Optimization, Design, and Demonstration 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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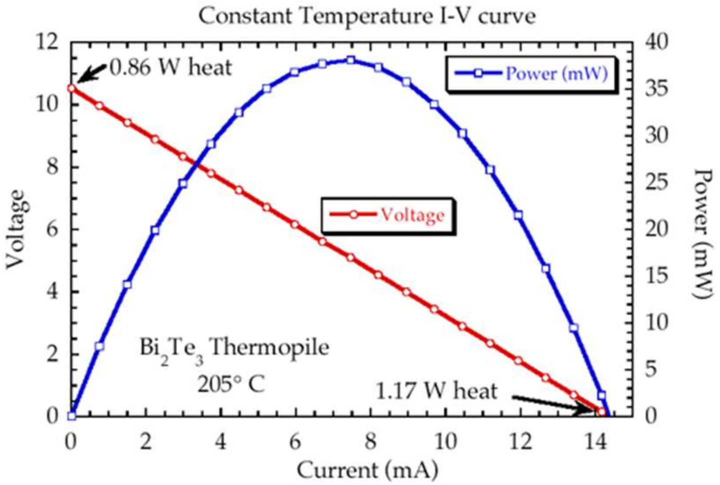
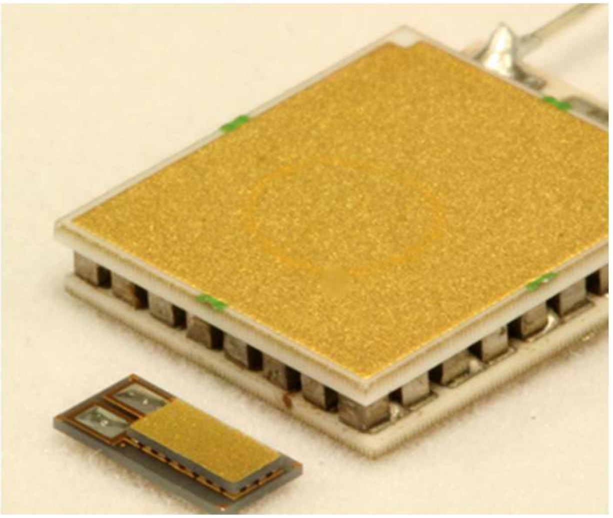
Thermoelectric control

Thermoelectric generator systems

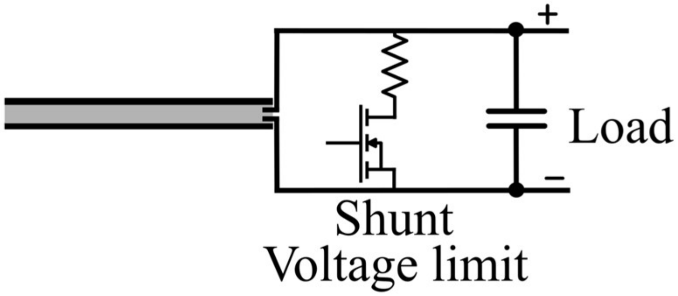
- ✓ Solid-state
- ✓ Simple control
- ✗ ~6% efficient



Thermoelectric linear current/voltage relationship[1]



Controlled with a simple shunt voltage limiter

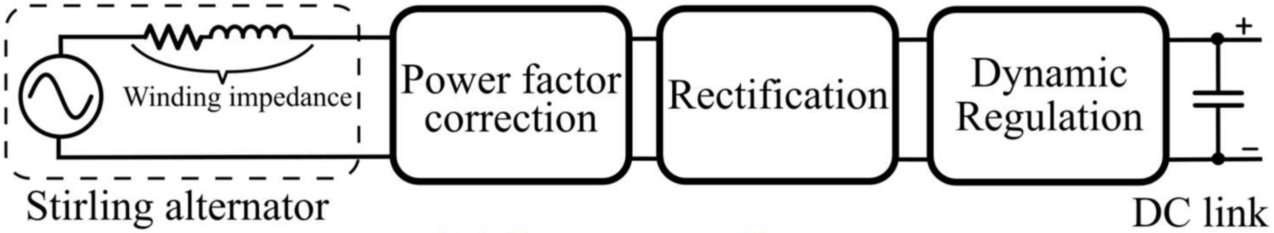


1) Northwestern Materials Science and Engineering

Stirling convertor control

Stirling Generator Systems

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



Stirling control stages

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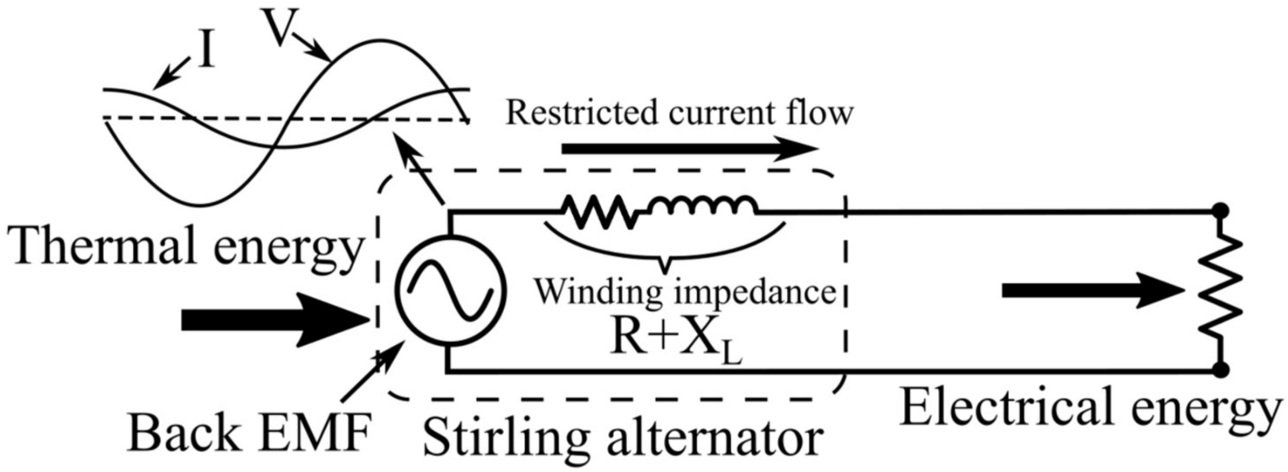
Stirling control – Energy balance

