A comparative study of different solar power tracking control techniques

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Abstract. Solar tracking conventionally uses mathematical calculations to know the exact position of the sun. In an attempt to further increase yield efficiency, this paper looks at control techniques to achieve maximum power. Converting irradiation into electricity is the main function of a photovoltaic panel. Then, why not orientate the solar panel in a position where it can yield maximum power? In other words, this research tests the feasibility of building a 'power tracker' instead of a solar tracker. The two proposed algorithms are namely, Extremum Seeking Control and Perturb and Observe. Simulations were done on MATLAB/Simulink and a prototype was built for a comparative study of different tracking control techniques.

Keywords: Power tracking, Solar tracking, Maximum power, Extremum seeking control, Perturb and observe, Photovoltaic panel, Optimum energy generation.

1. Introduction

Nowadays, fossil fuel energy, such as coal, natural gas, and so on, contributes significantly in the development of industrial society. The diminishing fossil fuel resources are expected to be exhausted within the next hundred years[1]. Furthermore, there is a rise in the price as supplies are continuously struggling to meet demands. A great alternative is in the form of solar power. The total amount of solar energy reaching the Earth in 40 minutes is equivalent to humankind's annual energy requirement[2], [3]. Optimally harvesting this energy however is quite a challenge. One of the easiest ways to increase this efficiency is by using a tracking system which can increase energy yield by 20 to 50%.

The performance of solar panels obviously depends on the direct energy received by the sun. It is agreed upon that more light implies more energy[4]. Orienting a solar panel perpendicular to the sun generates more power. However, a recent study has shown that this is not always the case when it is cloudy. The work measured the solar irradiance during cloudy periods. During overcast conditions, nearly all of the solar irradiance is diffuse radiation which is distributed isotopically. In brief, the data collected by the scientists showed that in cloudy situations, the optimum point might not always be perpendicular to the sun[5].
Another study confirmed this phenomenon by reflections and refractions of light. Refraction can concentrate the energy towards the edge of a cumulonimbus cloud and sometimes also a cumulus cloud, depending on its thickness[6].

Power tracking, on the other hand, will look for the optimum power independent on the weather conditions. Not to be confused with Maximum Power Point Tracking (MPPT) solar charge controller, here we are discussing about the orientation of the solar panel towards the maximum power. It is to be noted that in the course of this research, no evidence of any existing power tracker was found.

1.1 Problem Statement

In this paper, we propose alternative tracking methods which will locate the optimum power generation point of a tracker whatever the weather conditions.
A solar tracker can be modeled as a second order system. Applying a control signal $\boldsymbol{u}$, will result in the rotation of the solar panel(s) and will produce a non-linear power equilibrium map. Algorithms such as Extremum Seeking Controller(ESC) or Perturb and Observe(P&O) determine the appropriate control signal $\boldsymbol{u}$, in order to locate the maximum power point of that map in the shortest time possible.

2. Modelling

The whole plant, consisting of a 40 W panel, dc motor and a controller, is modelled on MATLAB/Simulink along with the different controllers.

2.2 Calculation algorithm (SPA)

Calculation algorithm, also known as Solar Position Algorithm (SPA) is an open loop control (OLC) technique which calculates solar zenith and azimuth angle. The model below is based on work of Reda and Andreas which according to them has an uncertainty of ±0.0003°[7].

Declination angle formula:

$$\delta=20.3 \sin[360/363(284+n)] \quad \textbf{(1)}$$

Hour angle formula:

$$\omega = \frac{12-T}{24}\, 360^0 \quad \textbf{(2)}$$

Where,

δ is the declination angle in degrees,
n is the day of the year,
ω represents the hour angle in degrees,
T is time of the day on a 24 hr clock.

2.3 Perturb and observe (Power tracking)

This is one of the most used algorithms because of its simplicity. It varies the angle and observes the output power. Depending on this observation, the operating point is "pushed" in the direction of growing power until the maximum power point is reached. The main advantage of the P&O is that it is relatively simple to implement. There is only one main parameter, gain, which needs to be tuned. If the gain is low, steady state oscillations is low but the response time becomes high. A tradeoff has to be therefore made between the *steady state error* and the *response speed*.

