Progress in Control Implementation and Power Transmission for Stirling-based Power Conversion Systems

Christopher B. Barth, Ph.D.[1], Donguk Max Yang, Ph.D.[1], David C. Pike[1], Michael R. Casciani[2], Brian J. Tomko[1], Nicholas A. Schifer[1], Pablo Paramio Valdés[3]

[1]NASA Glenn Research Center, 21000 Brookpark Dr., Cleveland, OH, 44135
[2]HX-5, 3000 Aerospace Parkway, Brook Park, OH 44142
[3]ICAI School of Engineering, C. de Alberto Aguilera 25, 28015 Madrid, Spain

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Outline

- Application Overview
- Stirling Control
- NASA Controller Implementations
  - Analog vs Digital Control
  - Core Technology
  - 80 W Class Controller Results
- Power Transmission
- Stirling Convertor Hardware Safety and Support
- Stirling Simulators for Development and Testing

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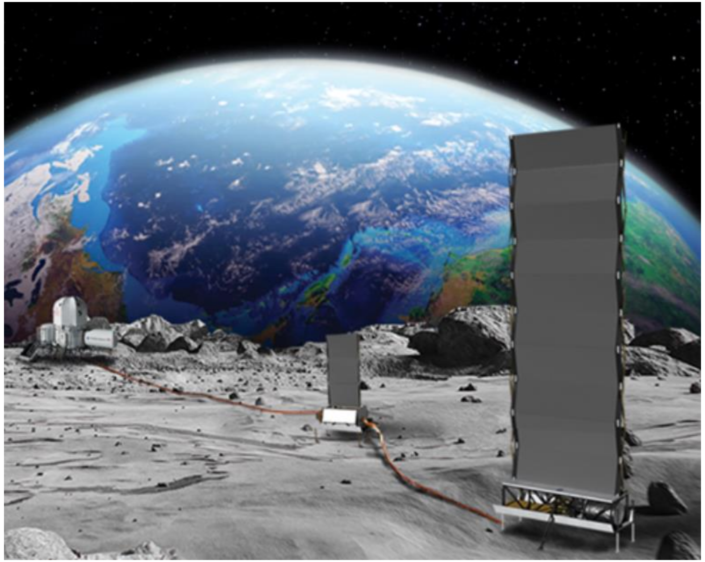
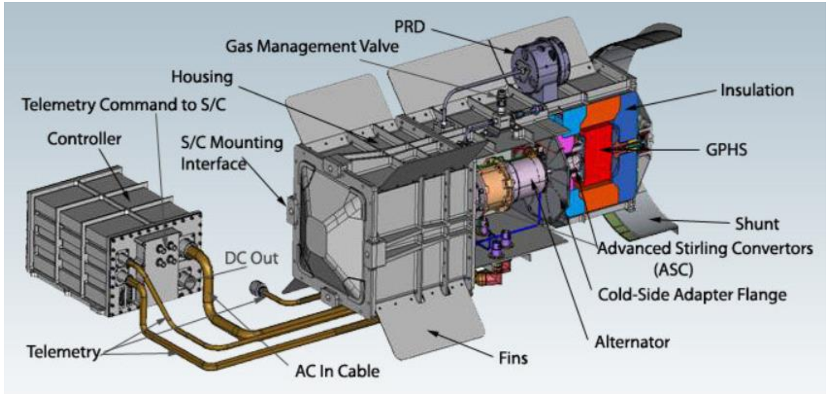
Application Overview

- Fission Surface Power is expected to be deployed in the 10-40 kWe range
- Stirling controllers are required for all Stirling-based microgrid (Radioisotope power systems, low power fission NEP, mobile terrestrial applications, etc.)



Fission Surface Power (10's of kW)



Plutonium-238 Fueled Radioisotope Powered system (100's of W)

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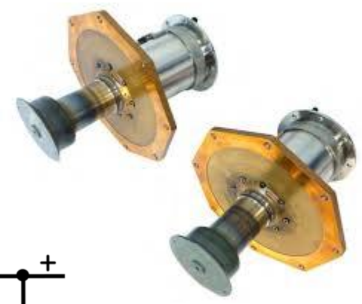
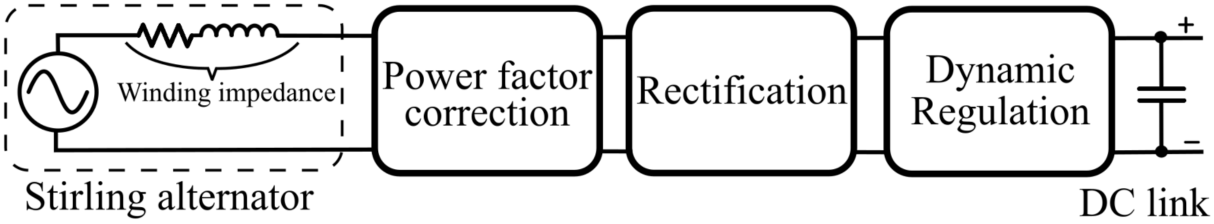
Stirling Control