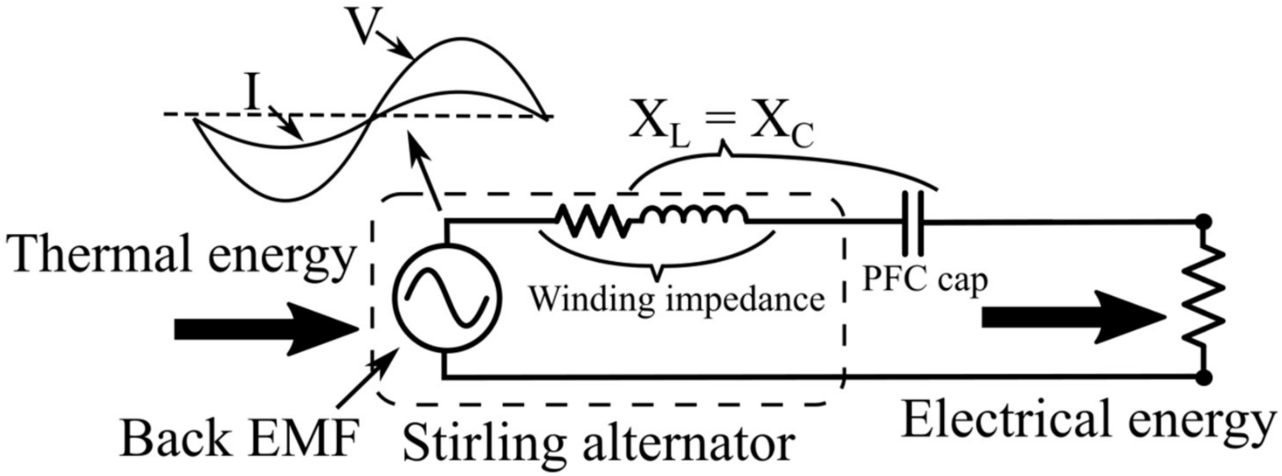
- Thermal energy flowing into engine is roughly constant
  - Thermal energy is constant on engine time scale for NASA radioisotope and fission systems
- Energy must be extracted to limit piston motion
- Stirling alternator inductance limits power flow from alternator*.
- Energy accumulation in the piston results in overstroke.



*New low-inductance alternator designs are also being explored in LET.

Stirling control – Power factor correction

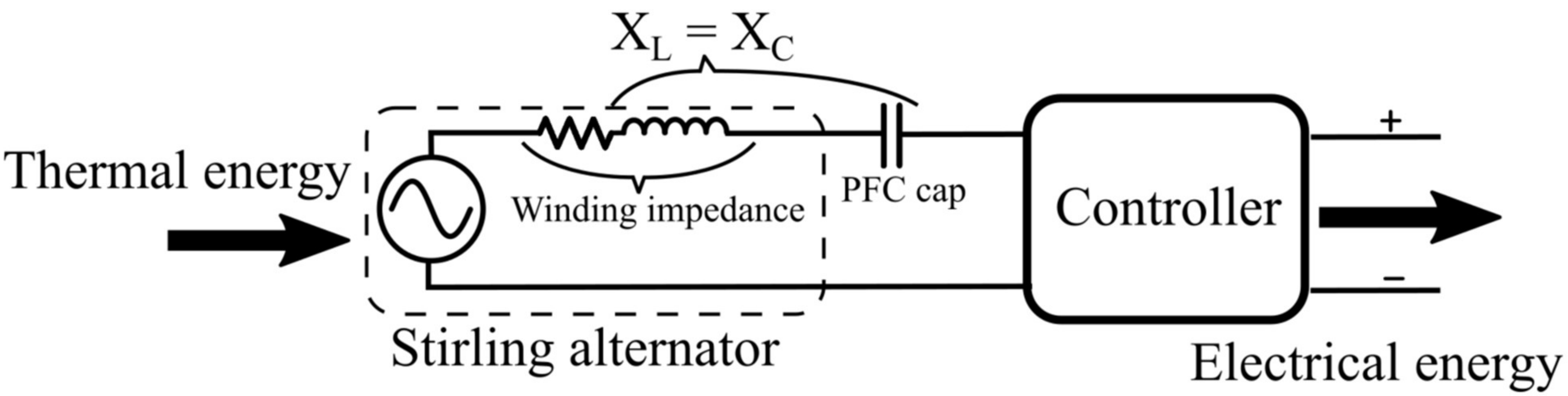
- Power factor correction (PFC) negates alternator impedance
  - Can be implemented using a capacitor



Energy balance facilitates stable operation

Stirling control – Load regulation

- 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



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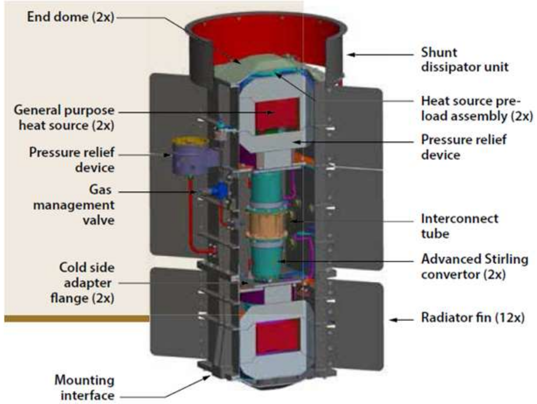
Dynamic Radioisotope Power Systems (DRPS)

Goal:

- Extract more electrical energy per unit of plutonium-238 than has been achieved using thermoelectric generation technology
- 110-130 watts of electrical power from 1 kg of fuel

Core concepts:

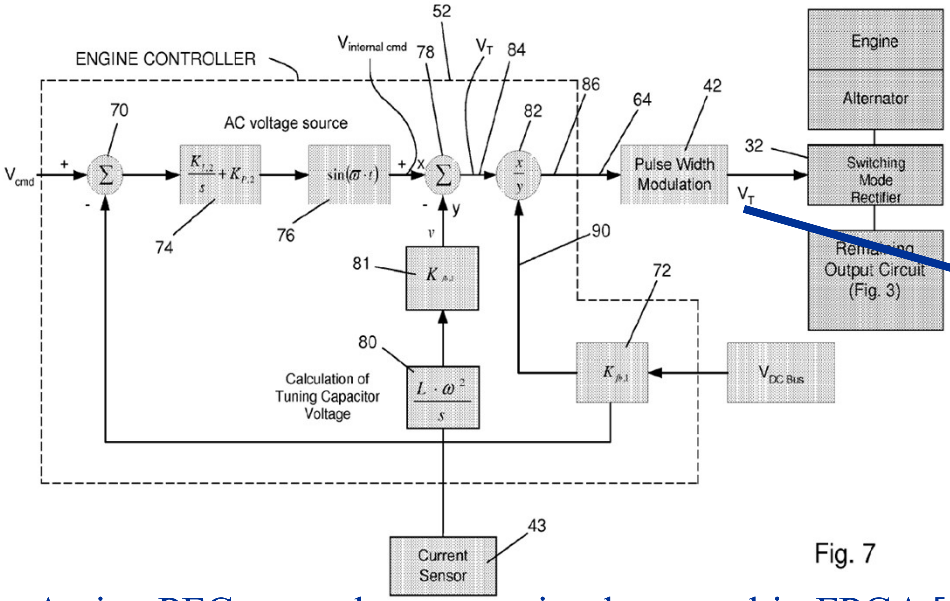
- Maintain stable Stirling operation during launch
- Incorporate redundancy in design
  - Loss of single engine would lead to mission failure
- 17-year mission life



