



**NUCLEAR and
EMERGING
TECHNOLOGIES for
SPACE**

May 6-10, 2024, Santa Fe, NM

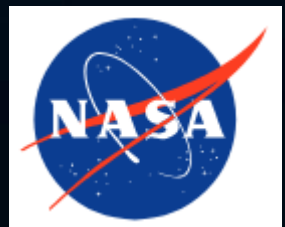
Overview of Advanced Stirling Converter Dual Converter Controller Development and Testing at NASA Glenn Research Center

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**POWERING
THE FINAL
FRONTIER**



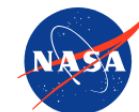
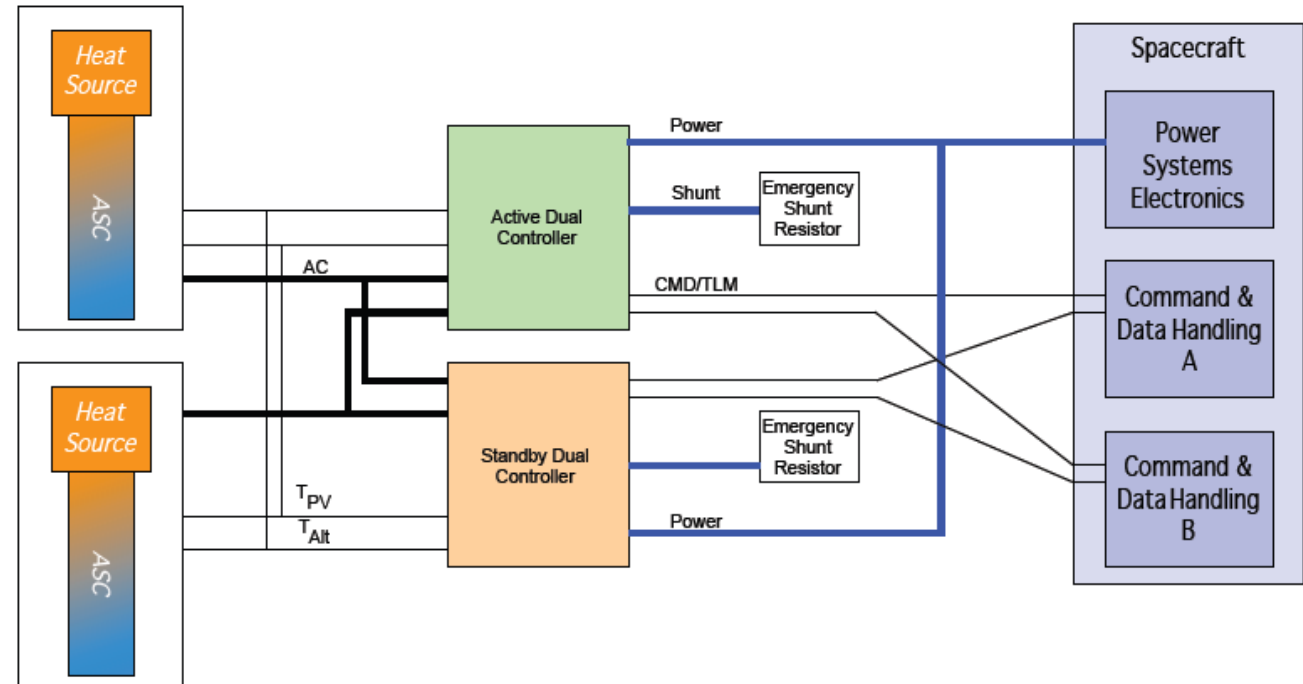
Outline

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- Application: Radioisotope Power System (RPS)
- Stirling Simulator and Convertor
- DCC Development & Functionality
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- DCC Testing
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- Lessons Learned: Modeling
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Application: Radioisotope Power System (RPS)

