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MECHANICAL SUN-TRACKING TECHNIQUE IMPLEMENTED FOR MAXIMUM POWER POINT TRACKING OF A PV SYSTEM FOR EFFECTIVE ENERGY SUPPLY

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ABSTRACT

This paper elucidates a single axis solar tracker system that automatically searches the optimum PV panel position with respect to the sun by means of a DC motor controlled by an intelligent drive unit that receives input signals from light dependent sensors. A prototype of the mechanical maximum power point tracker (MMPPT) was implemented with a motor size of 48W. The power supply unit consists of only supply source which is the AC mains. The sensor unit consists of six sensors. While five are fixed and adjacently aligned at 36º to each other (tracking sensors), the sixth one is movable as it is attached to the surface of the PV panel (feedback sensor). The control unit is divided into two parts: A priority voltage selector and a movement controller. The priority voltage selector comprises of cascaded comparators which compares the five voltage outputs from the sensors and selects the highest voltage (priority voltage).The movement controller compares the feedback voltage with the priority voltage and logically decides whether to move the motor clockwise or anti-clockwise. The solar panel is allowed to move from east to west and back forth with a maximum allowable angle of 180º. Its movement is in only one axis. The prototype built carries the panel from eastward to westward tracking the sun movement from sun rise to sun set and then reset to face eastward as darkness sets in. The results obtained from the prototype MMPPT were used to compare with the results obtained from fixed panel under the same environmental conditions and at the same time interval of 30 minutes using the same type of PV panel. The result from MMPPT has a gain of 5.77% over its counterpart which is fixed panel.

Keywords: *Solar panel, maximum power point tracker, Sun tracker, tracking sensors, priority voltage, Mechanical maximum power point tracker.*

1. INTRODUCTION

Concepts related to the solar energy have constantly been under heavy research and development. The amount of power produced by a solar system depends on the amount of sunlight to which it is exposed. As the sun's position changes throughout the day, the solar system must be adjusted so that it is always aimed precisely at the sun and, as a result, produces the maximum possible power. In order to ensure maximum power output from PV cells, the sunlight's angle of incidence needs to be constantly perpendicular to the solar panel. This requires constant tracking of the sun's apparent daytime motion, and hence the essence of this paper which is the development of an automated sun tracking system which carries the solar panel and positions it in such a way that direct sunlight is always focused on the PV cells. A tracking mechanism must be reliable and able to follow the sun with a certain degree of accuracy, and then return the panel to its original position at the end of the day or during the night, but keeps the record of tracking at a fixed point during periods of cloud cover. To this effect an attempt had been made to build a prototype of MMPPT from which the results obtained from the prototype were used to compare with the results obtained from fixed PV panels under the same environmental conditions.

Regarding movement capability, two main types of sun trackers exist:

- One axis trackers,
- Two axes trackers [1].

Single axis solar trackers can either have a horizontal or a vertical axle. The horizontal type is used in tropical regions where the sun gets very high at noon but the days are short, this is the type that was considered in this paper. The vertical type is used in

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high latitudes where the sun does not get very high, but summer days can be very long [2]. Dual axes tracking system is beyond the scope of this research.
PV array is able to deliver maximum available power to the load which is also necessary to maximize the photovoltaic energy utilization. The extractions can be done using any of the two techniques below.

- using automatic sun tracker and,
- Electronic searching for the MPP conditions [3]

