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DESIGN AND ASSESSMENT OF LOW-COST DUAL AXIS SOLAR TRACKING SYSTEMS FOR MAXIMUM SOLAR PHOTOVOLTAIC POWER EXTRACTION

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ABSTRACT

A microcontroller-based dual axis solar tracking system is presented and implemented using computational algorithm. The experiment is conducted in two different test days; test day1 28th April 2020 and test day2 29th May 2020 for the evaluation of data collected in Zaria-Nigeria in a site located at 11.092 o N Latitude, 7.72o longitude. The panel is fixed at inclination of the site's latitude with respect to the horizon on the northern hemisphere facing south. Whereas the automatic tracking mechanism is allowed to track the sun's trajectory automatically in one axis (single axis) and two axes (dual axis). Radiation intensity sensors circuit is designed using Light Dependent Resistors (LDR) and Microcontroller on which the tracking algorithm was compiled. Iterative method based on Newton-Raphson is used to characterize the Photovoltaic (PV) panel. The study shows that the single axis generated 34.8% and 26.2% average increase in efficiency than that of the fixed mount for the test day 1 and test day 2 respectively. While the dual axis has 42.5% and 32.5% more than that of the fixed mount respectively for the test day 1 and test day 2. The daily average power calculated for dual axis produced more power than that of the single axis as well as that of the fixed mount system. The hardware chosen are of low-cost, versatile and simple to use. This automatic dual axis tracking topology can help to improve optimum power generation and management system.

Keywords: Dual Axis Solar Tracking System, Photovoltaic power optimization, Microcontroller-based solar tracker, Renewable energy efficiency

INTRODUCTION

Energy crisis is the most important problem in the world today. When it comes to the development of any nation, energy is the main driving factor. There is an enormous quantity of energy that gets extracted, distributed, converted and consumed daily around the globe (Wang et al., 2013). Conventional energy resources such as nuclear, coal and natural gas are not only getting exhausted but also contaminate the environment (Marques et al., 2016). As energy consumption and demand levels continue to increase with the growing global population therefore, scientists are looking out for means of filling the gap through renewable energy supplies. The current emphasis on renewable energy resources is to reduce the dependency on the conventional energy resources. Derived Energy from the sun, also known as solar energy, is mostly and rapidly gaining attention as it is clean, environmentally friendly, readily available and an abundant source of energy specifically in the tropical regions of the world (Solanki & Malviya, 2016). This renewable energy type has so far been established to be the most dependable and sustainable source of renewable energy globally.

Solar energy, the main source of most renewable energy, has become an interesting practical field of research. A way to overcome these difficulties and to satisfy the growing electricity demand around the world is the application of photovoltaic (PV) systems which allow converting solar energy into electricity from sunlight (Abdo et al., 2019). This clean technology encouraged many researchers who studied the performance of different systems targeting to maximize the PV production with the least cost modifications.

There are several approaches by which the optimum yield of PV systems could be enhanced. The first approach is to increase the generation efficiency of solar cells (Murad, 2019); the second is associated to the energy conversion system using maximum power point tracking (MPPT) control algorithms (Kalpana et al., 2013); and the third approach is to adopt solar tracking system to obtain maximum solar energy input from the sun (Nayak et al., 2018). These approaches can be achieved from one of the methods; fix (Stationery) axis, single (one) axis and dual (two) axis techniques (Nayak et al., 2018). The energy delivered by solar panels depends on various factors; the construction and efficiency of the solar cells, the temperature and the intensity of the irradiated light. Even under clear weather conditions the position of the sun changes during the day, which in the case of fix mount installed solar panels leads to changes in the effective surface of the solar panels towards the sun and a decreased output power (Nayak et al., 2018).

The optimum position is when the solar panels are perpendicular to the light (Amadi & Gutiérrez, 2019), it has been estimated that the use of sun tracking system over a fixed system, can increase the power output by 30% -60% (Abdollahpour et al., 2018). A solar tracking system orients or directs solar photovoltaic panels by keeping track of the sun's movement from dawn to dusk, thus maximizing solar energy power generation efficiency (Nayak et al., 2018). Sun tracking systems are typically classified into two categories, namely passive (Mechanical) and active (Electrical) trackers (Nayak et al., 2018). Passive solar trackers do not incorporate sensors or actuators but are based on thermal expansion of a matter or on shape memory alloys. Usually this kind of tracker is composed of couple of actuators working against each other which are, by equal illumination, balanced. Active trackers are systems whose motion is performed by actuators controlled by signals of a sensor. Active trackers can further be characterized as microprocessor and electro-optical sensor based, Personnel computer (PC) controlled date and time based, auxiliary bifacial solar cell based and a combination of these three systems; LDR and photodiode as sensors, geared DC motor and stepper motor as the actuators (Nayak et al., 2018).