- **Goal:** Design a RPS generator applicable to a wide range of missions.
- **The RPS includes:**
 - DCC
 - Two Advanced Stirling Convertors (ASC)
 - Integrating structure providing thermal insulation and radiators
 - Power shunts
 - Thermal input power comes from attached and insulated Pu238-fueled General Purpose Heat Source (GPHS) modules.
- **Core Requirements:**
 - Life: 17-years (3 storage + 14 mission)
 - Efficiency: $\geq 20\%$
 - Mission Environments: Deep space, Lunar, Titan, Europa, Enceladus
 - Power: 150 W continuous power



Stirling Simulator and Converter

Stirling Converter Simulator

- Test Stirling convertors without risking damage to Stirling convertor hardware.
- Uses custom-designed circuits, commercial equipment, and a linearized ASC model implemented in software on an off-the-shelf digital signal processor (DSP) development board.
- Alternator inductance and resistance are modeled with physical components.
- Used to test the DCC prior to integration with ASCs and has operational characteristics comparable to that of an ASC.

Stirling Converter

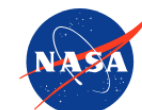
- ASCs with 55 (~15 V) & 77 (~22 V) turn alternators.



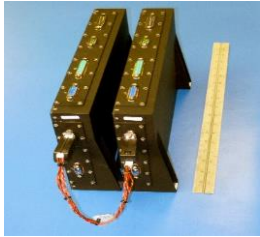
Advanced Stirling Convertors (ASC)



Dual Advanced Stirling Converter Simulator (DASC)



DCC Development & Functionality



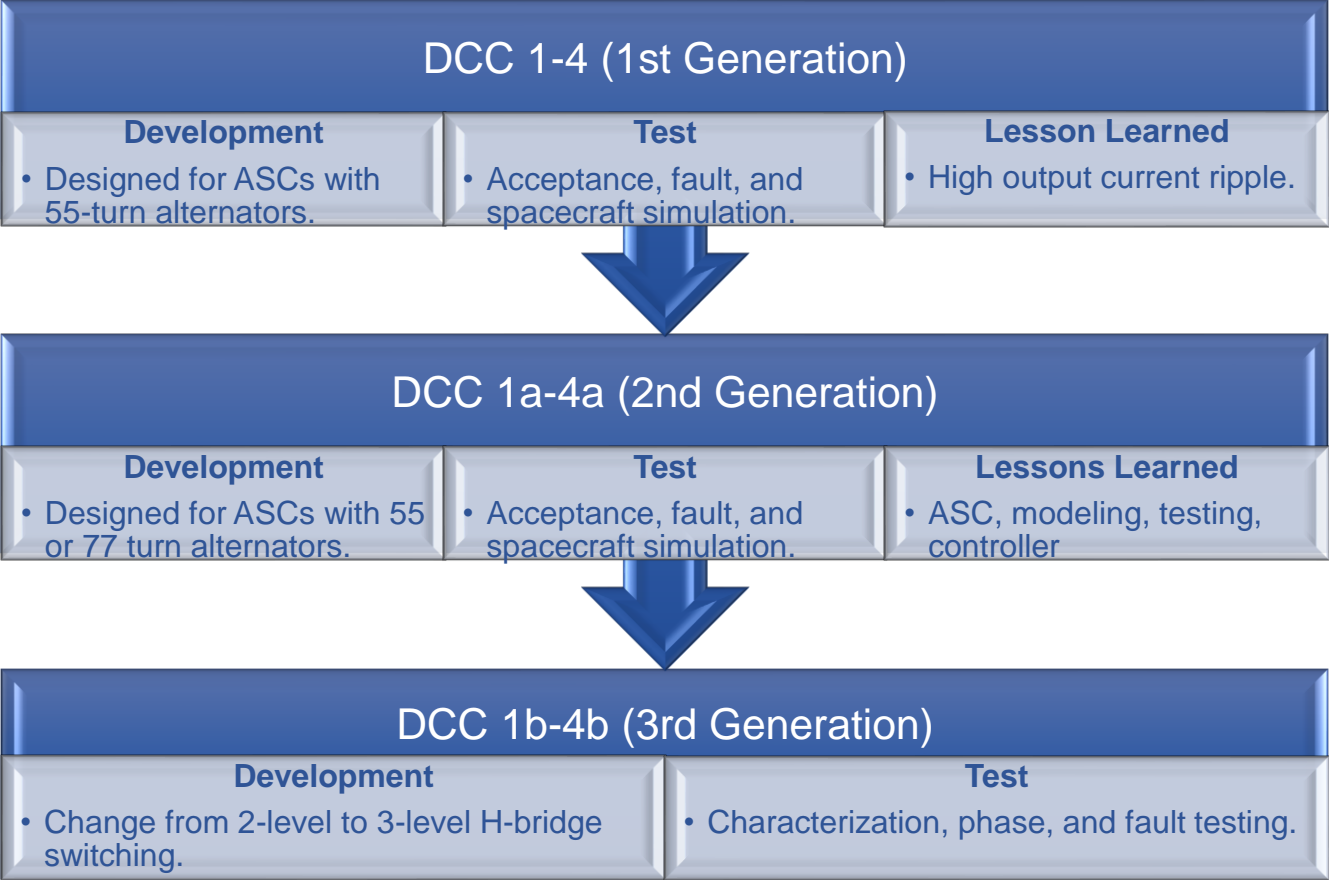
DCC	Efficiency (55-turn)	Efficiency (77-turn)
First Generation	82-84%	N/A
Second Generation	71-74%	N/A
Third Generation	86-91%	88-92%

