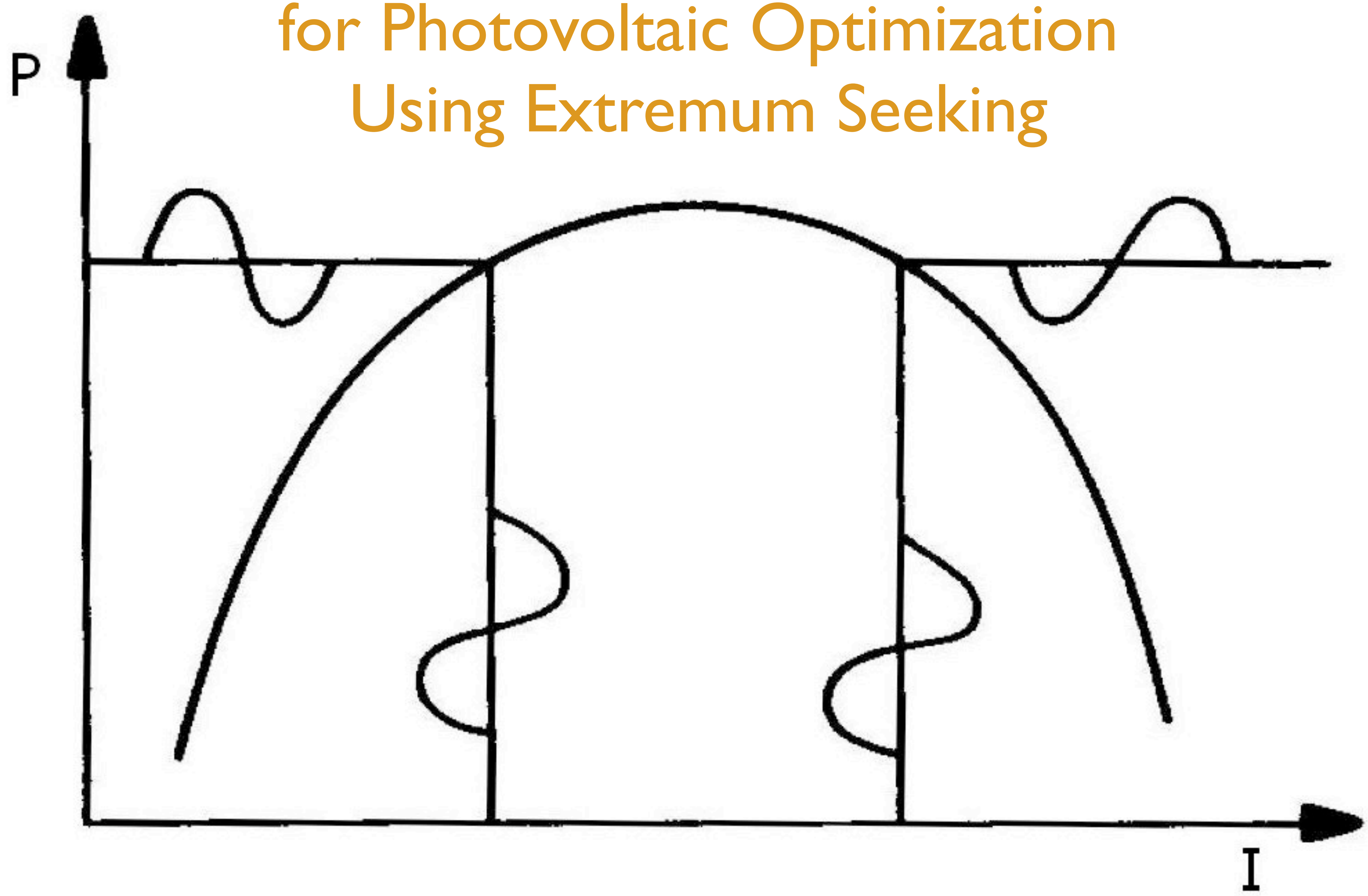
Maximum Power Point Tracking for Photovoltaic Optimization Using Extremum Seeking



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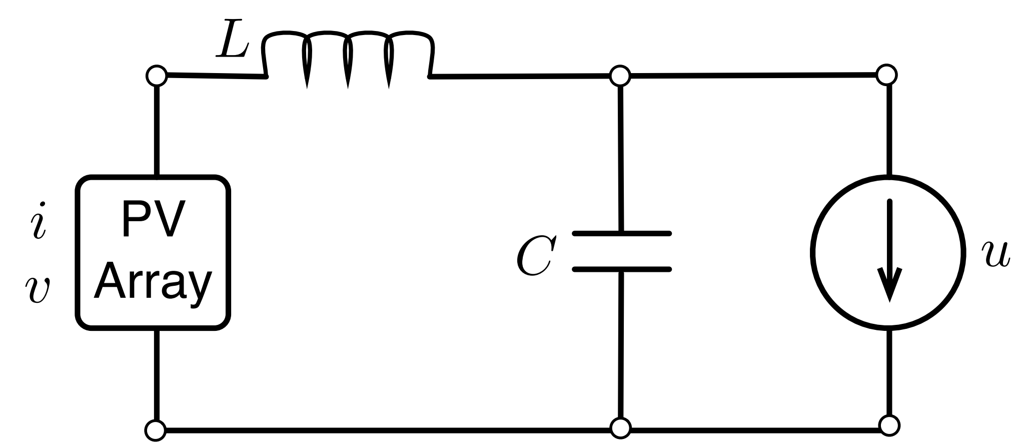
[1]Princeton University
[2]ITT Space Systems Division

34th IEEE PVSC

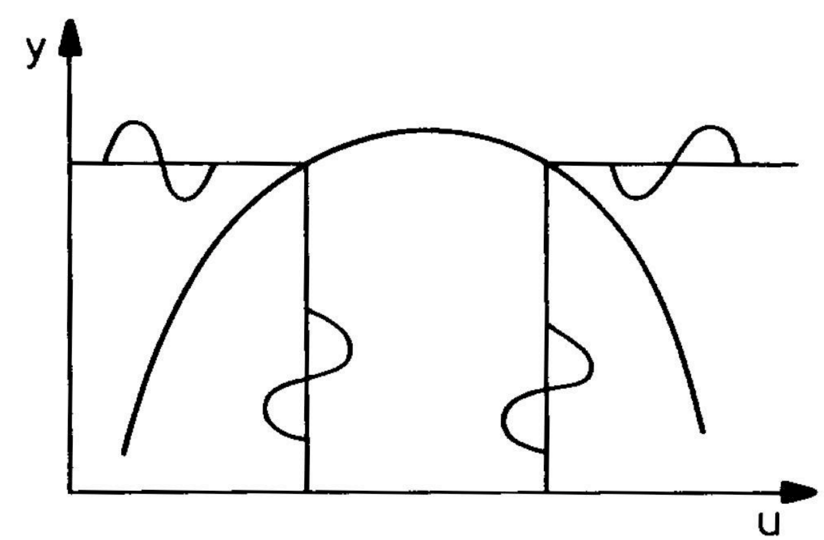
Outline

1. Overview of goals
   - Maximum power point tracker for NJ
   - Robust to highly variable weather

2. Solar array-inverter model
   - Solar array IV curves
   - Grid-tie inverter



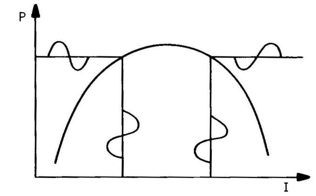
3. Maximum Power Point Tracking
   - Perturb and observe
   - Extremum seeking controller



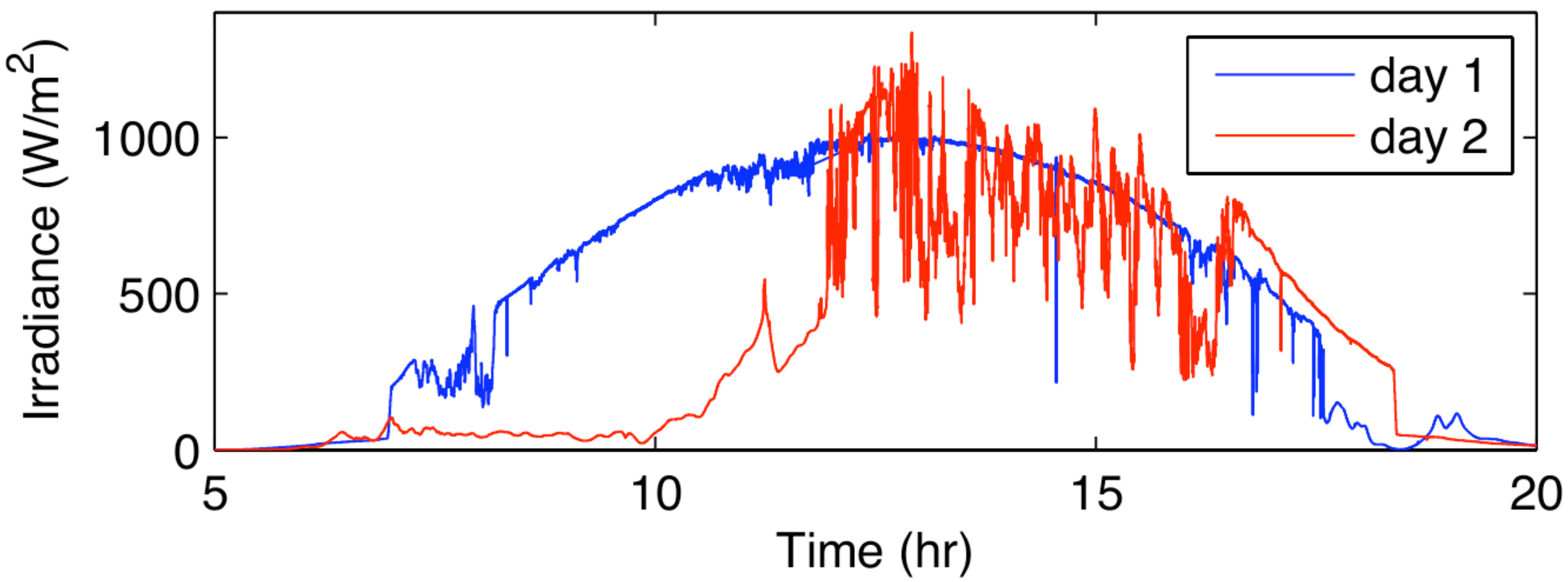
4. Results and Conclusions

Sunny Day

Cloudy Day



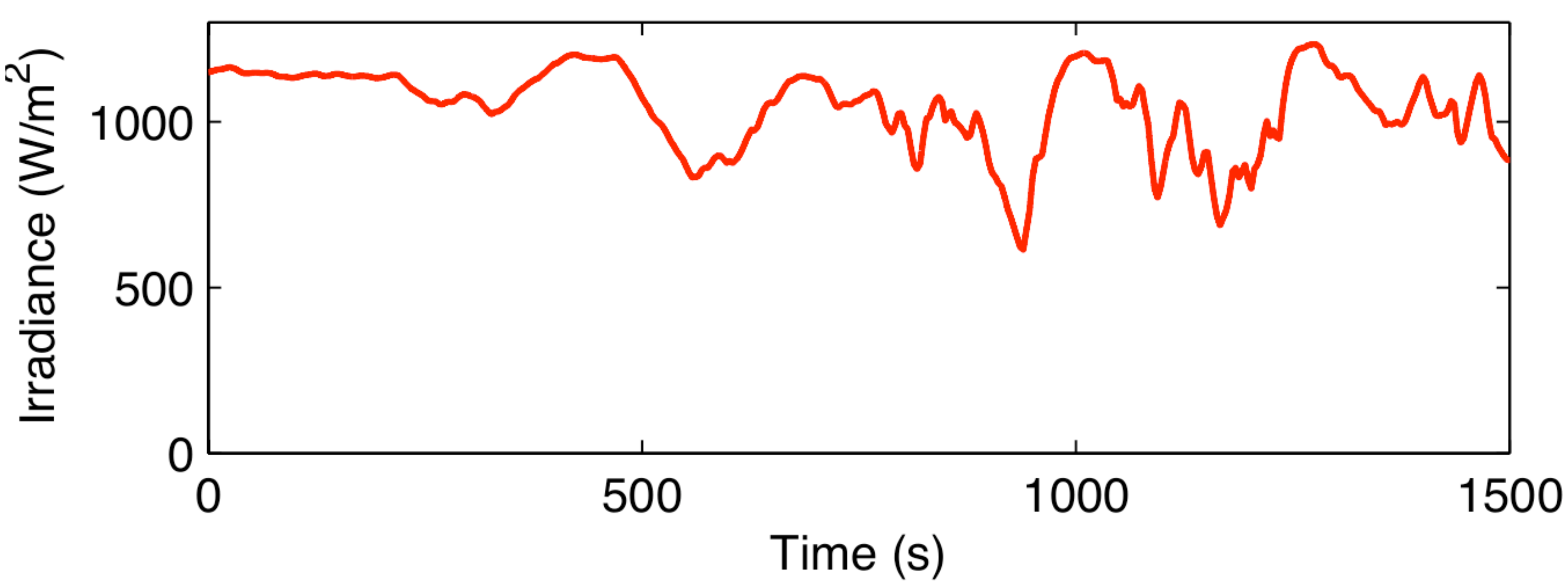
Irradiance Data



Data specifics:

Two consecutive days in June, 2007

Measured on Princeton solar deck

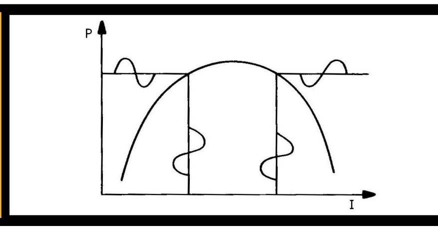


25 minutes of data:

25 minute data set measured between 12:34 and 12:59AM, June 20th, 2007.

