Solar tracking for optimum energy generation using Extremum Seeking Control

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***Abstract*— Access to electricity is a necessity in the modern world. To cater for increasing demand, solar power is now readily available and is harnessed in an efficient way to power the world. In this work, we present a relatively new approach called Extremum Seeking Control (ESC) used to track the sun for optimal solar power generation. Extremum seeking control is known for its robustness for non-linear systems and it is immune to disturbances that can occur in the system. We present simulation results of the closed-loop system and compare them with experimental results obtained from the prototype constructed for this project.**

Keywords*— Extremum seeking control, tracking control, solar power.

I. Introduction

Nowadays, we see the world gradually going green, that is, we are using green energy and renewable sources of energies as an alternative to fossil fuels. Renewable energy is a source of energy that is naturally replenished, free and is available in abundance [1]. The latter exists in different forms which can be, solar, wind, water, tide, wave and bagasse. These energies cannot be exhausted and are constantly renewed [2].

Conventional energy sources like petroleum, coal and natural gas on the other hand are being depleted at increasing rate and thus, it is necessary to invest in renewable energy sources for a cleaner world. It is estimated that renewable energies could expand by 50% in the next five years [3].

Solar power is the third biggest renewable power source in the world. The sun has been burning for over 4 billion years and it is known that in one minute, the latter can supply the world's energy needs for one year [4]. However, the world is not ready to harness all the energy generated by the sun. The technology required for capturing solar energy is present but does not have the efficiency required and is not cheap enough to be adopted at very large scale yet.

The efficiency of most of the existing sun tracking systems are affected when there is a change in weather condition. We will show in this work that a power tracker with ESC controller works well and provide better performance in terms of energy generated compared to a fixed panel.

A dual axis solar tracker provides more power than a fixed panel because the tracker system will allow maximum irradiation to be captured through the orientation of the panel as illustrated in Fig. 1.

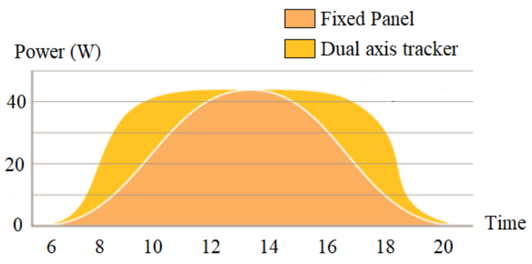

Fig. 1. Power comparison between fixed panel and dual axis tracker

II. Problem Statement

Extremum seeking controller (ESC) finds its way in several applications like anti-lock braking system, swarm particle optimisation, formation flight amongst others but none has been successful in adapting this controller in the solar tracking system. ESC autonomously finds the optimal system behaviour of closed-loop systems and maintains the stability of signals. Therefore, it is largely used for the tracking of a varying maximum or minimum (extremum) of a performance function and in the realisation of real-time optimization for dynamic systems. Researchers have proposed several algorithms that have good searching speed and resolution and good tracking accuracy. These algorithms include: Perturb and Observe (P&O), Hill Climbing [HC] and Incremental Conductance (IC).

Shadowing is one the main factor that affects the performances of a Photovoltaic (PV) panel. These performances can be considerably reduced when a small portion of the panel is exposed to shadow or when several PV panels are connected in series and one panel is partially shaded. In this work, we investigate the ESC approach as an alternative tracking method to the other existing approaches to locate the optimum power generation point of a tracker whatever the weather conditions.

The ESC is carefully tuned such that when the control signal u generated by the ESC is applied to the plant, the motors move the solar panel to a position of optimal power or when there is a change in power. The ESC is a nonlinear controller and is appropriate for the solar tracking system which turns out be also be a nonlinear system. The advantage of the ESC approach is that it responds more quickly to change in operating conditions which can make a considerable difference in energy generated on a large scale, for example on solar farms.

III. MODELLING

MATLAB/Simulink is used to model the solar tracking system (referred to as the plant) comprising of solar panel, DC motor, load (power resistor) as well as the extremum seeking controller as shown in Fig. 2. In order to investigate the behaviour of the ESC algorithm, the solar panel and DC motor should be studied at first.

