/I_B, the current gain of the phototransistor β_p will be defined as the ratio between the collector current I_C and the illumination E_v, i.e.

$$\beta_p = \frac{I_C}{E_v} \quad (4)$$

This will help finding the value of the outputs of the opamps A and B in terms of the illumination E_v. The voltages of the phototransistors QE and QW are given by

$V_{QE} = V_{CC}–I_{CQE}R$ (5a)
$V_{QW} = V_{CC}–I_{CQW}R$ (5b)

Substituting eqs (5) and (4) into eq (3) we get

$V_A = 10\ \beta_p R \Delta E_v$ (6a)
$V_B = –10\ \beta_p R \Delta E_v$ (6b)

Where

$\Delta E_v = E_{vE}–E_{vW}$ (7)

which represents the difference of illumination on the east side phototransistor QE and the west side phototransistor QW. The V_{CC} value is chosen to be 12V, and since the value of R in Fig. 7 is 1kOhm, the load line can be drawn as shown in Fig. 8 from the point I_C=12mA & V_{CE}=0 to the point I_C=0 & V_{CE}=12V (these points are outside the graph). The Q point in the middle of the line is approximately I_C=5mA, V_{CE}=5.6V and Ev=200lx. From eq (4), β_p can be found approximately to be 0.025mA/lx. Taking into account that the value of R is chosen to be 1kOhm, eq (6) becomes

$V_A = 0.25\Delta E_v$ (8a)
$V_B = –0.25\Delta E_v$ (8b)

The above equation shoes that the values of V_A and V_B are sensitive enough for small difference in illuminations on the two phototransistors that will make the controller able to detect any slight movement of the sun. On the other hand V_A and V_B have the same magnitude but opposite signs, this is to determine the direction of movement of the sun.
The next stage of the circuit is the comparators stage where the opamps C and D are used to provide the signaling to the DC motor. The threshold voltage is made variable by a multi-turn potentiometer to the user preference, this is important to stop the movement of the tracker when the magnitude of V_A and V_B which are proportional to the difference of illumination ΔE_v is low. This can happen in a cloudy day when the sun is hidden, so, in such case the tracker is stopped because there is no point of wasting energy by the motors. So when the magnitude of the voltages V_A and V_B are less than the threshold voltage, both outputs of the comparators will be zero. When the magnitude of the voltages V_A and V_B are higher than the threshold, the opamp with negative input voltage will produce zero output and the opamp with positive voltage will produce a positive voltage ($+V_{CC}$) that is fed to the motor drive stage to rotate the motor. When the motor is rotated, the PV panel will be rotated towards the sun along with the phototransistors, and during the rotation the difference in the illumination ΔE_v will decrease until it makes the magnitudes of V_A and V_B fall below the threshold voltage and then the motor stops.
Another element of the controller circuit is the 555 timer whose purpose is to make sure that the controller is not active all the time and there is no continuous unnecessary movement of the motor due to the slow motion of the sun to reduce energy

consumption. Instead, the timer is set to deactivate the controller for about 15 minutes so that the sun will have an appreciable change of position, after that the controller will be activated for about 30 seconds which is enough time for the motor to adjust the position of the PV panel and the having the magnitudes of V_A and V_B below the threshold voltage, this means that the motor will stop before the end of the 30 seconds. The deactivation of the controller is made by pulling to ground the two non-inverting inputs of the opamps A and B so that the outputs V_A and V_B will be both negatives making the outputs of the comparators C and D both zeros.