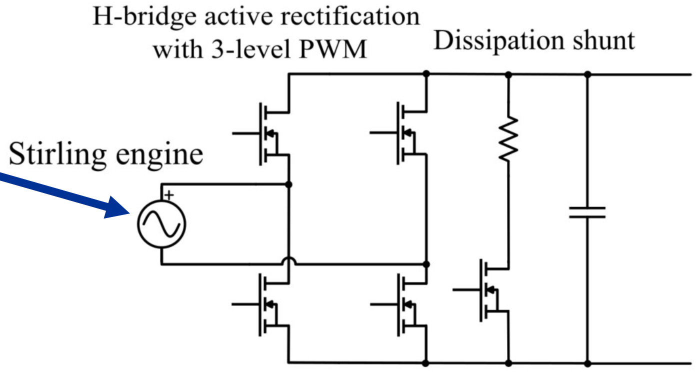
Advanced Stirling Radioisotope Generator

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



Active PFC control structure implemented in FPGA [1]

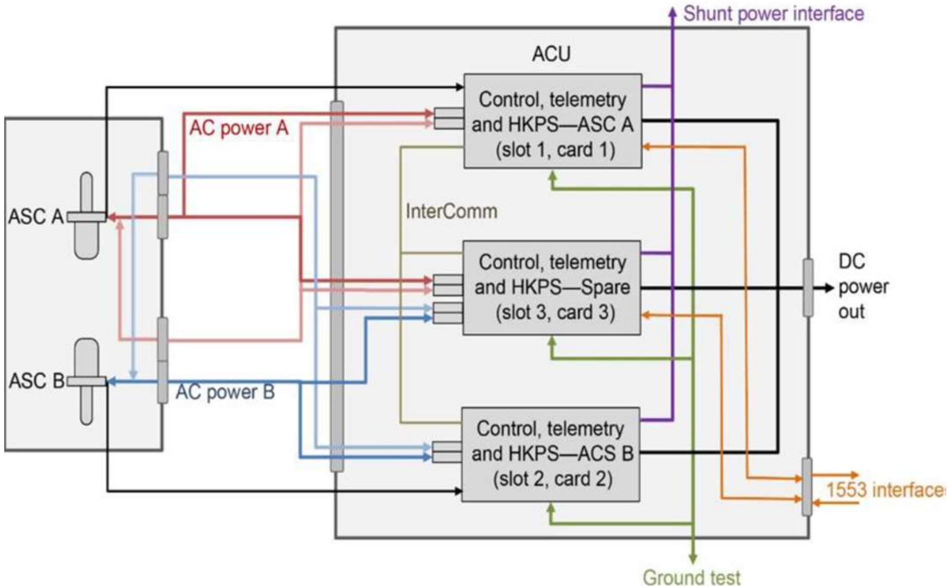


H-bridge structure for active PFC

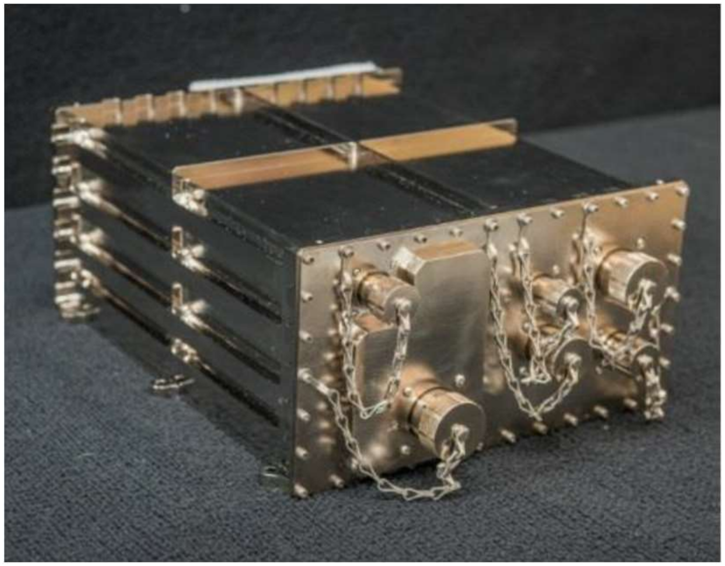
1) E.S. Holliday, "Controller computing a virtual tuning capacitor for controlling a free-piston Stirling engine driving a linear alternator," United States Patent 7,511,459, Mar. 31, 2009

ASC Control Unit (ACU)

- Specs:
  - Dual channel (2 Stirlings) 12 Vrms, 7 A, 80 W
  - Spacecraft dc bus was 28 Vdc
- Developed by Lockheed Martin
- Hardware is at “engineering model” level
- Not under active development (program ended in 2013)



ACU power path*

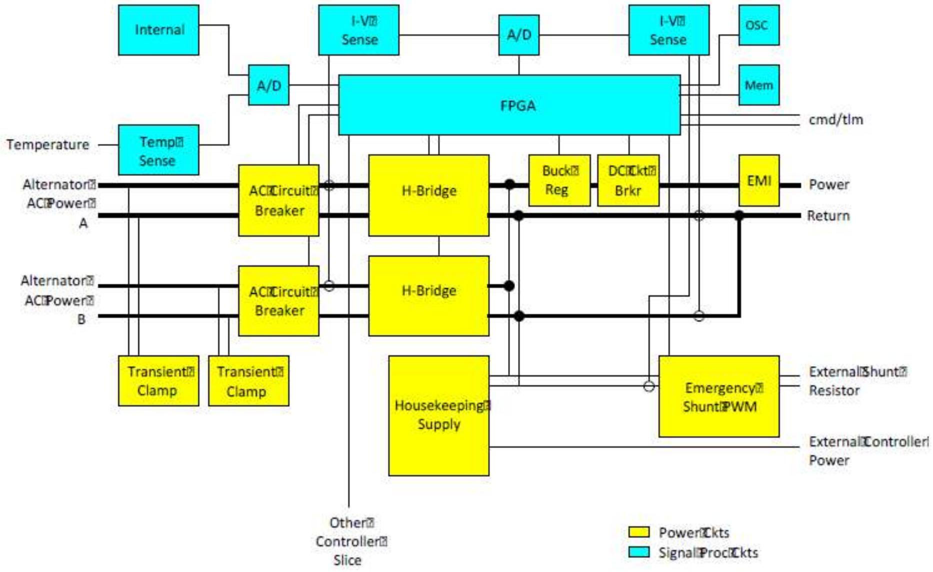


ACU controller unit

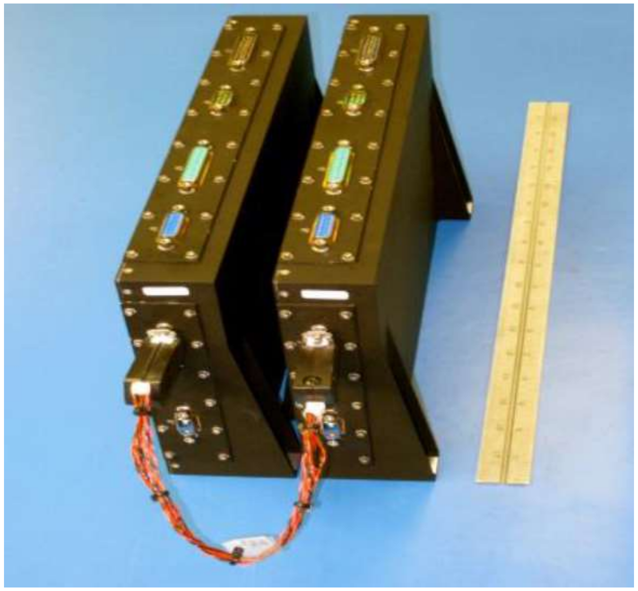
*Dugala et al., Advanced Stirling Convertor Control Unit Testing at NASA Glenn Research Center in the Radioisotope Power System Integration Laboratory

