



A Solar Radiation Tracker for Solar Energy Optimisation

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Authors' contributions

This work was carried out in collaboration between both authors. Author EN designed the research study, performed the editing, wrote the abstract and wrote the first draft of the manuscript. Author ARA designed the block diagram, the control circuit, flow chart, programming of the microcontroller and formatting. Both authors read and approved the final manuscript.

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ABSTRACT

The need to produce readily accessible, pollution free natural energy such as solar energy has been drawing increasing attention globally. This is due to energy demand, global environmental protection, fast growing population and diminishing resources of grid supply. Effective utilisation of solar energy requires tracking of the sun. In this paper, we proposed a hybrid hardware/software embedded PIC16F877A microcontroller-based dynamic dual axis tracking system. It utilises the solar panel itself as a sensor to determine which part of the sky delivers the most power to the load using stepper motors for alignment. Employing control software, the system automatically controls the PV panel to receive maximum solar energy all day. The PIC16F877A microcontroller, two M42SP-7 stepper motors, two ULN2003 stepper motor drivers, two gear drives and a 10 Watt 12 V monocrystalline solar panel were employed in the hardware design. Programming of the hardware was conducted using mikroBasic software. Cost analysis of the design yielded GH ¢ 522.69 (US \$ 124.45). The resulting sun tracking system is therefore cost effective and will go a long way to help rural electrification as well as reduce the burden on grid supply.

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Keywords: Energy optimisation; rural electrification; solar tracker, stepper motor.

ABBREVIATIONS

AC : Alternating Current
ADC : Analog - to - Digital - Converter
DC : Direct Current
MPP : Maximum Power Point
PC : Personal Computer
PV : Photovoltaic
PI : Proportional Integral
PIC : Programmable Intelligent Computer
PLC : Programmable Logic Controller
ULN : Unique Learner Number

1. INTRODUCTION

With the increasing concern about global environmental protection and energy demand due to rapid growth of population in developing countries and the diminishing resources of grid supply, the need to produce freely available, pollution free natural energy such as solar energy has been drawing increasing interest in every corner of the world [1-3]. As the range of applications for solar energy increases, so does the need for improved materials and methods used to harness this power source. There are several factors that affect the efficiency of the collection process. Major influences on overall efficiency include solar cell efficiency, intensity of source radiation and storage techniques [4]. Solar energy refers to the energy obtained from the sun. One of the most important problems facing the world today is the energy problem. This problem resulted from the increase in demand for electrical energy and the high cost of fuel. The solution therefore, is by making good use of the renewable energy sources such as solar, wind and potential energy which are abundantly free in nature. According to the study presented by the German Advisory Council on Global Change, it is expected that the Sun will become the main electricity production source by the year 2100 due to the remarkable advantages of solar energy: it needs no fuel, it has no moving parts, it is non-polluting and quick responding, it is adaptable for on-site installation, it is integrative with other renewable energy sources, it is simple and efficient and overall, the sun is available during the day time everywhere and free of charge [4]. Its setbacks however, are its poor reliability, low output and uncertainties in the weather conditions [3].

Sun tracking systems have been studied with different applications to improve the efficiency of solar systems by adding the tracking equipment to these systems through various methods [5-9]. A solar tracker is a device for orienting a solar photovoltaic panel or concentrating solar reflector or lens towards the sun. The sun's position in the sky varies both with the seasons (elevation) and time of day as the sun moves across the sky. Solar trackers are of varying costs, sophistication, and performance. The most attainable method of improving the performance of solar power collection is to increase the mean intensity of radiation received from the sun [4,10-12]. The current obtained from solar cells is influenced by the angle at which the sun's incident rays strike the cell surface [8,9,12,13]. To maintain maximum power output from a solar array, the angle of incidence must be held at zero degree. Hence the array must constantly face the sun. This requires a tracking system that can continuously align the array into the desired position [10,14]. There are three major approaches for maximising power extraction in medium and large scale solar energy systems. They are sun tracking, Maximum Power Point (MPP) tracking or both [15,16].

The solar generating array consists of photovoltaic (PV) cells connected electrically in series and/or parallel to give a PV module. The PV modules combined give the solar panel while a number of the panels are combined to give a complete PV generating array [17].

