Solar Tracking System

Design based on GPS and Astronomical Equations

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***Abstract*— The paper presents the design of a reliable, accurate, and easy to install solar dual axis tracking system. This system utilizes the GPS for fixing the time, date and location in terms of longitude and latitude. Astronomical equations with good accuracy are selected to find the sun locations according to the tracker in any chosen location on earth. The proposed system is standalone, accurate, durable, reliable, and cost efficient. Annual energy assessments of the system are also given.**

Keywords—component; Solar tracker; Sensorless Tracker; Dual axis trackers; embedded system, microcontroller; GPS based system.

I. INTRODUCTION

In a step to overcome the limitations of sensor based solar tracking system, a design tracking strategy is presented which is based on astronomical equations. This strategy has to take two important factors into consideration. The first one is finding the more accurate equations and figure out the ability of implementing such system which can deal with these complicated equations that are based mainly on trigonometric functions. The second factor is how to design a reliable, uninterrupted, accurate and global system that is able to calculate the local time, date and location in terms of longitude and latitude.

So the main aim of this paper is to design a global dual axis solar tracker that can process the data with high efficiency and is able to deal with these complicated equations and gather the required data from the GPS card and save and manage them in accurate, reliable and uninterrupted real time controller. The Plug in GPS card may be built in the main card or can be plugged in only in the initializing phase [1,2].

II. RADIATION INCIDENT ANGLE

The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the sun). However, as the angle between the sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight. The percentage tracking efficiency η_T in terms of the incidence angle θ is defined as:

$$\eta_T = (100.\sin(\theta))\ \% \qquad (1)$$

Fig. 1 shows the efficiencies for different incidence angles.

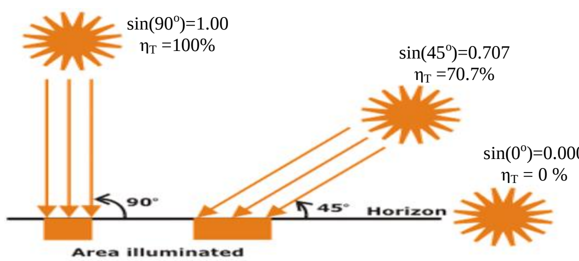

Fig 1. The efficiencies for different incident

The lower Sun angle (45°) causes the radiation to be received over a much larger surface area. This surface area is approximately 40% greater than the area covered by an angle of 90°. The lower angle also reduces the intensity of the incoming rays by about 30% [1,2].

III. GPS RECEIVER

Presently, GPS is fully operational and meets the criteria established in the 1960s for an optimum positioning system. The system provides accurate, continuous, worldwide, three-dimensional position and velocity information to users with the appropriate receiving equipment. GPS also disseminates a form of Coordinated Universal Time (UTC). The satellite constellation nominally consists of 24 satellites arranged in 6 orbital planes with 4 satellites per plane. A worldwide ground control / monitoring network monitors the health and status of the satellites [3].

The Fastrax UP500 module supports enhanced navigation accuracy by utilizing WAAS/EGNOS corrections. The Fastrax UP500 module provides complete signal processing from the internal antenna to the serial data output in NMEA messages. PPS signal output is available for accurate timing applications. The Fastrax UP500 module interfaces to the customer's application via one serial port, which uses CMOS voltage levels. If RS232 signal levels are required, there is a variant of Fastrax UP500 available with on-board CMOS-to-RS232 level converter. PPS output is available from the module with

CMOS levels. This E-block allows investigation of the global positioning system used in modern satellite navigation equipment. The board allows GPS to be added to microcontrollers and other processors that do not have GPS peripherals embedded into them. The board uses a state of the art UP500 GPS module from Fastrax. The GPS module uses multiple orbiting satellites to calculate its position. Once an initial position has been acquired the GPS receiver continues to send position information directly to the microcontroller ready for further processing. The GPS is also capable of streaming universal time and date data (UTC) directly to the microcontroller for use in the specified application [4].