Development

- Three generations of the DCC developed from 2012-2021.
- Each generation designed based on lessons learned from the previous.
- A total of four boxes, each box houses a DCC board, were built and interchangeable to make a fault tolerant DCC.
- DCC development starts with modeling of the controller and a linearized version of the Stirling convertor model.

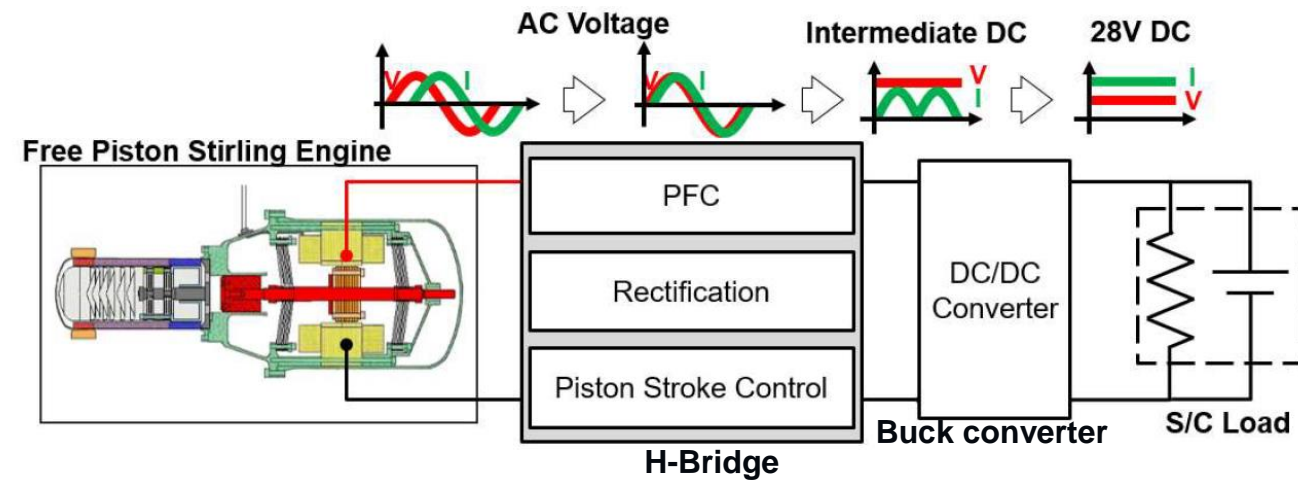
Functions

1. Perform an AC to DC conversion of the convertor outputs.
2. Synchronizing the convertors to reduce disturbance force.
3. Controlling the convertors' operating frequency and voltage.
4. Deliver power to a spacecraft.
5. Receive and execute a command set from the spacecraft.
6. Provide state of health as telemetry to the spacecraft.
7. Respond to faults at the spacecraft load interface.
8. Respond to faults within a Stirling Convertor.
9. Maintain Stirling convertor operation in the event of an internal controller failure.
10. Prevent propagation of faults to other boards within the controller.



DCC Design

H-bridge



Function

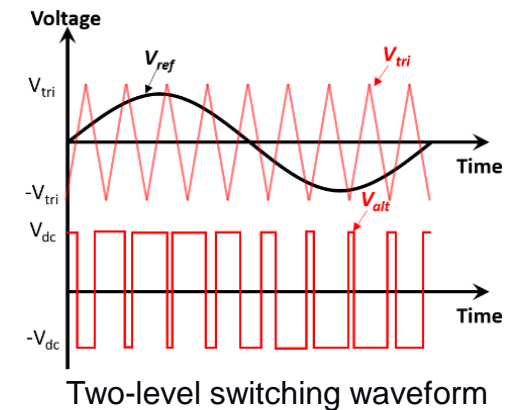
- Power factor correction
 - Controls the voltage across the alternator terminals so that the average voltage is the same as the voltage produced by an AC voltage source in parallel with a tuning capacitor.

- AC-DC rectification
- Piston Stroke Control

$$V_{ref} = V_{AC} + V_t$$

2-level

- Switches, 23 kHz, two diagonal MOSFETs to either produce +Vdc or -Vdc across the alternator.
 - V_{tri} much higher frequency and amplitude than the V_{ref} frequency and amplitude is compared to the reference voltage signal to generate a modulated signal V_{alt}
- The alternator current dithers at the switching frequency above and below the mean current with a peak-to-peak amplitude of 0.5 amps.
 - This current ripple causes rapid magnetization changes in the alternator/magnet assembly leading to alternator power loss due to heat dissipation.



3-level

- Switches, ~23 kHz, between +Vdc, 0, & -Vdc.
- Average voltage across the inductor is reduced and therefore power loss due to rapid magnetization changes is reduced.

DCC: Testing

Acceptance Testing

- First test performed after the DCC is delivered to GRC.
- Acceptance testing verifies that the DCC controlled the ASC at full convertor power output and provides power to the spacecraft.
- Acceptance testing performed with the convertor simulator first, as a risk reduction to hardware, and then a pair of ASCs.

Second Generation DCC (DCC 1a-4a)

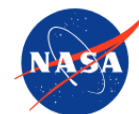
- Issue identified during acceptance testing.
 - Testing revealed that the DCC DC output, power provided to the spacecraft (DC output power), was producing ~9W less power than expected.
 - A DC output power loss is expected due to the power needed for internal DCC circuitry. The power loss observed during this acceptance test was 9W greater than what was expected.
- The excessive DC output power loss was present while operating with a pair of ASCs **but** not when operating with the convertor simulator nor in the modeling platform.
- Troubleshooting efforts began to understand:
 - What was causing the excessive power loss? A loss in the DCC, loss in the alternator, and/or an external factor?
 - Why was the excessive DC output power loss not seen while operating with convertor simulators?
 - Why was the excessive DC output power loss not seen in the model?