Data is low-pass filtered to eliminate sensor noise.

Outline



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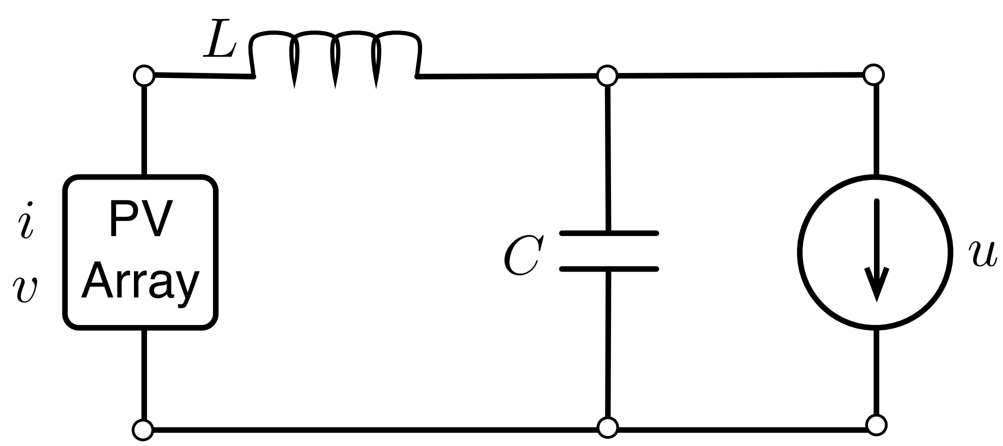

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   - Solar array IV curves
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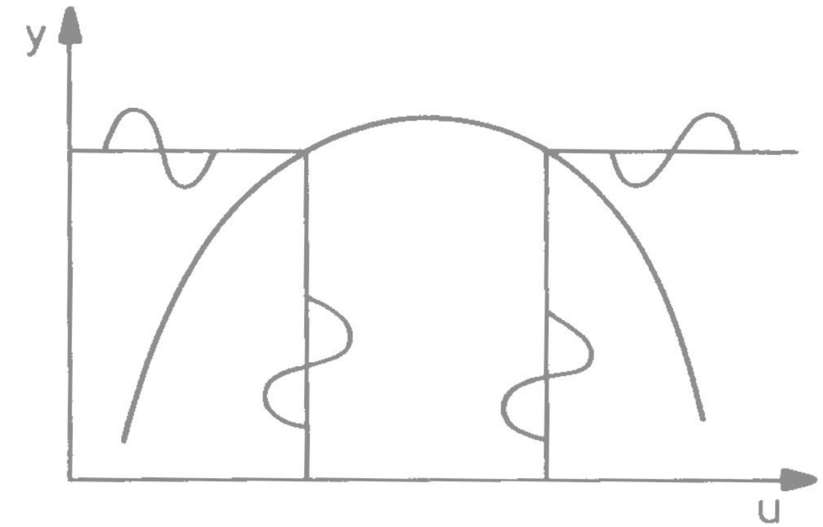


4. Results and Conclusions

Solar Array IV Curve

Lighted diode equations:

Basis for solar array IV curve model

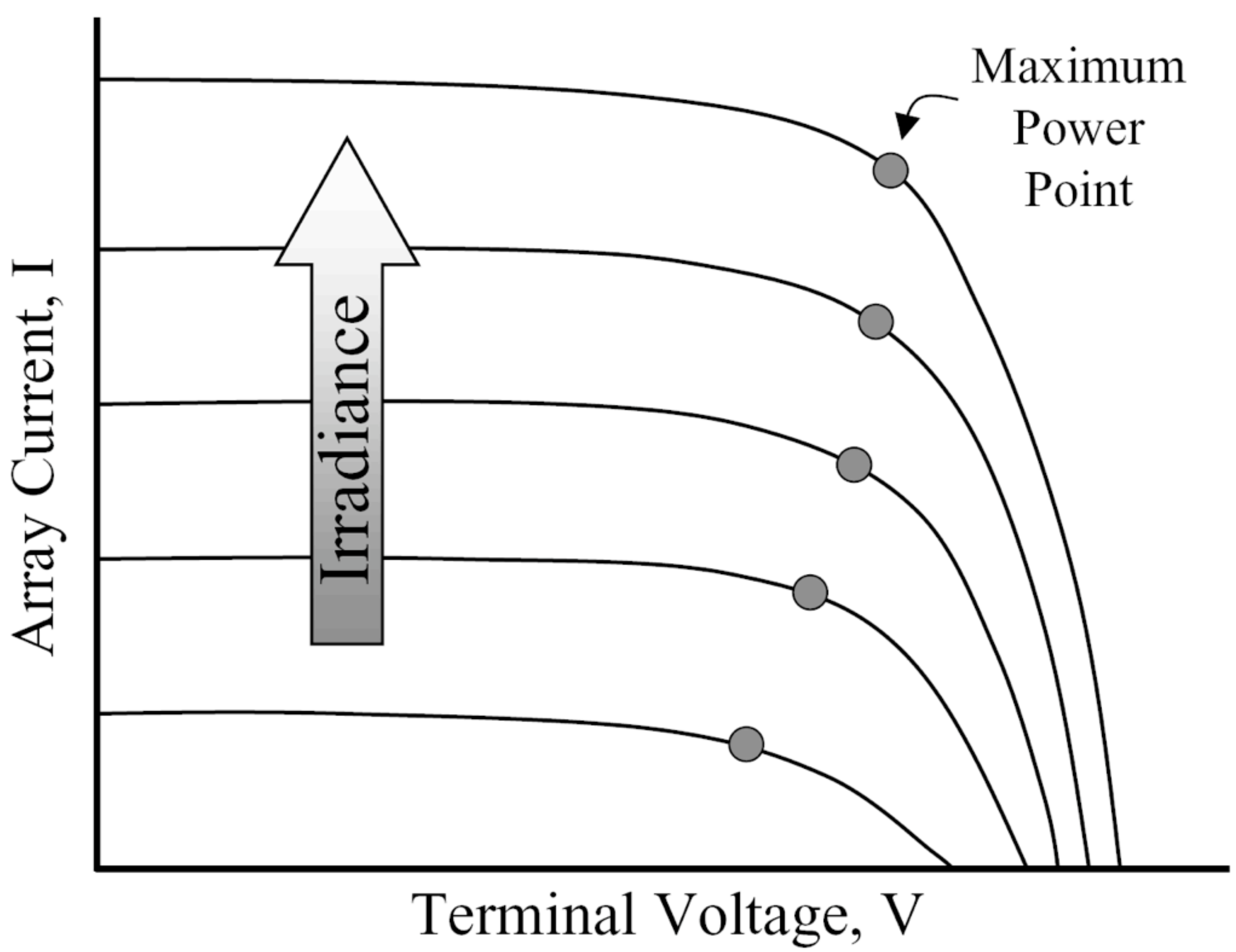
Sometimes need to implicitly solve for current, I

$$I = I_L - I_{OS}\left[\exp\frac{q}{Ak_BT}(V+IR)-1\right]$$

$$I_{OS} = I_{OR}\left(\frac{T}{T_R}\right)\exp\left(\frac{qE_G}{Ak_B}\left(\frac{1}{T_R}-\frac{1}{R}\right)\right)$$

$$I_L = \frac{G}{1000}\left(I_{SC}+K_{T,I}(T-T_R)\right)$$

$$V = \frac{Ak_BT}{q}\ln\left(\frac{I_L-I}{I_{OS}}+1\right)-IR$$



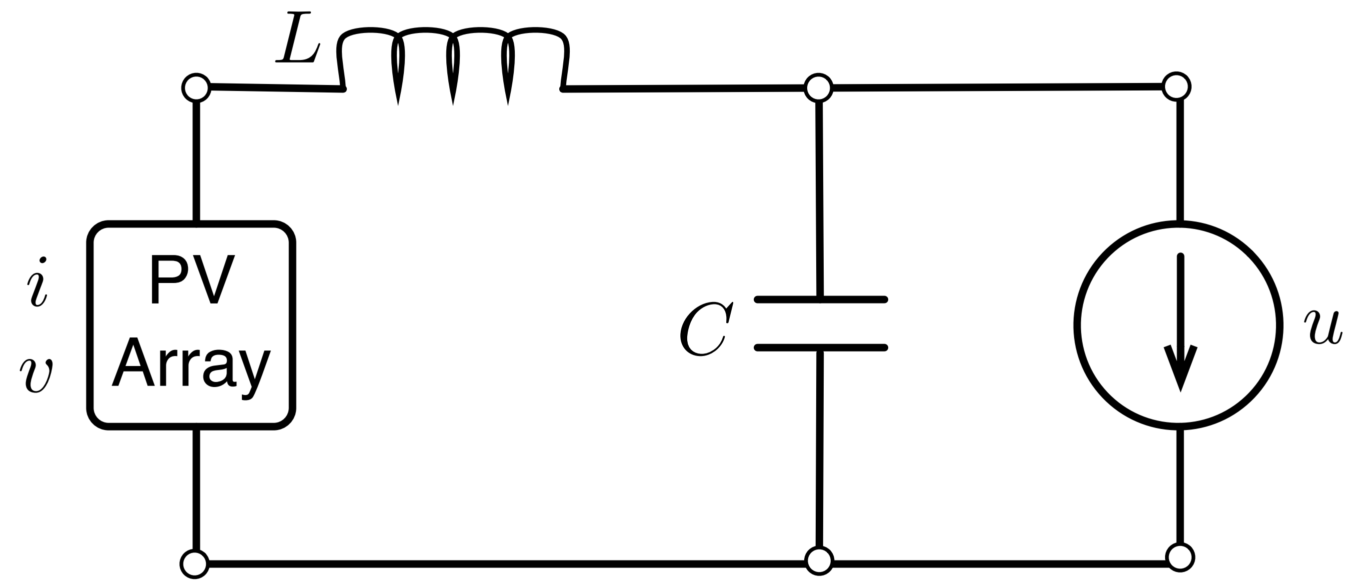
IV curve characteristics:

Single maximum power point at the "knee" of the IV curve

Nonlinear dependence on irradiance and temperature

Array-Inverter Model

(Princeton University solar deck)



(SunnyBoy Inverter)

Grid-tie inverter:

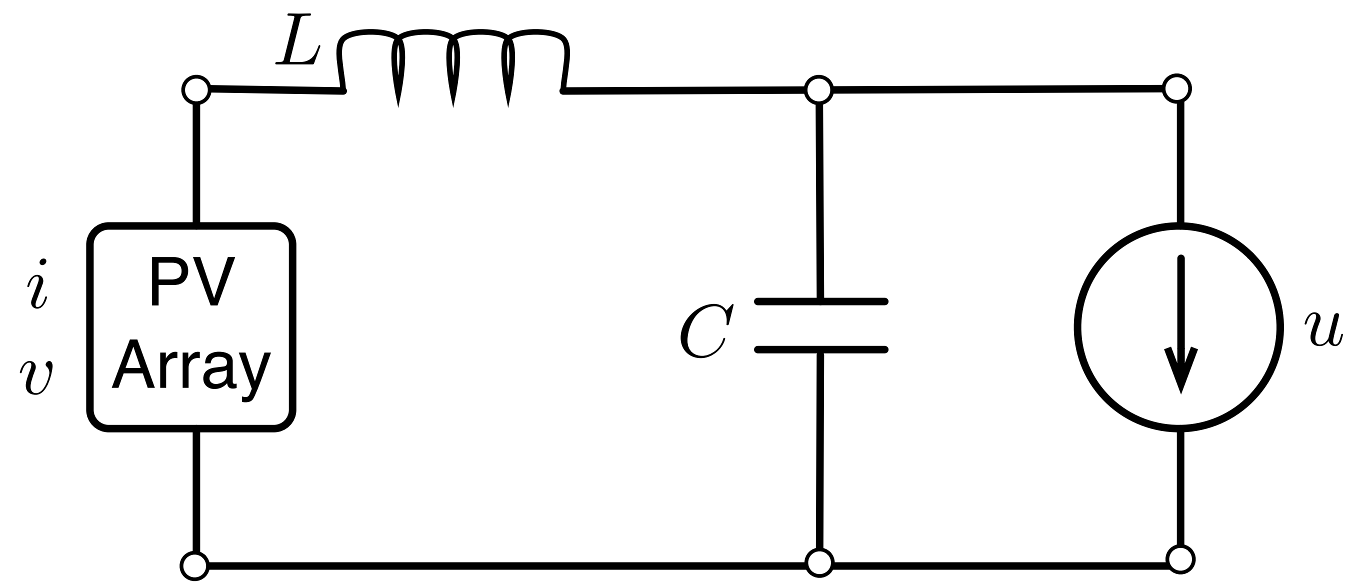
Grid-tie inverter allows us to connect the solar array to the power grid.

Inverter flows AC power into the grid, using DC power drawn out of a capacitor.