The Motor Drive

The circuit diagram of the motor drive is shown in Fig. 9, where the H-type drive is used to provide direction reversal of motor motion. The main elements are the four BDX53C Darlington transistors that act as the main switching elements. To rotate the motor in a certain direction one of the control voltages V_1 or V_2 should be set to V_{CC} and the other to ground. If we assume that V_1 equals V_{CC} and V_2 is grounded, the transistor Q_1 will be ON connecting the (+) terminal of the DC motor to ground and the transistor Q_8 will also be ON allowing the base-emitter junction of the PNP transistor Q_6 to be in the forward direction and hence Q_6 will also be ON. This will make the current to flow in the base-emitter junction of the Darlington transistor Q_4 making it ON and this will connect the (-) terminal of the DC motor to V_{CC} and the motor will rotate. For V_2 being grounded the transistors Q_3, Q_7, Q_5 and Q_2 will be OFF. If V_1 is grounded and V_2 is set to V_{CC}, the situation is reversed and the motor will rotate in the reverse direction. The motor current was measured and found to be around 0.1A when the moving is far from the end of movement points and the current rises to 0.5A when the moving base is near its end of movement points. These values of current are acceptably small values especially if we consider that the motor is only allowed to rotate for a small amount of time that is determined by the timer of the controller. So, the loading of the motor to the power source of the PV panel is insignificant. The control voltages V_1 and V_2 are taken from the outputs of the comparators C and D and they cannot be both set to VCC, because this will cause damage to the transistors. This condition is guaranteed by the arrangement of the inputs of the opamps A and B as discussed earlier.

The control voltages V_1 and V_2 are connected to the driver circuit through the normally closed contacts of the switches S_1 and S_2 which are limit switches that are put on the extreme ends of the actuator to ensure that the motor would not rotate the mechanical structure beyond the permissible span.

One last issue about which of the control voltages V_1 and V_2 is to be connected to the output of the comparator C or D, because the wrong connection will make the moving base to move away from the sun. Since there are many factors affecting this decision, like the polarity of the DC motor and its mechanical orientation, the ambiguity can only be resolved by a simple trial and error experiment. A choice is made by connecting, for example, V_1 to output C and V_2 to output D and the motion of the moving base is observed, if the moving base is following the sun then this connection is correct, otherwise if the moving base is moving away from the sun the connection is reversed.

The Mechanical Structure

As has been mentioned earlier the choice of the mechanical structure was made to be a moving base of satellite antenna reflector that is shown in Fig. 10. This choice was mainly because of the availability, low cost and suitability of this moving base for the intended purpose. Although the moving base is having a single motor making the system a single-axis tracking system, but the actuator of the motor is connected to the moving base in a way allowing the base to trace an arc with changing altitude and azimuth angles. This will provide an approximate trace to the exact sun path. The error will be from the difference of the actual altitude of the sun and the altitude angle established by the moving base. The moving base is equipped by a manual mechanical adjustment of the altitude providing the ability to change the range of the altitude angle according to the season. So, the user can make this adjustment every 3 months, for example, to minimize the altitude angle difference error.

This moving base can hold a reflector of 1.5m diameter, that is an equivalent area of 1.77 m^2 and it was tested to hold with motor rotation 15kg weight. So, any PV panel with such dimensions and weight can be used with this moving base. In case of larger PV panels are required, a specially designed moving base will be required without modifications to the controller and the driver circuits.

Since the proposed system is only a prototype, the solar cell that was used for the measurement purposes was a small one with open circuit voltage V_{oc}=7.5V And short circuit current I_{sc}=0.333A. This solar cell is not powerful enough to rotate the motor, therefore, an external power supply of 12V was used to operate the system. In actual system the output of the solar panel should be used as a power supply of the tracking system.

MEASUREMENTS AND RESULTS

Two sets of measurements were taken for comparison, one for the sun tracking system and one for the fixed system. The altitude angle was calculated for the midday time which is 12:00pm according to the longitude and latitude of Baghdad (33° 20' N, 44° 24' E) and the date of 12/6 using sun position calculator [12], the calculated value was about 80^o [12]. The moving base adjusted according to this angle for noon time and measurements were taken from early morning until afternoon every 15 minutes.

Table 1 shows the output voltage of the moving and fixed solar cells with load termination equals R_L=25 Ohm obtained every 15 minutes during the day. The graph of these results is shown in Fig. 11, where it can be seen that the curve of the tracking system is more flat than the fixed system, this means that the load of the tracking system will have a constant voltage for more time that the fixed system. In terms of power, the average power for both systems can be calculated as

$$P = \frac{\sum V_i^2 / R_L}{N} \qquad (9)$$

Where N is the number of the measurement points. The amount of power increase using the tracking system over the fixed system can be found to be 57%.

