https://ntrs.nasa.gov/search.jsp?R=20170008115 2020-05-10T05:29:11+00:00Z

National Aeronautics and
Space Administration

John H. Glenn Research Center

150kW Class Solar Electric Propulsion Spacecraft Power Architecture Model

Jeffrey T. Csank and Michael V. Aulisio

NASA Glenn Research Center

Cleveland, OH

Benjamin Loop

PC Krause and Associates

West Lafayette, IN

15th International Energy Conversion Engineering Conference

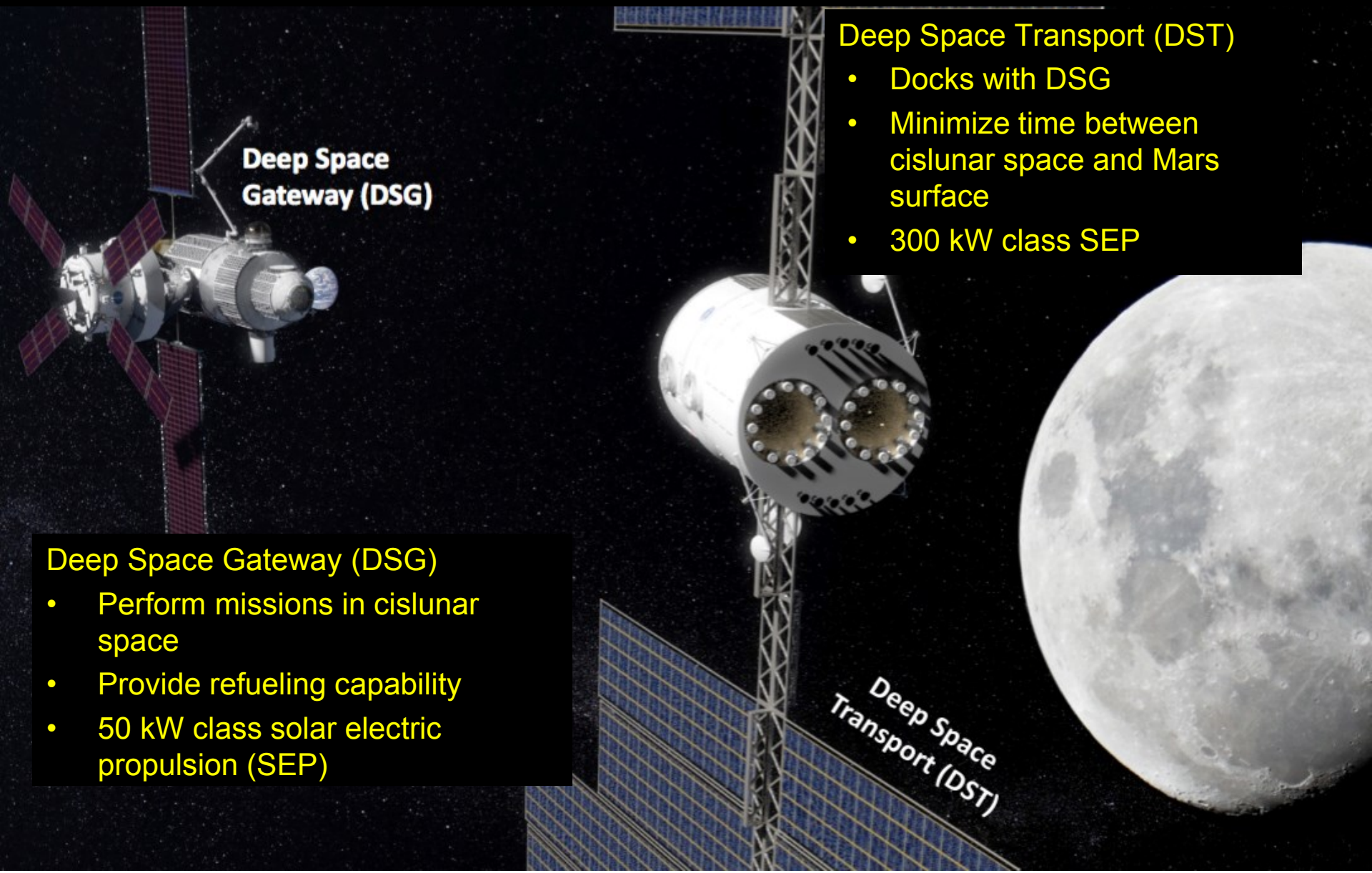
APS-02 Spacecraft/Aircraft Power Generation, Energy Storage, and In-Orbit Experience

July 11, 2017 3:00 – 6:00 PM

Atlanta, GA

Authors would like to thank the Space Technology Mission Directorate, Technology Demonstration Mission (TDM), Solar Electric Propulsion (SEP) project for funding this work.

