Digital Communications and Networks 6 (2020) 51–57

Contents lists available at ScienceDirect

Digital Communications and Networks

journal homepage: www.keaipublishing.com/dcan

Wireless sensing for a solar power system

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ARTICLE INFO

Keywords:
Wireless communication
Wireless sensor network
Zigbee
Photovoltaic
Monitoring
Xbee

ABSTRACT

Wireless sensing is an excellent approach for remotely operated solar power system. Not only being able to get the sensor data, such as voltage, current, and temperature, the system can also have a proper control for tracking the Sun and sensing real-time data from a controller. In order to absorb the maximum energy by solar cells, it needs to track the Sun with proper angles. Arduino, H-bridge motor driver circuit, and Direct Current (DC) motor are used to alter the tilt angle of the solar PhotoVoltaic (PV) panel following the Sun while the azimuth and the elevation angles are fixed at noon. Unlike the traditional way, the tilt rotation is proposed to be stepped hourly. The solar PV panel is tilted 7.5° in advance of current time to the west to produce more output voltage during an hour. As a result, the system is simple while providing good solar-tracking results and efficient power outputs.

1. Introduction

Electricity, which is daily necessity, can be generated from a variety of resources including hydroelectric power, nuclear power, and off-grid systems such as solar, wind, and biomass. Having a solar panel in conjunction with the enormous amount of sunlight available in tropical countries can provide sufficient energy for lighting systems. With the efficiency of PhotoVoltaic (PV) cells being increased significantly in the past few years, solar energy has recently become more attractive to residential and industrial premises [1]. Light energy from the Sun is used by solar panels to generate electricity through the PV effect. The electricity is charged in a battery and controlled by a charge controller. This can ensure stable power supply that can operate at night time when the system receives no solar energy. The charge controller controls the electricity from the solar PV panel and distributes the Alternating Current (AC) or Direct Current (DC) to the electrical equipment [2]. However, when a problem occurs in the system, it is inconvenient to go to the place where the solar panel is assembled and check. Therefore, it is important for the user to be able to remotely monitor the entire system from other locations so that if there is an emergency, the responsible person can know it and take necessary safety actions immediately, for example, remote configurations, remote operation, and remote cutoff of battery power to DC-DC converter and motor, just to name a few.

From the perspective of wireless communication, a point-to-point two way wireless communication is usually considered. A wider variety of wireless data transmission technology has been reported, such as satellite communications [3]; Second-Generation (2G) digital cellular network, e.g., Global System for Mobile communications (GSM) [4,5]; short range communications, e.g., ZigBee [6,7], and other unspecified RF devices [8,9]. Among these wireless data transmission systems, ZigBee well matches our criteria when low power consumption, low cost, short data transmission time, close proximity and low data transfer rate are the key points of consideration [7]. In addition, ZigBee offers years (2–3 years) of operation on non-rechargeable battery and it can connect to more nodes ($2^{16} = 16$-bit address $> 65,000$), while Bluetooth only offers 8 devices connection in a piconet. Moreover, ZigBee is designed to monitor and control while Bluetooth is used just as a cable replacement. The power from a linear regulator has been used to prevent the effects of noise of switching regulator to XBee [10]. Different sampling intervals have been used in the previous works, ranging from as low as 1 s or less [11], 1 min [7], and up to an hour [12]. The data measurements are done at a sampling interval of 10 s on the first data collection and 3 min on the second data collection in our research. In Refs. [7,11] they have only implemented for wireless sensing whereas our system includes also visual alerts of the state of PV system at the remote user's computer.

1.1. Main contributions

At present, solar PV generation is assumed to be extremely important as a Renewable Energy Source (RES) application. The main contribution of this paper is to design and develop a ZigBee-based wireless sensing system for fully performing remote operation of a solar power system. ZigBee is a wireless 2.4 GHz standard built on IEEE802.15.4. A dual axis solar tracker including tilt angle in auto-mode and elevation in manual-

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https://doi.org/10.1016/j.dcan.2018.11.002
Received 6 January 2018; Received in revised form 15 August 2018; Accepted 14 November 2018
Available online 20 November 2018

mode is used to generate more electricity than a fixed rack. Moreover, a tilt rotation of solar PV panel is hourly performed by an Arduino control H-bridge motor drive. The “Processing” software, which is related to the Arduino programming and user-friendly, is used to program all features. The proposed system consists of the following six sensors: two voltage sensors, two current sensors, a converter transistor temperature sensor, and a tilt angle sensor. The system is intended to monitor all the parameters 8 hours a day (8:00 a.m. to 4:00 p.m.). The system hourly uses step tracking. The solar PV panel can supply power to all sensors, the Arduino with the XBee shield, and the corresponding circuits. While ZigBee is a standard as earlier mentioned, XBee is a product series name from Digi International. The battery is also charged with the solar PV panel. The power harvested from the solar PV panel is sufficient for our system. Moreover, a Compact Fluorescent Lamp (CFL) can be used at night time for lighting. Overall, the capabilities of the proposed system include continuously and remotely monitoring, remotely configuring, remotely disabling battery power to DC-DC converter and motor. In addition, the proposed system includes visual alerts at the remote user's computer.