In this work, an overview of single and dual axis tracker is presented. The automatic dual axis tracker is proposed and implemented experimentally. The experimental results are given to verify the advantages of the dual axis tracker in power optimization over a single axis tracker and fixed mount in order to achieve utilization of solar irradiation. Background theory of power extraction is highlighted in section 2. An overview of the system is described in section 3. Section 4 addresses the detailed methodology and implemented experimentally. The result of the experiment is presented in Section 5, several significant results show improvement in the overall power and efficiency of the dual axis tracker over the fixed mount and single axis tracking system, which shows improvement of utilizing the solar radiation using the dual axis tracker system. Finally, a conclusion will be drawn in section 6.

Theoretical Consideration

The fundamental non-transcendental current–voltage governing equation of a photovoltaic cell is given by equation (1). Figure 1 shows the equivalent circuit of the photovoltaic (PV) cell empirical model of the equation (Hasan & Parida, 2016);

$$I = I_{ph} - I_o\left[exp\left(\frac{V+I\cdot R_s}{A\cdot V_t\cdot N_s}\right) - 1\right] - \frac{V+I\cdot R_s}{R_{sh}} \qquad (1)$$

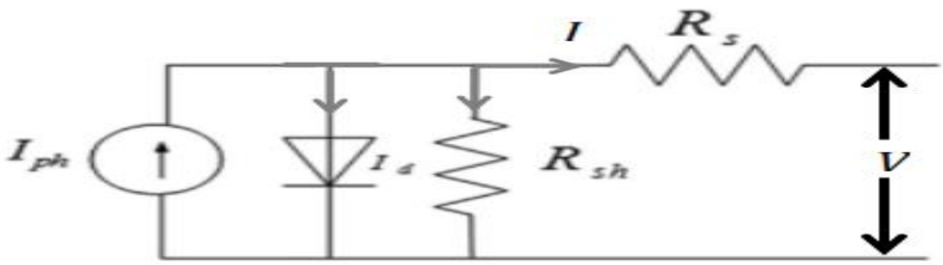

Figure 1: Equivalent Electrical Circuit of the Single Diode Model

Where I_{ph} is the photocurrent in (A), I_o is the diode saturation current (A), $V_t = kT/q$ thermal voltage (V), A is the ideality factor, k the Boltzmann constant, N_S number of cells in series $q$is the electronic charge, R_s the series resistance, R_{sh} is the shunt resistance, T is the cell temperature (Mohammed, 2011).

Several models for diode saturation current I_0 were in literature based on certain assumptions (Abdo et al., 2019; Bouraiou et al., 2015; Chouder et al., 2012; Jack et al., 2015);. However, the most suitable model of $I_0$is given in equation (2) which is based on the fact that I_0 depends on open circuit voltage, V_{oc}, which in turns depends on temperature, T, as well as on irradiance, G(Obbadi et al., 2016);

$$I_o = \frac{I_{sc}\left(1+\frac{R_S}{R_{sh}}\right)-\frac{V_{oc}}{R_{sh}}}{exp\left(\frac{V_{oc}}{AN_SV_t}\right)-exp\left(\frac{R_SI_{sc}}{AN_SV_t}\right)} \qquad (2)$$

Where I_{sc} is the short circuit current and $R_{sh}$is given by equation (3)And:

$$R_{sh} = \frac{V_{mpp}+I_{mpp}R_s}{I_{ph}-I_{mpp}-I_o\left[exp\left(\frac{V_{mpp}+I_{mpp}R_S}{AN_SV_t}\right)-1\right]} \qquad (3)$$

Where $V_{mpp}$and $I_{mpp}$are respectively the maximum power point voltage and current given as equation (4) and (5) (Saloux & Teyssedou, 2011)

$$V_{mpp} = \frac{AN_sk_BT_{pv}}{q} ln\left[\frac{AN_sk_BT_{pv}}{qI_o}\frac{I_{sc}}{V_{oc}}\right] \qquad (4)$$

$$I_{mpp} = I_{ph} + I_o - \frac{AN_sk_BT_{pv}}{q}\left(\frac{I_{sc}}{V_{oc}}\right) \qquad (5)$$

And the maximum power output, P_{mpp} of the PV panel is given as;

$$P_{mpp} = I_{mpp}V_{mpp} \qquad (6)$$

Several parameter estimations approaches are in literature and classified as; differential evolution (Ali & Yusuf, 2017; Ishaque et al., 2012; Yusuf & Ali, 2016), Analytical [7], [10] and Iterative [10]–[12] method. Iterative method is considered in this work. An iterative method is a mathematical procedure that creates a sequence of developing approximate solutions for a class of problems, in which the nth approximation is derived from the preceding ones (Ali & Yusuf, 2017; Kelley, 1995; Singh & Gupta, 2015). Several iterative techniques were available, this work considered Newton-Raphson iterative technique, being an easy and precise way to reduce the number of equations to four by modifying the series resistanceR_S(Abdul-Jaleel et al., 2012; Sethi et al., 2012).

Newton-Raphson Method is an iterative technique that involves estimation of a given function$f(x_{n+1})$with an initial guess. The method is obtained through the Taylor series expansion in$(x_{n+1} - x_n)$ given below (Reis et al., 2017);

$$f(x_{n+1}) = f(x_n) + f'(x_n)(x_{n+1} - x_n) + \frac{1}{2!}f''(x_n)(x_{n+1} - x_n)^2 + \ldots = 0 \qquad (7)$$

Where x is the independent variables, n is the iteration number.

