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Article

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Research paper

Single axis automatic tracking system based on PILOT scheme to control the solar panel to optimize solar energy extraction

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HIGHLIGHTS

- Solar energy is maximized by exposing the panel to irradiation for maximum time.
- Energy consumption by the drive is kept to its minimal.
- Technique could help in designing future optimized panel.
- A considerable improvement in solar efficiency is feasible.

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ABSTRACT

Two types of solar panels are currently in use. Fixed panels; where they are placed at a convenient angle depending on the geographical location with a fixed tilt angle. But irradiation time merely exceeds six hours/day. The second type is rotating panels, either by continuously tracking the sun or through a preprogrammed angle at preprogrammed time. Unfortunately, both schemes, continuous tracking or pre-programmed are inefficient. In the first one, motor running at a very low speed requires a high torque which requires high current, leading to more driving power. In the second scheme, the system rotates at predetermined small angles independently whether the new position contributes to extra energy or not. In fact, it may have the opposite effect where all the extracted energy could be consumed by the driving system. This paper presents a new technique where those two drawbacks have been addressed. The design uses a microcontroller-based control mechanism to maximize solar energy extraction. This is done by the design of a tracking system known as the PILOT and cells rotating system known as PANEL. First the system is oriented towards the east waiting for sun to rise. When this happens, the PILOT keeps tracking the sun. This is done with the aid of a light to frequency converter (LTF) mounted on a miniature electric motor. This converter always lines the PILOT with the sun. Two identical light dependent resistors (LDR) are mounted, one on the PILOT and the other on the PANEL. After each positioning of the PILOT, a comparison process takes over. If the voltage induced by the PILOT LDR is greater than that induced by the PANEL LDR plus a preset offset, the PANEL aligns itself with the PILOT, otherwise, it stays at its current position, and waits for the PILOT to move to new position, and the process repeats itself. By doing so, the PANEL only moves to the new location when the latter produces higher energy. At the end of the day, after sun set, the system returns to its initial position and waits for the following day.

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1. Introduction

With the scarcity of fossil fuel as well as its warming effect on the environment, and the great danger posed by nuclear energy, such that suffered by Chernobyl nuclear disaster in 1986 and Fukushima nuclear disaster after the 15 m tsunami that hit Japan's coast, on March the 11th, 2011, and despite being rated to be highly safe, researchers have been looking for safe and cost effective alternative ways. They returned their attention towards

renewable energy such as wind, waves, heat, solar just to name a few. But amongst them all, probably solar energy has become more popular and has more chance to survive due to its abundance and decreasing cost and availability of its technology. But solar energy suffers from several drawbacks; up to recently its efficiency is considerably low. The cost was considerably high and most of the panels were stationary, so the extraction times is only limited to few hours a day. But with technology development, efficiency is climbing rapidly where it has been reported to be on the verge of 50% [Wesoff (2016) 24.1%, Green et al. (2016) 38.8%, King et al.

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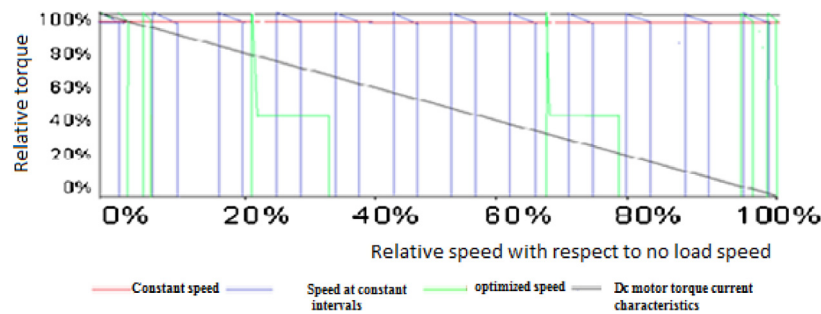


Fig. 1. Different scenarios of motor speed control. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2012), Solar cell (2012) 40%, Fraunhofer ISE (2016) 43.3%, Dimroth (2013) 44.7%, Hossain et al. (2016) 47.2%].