- Stirling generator systems require regulation and control

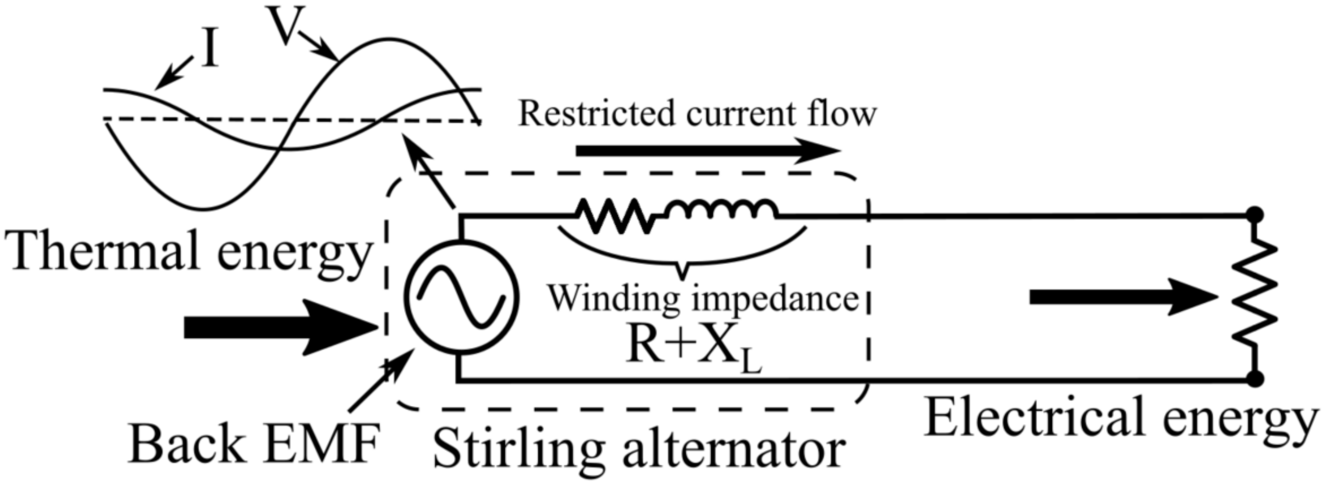




Stirling controller functional elements

Stirling control – Energy balance

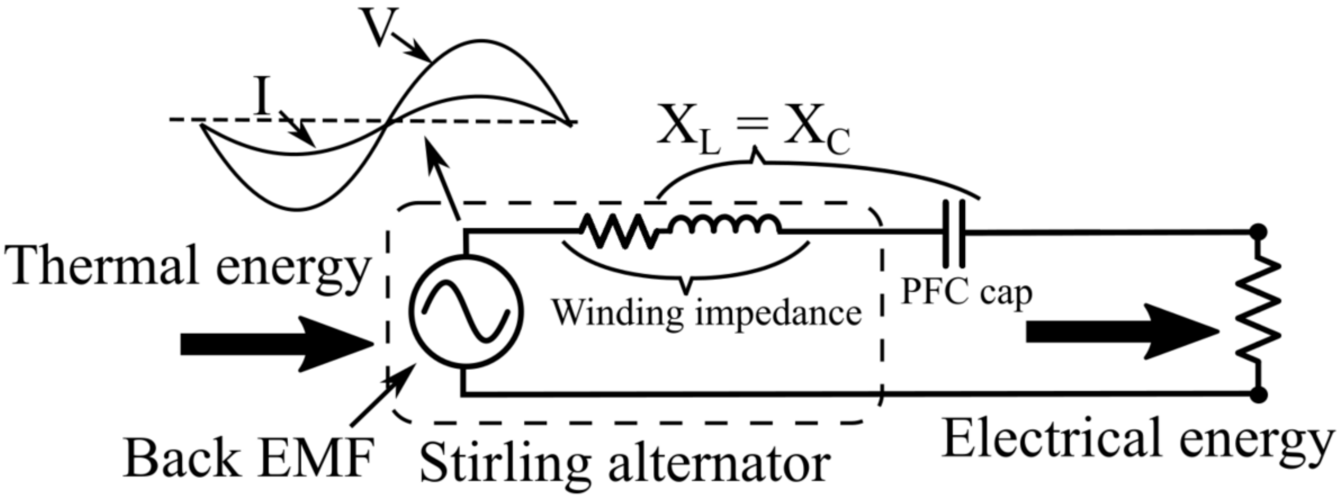
- Thermal energy flowing into Stirling is constant (at engine timescale)
  - Radioisotope or fission thermal power
- Energy must be extracted to limit piston motion
- Stirling alternator inductance limits power flow from alternator*.
- Energy accumulation in the piston results in overstroke.



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

Stirling control – Power factor correction

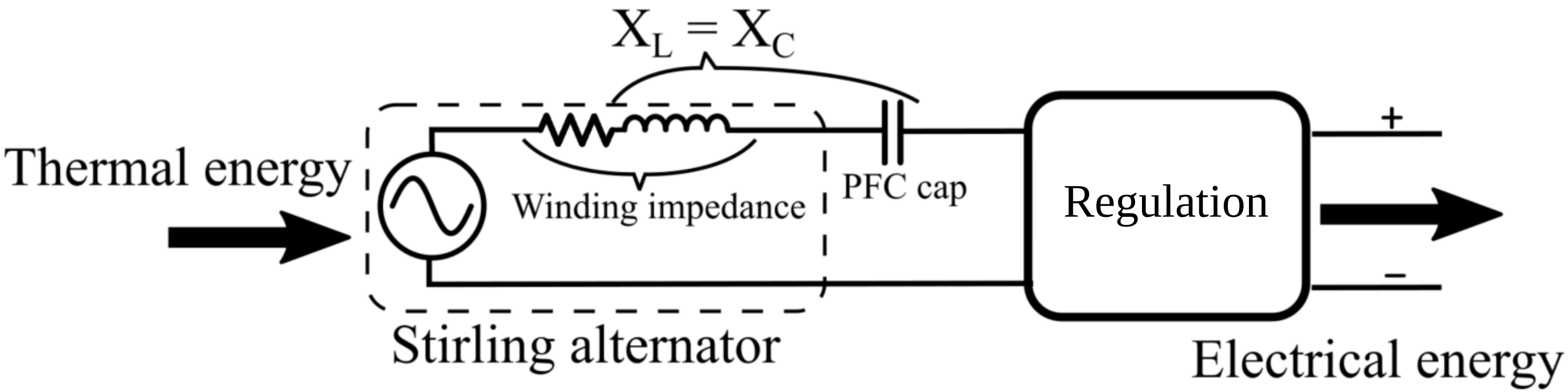
- Power factor correction (PFC) negates alternator impedance
  - Can be implemented using a capacitor or active control
  - NOTE: Stirling controller operation is more than an active rectifier



Energy balance facilitates stable operation

Stirling control – Load regulation

- A shunt/regulation stage is required to transfer energy to the user
- Load on Stirling must be consistent despite changing user load



Regulation stage accommodates changing user load while presenting constant load to Stirling

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NASA Controller Implementations

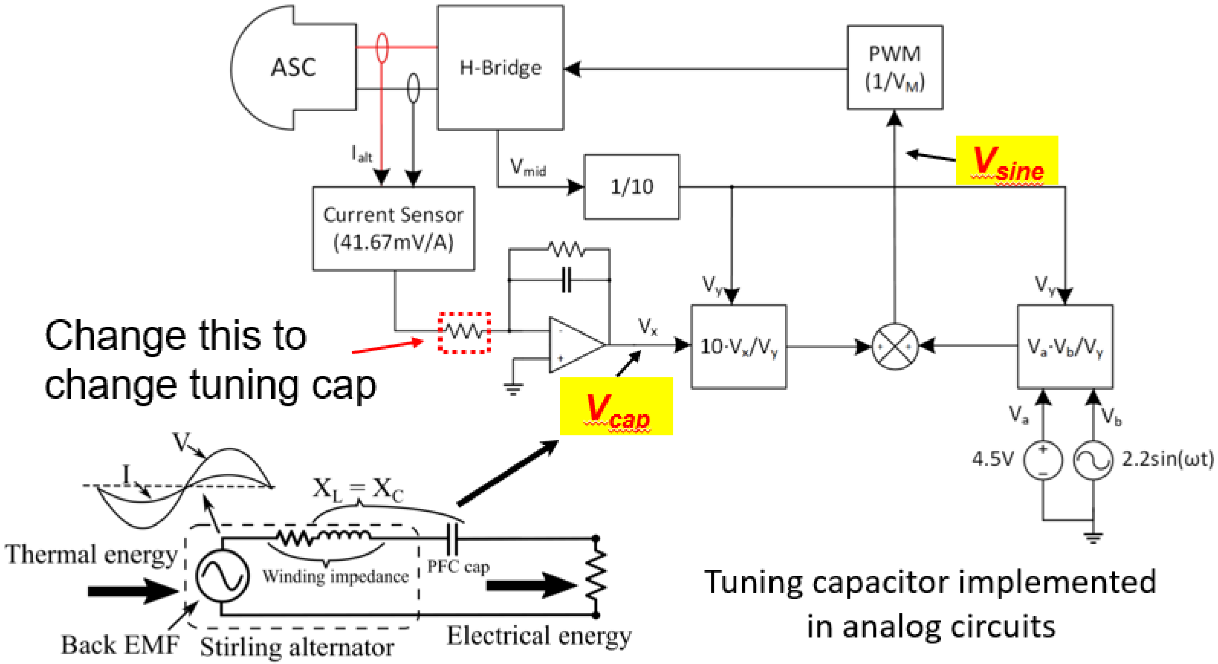
- <u>Objective:</u>
  - Demonstrate suite of Stirling controller and power transmission hardware using leading-edge core technology
- <u>Purpose:</u>
  - Validate and document simplified control strategy on high-efficiency hardware;
  - Set benchmark/standard for industry flight hardware on conversion efficiency and limited complexity;
  - Develop functional IP which is available for license
  - Reduce risk of project cost overruns
- <u>TRL Advancement:</u>
  - 3-4 with defined path for flight using radiation-hardened components
- <u>Funding:</u>
  - Fission Surface Power project (NASA Space Technology Mission Directorate)
  - Radioisotope Power Systems Program (NASA Planetary Science Division)
  - Additional sources of government and industry collaboration

NASA Analog and Digital Controller Implementations

- Both analog and digital strategies being developed in parallel

- Analog design offers high radiation tolerance (Potentially up to 1 Mrad TID), simplified verification and documentation, simplified IP transfer, and potential for implementation in ASIC technology

- Digital design offers ease of implementation and adaptation between missions



Tuning capacitor implemented in analog circuits

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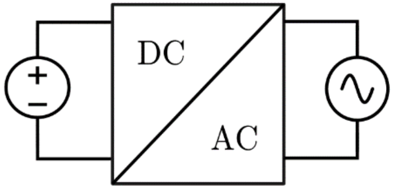
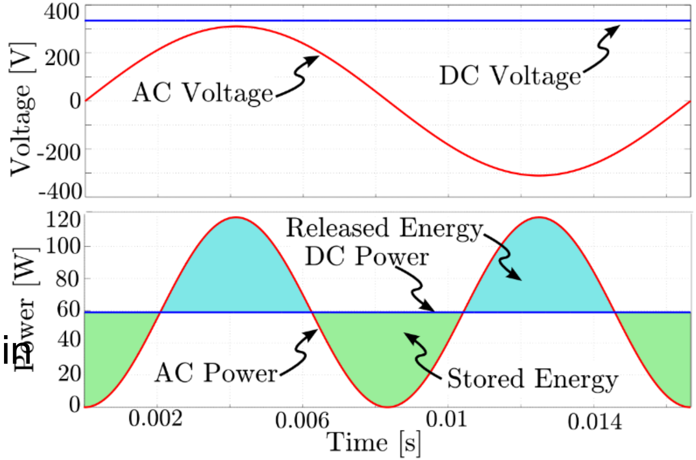
Controller Core Technology – Buffering Capacitors

