Maximum Power Point Tracking Techniques for Efficient Photovoltaic Microsatellite Power Supply System

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Outline of Presentation

- Why MPPT?
- Different algorithms
- Extremum Seeking Control
- Hardware Implementation
- Fractional Order Extremum Seeking Control
Maximum power point

- There is an exponential relationship between current and voltage in PV cell.

\[ I = I_{SC} - I_o_1(e^{qV/kT} - 1) - I_o_2(e^{qV/2kT} - 1) \]

\[ I = I_{SC}' - I_o_1(e^{q(V+IR_S)/kT} - 1) - I_o_2(e^{q(V+IR_S)/2kT} - 1) - \frac{(V + IR_S)}{R_{Sh}} \]

\[ I = I_{SC}' - I_o(e^{q(V+IR_S)/A_0kT} - 1) - \frac{(V + IR_S)}{R_{Sh}} \]

Different Algorithms of MPPT

- Voltage Based Peak Power Tracking.
- Current Based Peak Power Tracking.
- Incremental conductance.
- Perturb & Observe. (P&O)

Different Algorithms

Perturb and Observation

\[
\text{VCTRL}_x = 0 \text{ volts}
\]

\[
\Delta V_{SAx}_V = V_{SAx}_V(k) - V_{SAx}_V(k-1)
\]

\[
\Delta V_{SAx}_P = V_{SAx}_P(k) - V_{SAx}_P(k-1)
\]

\[
\Delta V_{SAx}_P > \text{Error1} \quad \text{Yes}
\]

\[
\Delta V_{SAx}_P < \text{Error1} \quad \text{No}
\]

\[
\text{Yes} \quad \text{VCTRL}_x = \text{VCTRL}_x + \Delta 1
\]

\[
\text{Store new } (k-1)
\]

\[
\text{No} \quad \text{VCTRL}_x = \text{VCTRL}_x - \Delta 1
\]

\[
\text{Store new } (k-1)
\]

\[
\text{No} \quad \text{VCTRL}_x = \text{VCTRL}_x - \Delta 1
\]

\[
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\]

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\text{No} \quad \text{VCTRL}_x = \text{VCTRL}_x - \Delta 1
\]

\[
\text{Store new } (k-1)
\]

\[
\text{No} \quad \text{VCTRL}_x = \text{VCTRL}_x - \Delta 1
\]

\[
\text{Store new } (k-1)
\]

\[
\text{Array Voltage has Collapsed}
\]

\[
\text{Power (W)}
\]

\[
\text{Voltage (V)}
\]
Extremum Seeking Control

It is crucial to note that all of the plant components are allowed to be unknown.
Extremum Seeking Control

The periodic perturbations used in the loop perform modulation and demodulation, and their role is to make the extremum of the equilibrium map, which is flat, and therefore appears as a zero gain block, appear, in a time-average sense, as a gain proportional to the second derivative at the extremum.

The role of the washout filter is to eliminate the bias to the DC component of the equilibrium map.
The EPS includes two solar array inputs that feed into separate Battery Charge Regulators (BCR). The BCRs use a buck converter topology implemented with a current mode DC-DC converter.
Constraints

- An ultra-low power FPGA is used to implement the algorithm and controller. The low power FPGA is a key component. It allows for minimum power consumption by the EPS and was selected due to a higher tolerance to radiation effects over other commercially available components.

- The low power simple architecture forces all algorithms to only use fixed point integer based math, No floating point. This becomes one of the major design constraints for this project.
Experiment Setup

MPPT Test Setup

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>Model Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agilent</td>
<td>E3631</td>
<td>Triple Output Power Supply</td>
</tr>
<tr>
<td>Agilent</td>
<td>E4360A</td>
<td>Modular SAS Mainframe</td>
</tr>
<tr>
<td>Agilent</td>
<td>E4362</td>
<td>Solar Array Simulator Module</td>
</tr>
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</tr>
<tr>
<td>Chroma</td>
<td>6314</td>
<td>Electronic Load Mainframe</td>
</tr>
<tr>
<td>Chroma</td>
<td>63102</td>
<td>Dual Channel Load Module</td>
</tr>
<tr>
<td>Chroma</td>
<td>63107</td>
<td>Dual Channel Load Module</td>
</tr>
<tr>
<td>Dell</td>
<td>M90</td>
<td>Laptop Computer + Monitor</td>
</tr>
</tbody>
</table>
**Experimental Results**

**Steady State:** This test was a 30 second sample in time of the EPS power output with a fixed solar array input.

<table>
<thead>
<tr>
<th>Metric</th>
<th>ESC Value</th>
<th>P&amp;O Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Peak-to-Peak</td>
<td>0.024 watts</td>
<td>0.109 watts</td>
</tr>
<tr>
<td>Average Power</td>
<td>7.199 watts</td>
<td>7.149 watts</td>
</tr>
<tr>
<td>Minimum Power Output</td>
<td>7.179 watts</td>
<td>6.933 watts</td>
</tr>
<tr>
<td>Maximum Power Output</td>
<td>7.212 watts</td>
<td>7.2093 watts</td>
</tr>
</tbody>
</table>
Experimental Results

Dynamic Testing:

Ramp Test - Channel 1 (Rate = 5mA/200ms)

Source Pulse/Step Test (Imp = 100 to 600mA)

Sinusoidal input response (Imp = +/-250mA)
Conclusions:

- In the steady state condition, ESC can extract more power from PV panels, has smaller peak-peak power ripple, and provides greater immunity for channel to channel interference in comparison with P&O controller.