2. System model

The block diagram of the system model is depicted in Fig. 1. The system consists of the mentioned sensing components, an on-board processing, a communication part and a storage including a solar PV panel, a H-bridge motor driver circuit, a DC-DC converter circuit, two XBee Znet 2.5 modules, two Arduino Uno microcontrollers, a computer, a DC motor, a battery, and six sensors. A solar PV panel is a device that converts light into electricity. The 12 V rechargeable sealed lead-acid battery is charged with solar power. It is connected to the DC-DC converter (12 V–300 V), which is a type of electronic circuit that takes the DC source and then converts it from the current voltage into another voltage. It is connected to the CFL that can be used at night time. A sensor is often not only responsible for data collection, but also for in-network analysis, correlation, and fusion of its own sensor data and data from other sensor nodes. Those six sensors include: 1) battery voltage sensor for measuring battery terminal voltage, 2) solar voltage sensor for measuring solar voltage, 3) solar current sensor for measuring solar current, 4) load current sensor for measuring current to DC-DC converter, 5) temperature sensor for measuring the temperature of the power transistor of DC-DC converter, and 6) tilt angle sensor for measuring the tilt angle of solar PV panel according to the voltage across the potentiometer. The potentiometer is used as a tilt angle sensor. The output pin of potentiometer is connected to the Pin zero of Arduino Uno. Data Transmission (bit-hour code) for hours voltage relation is shown in Fig. 2. When the clock strikes 8:00 a.m., the motor turns the solar PV panel, the potentiometer rotates as it is connected to the axis of the solar PV panel with gears. When the voltage across the potentiometer reaches 0.75 V and it is sent to the Arduino as Analog to Digital Converter (ADC) value, Arduino stops the motor.

When the clock strikes 9:00 a.m., the motor turns the solar PV panel. When the voltage across the potentiometer reaches 1.25 V, the Arduino stops the motor. Likewise, it happens hourly till 4:00 p.m. When the clock strikes 4:00 p.m., the program turns the motor back to the 8:30 a.m.