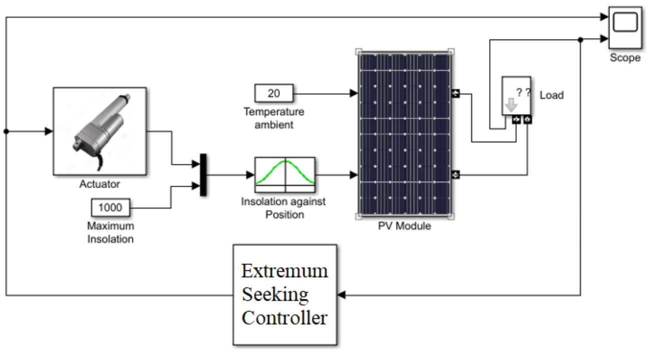

Fig. 2. Plant

A. Photovoltaic Panel

The electrical equivalent circuit of a photovoltaic cell is represented in Fig. 3. The circuit is also called a ‘four parameters model’ consisting of four components which are: a current source, a diode, a shunt resistance, R_{sh} and a series resistance, R_s.

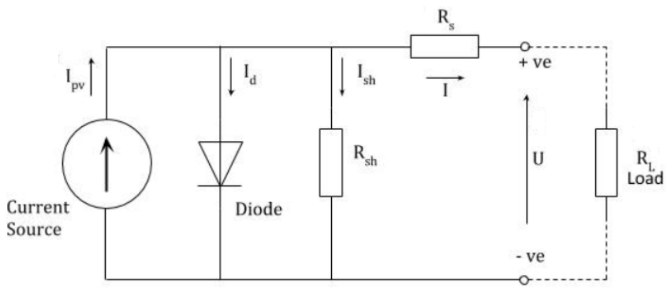

Fig. 3. Electrical equivalent circuit of a photovoltaic cell

The output current of the cell can be obtained by applying Kirchhoff’s current law in Fig. 3.

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

The photocurrent or light generated current is modelled and the latter varies with temperature and irradiance given by the following equation:

$$I_{ph} = \left[I_{sc} + k_i(T - 298)\ \frac{G}{1000}\right] \tag{2}$$

Where, I_{ph} is the photo-current,

I_{sc} is the short circuit current,

k_i is the short circuit temperature coefficient of the cell at 25□ and 1000W/m^2,

T is the operating temperature and

G is the solar irradiation.

The cell saturation current is given by:

$$I_0 = I_{rs}\left(\frac{T}{T_n}\right)^3 exp\left[\frac{q \times E_{g0} \times (1/T_n - 1/T)}{n \times K}\right] \tag{3}$$

Where, I_0 is the saturation current,

I_{rs} is the reverse saturation current,

T_n is the nominal temperature which is equal to 298,

q is the electron charge and is equal to 1.6 $\times 10^{-19}$,

E_{g0} is the band gap energy of the semiconductor,

K is the Boltzmann’s constant and is equal to 1.38 $\times 10^{-23}$ and

n is the ideality factor of the diode.

The reverse saturation current is given by:

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q \times V_{oc}}{n \times N_s \times K \times T}\right)} - 1} \tag{4}$$

Where, V_{oc} is the open circuit voltage (in Volts) and

N_s is the number of cells connected in series.

The current through the shunt resistor is given by:

$$I_{sh} = \left(\frac{V + IR_s}{R_{sh}}\right) \tag{5}$$

Where, I_{sh} is the current through shunt resistor,

R_s is the series resistance,

R_{sh} is the shunt resistance and

V_t is the diode thermal voltage.

Finally, the output current is given by:

$$I = I_{ph} - I_0\left[exp\left(\frac{q \times (V + IR_s)}{n \times K \times N_s \times T}\right) - 1\right] - I_{sh} \tag{6}$$

These equations are used to design a PV panel using block diagrams in Simulink as shown in Fig. 4.