- In the dynamic response test, the P&O algorithm clearly outperforms the IO-ESC algorithm as presently implemented.

- Because of time constraints, we were not able to implement the slope seeking control portion of the ESC algorithm and compare it to the P&O. Obviously; ESC cannot follow fast slopes and cannot satisfy high dynamic response MPPT requirements without this slope seeking portion as we can see in the experimental results.
Fractional Order ESC

- Replace Integer Order Integrator with Fractional Order Integrator.
Simulation results of FO ESC

- without noise
- in presence of noise
- different integration orders
Experimental results of FO ESC
Conclusions:

- the fractional order ESC has a better performance in comparison with integer order ESC.
Acknowledgments

We would like to acknowledge and thank

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- The **Space Dynamics Laboratory** and **Utah State University** for support of time and other laboratory resources involved in the testing.
Thank you!

Q&A?
Extremum Seeking Control

C(s) will be used to improve the stability properties of the extremum seeking scheme.

This compensator can be regarded as a phase-lead compensator which improves the phase margin in a loop with a high relative degree.

One limitation to the speed of adaptation will be imposed by the presence of the measurement noise input n.
Extremum Seeking Control

\[ \tilde{\theta} = \theta^* - \hat{\theta} \]

then, based on the above diagram, we have

\[ \theta(t) = \hat{\theta}(t) + a \sin(\omega t) \rightarrow \theta(t) = \theta^* - \tilde{\theta} + a \sin(\omega t) \]

\[ \rightarrow \theta(t) - \theta^* = -\tilde{\theta} + a \sin(\omega t) \]
Extremum Seeking Control

\[ J(\theta) = J^* + \frac{J''}{2} (\theta - \theta^*)^2 = J^* + \frac{J''}{2} (a \sin(\omega t) - \tilde{\theta})^2 \]

\[ = J^* + \frac{J''}{2} a^2 \sin^2(\omega t) + \frac{J''}{2} \tilde{\theta}^2 - J''a \tilde{\theta} \sin(\omega t) \]

\[ = J^* + \frac{a^2 J''}{4} - \frac{a^2 J''}{4} \cos(2\omega t)) + \frac{J''}{2} \tilde{\theta}^2 - J''a \tilde{\theta} \sin(\omega t) \]
Extremum Seeking Control

\[ \chi(t) = - \frac{a^2 J''}{4} \cos(2\omega t) + \frac{J''}{2} \ddot{\theta}^2 - J''a\ddot{\theta} \sin(\omega t) \]

\[ \xi(t) = \chi(t) \sin(\omega t) \]

\[ = - \frac{a^2 J''}{4} \sin(\omega t) \cos(2\omega t) + \frac{J''}{2} \ddot{\theta}^2 \sin(\omega t) - J''a\ddot{\theta} \sin^2(\omega t) \]
Extremum Seeking Control

\[\ddot{\xi}(t) = -\frac{a^2 J''}{4} \sin(\omega t) \cos(2\omega t) + \frac{J''}{2} \tilde{\theta}^2 \sin(\omega t) - J'' a \tilde{\theta} \sin^2(\omega t)\]

\[= -\frac{a^2 J''}{8} [\sin(3\omega t) - \sin(\omega t)] + \frac{J''}{2} \tilde{\theta}^2 \sin(\omega t) - \frac{J'' a \tilde{\theta}}{2} [1 - \cos(2\omega t)]\]

\[= -\frac{J'' a \tilde{\theta}}{2} + \frac{J'' a \tilde{\theta}}{2} \cos(2\omega t) - \frac{a^2 J''}{8} [\sin(3\omega t) - \sin(\omega t)] + \frac{J''}{2} \tilde{\theta}^2 \sin(\omega t)\]
Extremum Seeking Control

\[
\hat{\theta}(t) = -\gamma \frac{J''a\tilde{\theta}(t)}{s} \Longrightarrow \dot{\hat{\theta}}(t) = -\frac{\gamma J''a\tilde{\theta}(t)}{2}
\]

\[
\tilde{\theta} = \theta^* - \hat{\theta} \Rightarrow \dot{\tilde{\theta}}(t) = -\frac{\gamma J''a\tilde{\theta}(t)}{2} \quad \quad \gamma J''a > 0 \Rightarrow \tilde{\theta}(t) \Rightarrow 0
\]

\[
\theta^* - \hat{\theta} \Rightarrow 0 \Rightarrow \theta^* = \hat{\theta}
\]