Limiting the series in the second term, the general formula for Newton-Raphson's method can be obtained as given by equation (8) (Obbadi et al., 2016)

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \; n = 0,1,2,\ldots \qquad (8)$$

The corresponding equivalent for the nonlinear transcendental equation (1), equation (8) can be written as (Ali & Yusuf, 2017);

$$I_{n+1} = I_n - \frac{I_{ph}-I_o\left[exp\left(\frac{V+I_nR_S}{AN_SV_t}\right)-1\right]-\frac{V+I_nR_S}{R_{sh}}-I_n}{-\frac{I_oR_S}{AN_SV_t}exp\left(\frac{V+I_nR_S}{AN_SV_t}\right)-\frac{R_S}{R_{sh}}-1} \qquad (9)$$

Where n is the iteration number.

The maximum efficiency of the PV module is given as;

$$\eta_{mx} = \frac{P_{mpp}}{GA_{pv}} \qquad (10)$$

The average increase in efficiency $\eta_{avg}$of the PV panel can then be estimated as (Motahhir et al., 2019);

$$\eta_{avg} = \frac{\sum(P_n-P_o)}{\sum P_o} x100\% n = 1,2 \qquad (11)$$

Where P_o is the average output power of the fixed axis PV panel and P_n is average output power of the PV panel on automatic tracker, single axis (n=1) and dual axis (n=2).

MATERIALS AND METHODS

As the solar radiation is received on the LDR circuit board, each LDR will receive an amount of sun's intensity. Depending on the intensity established by the LDRs some will be illuminated while some will be partially shadowed by the opaque plate placed in-between the LDRs. The LDRs present in the side, in which the intensity is higher, will create a stronger signals and others a weaker. These amounts of intensity will be converted into electrical potential by the potential divider formed between the LDRs and the series resistors. The microcontroller will convert these analogue electrical potential signals into digital signals (in bits) by the internal Analogue to Digital Converter (ADC) inside the microcontroller. The microcontroller is programmed to compute the averages of every two adjacent LDR values (top left and top right, bottom left and bottom right, top left and bottom left, top right and bottom right). The microcontroller will again compare these averages between the tops and the bottoms, the difference between these values within a defined tolerance (1% of the supply voltage) will be converted into analogue signal at the output of the microcontroller by the internal Digital to Analogue Converter (DAC) which drives the mechanism in the direction in which the intensity of the solar radiance is maximum until the difference is below the defined tolerance. This tolerance is used to stabilize the controller and once the solar tracker is perpendicular to the sun, no further control is made.

The experimental set up is as shown on plate 1, the temperature of the PV panel, the ambient and the amount of irradiance were measured simultaneously with the current-voltage characteristics of the PV using digital multimeter (Model SD9205A), Solar radiation meter (Model pi 510) and dual digital thermometer (Model 6802II TWOK-TYPE) respectively. The accuracy of the temperature measurement is $\pm 0.5\ ^oC$and the irradiance is $\pm 1 Wm^{-2}$. A program is designed in MATLAB environment to develop current-voltage, power-voltage and power-time characteristics in order to evaluate the maximum power point parameters and other important PV parameters. The experiment was conducted at the three different scenarios (fixed mount, single axis and dual axis) at different time of the day (interval of hour). This experimental procedure was followed in order to get the load current, I_L and voltage, V_L characteristics of the PV panel, it also allowed to develop P_L-V_L, P_L-I_L characteristics as well as Power-Time characteristics of the day (Ali & Yusuf, 2017).

System Description

The automatic dual axis tracker consists of a supporting mechanism with two rotation axes controlled by two servo motors, east-west and base rotation (SM1 and SM2). Servo motor 1 (SM1) controls the rotation of the mechanism in east-west direction (Azimuth rotation) to cover daily movement of the sun while servo motor 2 controls the rotation of the mechanism in North-South (left-right) direction (altitude rotation). The servo motors are to change the incidence angle of the sun on the panel placed on the tracker, so that the sun's position is always perpendicular to the panel. Attached to the automatic tracker are four Light Dependent Resistors sensors (LDR) each placed in a quadrant of rectangular board with equidistance from any two adjacent ones separated by an opaque object to enable the sun to cast a shadow Figure 3. A chain-lever system is attached to the east-west servo motor to ease in lifting the top of the mechanism in directing the panel towards the sun at normal incidence. Each servo motor has an inbuild driver to allow for a slow rotation of the motors. Also, four Light Emitting Diodes (LEDs) were attached to the system just to indicate the direction of rotation of the mechanism. A microcontroller which is the heart of the automatic tracker system is also incorporated to the circuit. A program is written in C+ and assembly language in MPLAB IDE 8.66 software base on the system algorithm shown on Figure 2. The complete tracker mechanism is shown on Plate (1).