Dual Converter Controller (DCC)

- Specs:
  - Dual channel (2 Stirlings) 12 Vrms, 7 A, 80 W
  - Spacecraft dc bus was 28 Vdc
- Designed by APL with “path to flight” components
- Hardware is at “engineering model” development level
- Under active revision by team at APL for DRPS



DCC block diagram*



2 DCC controllers side by side

*Dugala et al., Advanced Stirling Convertor Control Unit Testing at NASA Glenn Research Center in the Radioisotope Power System Integration Laboratory

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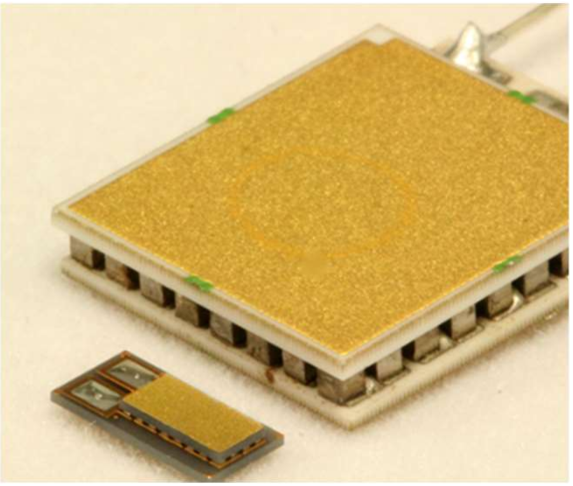
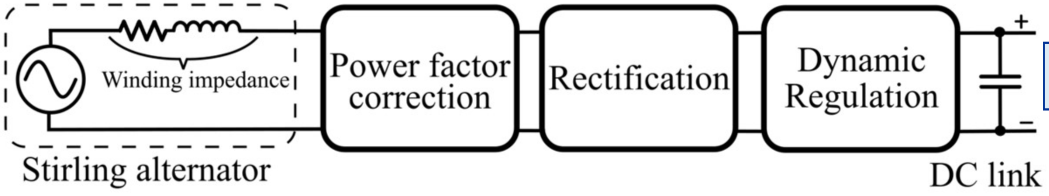
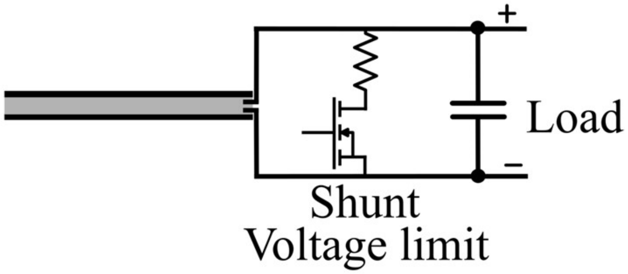
Objective – Provide reliable power

How can Stirling systems be simplified to reduce development risks?





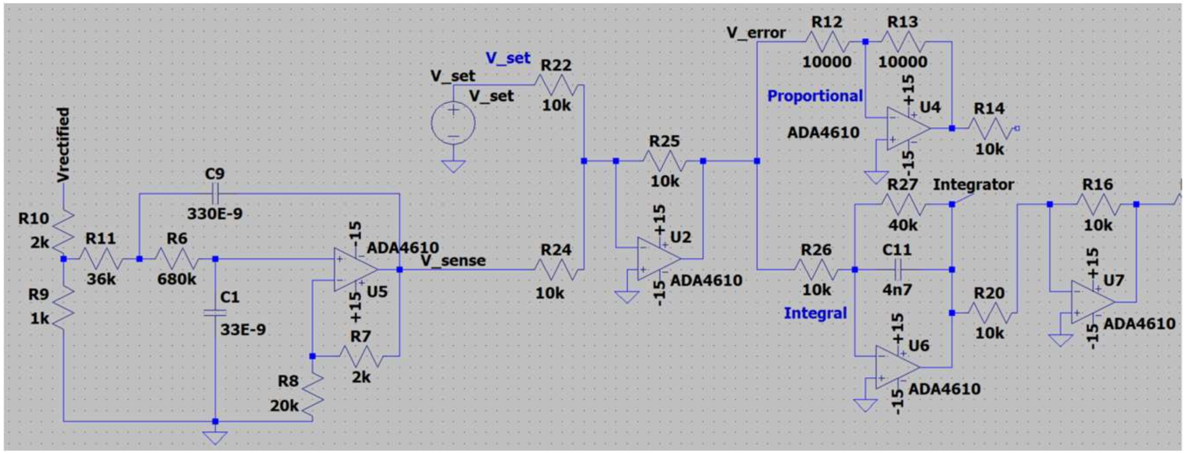


Analog Stirling control at GRC

- NASA Analog Controller
  - Designed by Michael Brace, GRC
  - Utilizes PFC capacitor and simple analog ICs for control
  - 80 W
- Cap-less NASA Analog Controller
  - Revision with additional analog functionality to eliminate capacitors
  - 80 W
- Mini-Stirling controller
  - Designed by Michael Casciani, GRC
  - For low-inductance miniStirling
  - 10 W

Motivation for analog control

- Analog circuits remove need for the firmware development and validation required for an FPGA
- Analog implementation offers potential for increased radiation tolerance
- Analog control limits functionality modifications during development. This can be problematic, but also limits “feature creep”



Analog control in LTspice

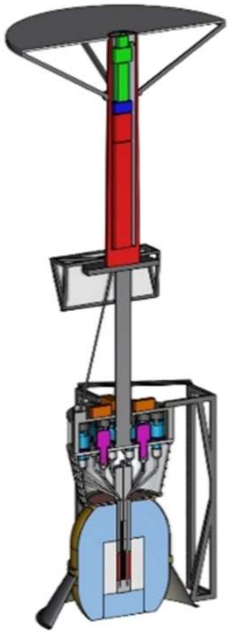
Focus of this work - Fission Surface Power (FSP)

Goal:

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

Core concepts:

- Start smoothly <u>after</u> lunar landing and deployment
- Incorporate redundancy at the <u>system</u> 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



Fission surface power concept

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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