If the solar panels are fixed midway between east and west, the extraction time is roughly between 10 O'clock and 15 O'clock in the afternoon on average. In fact, Salman et al. (Sections-Clouds, 0000) have shown that solar irradiation in Bahrain, reaches more than 80% approximately between 10 O'clock and 15 O'clock. The experiment was conducted in the middle of summer on June the 26th. Thus, the extracted energy is very limited. If the cleaning cost is added to this, especially in dusty areas like ours, it is quite a difficult challenge to be competitive vis a vis the classical energy produced from fossil fuels. For solar energy to be competitive, at least two issues have to be addressed. One on the cell side, where scientists have to come up with cells with high efficiency and on the engineering side, engineers have to find the optimum positioning of the cells. In the past, people used solar energy with fixed panels midway between the geographical east and west with approximately 26.8° tilt angle towards the south (in Bahrain). Studies have shown that this is not ideal positioning for maximizing energy extraction. A better way is to orient the panels continuously towards the sun, using single axis or double axis. Single axis was chosen for the following reason. As it was mentioned before tilt angle is about 26.8° south (Georgantopoulou and Vasilikos, 2017). That means, it is not very far from the equator. This means that tilt angle needs to be adjusted only twice or three times per year. This could be done offline and may not require automation. In fact, Jafarkazemi and Saadabadi (2013) recommended that tilt angle could be at least changed twice every year in Abu Dhabi which has almost the same tilt angle as Bahrain. Determining the tilt angle requires another motor which requires extra energy consumption, but this is not significant because the tilt angle could be probably adjusted at most four times per year. Many researchers have published their work on the subject. Hession and Bonwick (1984) designed a sun tracker where the sun position is sensed using photo transistors connected to a 2.34-m² cylindrical parabolic collector mounted on a simple structure. Clifford and Eastwood (2004) reported that computer modelling predicted an increase in efficiency of up to 23% over fixed panels. They also claimed that experimental testing showed excellent agreement with computer model. Huang et al. (2011) developed a 1 axis 3 position sun tracking PV to measure the daily and term power generation of the solar PV system. Chin et al. (2011) designed a compact solar tracker mounted on a wall. This system was operated at different modes to accommodate for weather conditions. To increase still the efficiency of energy extraction, many two axes systems were developed. Al-Soud et al. (2010) have designed a parabolic solar cooker using two axes tracking system. They showed that the temperature inside the heating tube, reached 90 degrees Celsius. Even better, Abu-Malouh et al. (2011) reported that they constructed a solar cooking system, with a dish built to concentrate solar radiation on a pan that was fixed at the focus of the dish and they showed that the temperature inside the pan reached 93 degrees Celsius. Batayneh et al. (2013)

followed different approach by designing a fuzzy based two axis tracking system. Though, the system looks to be promising from simulation point of view, it needs to be tested experimentally. Bentahar et al. (2014) developed a solar tracking system based on LDRs using electro-optical tracking. They reported that acceptable results were obtained. Yao et al. (2014) presented a study dealing with multipurpose dual-axis solar tracker. The tracker uses a declination clock mounting system to locate the primary axis east-west direction. The secondary rotates at a constant speed of 15°/h. Ahmed et al. (2013) developed a hardware and software for sun tracking mechanism. The system has two axes tracking with accuracy of 1° controlled by a programmable logic controller. Sidek et al. (2017) presented a study on an automated positioning open-loop dual-axis solar tracking system.

2. Background

Despite the intensive research to maximize energy extraction by orienting the panels towards the sun, by continuously rotating the solar panels in order to track the sun, a major problem still remains. That is: to rotate thousands of panels, electric motors are required. Those motors draw very high currents to produce high starting torque especially at the start of rotation in order to overcome the panel's inertia. It is well known that in a DC motor, the torque is proportional to the armature current provided the excitation field is kept constant, according to Eq. (1)

$$T = K\phi I_a \quad (1)$$

where T is the torque in N m, K is constant depending on the coil geometry, ϕ is the flux in Weber, and I_a is the armature current in Amperes. It could also be noticed that to reduce the torque, hence the armature current, one needs to increase the speed. By referring to Fig. 1, the Torque is governed by:

$$T = -\frac{W}{W_s} T_s + T_s \quad (2)$$

where T is the torque in N m, W is the rotational speed in Radians/s, W_n is the rotational no load speed in Radians/s and T_s is the stall torque in N m (Collins 2015).

There are three different possible scenarios for motor drive. The first scenario is to drive the panels continuously at a very low speed (Ghassoul, 2010). This could result in feeding back the converted energy into the drive to overcome the torque without extracting additional energy if not more energy is fed back from the storage. On top of that, is the heating effect on the motors due to high torque hence high current. So this option is not feasible. This is shown in Fig. 1 in red where the motors draw high current continuously. The second scenario is to rotate the motors through a fixed angle at fixed periods of time (Ghassoul, 2001). This is shown in Fig. 1 in blue. Though the energy extraction efficiency has been improved because the driving motors rotate faster hence

smaller driving current, as well as they are at standstill most of the time, the energy extraction is not optimum. Moving panels from current step to the next does not mean net extra energy. The new position may or may not contribute to more energy extraction because the extra energy if any may be consumed by the drives. This has lead to a third scenario which is addressed here. The scenario is that the panels move to the new location only when the new position provides more energy then that consumed and by at least the predetermined offset. This is shown in green in Fig. 1. This scheme has two main advantages; one is that the new position does effectively contribute in extracting more energy and the gained energy is higher than that consumed. On top of that, as it will be shown later, unlike the other mentioned techniques in literature, it was found that only few movements are required during the whole day. In fact this study has shown that in the area where the study took place (Bahrain) less than six movements at most are enough. This latter scenario is the subject of the current study.