Third Generation DCC (DCC 1b-4b)

- Once the excessive DC output power loss issue was understood, the DCC design changes were made, and it was delivered to GRC.
- A more comprehensive test, characterization testing, which included acceptance testing, was performed after delivery.
- Characterization testing verifies the DCC performance at various bus voltage (22, 28, 34, & 36), when the DCC backup card is not powered, when connected/disconnected to the spacecraft load, & turning the power meter line filter setting on/off.
 - The extended test sequence was created to better understand the DCC performance and to verify that the DCC design changes resolved the excessive DC output power loss.

Test Setup

- Alternator power measured at the input to the DCC.
- DCC output power provided to an external shunt resistor or a spacecraft bus (DC electronic load).



Lesson Learned: ASC

ASC alternator inductor characterization is essential.

Issue

- When testing with a pair of ASCs, the DCC output produced 9 W less power, when connected to the spacecraft load, than when using the convertor simulator at the same input power (as measured by a low bandwidth power meter).

Troubleshooting

- Impedance sweep, 500 Hz-10 MHz, of the ASC alternator and convertor simulator inductor.
- Improved modeling of the alternator inductor.

Results

- Impedance sweep revealed that the inductor/resistor in the convertor simulator did not accurately represent the ASC alternator.
- High frequency switching of the H-bridge caused more alternator power loss in the ASC than the convertor simulator due to power being consumed in the ASC alternator core.
- Alternator core loss was not represented in the convertor simulator physical components.