IV. GPS SENTENCES

There are many sentences transmitted by the GPS but the following information describes the most common NMEA-0183 sentences transmitted by GPS receivers. The NMEA standards as shown in Table I provide quite a range of sentences, but many are related to non-GPS devices and some others are GPS related but rarely used. NMEA mode is the most recommended for new GPS applications to give maximum compatibility with all GPS receivers. Most GPS receivers also have a binary mode but it is normally best to reserve the use of binary GPS protocols for applications that really require their use, such as those requiring position updates of greater than once per second [5].

TABLE I. COMMON NMEA SENTENCE TYPES

Common NMEA Sentence types	
Sentence	**Description**
$GPGGA	Global positioning system fixed data
$GPGLL	Geographic position - latitude / longitude
$GPGSA	GNSS DOP and active satellites
$GPGSV	GNSS satellites in view
$GPRMC	Recommended minimum specific GNSS data
$GPVTG	Course over ground and ground speed

The RMC sentence has been adopted in this project because it has all the required information. Details of the following example code ($GPRMC,092204.999,A,4250. 5589,S,14 718.5084,E,0.00,89.68,211212,,*25) are shown in Table II.

TABLE II. RECOMMENDED MINIMUM SPECIFIC GNSS DATA

RMC		
Field	**Example**	**Comments**
Sentence ID	$GPRMC	
UTC Time	092204.999	hhmmss.sss
Status	A	A = Valid, V = Invalid
Latitude	4250.5589	ddmm.mmmm
N/S Indicator	S	N = North, S = South
Longitude	14718.5084	dddmm.mmmm
E/W Indicator	E	E = East,
Speed over ground	0.00	Knots
Course over	0.00	Degrees
UTC Date	211212	DDMMYY
Magnetic variation		Degrees
Magnetic variation		E = East, W = West
Checksum	*25	
Terminator	CR/LF	

The local time can be found as shown in (2), (3) and (4) below. The date is also available in this sentence taking into consideration that when local time is crossing the midnight in local area date should be increment by one day.

- Local Standard Time Meridian (LSTM)

The Local Standard Time Meridian (LSTM) is a reference meridian used for a particular time zone and is similar to the Prime Meridian, which is used for Greenwich Mean Time.

The (LSTM) is calculated according to the following equation:

$$LSTM = 15°.\, \Delta T_{GMT} \quad (2)$$

Where ΔT_{GMT} is the difference of the Local Time (LT) from Greenwich Mean Time (GMT) in hours. 15°= 360°/24 hours.

- Time Correction Factor (TC)

The net Time Correction Factor (in minutes) accounts for the variation of the Local Solar Time (LST) within a given time zone due to the longitude variations within the time zone, and the Equation of Time (ET). It is given by:

$$TC = 4\,(longitude - LSTM) + ET \quad (3)$$

The factor of 4 minutes comes from the fact that the Earth rotates 1° every 4 minutes.

- Local Solar Time (LST)

The Local Solar Time (LST) can be determined from the previous two corrections to adjust the local time (LT):

$$LST = LT + (TC/60) \quad (4)$$

Note that angles in degrees and minutes may be converted into regular form as follows:

$$Angle\ (degree) = Degree + (Minute/60) + (Second/3600) \quad (5)$$

V. TRACKER STRUCTURE

The adopted mechanical structure and the tracking technique are shown in Fig. 2. It is based on full tracking with tilt and polar angles. The system uses two actuators with built in reed sensors [6]. The figure shows the design structure which can carry six solar panels (130 watts, 11 kg each) as a static load taking into consideration the dynamic loads such as wind and rain.