Array-Inverter Model

Kirchoff's Laws:

$$
\begin{aligned}
i &= u + i_C \\
v_C &= -v - v_L
\end{aligned}
$$



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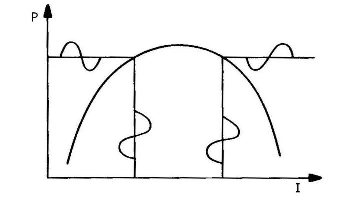

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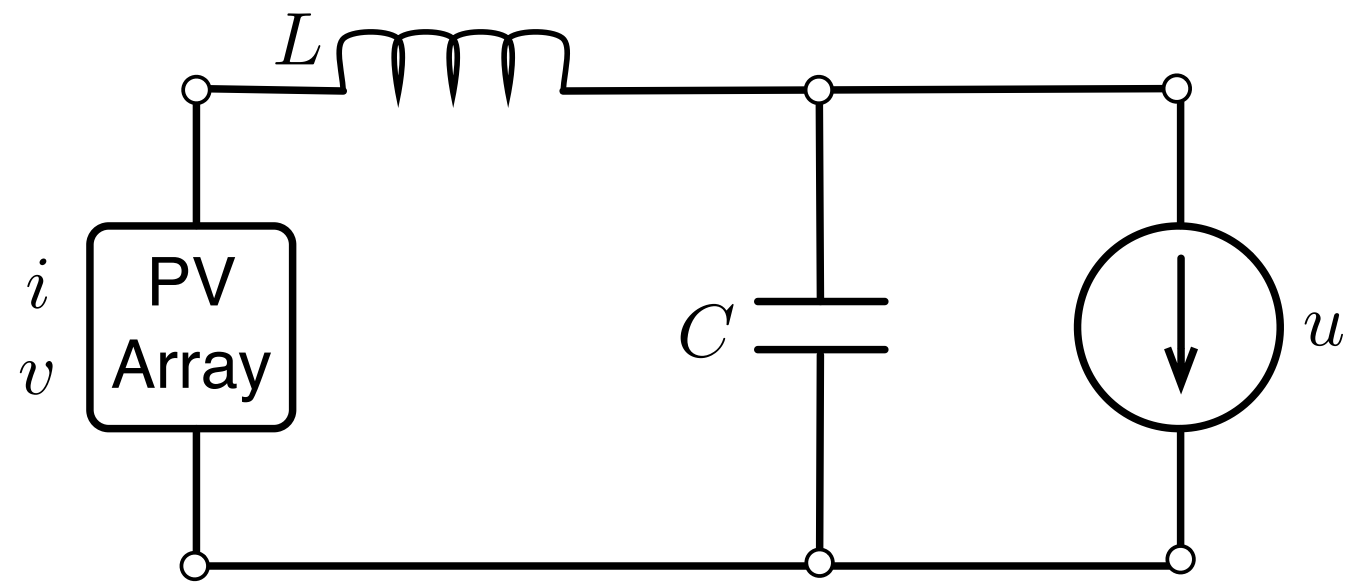
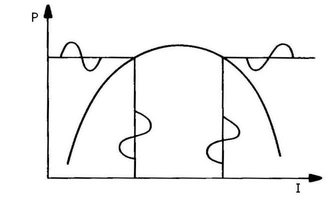


Array IV curve is $v = f(i, G)$

$$
\begin{aligned}
v_C &= -f(i,G) - L\frac{di}{dt} \\
\implies \quad -\frac{dv_C}{dt} &= \frac{d}{dt} f(i,G) + L\frac{d^2 i}{dt^2} \\
&= \frac{\partial f(i,G)}{\partial i}\frac{di}{dt} + \frac{\partial f(i,G)}{\partial G}\frac{dG}{dt} + L\frac{d^2 i}{dt^2}
\end{aligned}
$$



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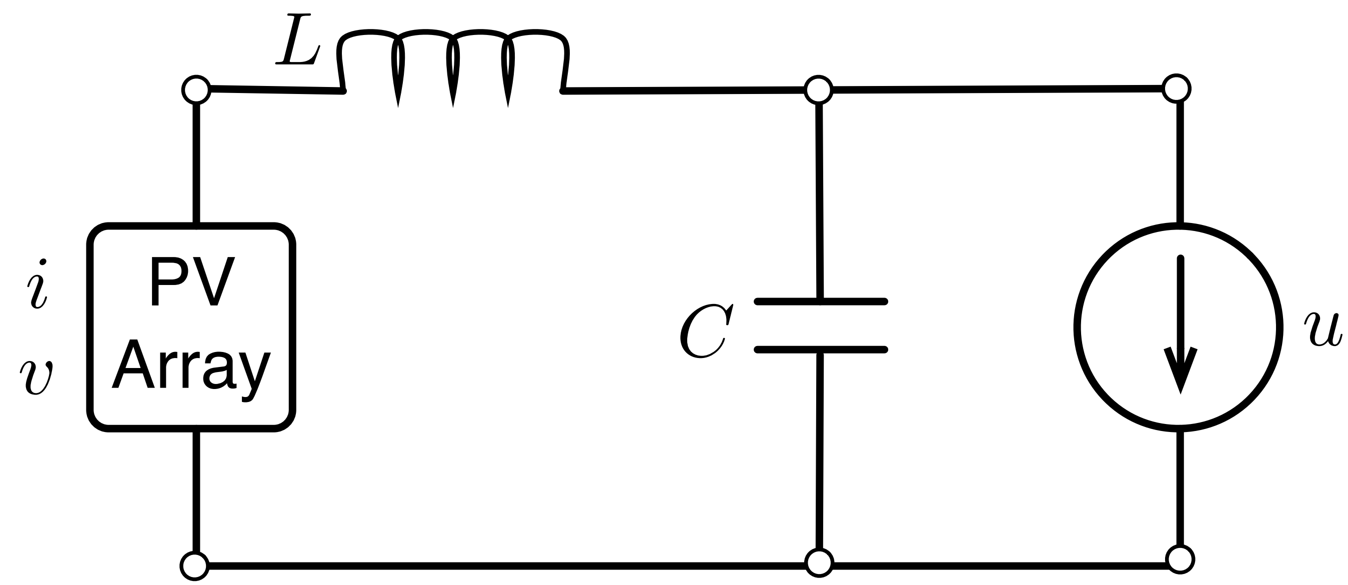

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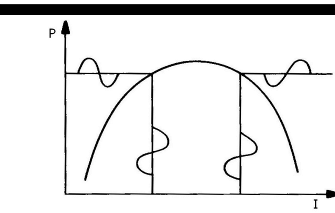
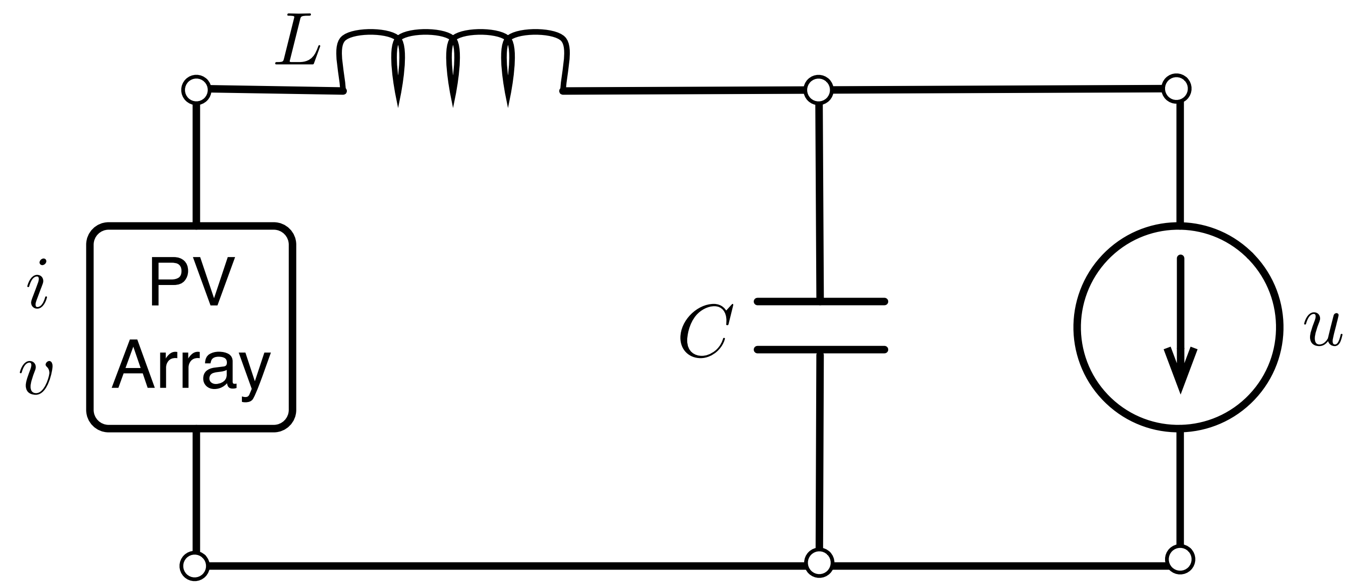
Capacitor equation: $\dfrac{dv_C}{dt} = \dfrac{i_C}{C} \quad \implies \quad \dfrac{dv_C}{dt} = -\dfrac{1}{C}(u - i)$

Array-Inverter Model



Kirchoff's Laws:

$$\begin{aligned} i &= u + i_C \\ v_C &= -v - v_L \end{aligned}$$



Array IV curve is $v = f(i, G)$

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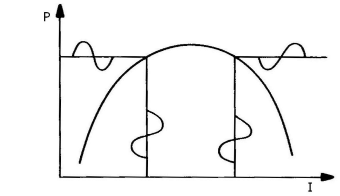
$$= \frac{\partial f(i,G)}{\partial i}\frac{di}{dt} + \frac{\partial f(i,G)}{\partial G}\frac{dG}{dt} + L\frac{d^2 i}{dt^2}$$

Capacitor equation: $\frac{dv_C}{dt} = \frac{i_C}{C} \quad \Longrightarrow \quad \frac{dv_C}{dt} = -\frac{1}{C}(u - i)$

$$\Longrightarrow \quad LC\frac{d^2 i}{dt^2} + C\frac{\partial f}{\partial i}\frac{di}{dt} + i = u - C\frac{\partial f}{\partial G}\frac{dG}{dt}$$

Outline



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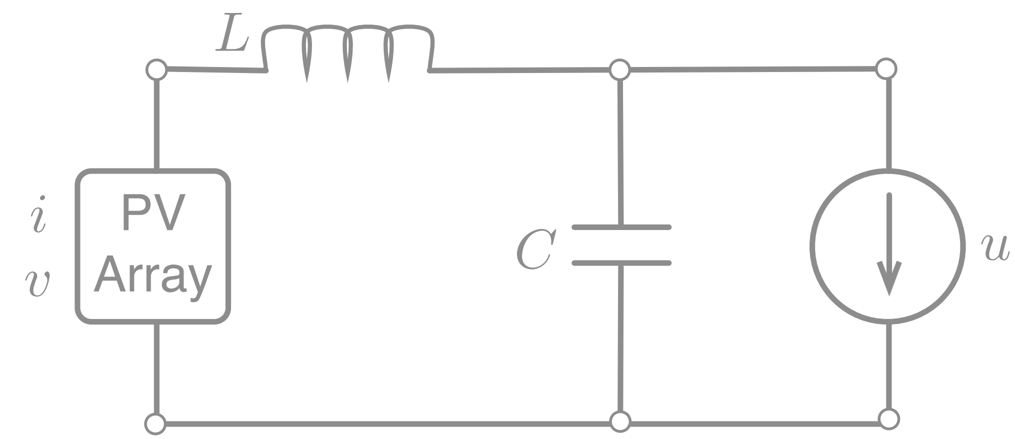
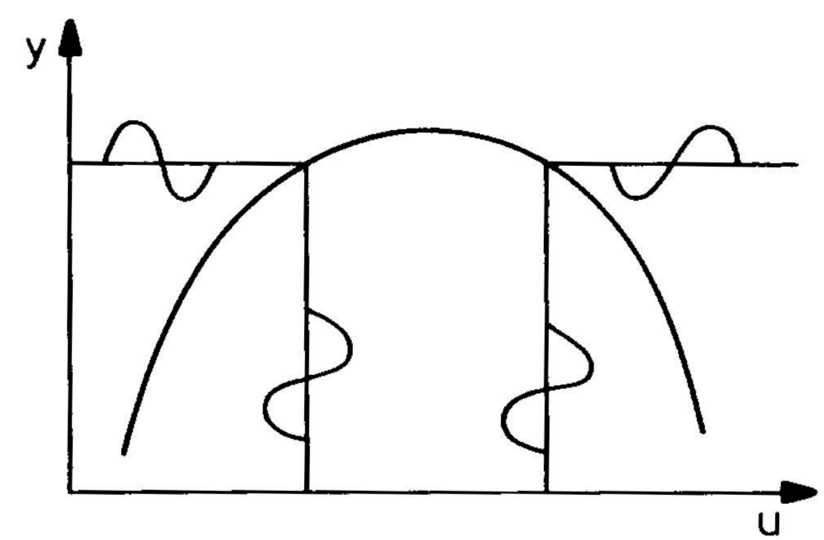
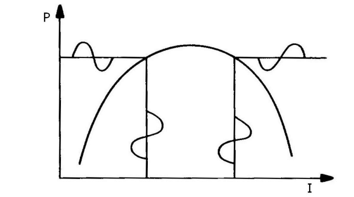


3. **Maximum Power Point Tracking**
   - **Perturb and observe**
   - **Extremum seeking controller**



4. Results and Conclusions

Perturb and Observe



Basic idea:

At every time step, perturb the control input by a small, fixed value:

- If the power increases, keep perturbing in this direction
- If the power decreases, change direction.