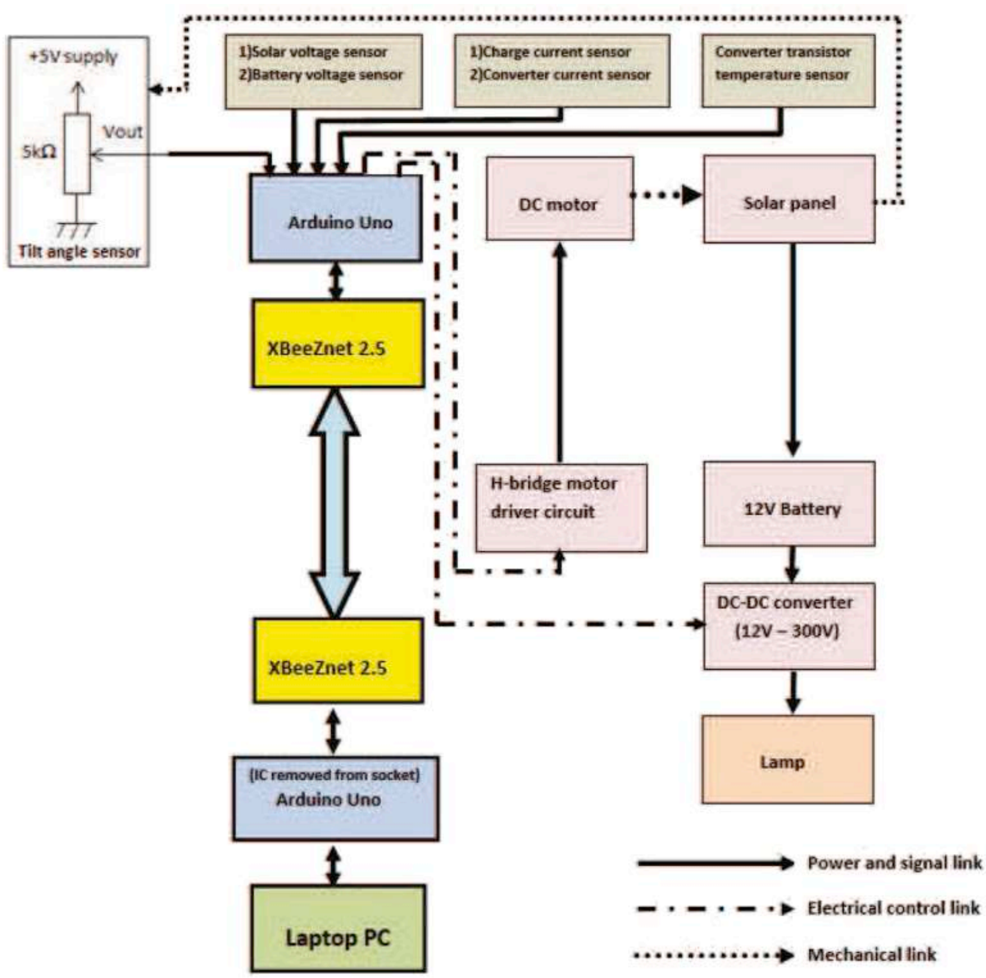

Fig. 1. Block diagram of system components.

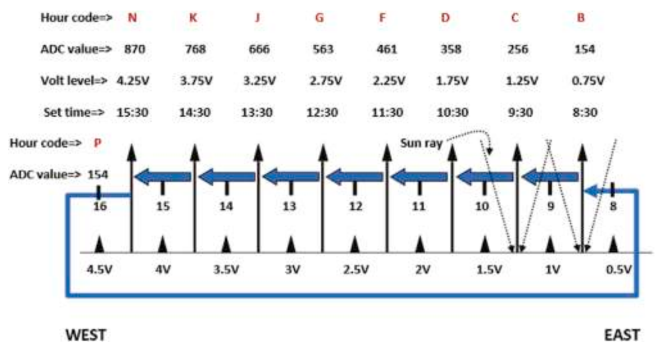

Fig. 2. Data transmission (bit-hour code).

position, as can be seen in Fig. 2. All these sensors are connected to the Arduino Uno (microcontroller), which is connected to an XBee ZNet 2.5 module used as a ZigBee end device. The XBee Znet 2.5 transmits signals, i.e., PV voltage, PV current, battery voltage, load current, and converter transistor temperature to the other XBee Znet 2.5 wirelessly. The second XBee Znet 2.5 used as a ZigBee coordinator is connected to a computer. The system control is done via a Graphical User Interface (GUI) created using Processing software. The voltages, the currents, and the temperature are displayed on the computer monitor.

Once the sensing components operate, the sensed data is sent to the computer using two XBee Znet 2.5 modules. The system control is done via a GUI created by Processing software. The real-time sensed data and status are also shown in the computer using GUI as shown in Fig. 3. The Arduino Uno turns the motor of the solar PV panel in hour-step via the H-bridge motor driver circuit. The net energy obtained from the solar PV panel is stored in the battery for supporting the CFL at night time.

The system provides the following key features:

1. Detecting transistor temperature,
2. Detecting solar voltage and battery voltage,
3. Detecting solar current and current to DC-DC converter (load current),
4. Tracking the Sun using DC motor, and
5. Display the results on the computer.

Fig. 3. GUI using Processing software in main base control system.

With all these features, the system can be beneficial to residential as well as industrial premises.

2.1. Solar astronomy

In summer time, the solar PV panel elevation is given by

$$\psi = Lat - 23.5 \tag{1}$$

where *Lat* is latitude. In winter time, the solar PV panel elevation is given by

$$\psi = Lat + 23.5 \tag{2}$$

Total elevation changes is equal to the subtraction of the winter elevation and the summer elevation as

$$Total\ elevation\ changes = Lat + 23.5 - (Lat - 23.5) = 47^{\circ} \tag{3}$$

Thus, $47/6 = 8^{\circ}$ in average changes from month to month. The declination angle is calculated as

$$\delta = 23.45 \sin\left[360\frac{(283.75 + n)}{365}\right] \tag{4}$$

and

$$Panel\ elevation(\text{in Bangkok}) = \delta - Lat \tag{5}$$

where δ is the declination angle and n is the day of the year such that $n = 1$ for January 1^{st} [13].