- Capacitive energy buffering required for AC-DC conversion
  - $\overline{P_{DC}} = \overline{P_{AC}}$, but $p_{dc} \neq p_{ac}$
  - $E_{store} = \frac{P_{dc}}{2\pi f_{line}}$
- The energy stored in a capacitor is a function of voltage ripple
  - $E_{store} = \frac{P_{dc}}{2\pi f_{line}} = \frac{1}{2} C {V_{max}}^2 - \frac{1}{2} C {V_{min}}^2$

$$= C * V_{avg} * \Delta V$$

- <u>Small</u> ripple requires a <u>large</u> capacitance
- <u>**8L+**</u> of flight film capacitors for 10 kW Stirling system
- Commonly used ceramic capacitors are fragile and bias dependent
- Some flight implementations use 100's of ceramic capacitors in parallel.



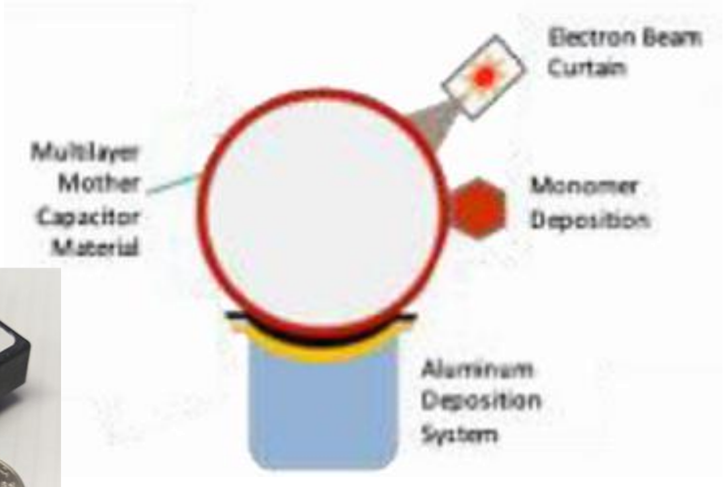


A better solution is needed!

Controller Core Technology – Buffering Capacitors

- Polymer Multilayer Capacitors
  - Comparable energy density to ceramics lower dissipation factor and zero bias dependence or piezoelectric effect
  - Roughly 50X density improvement over MIL-PRF-39022/12 devices
  - Radiation tolerant (Polypropylene capacitors are susceptible to radiation)
  - Self-healing, fail open, low ESL, low ESR
  - Stable capacitance from -196^{o}C to 200^{o}C
- Completed NASA defined "Acceptance Testing"
- Preliminary testing completed at NASA Goddard [1]
  - Gamma radiation
  - Moisture
  - Highly Accelerated Life Testing (HALT)
  - AC Characteristics
  - Calculation of reliability acceleration factors
  - Additional testing in process

Sigma Technologies

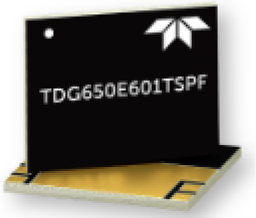


PML Capacitor Process Schematic

[1] Teverovsky, Alexander A. "Evaluation of Elements used for Manufacturing of NanoLam Metallized Polymer Film Capacitors." (2023).

Implementation Core Technology – GaN E-HEMT

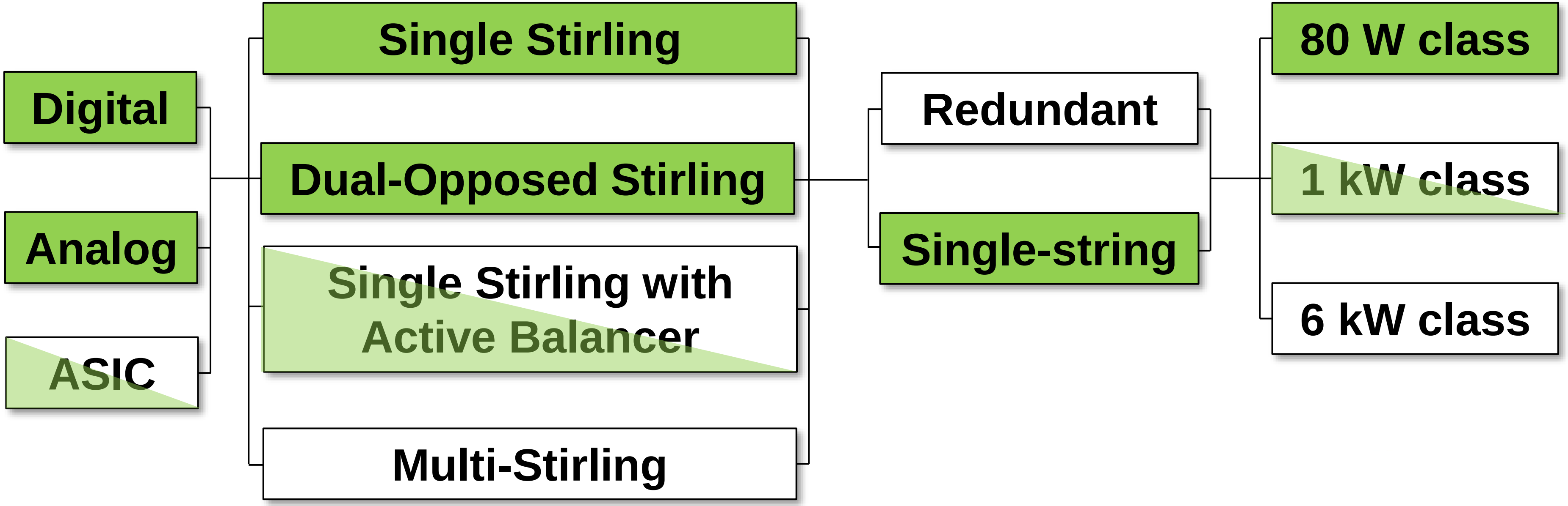
- Stirling controllers implemented with GaN Enhancement-Mode High Electron Mobility Transistors (E-HEMTs)
- Single event effect (SEE) susceptibility has limited voltages in NASA missions [1]
  - Radiation hardened Si MOSFETS lag commercial devices by an order of magnitude
  - Wide-bandgap SiC MOSFETs have proven extremely susceptible to Single Event Effects
- High-power missions with power transmission require elevated voltage to reduce conduction losses and system mass
- Recent testing by NASA has raised confidence in operating GaN E-HEMTs in the space environment [1,2]



[1] Boomer K, Scheick L, Hammoud A. Body of knowledge for Gallium Nitride power electronics. NASA Electronic Parts and Packaging (NEPP) Program Website. 2020 Oct 2.
[2] Contact: Jason Osheroff (jason.m.osheroff@nasa.gov), Ansel Barchowsky (ansel.barchowsky@jpl.nasa.gov)