Type	Property	ASC-E3	SRSC	FISC	P2A
	Converter Power	80 W	62 W	71 W	1100 W
	Convertor Voltage	20 Vrms	24 Vrms	60 Vrms	250 Vrms
Film capacitor (M83421/2 spec)	Capacitor Count	34	22	16	36
	Size*	64.2 in^3 (1.1L)	41.5 in^3 (0.68L)	30.2 in^3 (0.49L)	72 in^3 (1.2L)
	Component Weight*	1.42 lbs	0.92 lbs	0.67 lbs	1.5 lbs

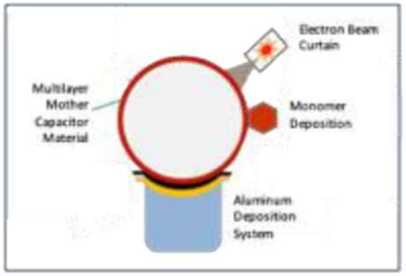
*Assumes no redundancy

Polymer-multilayer capacitors

- Game-changing energy storage density
  - Roughly 90X capacitance density improvement (unpackaged) over MIL-PRF-39022/12 devices (packaged)
- Radiation tolerant
  - Polypropylene capacitors are susceptible to radiation
- Bias independent permittivity
  - Bias-dependent permittivity is a problem for ceramics
- Open failure mode
- DC and AC devices under development

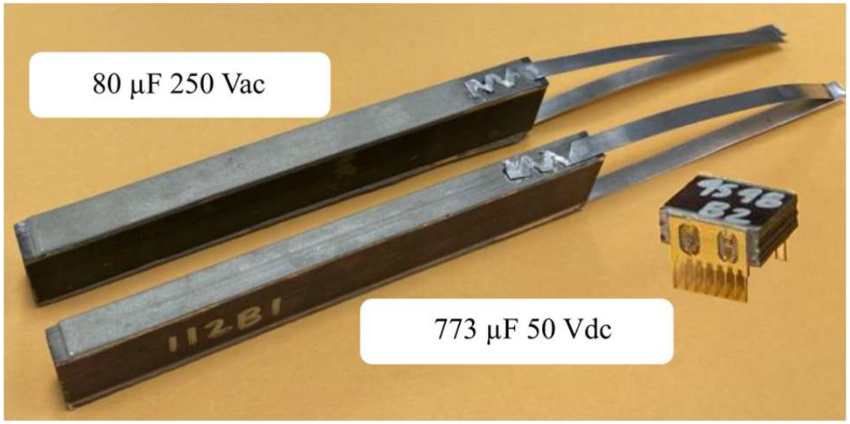
POLYCHARGE

Sigma Technologies

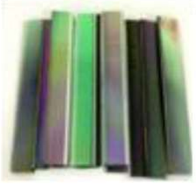


PML Capacitor Process Schematic

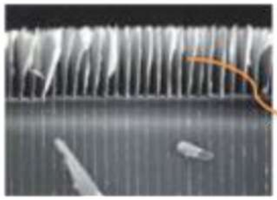
Segmented Mother Capacitor Material



Unencapsulated NanoLam capacitors



Individual Capacitor Elements



Aluminum Electrodes

Arc Sprayed Termination

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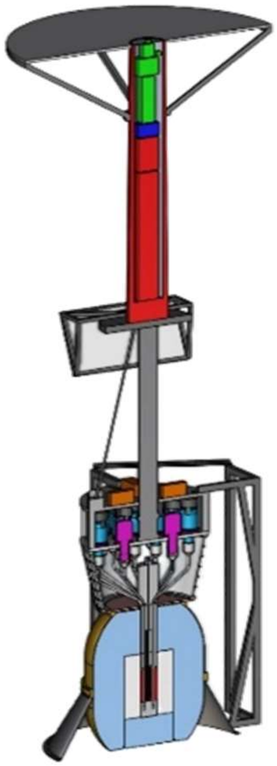
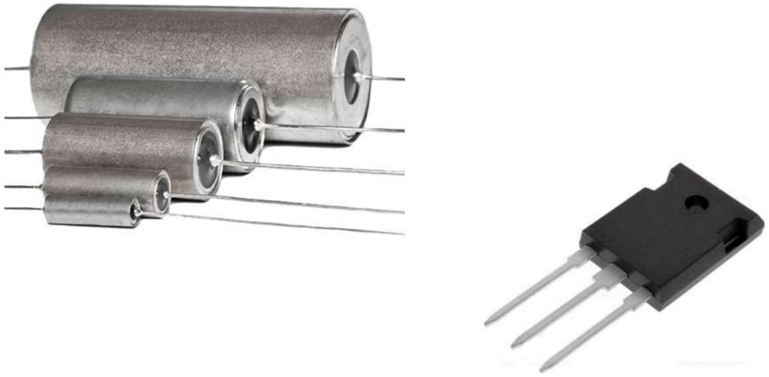
Project application

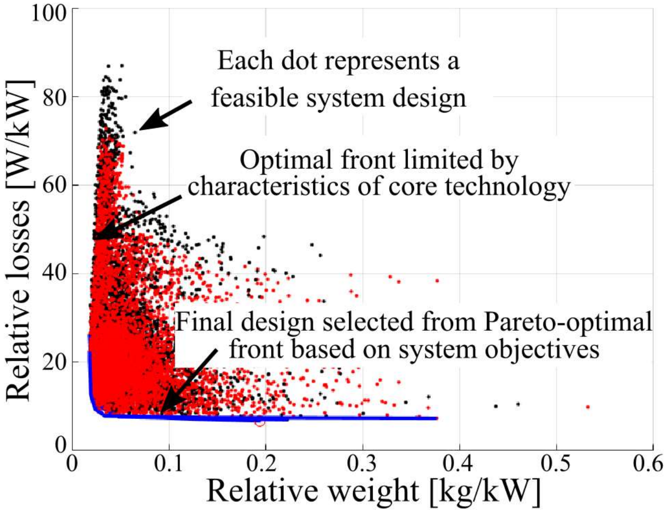
- Stirling controller tailored for the Fission Surface Power government reference design
  - Optimized for 1 kW, 240 V Stirling
  - Compatible with 10-12 Stirling array required for FSP system
- Goal: Simplicity with efficiency
  - Analog implementation
  - Technology used should have a clear path to flight
- Controlled operation under all conditions experienced by Fission Surface Power system
  - Startup, shutdown, throttled operation



Pareto optimization of Stirling system

- Combined optimization of alternator and controller
- Accounts for both continuous and discrete variables
  - Continuous variables
    - Alternator current/voltage, switching frequency
  - Discrete variables:
    - Switches, inductor core, capacitor
- Based on linear equivalent circuit models
  - Objective functions for mass and efficiency