2.2. Solar-tracking methods

Solar-tracking systems are usually classified into two categories: passive (mechanical) and active (electrical) trackers [14]. Solar trackers are highly efficient, and are a great fit for both large and small project sites given a proper location and site conditions [15]. The direct power loss *Loss* (in%) due to the misalignment θ is computed as [15].

$$Loss = 1 - \cos(\theta) \tag{6}$$

Table 1 shows the power loss versus the time difference between the solar PV panel and the Sun [15]. In our case, the misalignment is 3.75°, the maximum power loss is calculated based on the azimuth and the tilt misalignment and is equals to 2%, which can be negligible. Unlike some literature, for instance [16,17], which use one axis three positions tracking solar PV, we use a dual axis tracking solar PV system, which provides two degrees of freedom that act as the axes of rotation. These axes are typically normal to one another. A dual axis tracker allows for optimum solar energy levels due to its ability to follow the Sun vertically and horizontally. No matter where the Sun is in the sky, a dual axis tracker is able to angle itself to the direction towards the Sun. In stand-alone solar PV system, the tilt misalignment is 37.5° and the power loss is 20.66%. The azimuth misalignment is 5° and the power loss is 0.38%. Consequently, the overall power loss based on both the azimuth misalignment and the tilt misalignment equals to 21.04%.

The Sun traverses 15° per hour as it moves across the sky from the east to the west. Hour angle ω is defined as the angular displacement of the

Table 1
Power loss versus time difference between the solar PV panel and the Sun for five different misalignments [15].

θ (degree)	Time Difference (hours)	Power Loss (%)
15°	1	3.4
30°	2	13.4
45°	3	30
60°	4	>50
75°	5	>75

Sun, either the east or the west of the local meridian due to the rotation of the Earth on its axis at 15° per hour. At solar noon (the time when the Sun is directly overhead) the hour angle is zero. In the morning it is negative, while in the afternoon, it is positive [18]. The variation of the hour angle over a day is at 15° per hour. Therefore, the hour angle is calculated as

$$\omega = 15(t - 12)\text{degrees} \tag{7}$$

t is solar time in hours. For example, at 10 a.m. and 4 p.m. the hour angles are −30° and 60°, respectively.

In our system, the sunray travels 7.5° from the vertical line. Fig. 4 shows that the angle of the vertical line to the solar PV panel is always 7.5° to the west of current-hour line. In Fig. 5, the Sun travels 7.5° from the vertical line. It shows that the Sun travels only 7.5° to and away from the vertical line during an hour.

When the clock strikes 1 p.m., the Arduino program turns the motor to make the right-angle-line 7.5° away from 1 p.m. to the west. The sunray and the tracking go on, as shown in Figs. 4 and 5, until 4:00 p.m. and the program turns the motor back to 8:30 a.m. position when the clock strikes 4:00 p.m. It produces more output voltage during an hour.

A small solar tracker set is built to test the correctness of information available from different sources. The tilt, azimuth, and elevation are measured by the set as shown in Fig. 6. The solar tracker complete set and the elevation adjustment with the viewing pad are also shown in Fig. 6.

2.3. Design of dual axis solar tracking PV module

The design of a solar tracking system usually can be done by one of the following methods or a combination of them: 1) altering the tilt; 2) altering the azimuth; 3) altering the elevation, and any combination of method 1, method 2, and method 3. The combination of method 1 and method 3 is used in our system. The elevation is calculated for the whole year using (4) and (5). We track the Sun by altering elevation angle once a month manually and altering the tilt automatically. When altering the tilt, we use the 7.5° based method as earlier introduced.

2.4. Data transmission

The data transmission from the bits to the hours codes including the Arduino Analog to Digital Conversion (AADC) value is shown in Fig. 2. The bit size used is 10 bits, which is equal to $2^{10} = 1024$ values, (0–1023). Thus, the conversion voltage 5 V equals to 1023/5 = 204.6 values per V. The AADC value is calculated by multiplying the voltage level and the values per V. Therefore, value between each adjacent hour is 1 h or 102 AADC value or 0.5 V. The tilt rotation is hourly done by the Arduino control H-bridge motor drive. When the Personal Computer (PC) time reaches 8:00 a.m., the program turns the motor to the 8:30 a.m. position. When PC time reaches 9:00 a.m., the program turns the motor

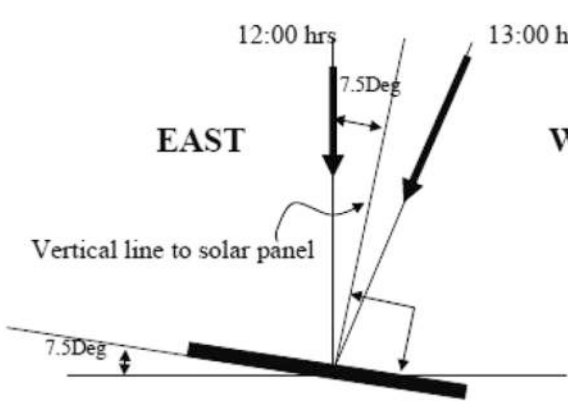

Fig. 4. The angle of the vertical line to the solar panel is always 7.5° to the west of the current-hour line.