Solar trackers typically increase irradiation by 1.2 to 1.4 times (for 1-axis trackers) and 1.3 to 1.5 times (for 2-axis trackers) compared to a fixed surface at the optimal tilt angle [4].
Since PV power output is always non-linear in shape, there is the need to maximize the power that is being transferred to the load. High efficiency can be achieved by controlling the PV unit to operate at its maximum power extraction, refer to fig 1.As seen from figure 1 the power from the PV at any irradiance will be extracted using MPPT (MMPPT or electronic MPPT) and then transferred to the load via a converter.
In automatic sun tracker systems, the solar panels are made to track the movement of the sun. Hence, a tracking mechanism (mechanical device) that requires constant tracking of the sun's apparent daytime motion, and hence develops an automated sun tracking system which carries the solar panel and position it in such a way that direct sunlight is always focused on the PV cells for maximum efficiency. The solar path varies the Sun coordinates throughout the day. This can be seen in Figure 2, where *h* is the solar altitude and α_s is the solar azimuth angle. It's verified that the Sun apparent position relatively to Earth, varies in both height and azimuth at each time [5]. When someone wants to install a solar system, one must take special care in selecting the inclination and orientation of the panels, which are the two installation factors that will have major influence on system's performance, since these depend on the incoming radiation level. Similarly, the second aspect searches for MPP electronically.
Sun is moving across the sky during the day as mentioned earlier. In the case of fixed solar panel, the projection of the collector area on the plane, which is perpendicular to the radiation direction, is given by function of cosine of the angle of incidence [6] (Figure 3).
For a fixed panel, the projection area on the area oriented perpendicularly to the radiation direction is $S = S_0\cos\theta$, where θ is changing in the interval $(-\pi/2, +\pi/2)$ during the day. The angular velocity of the sun moving cross the sky is $\omega = 2\pi/T = 7.27 \times 10^{-5}$rad/s and the differential of the falling energy is $d\omega = ISdt$ [6], where the panel area is marked as S_0 and I is maximum radiation intensity (W/m^2). The higher the angle of incidence θ, the lower is the power hence the fixed panel has higher incidence angle compare to movable panel (MMPPT). That may the reason fixed surface always produce less power compare to movable surface. Several African countries are in severe electricity crises, Nigeria being among them [7]. Solar arrays currently being installed were fixed on rooftops or any favourable open space, at a fixed angle of inclination with the surface.

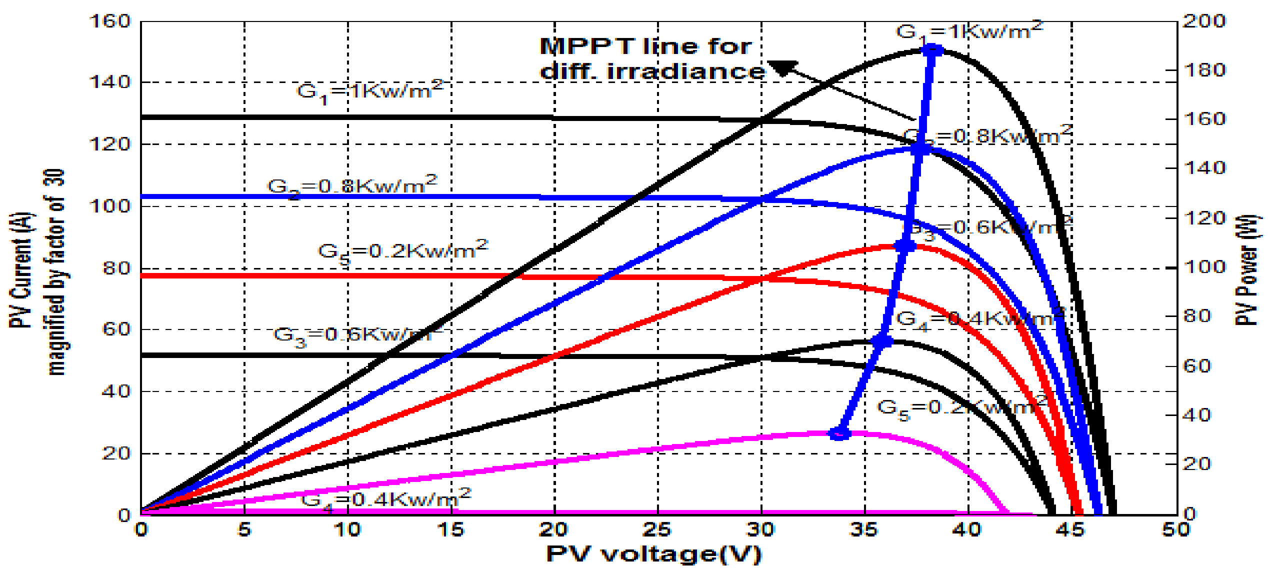

Figure 1: MPPT at different irradiance for I-V & P-V of PV panel at constant temp. of 25°C

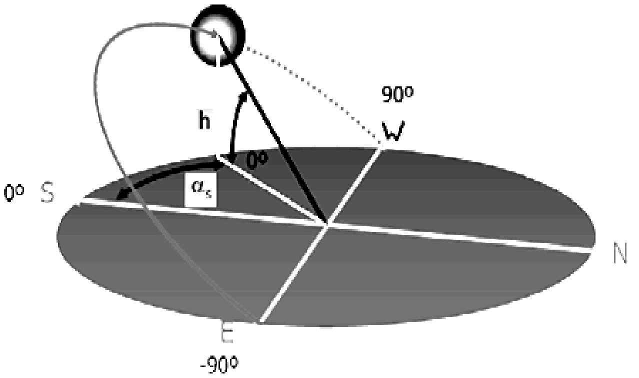

Figure 2: Sun's path [5]

