EVOLVABLE ARM TO TRACK THE MAXIMUM POWER POINT OF A PV CELL USING BI-LEVEL OPTIMIZATION

S. B. Sivasubramaniyan[1], Dr. R. Seshasayanan[2]
[1]Assistant Professor, Department of EEE, Meenakshi Sundararajan Engineering College, Chennai
[2]Professor, Department of ECE, College of Engineering, Guindy, Anna University, Chennai

Abstract: The present work draws inspiration from phototropism exhibited by the plants. The leaf and stem always align towards light source and the root, the other way. Solar cell constituting a solar panel is individually visualized as leaf of a plant and allowed to evolve to align itself towards the sun. An evolvable arm is designed to move in a spherical coordinate system to take up the optimum position. The evolution is guided by the bi-level optimization. The simulation result shows an improved energy generation during partial shading condition.
Key words: Phototropism, Evolutionary Algorithms, Bi-Level Optimization, MPPT.

I. INTRODUCTION

The ever increasing impetus towards alternate energy is a positive signal towards environment. The paradigm shift would become complete only when the utilization of renewable sources is efficient by any standards. Sun provides light and heat energy which could be tapped for efficient energy generation. Solar power installations worldwide has crossed the 300 GW limit last year. China tops the list of solar PV installations followed by Japan, Germany and the U.S. India's PV installations amounts to 12 GW as of 2017. However, the 300 GW capacity accounts to just 1.8% of world's total energy consumption [1]. The striking point is the growing awareness of harnessing the sun's power which is relatively less hazardous than the energy generation using fossil fuels. Resorting to renewable energy, particularly in solar energy among various other ways, to power generation could fulfill the ambitious attempts in limiting the increase in the global temperature to well within 2 degree Celsius. With abundant solar energy available, India is blessed with 250 to 300 days of sunny days. It scales to 5000 trillion kWh of potential energy per year. By 2022, India is planning to set up 175 GW of PV system. With the potential benefits in sight, the effective utilization of solar energy becomes imperative by any standards. Solar energy is erratic as it is intermittent. The Irradiance from the sun follows Gaussian distribution throughout the day. Solar cell placed at a particular location should be properly optimized in its position to track the sun. Solar panels at the northern hemisphere are placed facing south at an angle as prescribed by the latitude of the place. This makes the panel to be tilted at an angle of 13 degree in Chennai . This position harvests the maximum energy from the sun and clocks at 5.5 solar hours per day. Mechanical tracking of the panel to track the trajectory of the sun results in much higher solar hours. However, the application of evolutionary algorithms to track the sun is not needed in the first place, as the movement of the sun over the sky is deterministic as shown in fig 1. Sun makes a definite 15 degree every hour over the sky with respect to earth's surface. If the angle made by the sun is taken as 90degree at zenith, then the sun makes 0 degrees and 180 degrees at 6 am and 6 pm respectively. The sun tracker system, thus, is a deterministic problem. But the energy involved in accomplishing the mechanical tracking makes it not feasible to implement the same. Drawbacks in tilting the entire structure made researchers to try novel methods in mechanical tracking [2]. A novel nanocomposite material based mechanical tracking without actually involving motors is also been reported [3]. The electrical tracking of the solar power is a viable option to harness maximum energy availability from the