Use of stepper motors in tracking systems has been highly acknowledged as compared to the use of DC and AC servomotors [18]. The unique merits of using stepper motors over other applicable motors are three fold: control signals determine the rotor position as opposed to the rotor speed, so that the stepper motor is used in position servo systems without the necessity for servo-control systems and position feedback transducers such as encoders. Secondly, they are directly controlled by computers, microprocessors and programmable logic controllers. Thirdly, they give significant cost savings. However, the Achilles heel of stepper motors is the tendency of inherent missing of steps which are usually unaccounted for [19,20].

Many solar radiation tracking techniques have been reported in the literature in recent times. Some are Programmable Intelligent Computer

(PIC) or microcontroller based resulting in low cost, simplicity and high efficiency [21,4,15,22]; both microcontroller and sensor based [23]; use of multiple sensors for multiple targets tracking [24]; use of sensor data acquisition with PC based fuzzy logic control algorithm and a permanent magnet DC motor [7,2]; use of PIC for generating control signals for a stepper motor and a single axis solar array [4]. Sungur [25] developed an electromechanical control system using a Programmable Logic Controller (PLC) instead of the widely used photo sensors for tracking the sun. Tudorache and Kreindler [2] had designed a single axis DC motor actuated light sensor based solar tracker system for PV power plants. A number of tracking techniques reported are of the open-loop, algorithm single axis [26] and dual axis open loop with a PLC [14,27]; the closed loop is mostly photosensor based optimal trackers [28-31].

Although closed-loop sun-tracking systems produce a much better tracking accuracy, they lose their feedback signals when the sensor goes shaded or when the sun is blocked by clouds. Open-loop sun trackers as an alternative, use open-loop sensors that do not require any solar image as feedback. The open-loop sensor ensures that the solar collector is positioned at pre-calculated angles obtained from a special formula or algorithm according to date, time and geographical information. They however suffer from problems of high accuracy. Hybrid sun-tracking systems have been reported in the literature as well. [32,27] adopted both the open-loop and closed-loop tracking schemes. The open-loop operation was achieved by theoretical calculations while the closed-loop control was achieved by the use of photoelectric sensors. Luque-Heredia Cervantes and Quéméré [31] proposed a novel Proportional Integral (PI) based hybrid sun-tracking algorithm for a concentrator photovoltaic system. A mathematical model that involves a time and geographical coordinates function as well as a set of disturbances provides a feed forward open-loop estimation of the sun's position. To determine the sun's position with high precision, a feedback loop was introduced according to the error correction routine which is derived from the estimation of the error of the sun equations that are caused by external disturbances at the present stage based on its historical path. [33] fabricated and evaluated a new control strategy for a photovoltaic (PV) solar tracker that operated in two tracking modes, that is, normal open-loop tracking mode and a closed-loop tracking search mode. [34] proposed

an active sun tracking scheme without any light sensors using an adaptive step-perturbation method. [35] developed a new algorithm for the determination of the solar position.

The generation of maximum energy from solar has gained much interest and popularity. However, the use of sensors in particular increased design cost and circuit complexity. Elimination of this problem ended up with a single axis tracking system which could not take care of changes in the sun's location due to seasonal changes and therefore maximum output was probably affected. The required accuracy of the solar tracker depends on the application. Typically, concentrator systems will not work at all without tracking, so at least single-axis tracking is mandatory. Non-concentrating applications require less accuracy, and many work without any tracking at all. However, tracking can substantially improve the amount of power produced by the system. Use of trackers in non-concentrating applications is usually an engineering decision based on economics. Compared to photovoltaic modules, trackers can be relatively inexpensive. This makes them especially effective for photovoltaic systems using high-efficient panels. For low-temperature solar thermal applications, trackers are not usually used, owing to the relatively high expense. This is all because of more collector area requirement of the tracker and the more restricted solar angles required for efficient performance, which influence the average year-round system capacity. Some solar trackers may operate most effectively with seasonal position adjustment and most will need inspection and lubrication on an annual basis.

This paper is focused on a sensor-free dual axis tracking system for maximum energy output. The purpose is to design a more reliable, efficient and cost effective solar tracking system that would automatically keep the solar panel facing the sun throughout the day.

2. METHODOLOGY

An effective solar tracking system should be able to follow the sun with a certain degree of accuracy, return the collector to its original position at the end of the day and also track during periods of cloud cover [16].