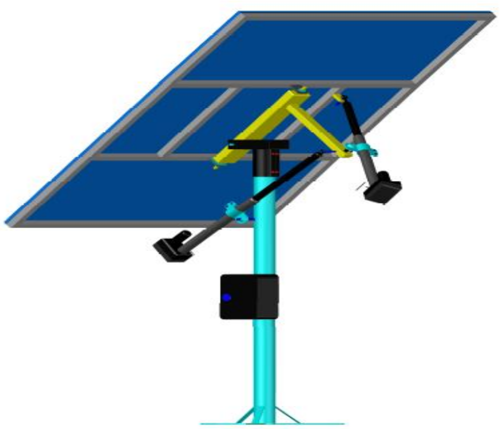

Fig 2. Tracker structure

VI. THEORY OF TRACKING

The proposed system tracks the sun based on astronomical equations. These equations are important to calculate and manage the tracking system. Some of these equations are described in many forms with different accuracies in comparison with the reference published astronomical tables. The basic two of these equations used for sun tracking purposes are the Declination Angle (δ), and the Equation of Time (ET). The following equations were selected in terms of minimum least squared error criteria [6,7].

A. Astronomical Equations

- *Declination Angle*

$$\delta(n) = 57.296\{0.006918 - 0.399912\cos(\omega) + 0.070257\sin(\omega) - 0.006758\cos(2\omega) + 0.000907\sin(2\omega) - 0.002697\cos(3\omega) + 0.001480\sin(3\omega)\} \quad (6)$$

Where ω is the day angle in radian, ($\omega = 2\pi\,(n-1)/365$).

- *Equation of Time*

$$ET(n) = 229.18\{0.000075 + 0.001868\cos(\omega) - 0.032077\sin(\omega) - 0.014615\cos(2\omega) - 0.04089\sin(2\omega)\} \quad (7)$$

Where ω is the day angle in radian; $\omega = 2\pi\,(n-1)/365$) [2,8].

- *Hour Angle, h*

$$h = \pm\,(\text{Minutes from local solar noon})/4 \quad (8)$$

- *Sunset and Sunrise Time*

Hrs is the time between the local noon and the sunrise time and Hss is the time from the local noon to the sunset time.

$$Hss = -\,Hrs = \operatorname{acos}(-\tan(L)\tan(\delta))/15 \quad (9)$$

$$\text{Local noon} = 12{:}00 - ET\,(\text{min})/60 \quad (10)$$

$$\text{Sunrise Time} = \text{Local noon} - Hrs \quad (11)$$

$$\text{Sunset Time} = \text{Local noon} + Hss \quad (12)$$

$$\text{Day Length} = 2Hss \quad (13)$$

B. Tracking Angle

There are two important equations that describe the dual axis, namely, Tilt Angle (TA) and Polar Angle (PA). Fig. 3 shows these angles.

$$\text{Local Time} = GMT + \text{Longitude}/15 \quad (14)$$

$$TA = 90 - ABS\,(L - \delta) \quad (15)$$

$$PA\,(\text{local time}) = 90 - (\text{Local noon} - \text{Local Time})/4 \quad (16)$$

It follows that, the Starting Tracking Angle (STTA) and Stop Tracking Angle (SPTA) in degrees may be defined as:

$$STTA = \text{Polar Angle}\,(\text{Sunrise} + \text{Hold Time}) \quad (17)$$

$$SPTA = \text{Polar Angle}\,(\text{Sunset} - \text{Hold Time}) \quad (18)$$

Where, Hold Time is a chosen time to hold tracking after sunrise or before sunset since the sun irradiance is low at these times. The Sun location depends directly on three important factors; time, date and location. These three factors lead to find the sun location in any location on earth. It is clear that the accuracy in determining these factors will be reflected in the accuracy of the sun location.