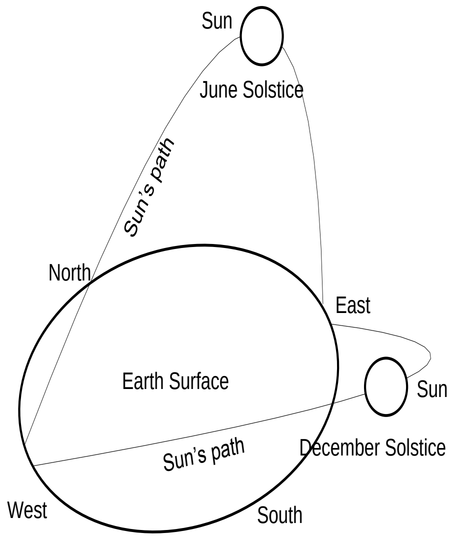

Fig. 1:. Sun's movement over the sky wrt the earth

sun. However, electrical maximum power tracking accounts for maximum power under operating conditions rather than the maximum power given by standard test conditions. Power reduction from solar panel is accompanied with partial shading conditions. There are various configurations proposed to overcome the detrimental effects of partial shading and draw maximum power form the panel under partial shading conditions. The effects of partial shading is countered using insolation dependant shunt resistances wherein separate shunt resistances for each of the rows of the solar cells is configured to add the row or break the row from power generation [4-6].

Solar panel, still away from standardization, comes with various power configurations. This make the panel differ from various manufacturers. The solar cell is brittle and prone to damage when handled incorrectly. As the case may be, the solar cell is arranged in a robust casing with a glass plate on top with strong back plate and an aluminum side frame to make it mechanically stronger. All these arrangement make the panel weigh more. A typical solar cell with all the necessary mechanical support makes it tougher to design a tracker system as the motor is forced to generate higher torque.

It is logically easier to track the cell against tracking the panel. The proposed idea is to make the tracker system for the individual cells considering the cells as leafs of a plant.

The present work is inspired by the phenomenon exhibited by the plant referred as Phototropism. A plant leaf produces its own food harnessing the light from the sun by photosynthesis. The presence of Auxin, the hormone present in the tip of the stem makes the plant align towards the light source. The studies clearly indicate plant organs alignment towards the possible source of light and gravity during growth [7, 8].

The evolvable antenna proposed by Lohn et al for NASA's mission is emulated here to determine the placement of cells on the arm [9]. The evolvable design of the antenna reported better performance under changing environment. The proposed work is designed with a single arm carrying a solar cell. The arm is made to evolve on its own to find the optimal position for the solar cell with the help of evolutionary algorithms using Bi-Level optimization. There were designs of Bi-Level optimizations with only one level equipped with evolutionary algorithms. The design in which two levels of optimizations equipped with evolutionary algorithms exhibits better performance as reported in [10]. The proposed work has two levels of optimization with evolutionary algorithms at both the levels. However, the present work is not aimed at comparing the effectiveness of evolutionary algorithms which is left for the future. The presented work circles around partial shading conditions and aims at drawing more power during such conditions.

II. PROPOSED SYSTEM

The Proposed system encompasses three distinct domains – Phototropism exhibited by the plants, Maximum power point tracking of the solar PV system and the Evolvable system. The work focuses on mimicking the natural process followed by a plant to extract maximum possible resources from the environment for its growth.

A Phototropism: Plants align its organs such as leaves, stem and roots in a way to extract optimum energy from the environment. Leaves and stem align towards the light source to harness maximum solar energy whereas roots align away from the light and move towards the soil wherein rich nutrients and water are available. The movement of leaves and stem towards a light source takes place through a hormone Auxin. The knowledge of the presence of hormone Auxin dates back to Charles Darwin but quantified only few decades ago.

The movement exhibited by the plant organs includes the nastic movement of the plant organs, circadian based movements, light driven movements and presence of pulvinar or motor cells. The stem movements which are light dependant occur by means of cell elongation and the leaf movement occurs due to the presence of pulvinar or motor cells. The nastic movements which are neither light dependant nor circadian based are also due to motor cells referred as osmotic motors. As mentioned earlier, the presence of Auxin stimulates the movements which make the leaf get itself placed optimally to draw maximum sunlight on its surface. Also the arrangement of leaf on the stem, referred as Phyllotaxy makes the leaf to get exposed to the sunlight evenly. In all the types of leaf arrangements – alternate, opposite, whorled – no one leaf is seen occupying a position which hides the other from the sunlight. Even though the plant appeared to be under shade, all the leaves are arranged in a manner to have an even distribution of sunlight among them. The proposed idea is to mimic the leaf arrangement to the solar cells. However, the work is limited with single arm tracking the sun and will be continued with more than one arm to mimic a complete plant in the future.