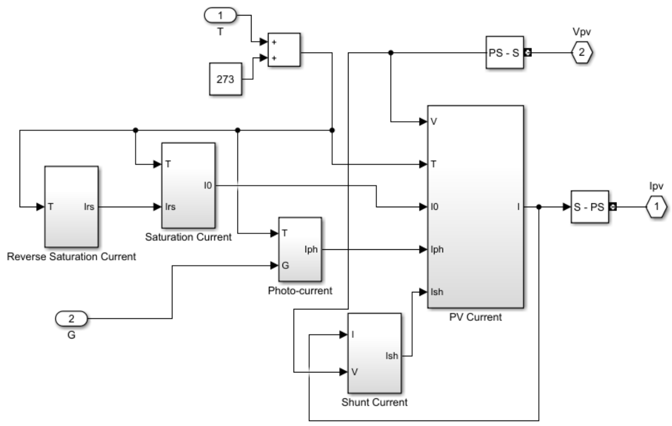

Fig. 4. Designed photovoltaic panel

The output of a PV panel is affected by 2 variable parameters which are:

1) Insolation level falling on the array, *G*.
2) The ambient Temperature, *T*

Fig. 5 and Fig. 6 represent the simulation results under varying irradiation and temperature levels for the designed PV panel.

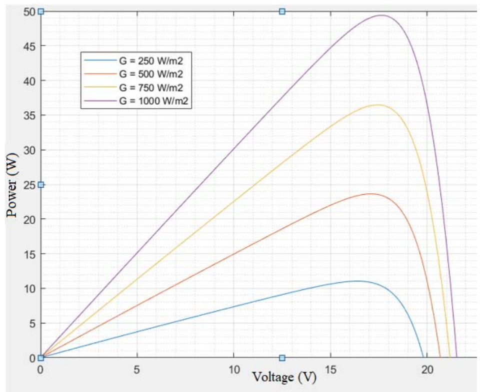

Fig. 5. P-V curves for varying irradiation levels

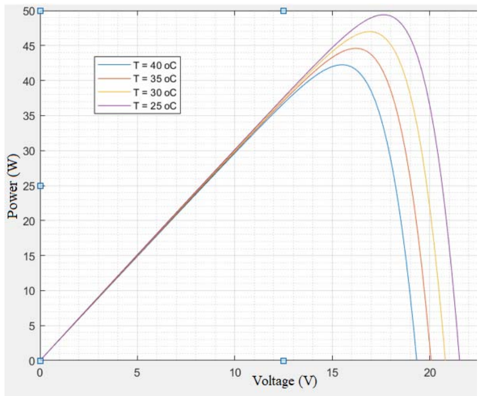

Fig. 6. P-V curves for varying temperature levels

B. *DC motor/Actuator*

Fig. 7 shows the equivalent circuit of a DC motor.

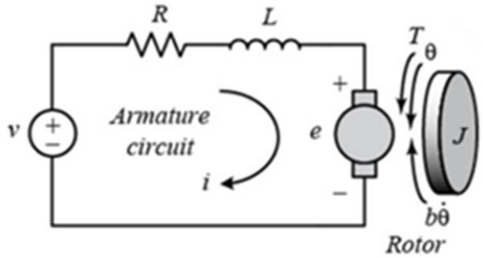

Fig. 7. Equivalent Circuit of DC motor

Where,

$\dot{\theta}$ is the rotational speed of the shaft,
v is the voltage source,
J is the moment of inertia of the rotor,
b is the motor viscous friction constant,
R is the electric resistance and
L is the electric inductance.