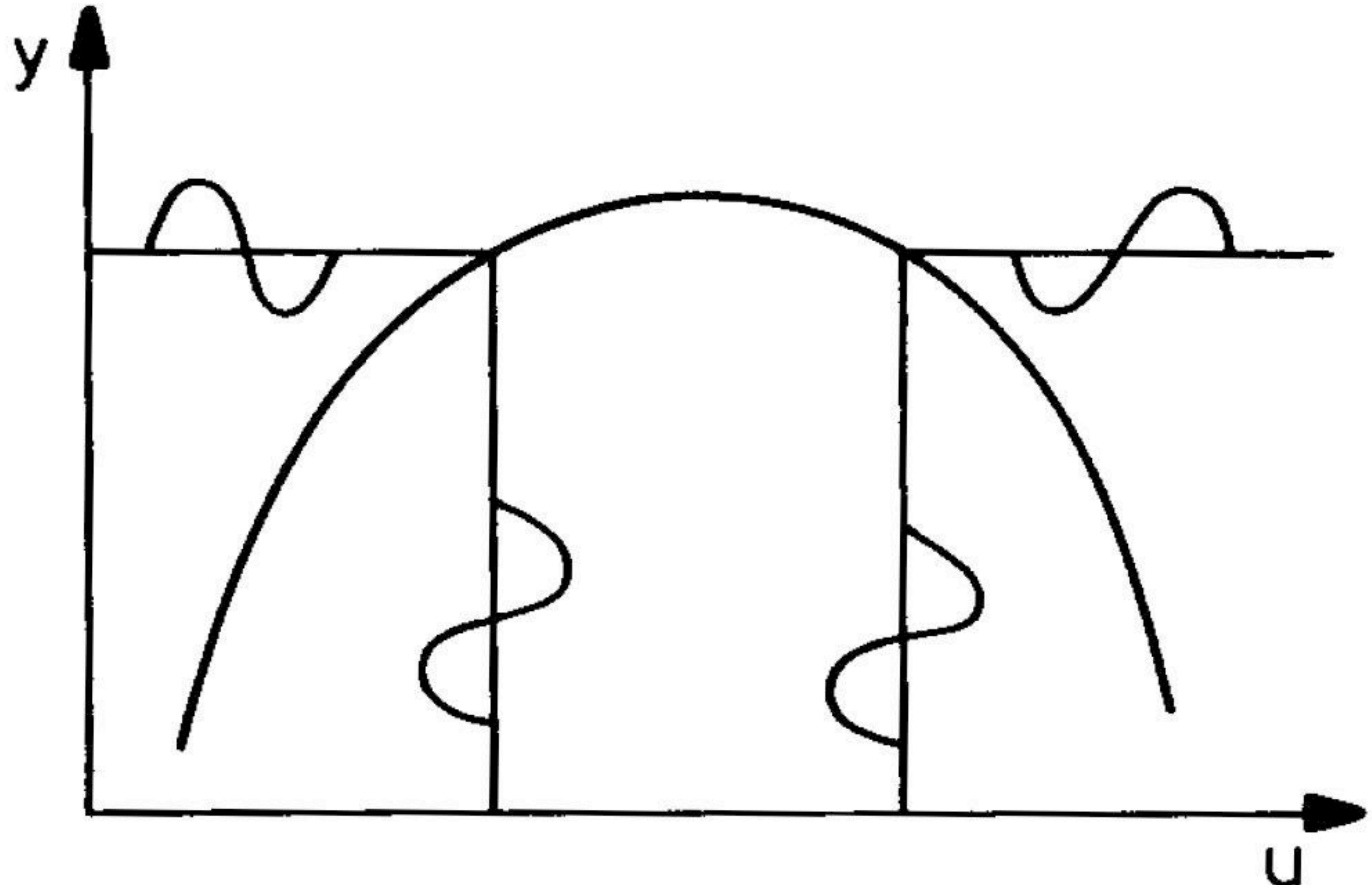
Positives:

- Very popular method because of its simplicity
- Does not require any extra irradiance sensors or models

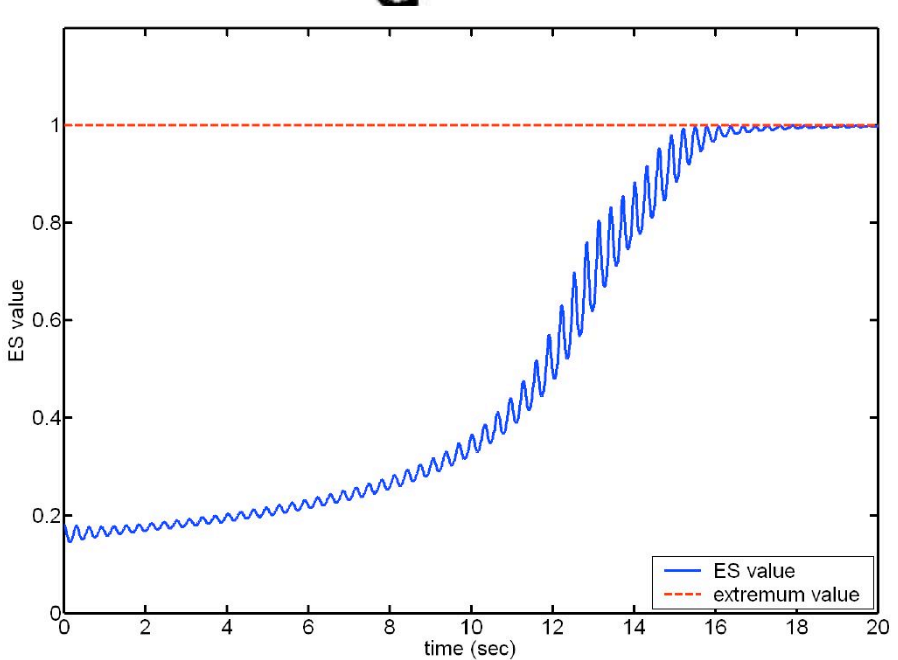
Negatives:

- Not adaptive
- Slow rise time, large oscillations about maximum power point
- Tradeoff between rise time for transients and performance at maximum power point

Extremum Seeking Control



Basic concepts:

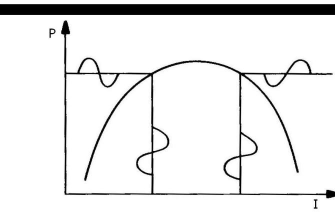


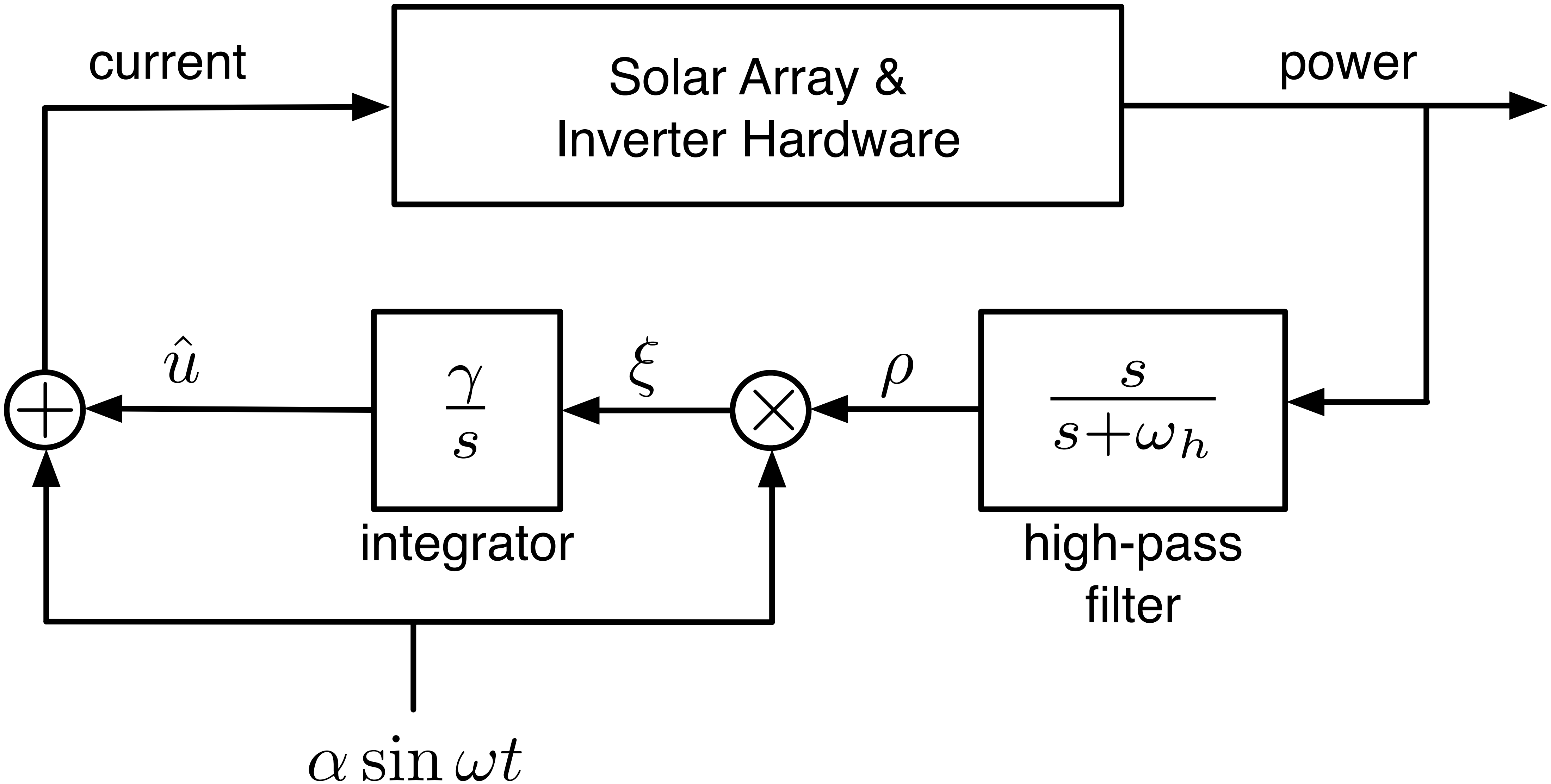
Inject a sinusoidal perturbation on top of "best guess" for input which maximizes output.

Add demodulated signal (multiply input & output sinusoids) to best guess.

If left of maximum, signal is positive
If right of maximum, signal is negative!

Extremum Seeking Control





Time scales:

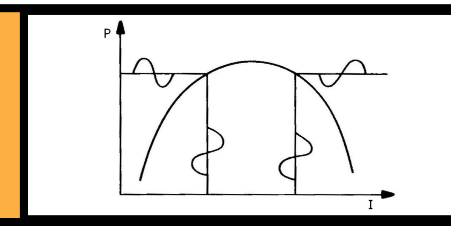
Fast - plant dynamics

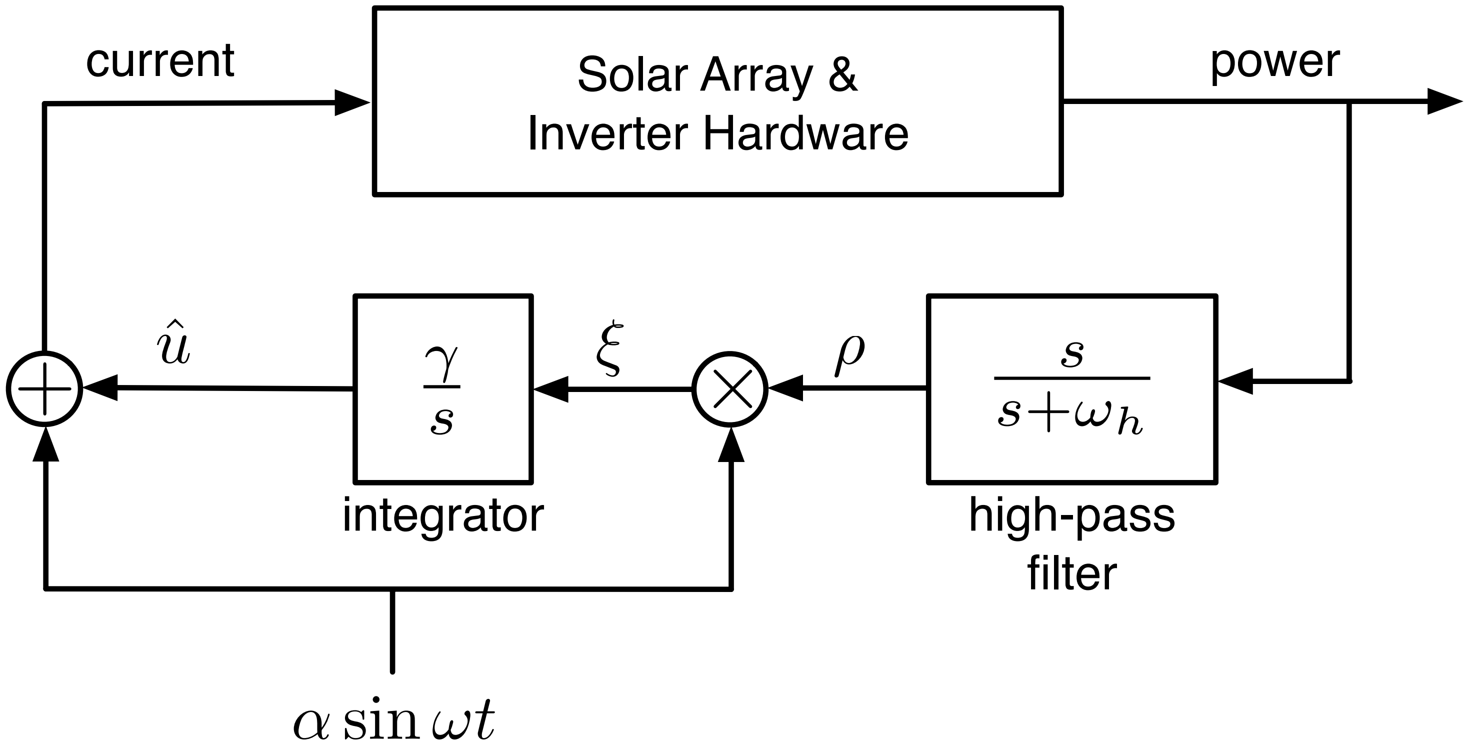
Medium - periodic perturbation

Slow - high/low pass filters

M. Krstic & H.H. Wang, *Automatica*, **36**, 2000.

Extremum Seeking Control

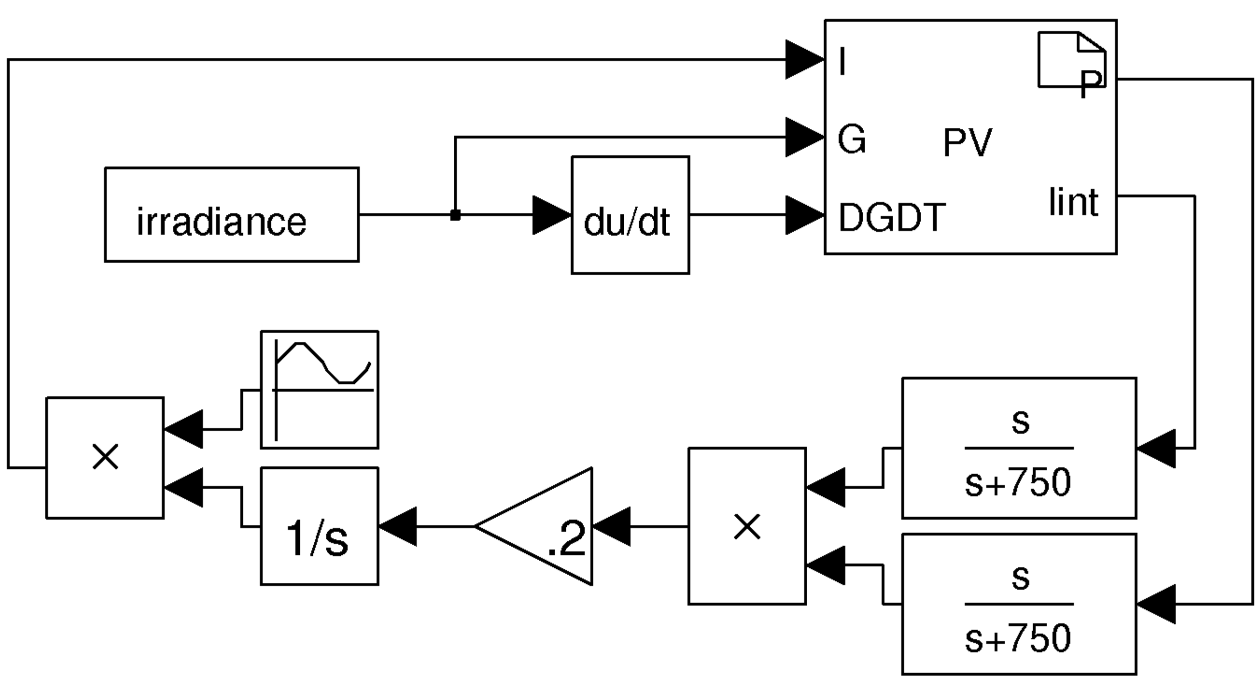




Standard method:

Sinusoidal perturbation is added to average control current $\hat{u}$

Use the same perturbation to demodulate the output power



Modified method:

Converter commands current at 120 Hz

$$u = \hat{u}\,(1 + \sin(120 \times 2\pi t))$$

LC circuit acts as filter, so a 3% ripple reaches the solar array at 120 Hz

$$i \approx \hat{u}\,(1 + .03 \sin(120 \times 2\pi t + \varphi))$$

Demodulate array power with array current

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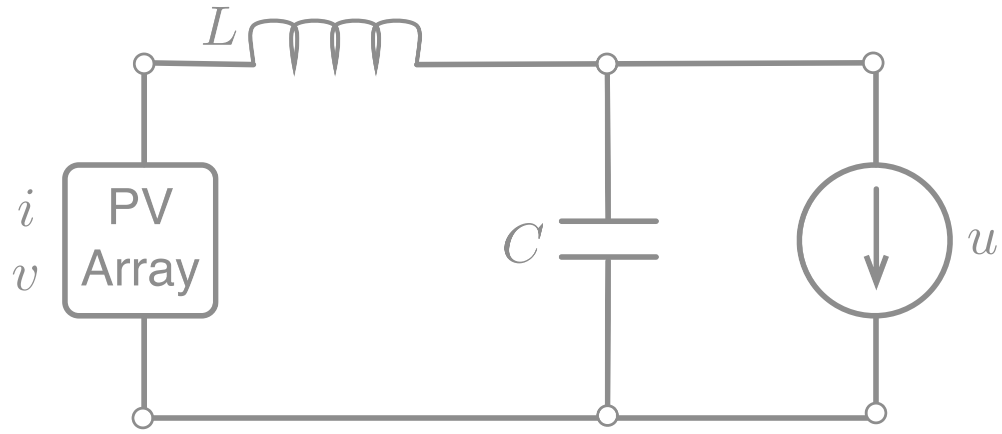

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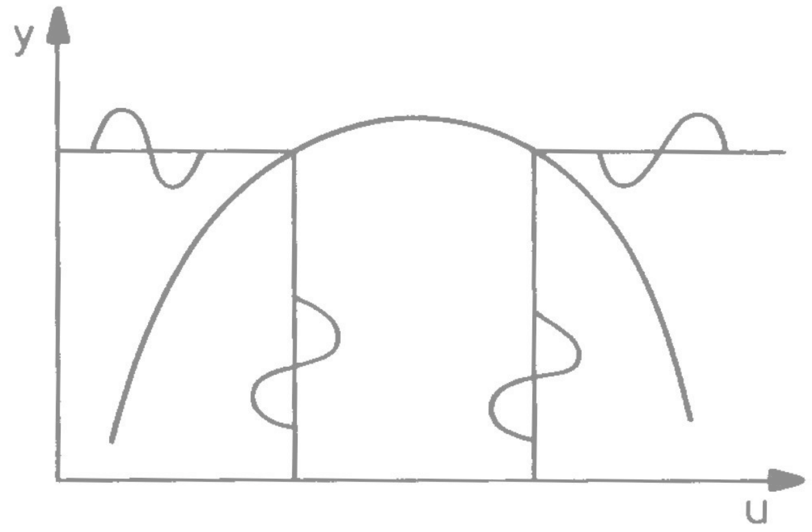
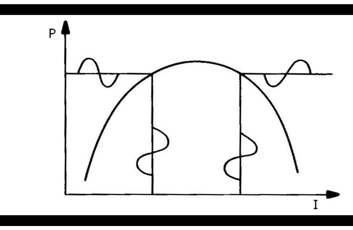
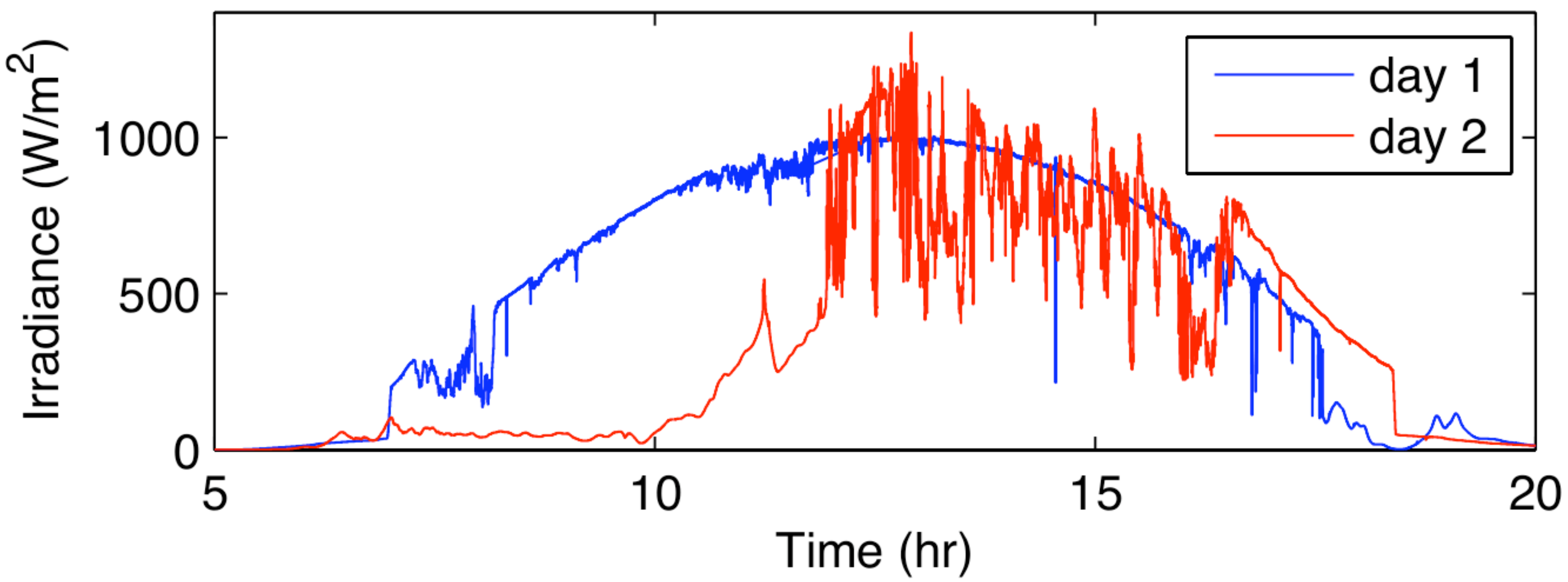


4. **Results and Conclusions**

Comparison on Simulated Array

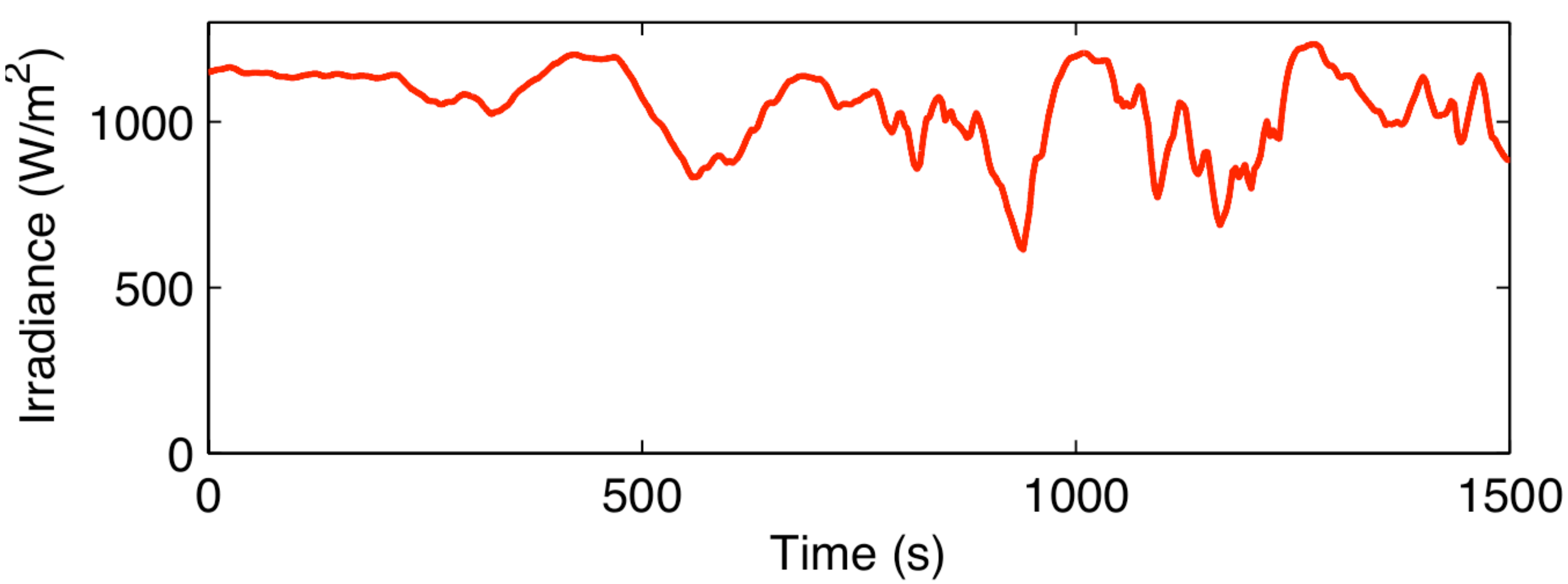




Simulation specifics:

All simulated experiments are run on the 25 minute data set shown below.