Auxin hormone has a major role through Auxin Response Factors in the growth of leaf, shoot and root [11]. The morphology of leaf also has a direct relation to the resources available to harness and conserve the maximum resources for overall plant growth [12]. The process effecting the bending of a plant towards a light source may look natural and extremely simple but research shows the complex events taking place in the transport of the specified hormone and eventual bending of the plant [13].

B Photo Voltaic System: Solar energy seems to the most dependent form of energy generators in the days of climate change. When the whole world is reeling under the impact of green house gases and attempts are taken in every possible way to bring the global temperature down to 1.5 degree Celsius, solar energy seems to be a viable option.

Solar radiation follows Gaussian distribution during a particular day. The PV system designed to tap maximum energy from the sun during a day can generate maximum energy only when the PV panel stays perpendicular to the sun's race. Also the PV system suffers from the adverse effects of partial shading. Partial shading happens due to cloud cover, shade from trees, dust accumulated on the surface of the panel and occasional bird's droppings. The earth's rotation from west to east causes the eventual movement of sun from east to west with respect to stationary position on earth's surface. At a particular point in the northern hemisphere, the ideal angle for a PV panel to be positioned is determined by its latitude, facing the south. Chennai's latitude is 13 degree and it makes a PV array to be fixed at this angle facing the south. Placing the PV panel at a fixed angle reduces the generation hours from the PV system. At Chennai, typical solar hours, by which we specify the ideal generation hours from a PV system is 5.5. The number of hours could be increased if the panel is allowed to track the sun mechanically using motors and photo sensors. Mechanical tracking makes the PV panel to align itself perpendicular to the sun's race all along the day to generate maximum energy. This is accomplished using a photo sensor as a feedback for tracking the sun. However, the energy spent to design the mechanical tracker sun should also come from the PV system for which it is designed. Literature suggests various attempts made to design an economic tracking system [14 – 16]. Partial shading of the cell due to cloud cover, dust and occasional bird droppings develop hot spots in the array which eventually damages the life of the cell. Methods to overcome the partial shading include bypass diodes which, as mentioned, would make or break the cell out of the array.

The electrical maximum power point tracking (MPPT) tracks the operating power at specified instants and sets the operating voltage for tracking the maximum power under those operating conditions. This method of maximum power point tracking cannot track the actual maximum power of the panel rather tracks the maximum power under operating conditions. There are attempts to improve the tracking of electrical MPPT systems [17]. The combination of mechanical maximum power tracking along with electrical maximum power tracking resulted in improved results [18, 19]. The present work focuses on mechanical tracking of maximum power and not electrical maximum power tracking.

C Bi-Level Optimization: Bi-Level optimization problem are hierarchical in which decisions taken at one level of optimization influences the other level. The two levels are referred as the lower level and the upper level in the literature. The two levels are characterized as interactive, hierarchical and influenced by the other. Both levels have different objective functions. The variables which determine the objective functions at one level are influenced partially by the other. The lower level optimization problem works with lower level variables and optimizes to determine the feasible solutions. The feasible solutions at the lower level are considered for the upper level if they satisfy the constraints of the upper level [20]. The two optimization levels are nested.