Example of Pareto optimization

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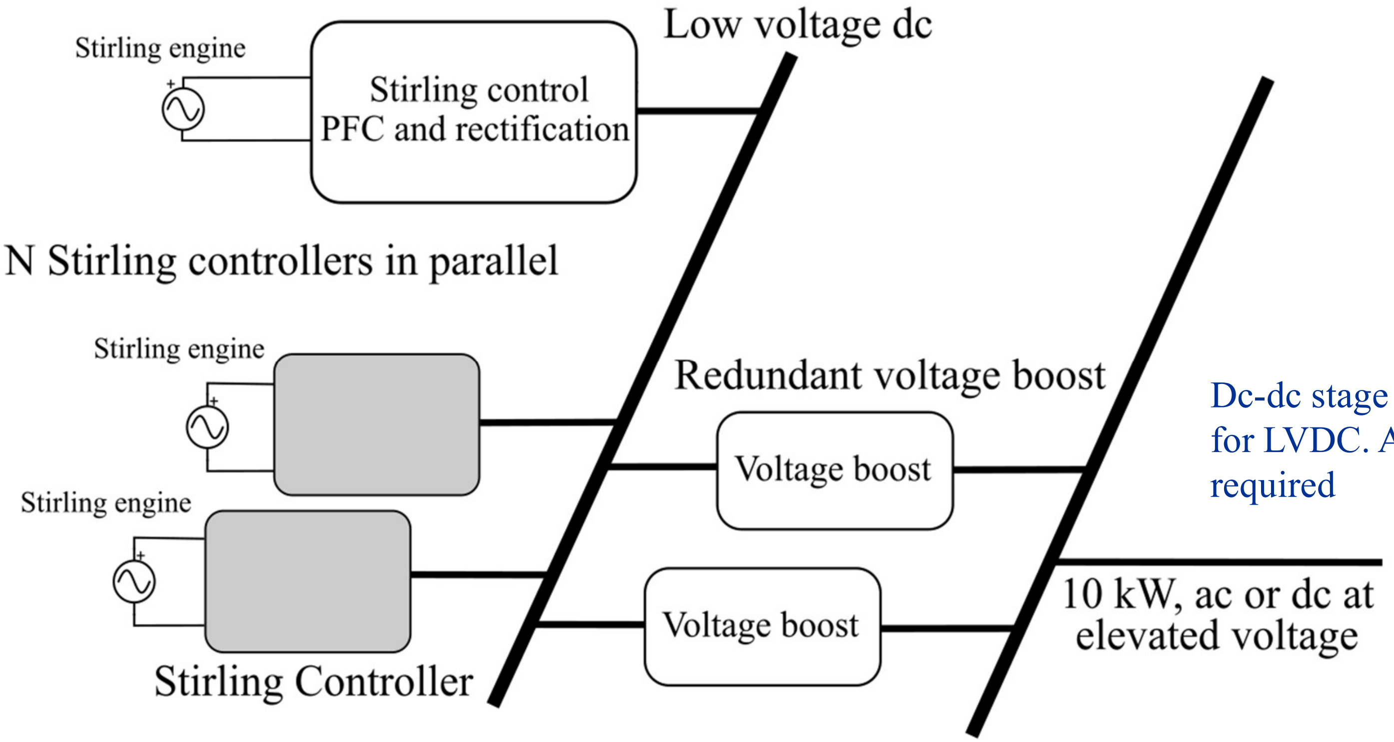
Proposed fission generation system architecture

- Complexity of high-voltage boost motivates a 2-stage approach
  - 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. Minimizes required twice-line-frequency filtering capacitance