For a serially excited DC motor, the motor energy consumption when constant pulses are used is given by:

$$E_1 = R_T * I_{1s}^2 * t \quad (3)$$

And energy consumption when tracking is used:

$$E_2 = R_T * I_{2s}^2 * t \quad (4)$$

where R_T is the total rotor and stator winding resistor, I_{1s} is the average series current when constant steps are used and I_{2s} is the current when tracking is used. Because R_T is the same for both cases and t the total running time for the motor to rotate through the full run of 180 degrees is also the same, providing the speed is almost the same in both cases, it could be deduced that:

$$\frac{E_2}{E_1} = \frac{I_{2s}^2}{I_{1s}^2} \quad (5)$$

The Panel peak current was measured and found to be 1.05 A and the average currents were found to be $I_{1s} = 0.925$ A and $I_{2s} = 0.825$ A. The current ratio is: $\frac{I_{2s}}{I_{1s}} = \frac{0.825}{0.925} = 0.892$. The motor angular velocity was approximate to be the same in both cases and the transition from maximum current to nominal current to be almost linear. It was also noticed that the decay takes about 0.59 s (Fig. 1). It was noticed that the motor never reaches nominal current when rotated through small angles. Replacing I_{1s} and I_{2s} in Eq. (5):

$$\frac{E_2}{E_1} = \frac{0.825^2}{0.925^2} = 79.54\%. \text{ This leads to up to 20\% in energy saving.}$$

3. Design

To extract energy from the sun using photovoltaic devices, thousands of cells if not millions are required. This is possible in our region where space and energy are in abundance. As mentioned fixed panel is not the solution, and moving panels have to be carefully addressed. The scheme presented here addresses the design of an optimal positioning mechanism of the panels so that maximum energy is extracted with minimum movement of the panels and regardless of the weather conditions as well as the length of the day for different seasons, with minimum energy possible consumption by the drives. During cloudy or rainy days, irradiation will be certainly reduced whether fixed or moving panels are used; but the proposed system is not affected because even in these extreme conditions, it recovers and aligns itself properly due to the light detector which allows the system to rotate back if necessary. But this is not a major problem in Bahrain where it seldom rains. The scheme comprises of two submechanisms. The role of the

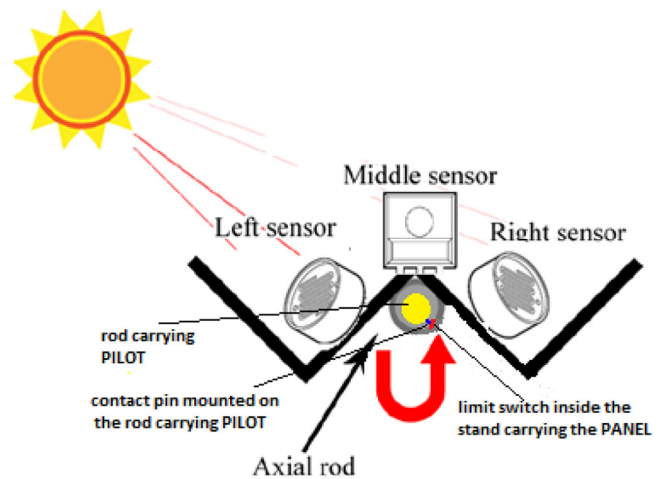


Fig. 2. Sensing mechanism mounted on the PILOT.

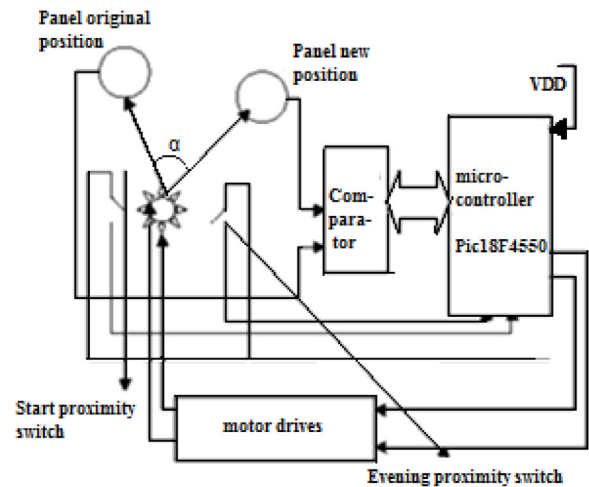


Fig. 3. Tracking system for maximum sun inclination angle.