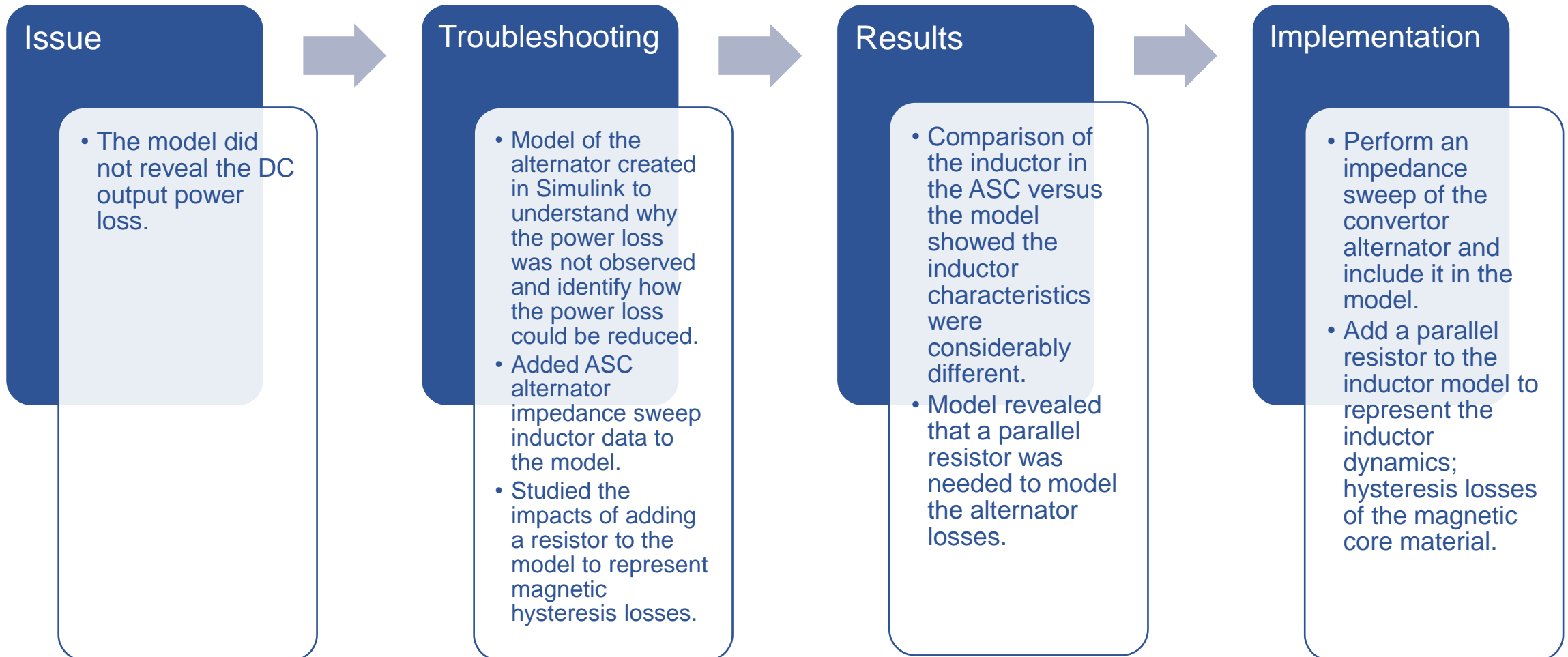
Implementation

- Perform an impedance sweep on the convertor alternator and design the convertor simulator alternator physical components to match those results.
- Include a resistor in the convertor simulator alternator to represent hysteresis effects of the magnetic core material.



Lesson Learned: Modeling

Alternator inductance characterization data should be included in the model.



Lesson Learned: Testing

Select a power meter with a high enough bandwidth so that the high frequency component is measured.

Issue

- Determine the best way to measure alternator input power to the DCC given the DCC 23kHz switching.
- Alternator power was measured with a power meter that had a limited bandwidth and used a 500 Hz line filter.

Troubleshooting

- Test with various power meters and filter settings.
- The power loss was not observed with the 500 Hz line filter on or off due to the 100 kHz bandwidth of the power meter.
- High frequency component, due to the 23 kHz switching, was ignored and therefore measured input power to the DCC was incorrect.

Results

- The power meter bandwidth, 100 kHz, masked the impact of the harmonics generated by the DCC's switching frequency.
- High frequency harmonics in the alternator current drive high-frequency losses and reduce the power extracted from the convertor.
- High frequency components are beyond the bandwidth of the power meter being used; measured input alternator power to the DCC was under reporting the true DCC input power.