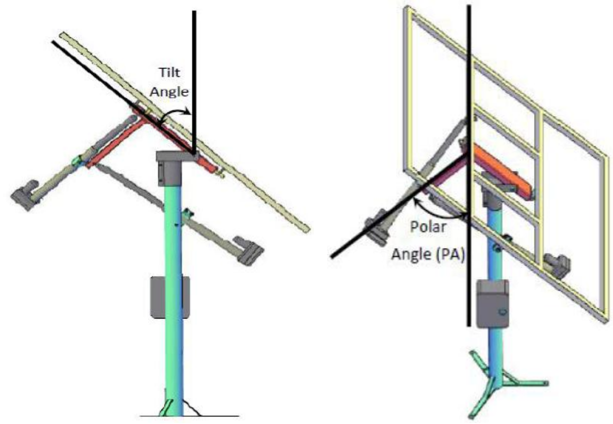

Fig 3. Tilt and polar angle representation

VII. SOFTWARE ALGORITHM

A. Data Acquisition

The GPS sends different types of sentences with different data or arrangement but there are common things between these sentences. Most of these sentences start with "$" followed by "GP" in the sentence ID. The other common things is that the sentences have a "*" before the checksum at the end of the sentence. Fig. 4 shows part of the flowchart related to data acquisition from the GPS.

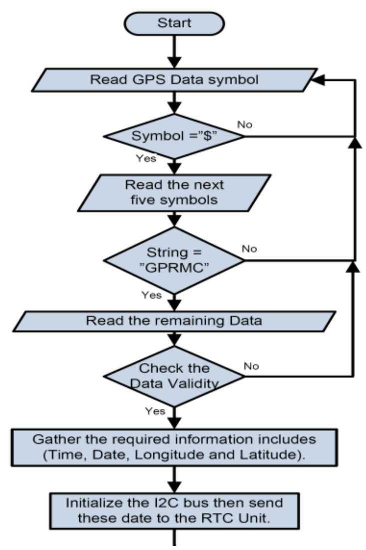

Fig 4. Data Acquisition flowchart

To catch the beginning of any sentence it is required to read the string characters one by one until the character "$"is reached, then it is required to read the next five characters which represent the sentence ID. This ID gives the receiver a complete idea about the followed structure of the sentence. After that it is required to figure out if this statement will satisfy the system data requirement, since some sentences have no information about the date. However, the used sentence in this design is RMC which has all the required data. So when the receiver catches the RMC ID, it will keep reading the sentence to the end. Now the microcontroller checks the validity of the data based on the status of the sentence to decide if it uses these data in this sentence or skips them and goes back to read the new update.

Now if the sentence is a valid and has no error relative to the checksum, the sentence will be ready to be used by the system. The required data like the UTC time, date, latitude and longitude are gathered in this part of the algorithm. Then the microcontroller initializes the I^2C communication line to start communication with RTC circuit. The step is considered to be the last step in the initializing phase of the RTC and from then on any data required about the time, date or location will be requested from the RTC unit because it manages these data with high precision. The location information will be saved in the free RAM that is available on the same chip. Fig. 5 shows the flowchart related to the data management and processing.

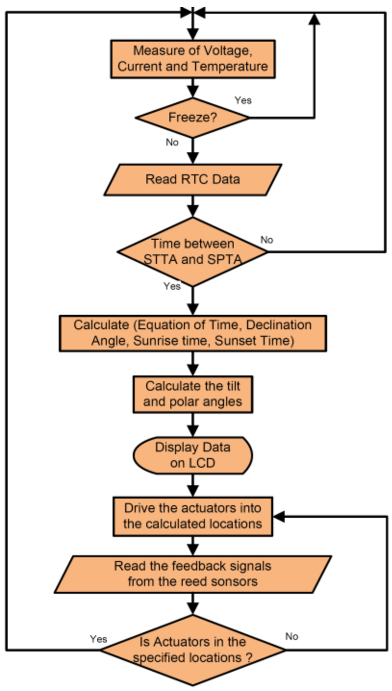

Fig 5. Data management and processing Flowchart

B. Power and Temperature Monitoring and Control

The adopted system is not only driving the solar panel to the exact position facing the sun but also has a power and temperature measuring and monitoring capabilities. In this phase the system measures and monitors the voltage, current and temperature continuously and there are many reasons for that. The system measures the voltage and current for maximum power point tracking MPPT, and the voltage measurement gives an indication of the system to freeze the tracker in cloudy days to save the tracking power. The temperature is measured here for two reasons. The first reason is to warn and alarm for overheat in different levels of temperatures as kind of protection. The second reason is that it could be used for MPPT prediction.