From the economical point of view, we can take an example of a PV panel available in the market of 36W power that costs 200’000ID. As has been stated earlier the cost of our tracking system is 30000ID which is 15% extra cost to the PV panel, in return 57% increase of output power is obtained. Since the cost of the tracking system is the same for a larger PV panel with higher output power, the relative cost will be reduced while obtaining the same percentage of power increase.

CONCLUSION

The purpose of this paper is to motivate for more research in the fields of renewable energy. A design of a sun path tracking system has shown an increase in the output power of 57% of the moving PV panel over the fixed moving PV panel using simple mechatronics with added cost of about 15%. The relative cost can be lowered when using solar panels of higher output power.

REFERENCES

- Alexandru, C.; Pozna, C. “Virtual Prototype of a Dual-Axis Tracking System used for Photovoltaic Panels”, IEEE International Symposium on Industrial Electronics, ISIE 2008. June 30 2008-July 2 2008. Cambridge, UK.
- Mashohor, S.; Samsudin, K; Noor, A. M.; Rahman, A. R. A.; “Evaluation of Genetic Algorithm based solar tracking system for Photovoltaic panels” IEEE International Conference on Sustainable Energy Technologies, 2008. ICSET, 2008. Singapore.
- Hua C.; Shen C., “Comparative study of peak power tracking techniques for solar storage system” 13th Annual Applied Power Electronics Conference and Exposition, 1998. APEC '98. Conference Proceedings 1998. California, USA. Volume: 2.
- Armstrong, S.; Hurley, W.G.; “Self-regulating maximum power point tracking for solar energy systems”, 39th International Universities Power Engineering Conference, 2004. UPEC 2004. Bristol, UK. Volume: 2.
- Armstrong, S.; Hurley, W.G.; “Investigating the Effectiveness of Maximum Power Point Tracking for a Solar

System" IEEE 36th Power Electronics Specialists Conference, 2005. PESC '05. Brazil

- Barsoum, N.; "Implementation of a Prototype for a Traditional Solar Tracking System" Third UKSim European Symposium on Computer Modeling and Simulation, 2009. EMS '09. Athens, Greece.
- Jung-Sik Choi; Do-Yeon Kim; Ki-Tae Park; Chung-Hoon Choi; Dong-Hwa Chung; "Design of Fuzzy Controller based on PC for Solar Tracking System" International Conference on Smart Manufacturing Application, 2008. ICSMA 2008. South Korea.
- Omar, A.M.; Shaari, S.; Omar, A.R.; Yahaya, M.R.Y.; "An Automated Solar Photovoltaic Biaxial Tracking System: SolT2A " IEEE International Power and Energy Conference, 2006. PECon '06. Malaysia.
- Jing Xu, Kaihua Wu, Li Ma; "All-weather automatic solar tracking method applied in forest fire prevention" 9th International Conference on Electronic Measurement & Instruments, 2009. ICEMI '09. Beijing, China.
- Hossain, E.; Muhida, R.; Ali, A.; "Efficiency improvement of solar cell using compound parabolic concentrator and sun tracking system" IEEE Canada Electric Power Conference, 2008. EPEC 2008.
- Millman, J. and Halkias C. "Integrated Electronics", McGraw-Hill, 1972
- Sun Position Calculator http://www.susdesign.com/sunangle/

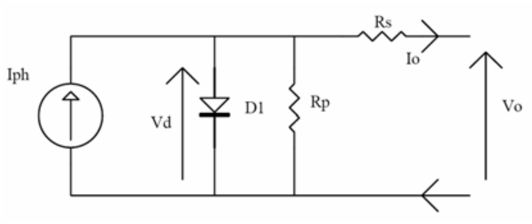


Fig. 1 The solar cell model.