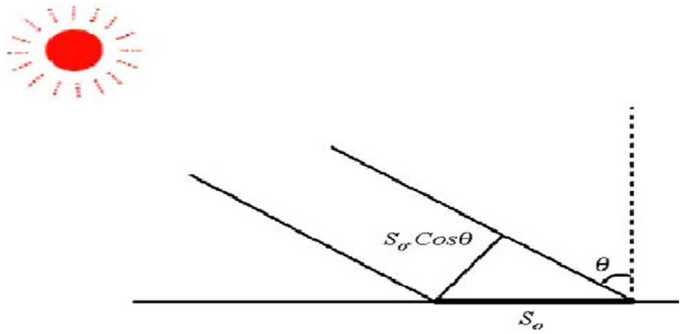

Figure 3. Angle of incidence u of the solar radiation [6]

However, this system is inefficient as most of the solar energy from the sun is not utilized unless an electronic MPP tracking system is used to track the maximum power point. But covering 0.16% of the land on earth with 10% efficient PV solar conversion systems would provide 20 TW of power, nearly twice the world's consumption rate of fossil energy [8], then with higher efficiency up to 18% of PV system one can image the power output. Trackers need not point directly at the sun to be effective. If the aim is off by 10^{o}, the output is still 98.5% of that of the full-tracking maximum [9].

It should be noted that the presence of a solar tracker is not essential for the operation of a solar panel, but without it, performance is reduced. At the same time certain environmental factors also affect the performance of PV panels [3]. Although solar trackers can boost energy gain of PV arrays, in their installation some problems such as cost, reliability, energy consumption, maintenance and performance must be considered.

All tracking systems have all/some of the following characteristics [2]:

- Single column structure or of parallel console type.
- One or two moving motors.
- Light sensing device.
- Autonomous or auxiliary energy supply.
- Light following or moving according to the calendar.
- Continuous or step-wise movement.
- Tracking all year or all year except winter.
  - Orientation adjustment with/without the tilt angle adjustment

2. ANALYSIS OF THE PROPOSED MPPT

The proposed sun-tracking system should satisfy certain technical requirements specific to the studied application, as follows;

- ❖ Simplicity of movement solution to reduce the cost and increase the viability
- ❖ Reliability in operation, under different perturbation conditions (wind, rain, dust and importantly, temperature and irradiance variations)
- ❖ Minimum energy consumption for optimum performance to cost ratio. (That is to ensure that that energy which the prototype device consumes for its operations will be such low that will not affect the general performance of the system when supplied to the load).

Taking into account these necessary technical requirements, the chosen solution to drive the PV panel consists of;

- ❖ A power supply unit
- ❖ A sensor unit comprising of LDR's
- ❖ A control unit which controls the movement of PV panel
- ❖ A drive unit comprising of a DC motor and a system of gears

2.1 Working Principle

The working principle of the system is that the sensor unit which consists of six sensors has LDR's (Light Dependent Resistor) as sensors. Its resistance depends on sunlight intensity (it decreases as the light intensity increases). A 2.5V input is fed to it. As its resistance varies, the voltage across it varies also. The sensor which receives the most light gives out the highest output voltage. The sensor unit consists of five of such tracking sensors which are adjacently fixed 36^{o} to each other. The sixth sensor which is the feedback sensor is movable and is mounted on the PV panel.

The control unit compares the voltage output of the five tracking sensors and selects the highest voltage (priority voltage). The priority voltage is then compared with the output voltage of the feedback sensor. If unequal, the control unit moves the PV panel upon which the feedback sensor is mounted clockwise or anti-clockwise (via the drive unit) until a point is reached where the output voltage of the feedback sensor becomes equal (or nearly equal) to the priority voltage. And if the feedback voltage becomes equal (or nearly equal) to the priority voltage, the movement controller stops moving the motor. The movement controller controls the movement direction of the DC motor by reversing its voltage polarity. At this point, the solar panel faces directly at the sun. An overview of the system block diagram is shown in Figure 4.