Plate 1: Completed Solar Tracking Mechanism


Plate 2: Servo Motor

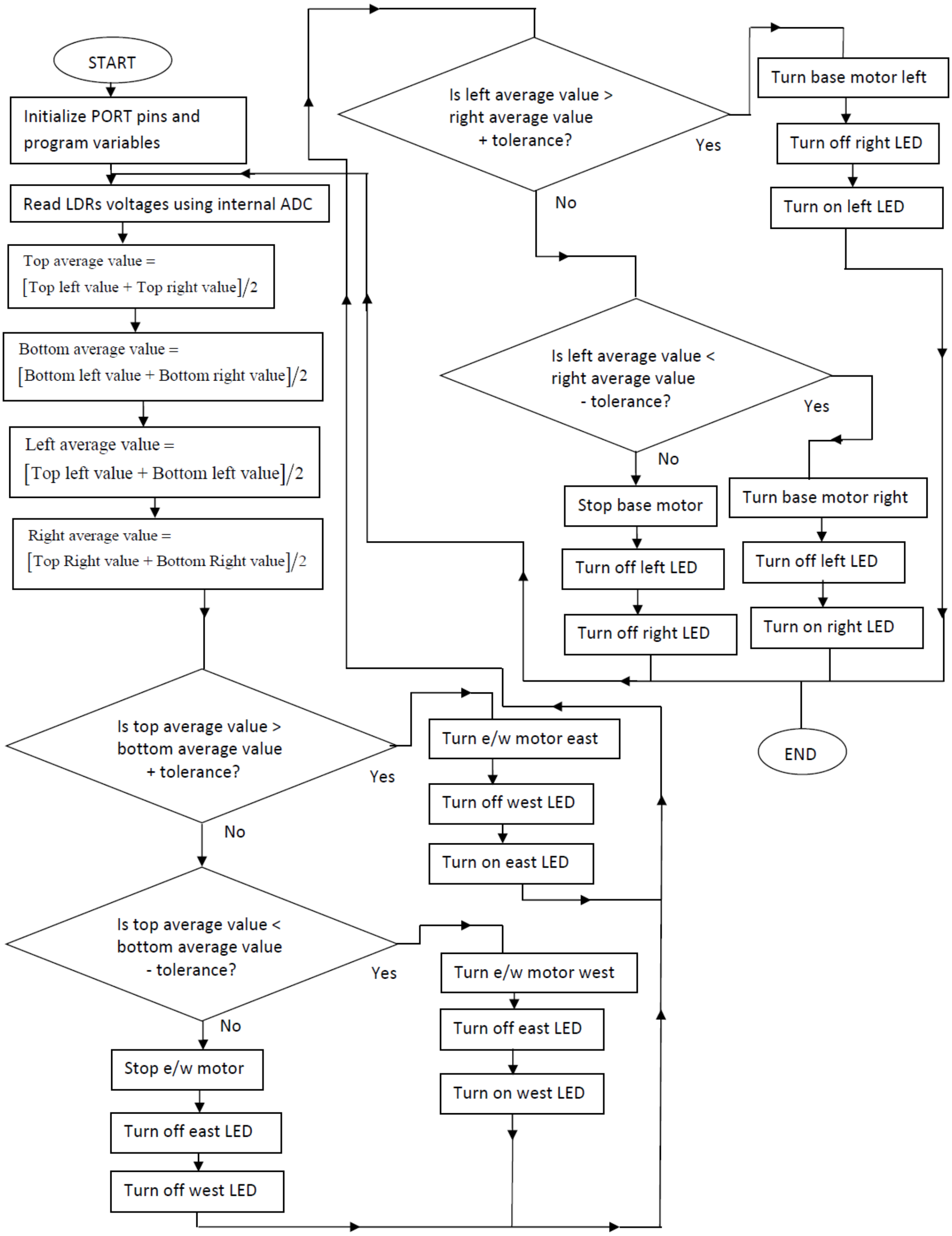

Figure 2: Computational Algorithm for the Implementation of Single

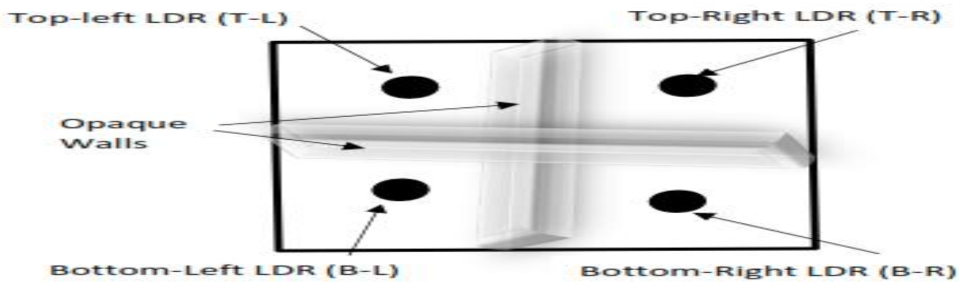

Figure 3: LDR Circuit Board

RESULT AND DISCUSSION

The characteristics of both the P-V and I-V curves as well as the known model parameters from datasheet under Standard Test Condition (STC) were plotted in MATLAB environment Figure 4 and Figure 5 respectively. The measured I-V characteristics obtained in two different test days for the three different scenarios; fixed mount, single axis and dual axis panel orientations were plotted in MATLAB environment Figures 6-9 to generate the unknown parameters at the outdoor environment. Since the in practice, PV panels do not operate under ideal condition (STC) in outdoor measurement. The measured data solar radiation, cell temperature, short circuit current, open circuit voltage and the ambient temperature were collected. Iteration method was adopted based on Newton-Raphson technique. The maximum power point parameters for single and dual axis orientations identified in MATLAB where identified and compared with the fixed mount.