The DC motor generates torque that is proportional to the armature current and the strength of the magnetic field given by the following equation.

$$T = K_t\, i \tag{7}$$

The back emf, e, is proportional to the angular velocity of the shaft and is given by:

$$e = K_e\, \dot{\theta} \tag{8}$$

Assuming the constants K_t and K_e are equal and using K to represent both the motor torque constant and the back emf constants,

$$K = K_e = K_t \tag{9}$$

Applying Newton's 2nd law and Kirchhoff's voltage law yields the following equations:

$$J\ddot{\theta} + b\dot{\theta} = Ki \tag{10}$$

$$L\frac{di}{dt} + Ri = V - K\dot{\theta} \tag{11}$$

Laplace transform is applied to the above equations and are expressed in terms of s.

$$s(Js + b)\theta(s) = KI(s) \tag{12}$$

$$(Ls + R)\mathrm{I}(s) = \mathrm{V}(s) - \mathrm{Ks}\,\theta(s) \tag{13}$$

The transfer function P(s) is given by the following equation where the armature voltage is considered as input and rotational speed is considered as output.

$$P(s) = \frac{\dot{\theta}(s)}{V(s)} = \frac{K}{(Js + b)(Ls + R) + K^2} \tag{14}$$

The transfer function of the motor is designed as in Fig. 8.

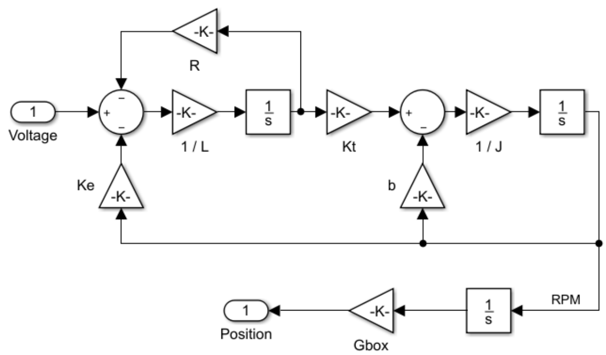

Fig. 8. Designed DC motor

IV. Extremum Seeking Control

Extremum Seeking Control is an adaptive control approach that has as main objective to find the extremum value of a nonlinear system [5]. It allows for the optimisation of a measure of performance in a system by automatically adjusting one or more inputs to the system [6]. The control design engineer does not however require explicit knowledge of the input-output characteristic of the system, but should know whether the nonlinear function has an extremum. In the control community, this approach although well documented, remained dormant until it was proved to be stable [7]. Nowadays, many systems uses this control approach as it is robust and provide better performance than other types of controllers.

In extremum seeking control, a dither signal is used to continuously excite the system [8] as represented in Fig. 9. The effect of this dither signal is to direct the direction as well as the magnitude of the control system to be generated. The controller parameters and the dither signal are tuned until the closed-loop performance is determined to be satisfactory. There is a body of references to explain the reasoning behind the tuning of the parameters of the controller and the order in which it should be done to get started.

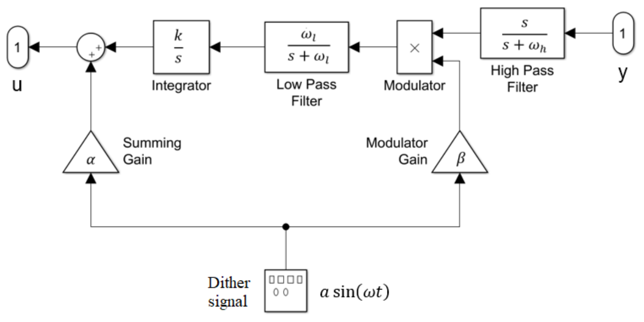

Fig. 9. Extremum Seeking Controller

A. Extremum seeking control parameters

1) Dither

The dither signal employed in the extremum seeking scheme is generally sinusoidal in nature. However, other types of dither could be used to improve the efficacy of the controller. According to [9], square waves will provide faster convergence than sinusoidal or triangular waves as square waves yield larger normalised power.

2) Dither frequency

The dither frequency, ω is tuned to have a fast convergence. However, it should be noted that if the dither frequency is too fast, the system may be affected by noise, preventing the dither signal to drive the controller.

3) Integrator gain

The integrator gain, k amplifies the average component of the control signal, u, before being applied to the plant.

4) High Pass Filter

The high pass filter removes dc components allowing the dither to pass through.