C. Data Management and Driving Control

The system is designed to read the time and date periodically from the RTC and calculate the declination angle δ, Equation of Time ET, TA, PA, STTA, SPTA and all the required data to find the sun location.

After calculating the TA and PA the system starts moving the solar panel into the specified location. The system uses a DC actuator similar to the one used in moving a satellite dish. Three control signals are sent by the MCU to drive these two actuators. These three signals are (EN, R/L and M1/M2). EN is responsible for switching the power into the actuators, R/L is for switching the polarity for right or left direction and M1/M2 is responsible for choosing the actuator that needs to be driven.

As a feedback signal the design uses the built in reed sensor inside the actuator case with no extra cost. This sensor sends 45 pulses per inch which gives a high accuracy to the system. There is one problem with this sensor that the actuator location can be figured out by counting the number of the transmitting pulses and losing the power may cause to lose the location but this problem has been solved by adopting two techniques. The first is resetting both actuators every time the tracker gets reset which guarantees reset the counter, and the second is using the built in flash RAM inside the MCU which keeps the actuator location even with losing power. By the end of the day the MCU returns the solar panel to the STTA of the next day.

D. Monitoring Data

The design includes a 4x20 LCD screen to monitor data and display warning or alarm if any. The data are displayed in accordance with the type on three pages. These pages can be changed by pressing a Left or Right bottom. The first page displays time, date and the current TA and PA as shown in Fig.6.a Second page displays the astronomical data which includes the latitude, declination angle, equation of time, hold time, STTA and SPTA as shown in Fig Fig.6.b. The last page displays temperature, voltage, current and power as shown in Fig.6.c.

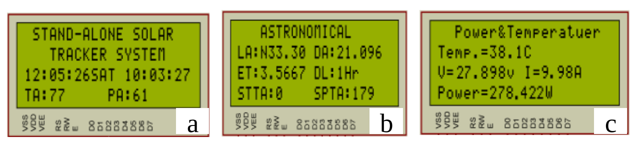

Fig 6. LCD data arrangement

VIII. HARDWARE SPECIFICATIONS

The design includes an ATmega32 microcontroller to manage, control and monitor all the circuits, see the Fig. 7 [9].

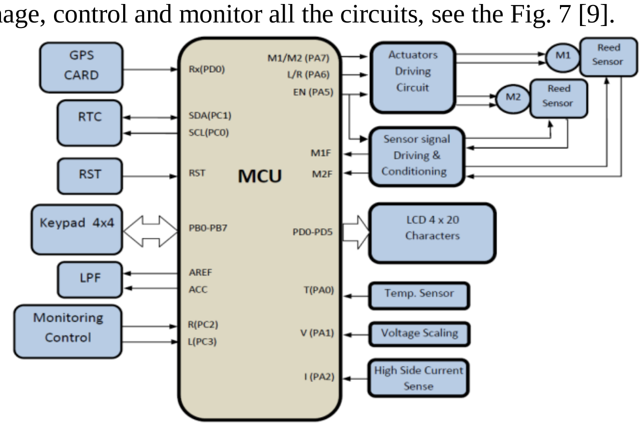

Fig 7. Block Diagram for Main Controller

- GPS Card: ATmega 32 has a built in Universal Synchronous and Asynchronous serial Receiver and Transmitter (USART). This USART is a highly flexible serial communication device. The MC reads the received data from the GPS card through RXD (PD0) with a baud rate of 9600 kbps. This MC has the ability to interrupt by Rx signal and that is important for synchronization purposes. The used Card has MAX3002 for voltage shifting. The Card photo is shown in Fig. 8.