2.1 System Hardware Design

The hardware design involves the rotation of a dual axis solar tracker with the PIC16F877A

microcontroller being the core of the system. In-circuit current or voltage from the PV panel is first fed to an analogue-to-digital converter which is embedded in the microcontroller to convert the analogue voltage input to digital signal for the microcontroller. According to the microcontroller's program, command pulses are generated to drive two stepper motors through two ULN2003 motor drivers. The PV panel is coupled to the two stepper motors through two

gear drives for a two axis rotation; that is one for azimuth (horizontal) rotation and the other for altitude (vertical) rotation as indicated in the block diagram in Fig. 1 [36]. Fig. 2 gives a diagram of the tracking mechanism [23]. The main components of the system hardware design consist of microcontroller, stepper motor driver, stepper motor, gear drive and the PV panel to be turned. Table 1 gives the selected materials and their descriptions.

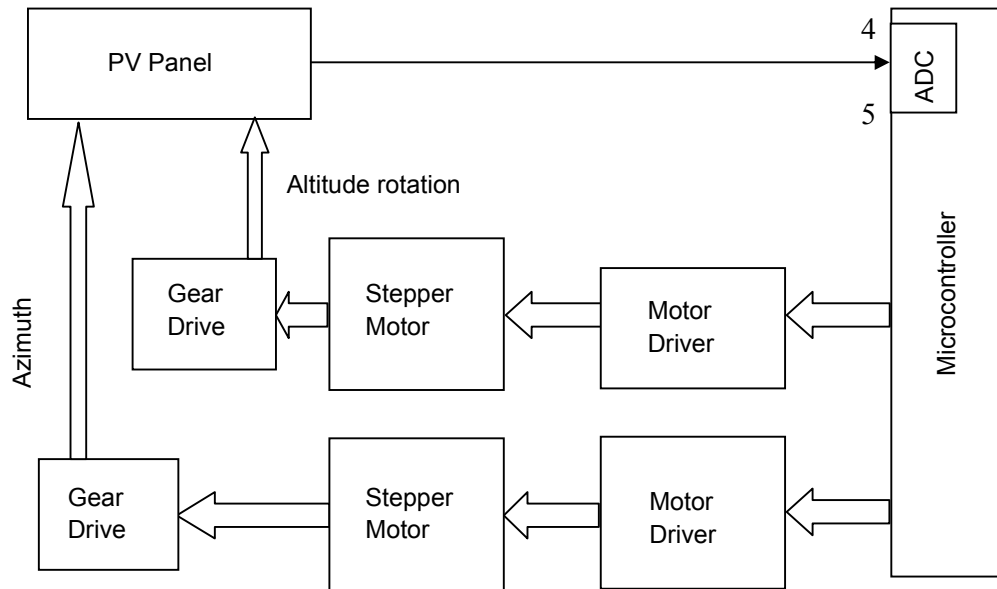


Fig. 1. Block diagram of proposed solar radiation tracker

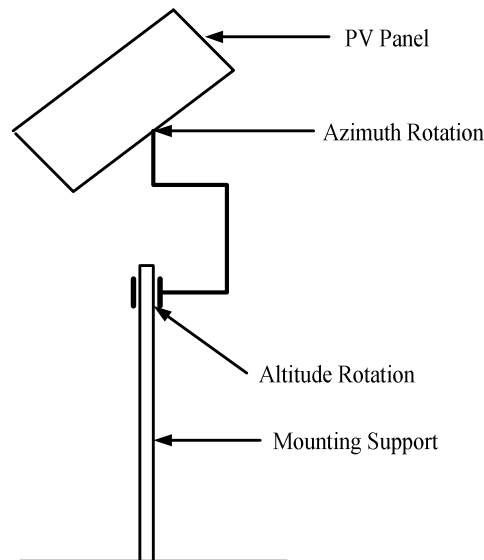


Fig. 2. Tracking mechanism of the solar tracker

For precise alignment of the PV panel with the sun's radiation, a four-phase unipolar M42SP-7 stepper motor was used. By way of appropriate sequential command pulses from the programmed microcontroller and by way of appropriate gearing, the stepper motors turn the PV panel accordingly.

