Optimization and Design of 1 kW Stirling Controller using Capacitor-based Power Factor Correction

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Outline

• Thermoelectrics and Stirling convertors
• Background in Stirling control
• Historical approach
• Simplified Stirling control
• High density capacitors
• Application and system optimization
• Control strategy
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Thermoelectric control

Radioisotope thermoelectric generator

✓ Long historical precedent
✓ Solid-state
✓ Simple control
✗ ~6% efficient

Thermoelectric linear current/voltage relationship[1]

Controlled with a simple shunt voltage limiter

1) Northwestern Materials Science and Engineering
Stirling convertor control

Stirling generator systems

✓ Higher specific power than GPHS-RTG [1]
✓ ~20-27% efficient, 3X to 4X more power available for exploration
× Mechanical system (Addressed with extended operation at the Stirling research lab (SRL))
× Rectification and dynamic control required

1) Atomic Power In Space II – A History of Space Nuclear Power and Propulsion in the United States, Idaho National Laboratory, 2015
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Stirling control – Energy balance

- Thermal energy flowing into Stirling is constant (at engine timescale)
  - Radioisotope or fission thermal power
- Energy must be extracted to limit piston motion
- Stirling alternator inductance limits power flow from alternator*.
- Energy accumulation in the piston results in overstroke.

*New low-inductance alternator designs are also being explored in LET.
Stirling control – Power factor correction

- Power factor correction (PFC) negates alternator impedance
  - Can be implemented using a capacitor

Energy balance facilitates stable operation
A power controller is required to transfer energy to the user.

Active control is needed to precisely match the load to the operation of the Stirling

Stirling control – Load regulation
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Dynamic Radioisotope Power Systems (DRPS)

Goal:
- Extract 110-130 watts of electrical power from 1 kg of plutonium-238

Core concepts:
- Maintain stable Stirling operation during launch
- Incorporate redundancy in design
  - Loss of single engine would lead to mission failure
- 17-year mission life

Advanced Stirling Radioisotope Generator
Active power factor correction

- Capacitor-based PFC has challenges
  - Existing capacitor technology is large
  - There are challenges in validating the 17 year lifespan required for DRPS
- Active PFC circumvents these challenges with active control

Prior “engineering model” controllers

- **Specs:**
  - Dual channel (2 Stirlings) 12 Vrms, 7 A, 80 W
  - Spacecraft dc - 28 Vdc

- **ASC Control Unit (ACU)**
  - Developed by Lockheed Martin
  - Not under active development (program ended in 2013)

- **Dual Converter Controller (DCC)**
  - Designed by APL with “path to flight” components
  - Under active revision by APL for DRPS
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Objective – Provide reliable power

How can Stirling systems be simplified to reduce development risks?
Simplification with analog control

- Analog circuits remove need for the firmware development and validation required for an FPGA
- Analog implementation offers potential for increased radiation tolerance
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Power factor correction (PFC) capacitors

- Limited selection of capacitors suitable for flight applications
  - MIL-PRF-83421/2 capacitors selected as best existing solution
- Available capacitor solutions are bulky and require significant packaging design due to high component count

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<th>Type</th>
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<td>62 W</td>
<td>71 W</td>
<td>1100 W</td>
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<td>Convertor Voltage</td>
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<td>Capacitor Count</td>
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<td>Size*</td>
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<td>41.5 in³ (0.68L)</td>
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<tr>
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<td>0.92 lbs</td>
<td>0.67 lbs</td>
<td>1.5 lbs</td>
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</table>

*Assumes no redundancy
Polymer-multilayer capacitors

- **Game-changing energy storage density**
  - Roughly 90X capacitance density improvement (unpacked) over MIL-PRF-39022/12 devices (packaged)

- **Radiation tolerant** – (Confirmed by government agency)
  - Polypropylene capacitors are susceptible to radiation

- **Bias independent permittivity**
  - Bias-dependent permittivity is a problem for ceramics

- **Open failure mode**
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Focus of this work - Fission Surface Power (FSP)

Goal:
• Efficiently convert reactor-generated thermal energy into electricity
• Maximize specific power density (kW/kg)

Core concepts:
• Start smoothly after lunar landing and deployment
  – No operation during launch
• Incorporate redundancy at the system level
  – 8-12 parallel Stirling engines envisioned in concepts
  – Loss of 1-2 engines is acceptable while still meeting mission goals
• 10-year mission life
• Survive in the presence of elevated radiation
• Reduce complexity to minimize development risk
Pareto optimization of Stirling system

- Random processes used to develop a large number of candidate designs
  - Continuous variables: Alternator current/voltage, switching frequency
  - Discrete variables: Switches, inductor core, capacitor
- Mass and efficiency calculated based on linear equivalent circuit models
- Pareto plot formed showing trade space between efficiency and power density
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Proposed fission generation system architecture

- Two-stage approach envisioned
  - Stirling controllers operating in parallel followed by voltage boost stage in parallel

- Intermediate bus voltage is not fixed
  - Voltage will fluctuate based on current push from Stirling controller and constant current draw by voltage boost stage.
Controller front-end topology

- Totem-pole architecture combines rectification and voltage boost functionality.
- Three-level PWM accomplished with basic logic components.

*Disclosed in NASA NTR “Simplified Stirling Control Using Discontinuous Conduction Mode”, LEW-20262-1*
Boost control

- Boost converter operated in discontinuous conduction mode (DCM) with constant duty ratio acts as a constant impedance adjustable with duty ratio.

*Disclosed in NASA NTR “Simplified Stirling Control Using Discontinuous Conduction Mode”, LEW-20262-1*
Boost converter control

- DCM eliminates need for fast dynamic control
- Thermal changes in engine operation are slow
  - Only slow tuning of duty required

Conceptual controller

Functional control diagram
Boost converter control strategies

- Preliminary control implemented in analog ICs for easy conversion to flight-qualified components
- PCB design in process

Control implementation
Simulation of Stirling regulation

- Stirling loading proportional to duty ratio
  - Voltage inversely proportional to duty

Alternator RMS voltage decreases with increasing duty ratio.

Plot of filtered voltage at startup with 10% to 90% duty.

Control at steady-state with minimal dynamic performance requirement.
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Questions?