Table 1 presents the output parameters for fixed mount, single axis and dual axis on 28 April 2020 from 8:00am to 5:00pm. The daily average power calculated for test day 1, 28th April 2020 and test day 2, 29th May 2020 shows that the single axis generated respectively 34.8% and 26.2% average increase in efficiency than that of the fixed mount. This is highlighted from Figure 10 and Figure 11 from the MATLAB simulation.

Table 1: Output Parameters for Fixed Mount, Single and Dual Axis Taken on 28th April 2020

TIME/Hour	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00
Fixed Mount Orientation										
G/Wm^{-2}	472	505	525	546	609	846	729	720	650	553
I_{SC}/A	0.45	0.48	0.5	0.52	0.58	0.82	0.7	0.69	0.62	0.53
V_{OC}/V	19.81	19.73	19.7	19.24	19.22	19.15	19.19	19.01	18.83	18.67
I_{MP}/A	0.402	0.429	0.446	0.463	0.517	0.72	0.618	0.61	0.55	0.469
V_{MP}/V	15.089	14.954	14.91	14.555	14.435	14.282	14.299	14.221	14.168	14.106
Single Axis Orientation										
G/Wm^{-2}	722	745	775	826	895	940	909	884	796	649
I_{SC}/A	0.69	0.71	0.74	0.79	0.86	0.91	0.88	0.85	0.76	0.62
V_{OC}/V	20.1	19.95	19.89	19.71	19.46	19.32	19.33	19.3	19.41	19.21
I_{MP}/A	0.615	0.634	0.659	0.702	0.761	0.804	0.773	0.75	0.674	0.551
V_{MP}/V	15.305	15.115	15.05	14.904	14.609	14.407	14.398	14.433	14.601	14.511
Dual Axis Orientation										
G/Wm^{-2}	785	796	836	869	978	998	991	896	805	641
I_{SC}/A	0.75	0.76	0.8	0.83	0.94	0.97	0.96	0.86	0.77	0.62
V_{OC}/V	20.9	20.1	19.93	19.86	19.59	19.39	19.43	19.35	19.45	19.21
I_{MP}/A	0.669	0.678	0.711	0.738	0.833	0.852	0.844	0.76	0.682	0.552
V_{MP}/V	15.912	15.228	15.077	15.016	14.704	14.457	14.471	14.471	14.63	14.511