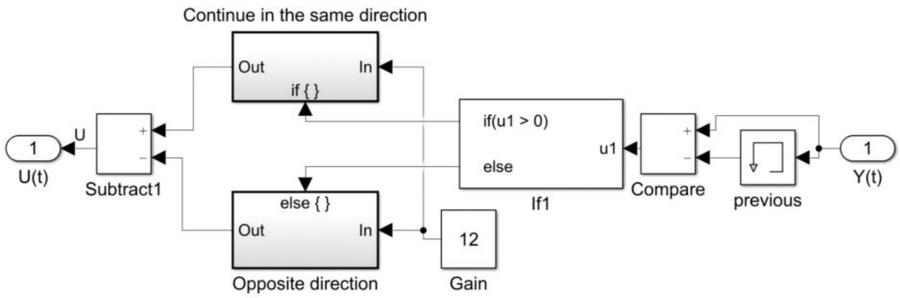

Fig 1: Overview of Perturb and Observe control

2.4 Extremum Seeking Control

Extremum Seeking Control works in a similar way to that of Perturb and Observe, except for the fact that one has much better control over the rate at which the maximum power point is attained. The gradient is determined by probing a sinusoidal or square wave signal to the nonlinear output. This is because the solar panel output power is non-linear with respect to position and has a maximum point.

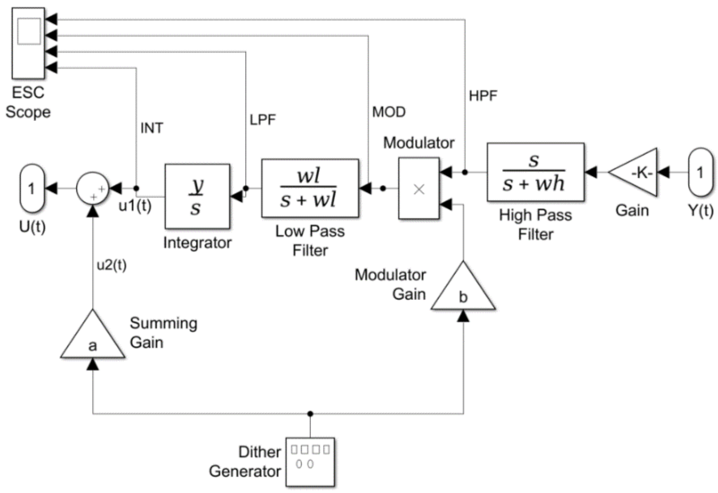

Figure 2: Overview of the Extremum Seeking Control.

The measurement y = f(θ) corresponding to power is obtained from the solar panel and is assumed to have a maximum at which the rate of change of f(θ) is zero. The proposed algorithm will determine the plant input, u, corresponding to the voltage of the actuator such that f(θ) is maximised. The parameters of the extremum seeking controller are given in Table 1.

Table 1. Extremum Seeking Parameters

Parameters	Purpose	Limitation	Value
Dither frequency	Increasing the frequency allows *faster convergence*	A high value may cause instability in the system.	12.2
Dither amplitude	Helps in *overcoming a local maximum/minimum*	Causes oscillations about the optimal value.	0.25
Integrator gain	Directly affects the *speed of convergence*	if too large may amplify disturbances	6.7
High pass filter	Removes the DC components before modulation	Induces a phase lag	10
Low pass Filter	Remove both the dither perturbations and the noise in the error signal.	Slows down the system	4

3. Simulations

Simulations were performed to optimally tune the parameters and to determine the behavior of the power tracker.

3.1 Dynamic response using Extremum Seeking Controller

An ideal sun path has been modeled. The irradiation level varies with time, having lowest value of around 100 W/m^2 and a peak of 1000W/m^2. To prevent the simulator from crashing, the time period for a day has been scaled down to represent the sun movement for a day in a period of 3600 seconds.