Considering the 12 V DC M42SP-7 Stepper Motor:

$$\text{Resolution} = \frac{360}{\beta} = \frac{360}{7.5} = 48 \text{steps / rev} \text{ steps / rev} \tag{1}$$

$$\text{Motor shaft speed, } N = \frac{\beta f}{6} = \frac{7.5 \times 600}{6} = 750 \text{rpm} \tag{2}$$

where β is step angle and f is stepping frequency (or pulse rate) in pulses per second (pps). 48 pulses are needed by the stepper motor to complete one revolution. Each pulse moves the rotor by 7.5 degrees. The sequence has to be repeated 12 times for the motor to complete one revolution. The stepper motor M42SP-7 is selected over other stepper motors due to its high output torque, superior quite running capability and stability and excellent responsiveness.

Each of the stepper motors for the altitude and azimuth rotation requires an appropriate coupling to the PV panel. A gear box having reduction ratio of 1:15 with 25 teeth on driving gear and 375 teeth on the driven gear is chosen for the application. The speed of turning of the PV panel is given by Equation (3) as the speed of the driven gear.

$$\begin{aligned} S_2 &= \frac{N_1}{N_2} \times S_1 \\ &= \frac{25}{375} \times 750 = 50 \text{rpm} \end{aligned} \tag{3}$$

where N_1 is number of teeth on the driving gear, N_2 is number of teeth on the driven gear and S_1 is speed of driving gear (that is speed of the stepper motor = 750 rpm) and S_2 is speed of driven gear. These considerations are made based on the fact that more precise tilting and rotation of the panel is required.

In driving the stepper motor, a 12 V zener diode is connected between the power supply and V_{DD} (Pin 9) on the chip in order to absorb reverse

electromotive force from a collapsing magnetic field when motor coils are switched off [37,38]. By way of the command pulses received by the driver from the microcontroller, the motor runs accordingly. The control circuit diagram of the entire hardware design modified after [15] is as shown in Fig. 3.

Operationally, an analogue supply voltage of +5 V is applied to the microcontroller input through a 10 kΩ resistor. An ADC in the microcontroller converts the analogue voltage input from the panel to digital output for the microcontroller. Reference voltage of the ADC is chosen by programming the ADC converter registers and is typically +5 V. Digital command pulses are given to the ULN2003 motor driver from the programmed microcontroller and the stepper motor operates accordingly.

2.2 Control Software of the Hardware Design

In developing the control software of the hardware design, a flowchart was developed based on full functionality of the solar radiation tracker. The hardware design is then programmed using mikroBasic for PIC. Fig. 4 shows the Graphical User Interface (GUI) of the mikroBasic Integrated Development Environment (IDE) window that we used to write the control codes for the hardware design. The flowchart for the control software is as shown in Fig. 5. The threshold value as stated in the flowchart varies from place to place since the intensity of the sun varies from one place to the other. The mikroBasic code of the program is as shown in Fig. 6.

Table 1. Selected materials and descriptions

SN	Item	Model/Description
1	Microcontroller	PIC 16F877A
2	Stepper Motor Driver	ULN2003
3	Stepper Motor	12 V M42SP-7
4	Gear Drive	1:15 reduction gear box
5	PV Panel	10 Watt 12 V monocrystalline 36-cell