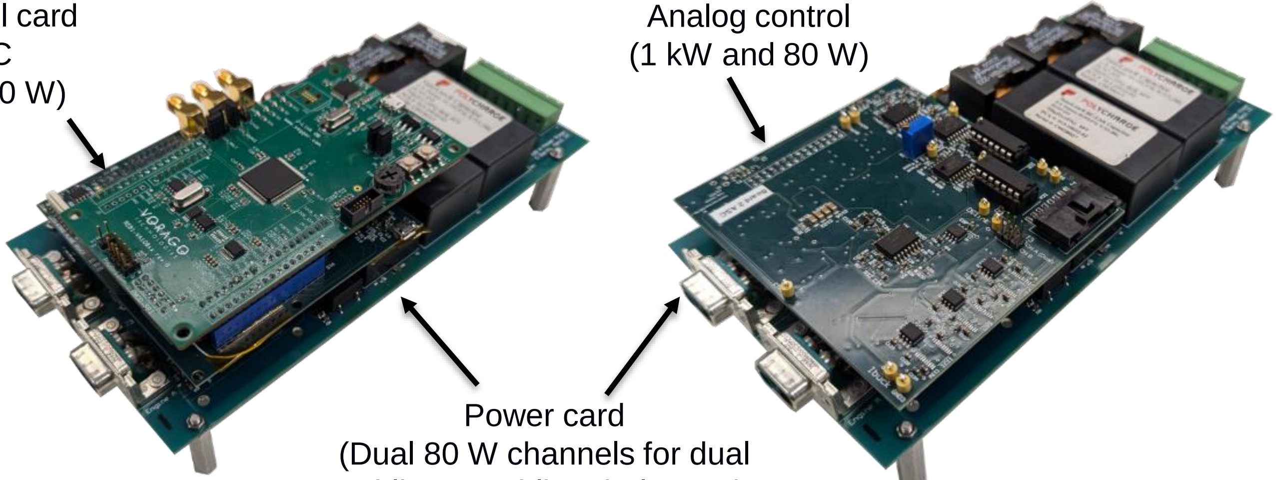
NASA Controller Taxonomy

- Controller building block designs being developed
- Functionality can be mixed and matched to meet application
- Green blocks have undergone initial demonstration



Controller Hardware

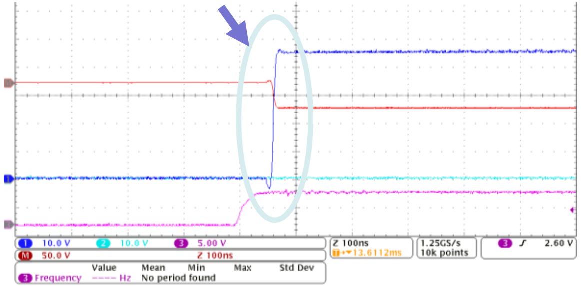
- Breadboard controller designed with interchangeable power and control cards
  - Digital control card: VA10805 Arm Cortex M0 from VORAGO with separate 16-bit ADC
  - Analog control card: COTS OP-amps, comparators, dividers, etc
- Design licensing available to industry via government use license



Controller Hardware

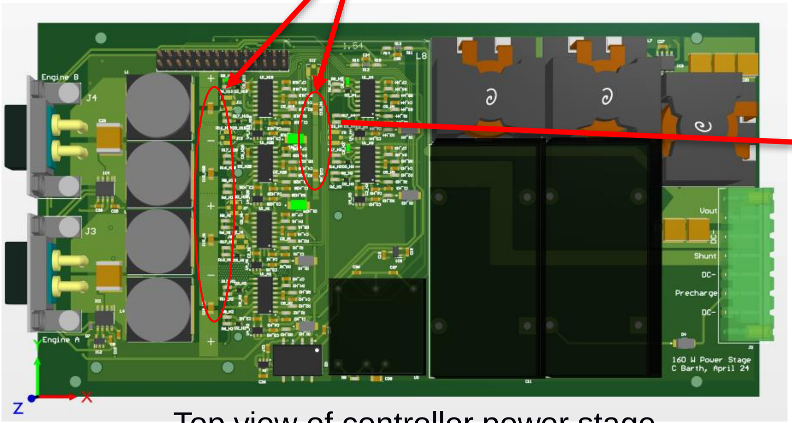
- Careful layout facilitates high switch transition speed with minimal ringing

Blue voltage trace shows voltage across switch turn rise as switch turns off

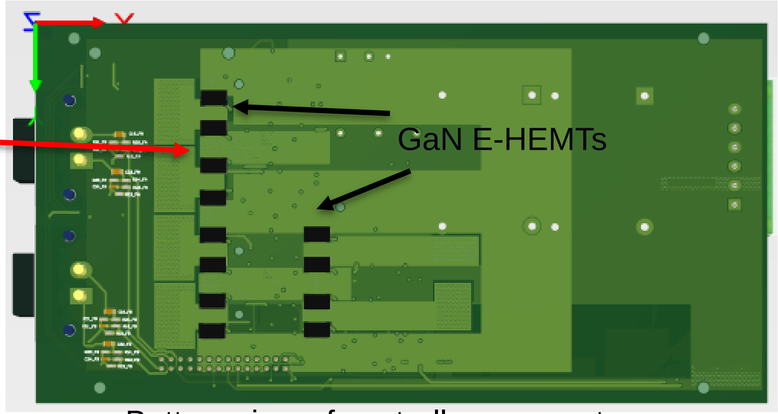


Optimized circuit layout minimizes parasitic inductances and virtually eliminates ringing at switch transitions

Decoupling capacitors directly across half-bridge pairs to negate switching loop inductance