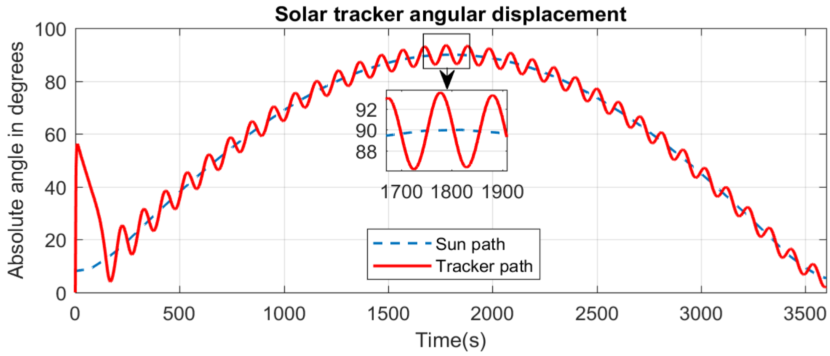

Fig 3: Solar tracker and Sun path under direct irradiation.

From fig 3, it can be observed that the algorithm struggles for very low irradiation level. The system has a rising time of approximately 150s. Once the optimum position is found, tracking goes on smoothly.

3.2 Comparison between ESC and P&O

A comparison between the two power tracking algorithms was done, showing their behaviour while finding an optimum power point which is at 40W.

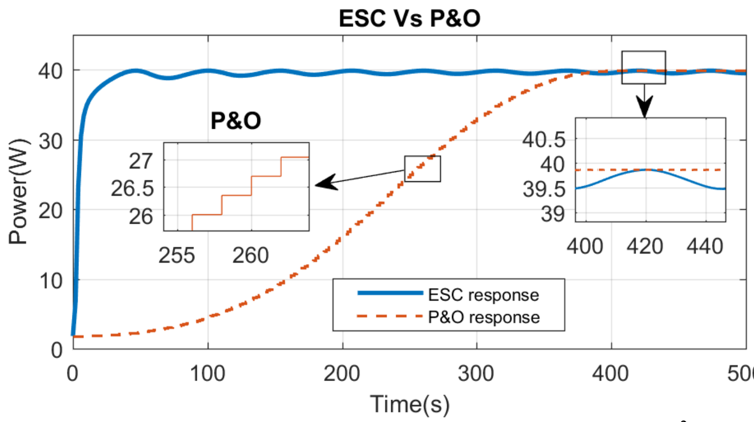

Fig 4: ESC vs P&O in a static environment under 1000W/m^2

The P&O with a gain of ±12 has slower settling time of around 400s compared to 50s as seen in fig 4. Conversely, P&O has a smaller steady state error.

4. Implementation

A prototype was built using different manufacturing processes such as welding, machining, forging, bending and joining. It was then assembled as shown in the exploded view in Figure 5. The components used were an Arduino for the controller, 12V DC linear actuator, 40 W PV panel and scrap materials for the structure.