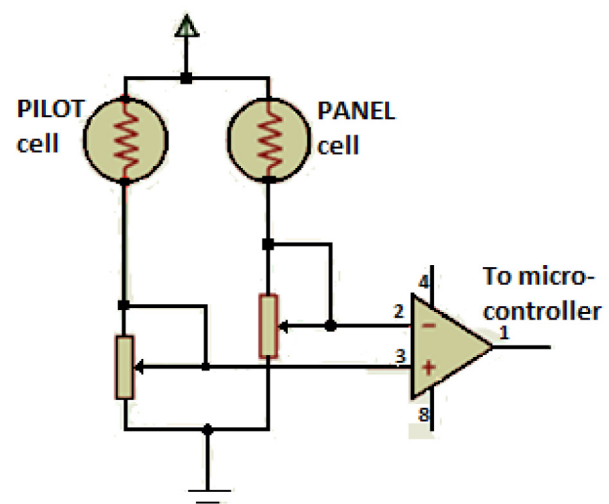
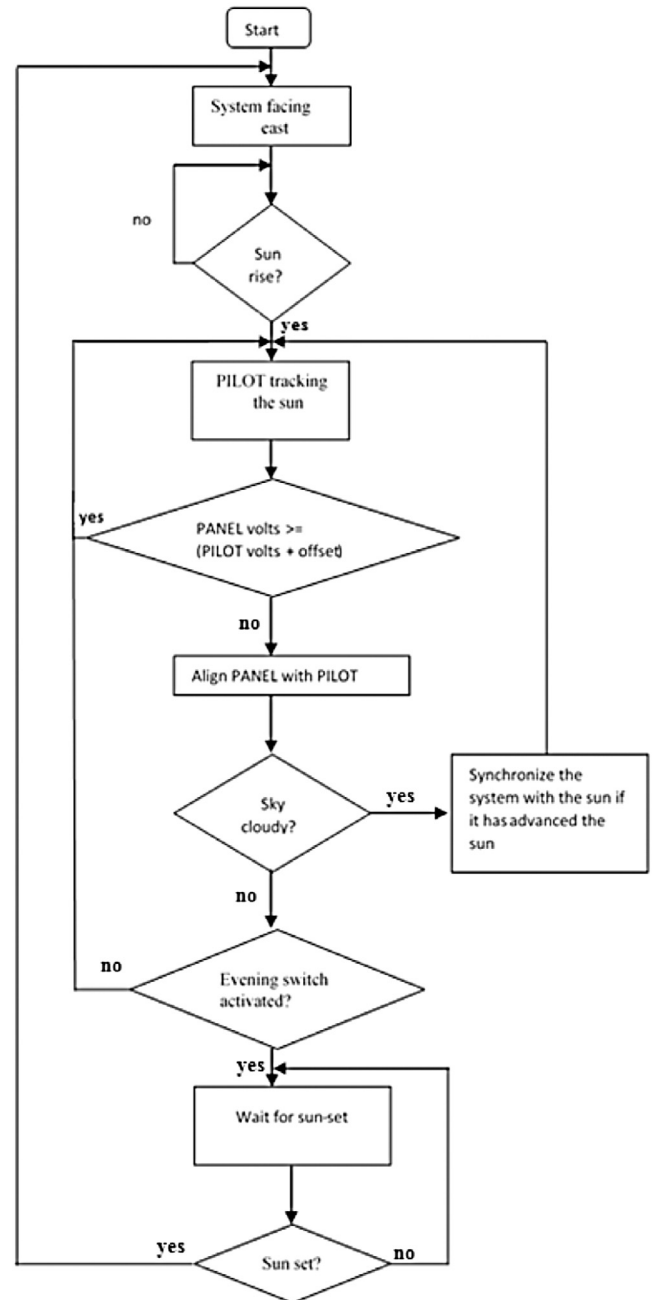


Fig. 4. Detection of voltage difference between PILOT LDR voltage and PANEL LDR voltage.