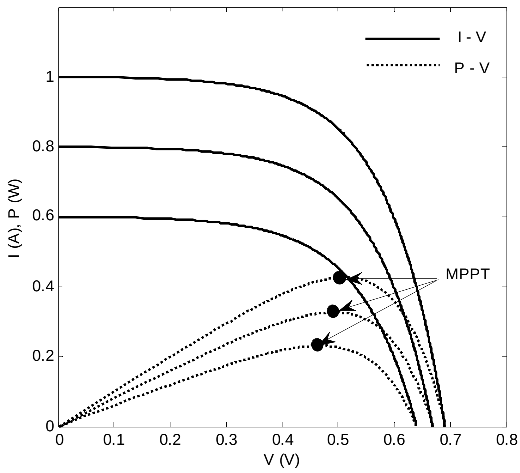


Fig. 2 The I-V and P-V characteristics of the solar cell for different irradiation levels.

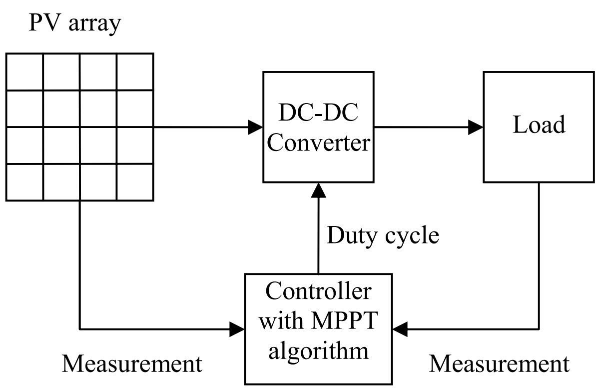
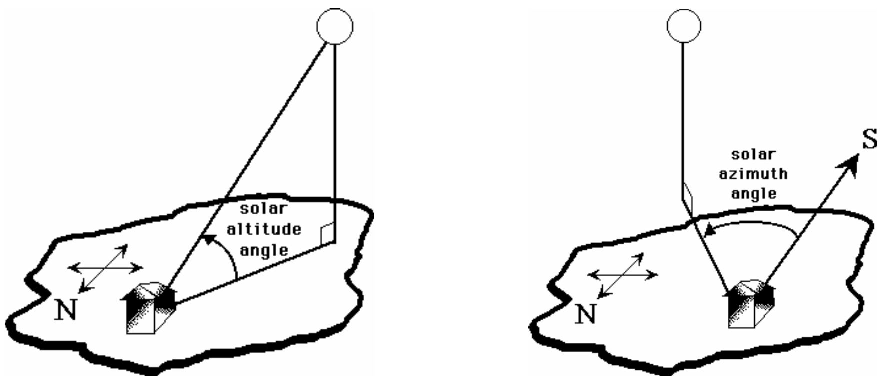


Fig. 3 Block diagram of MPPT technique



(a) (b)

Fig. 4 a: the altitude angle. b: the azimuth angle.