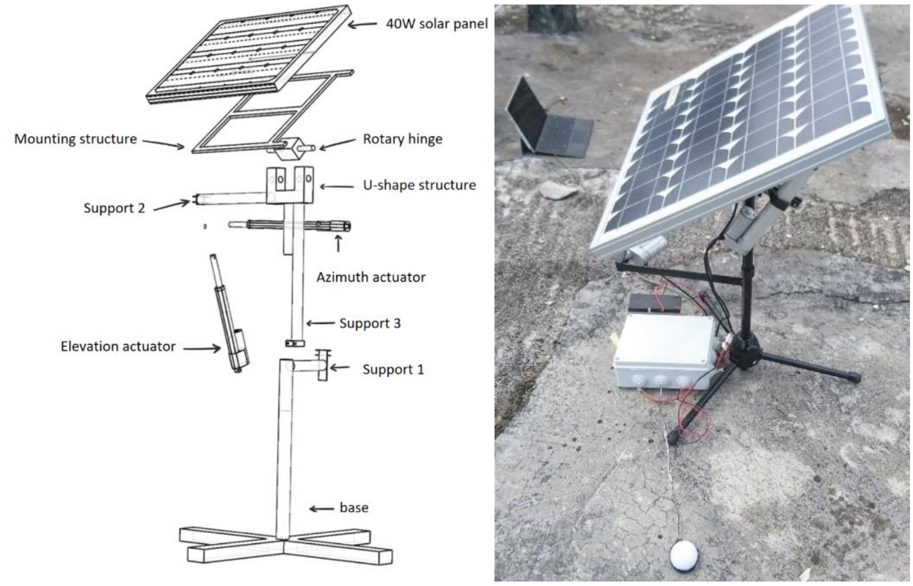

Fig 5 shows a dual axis tracker with a 40W panel, a controller, a battery and PC for data logging.

5. Results and Discussion

5.1 Response analysis of ESC

The response analysis demonstrates the amount of time for the ESC, a power tracker to find its targeted point, hence yielding maximum energy. The experimental result is compared to the MATLAB simulation.
The tracker was initially set at an angle 30^0 and the controller was switched on at 14:40.

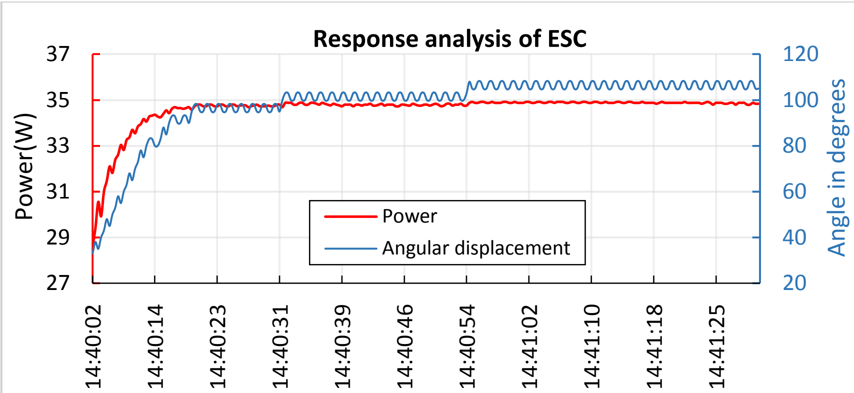

Fig 6: Experimental Result

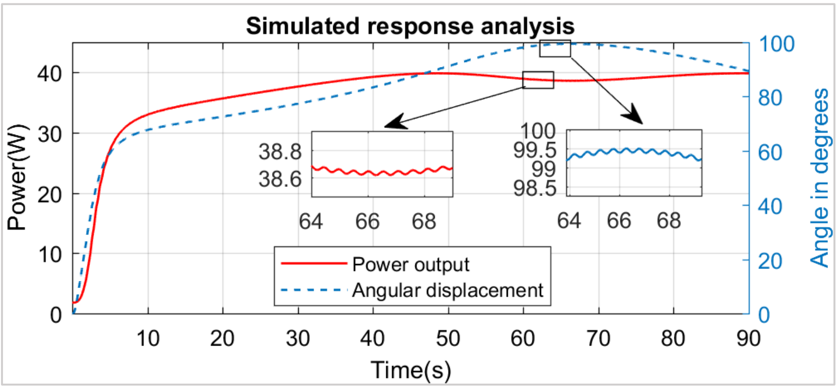

Fig 7: Simulation Result

The discrepancy between the simulation and experimental results was due to an additional filter required in practice to filter out high frequency noises. Moreover, the step size of the mechanical hardware used limited the level of precision that could be achieved. They both have a settling time of around 50s. The optimum point at that particular time was around 107^0. The tracker oscillates at a frequency of approximately 1Hz with amplitude of 3^0.