5) Low Pass Filter

The low pass filter removes noises and high frequencies in the signal, allowing low frequencies to be integrated.

TABLE 1. Extremum Seeking Control parameters

Parameters	Values
High Pass Frequency, ω_h	10
Low Pass Frequency, ω_l	3.9
Integrator Gain, k	16.2
Modulator Gain, β	0.95
Summing Gain, α	0.08
Dither Frequency, ω	9
Dither Amplitude	2

V. SIMULATION

The Simulink block diagram used for simulating the ESC along with the actuators and PV panel is shown in Fig. 10. The control signal u and output signal y are tracked under a scope.

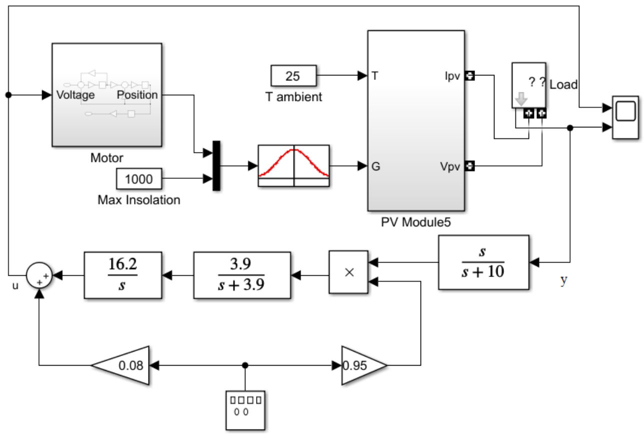

Fig. 10. Simulink block diagram

The system is simulated for 300s. The power output response has a very good rise time of 9.7s and a percentage overshoot of 0.505% as illustrated in Fig. 11.

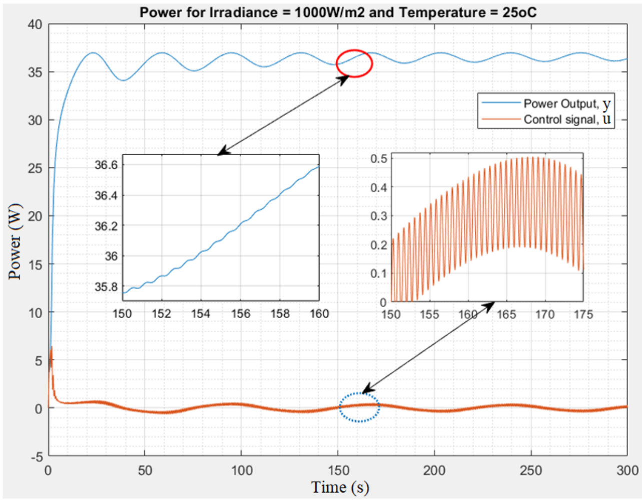

Fig. 11. Response of Extremum Seeking Controller

The ESC is also observed under varying insolation and temperature levels as represented in Fig. 12 and Fig. 13.

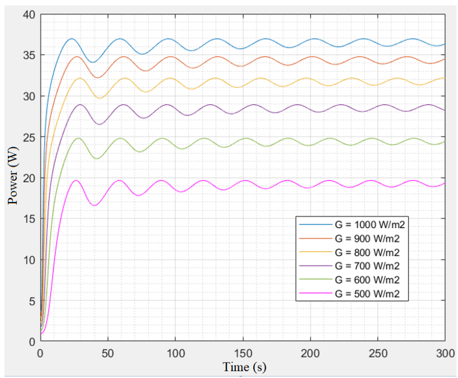

Fig. 12. ESC response under varying insolation levels

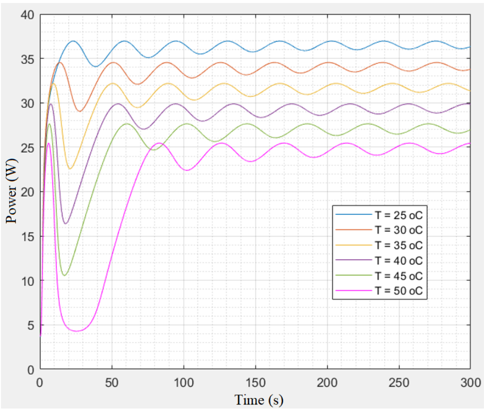

Fig. 13. ESC response under varying temperature levels

From Fig. 12 and Fig. 13, it can be seen that the controller works best when the insolation level is high and the temperature level is low.