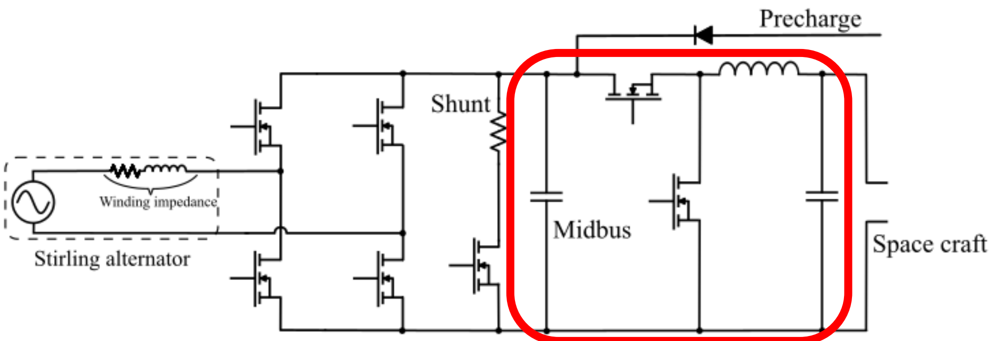
Top view of controller power stage



Bottom view of controller power stage

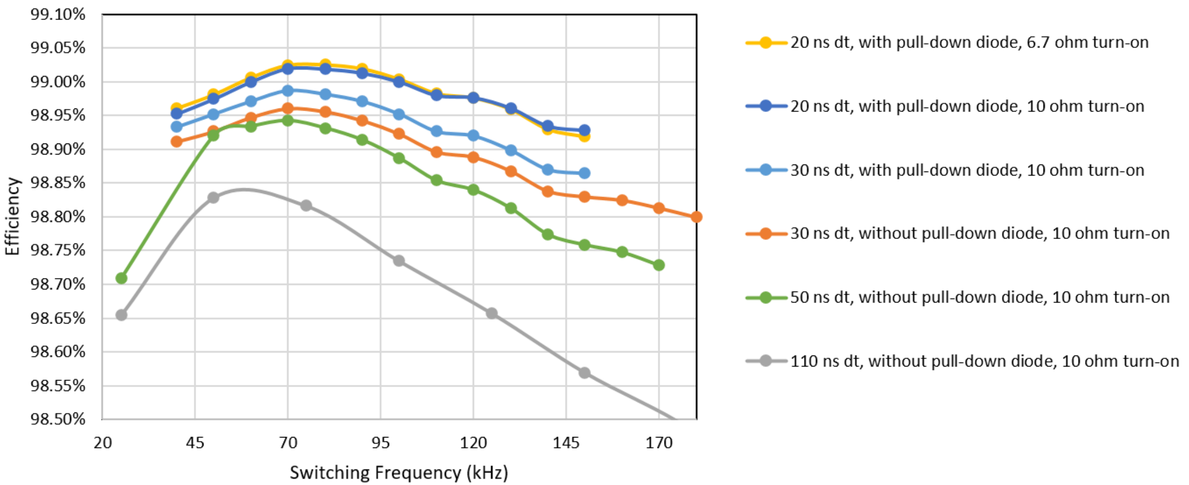
Controller Hardware

- Output regulator efficiency refined experimentally



Schematic of Stirling controller power path

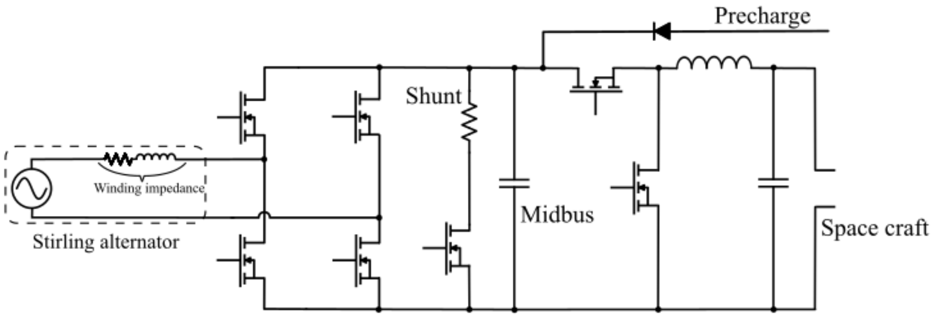
Regulator stage



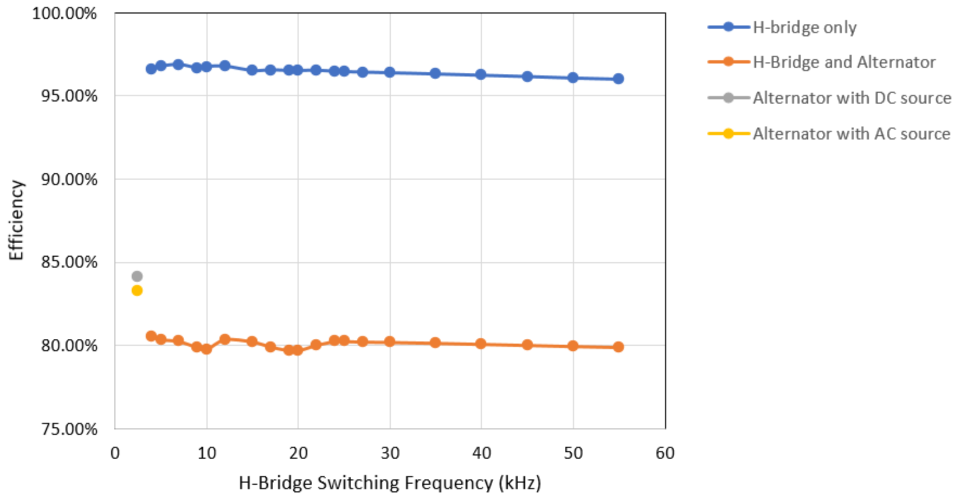
Optimization of buck regulation stage

Controller Hardware

- H-bridge EMI filtering requirements are set by mission. Fully enclosed generator concepts require limited filtering.
- H-Bridge + alternator efficiency must be maximized
- Sweep of switching frequency confirmed that system losses are relatively independent of switching frequency due to large alternator inductance limiting current ripple



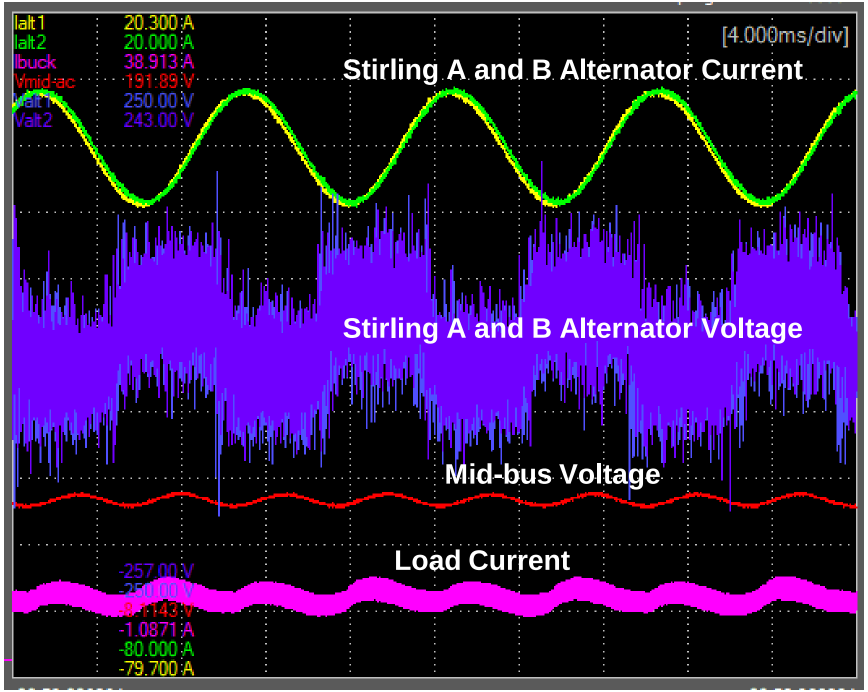
Stirling controller power path



Efficiency of H-bridge + alternator windings

Low-power Controller Results

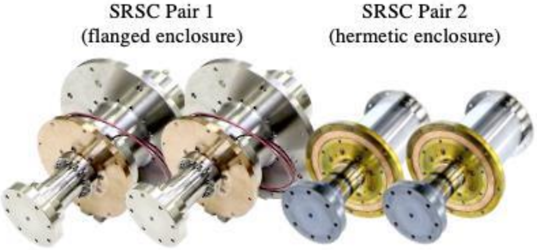
- Operation with dual ASC Stirling convertors
- Full power (Measured at controller)
  - Stirling A: 26.15 V, 5.99 A, 58.72 W
  - Stirling B: 26.51 V, 5.88 A, 58.14 W
  - Spacecraft bus: 28.03 V, 110.9 W
  - Power path efficiency: 94.9%
  - Efficiency with analog control: 90%
- <u>Redesign in process to reduce analog logic power 75% or more</u>



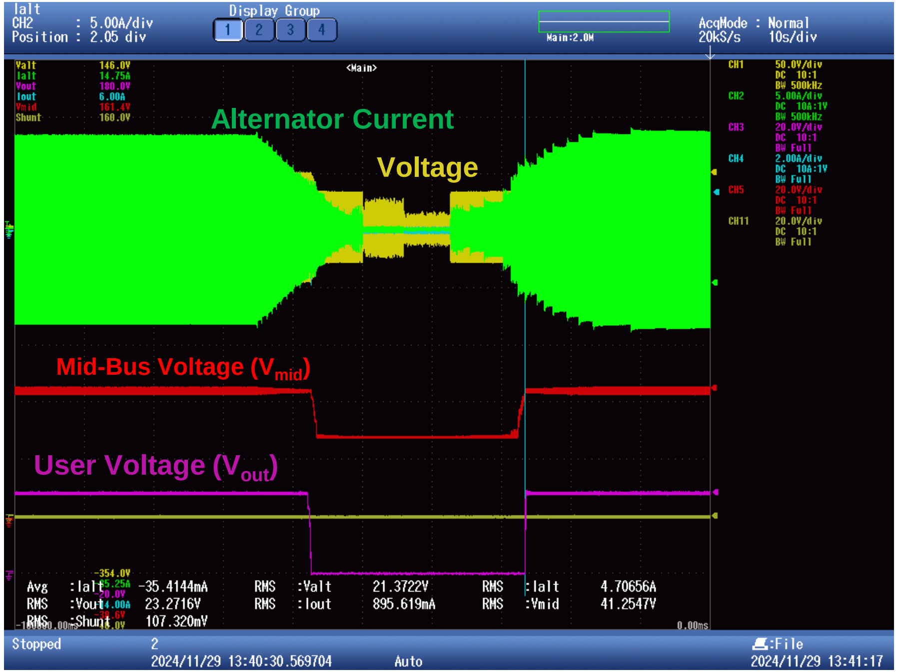
Nominal dual engine operation

Low-power Controller Results

- Operation with single SRSC convertor
- Full power (Measured at controller)
  - Stirling: 27.51 V, 5.82 A, 39.58 W, 99.6 Hz
  - Spacecraft bus: 28.08 V, 1.160 A, 32.36 W
  - Efficiency with analog control: 81.8%
- <u>Redesign will reduce analog control power requirements</u>



Sunpower Robust Stirling Convertor (SRSC) [1]