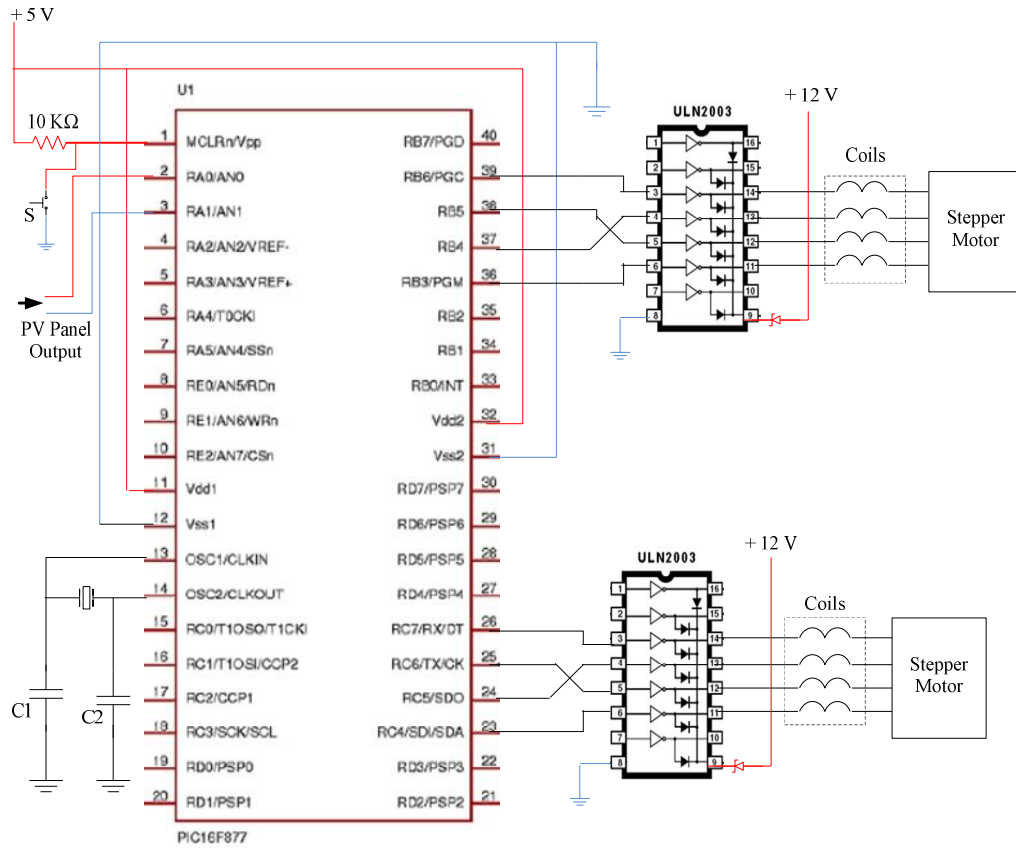


Fig. 3. Circuit diagram of the hardware design of the solar radiation tracker

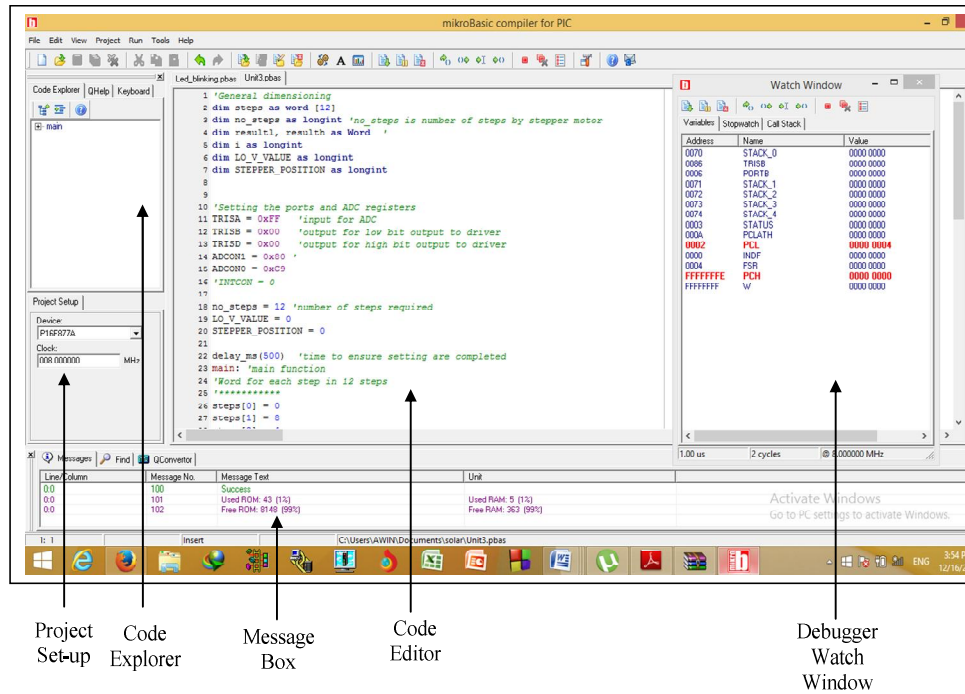


Fig. 4. MikroBasic IDE window

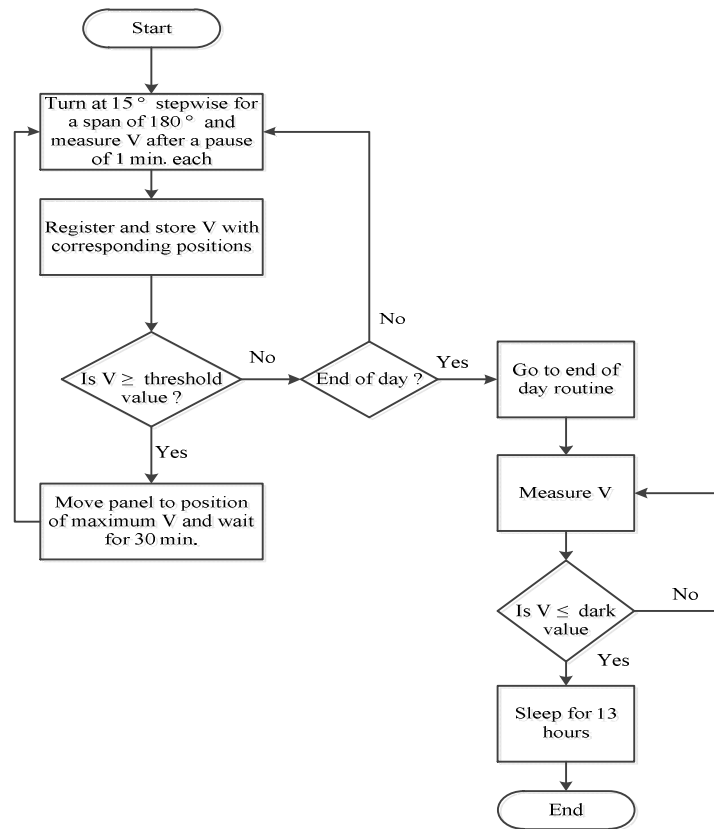


Fig. 5. Flowchart for control software

```
'program stepper_motor
```

```
'General dimensioning
```

```
dim steps as word [12]
```

```
dim no_steps as longint 'no_steps is number of steps by stepper motor
```

```
dim resultl, resulth as Word
```

```
dim i as longint
```

```
dim LO_V_VALUE as longint
```

```
dim STEPPER_POSITION as longint
```

```
'Setting the ports and ADC registers
```

```
TRISA = 0xFF 'input for ADC
```

```
TRISB = 0x00 'output for low bit - output to driver
```

```
TRISD = 0x00 'output for high bit - output to driver
```

```
ADCON1 = 0x80
```

```
ADCON0 = 0xC9
```

```
'INTCON = 0
```

```
no_steps = 12 'number of steps required
```

```
LO_V_VALUE = 0
```

```
STEPPER_POSITION = 0
```

```
delay_ms(500) 'time to ensure settings are completed
```

```
main: 'main function
```

```
'Word for each step in 12 steps
*****
steps[0] = 0
steps[1] = 8
steps[2] = 4
steps[3] = 2
steps[4] = 1
steps[5] = 12
steps[6] = 10
steps[7] = 9
steps[8] = 14
steps[9] = 15
steps[10] = 16
steps[11] = 24
*****
AGAIN:
for i = 0 to 11 'no_steps-1
  PORTB = steps[i]
  delay_ms(500) 'number of seconds to finish 1 step
'code to ensure complete conversion of data from analogue to digital
*****
WT: delay_ms(1)
  if ADCON0.2 = 1 then
    goto WT
end if
*****
*****
if ADRESL > resultl then 'compare ADC value to already stored value
  resultl = lo(ADRESL) 'store its corresponding stepper position