first sub-mechanism is to locate the position where maximum energy could be extracted from and is known as the PILOT, and

a second sub-mechanism is made up of the solar panels and is known as PANEL. The position is determined by using a search technique, based on the PILOT scheme. The PILOT is built around a small sensor mounted on a miniature electric motor, which only consumes a very tiny amount of energy. The tracking system is shown in Fig. 2. The optimum irradiation position is determined by three detectors working in synchronism; one is the TSL235R light to frequency converter (LTF) and two LDRs. The LTF combines a photodiode and a current to frequency converter on a single monolithic CMOS integrated circuit. It produces a 50:50 duty cycle square wave with frequency proportional to the light intensity (irradiation). According to the chip datasheet (2007), the device was designed to respond over the range of 320 nm to 1050 nm. The device has three main advantages. It does not need any extra circuitry. It could be interfaced easily to a microcontroller and it could be easily programmed to track the sun. The LTF is fixed on the middle tip of the W shape stand and the two LDRs in the troughs of the shape on either side of the LTF. The system works according to the following chronology. Before sun rise, both PANEL and PILOT point towards geographical east and wait for sun rise. For synchronization purpose, their position is determined by a proximity switch known as Start proximity switch (refer to Fig. 3). The aim of the PILOT is to freely track the sun. The tracking of the sun is done thanks to the light to frequency converter sensor (LTF). While the sun is continuously moving in its orbit, the LTF monitors the irradiation by converting it into frequency. As a consequence, the PILOT follows suit until maximum frequency is reached, it comes to a standstill. On each movement of the PILOT, a comparison of the induced voltage of the PILOT with the voltage induced at the previous position of the PANEL through two identical LDRs, one mounted on the PILOT and the other on the PANEL. This is shown in Fig. 4. If the voltage of the PILOT sensor is bigger than that of the PANEL by a preset offset value (The offset is programmable, so it could be set to any convenient value), indicating that the new location has a better energy extraction, the output of the comparator goes high, interrupting the microcontroller to guide the PANEL to align itself with the PILOT, until it activates a switch mounted on the inside wall of the tube carrying the PILOT, it comes to a standstill. The switch is just a micro limit switch fixed on the inside wall of the hollow stand carrying the PANEL. On activation, the PANEL rotates until it comes into the proximity of the PILOT where the macro-switch is activated by a small pin mounted on the rod carrying the PILOT. The PANEL then comes to a standstill. If the comparator does not go high, indicating that the new position does not contribute more energy extraction, the PANEL stays at old position and the PILOT continues the search and the procedure continuously repeats itself. For the tracking to be effective, three sensors are mounted on the PILOT; two LDRs and one TSL235R light to frequency converter. As shown in Fig. 2, the role of the left LDR is to locate the sun when it is on the left side, so the PILOT rotates towards the left; and the right sensor is to locate the sun when it is on the right side, so the PILOT rotates towards the right. The middle sensor (TSL235R) keeps the PILOT exactly facing the sun all the time, by converting the highest possible irradiation into the highest frequency possible. This technique is particularly useful during cloudy days, so the system differentiates between the diminution of the irradiation due to misalignment or it is due to cloudy sky. If it were due to cloud, and after the clouds clear, if the PILOT is in synchronism with the sun, it continues its tracking, but if the PILOT has advanced the sun, it adjusts itself by rotating back and aligns itself with the sun again and so does the PANEL. Luckily in this part of the world, the clouds only appear for few days per year. According to weatherspark (Ghassoul, 2001), more than 93% of the time, the sky is clear let alone rain, where it rains at most for less than 9.9 days per year (Light of frequency, 2007). So cloud is not a big issue. Because of the difference between

day length during different seasons, this has been accounted for by the tracking system, where the system never overpasses the sun regardless of the day length. However to make sure, in case that the tracking fails, a limit switch is placed exactly facing the geographical west known as evening switch, at 180° from the start. This is so, in order to avoid the system overrunning the trajectory during shorter days. When the switch is hit by the PILOT, the whole system comes to a standstill and waits for the sun to set. When that is the case, the whole system rotates back towards the start facing east and waits for the following day, and the procedure repeats itself. The beauty of the system is that only a single PILOT is required to drive a large number of solar cells. Fig. 5 as well as the flowchart below show the chronology of the tracking system during the full day including the possibility of cloudy days.