Overview



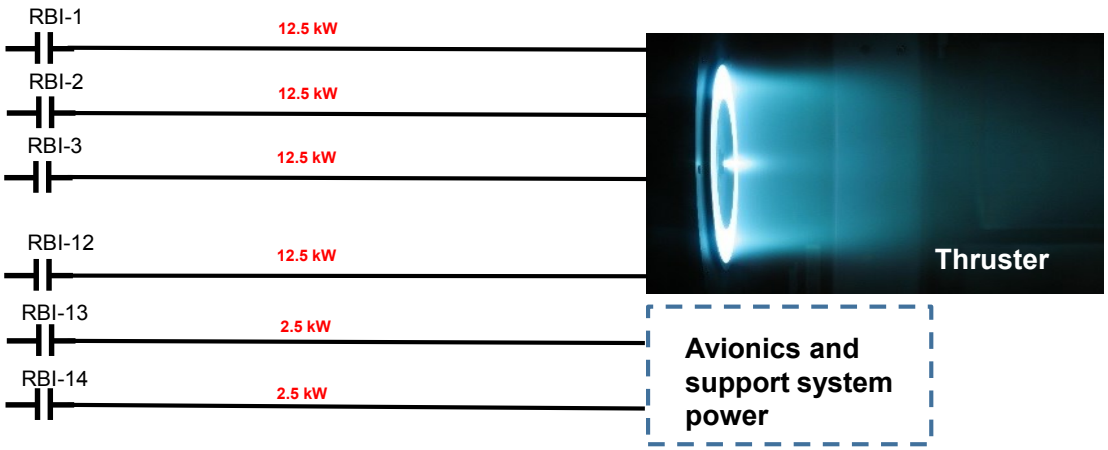
Deep Space Transport (DST)

- Docks with DSG
- Minimize time between cislunar space and Mars surface
- 300 kW class SEP

Deep Space Gateway (DSG)

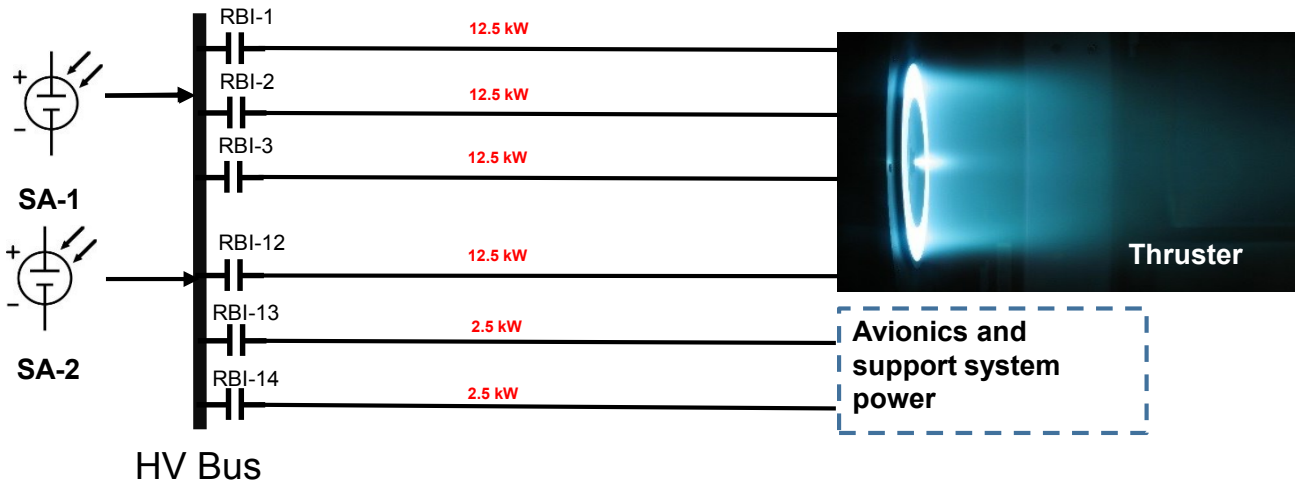
- Perform missions in cislunar space
- Provide refueling capability
- 50 kW class solar electric propulsion (SEP)