The control unit is divided into two parts: A priority voltage selector and a movement controller. The circuit diagram for the priority voltage selector is shown in Figure 6 below.

2.2 Priority Voltage Selector

At sunrise, sensor1 as seen in Fig. 5 receives the maximum sunlight hence its output voltage is maximum. The output voltages (V_1, V_2, V_3, V_4, and V_5) corresponding to the five sensors are amplified by the non-inverting operational amplifiers, U_2, U_3,U_4, U_5 and U_6 respectively before being compared by the cascaded comparators (U_7, U_8, U_9, U_{10} and U_{11}).

The voltage gains of the amplifiers are all the same (G = 2.8). Comparator 1 (U_7), compares the voltages V_1 and V_2. If V_1 is greater, it gives out on output, otherwise, no output. Comparator 2 (U_8) compares the voltages V_2 and V_3. If V_2 is greater, it gives out on output and in that order. The comparators give out negative voltages with respect to the ground. However, a positive voltage is desired for the design, hence the outputs are inverted by the NOT-gates, U_{12}, U_{13}, U_{14}, U_{15} and U_{16} respectively. It is seen from the arrangement of the sensors in fig. 5 that at sunrise, V_1 is greater than V_2. Also V_2 is greater than V_3, V_3 is greater than V_4 and V_4 is greater than V_5. This implies that comparators U_7, U_8, U_9 and U_{10}, will give out outputs. Multiple outputs are not desirable. Only a single output which will correspond to the maximum voltage is desired. To achieve this, priority is assigned to each of the voltages.

The priority action is that, a comparator gives out an output only when the voltage at the inverting terminal (V-) is greater than the voltage at the non-inverting terminal (V+). Comparators 2′, 3′, 4′, and 5′, (U_{20}, U_{19}, U_{18} and U_{17} respectively) are initially set off by the 470km resistors connected to their non-inverting terminal (V- < V+). These comparators however come on when they receive voltages from their complementary comparators 2, 3, 4 and 5 (V- > +). The comparators again go off when they receive a 'suppress' voltage from a complementary comparator with a higher priority (now, V- < V+). The outputs from the comparators (U_{20}, U_{19}, U_{18} and U_{17}) are again inverted by NOT gates before they are used to switch relays (via transistors). Each relay has a sensor output voltage (first buffered by Op-amp voltage followers) connected to its normally open terminal and only transfers it to the common terminal when energized by the transistors. This way, the priority voltage selector selects only the maximum sensor voltage, V_{pr}.

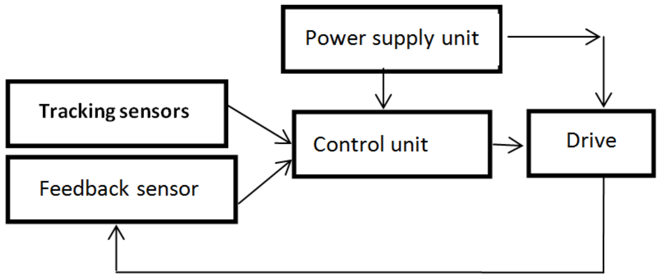

Figure 4: System block diagram

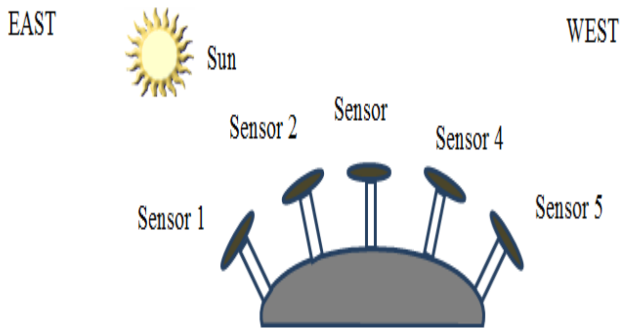

Fig 5: Sensor unit positioning

2.3 Movement Controller

The priority voltage, V_{pr}, which is fed to the movement controller, refer to Figure 7 is compared with the feedback voltage by two comparators U_{32} and U_{33}. U_{32} gives out an output when the feedback voltage, V_F, exceeds the priority voltage, V_{pr} while U_{33} gives out an output when the feedback voltage, V_F, is less than the priority voltage, V_{pr}. The outputs from these comparators are further fed to another set of comparators (U_{38} and U_{39}) which compares them with the sleep signal before giving out a final output. U_{38} and U_{39} are initially set off by the 1MΩ resistors connected to their non-inverting terminals (V -< V+). They are set on when they receive signals from the comparators IC_{10} and IC_{18}(V -> V+). However, there are set-off again when they receive the sleep signal (V- <V+).The sleep signal is generated by the comparator U_{34} which compares the maximum voltage,V_M with a reference sleep voltage (adjustable by the 5Ω variable resistor). If the maximum voltage is less than the sleep