Flowchart showing the chronology of the tracking during the course of the day

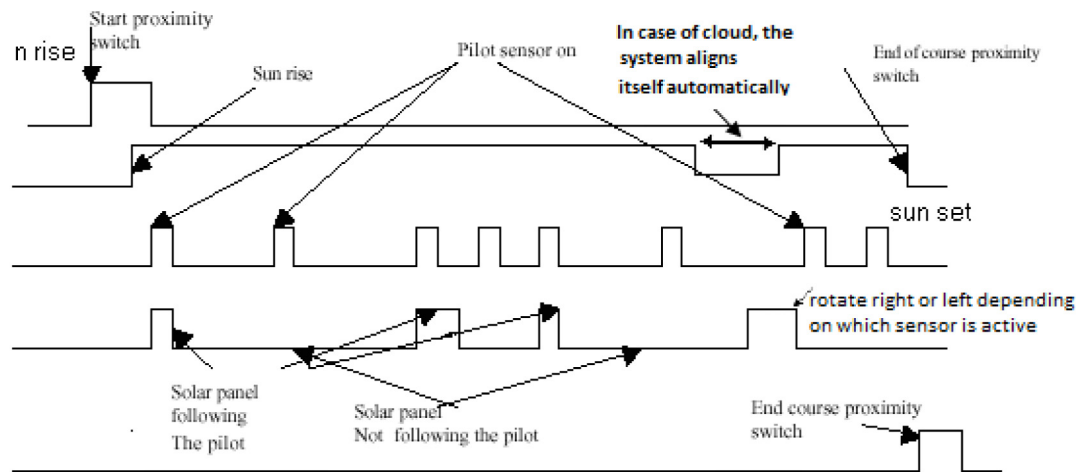


Fig. 5. Chronology of system during the course of full day.

4. Motor drive

For the PANEL to track the PILOT, a special design was adopted as shown in Fig. 6. The PILOT is mounted on a tiny very light rod, inserted into a hollow stand, on which is mounted the PANEL. The stand is driven by a miniature motor which only consumes a tiny amount of energy. When new optimum location is found, the PANEL rotates towards the PILOT. When it is exactly aligned with the PILOT, it activates a sensor which is mounted on the PILOT stand. This in turn triggers the microcontroller to stop the PANEL mechanism. Because both systems are rotating forwards and backwards, they are driven by an H-bridge with high current rating. The bridge used is L293d which could be either connected as a four half bridges or two full bridges. It has high current capability with a wide range supplying voltage varying from 4.5 to 36 V. This is shown as a block diagram as shown in Fig. 7. The first bridge drives the PILOT and the second one drives the PANEL. Each bridge is controlled by two tri-state buffers. Buffers 1 and 2 are used to control the PILOT's motor and buffers 3 and 4 are used to control the PANEL's motor. The four buffers are driven by the microcontroller digital PORTD, where RD0 is connected to buffer4, RD1 to buffer1, RD2 to buffer2 and RD3 to buffer3. The enabling pins of the buffers are tied to +5 V so that they are continuously enabled. For the PILOT motor to rotate clockwise, RD1 is pulled high and RD2 is pulled low. The current flows from RD1 through buffer1, to the motor through the bridge pin3 then out of the motor to bridge pin 6 then to the ground through pin RD2. When motor is to be rotated anticlockwise, RD1 is pulled low and RD2 pulled high. The current flows RD2 through buffer2, then out of pin6, through the motor then to the ground through RD1. Likewise, for the PANEL motor to rotate clockwise, RD0 is pulled high and RD3 low and the current flows from RD0 through buffer4, then through the motor and returns to ground through pin RD3. If the motor is to be rotated anticlockwise, RD0 is pulled low and RD3 is pulled high. The current flows from RD3 through the buffer3, then through the motor, then through buffer4 and returns to ground through RD0. If both RD1 and RD2 or RD0 and RD3 are simultaneously pulled high, no current flow through the motor. Needless to say, that the four flywheel diodes on each bridge are used to prevent the control circuit from any surge due to the rate of change of current during the switching. This design was adopted instead of using a classical transistor-based bridge in order to avoid any short circuit which may result by switching accidentally any two transistors on either leg of the bridge. This is shown in Fig. 8. The project was implemented using Microchip PIC 18F4550 flash microcontroller with specification shown in Table 1, and the

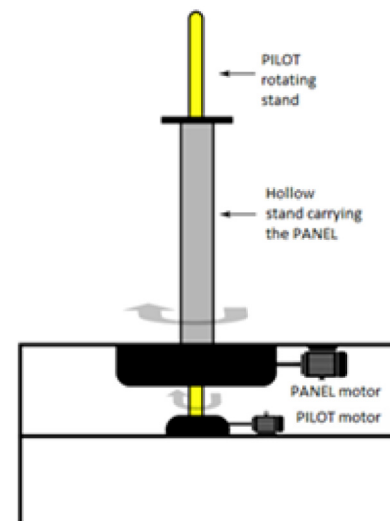


Fig. 6. PILOT stand inserted inside a hollow tube carrying PANEL with location sensor inside it.