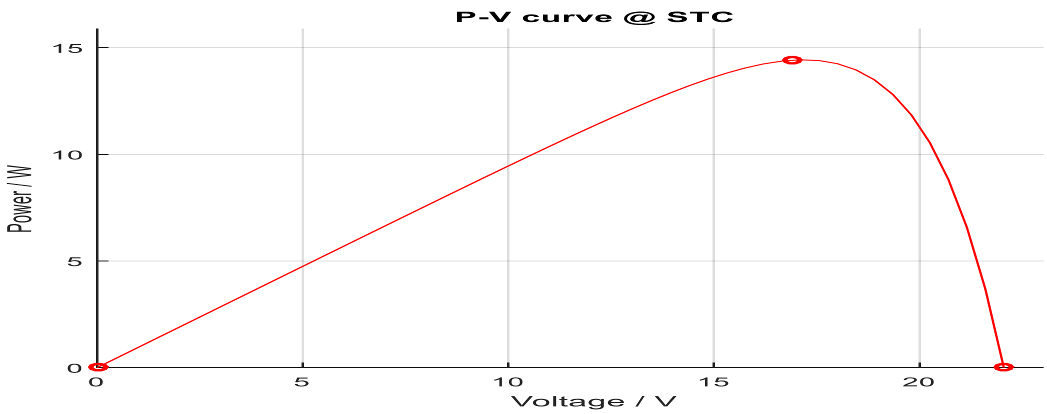

Figure 4: P-V Characteristics at STC

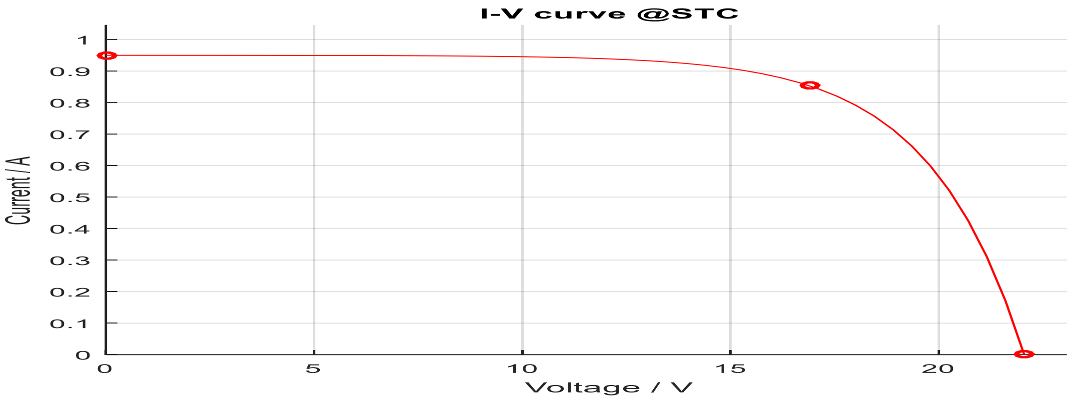

Figure 5: I-V Characteristics at STC

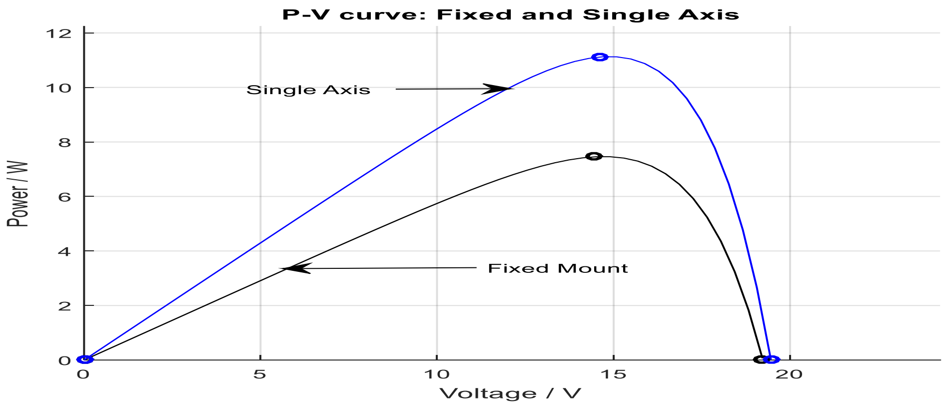

Figure 6: Comparison of P-V Characteristic for the Fixed Mount Versus Single Axis Tracker System on Test Day 28th April 2020

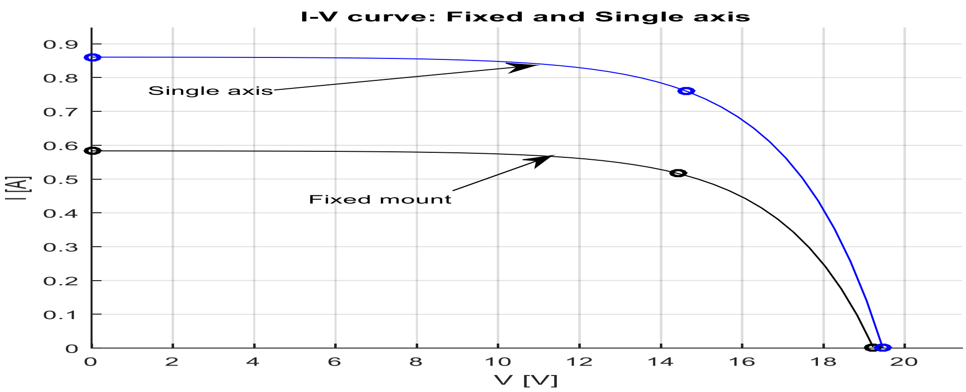

Figure 7: Comparison of I-V Characteristic for the Fixed Mount Versus Single Axis Tracker System on Test Day 28th April 2020

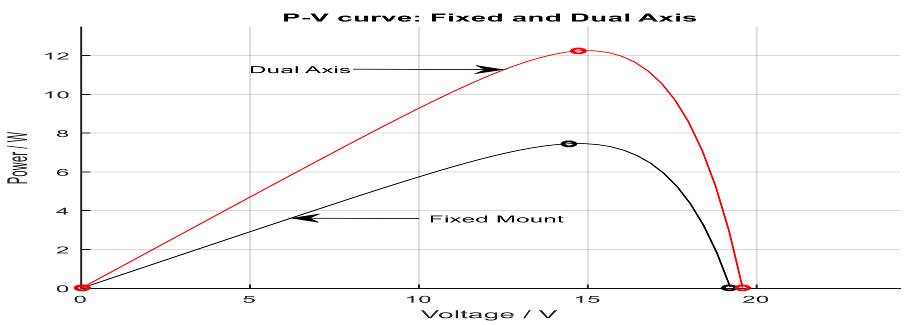

Figure 8: Comparison of P-V Characteristic for the Fixed Mount Versus Dual Axis Tracker System on Test Day 28th April 2020.