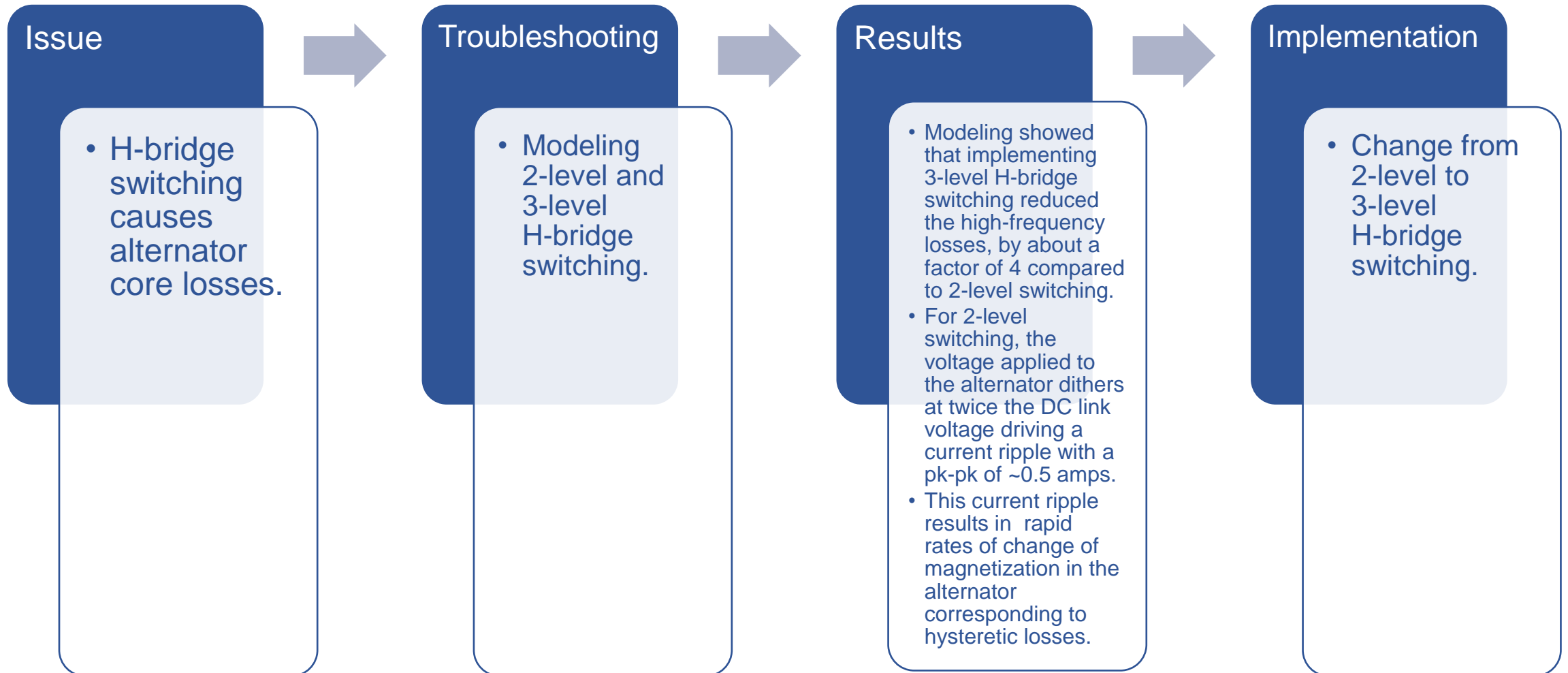
Implementation

- Select a power meter with a bandwidth up to 1 MHz.



Lesson Learned: Controller