A Bilevel optimization problem can be formulated as below.

$$\min_{x \in x, y \in Y} F(x, y)$$ Upper level optimization

Subject to

$G_i(x, y) \le 0, i \in \{1, 2, ..., I\};$ where G_i is the upper level constraints

$$y \in \arg\min_{z \in y} \left\{ f(x, z) : g_j(x, z) \le 0, j \in \{1, 2, ..., J\} \right\}$$

Lower level optimization

g_j is the lower level constraints

Where, $F, f : R^{n_x} \times R^{n_y} \to R$

$$G_i, g_j : R^{n_x} \times R^{n_y} \to R$$

$$X \subseteq R^{n_x}; Y \subseteq R^{n_y}$$

In bi-level optimization methods, evolutionary strategies finds place at one level along with classical approaches such as Karush-Kuhn-Tucker approach, branch and bound techniques etc. at the other level. However the use of evolutionary techniques at both the levels of optimization has yielded better optimizations [10]. Evolutionary algorithms based bi-level optimization applied to two transportation problems such as toll problem and traffic signal control offer better results [21]. Many real time applications such as transportation, environmental economics, structural optimization, defense machine learning etc. fall under the bi-level optimization paradigm. In the proposed system, the arm moves in a spherical coordinate system, as shown in fig. 2, tracking the movement of the sun. ρ, π and θ denote the three parameters of the spherical coordinate system. ρ is the length of the vector perpendicular to the x-y plane. θ is the angle made by the vector to the x-y plane. ϕ is the angle made with the vertical z-axis. ϕ is constrained to 0 to π. Among the three parameters ρ, π and θ, θ forms upper level of optimization and π forms the lower level of optimization. ρ is untouched in this present problem.

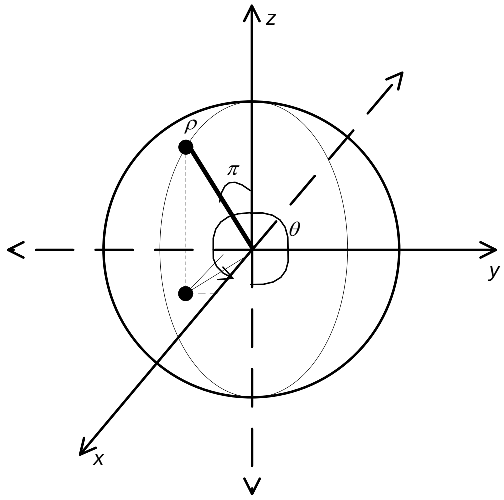

Fig. 2: Spherical coordinate system

The two axes of the mechanical tracking system are taken care as a special case in the lower level of optimization. The proposed work uses evolutionary algorithms in both the levels of optimization. The proposed work is not aimed at validating the effectiveness of various approaches of bi-level optimization, rather focused on applying the mechanical tracking of the solar cell to mimic the phototropism exhibited by the plants.

D Proposed System (Solar Tree): The proposed system is a combination of all the three domains mentioned above. The system draws inspiration from phototropism seen in the plants. The solar cells are allowed to evolve based on bi-level optimization to track the sun's movement from east to west. However, the movement of the sun over the sky is highly deterministic and application of evolutionary algorithm for the same holds no relevance. Nevertheless, the role of evolutionary computation for maneuvering individual cells during partial shading conditions reports increased energy harnessing.

The solar panel which weighs increasingly higher compared to light weight solar cell is made up of individual solar cells each capable of tracking the sun's movement in the way the plant responds to the movement of sun.

III. SOLAR TREE

The solar panel weighs higher compared to the individual solar cell. Solar cells are arranged in between a back plate and a glass plate and fastened with the help of an aluminum frame. This gives the solar panel robustness and makes it mechanically stronger. The heavier panel requires higher energy to track the sun. The present idea is to simulate the design a tracker in which the individual solar cells, rather than the panel, track the sun. The cells are programmed to occupy the position of maximum illumination under partial shading condition. The cells occupy a point in a spherical coordinate system. The simulated robotic arm carries a single cell which alters its position so that the cell generates maximum power during a particular time of the day. The arm, referred as A1, is designed with three servo motors denoted as SM1, SM2 and SM3 and a Stepper motor, S1 as shown in the Fig. 3. The second arm, A2 is also equipped with the same capabilities as A1. Fig. 3 shows A1 alone. The arm maneuvers in a spherical coordinate system. The three parameters θ, π and ρ of the spherical coordinate system are taken care by S1, SM3 and the length of the arm A1 respectively. Sun moves from east to west during the day with respect to earth. The position of the sun takes a point in the spherical coordinate system with respect to the horizontal plane. Even though the sun's movement is not in the entire sphere in question and the locus is a semicircle, the problem assumes the spherical coordinate system.