VI. Experimental Setup

A prototype was built to validate the simulation results obtained and we tried to obtain hardware components to exactly match the components used for simulation. The prototype consists of a 50W panel, two 12V DC linear actuator, Arduino Uno for the controller and a stand to hold the PV panel as shown in Fig. 14.


Fig. 14. Final prototype

A. Controller Hardware and Software used

The Arduino Uno is programmed using MATLAB and SIMULINK Arduino support package. The Extremum Seeking Controller is easier and more efficient to be programmed using the support package that MATLAB provides rather than writing codes for each block diagram in the controller. The package allows the user to communicate interactively with the hardware and to verify the output via a scope. The same extremum seeking controller is programmed for both the elevation and azimuth actuators on different pins on the Arduino as in Fig. 15.

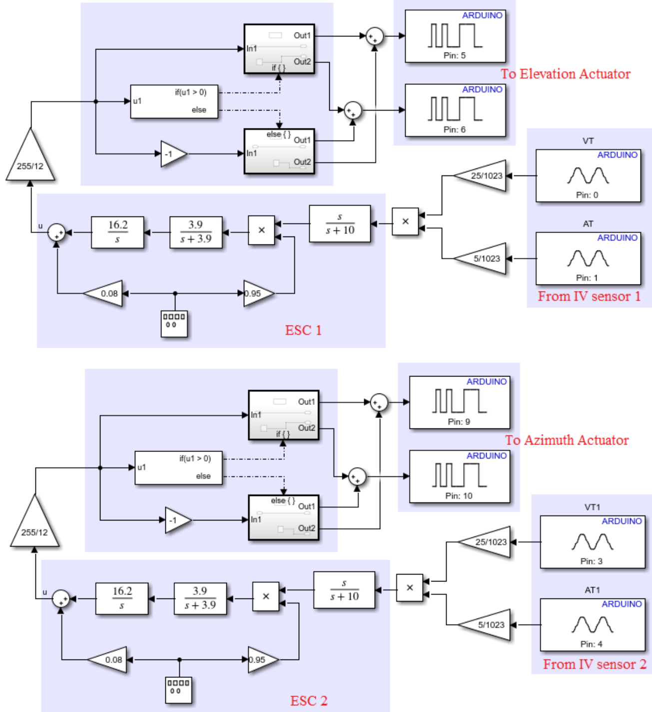

Fig. 15. Block diagrams sent to Arduino

B. Electrical Hardware Design

A detailed circuit for the whole system is designed as in Fig. 16 to understand fully how each and every components are connected for tracking the sun.

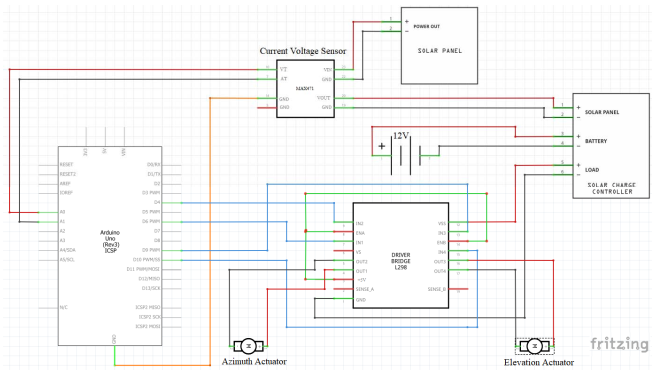

Fig. 16. Electrical Circuit

The output of the solar panel is connected to an IV (Current Voltage) sensor which in turn is connected to a solar charge controller and an Arduino Uno. The IV sensor senses the current and voltage generated by the panel and sends the data to the Arduino for recording. A solar charge controller is used for optimum charge and discharge of the battery and to power the load as well as the azimuth and elevation actuators. Four Pulse Width Modulation (PWM) pins in the Arduino are used to drive the two actuators to locate the maximum irradiation point of the sun. The actuators are able to move clockwise as well as anticlockwise with the help of a driver bridge which is connected in between the Arduino and the actuators.