Basic 150 kW Architecture



- 12 electric propulsion strings, each nominally consuming 12.5 kW
- 2 additional strings for avionics and support system power
- 158.8kW of total power including system losses
- Power system modeled in MATLAB® / Simulink ® (the MathWorks, Inc) using the ISS Model Library (Toolbox developed by PC Krause and Associates (PCKA).

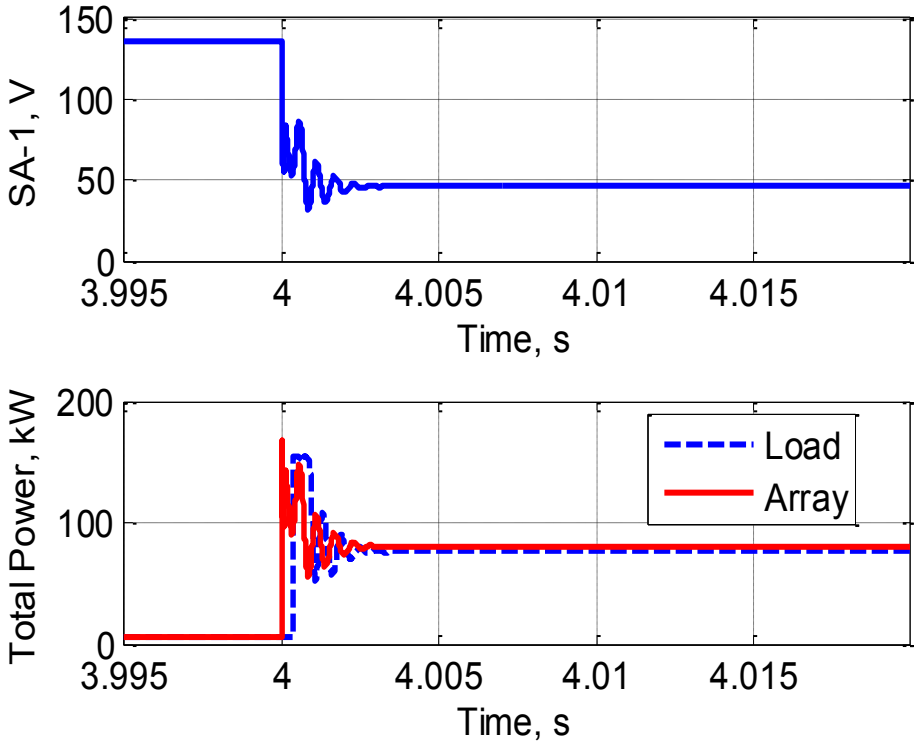
Non-Segmented Architecture



- Un-regulated Common bus architecture – 2 solar arrays designed to provide 155kW+ of power to a single HV bus

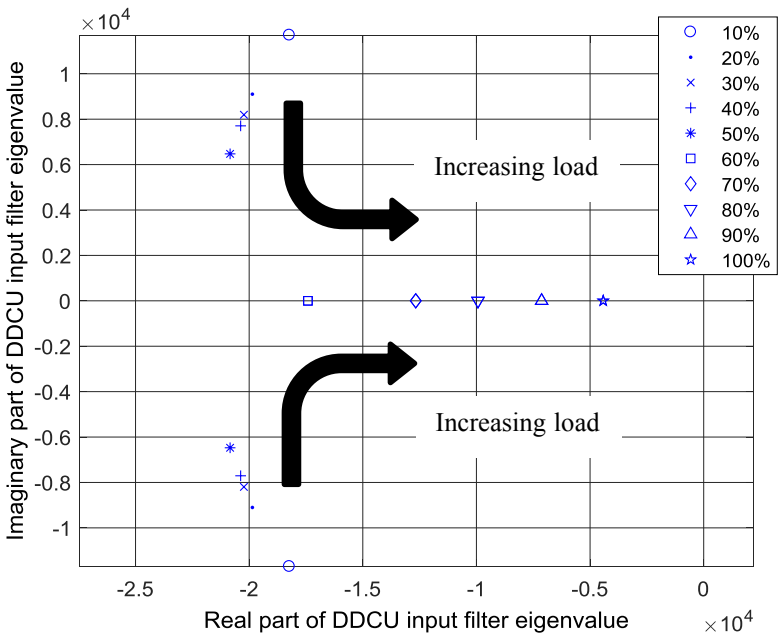
Transient Response – All Loads Turned On