  resulth = hi(ADRESH) 'this ensures only max V value is stored
  STEPPER_POSITION = i 'corresponding stepper motor position
end if
*****
'if max V is greater than end of day value then move stepper motor to position corresponding to max
V.
'if less than end of day value, go to position 1 and sleep for 30 minutes
*****
next i
if resultl > LO_V_VALUE then
  PORTB = steps[STEPPER_POSITION]
  delay_ms(1800000)
  goto AGAIN
else
  PORTB = steps[0]
  delay_ms(500)
  goto AGAIN
end if
end.
```

Fig. 6. MikroBasic code programming of the PIC16F877A microcontroller of dual axis solar radiation tracker

3. RESULTS AND DISCUSSION

3.1 Results

In this section, we present the results and discussion of the solar radiation tracker.

The results as presented centred mainly on the respective software interfaces during building,

running and debugging of the program. Cost analysis was also given.

3.1.1 Program software interfaces

Results obtained for building the program are shown in Fig. 7. Fig. 7 is used to emphasize the point that the control program as in Fig. 6 was successfully compiled without errors. Due to lack of financial resources to physically construct the tracker, the control program for the hardware design was only run using the computer. So we compared our observations before and after debugging the program in Fig. 8 and Fig. 9 respectively. The program after the 12 step (solar radiation searching steps) execution, gave a STATUS position of 0 as observed in the watch window in Fig. 9. This was particularly so because the solar PV tracker was not interfaced with the microcontroller.