Stirling engine

Stirling control PFC and rectification

Low voltage dc

N Stirling controllers in parallel

Stirling engine

Stirling engine

Stirling Controller

Redundant voltage boost

Voltage boost

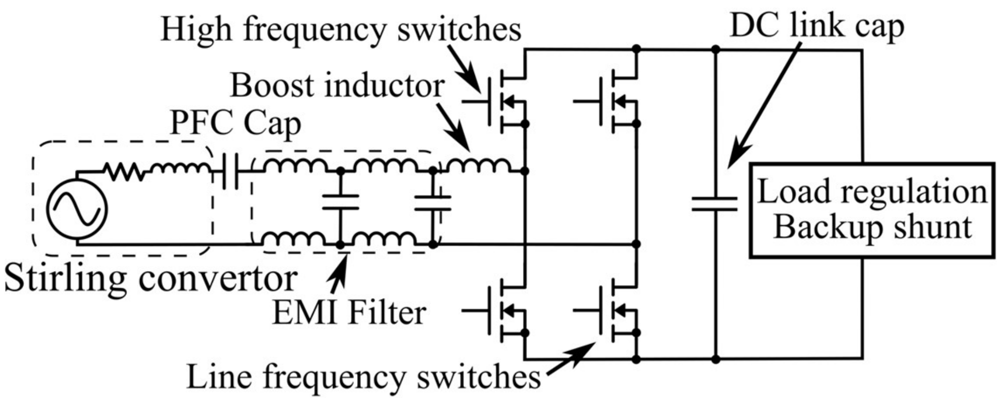
Voltage boost

10 kW, ac or dc at elevated voltage

Dc-dc stage may not be needed for LVDC. Additional evaluation required

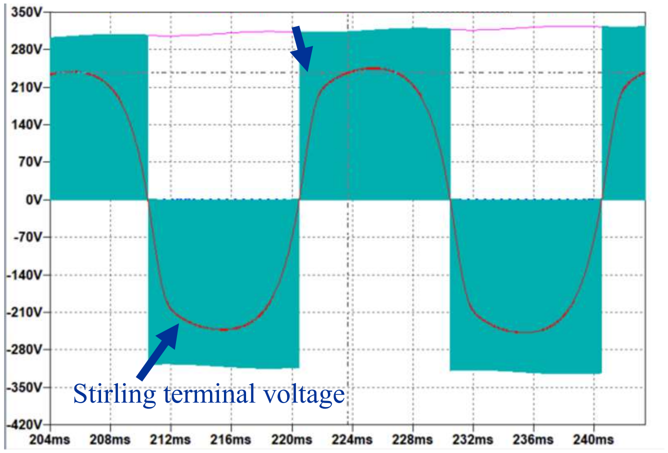
Controller front-end topology

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



Stirling controller front-end

PWM boost inductor voltage



Stirling terminal voltage

Stirling controller front-end

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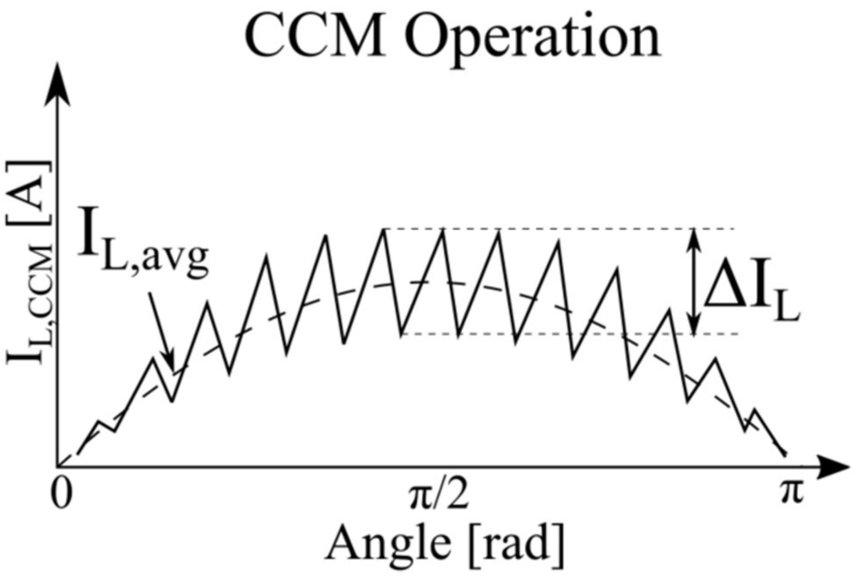
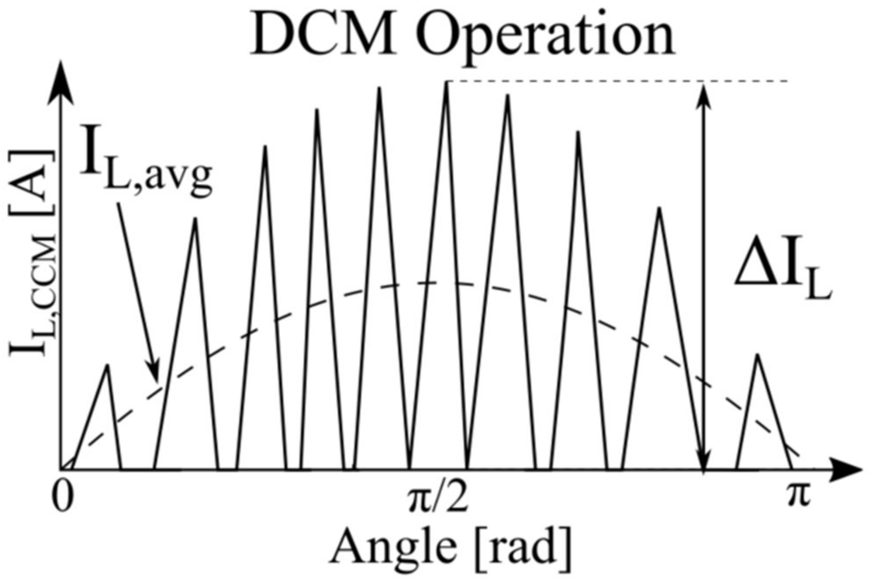
*Disclosed in NASA NTR “Simplified Stirling Control Using Discontinuous Conduction Mode”, LEW-20262-1

Boost control

- Efficiency of a well-designed DCM boost can be comparable to continuous conduction mode (CCM)*
- Boost converter operated in discontinuous conduction mode (DCM) with constant duty ratio acts as a constant impedance adjustable with duty ratio
- Input impedance of the controller matched to rated load impedance of the Stirling





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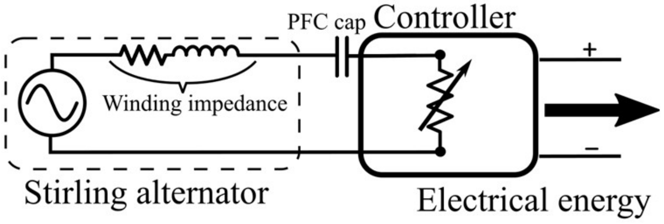
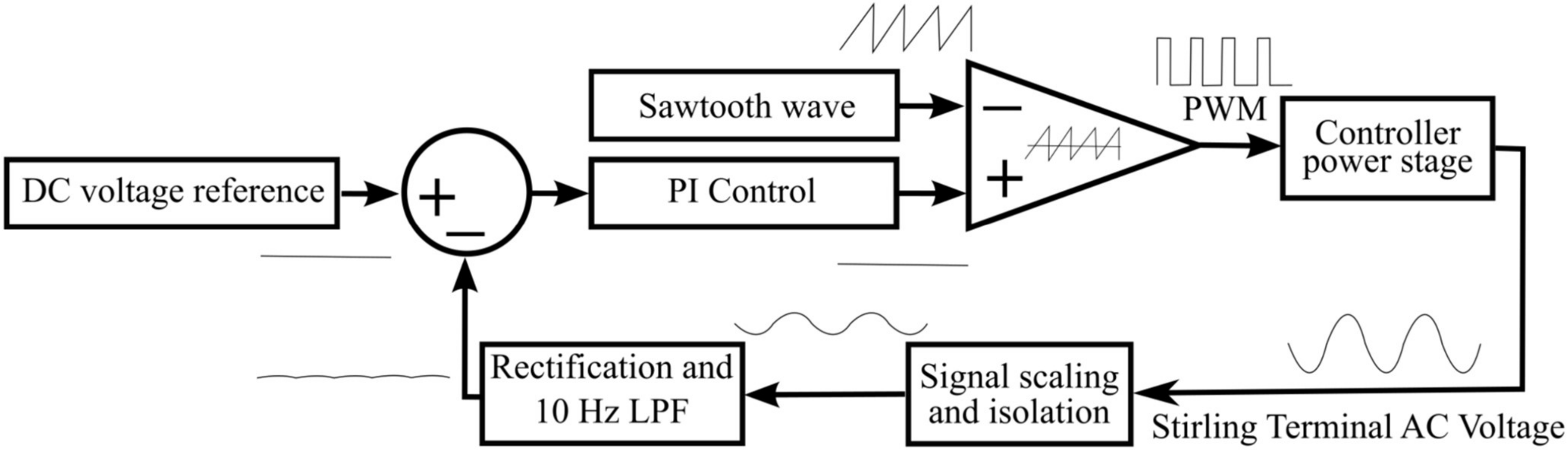
Boost converter control

- Thermal changes in engine operation are slow
  - Dynamic adjustment is not required
  - Only slow tuning of impedance required
- Opportunity to apply average control
  - Previously used for parallel electric inverters