S1 takes care of the angle θ of the spherical coordinate system. θ is the angle made by the vertical arm to the x-y plane. SM1 takes care of ϕ of the spherical coordinate system which is constrained to 0 to π. ϕ is the angle made with the vertical z-axis. ρ is the length of the arm which moves making an angle with z-axis and is constant in the present work. SM2 is fitted in the end of the arm makes 180 degree on a vertical plane. SM3 makes 180 degree movement normal to the plane of SM2. The number of servo motors used in the problem is limited to three. It could be increased for greater flexibility and better tracking.

The movements of the servomotors are aligned with the first servomotor following its trajectory on its plane. For a single angle made by SM1, SM2 and SM3 follow a particular path and the power is measured. The process is repeated for different positions of SM2 and SM3 with reference to SM1. The arm rests on the final position which gives the maximum power. SM3 is allowed to evolve over a set of generations to choose the optimal position for harnessing maximum power followed by the optimal positions for SM2 and SM1. Stepper motor follows to evolve for the optimal position for maximum power tracking during partial shading condition.

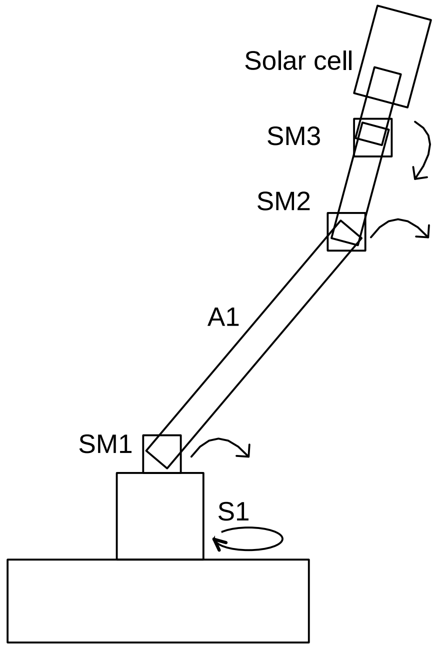

Fig. 3: Proposed system (Solar Tree)

Arm A1 is evolved in two levels. The first level or the lower level constitutes the SM3. The next level or the upper level is formed by SM2, SM1 and the stepper motor. Multiple stages form the lower level. The fit values from the lower level form the population for the upper level for evolution. The number of stages in both the levels can be increased or decreased for better results.

IV. RESULTS AND DISCUSSION

The sun's movement over the sky is highly deterministic. A robotic arm placed normal over the earth's surface makes a definite angle with the surface for a particular time of the day as given by hour angle, H given in equation 1.

$$H = \frac{360}{24}\left(12 - T\right)^{o} \qquad .... 1$$

Where, T is the solar time.

This makes the entire problem deterministic paving no stage for evolutionary computation to be applied if the controller is fed with solar time. The role of evolutionary computation becomes apparent once the partial shading is present. The robotic arm is allowed to evolve to align with the sun making the evolutionary computation relevant.

The complete experiment is simulated with 8 solar cells divided into two groups of 4 each. Each cell is rated for 0.5 V_{OC} and 100 mA as I_{SC}. The four cells are connected in series parallel combination in both the groups, making the overall output at 1 V_{OC} and 200 mA as I_{SC} .The first group is a dual axis mechanical tracking PV system. The second group is made up of two sub groups with 2 cells each. The first subgroup is a simulated robotic arm with 2 cells in series and the other sub group is also a simulated robotic arm with 2 cells. Each arm is equipped with separate motors to maneuver.