voltage, then the sleep signal is generated. The outputs from the ICs, U_{38} and U_{39} are used to switch the relays (through transistors). The motor is initially at rest as its two terminals are grounded by the relays. It however detects a potential difference when one of the relays switches, hence it moves in either clockwise or anticlockwise direction as the case may be.

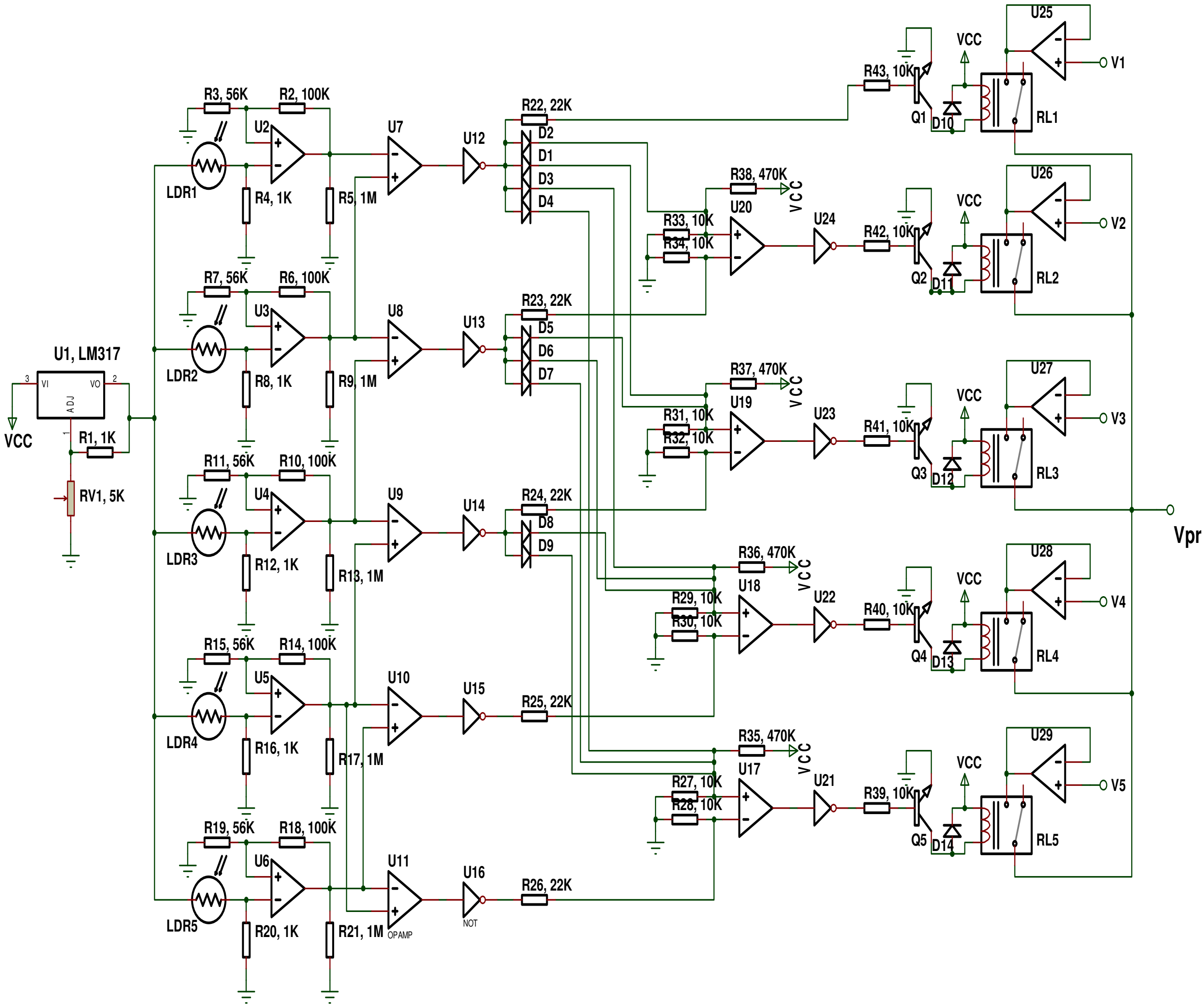

Figure 6: Priority voltage selector circuit diagram

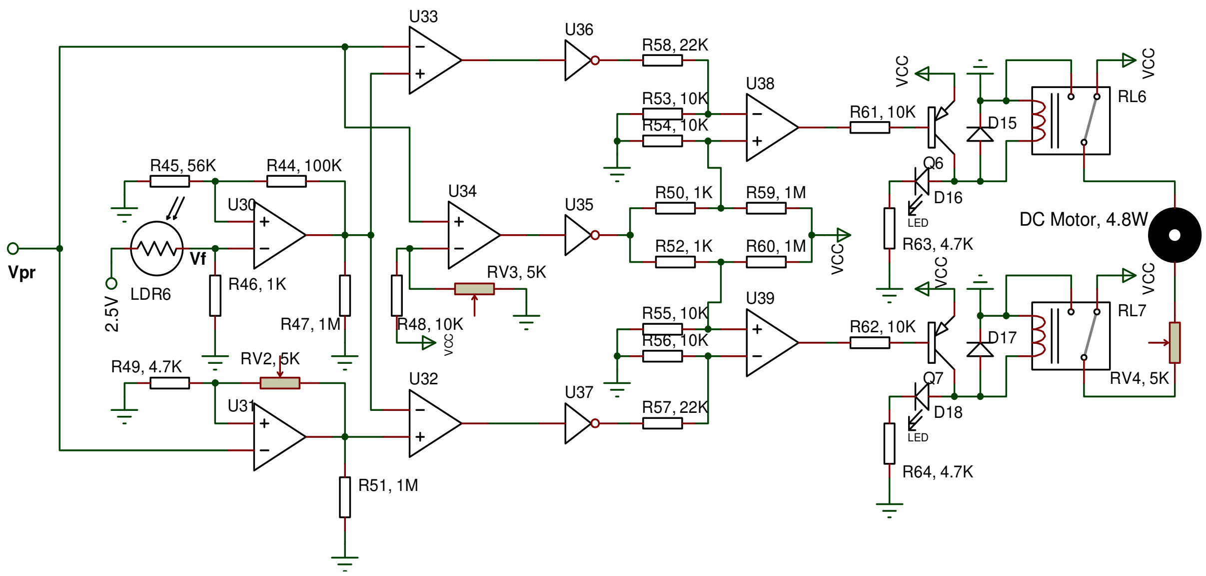

Figure 7: Movement controller circuit diagram

3. SELECTION OF COMPONENTS FOR THE PROTOTYPE MMPPT

The datasheet [10] for the IC LM317 (U_1) which is voltage regulator gives the value of R_1 as 220Ω. The equation for the calculation of R_2 as obtained from the datasheet of LM317 is

$$V = 1.25 \times \left[1 + \left(\frac{R2}{R1}\right)\right] \quad (1)$$

Where V is the output voltage, now, for a desired voltage output of 2.5V, R_2 is calculated to be 220Ω. However, as the voltage output may need to be varied from 2V to 5V, a variable resistor of 5KΩ is used instead.

Consider the circuit of Figure 8 for resistor gain,

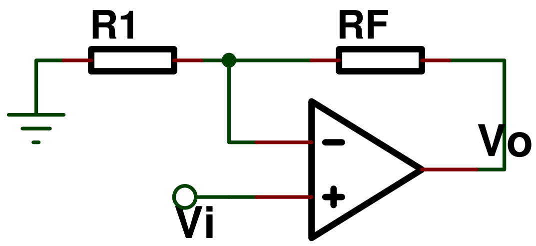

Figure 8 Amplifier circuit

For the non-inverting operational amplifier, the voltage gain is defined by the equation;

$$G = \frac{R_f}{R1} + 1 \quad (2)$$

For the design, a voltage gain of 2.8 is desired, therefore to obtain the values of R_f and R_1, one must be set and the other calculated. R_f is set to be 100KΩ