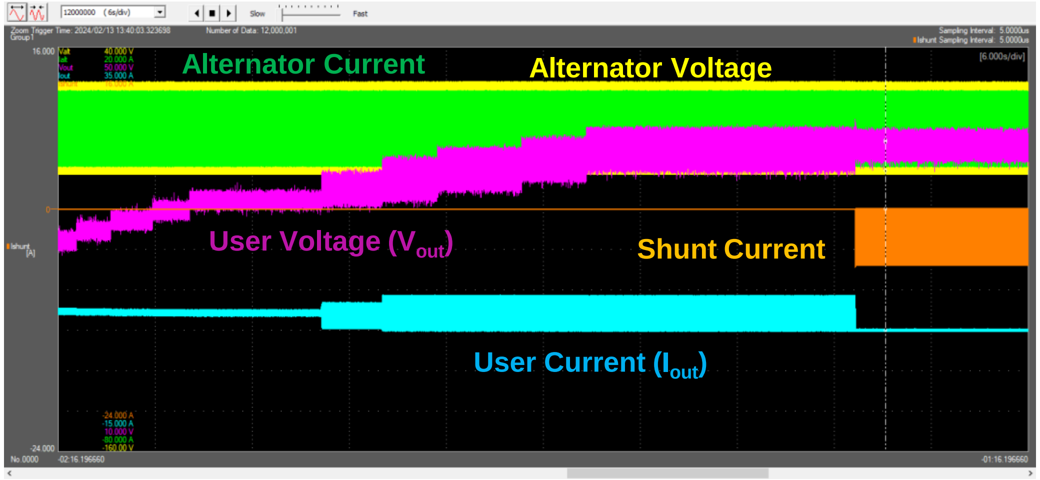


Hot-stall and restart of Stirling

[1] J. COLLINS, J. STANELY, G. WOOD, "Sunpower Robust Stirling Convertor (SRSC) Phase III Overview", *Nuclear and Emerging Technologies for Space*, Cleveland, Ohio, May 8 – May 12, 2022.

Low-power Controller Results

- Load fault functionality demonstrated while maintaining un-interrupted engine control.
  - **Open load** - Controller disconnects from user network in the event of a high-voltage fault and reconnects after power transmission resumes.
  - **Shorted load** - Controller transitions seamlessly into current limit mode to maintain engine control without disconnecting from user network. Seamless return to normal operation after fault clears.



High bus voltage fault

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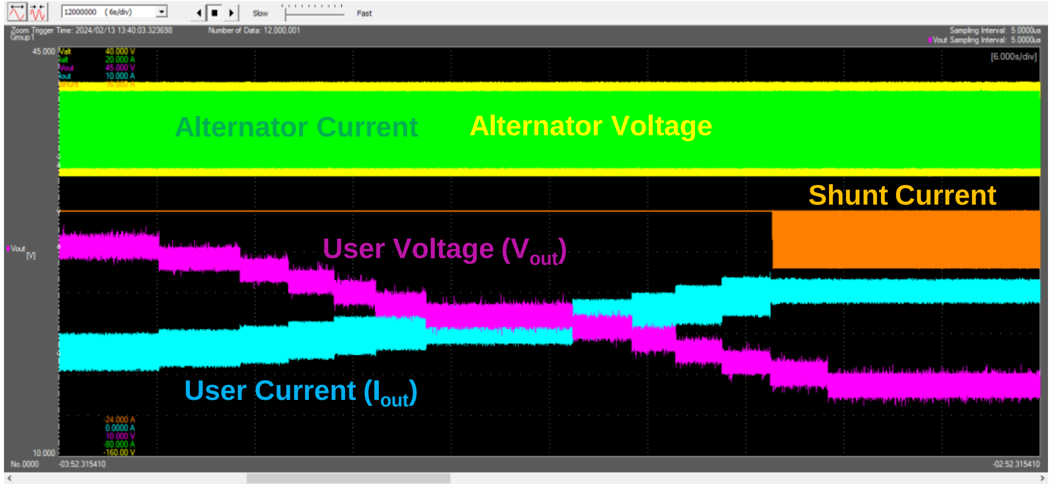
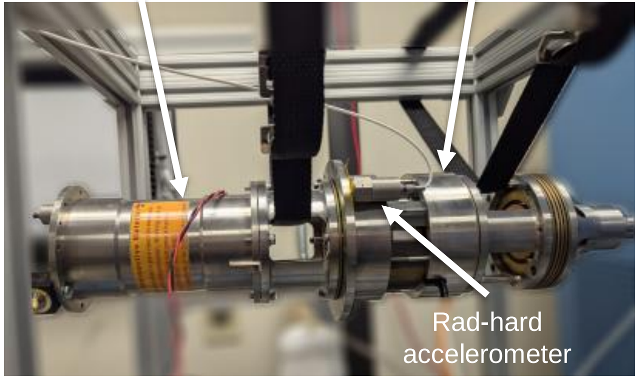


Low/shorted bus voltage fault

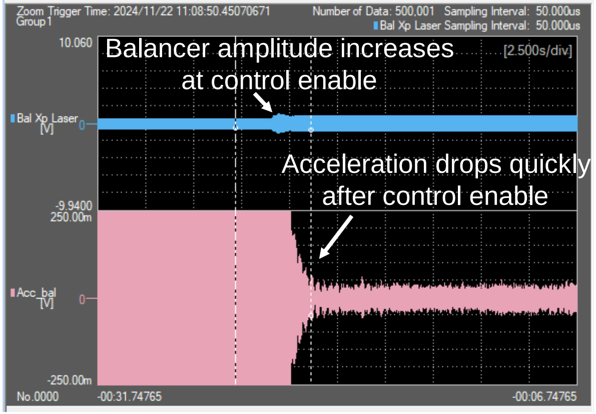
Low-power Controller Results

- Stirling balancer control (Used for engine with balancer configuration)
  - Implemented digitally using a “Least Mean Squares” (LMS) approach
  - Analog implementation in process
  - Balancer control demonstrated in hardware

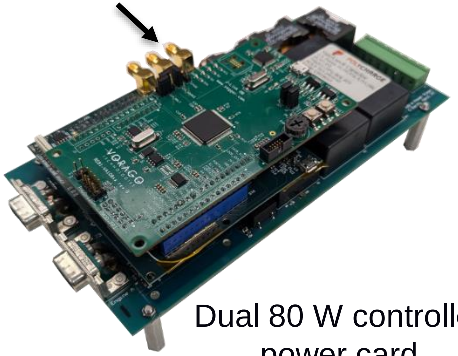
MEGGiTT Piezoelectric Accelerometer
- -55C to +399C
- Radiation-hardened



Suspended balancer/linear motor for balancer controller development



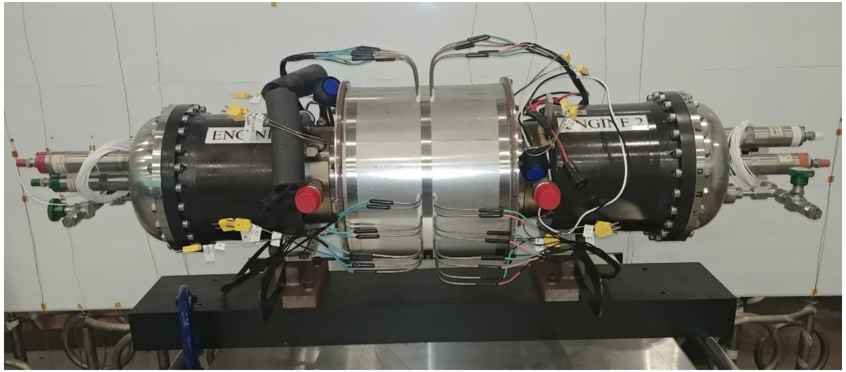
Balancer reduces acceleration of system from 0.88 grms to 0.03 grms



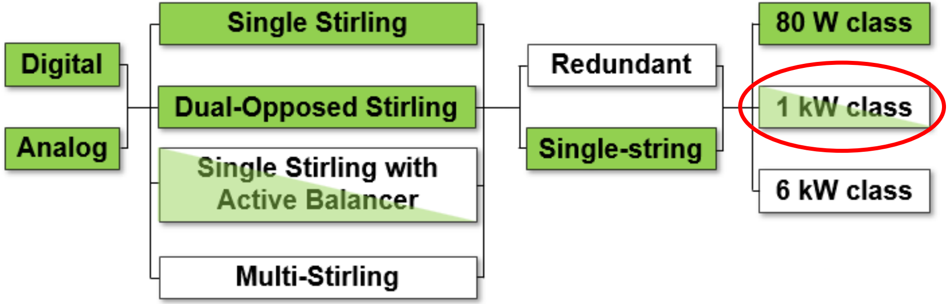
Dual 80 W controller power card

1 kW Controller

- 1 kW controller power card in process
- Demonstration and paper to follow in 2025