The Evolutionary computation run is carried out with SM3 taking up 5 different positions which is allowed to evolve for 12 generations. The evolved SM3 positions are repeated for 6 different SM2 positions which are further evolved for 5 different SM1 positions. The simulation is run from 7 am till 5 pm with each hour carefully dictating the angle to servo motors in a constrained evolutionary computation. The two stepper motors are aligned in such a way not to occupy the position of the other arm. Two simulated robotic arms A1 and A2 moves in the spherical coordinate system with S1, accounting for θ, starts with a random population.SM3, SM2 and SM1 follows S1 one after the other in each of the arms. The presence of partial shading makes the solar tree more efficient in tracking the sun.

The partial shading condition is simulated at pre-determined instants once during forenoon and twice after that. Fig. 4 and Fig. 5 gives an idea of a clear sky and the one during partial shading condition. The measured open circuit voltage for the two systems over the entire day is plotted.

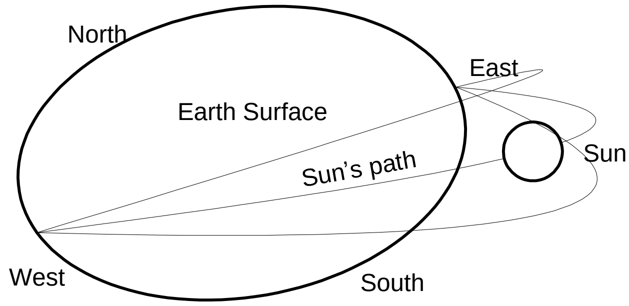

Fig. 4: Clear sky

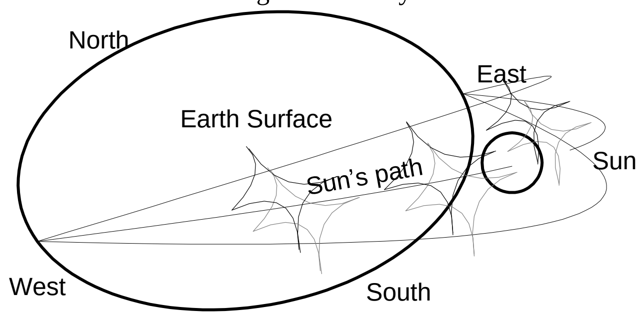

Fig. 5: Partial shading

The simulation in an open source platform shows improved performance for the proposed solar cell tracker.

Table 1. shows the tabulated simulation results of the solar tree and the dual axis PV system with and without partial shading. As mentioned, partial shading condition is artificially simulated during 10 am to 11 am, 1 pm to 2 pm and 2:30 to 3:30 pm. The data during partial shading condition is shown bold in the table 1.