Fig 8. GPS board by Matrix multimedia

- RTC: The used Real Time Controller (DS1307) has Real time clock to count seconds, minutes, hours, the date of the month, month, day of the week, and year with leap year compensation valid up to 2100, 56 bytes nonvolatile RAM for data storage, 2-wire serial interface, Programmable square wave output signal, Automatic power-fail detect and switch circuitry, Consumes less than 500 nA in battery backup. The MC communicates with RTC via I^2C (SDA & SCL) as shown in Fig. 9.

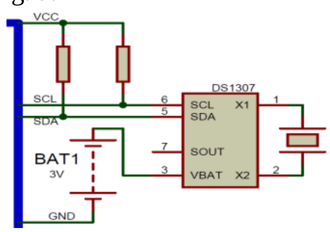

Fig 9. RTC DS1307 Pin Configuration

- RST: This is used to reset the controller and load the data from the GPS to RTC. This is because the design has a standalone time controller which needs to be initialized by the GPS for time and data and to store the location data.

- Keypad: A 4x4 matrix keypad is used to enter data but it is optional.

- LPF: Low Pass Filter is used for ADC Noise Reduction.

- Monitoring Control of the LCD screen: There are two left and right switches used to slide the LCD view left or right.

- Actuator Driving Circuit: This is responsible for driving the power into the specified actuator with specified polarity to move the actuator in and out as shown in Fig. 10.

- Sensor Signal Driving and Conditioning: This circuit is responsible on driving the EN signal into the Reed Sensors conditioning the received signal to the MC.

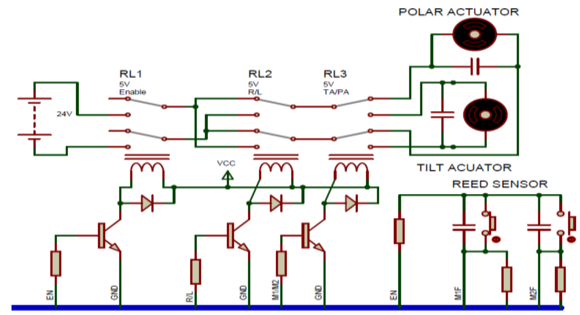

Fig 10. Actuator Driving Circuit

- LCD: The LCD screen 4x20 (LM044L) characters controlled by the MC via port D.

- Temperature Sensor: LM35dz (–50 to 150) sensor is used to measure temperature for the controlling purpose. The LM35 series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature.

- Voltage Scaling: This circuit used to scale the solar panel voltage from any level into 0-5 Volt level to be compatible with MC ADC.

- High Side Current Sensor: The INA168 is a high-side, unipolar, current shunt monitors. Wide input common-mode voltage range, low quiescent current. The device converts a differential input voltage to a current output. This current is converted back to a voltage with an external load resistor to set any gain from 1 to over 100. This sensor uses a shunt resistor (R_{sh}=0.0001Ω) which is a piece of the main cable with specified length based on its resistivity. See Fig. 11.

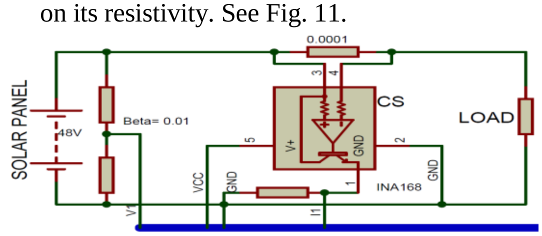

Fig 11. Voltage Scaling and Current Sensing Circuits

The photos in Fig. 12 show the mechanical structure and the control box.

Fig 12. Mechanical Structure and Control Box

IX. ENERGY ASSESSMENTS

A. Energy Consumed by Polar Actuator

The range of daily tracking in degrees is given by:

Tracking range per day (TR) = SPTA – STTA (19)

The system is designed to push the actuator shaft (3mm/Deg) ie. "Shaft length / Tracking range" by speed equals to (4.2 mm/Sec) and power 9.6 watts according to the actuator specifications. Now, it is required to introduce the tracker running time (TRT) which is defined as the time spent to move the panel from STTA to SPTA per one day.