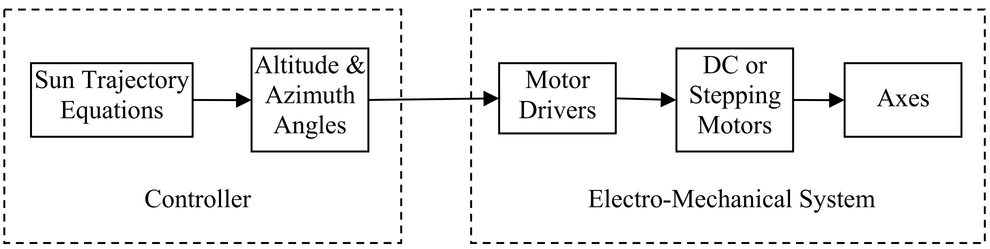


Fig. 4 Open loop control system of the sun path tracking

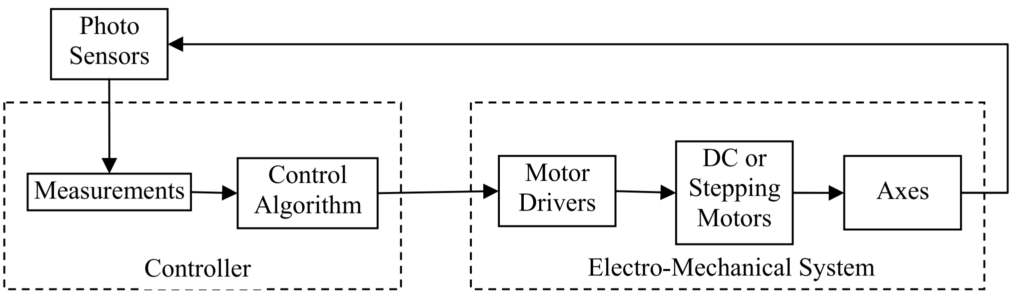


Fig. 5 Closed loop control system of the sun path tracking

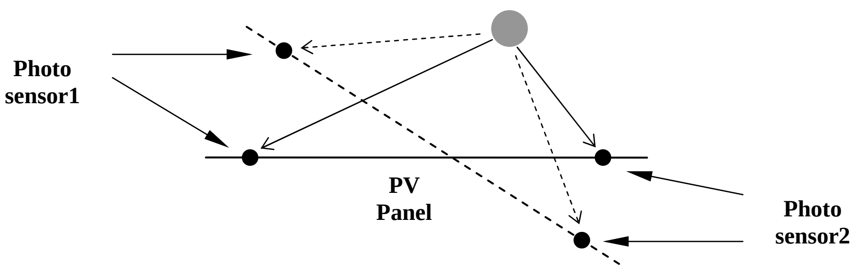


Fig. 6 The adjustment of photo sensors orientation with respect to sum.

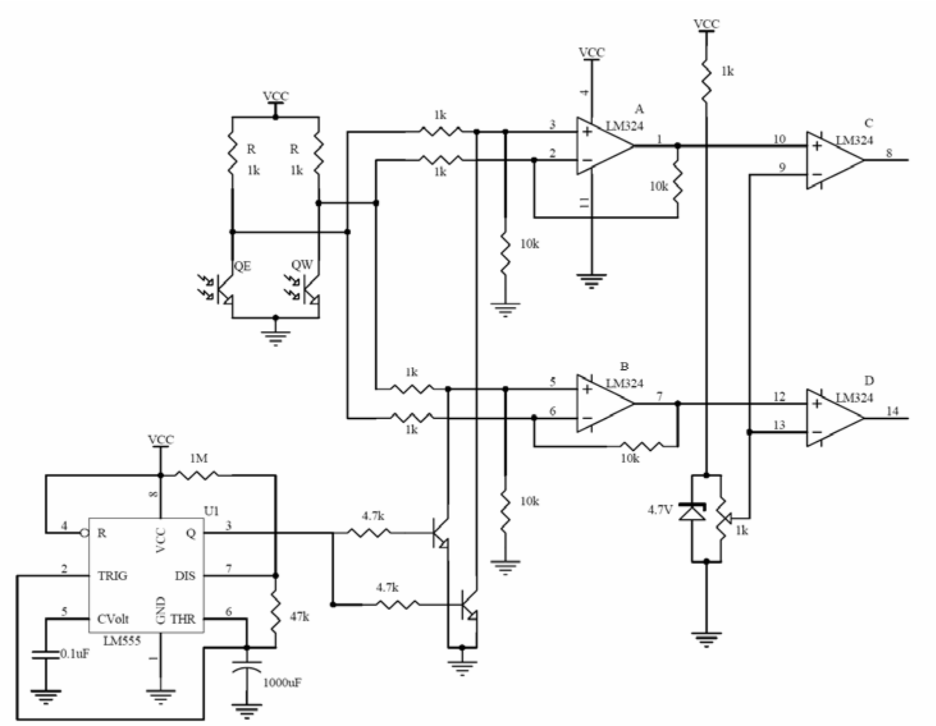


Fig. 7: The circuit diagram of the controller.