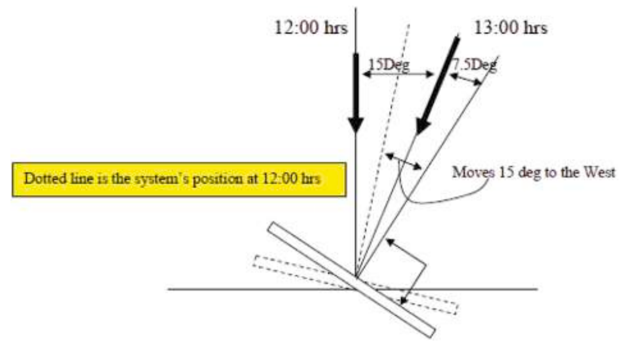

Fig. 5. When clock strikes 1p.m., the Arduino program turns the motor to make the right-angle-line 7.5° to the west of 1p.m.

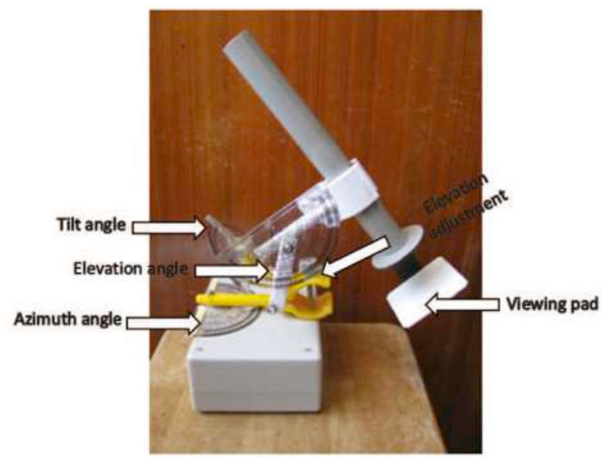

Fig. 6. Solar tracker complete set.

to the 9:30 a.m. position. Likewise, the program turns the motor back to the next day morning 8:30 a.m. position when the time reaches 4:00 p.m. as shown in Fig. 2. The XBee end device sends the sensed data (battery voltage, PV voltage, PV current, load current, and temperature of the power transistor of DC-DC converter) to the XBee coordinator every 10 s. The XBee end device gets the hour data from the XBee coordinator to alter the tilt angle in auto-mode. It can also read the data to rotate the tilt of the solar PV panel in manual-mode. It reads the power on/off data to turn on/off the CFL lamp. At the XBee coordinator side, IC 1 ATmega 16U2 is used. IC2 ATmega 328P is removed when the Arduino board is used as USB dongle. At the XBee end device side, IC 1 ATmega 16U2 is not connected to the USB port to avoid conflict between ATmega 328P and XBee. IC2 ATmega 328P is used and the Arduino program resides in it as shown in Figs. 7 and 8. The detailed description of data transmission between the XBee coordinator and the XBee end device is shown in Figs. 7 and 8.

3. Experiments

The system components of the proposed solar power system including the solar panel, the XBee end device, are installed outdoors as shown in Fig. 9, while a Personal Computer (PC) and the XBee coordinator are installed indoors. An actual tracking uses the tilt and elevation method. Since the tilt angle relates to the solar hour angle, which 1 hour equals to 15°, the PC real-time clock is used to turn the solar PV panel. The Arduino-Uno with the XBee shield and the "Processing" software are interfaced. The slave unit (Slave) reads battery voltage, PV voltage, PV current, load current, and temperature of the power transistor of DC-DC converter and then sends all the read data to the master unit (Master). Slave reads the hour data from Master to alter the tilt angle and reads the