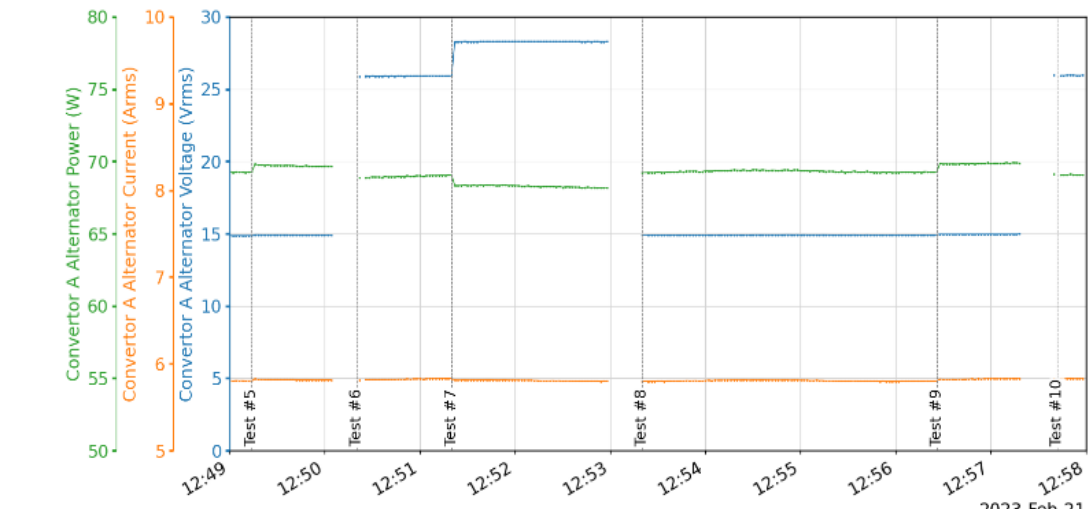
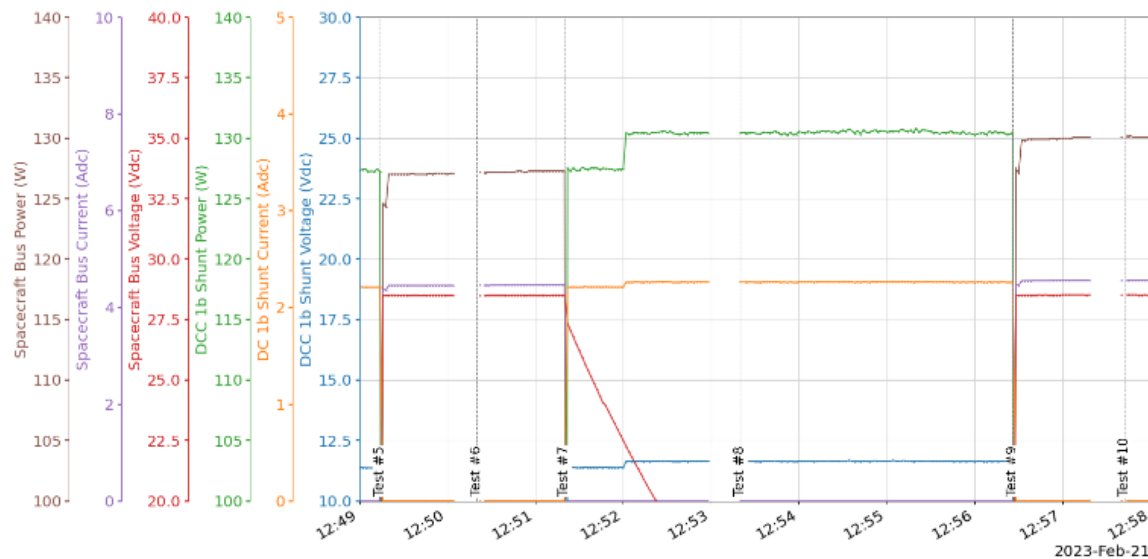
H-bridge switching techniques can impact alternator core loss.