Simulations are run in the MATLAB/Simulink modeling environment



Performance metrics:

Efficiency, measured as fraction of maximum power possible

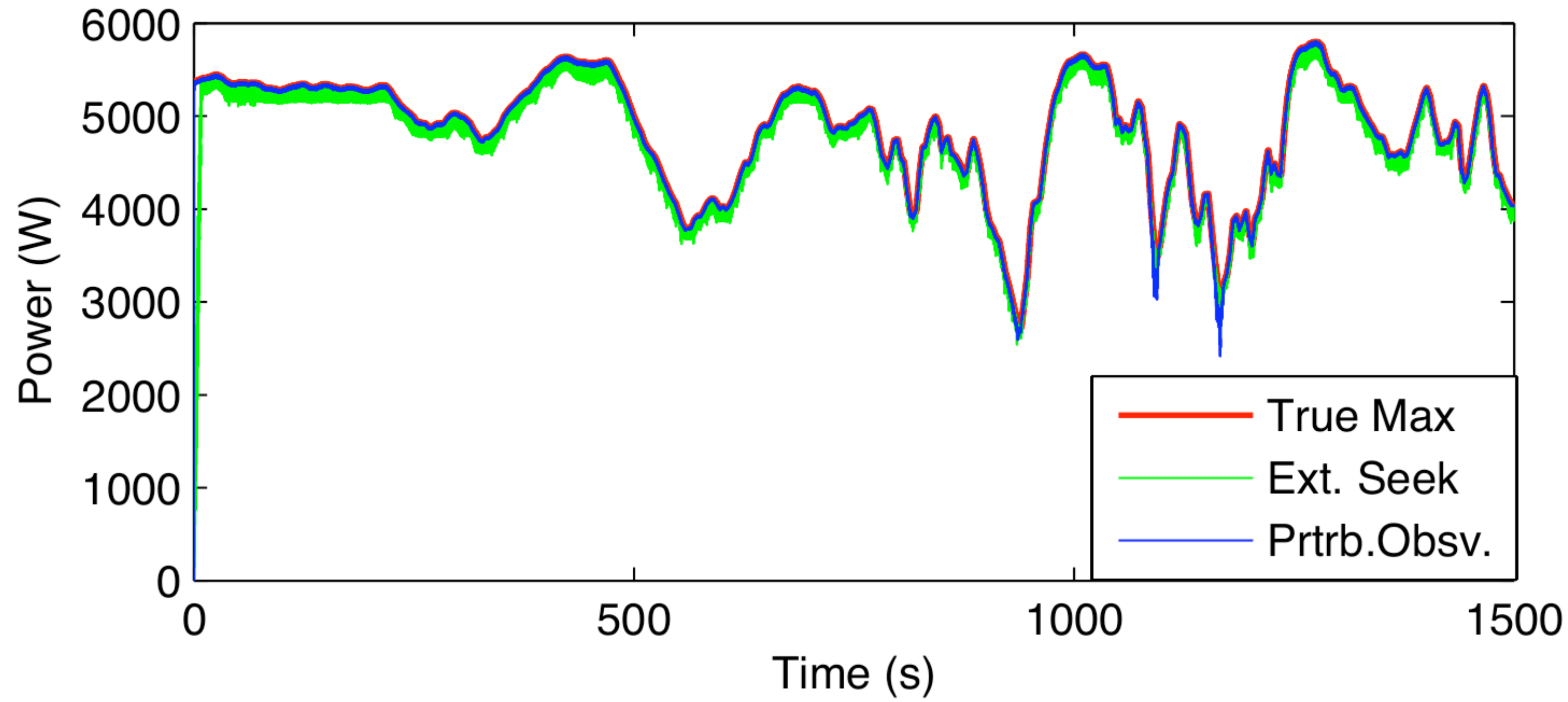
Rise-time of transients and deviation from maximum control current

Controller Performance

Efficiency:

Extremum seeking - 99.7%

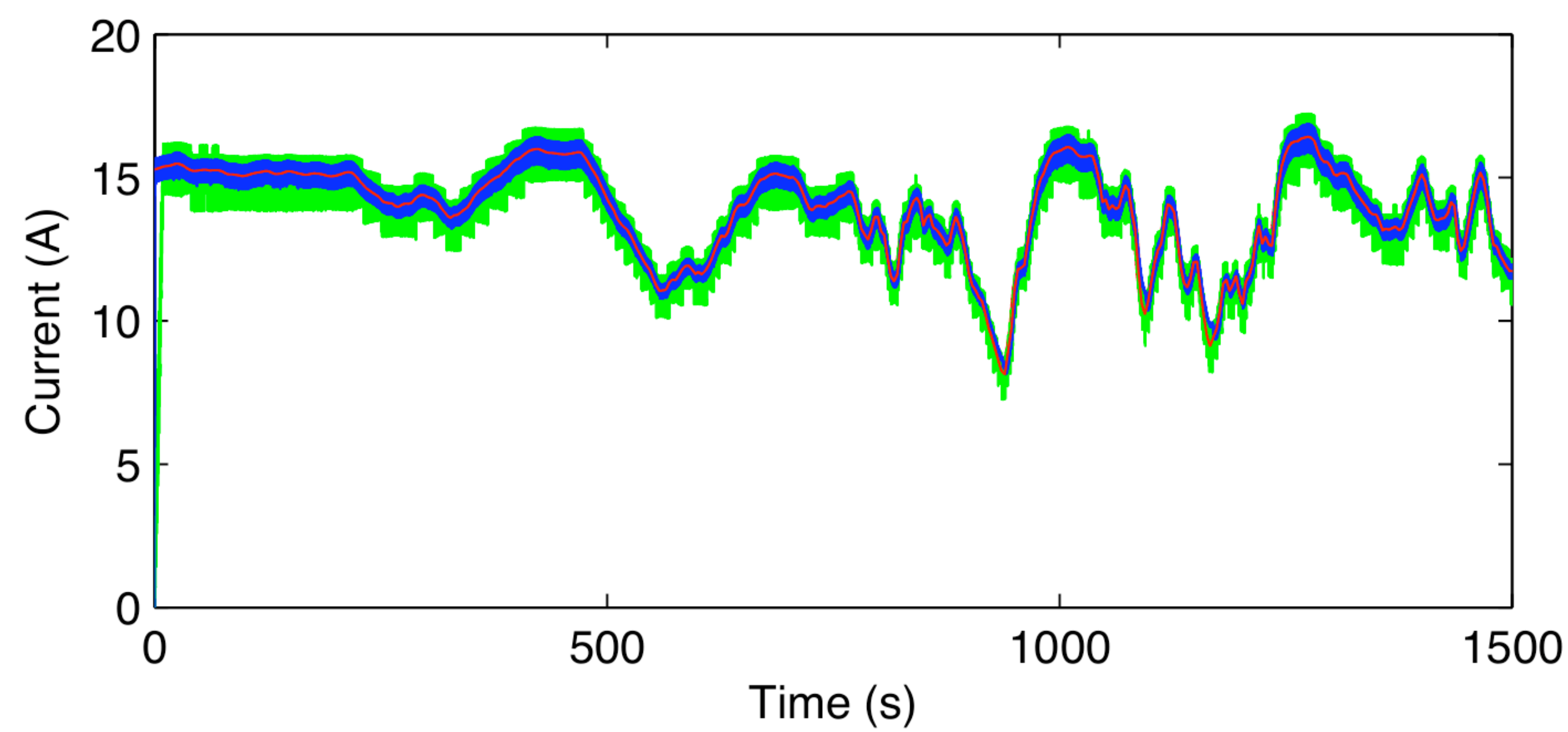
Perturb and Observe - 98.8%



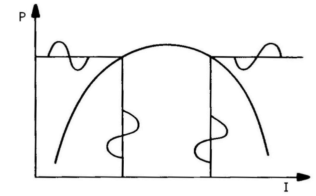
Command current:

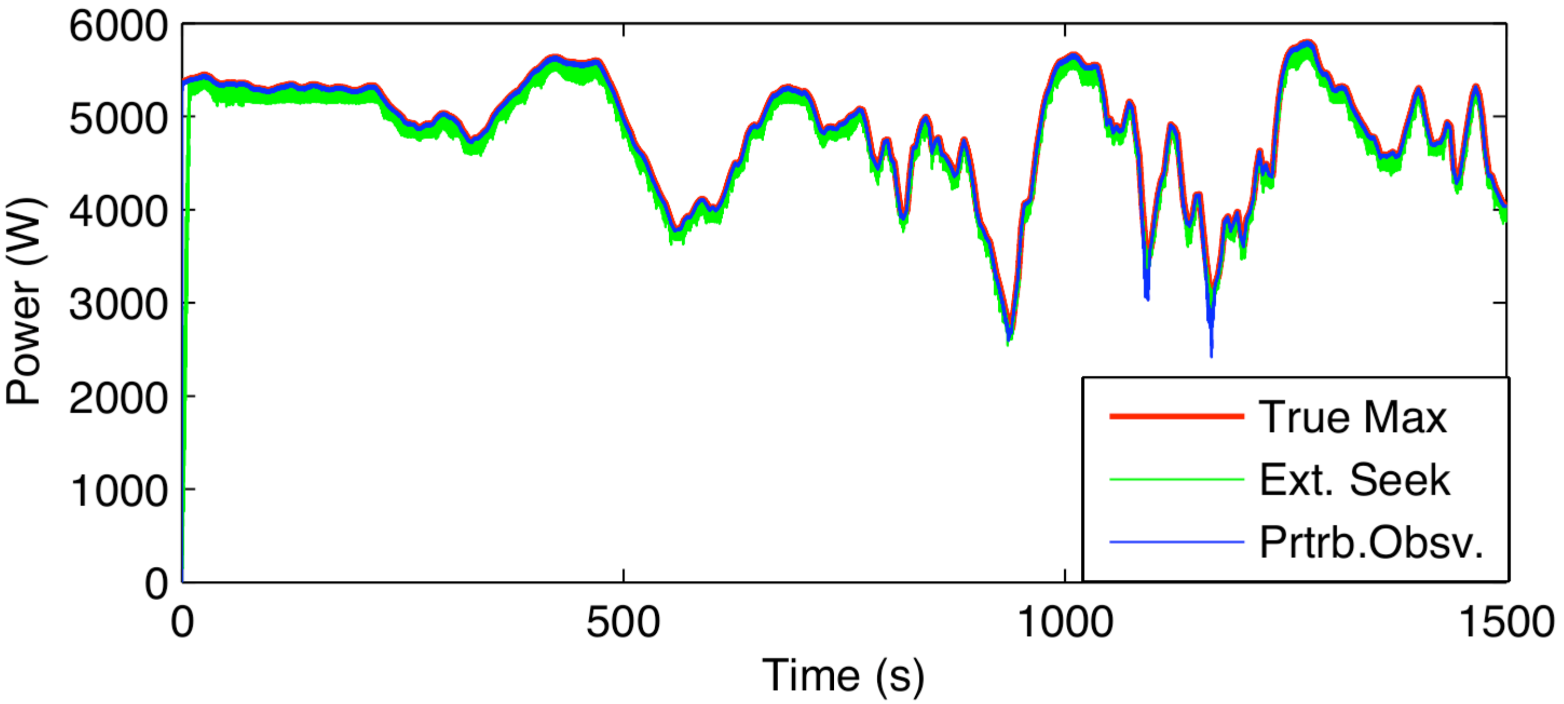
Extremum seeking algorithm has smaller envelope around MP current

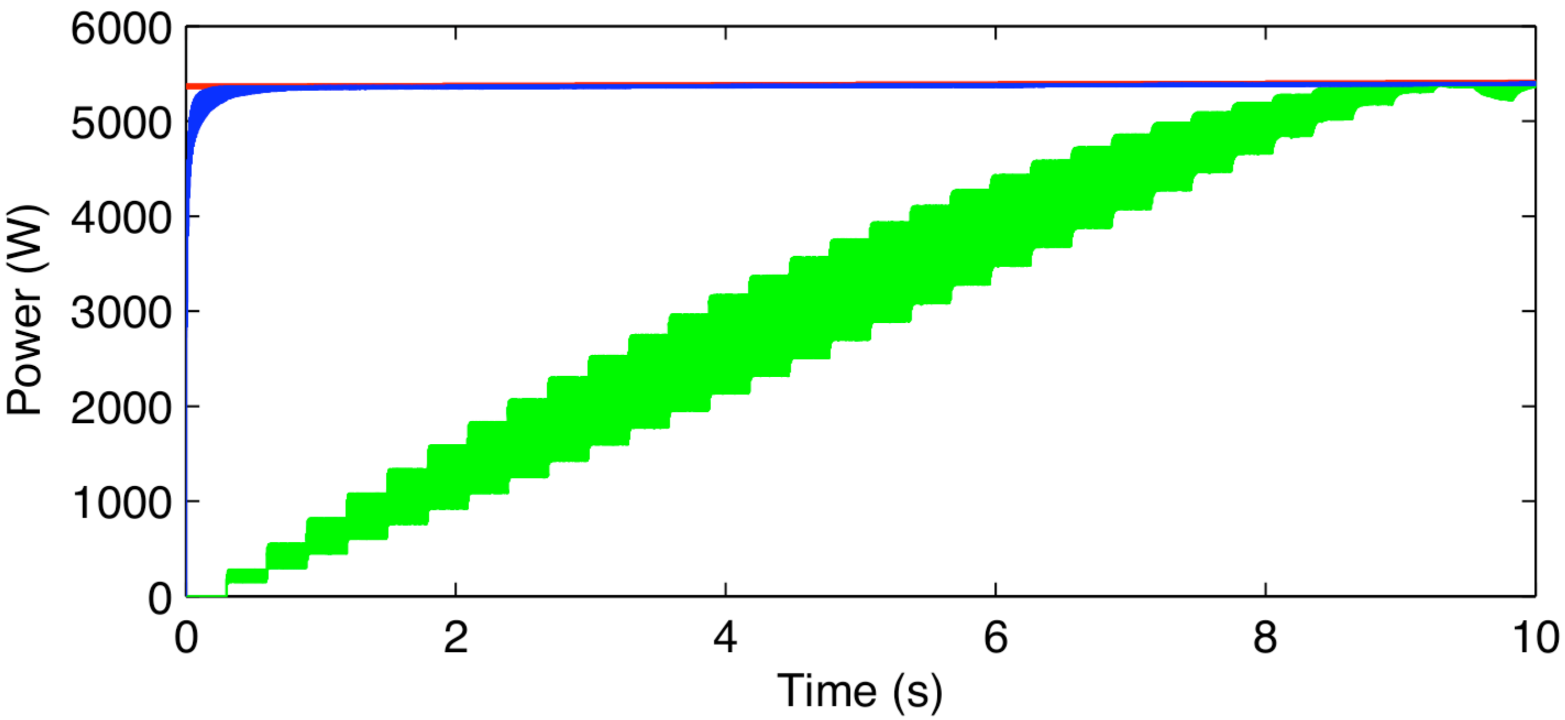
To match efficiency, perturb and observe takes very large .5 amp steps (may be unrealistic for inverter)



Controller Performance







Rise-time:

Extremum seeking - .1 second

Perturb and Observe - 10 seconds

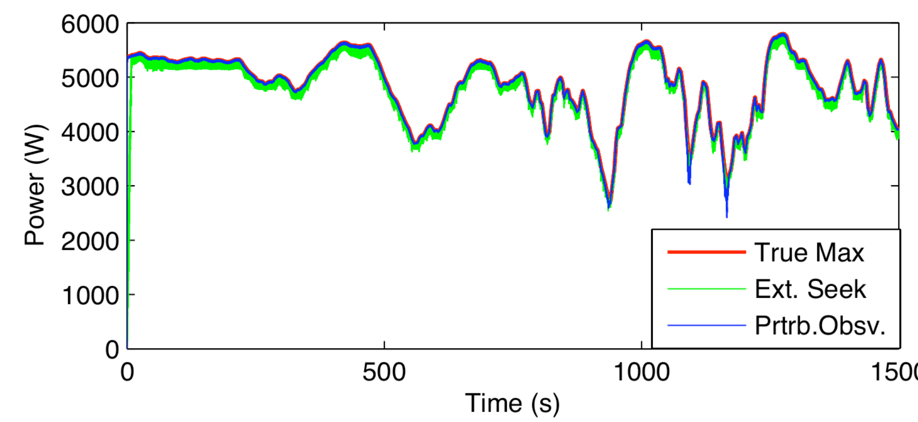
Conclusions

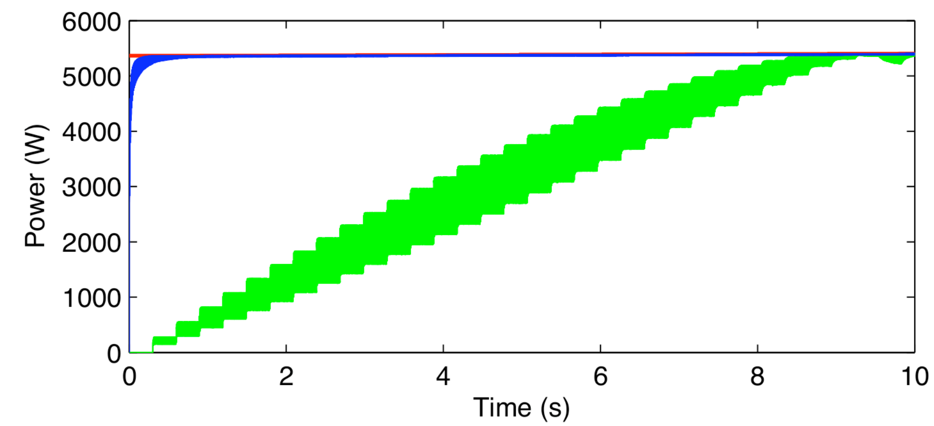
Extremum Seeking Performance:

99.7% maximum power point tracking efficiency on highly variable irradiance data.

Utilizes the natural inverter ripple

100x faster rise time than aggressive perturb and observe





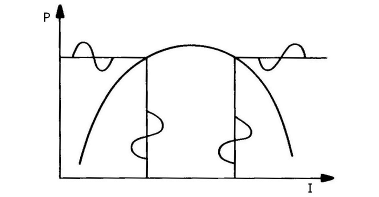
Future Directions:

Investigate adaptive gain extremum seeking

Implement on actual solar arrays located at Princeton University

Analyze performance with models for different solar panel technologies (crystalline vs. amorphous Si).

Acknowledgments



Princeton Power Systems

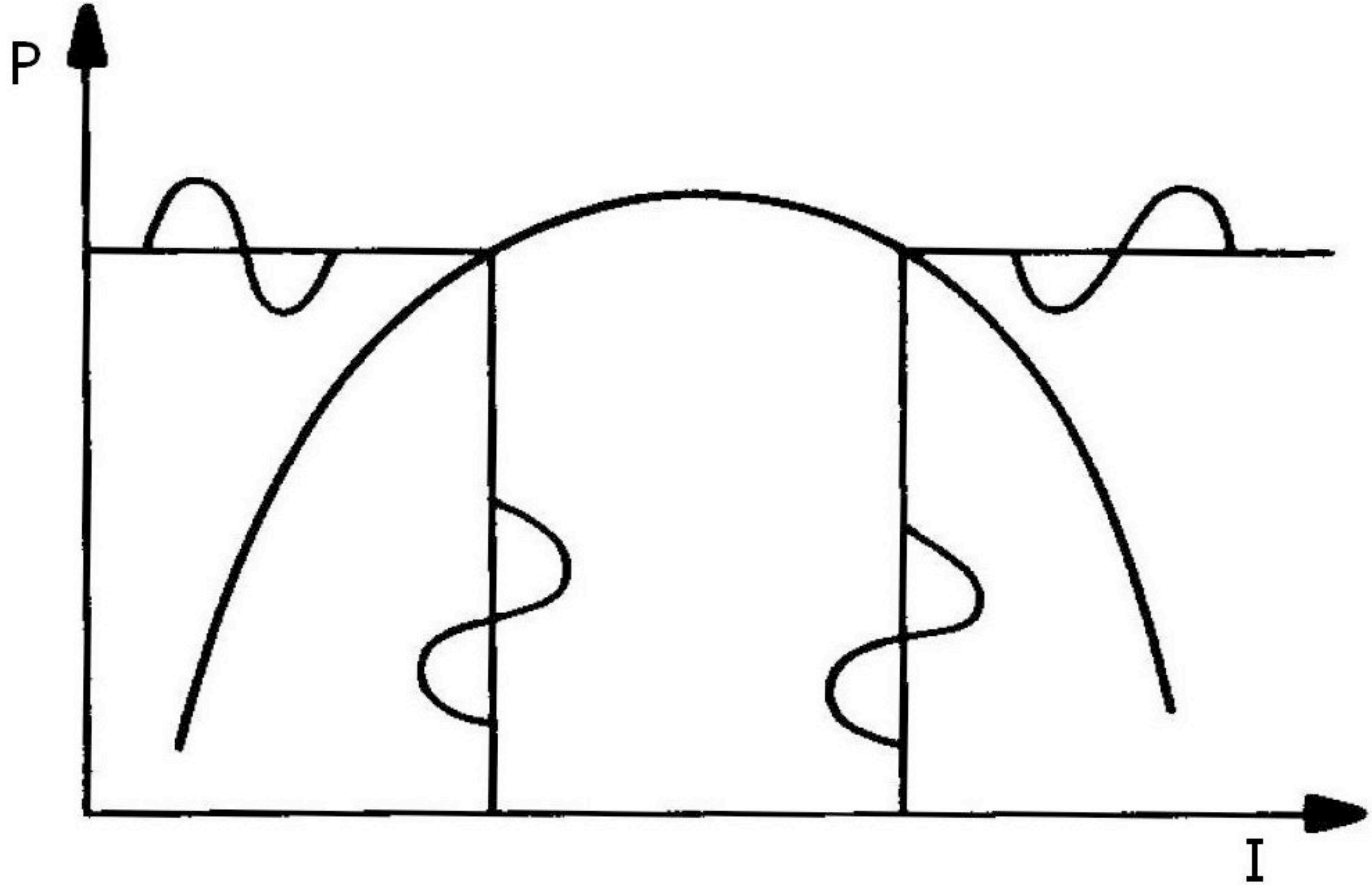
- Mark Holveck
- Erik Limpaecher
- Frank Hoffmann
- Swarnab Banerjee

EPV Solar

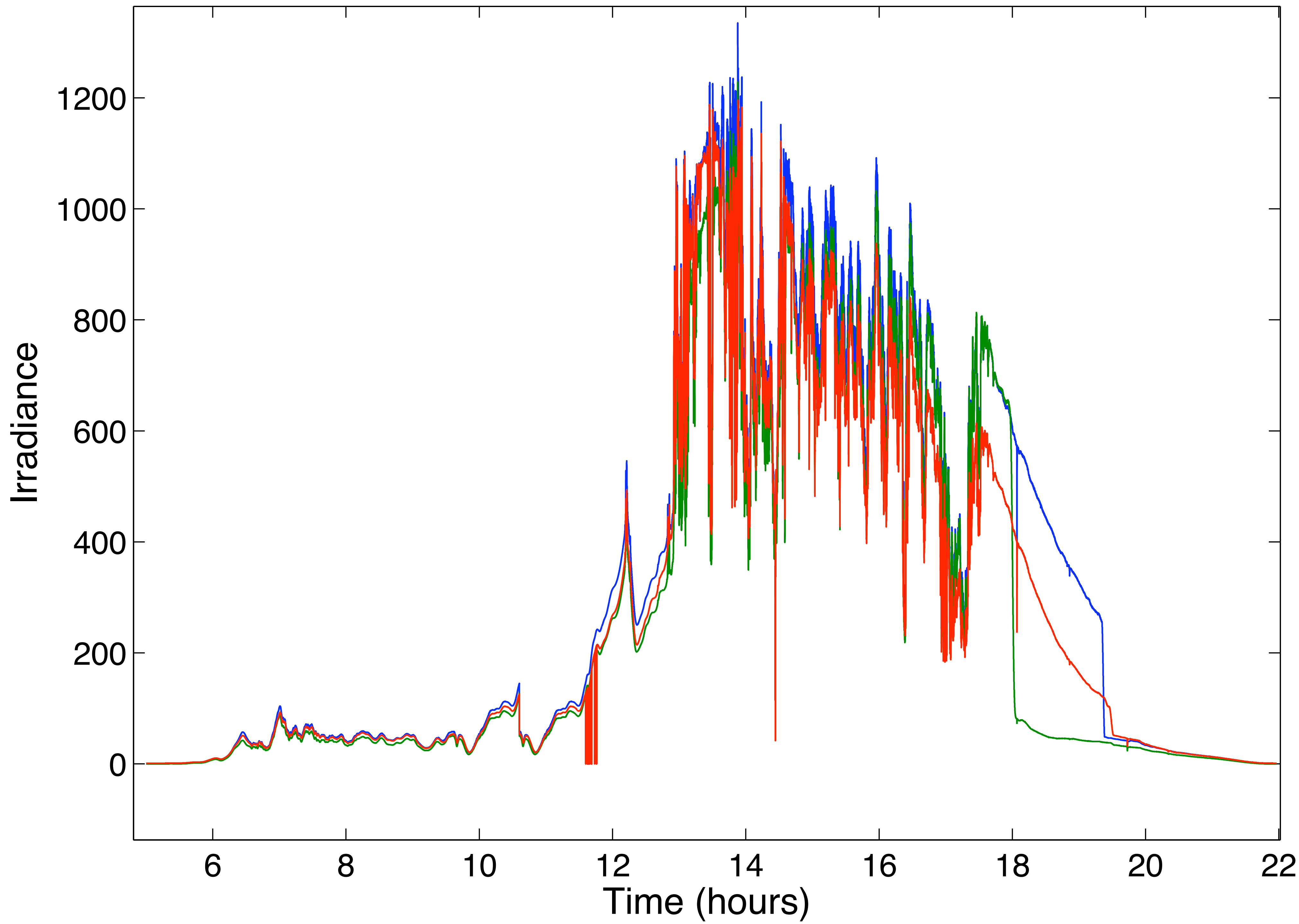
- Alan Delahoy
- Loan Le

New Jersey Commission on Science and Technology (NJCST)

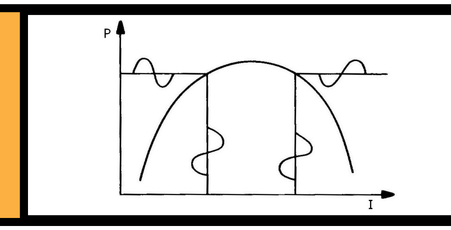
Questions?