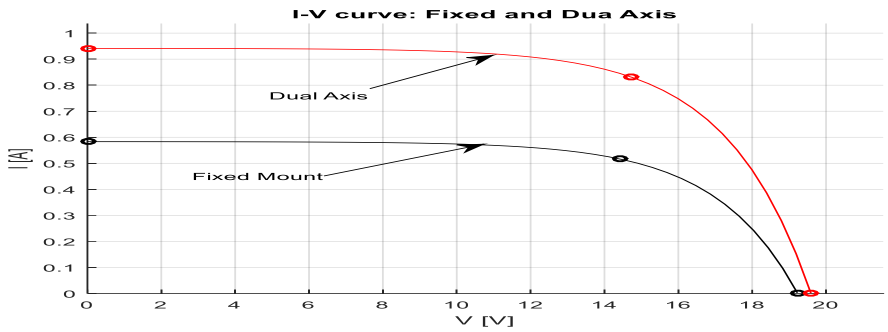

Figure 9: Comparison of I-V Characteristic for the Fixed Mount Versus Dual Axis Tracker System on Test Day 28th April 2020

The daily average increase in efficiency calculated for dual axis were found to be 42.6% and 32.5%more than that of the fixed mount for test day1 and test day 2 respectively. This is shown in Figure 11 from the MATLAB simulation. The daily average power and Efficiencies calculated show that the dual axis generated more power as compared to that of the fixed mount for the test days Figure 10 and Figure 11 respectively.

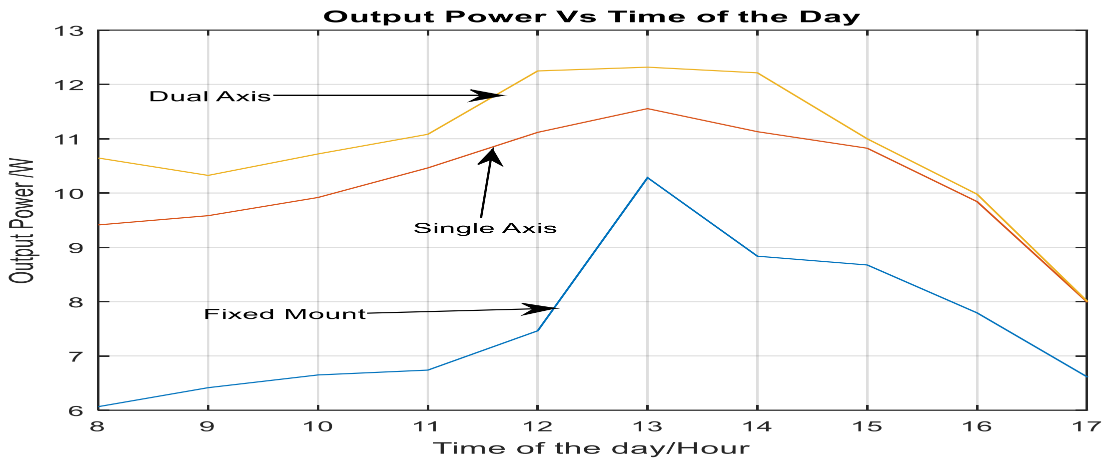

Figure 10: Simulation Result for Comparison of Variation of Efficiency Vs Time. for the Fixed Mount, Single Axis and Dual Axis Tracker System on Test Day 28th April 2020

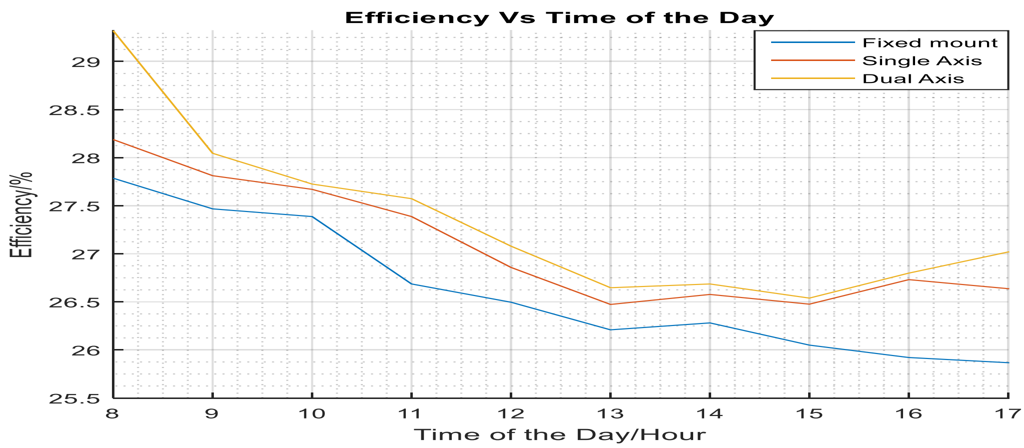

Figure 11: Simulation Result for Comparison of Variation of Efficiency Vs Time. for the Fixed Mount, Single Axis and Dual Axis Tracker System on Test Day 28th April 2020.