1 kW P2A engine pair
(2 kW total)



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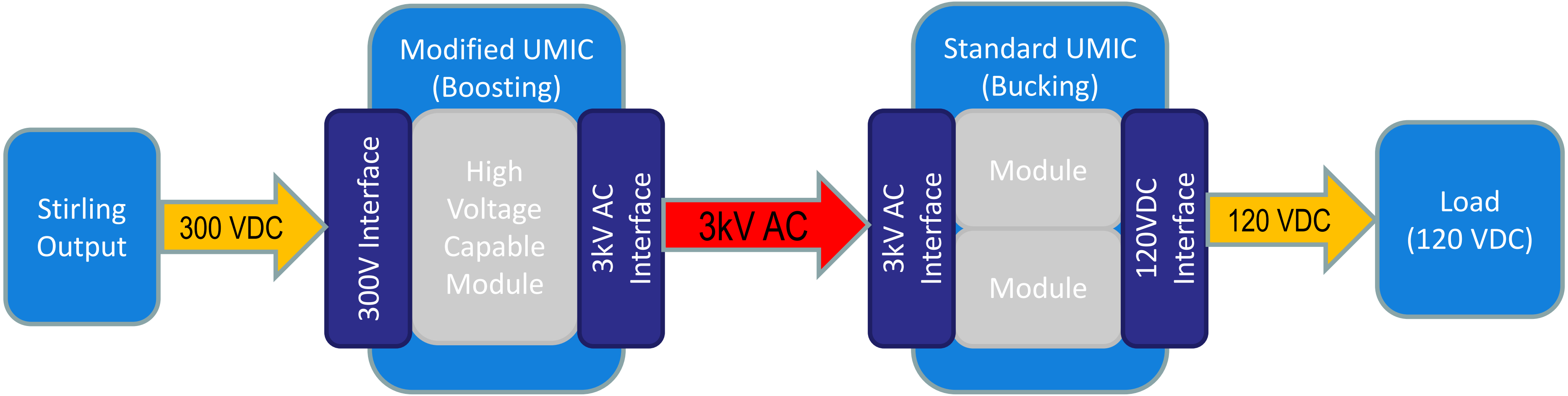
AC Transmission Implementation

- Universal Modular Interface Converter (UMIC) being adapted for FSP [1]
  - GaN devices enable raising DC link to 300 VDC
  - Breadboard demonstration at 3 kW, 3 kVAC, 3 kW

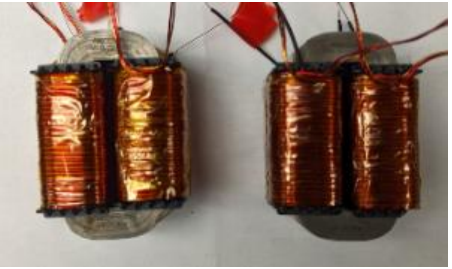


AC Transmission Strategy

[1] Thomas, George L., Matthew Granger, Brent Gardner, Luis Pinero, David Pike, Jeffrey Csank, Arthur Birchenough, and Ajay Krishnan. "A Modular AC to DC Interface Converter to Enable Lunar Surface Power Transmission." In *ASCEND 2023*, p. 4787. 2023..

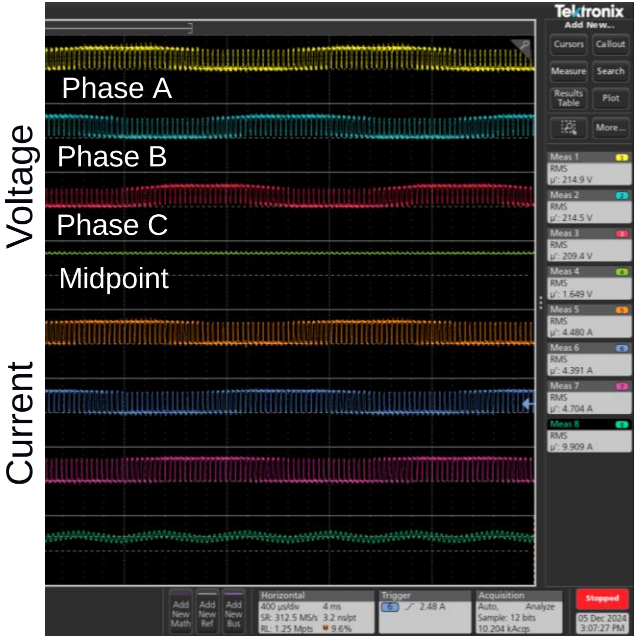
AC Transmission Implementation

- 3 kW inverter/voltage boost validation in progress
- Efficiency
  - Transformer: 98.7%
  - Inverter with AC filter: 94.5% (Preliminary)

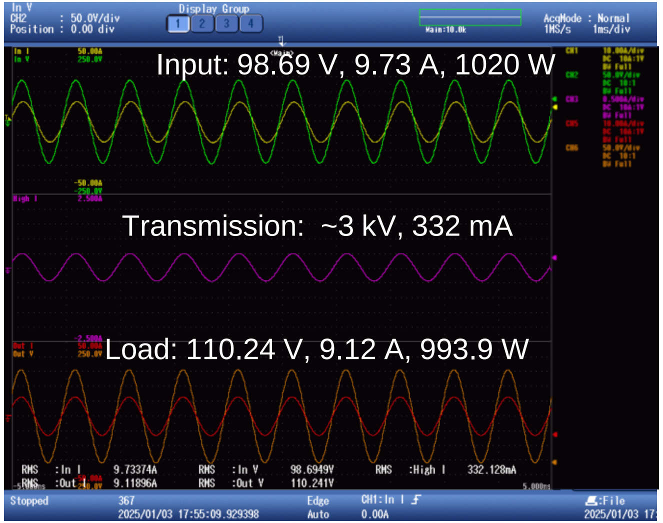


Transformer prototype (110 V to 3,000 V)

3 kW, 300 VDC inverter



Unfiltered, 3-phase inverter output



1 kW Transformer Validation

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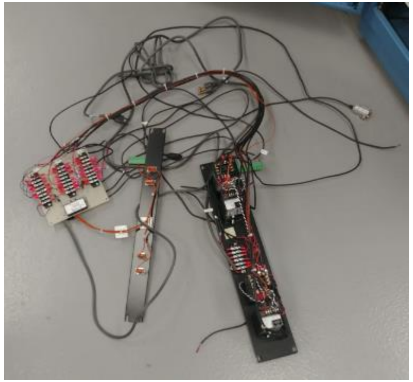
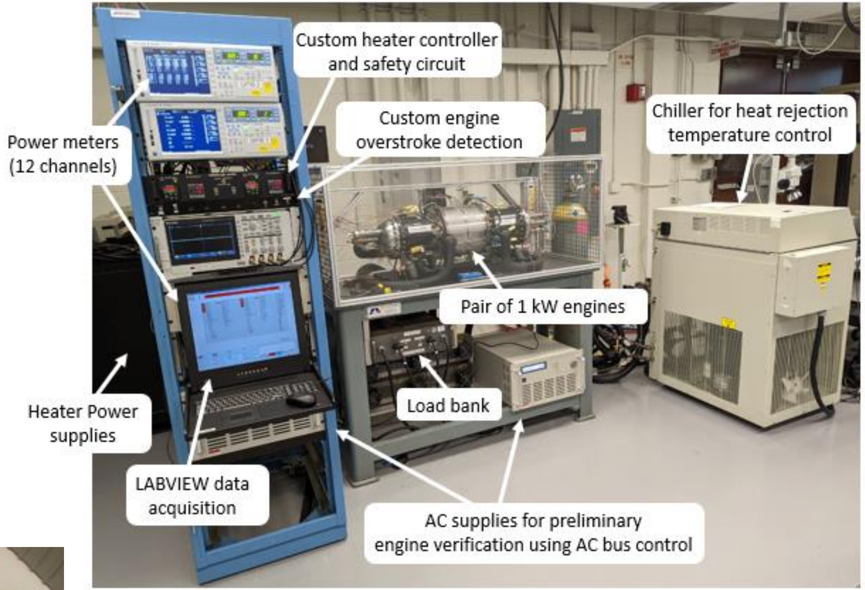
Stirling Convertor Hardware Safety and Support