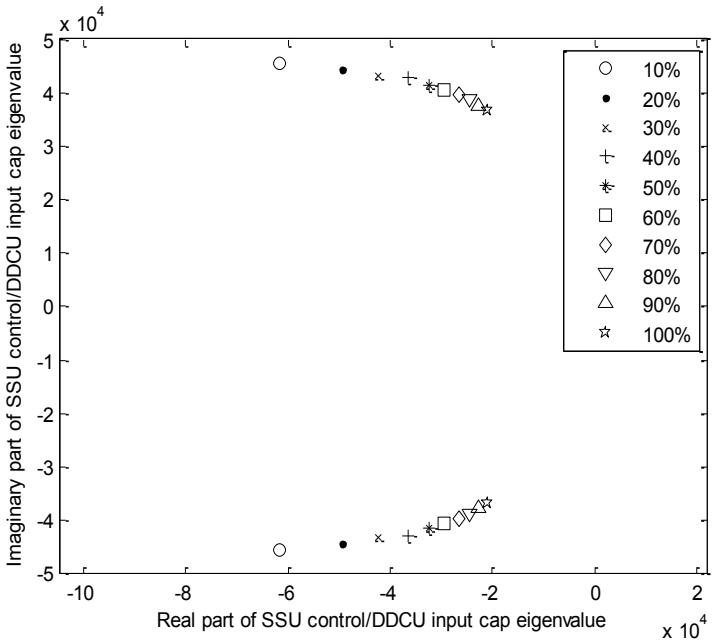
- All propulsion strings RBI's are closed at the same time.
- Solar Array 1 and 2 responses are identical.
- SA voltage reduces from the open circuit voltage (136 V) and reduces to 46 Volts.
- Total power increases from 5k+W to 80 kW. But system should be near 155kW (+losses)



Stability Analysis – Small Signal

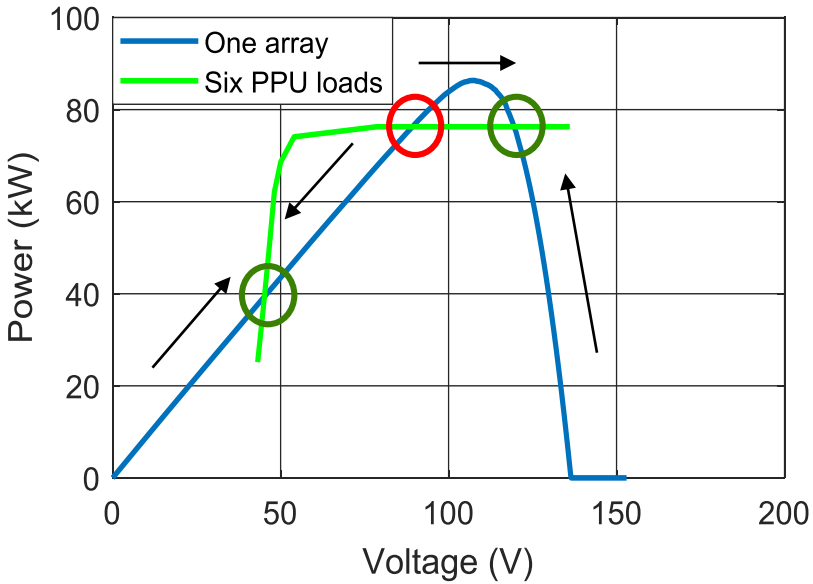
- PCKA developed tool to calculate eigenvalues of the power system
  - ISS Model Library
- Jacobian matrix calculated at 10 load levels in equal steps from 10% to 100% for all 12 PPUs
- Eigenvalue real parts are negative, therefore stability is not of a concern