5.2 Power comparison for different control system

Four main experiments were performed:

1. Tracking using ESC
2. Tracking using calculation algorithm(SPA)
3. Tracking using P&O
4. Non-tracking

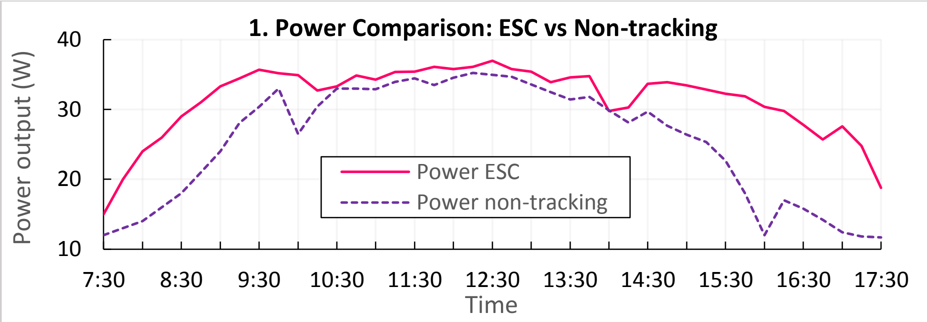

Fig 8: shows the power output comparison between tracking using ESC and non-tracking.

Separates experiments were formed on different days, under almost the same conditions. The ESC has the parameters listed in the table 1 and the fixed panel is oriented with azimuth 0^o and elevation 21^0.

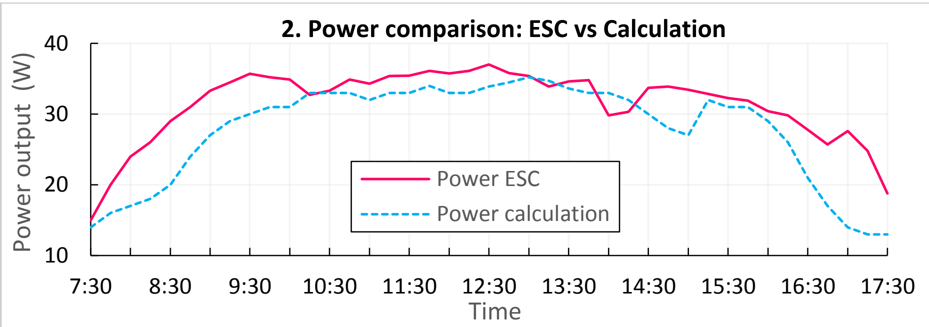

Fig 9: Power comparison between ESC and calculation

The Calculation(SPA) algorithm was tuned to move at a rate of 15 minutes. Fig 9 shows the power comparison between a closed loop system (ESC) and an open loop system(SPA).

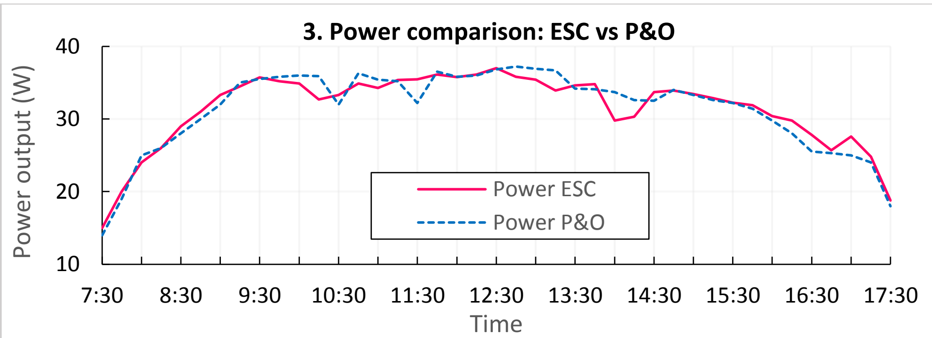

Fig 10: Power comparison between ESC and P&O

With a gain of 12, P&O demonstrate almost identical results to the ESC as seen in fig 10. They are both closed loop systems.