Hence,

$$R_1 = \frac{Rf}{(G-1)} = 56k\Omega \quad (3)$$

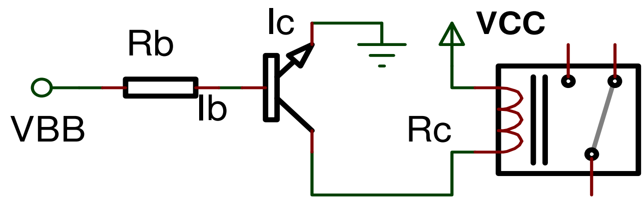

Figure 9 Transistor circuit

For the transistor shown in Figure 9, the collector current is given as:

$$I_c = \frac{Vcc}{Rc} = 0.1A \quad (4)$$

where, R_c is the resistance of the relay coil, which is measured to be 100Ω and Vcc is the power supply voltage (10V)

The base current can be calculated as;

$$I_b = \frac{Ic}{Hfe} = 1mA \quad (5)$$

Where, H_{fe} is the DC current gain of the switching transistor. H_{fe} is obtained from the datasheet of TIP41 to be 100.

The transistor base resistor value can now be calculated as,

$$R_b = \frac{V_{BB} - V_{BE}}{I_b} = 9.1k\Omega \quad (6)$$

where, V_{BB} = 9.8V (Input signal voltage) and V_{BE} = 0.7V (Transistor voltage drop)

However, a closer resistor value which can be found in the local market is 10KΩ.

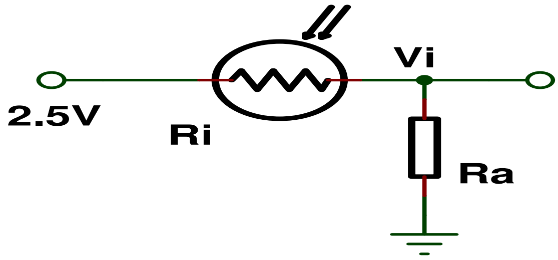

Figure 10 Voltage divider network

Consider the circuit in figure 10.

$$V_i = \left[\frac{Ri}{Ri+Ra}\right] * 2.5V \quad (7)$$

$$R_a = \frac{\frac{V_i}{2.5}R_i}{1 - \frac{V_i}{2.5}} \quad (8)$$

The resistance of the LDRs varies from 100KΩto 10Ω. The sensor output voltage varies from 0.1V to 2.4V. Now, for a resistance (R_i) range of 100KΩ to 10Ω and a desired voltage (V_i) range of 0.1V to 2.4V, a suitable resistance value for R_a is computed to be 1KΩ given the formula above.

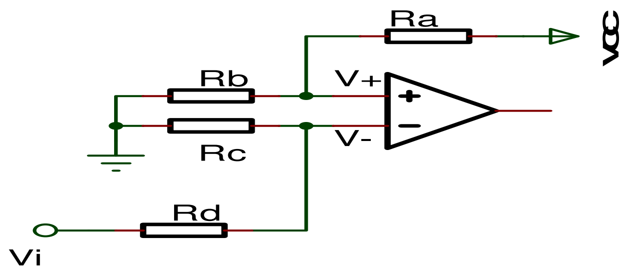

Figure 11 Comparator circuit

To set the reference voltage value V_+, one of the resistor values must be set and the other calculated see Figure 11. For a reference voltage (V_+) value of 0.2V, and Vcc = 10V, and R_b set to 10KΩ, R_a is obtained as seen in (9):

$$R_a = \frac{\left(1 - \frac{V_+}{V_{cc}}\right)R_b}{\frac{V_+}{V_{cc}}} = 470\Omega \quad (9)$$

Similarly at the inverting terminal (V_-), for a reference voltage value of 3V, and V_i = 9.8V, and R_c set to 10KΩ. R_d is obtained as

$$R_d = \frac{\left(1 - \frac{3V}{9.8V}\right)10K\Omega}{\frac{3V}{9.8V}} = 22K\Omega \quad (10)$$

To limit the current going to the LEDs, Resistor values for R_3 and R_5 are selected as 4.7KΩ.

Figure 12 shows the how solar panel is placed on the prototype MMPPT whereas Figure 13 indicates the control section of the prototype MMPPT.

4 RESULTS

Upon the completion of the final design, it was tested to verify its operation and performance. The prototype device tracks smoothly the sun and readings/data were taken at the interval of 30 minutes for five days but the data presented in this paper is the average values for the four days for want of space. After every 30 minutes, the current and voltage readings through and across the load of 100 Ω choke resistor rated 20W respectively for both fixed panel and the prototype MMPP sun tracker. The sleep mode operation works fine as the system was seen to stop tracking when the light intensity falls below a certain level. In the temperature measurement two different types of thermometers were used at the same time and the average used.