TRT= TR (Deg).shaft length(mm/Deg)/speed(mm/sec) (20)

By adding up the calculated tracking period (STTA to SPTA) for each single day from 1st January to 31st December for Holding Time equals two hours, the value of TRT for one year in Baghdad will be: TRT per Year = 31232 Sec,. Note that this value of TRT per year was taken from the ASTF report [10]. Since the tracker moves the panel back at the end of day for the next day STTA, so TRT per year should be multiplied by two (i.e., 31232 x 2= 62464 Sec). Then, the total consumed energy is equal to (9.6 w * 62464 sec) ≈ 599.6 kJ/year.

B. Energy Consumed by Tilt Actuator

This actuator runs in any location from the winter solstice (WS) to the summer solstice (SS) then goes back to the WS in one year, and the shaft moves 5mm/Deg with a speed of 4.5 mm/Sec.

TR= SS–WS= 23.45 – (–23.45)= 46.9 Deg.
Shaft Pushing length= 46.9 (deg.)* 5(mm/Deg)* 2=469mm.
The time required for this = length / speed =469/4.5=104 Sec.
Energy Consumed over a year= 9.6 * 104 ≈1kJ/year.
It follows that the total energy consumed by the two actuators over one year is approximately equal to:

599.6 kJ + 1 kJ = 600.6 kJ/year or 0.166 kWh/year

C. Energy Produced by the System

The total day time for the test location in Baghdad is equal to 4379h [10]. This number was determined by finding the sum of the day length of each single day which means that the average day length is equal to 11.99 Hours. To find the effective period of one day, it is required to subtract 4 hours per day (two after sunrise and two before the sunset). Hence, the Effective average Day Time =11.99 – 4= 7.99h ≈ 8h.

The average power produced (P) in one day is equal to the Solar panel power times the average day length (Sec). The system consist of 6 panels, 130 W each, i.e.,

The Total Produced Power = 6 * 130 = 780 W
kWh per day = 780 * 8 = 6.240 kWh.
Energy Produced/ year = 6.240 kWh/day*365 day
≈ 2277.6 kWh.

Note that all the above calculations were based on 1.0 k W/m^2, according to the testing data. But according to the test place in Baghdad 33.50 N, the solar irradiance is more than this value, for example see Fig. 13 which shows the solar irradiance for Baghdad given by *meteonorm 7* [11], on average 5.6 kWh/m^2/day. By adopting this value, the total produced power ≈ 2277.6*5.6 ≈ 12.756 MWh/ year.

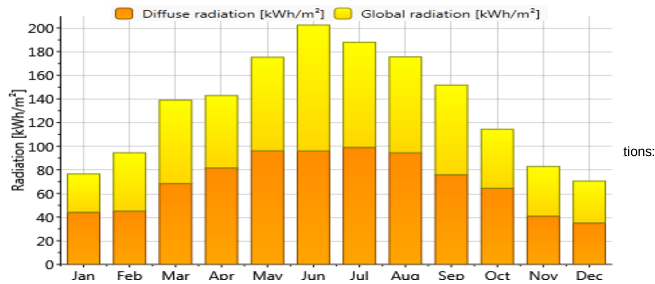

Fig 13. Solar Iradiance for Baghdad test site 33.3N, 44.4E

X. CONCLUSION

There is no doubt that the dual axis solar tracking system increases the productivity by more than 40% but there are many factors affecting the performance of such system. These factors include accuracy, durability, reliability, tracking power and cost. The proposed design discussed these factors from many practical viewpoints.

The system has taken into consideration all these factors by calculating the sun location based on carefully selected astronomical equations and GPS data. The main reason for adopting these equations is to avoid the use of sensors to track the sun location. The paper also gave critical assessments of the annual energy production of the system.

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