3.1.2 Cost analysis

The cost analysis showed that a total cost of GH ₵ 522.69 (US \$ 124.45) is needed to implement the entire project. This cost as compared to the long-term benefits of the system can be said to be bearable. Hence, investment into such a project is worth pursuing. A summary of detailed costing of the components used is presented in Table 2.

3.2 Discussion

Use of stepper motors enabled precise azimuth and altitude alignment of the photovoltaic panel. PIC16F877A microcontroller and appropriately developed flowchart facilitated easier programming of the hardware design as program build-up and debugging were very successful. Cost analysis strongly suggested implementation of the design at a cost of GH₵ 522.69 The dual axis solar radiation tracker is capable of not only reducing the burden on the national grid supply in remote areas but also provide an alternative, much needed means of electric power to the rural areas. The mikroBasic program of the hardware design automatically controls the azimuth rotation while the altitude rotation is controlled manually since altitude rotation takes account of seasonal changes which occur only twice in a year. Rotating the altitude axis all day is a waste of power.

Table 2. Cost analysis

SN	Item	Quantity	Cost (GH ₵)
1	Microcontroller	1	28.35
2	Stepper Motor	2	168
3	Stepper Motor Driver (ULN2003)	2	18.9
4	Gear Drive	2	25.2
5	Crystal Oscillator	1	12.6
6	10 kΩ Resistor	1	0.84
7	PV Panel	1	268.8
Total		10	522.69