Sl. No	Time of a day	V_{OC} of the Dual axis PV system		V_{OC} of the Solar Tree	
		Without partial shading	With partial shading	Without partial shading	With partial shading
1	7:00	0.65	0.68	0.74	0.85
2	7:15	0.68	0.69	0.85	0.95
3	7:30	0.68	0.71	0.8	0.84
4	7:45	0.69	0.75	0.79	0.86
5	8:00	0.75	0.85	0.74	0.75
6	8:15	0.72	0.84	0.89	0.85
7	8:30	0.71	0.84	0.92	0.76
8	8:45	0.82	0.82	0.89	0.96
9	9:00	0.79	0.79	0.79	0.74
10	9:15	0.85	0.84	0.88	0.89
11	9:30	0.84	0.84	0.94	0.96
12	9:45	0.81	0.79	0.88	0.87
13	10:00	0.69	**0.25**	0.85	**0.32**
14	10:15	0.79	**0.24**	0.95	**0.65**
15	10:30	0.82	**0.21**	0.84	**0.85**
16	10:45	0.766	**0.23**	0.79	**0.96**
17	11:00	0.867	**0.19**	0.83	**0.96**
18	11:15	0.766	0.75	0.81	0.96
19	11:30	0.8166	0.85	0.95	0.92
20	11:45	0.8666	0.86	0.93	0.89
21	12:00	0.766	0.21	0.91	0.26
22	12:15	0.9	0.23	0.88	0.45
23	12:30	0.966	0.26	0.91	0.89
24	12:45	0.933	0.28	0.96	0.95
25	13:00	0.833	**0.23**	0.87	**0.96**
26	13:15	0.8833	**0.87**	0.82	**0.8**
27	13:30	0.833	**0.29**	0.86	**0.25**
28	13:45	0.8466	**0.27**	0.82	**0.36**
29	14:00	0.8	**0.24**	0.74	**0.92**
30	14:15	0.79	0.23	0.76	0.96
31	14:30	0.82	**0.21**	0.79	**0.96**
32	14:45	0.76	**0.76**	0.82	**0.95**
33	15:00	0.82	**0.8**	0.79	**0.85**
34	15:15	0.79	**0.74**	0.86	**0.76**
35	15:30	0.81	**0.79**	0.81	**0.85**
36	15:45	0.84	0.79	0.8	0.86
37	16:00	0.86	0.74	0.76	0.74
38	16:15	0.79	0.75	0.84	0.85
39	16:30	0.8	0.76	0.79	0.89
40	16:45	0.81	0.79	0.88	0.83
41	17:00	0.79	0.7	0.82	0.86
42	17:15	0.78	0.69	0.79	0.8
43	17:30	0.74	0.74	0.78	0.86
44	17:45	0.71	0.71	0.82	0.85
45	18:00	0.75	0.72	0.86	0.79

Table 1: Open circuit voltage readings for dual axis PV system and the proposed solar tree system.

The central tendency measures for the table 1, is given in table 2.

Sl. No	Central tendency measures	Dual axis PV system		Solar Tree	
		Without partial shading	With partial shading	Without partial shading	With partial shading
1	Mean	0.84	0.60	0.80	0.81
2	Median	0.83	0.74	0.8	0.85
3	Mode	0.79	0.79	0.79	0.96
4	SD	0.067	0.261	0.059	0.188
5	Range	0.32	0.68	0.22	0.71
6	Variance	0.0045	0.068	0.0036	0.035

Table 2: Central Tendency measures of the two systems

From Table 2, it is inferred that, there is more area under the curve for the system with solar tree wherein the solar cells are free to move to align with the sun as against the fixed cell dual axis solar array. Fig. 6 shows the open circuit voltage from the two simulated robotic arms of the solar tree under no partial shading. Fig. 7 shows the case of dual axis solar PV system. Partial shading condition is simulated during 10 to 11 am, 1 to 2pm and 2:30pm to 3:30 pm in the open source platform. The plot of open circuit voltage under partial shading shows the improvement of the solar tree over the dual axis PV system (Fig. 8, Fig. 9). The plot shows the open circuit voltage from the PV system. The maximum power drawn from the PV system is a measure of the open circuit voltage and hence the improvement, as seen from Fig. 8 and Fig. 9, shows the solar tree is 26% more efficient than the dual axis PV system.