6. Discussion

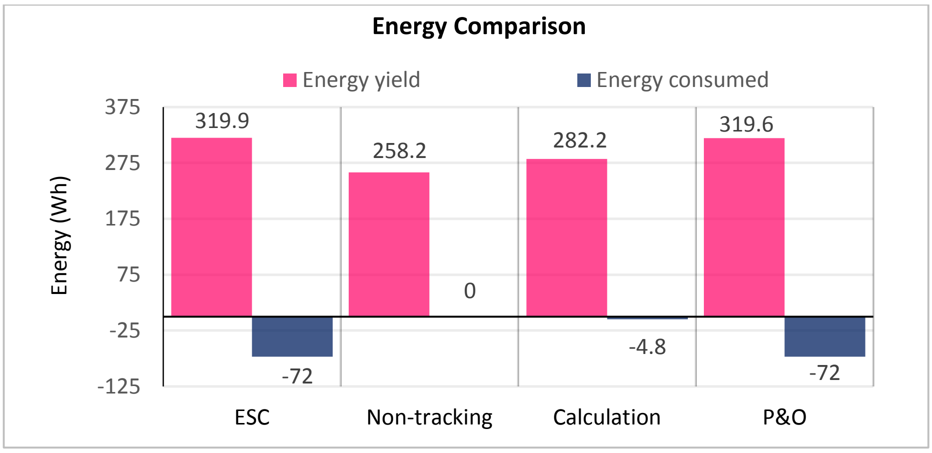

Fig 11: Energy yield comparison

Overall the ESC system collected the most energy, along with P&O. as shown in fig 11.

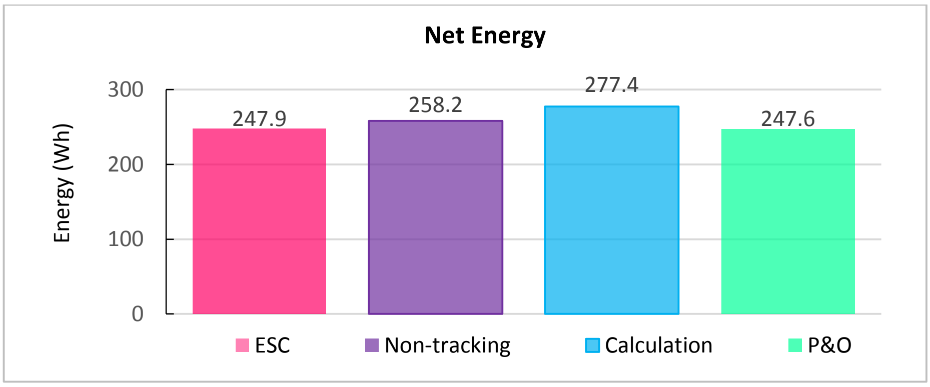

Fig 12: Net resultant energy comparison

When considering the amount energy used by the tracking system to achieve tracking, it can be perceived that the Calculation based system has better net energy yield. It is not so surprising to find that the non-tracking produces more useful energy than both the power tracker algorithm, as the tests were performed during peak summer time in Mauritius. The advantage of the tracking algorithms is expected to be much more evident over the long run and especially during winter. Moreover, the tests were not performed under exactly the same lighting conditions using separate solar panels in parallel.

7. Conclusion

A solar power tracker has been successfully designed and operated. This was achieved with mixed results. The tracking performance depends on ESC parameters selected. Depending on the needs, different conditions can be selected. There is a trade-off between speed of convergence and power consumptions of actuators. Note that in all cases, tracking performs better than non-tracking. Calculation, Open Loop Control, if wrongly calibrated, can actually show poorer performance than a fixed panel. There was no major difference observed between the performance of the ESC and P&O algorithms in practice. Furthermore, although the tracking algorithms harvest more energy than using a fixed solar panel, the net energy received is slightly lower. It is believed that a fuzzy logic algorithm combining ESC and calculation based method should improve accuracy and precision - hence , yielding more energy than any tested system in this research.

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