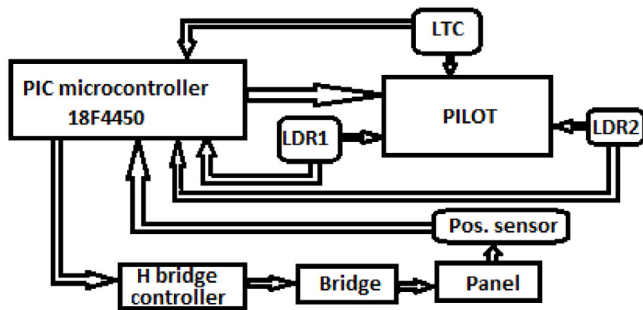
platform used is the Microchip MPLAB Integrated Development Environment, interfaced to an ICD3 debugging tool. The controller was inserted in a PICDEM 2 Plus demo board. The program was written using reduced instruction set computer (RISC) assembly language. The panel used for testing is an ICP Battery Saver Plus with dimensions 305×102 mm producing 125 mA at 15 V. The panel could be operated over a wide range of temperature (-40 to 80 °C). It has an internal diode which prevents power flow from the battery back to the panel. The output ranges from 17 to 25 V depending on the irradiation.

5. Experimental results and discussions

The system was tested using real data. In this study, voltage output was chosen instead of the usual power for the simple reason that different panels from different manufacturers produce different amount of power depending on the quality of the cells as well as the current produced; but here we are specifically concentrating on the effect of irradiation on the panels as a direct result of their positioning vis a vis the sun. So the open loop voltage is measured. The system was tested using real data. First by fixing the PANEL midway between east and west with a tilt angle of approximately

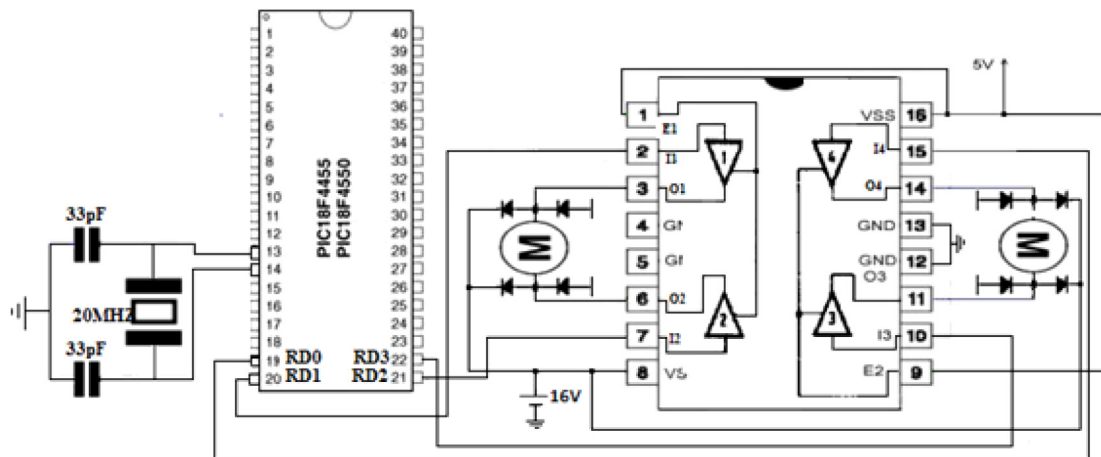
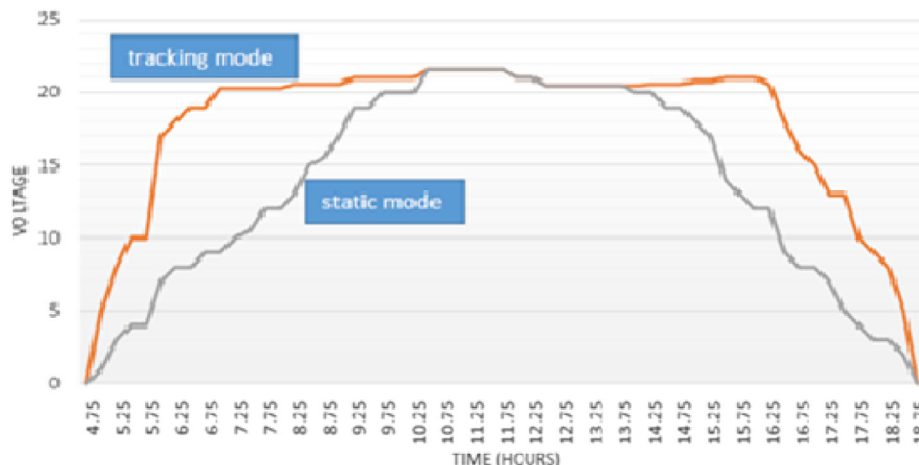
Table 1

Flash	Single word instruction	SRAM	EEPROM	I/O	10-bit A/D channels	SPI	USB	Timers
32 kb	16 384	2048 bytes	256 bytes	35	13	1	1	4