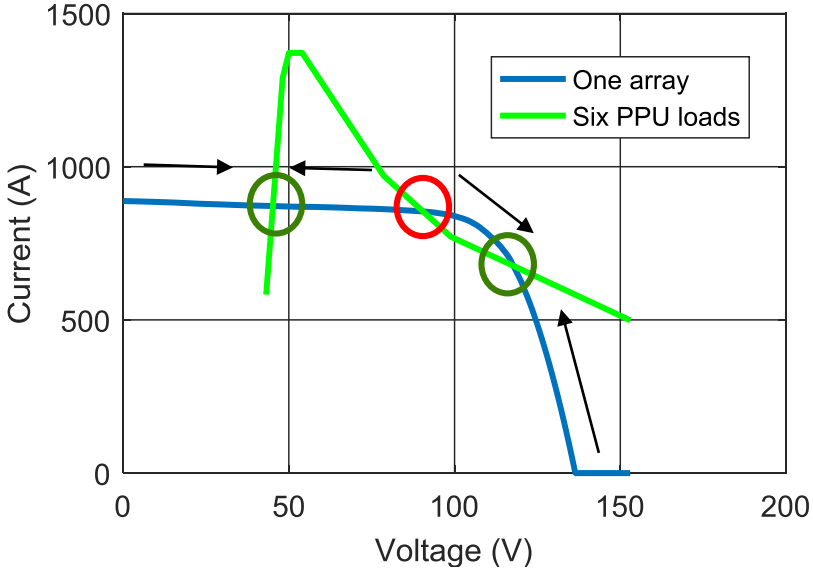




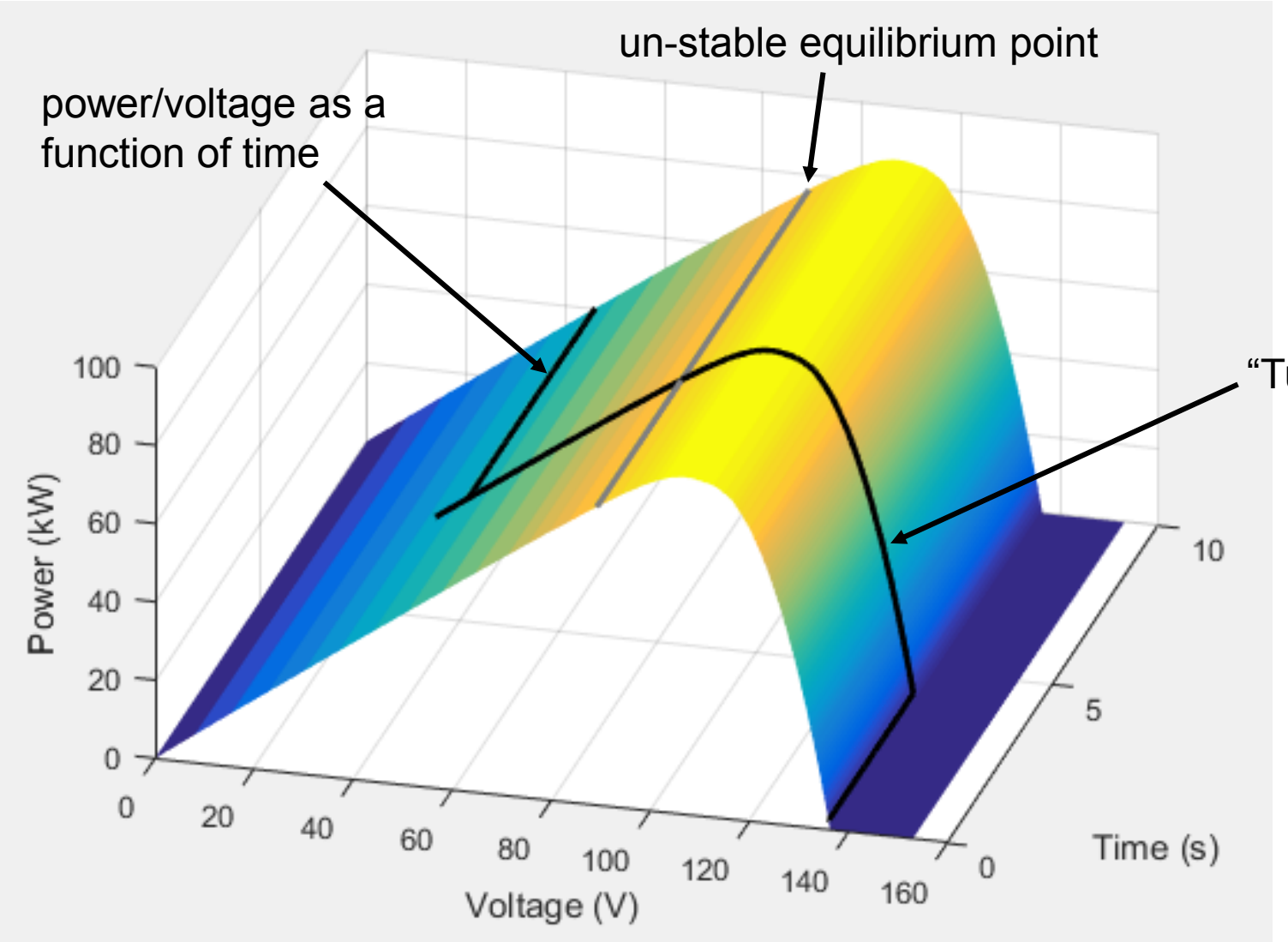
Stability Analysis – Large Signal

- Power/Voltage curve for 1 solar array superimposed with 6 loads
- Curves interest at 3 points (equilibrium points), creating 4 sections
- SA Power > Load Power
  - Array produces excess current and feeds system capacitance
  - **Increase voltage**
- SA Power < Load Power
  - Array draws current from system capacitance
  - **Decrease voltage**
- Stable equilibrium points
- Un-stable equilibrium points