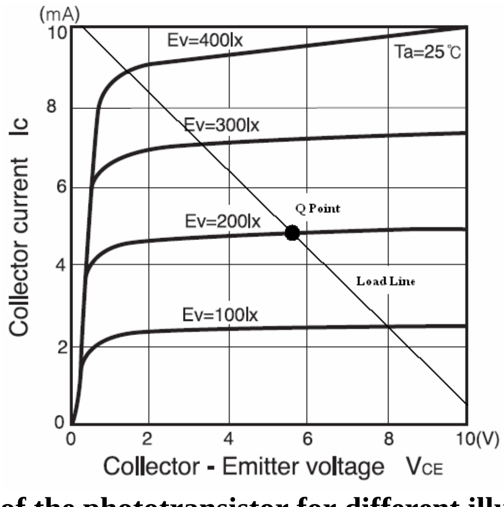


Fig. 8 I_C vs. V_{CE} of the phototransistor for different illumination values.

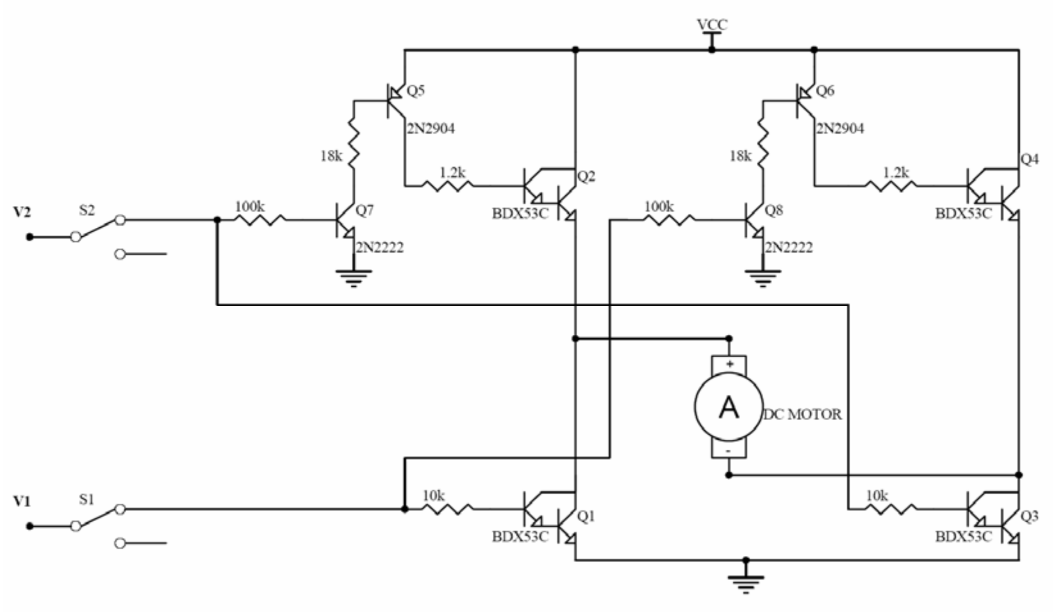


Fig. 9 The circuit diagram of the DC motor driver.

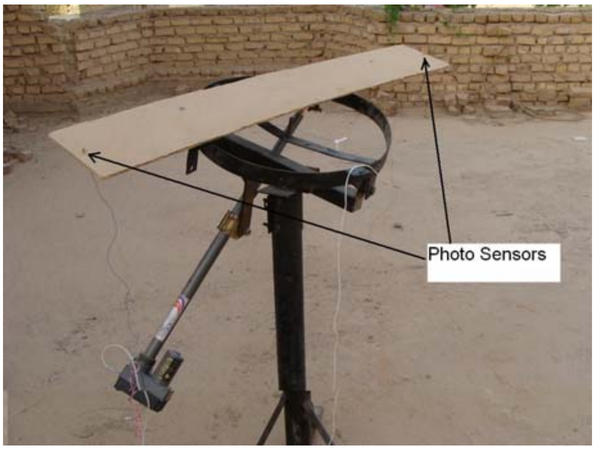


Fig. 10 The moving base with the photo sensors fixed to it.