**Fig. 7.** Tracking diagram with the H-bridge to drive both the PILOT and the PANEL.

26.8° south and the output was recorded against time for the whole day. The response is shown as static mode in Fig. 9. It could be easily noticed that significant power is only obtained for approximately for five hours/day, from 10:30 to 15:30. This recording was made by the end of May. Unfortunately, this is not efficient enough where sun shines for about fourteen hours/day. The same test was

repeated but this time by allowing the PANEL to continuously track the sun. The output is shown in Fig. 9 as tracking mode. It could be easily noticed that maximum extraction time has more than doubled. That means near maximum power extraction is obtained from about an hour after sun rise where it gets hotter and stays near maximum up to about an hour before sun set. To make the picture clear, by comparing the area under the two curves, it could be easily deduced that the moving PANEL (continuous tracking) produces about 40% more energy that when it was stationary (static mode). Though this apparently shows a big improvement but, it may not be the case. The continuous rotating PANEL suffers from two major setbacks as discussed earlier. Because the driving motor is rotating at a very low speed, this may cause an important heat increase in the machine and most importantly, because of this very low rotating speed, the motor draws a very high current to generate high torque to drive the PANEL. This in turn results in unnecessary energy consumption. In fact, it could happen that the consumed energy is much bigger than that produced. If that is the case nothing is gained. The system was then tested using the optimizing technique and comparing it with the continuous mode. After superimposing the two responses on the same graph, we obtained the response shown in Fig. 10. It indicates clearly the

**Fig. 8.** Power drive to PANEL and PILOT motors.**Fig. 9.** Voltages for both stationary and moving PANEL.

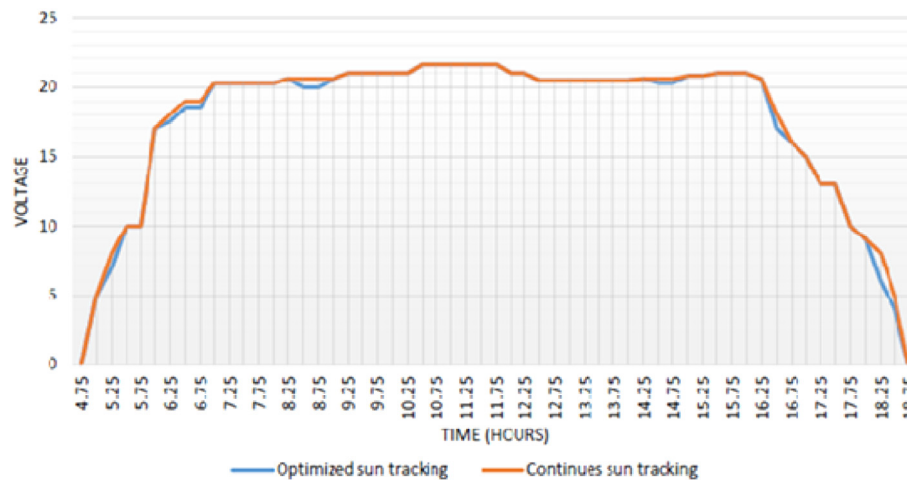


Fig. 10. Optimized tracking vs. continuous tracking.

extracted energy with the optimized technique is almost the same as that when the PANEL is continuously rotating and at the same time, the consumed energy is much less. It also shows that the number of movements of the PANEL is very limited during the whole day. In fact, only seven times at most, mostly during sun rise and sun set, where the sun irradiation increases and decreases rapidly respectively. While during the bright sun shine, it only needs between three to five movements, but through big angles in the order of 60 degrees. And this is what is exactly required. So the number of motor starts is very limited hence few starting recurrence torques hence current drawn is at its minimum. It is worth mentioning that clear or cloudy sky or even rainy does not affect the system because it is the same relative comparison which takes place in both cases regardless of the irradiation intensity. Last but not the least, the PANEL motor is very tiny and is drawing only 10 mA. This is negligible if compared to the PANEL's motor. In fact if thousands panels are used, we still need only a single PILOT to guide Them all.

6. Conclusions

It could be concluded that the proposed scheme does optimize solar energy extraction. By comparative study, which shows an increase of energy extraction by about 40% over fixed panels. The study has also showed the big advantage of the optimized scheme over continuously rotating panel. In fact it was found that the energy saving on the consumption side is just over 20%. More importantly during the peak hours where maximum energy is extracted, the panel only rotates for a handful times (in the case in hand only three times). On top of that the beauty of the scheme is that only a single tiny PILOT, drawing very small current, could be used to guide thousands of panels.

As a general conclusion, with the big progress in the cell design where it is on the verge of 50% efficiency mark together with a good optimum panels orientation like the one proposed here, with the saving on the energy consumption, the future of solar energy extraction looks very promising indeed.

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