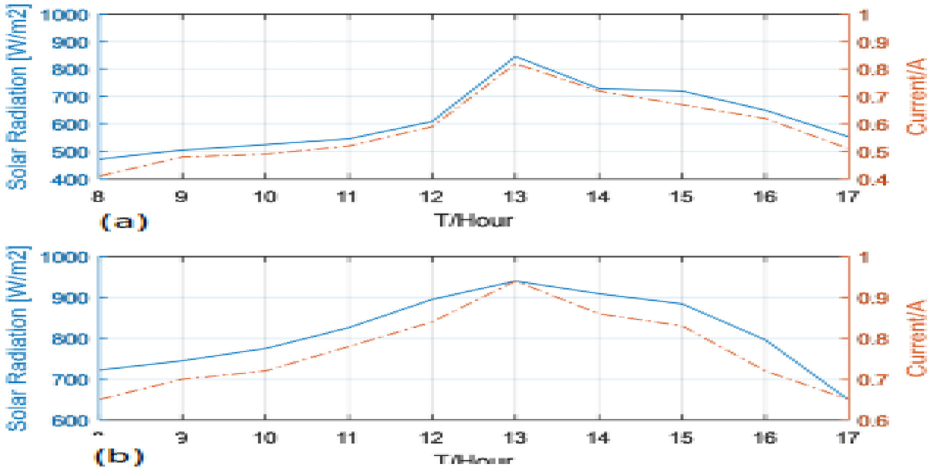

Figure 12: Variation of Solar Radiation Intensity and Short Circuit Current for (A) Fived Mount And (B) Single Axis on Test Day 28th April 2020

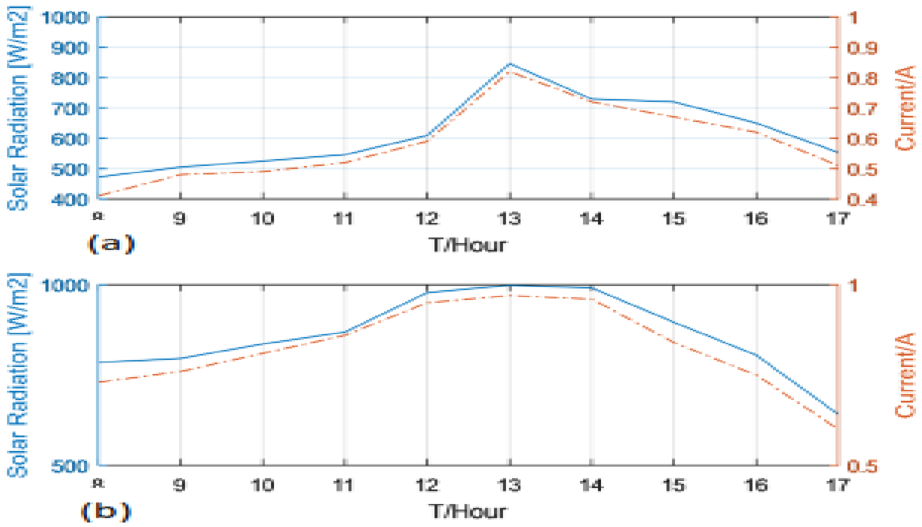

Figure 13: Variation of Solar Radiation Intensity and Short Circuit Current for (A) Fived Mount and (B) Dual Axis on Test Day 28th April 2020

Figure 12 presents the hourly variation of irradiance and the short circuit current for fixed mount and single axis driven panel tracking system. Figure 13 shows the variation of same fixed mount parameters and dual axis driven PV panel tracking system on test day1, 28th April 2020. From these Figures it can be seen that both single and dual axis tracking systems generated higher short circuit current and amount of irradiance as compared to that of the fixed mount throughout the test days. This is an indication that solar radiation as well as short circuit current increases from sun rise towards the noon time and decreases towards the sun set in all the three scenarios. This is due to the fact that irradiance is a measure of sun's energy which increases with slightest amount of fog present in the atmosphere as the sun is approaching overhead in which the fogs becomes quite small. It can also be seen that towards the noon as the temperature is approaching maximum value where the irradiance is supposed to be maximum the single axis and the dual axis power slightly deteriorate; this is due to the sudden increase in temperature of the solar cells which affect the performance of the solar panel. It can also be concluded that the problem of high ambient temperature around the noon time is translated into decrease in output power. This problem can be overcome if proper cooling is employed in the system which justifies the need for detailed tracking of solar-thermal base PV panels analysis.

CONCLUSION

A computational algorithm was drawn and implemented experimentally to evaluate the performance of single axis and dual axis tracking over a fixed Mount. The algorithm developed was programmed in MPLAB software and compiled in the microcontroller that controls the panel trajectory. The daily average power calculated for test day 1, 28th April 2020 and test day 2, 29th May 2020 shows that the single axis generated respectively 34.8% and 26.2% average increase in efficiency than that of the fixed mount. while the daily average increase in efficiency calculated for dual axis were found to be 42.6% and 32.5% more than that of the fixed mount for same period respectively. The daily average power calculated shows that the dual axis generated more power as compared to that of the single and fixed mount for the test days. The increase in temperature of the solar cells and the high ambient temperature around the noon time affect the performance of the solar panel which result into decrease in the output power, this problem can be overcome if proper cooling is adopted in the system which justifies the need for detailed tracking of solar-thermal base PV panels analysis.

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