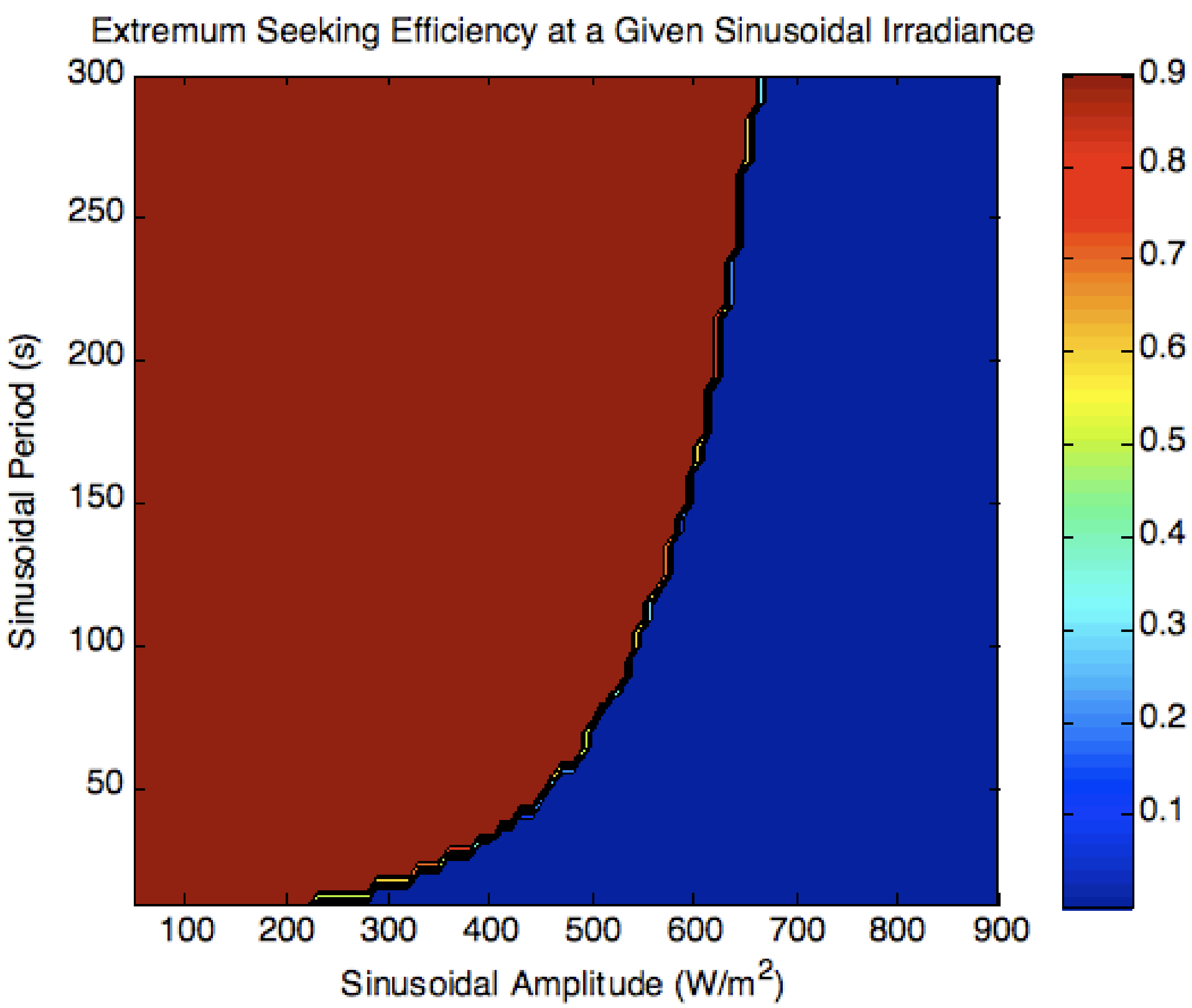
Irradiance Data



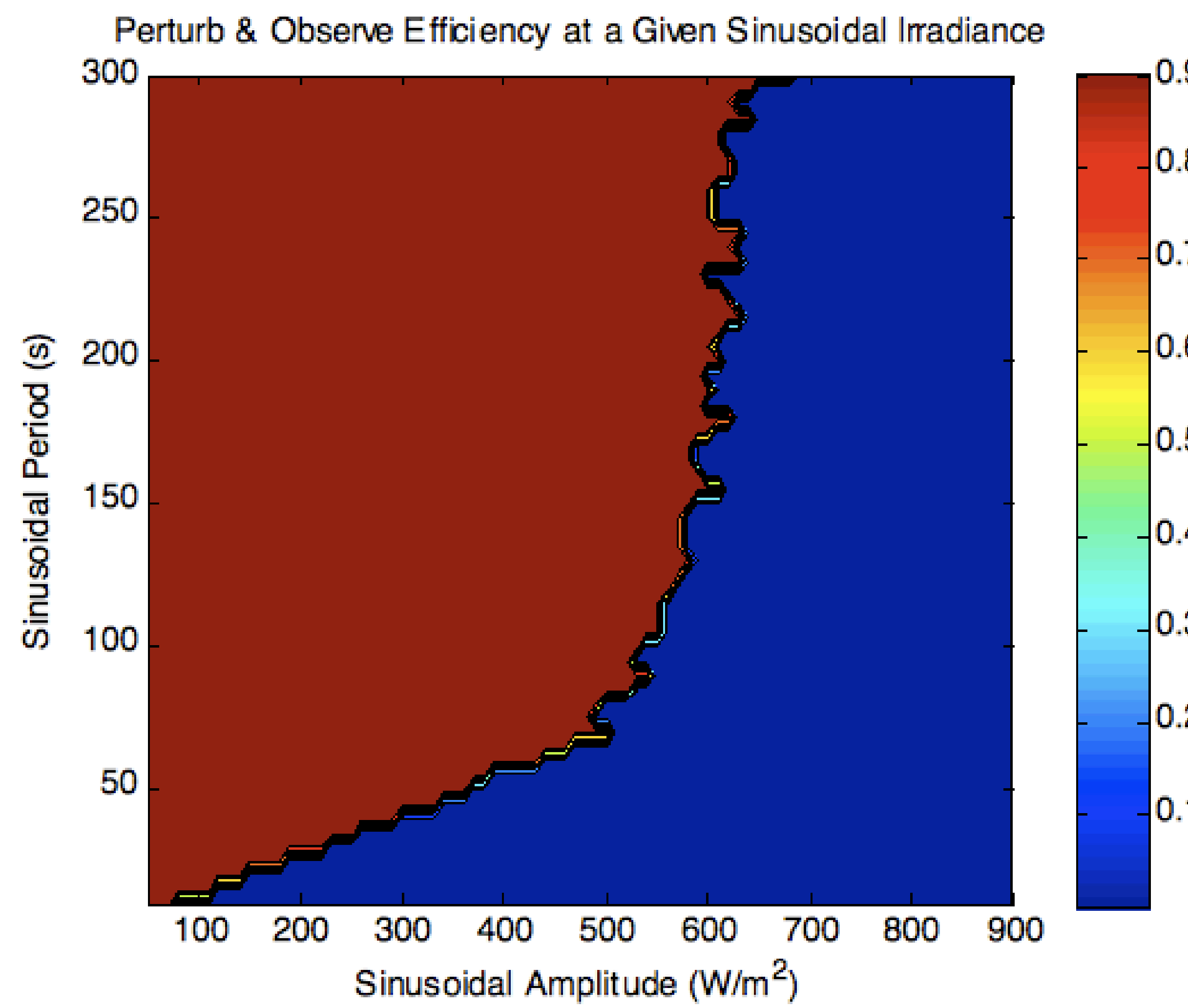
Tracking Comparison



Extremum Seeking



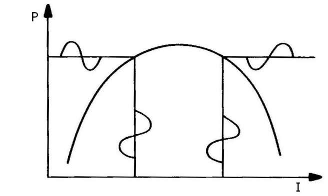
Perturb and Observe



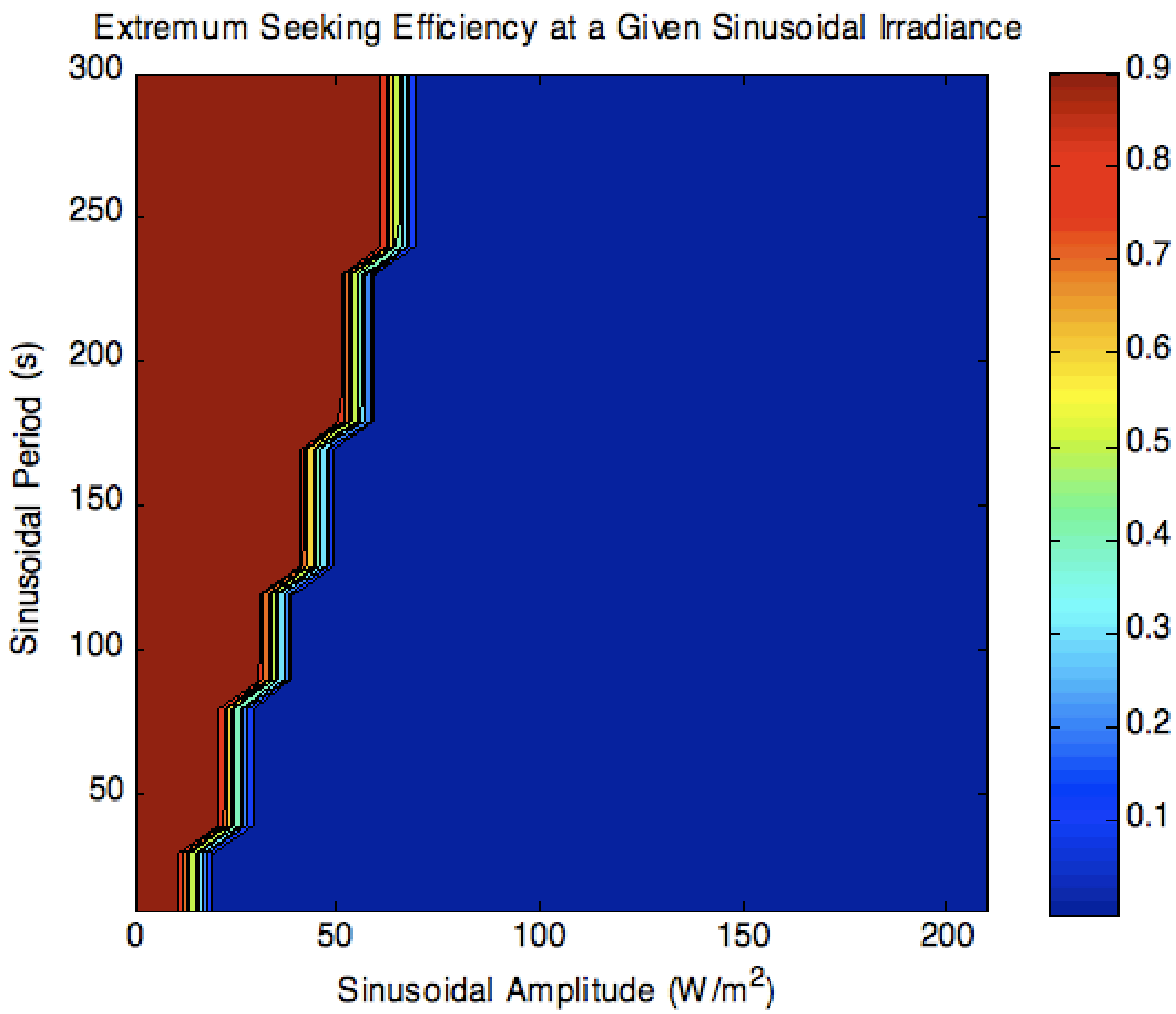
Tracking sinusoidally varying Irradiance

Extremum seeking outperforms Perturb & Observe at low frequency, high irradiance

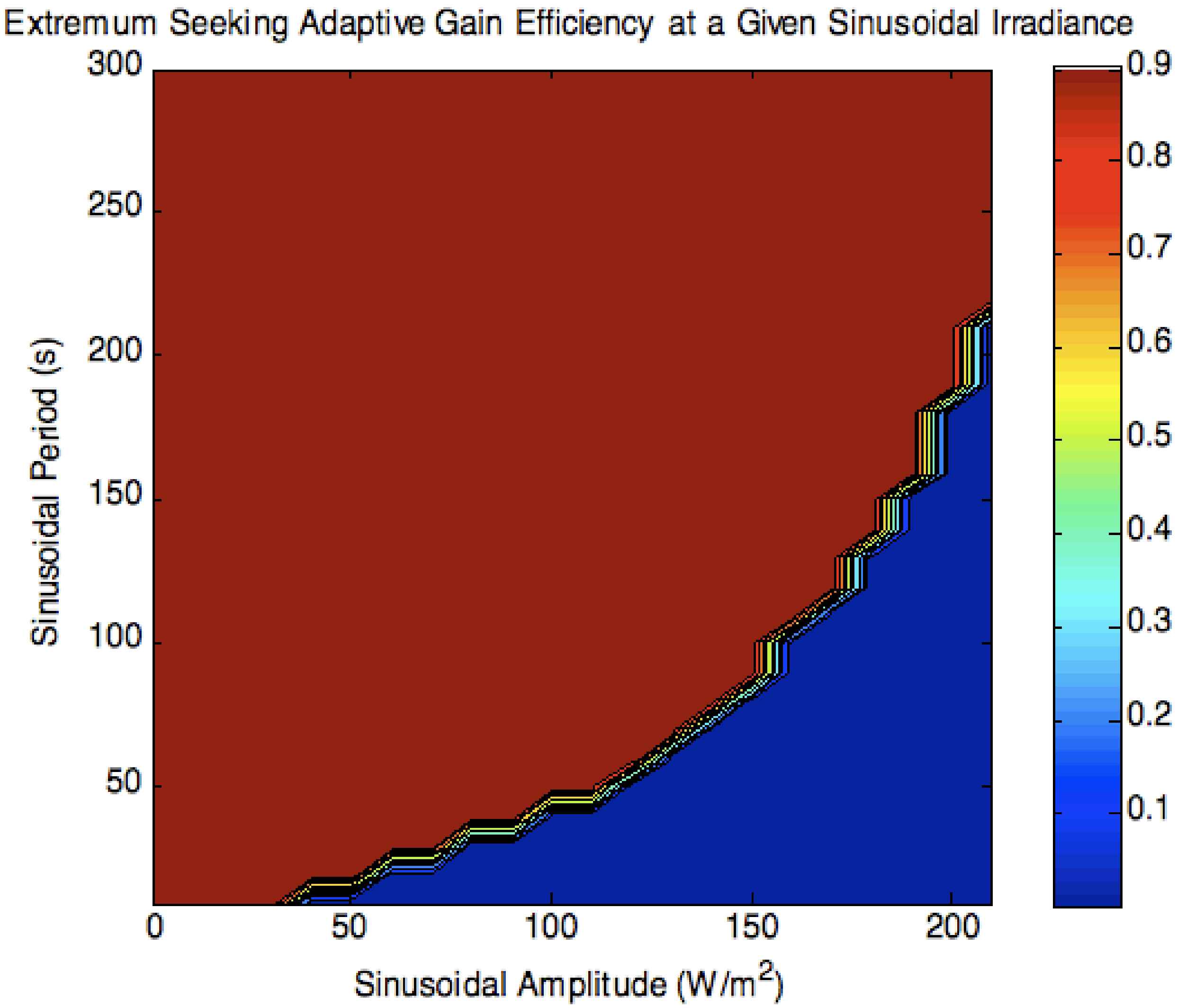
Extremum Seeking w/ Adaptive Gain



Extremum Seeking



Perturb and Observe



Tracking sinusoidally varying Irradiance: low irradiance max

Perturb and observe does not work at all in this range.

Adaptive gain drastically improves extremum seeking.

$$K = \frac{1500}{G} + \frac{400000}{G^2}$$