- Stirling convertor verification and controller testing requires a robust support system to protect Stirling from damage
  - Non-ideal behavior will be uncovered and back-up systems must be in place to protect Stirling and personal
- “Modular Support Rack” infrastructure in development to dramatically reduce project ramp-up costs and guard against convertor damage



Labor-intensive wiring

Standardized assembly



Kilowatt-class Stirling convertor testbed for demonstrating kilowatt-class controller and power transmission

Stirling Convertor Hardware Safety and Support

- Integrated Fault Protection Circuit (FPC) module includes:
  - Four analog channels to enforce adjustable limits on piston stroke and vibration (with disable option)
  - Interface for temperature and Labview limit signals
  - Individual stall controls for up to three engines
  - Emergency shut down (separate functionality from stall)
  - Power path control interface (Controller vs. AC bus)
  - Interfaces with one to three engines

Fault Protection Circuit front and rear

Stirling Convertor Hardware Safety and Support

- Power Path Module
  - Accomplishes power path routing and switching between PFC capacitors, AC bus controller, H-bridge controller, and two distinct stall loads
  - Configurable for both low voltage (high current) and high voltage engines 240 VAC.
- All modular components designed for low labor build-up
  - Low-cost, 2-layer PCBs
  - Interface connections made with coax and DB-9 cables eliminating the need for custom cable fabrication

Stirling rack power control PCB+Faceplate

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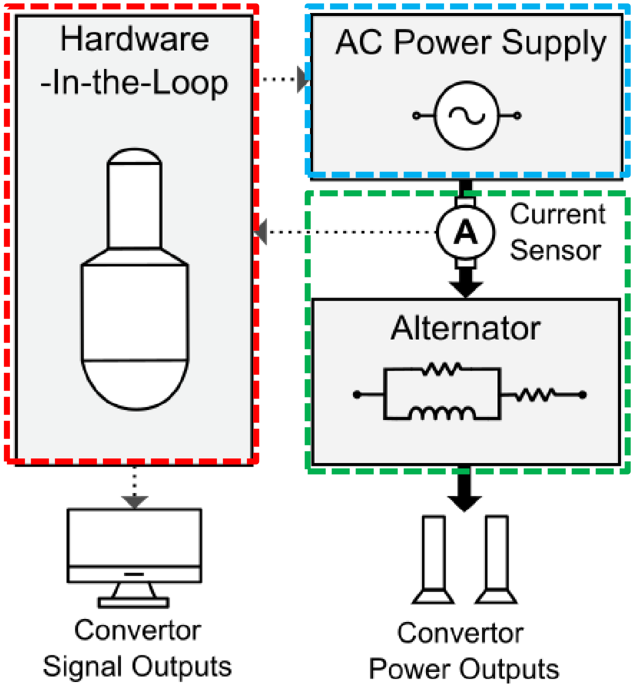
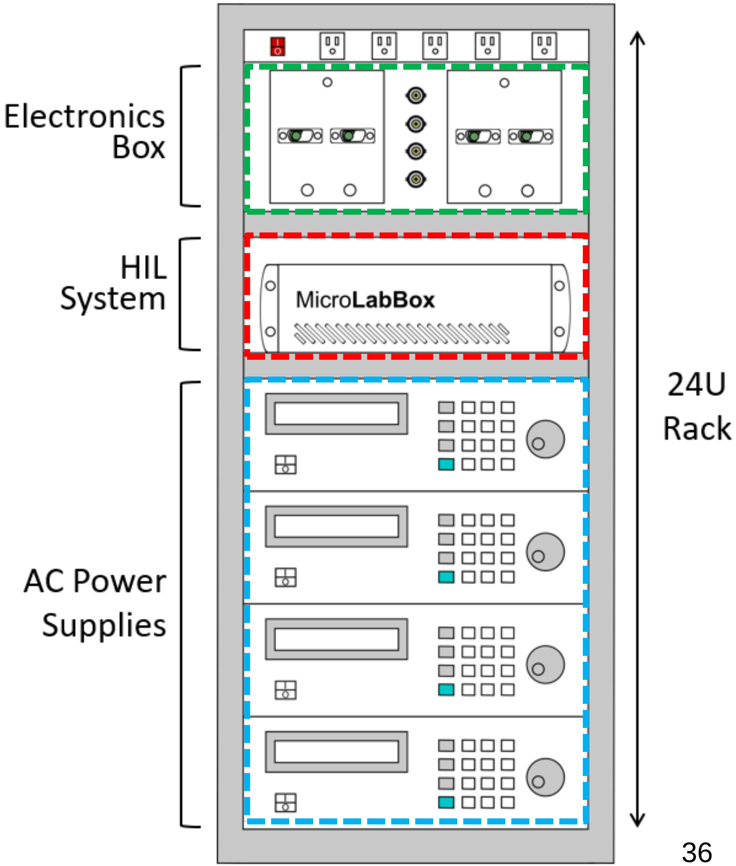
Stirling Simulators for Development and Testing

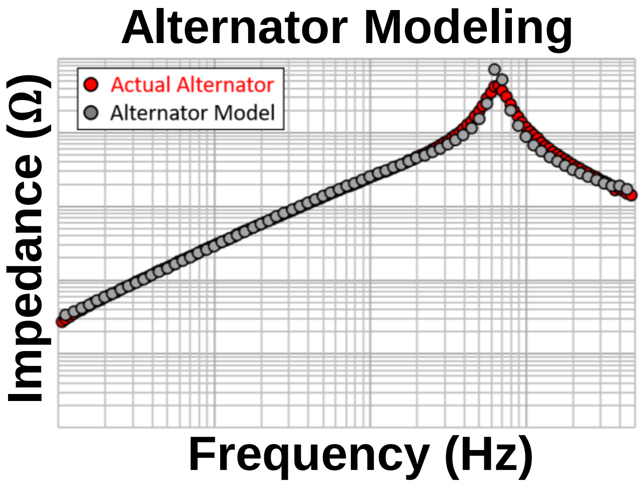
- Test Stirling controllers without risking damage to Stirling convertor hardware
- Save time required to heat and cool Stirling convertors at the start and end of controller testing

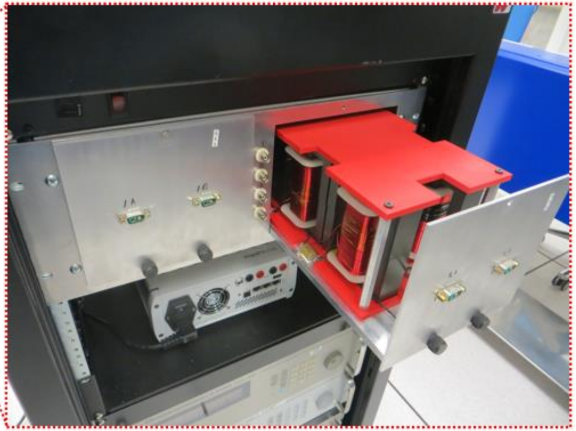


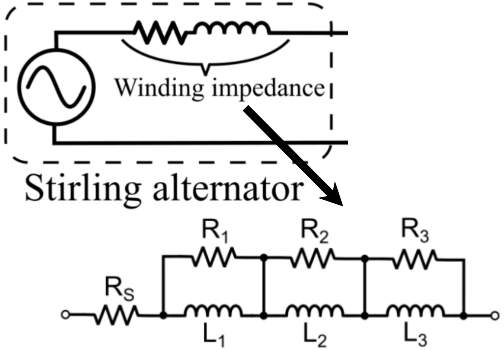


Stirling Simulators for Development and Testing

- A linearized Stirling gas dynamics model programmed in the HIL system.
- An R-L network represents frequency response of Stirling alternator







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Questions?

Contact: Christopher.b.barth@nasa.gov

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