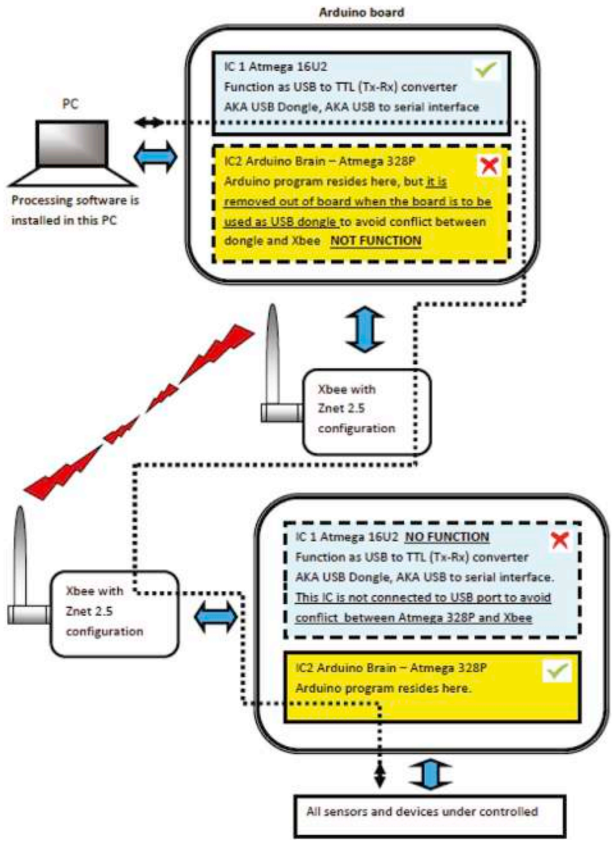

Fig. 7. PC and XBee End Node communication.

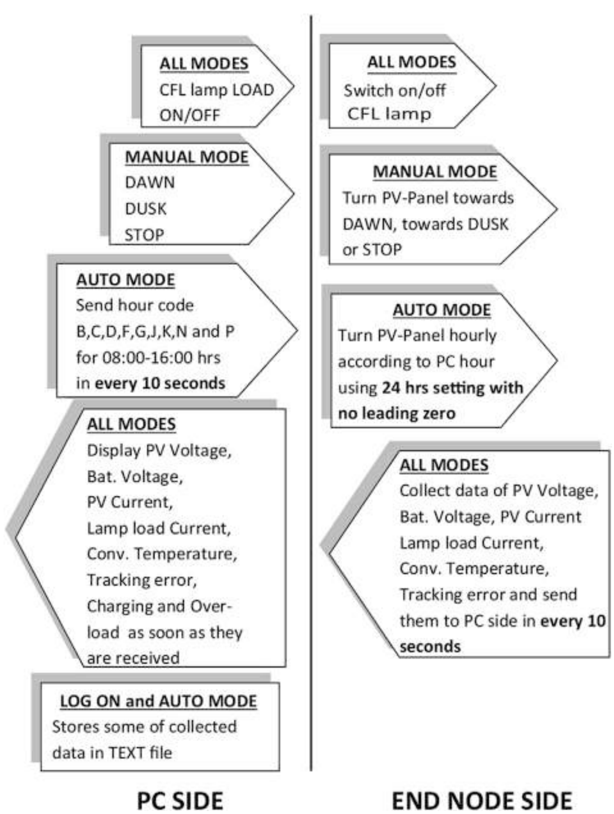

Fig. 8. Data transmission between the XBee coordinator and the XBee end device.

Fig. 9. Testing of wireless sensing of a solar power system.

power on/off data to turn on/off the load power. Slave reads all parameters once per 10 s and sends all the read parameters to Master. The Graphical User Interface (GUI) from the "Processing" software is used as the data collection and the mouse pressed buttons command to turn on/off the lamp, to rotate the tilt of solar PV panel in both auto-mode and manual-mode, and to log on/off the data as shown in Fig. 3. When both LOG ON/OFF button and AUTO button are chosen, the data is saved into the processing folder as text files. It is important to note that the PC time setting must be 24 hours with no leading zero.

The best way to harvest maximum daily energy from the Sun is to use correct tracking system. In the fixed racking systems on the roof, there is no dramatic change for power with offset angle (misalignment) from 10° to 20°, depending on the properties of PV used. When normal quality PVs are in the fixed racking, enough energy cannot be generated from these PVs. If the solar panels are installed in a fixed position, the optimum orientation is south facing and the optimum elevation angle depends only on the latitude in the northern hemisphere [19]. For example, as the latitude of Bangkok is 14°, the solar PV panel is fixed 14° elevated from the horizontal and oriented in south facing position. Instead of the solar PV panel in a fixed position, the tilt and elevation adjustment tracking system is used as it is more efficient, reasonable in cost, and simple. The system changes the elevation once in every month manually and the tilt in hour-step automatically.

4. Results and discussion

The data measurements are done for two days. Two scenarios are included in a ZigBee-based wireless sensing for a solar power system. The comparative tests between the fixed PV and the dual-axis tracking PV are carried out with one stand-alone solar powered CFL lighting system. In the first scenario, the dual axis solar tracking with 7.5° advanced tracking method is operated and the corresponding parameters are monitored. In the second scenario, the fixed racking is operated with the same solar PV panel and the corresponding parameters are monitored. The weather was partially diffuse in partly cloudy sky on April 29th, 2017. The data collected on the 1st day is based on the 7.5° advanced tracking method as shown in Figs. 10 and 11. The weather was clear sky, partly cloudy, and bright on April 30th, 2017. The data collected on the 2nd day is based on the fixed racking system, the tilt is fixed (the solar PV panel is facing to the south) and the panel's elevation is the latitude of Bangkok, i.e., 14° as can be seen in Figs. 12 and 13. The PV output is directly connected to test load (30 Ω wire wound resistor) to measure the data of the system.