Lessons Learned: Implementation Test Results

- The lessons learned were implemented in the third generation of the DCC.
- Characterization testing proved that the excessive DCC DC output power loss was resolved:
 - Performed with a pair of ASCs each producing ~69 W output power:
 - 55 turn (~12 Vrms) alternators
 - 77 turn (~15 Vrms) alternators
- The DCC efficiency is calculated as the DCC output power divided by the DCC input power. The DCC DC output power loss ranges from 12-15 W depending on the test condition. This output power loss is in the expected range and is due to the power needed for DCC internal circuitry.
- When the DC output is not connected to the spacecraft, all power is dissipated in the external shunt resistors. When the DC output is connected to the spacecraft, the external shunt is not dissipating power.

Test #	Backup DCC Card Powered	On the S/C Bus	DCC Fault Detect	Power Meter Line Filter	DCC Eff. (%)	DCC Eff. (%)
5	Yes	Yes	On	On	88	86
6	Yes	Yes	On	Off	89	87
7	No	No	Off	Off	92	91
8	No	No	Off	On	91	89
9	No	Yes	Off	On	90	88
10	No	Yes	Off	Off	91	89



Alternator Data: Operation of the DCC with a pair of ASCs with 77 turn alternators

2023-Feb-21



Conclusion

- Three generations of the DCC were developed; each generation designed based on lessons learned from the previous.
- Four significant lessons were learned from the second generation DCC acceptance testing.
- Lessons learned from the second generation DCC were implemented in the third generation of the DCC and the DCC GSE test setup.
- Characterization testing verified that the DC output power loss was resolved because of changing from 2-level to 3-level H-bridge switching in the DCC.

Topic	Lesson Learned	Implementation
ASC	Inductor characterization is important.	Perform impedance sweep on each alternator when the convertor is received.
Controller	H-bridge switching techniques can impact alternator loss.	Change from 2-level to 3-level H-bridge switching in the DCC.
Modeling	Inductor characterization data should be included in the model.	Perform impedance sweep on each convertor and include it in the model.
Testing	Select a power meter with a high enough bandwidth so that the high-frequency component is measured.	Select a power meter with a bandwidth up to 1 MHz.