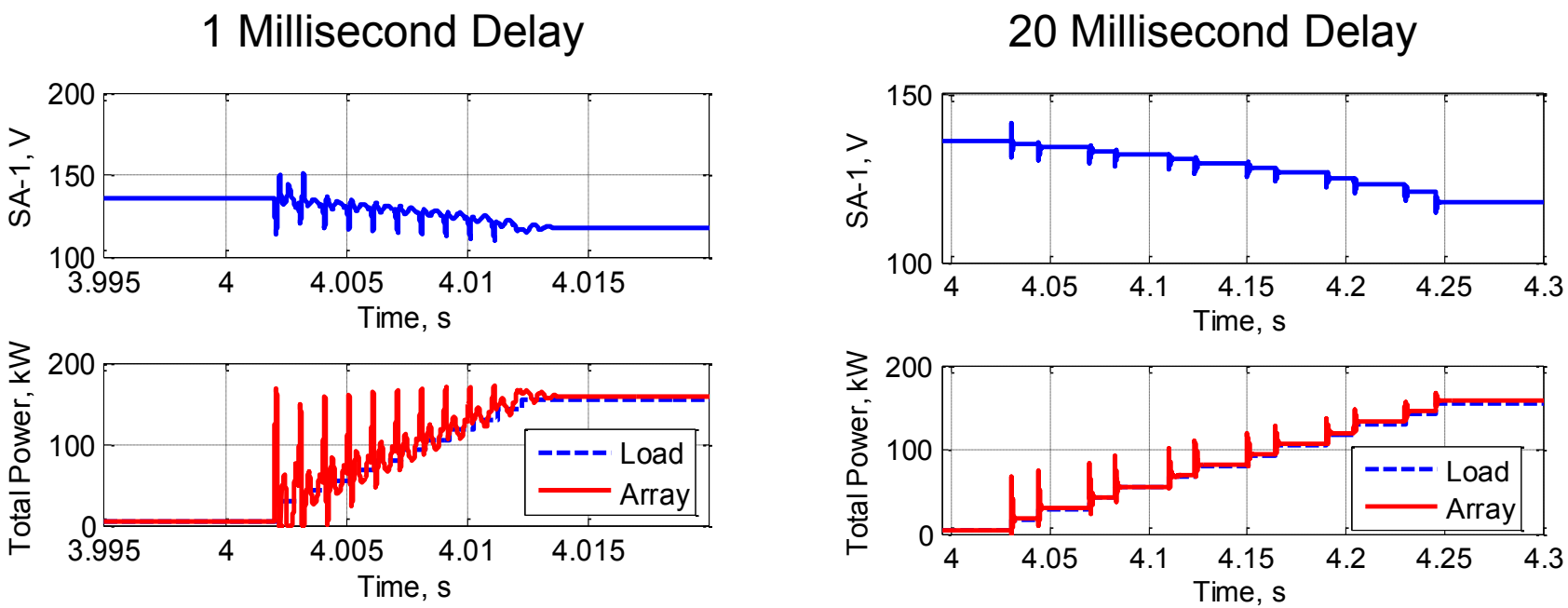




Power/Voltage Curve Vs Time

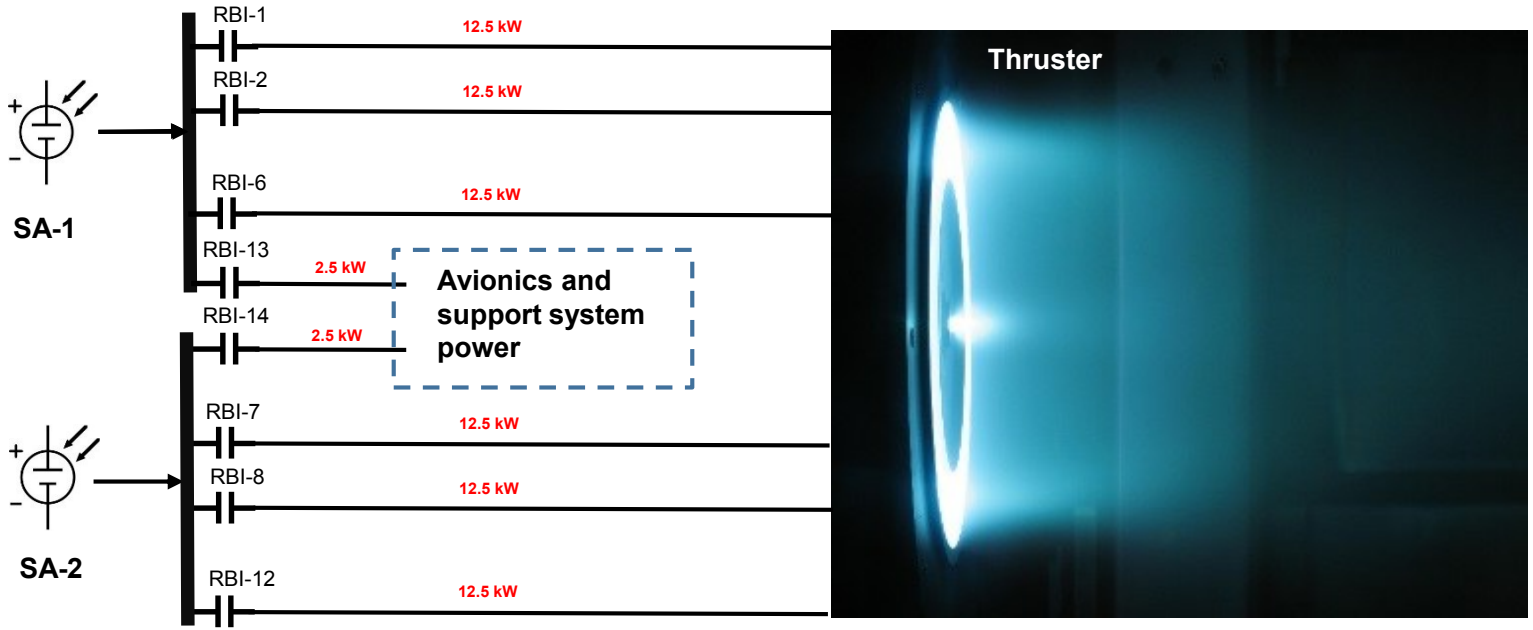


Transient Response to Incremental Commands



- Solar array voltage responses are identical (SA1 to SA2).
- Turning the loads on in a timed sequence allows the solar array voltage to settle at the higher equilibrium point (avoid exceeding the unstable equilibrium voltage).
- Increasing the delay time allows system to stabilize before turning on the next load.
- Flight controller update time is 1 second.