VII. Results and Discussion

Fig. 17 is a picture of two systems under test. Both panels have the same ratings and are tested at the same time. The panels are of course exposed to the same irradiation from the sun and their respective power generated are measured at different time intervals.

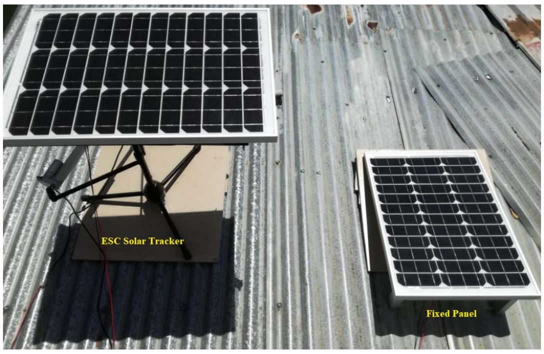

Fig. 17. ESC solar tracker and Fixed panel under test

Fig. 18 shows the panel positions under test at different times of the day. At around 9 a.m, the elevation and azimuth actuators are fully extended for tracking. As the sun moves in the sky, the actuators start retracting to move the panel in two axes.

Fig. 18. Panel Position

Fig. 19 compares the power plot of an ESC solar tracker along with that of the fixed panel. The data was collected from 8 a.m. to 5 p.m on a clear day for testing the prototype. Data was collected at 2 minutes interval. From the figure, it can be clearly seen that with the ESC in place, the panel was able to capture much more power than the fixed panel. This is because the controller is orientating the solar panel directly towards the sun. The peak power is around 41 W and remains close to that value from 10 a.m. to 3 p.m. for the controlled system (c.f. with 12 p.m. to 1:30 p.m. for the fixed system). The sudden drop in power (e.g. at 2:30 p.m) is due to clouds preventing direct sunlight from reaching the panel. It is interesting to note however that even in the presence of the clouds, the drop in power level for the controlled system is much less than that for the open loop uncontrolled panel.

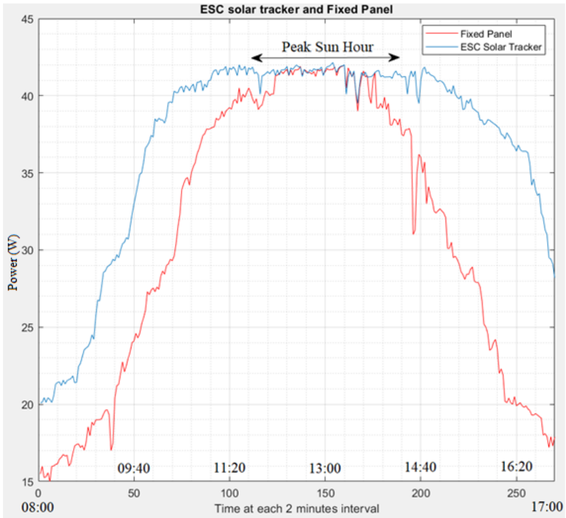

Fig. 19. Power Comparison between ESC solar tracker and Fixed panel

VIII. Conclusion

An extremum seeking controller was successfully simulated, implemented and tested on a solar tracking system. Experimental results obtained confirms that a well tuned ESC is suitable for a solar tracker and moreover very quickly reject disturbances in the system due to the presence of clouds, ensuring that maximum power is obtained from the solar panel at any given moment in time. In particular, the ESC is very quick to respond to changes which is a feature that can make a difference in total energy harnessed for solar farms subjected to unpredictable weather pattern. Future work could look at an adaptive scheme for the ESC, which should improve the performance further.

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