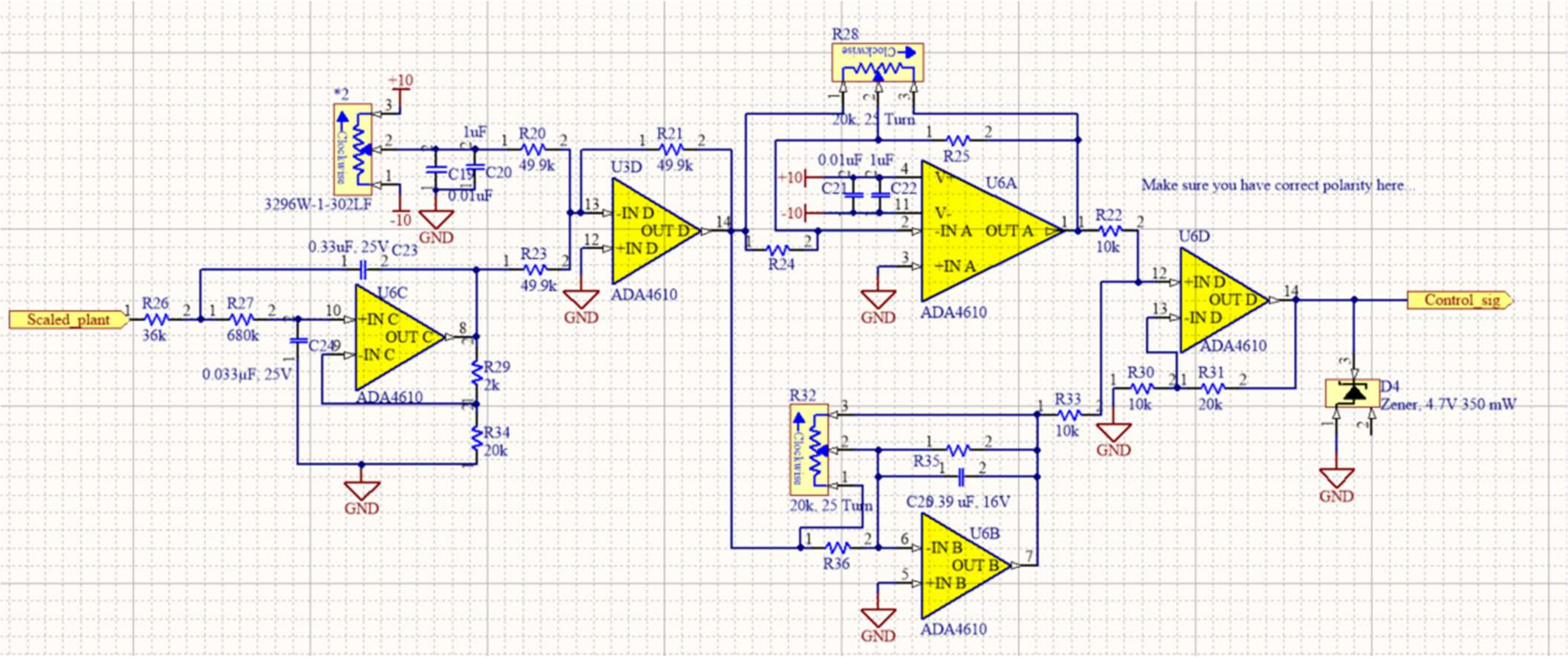
Conceptual controller



Functional control diagram

Boost converter control strategies

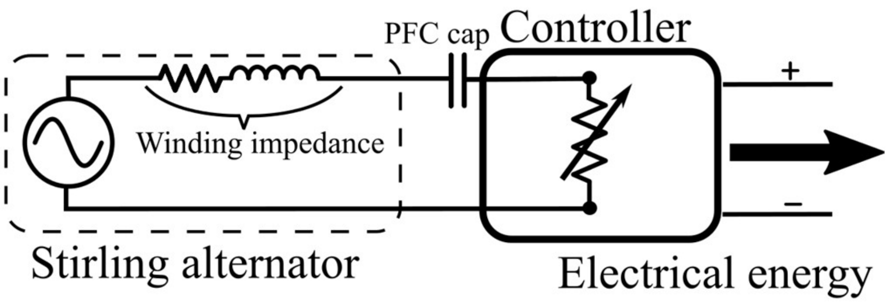
- Preliminary control implemented in analog ICs for easy conversion to flight-qualified components



Control implementation

Boost converter control strategies

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



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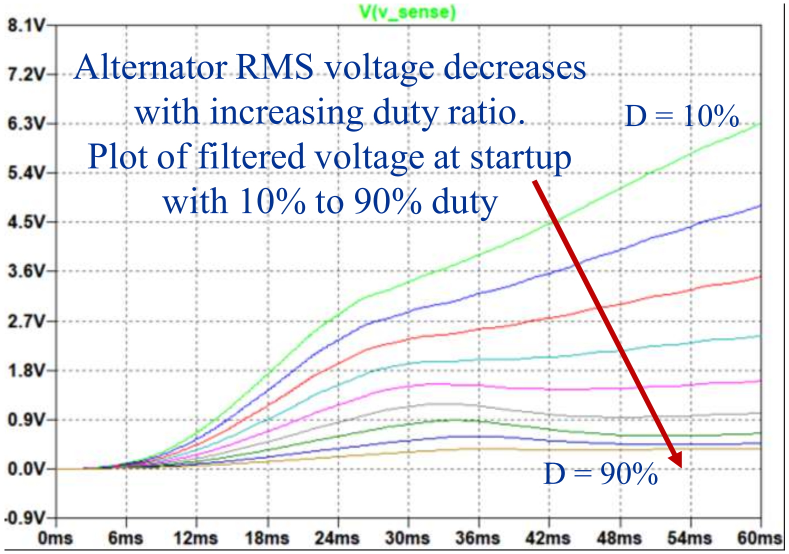
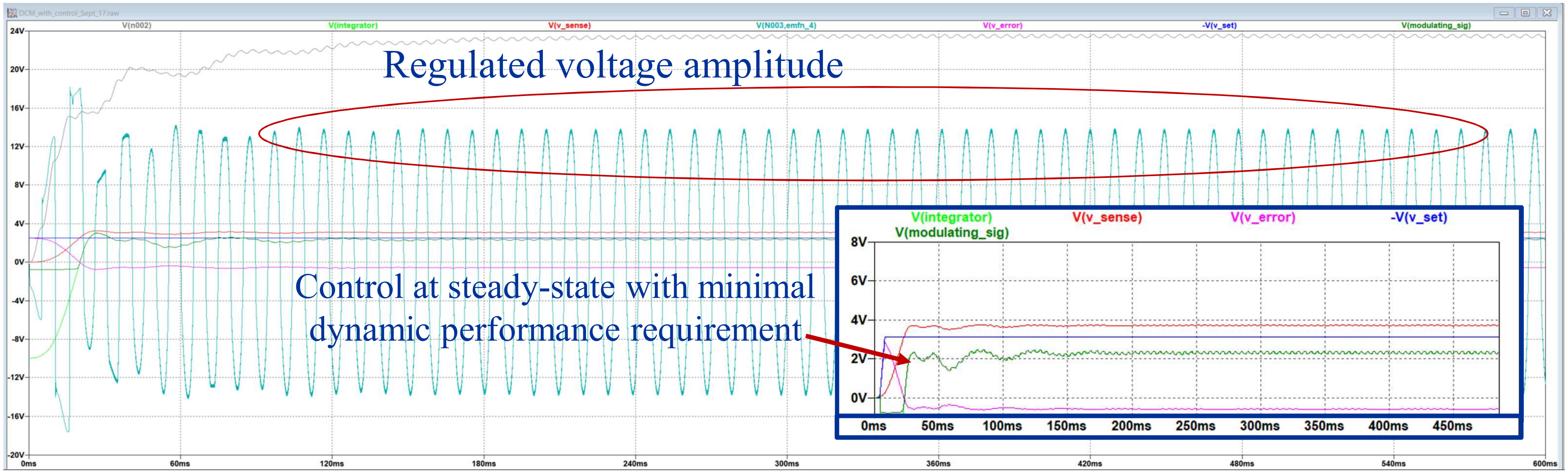


Alternator RMS voltage decreases with increasing duty ratio. Plot of filtered voltage at startup with 10% to 90% duty



Regulated voltage amplitude

Control at steady-state with minimal dynamic performance requirement

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Questions?