In the following paragraph, we represent the energy calculation of our 7.5° advanced tracking system. Let the abbreviation of hour be h. We monitor the following parameters from 8:00 a.m. to 4:00 p.m. on a day:

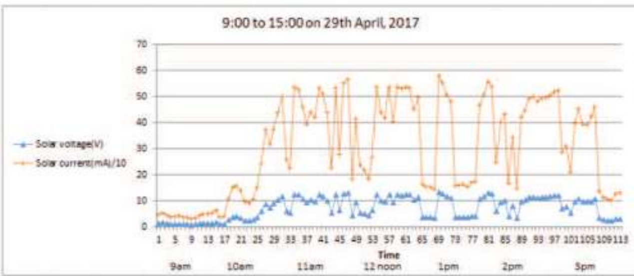

Fig. 10. Measured (from 9:00 a.m. to 3:00 p.m.) solar voltage and solar current.

Fig. 11. Measured (from 9:00 a.m. to 3:00 p.m.) solar power.

Fig. 12. Measured (from 10:00 a.m. to 2:22 p.m.) solar voltage and solar current.

Fig. 13. Measured (from 10:00 a.m. to 2:22 p.m.) solar power.

- The energy given by the solar cell equals to the average power[1] $\times$ 8 h[2] $= 7 \times 8 = 56$ W-hours.
- The energy taken by the XBee transmitter and the receiver equals to 3.3 V $\times$ 40 mA $\times$ 8 h $= 1056$ mW-hours $= 1.056$ W-hours.[3]
- The energy taken by the Arduino equals to 5 V $\times$ 10 mA $\times \frac{8}{1000}$ $= 0.4$ W-hours.[4]
- The energy taken by the motor,
  – When the motor starts at 120 mA[5] for 0.5 s[5] $\times$ 7 during 9:00 a.m.-3:00 p.m.[6], equals to $(120 \times 12\,\mathrm{V}$[7] $\times 0.5 \times 7)/(1000 \times 3600)$ W-hours $= 0.0014$ W-hours,
  – When the motor runs at 40 mA[8] for 1.5 s[9] $\times$ 7, equals to $(40 \times 12 \times 1.5 \times 7)/(1000 \times 3600) = 0.0014$ W-hours. Therefore, the total energy equals to 0.0028 W-hours,
  – When the motor starts at 120 mA for 0.5 s $\times$ 1[10], at 4:00 p.m., and the solar panel returns back to 8:30 a.m. position, equals to $(120 \times 0.5 \times 12)/(1000 \times 3600) = 0.0002$ W-hours,
  – When the motor runs at 40 mA for 15 s[11], equals to $(40 \times 12 \times 15)/(1000 \times 3600) = 0.002$ W-hours.

In addition, the energy available for other devices is investigated. The energy from solar cell-energy drawn by the XBee, the Arduino, and the motor is computed as 56–1.056–0.4–0.0028–0.0022 = 54.539 W-hours, this energy can light the 5 W CFL lamp for 10 h. Therefore, the energy efficiency of our system is equal to $54.539 \times \frac{100}{56} = 97\%$.

In the following paragraph, we represent the calculation of energy difference between our tracking system and the stand-alone system. The surplus power from the 7.5° shift tracking method can be gained over the fixed mount system. We pick the power level more than 6 W a day (High Jump method). When using the 7.5° shift tracking method, the weather is poor, i.e., partially diffused sky with moving low clouds, and we have 18 points of occurrence. Each point's time span is 3 min and the total energy of these points are computed as the average power $\times$ 3 min $\times \frac{18}{60} = 6.73 \times 3 \times \frac{18}{60} = 6.057$ W-hours. When using the fixed mount method the weather is good, i.e., blue sky with moving low clouds and we have only 5 points of occurrence. The total energy of these points are computed as $6.42 \times 3 \times \frac{5}{60} = 1.605$ W-hours. Therefore, the total energy difference of these two methods is 6.057–1.605 = 4.452 W-hours. If we deduct the energy used by the Xbee, the Arduino, and the motor, i.e., 4.452–1.056 - 0.4–0.0028 - 0.0022 = 2.991 W-hours. This means that we can obtain the positive gain even the weather is not favoring. For a larger system, available energy is likely much higher than the loss of the XBee, which is fixed at 1.056 W-hours, and then the loss of the Arduino, which is fixed at 0.4 W-hours. The motor consumption is a little higher but is a still very low figure due to the short period of usage. The energy of the stand-alone system equals to $6.42 \times 8\,\mathrm{h} = 51.36$ W-hours. The compared energy efficiency to the tracking system equals to $51.36 \times \frac{100}{56} = 91.71\%$.