Figure12 Single Axis Solar Tracker

Fig 13 Control circuit

From Table 1 it is observed that MPPT enhances the performance of solar panel(s). The essence of this enhancement is that the solar panel maximises almost all the particular wavelengths that are being converted to energy by effective sun position.

The current, voltage, and power gains are calculated to compare the two systems. Those gains are calculated using few days' average values in Table 1. The current gain (GI) is calculated and compared for the two systems as follows:

$GI(\%) = 100 * (1 - (1.30/1.37)) = 5.11\%$ (11)

The current gain of 5.11% is obtained from the sun tracking system.

The voltage gain (GV) is also calculated as shown below:

$GV\% = 100 * (1 - (63.04 / 63.48)) = 0.69\%$ (12)

The voltage gain of 0.69% is obtained from the sun tracking system.

The power of the sun module is calculated as below:

$P = I * V = 1.30 * 63.04 = 81.952W$ (for the fixed panel). (13)

$P = I * V = 1.37 * 63.48 = 86.968W$ (for the rotating single axis tracking system).

If the powers are compared to each other, the power gain (GP) is calculated as follows:

$GP\% = 100 * (1 - (81.952/86.968)) = 5.77\%$ (14)

The power gain of about 5.77% is provided using the single axis tracking system. From results calculated for just a single panel each, it proves that for a lot of energy is being conserved by applying MPPT to solar panel more especially the prototype MMPPT developed in this research.

5. CONCLUSIONS

Solar energy is renewable and free. Also, solar panels are easy to maintain and have a very long lifetime. With a sun-tracking system, this renewable energy could be harnessed more efficiently and thereby improving the output performance of solar panel hence ameliorating the problem of electricity in rural or remote areas of this country as has been proved by comparison of fixed and tracking panels in this paper. Having a gain of 5.77% for using the option of MMPPT just for one panel alone means that by connecting up to 7 panels, a gain of about 40.39% of energy will be available for the load to utilize instead of the popular option of fixed panel either on the rooftop or on the pole which are in use in Nigeria currently. More research on sun-tracking systems would help minimize the electricity crisis that is hitting Nigeria at the moment.

Finally, research work represents a functioning miniature scale model of sun tracking technique which could be replicated to a much larger scale if there will be funding or sponsors.

Table 1: Average data collected from 7th,8th,11th and 12th June 2012

S/N	TIME	Temp(°C)	Fixed Panel			Tracked panel		
			V_{oc} (V)	I_{sc} (A)	P (W)	V_{oc} (V)	I_{sc} (A)	P (W)
1	07.30am	26.10	60.6	0.65	39.39	61.01	0.72	43.93
2	08.00am	26.85	62.1	0.78	48.44	62.52	0.84	52.52
3	08.30am	26.50	62.5	0.80	50.00	63.02	0.86	54.20
4	09.00am	27.25	62.9	0.96	60.38	63.31	1.01	63.94
5	09.30am	27.31	63.0	1.00	63.00	63.45	1.07	67.89
6	10.00am	27.63	63.5	1.12	71.12	63.94	1.20	76.73
7	10.30am	27.81	63.8	1.41	89.96	64.22	1.47	94.40
8	11.00am	28.06	63.9	1.49	95.21	64.36	1.56	100.40
9	11.30am	28.50	64.0	1.61	103.04	64.49	1.66	107.05
10	12.oopm	28.50	64.2	1.67	107.21	64.63	1.76	113.75
11	12.30pm	29.13	64.5	2.06	132.87	64.93	2.12	137.65
12	01.00pm	29.38	64.8	2.10	136.08	65.24	2.17	141.57
13	01.30pm	29.19	64.7	1.96	126.81	65.16	2.05	133.58
14	02.00pm	29.13	63.0	1.61	101.43	63.41	1.68	106.53
15	02.30pm	29.25	60.9	1.26	76.73	61.38	1.33	81.64
16	03.00pm	29.13	62.7	1.16	72.73	63.11	1.22	76.99
17	03.30pm	29.25	62.4	1.10	68.64	62.89	1.17	73.58
18	04.00pm	29.25	62.0	1.02	63.24	62.42	1.11	69.29
19	04.30pm	28.58	62.3	1.01	62.92	62.63	1.08	67.64
Average Value			63.04	1.30	82.59	63.48	1.37	87.54

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