Table 1: The cost of the designed tracking system

Item	Cost (ID)
Moving base	12’000
Phototransistor 1KLB3B	2x3’500=7’000
Quad opamp LM324	500
Timer 555	500
Transistor BDX53C	4x750=3’000
Transistor 2N2222	4x500=2’000
Transistor 2N2904	2x500=1’000
Board	2x1’000=2’000
Various electronic components	2’000
Total	30’000

Table 2: Practical results

Time (hh:mm)	Tracking PV voltage (V)	Fixed PV voltage (V)	Time (hh:mm)	Tracking PV voltage (V)	Fixed PV voltage (V)
5:30 am	1.05	0.20	12:00 pm	5.76	5.75
5:45 am	2.10	0.41	12:15 pm	5.70	5.65
6:00 am	2.72	0.55	12:30 pm	5.68	5.52
6:15 am	3.14	0.71	12:45 pm	5.63	5.48
6:30 am	3.96	0.92	1:00 pm	5.60	5.44
6:45 am	4.63	1.03	1:15 pm	5.56	5.39
7:00 am	4.72	1.09	1:30 pm	5.51	5.35
7:15 am	4.80	1.14	1:45 pm	5.46	5.31
7:30 am	5.11	1.20	2:00 pm	5.40	5.24
7:45 am	5.30	1.50	2:15 pm	5.35	5.10
7:00 am	5.35	1.80	2:30 pm	5.30	4.95
8:15 am	5.40	2.00	2:45 pm	5.25	4.78
8:30 am	5.45	2.40	3:00 pm	5.20	4.60
8:45 am	5.50	3.26	3:15 pm	5.15	4.30
9:00 am	5.52	3.85	3:30 pm	5.10	3.50
9:15 am	5.51	4.36	3:45 pm	4.96	3.20
9:30 am	5.55	5.00	4:00 pm	4.79	2.90
9:45 am	5.56	5.11	4:15 pm	4.62	2.60
10:00 am	5.57	5.25	4.30 pm	4.38	2.30
10:15 am	5.58	5.36	4:45 pm	4.12	2.00

10:30 am	5.59	5.41	5:00 pm	3.85	1.80
10:45 am	5.61	5.48	5:15pm	3.50	1.60
11:00 am	5.64	5.54	5:30 pm	3.15	1.40
11:15 am	5.71	5.60	5:45 pm	2.70	1.20
11:30am	5.75	5.69	6:00 pm	2.12	1.00
11:45 am	5.76	5.73			

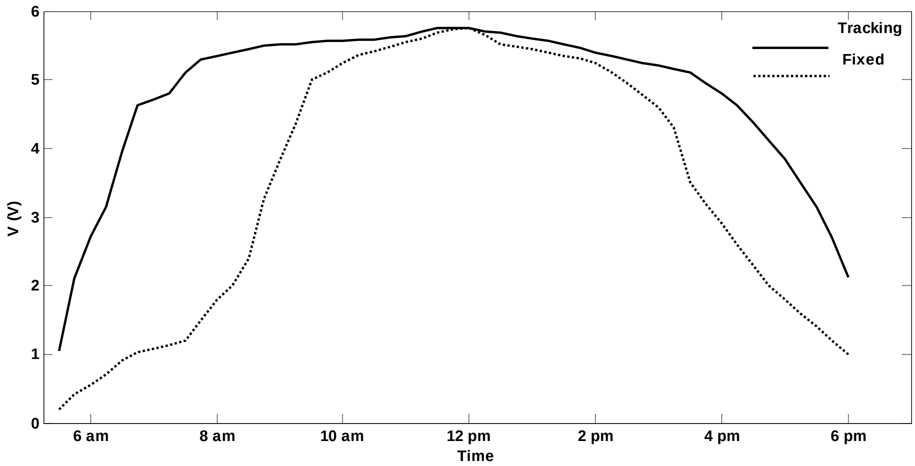


Fig. 11 Graph of the PV cell voltage for both fixed and tracking systems.