Table 2 shows the comparison of our tracking system and the stand-alone system. From the results, we can see the number of the points of occurrence above the power level of 6 W as the mean level as shown in Figs. 11 and 13. This provides the energy more than that of the fixed racking method yielding the positive gain of 2.991 W-hours. It means that our system tries to retrieve the power for more times than the fixed racking system throughout the day, even in poor weather conditions as can be seen in Fig. 14. Not only wireless sensing of the PV system, e.g. [6,7,11], but also a PV design with the new 7.5° advanced tracking method is performed in our study. The measured power loss due to the misalignment of our system is 2%. One axis three positions (1A-3P) tracking solar PV with stand-alone solar-powered LED lighting system has around 8% power loss due to alignment error to south direction installation for the maximum misalignment 45° [16,17]. The power loss due to the misalignment of our system is 6%, less than that of the 1A-3P tracking PV system. Therefore, it can be concluded that our 7.5°

[1] The measured average power is 7 W.
[2] 8 h is the duration from 8:00 a.m. to 4:00 p.m.
[3] It is calculated based on the specifications of Xbee Znet 2.5 module.
[4] It is calculated based on the specifications of Arduino Uno.
[5] Those values are measured by using oscilloscope.
[6] The motor turns 7times hourly from 9:00 a.m. to 3:00 p.m.
[7] The 12V dc motor was used.
[8] The running current of motor is 40 mA.
[9] It is the time taken of the motor running current flows.
[10] The motor also turns 1 time as the program turns the motor back to the next morning 8:30 a.m. position when the times reaches 4:00 p.m.
[11] It is the time taken to turn the motor back to the next day morning 8:30 a.m. position when the time reaches 4:00 p.m.

Table 2
Comparison of our tracking system and the stand-alone system.

	Tracking system	Stand-alone system
Energy Efficiency (η)	97%	91.71%
No. of points above 6 W a day	18 points of occurrence	5 points of occurrence
Total energy/day (Power level>6 W)	6.057 W-hours	1.605 W-hours
Losses due to misalignment of tilt angle and azimuth angle	2%	21.04%

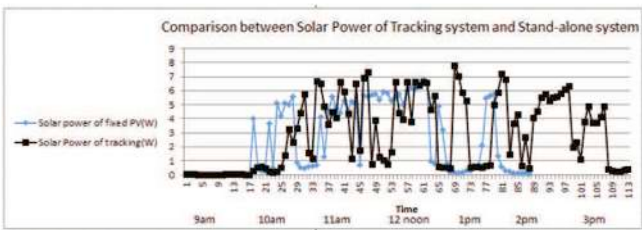

Fig. 14. Measured solar power of the tracking system and the stand-alone system.

advanced tracking method has excellent performance.

5. Conclusion and future works

The wireless sensing for a solar power system was designed and developed. It is a low power consumption and cost-effective solar PhotoVoltaic (PV) wireless sensing system using ZigBee technology. The Arduino based solar tracker with dual axis tracking was developed. The tilt of the solar PV panel is able to be controlled in auto-mode and manual-mode wirelessly. The energy from the Sun can be effectively harvested to drive our system. The Graphical User Interface (GUI) using "Processing" software is used to monitor real-time voltages, currents, and the state of the PV system. The experiments were performed under a moving cloud condition. The developed system offers the following advantages:

- It can be monitored remotely.
- Sensor nodes are electrically protected by fuse and electronic circuit.
- The dual axis tracking (time angle in auto-mode and elevation in manual-mode) is simple and effective.
- The DC-DC converter circuit and the H-bridge driver circuit are efficient.
- The visual indication of the state of PV system, such as No Tracking Error or Tracking Error Found, Charging or No Charging, Battery OK or Battery low voltage and Overload, are shown according to real situations.

Some proper modification should be done if this system is intended to be used for other places with different environments and weather conditions. In conclusion, the system is effective in terms of performances, cost, and power consumption.

Acknowledgements

I would like to thank my supervisor, Dr. Attaphongse Taparugssanagorn, for his guidance, constant encouragement, dedication and support to complete my work. Special thanks to Asian Institute of Technology (AIT), Pathum Thani, Thailand for providing financial assistance which had enabled me to undertake this research project.

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