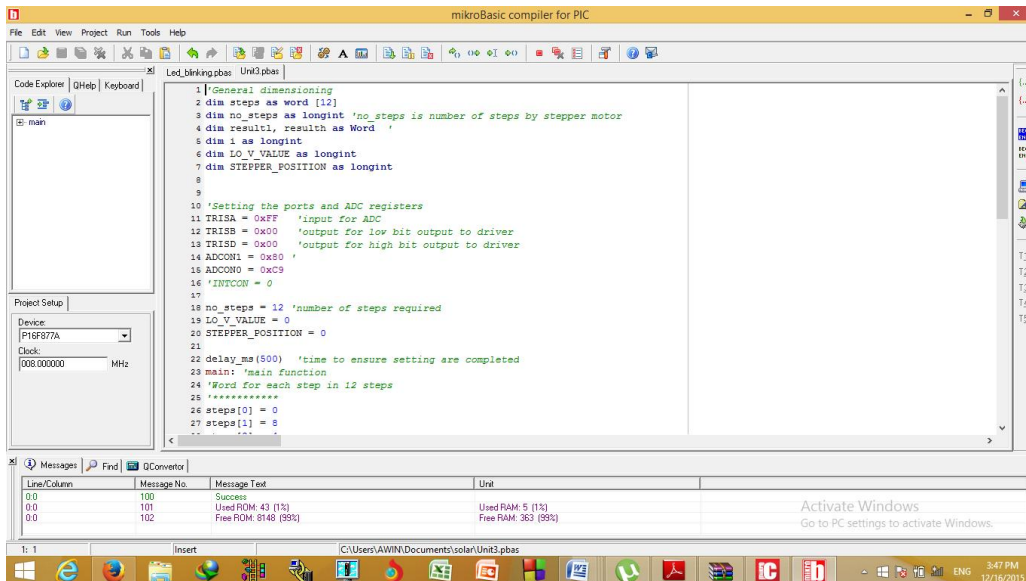


Fig. 7. Results obtained for building the program

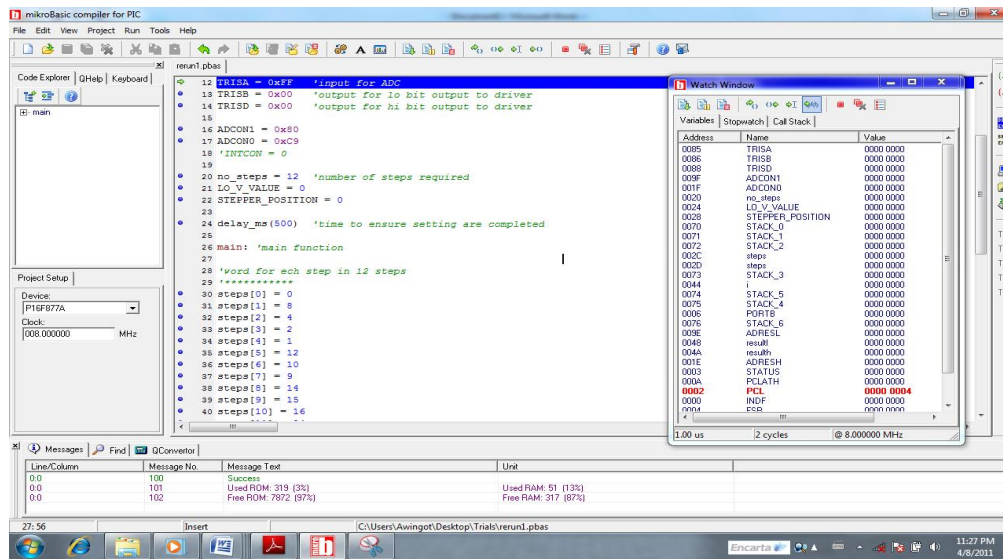


Fig. 8. Results obtained before debugging the program

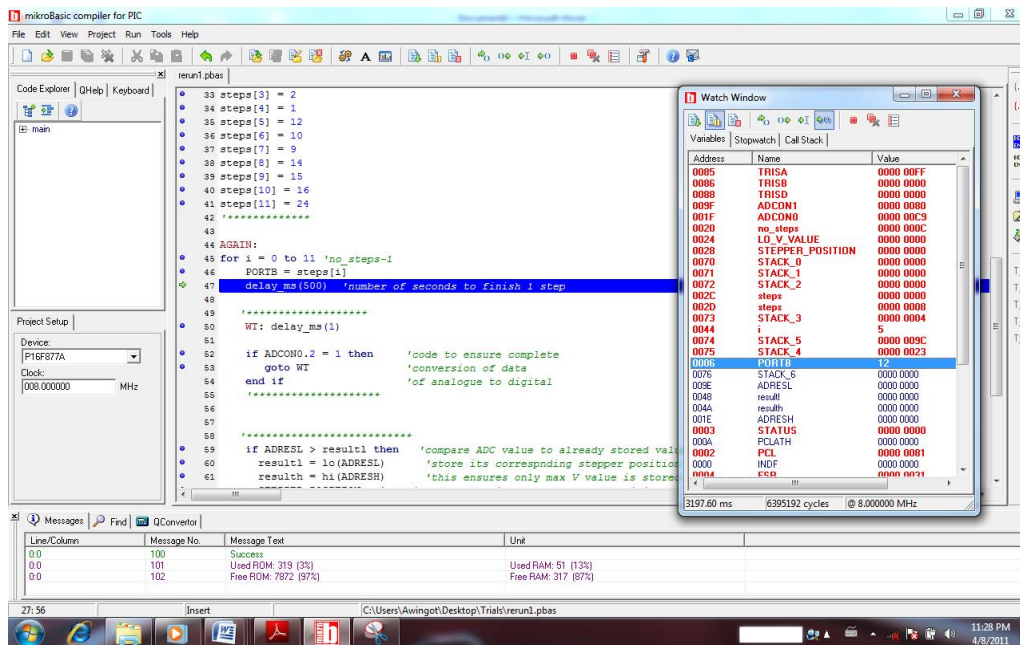


Fig. 9. Results obtained after debugging the program

4. LIMITATION OF THE WORK

As a result of limited financial resources, the solar radiation tracker could not be physically constructed to enable us perform field evaluations.

5. CONCLUSION

A dual axis solar radiation tracker for solar energy optimisation has been successfully

designed at a bearable cost of GH¢ 522.69. The proposed dual axis sun tracking solar array system is a practicable and more efficient method of maximising the energy received from the sun's radiation. Hardware design was carefully done to ensure use of minimum number of components for implementation. Accurate tracking is as a result of use of stepper motors together with the PIC16F877A microcontroller. This was achieved with the aid of hardware design programming. The design could be

adopted and implemented by the power generating companies as a means of reducing the burden on the grid supply. Also, it stands to serve as an alternative means of back-up power supply for utilities. Future work however need concentrate on proactive tracking activity in times of cloudy weather conditions as these conditions can put the tracker to sleep calling for its manual reset.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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