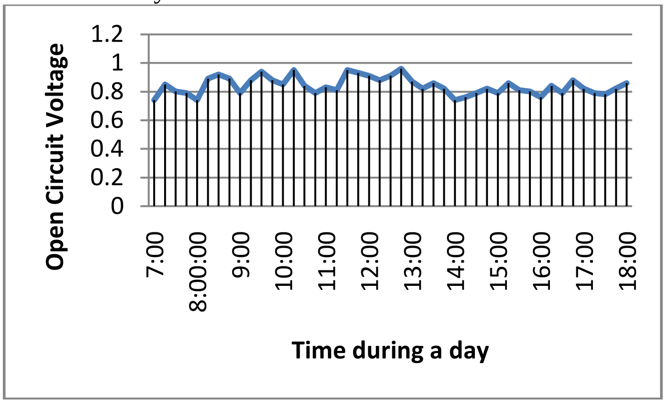

Fig. 6: Plot of open circuit voltage of a solar tree

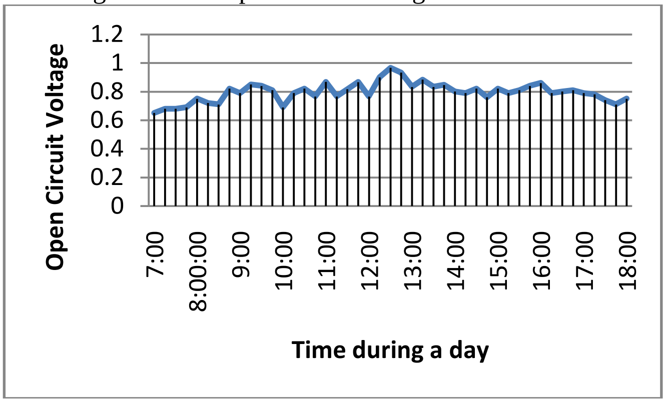

Fig. 7: Plot of open circuit voltage of a dual axis PV system

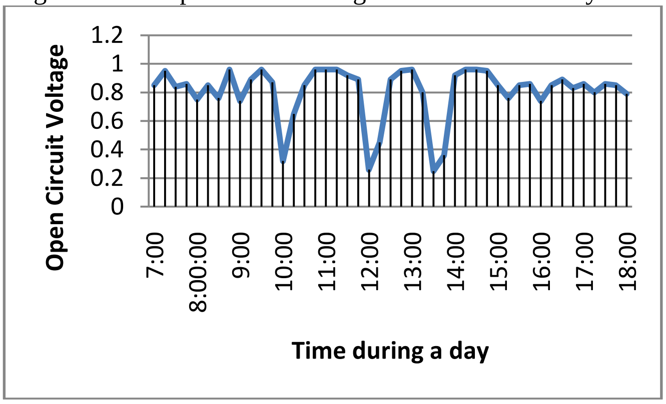

Fig. 8: Plot of open circuit voltage of a solar tree under partial shading conditions

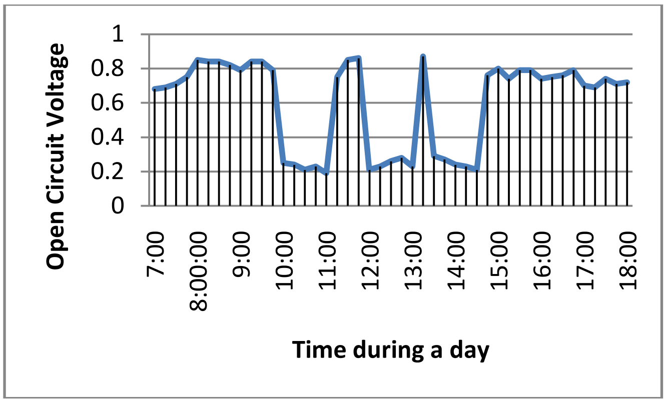

Fig. 9: Plot of open circuit voltage of a dual axis PV system under partial shading conditions

V. CONCLUSION

The electrical energy spent in tracking the heavier solar panel could be overcome by utilizing fractional watt servo motors to track individual solar cells. This became possible as the individual solar cells are visualized as leafs of a plant. The lighter solar cell is found to be easier to track the sun. The evolvable arm, inspired by the phototropism exhibited by a plant, on an open source platform showed improved results than the dual axis PV system. The simulation results indicate the effectiveness of the arm in the presence of partial shading. The prototype of the system is in the design stage.

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