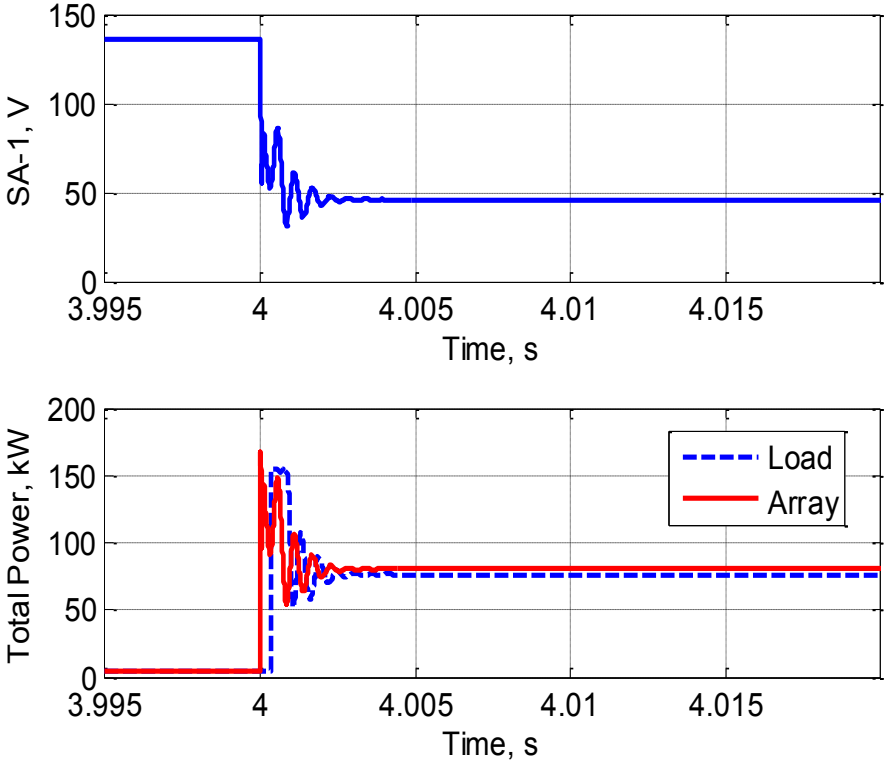
Segmented Architecture



- Segmented bus architecture – each solar array powers a single bus with +77.5kW of power
- Each bus provides power to 6 propulsion strings, 75kW + losses, and 1 string of avionics 2.5kW.

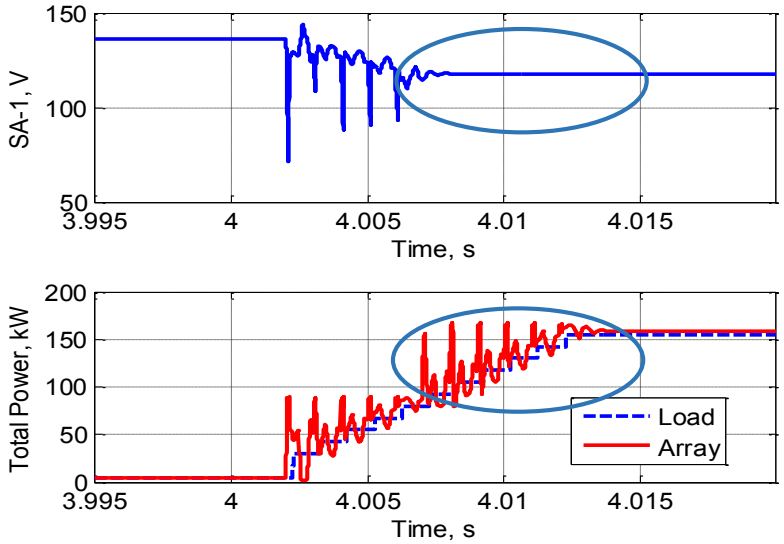
Transient Response – Turning on Loads

- Turning on all loads at the same time with the segmented bus at the same time has the same response as the non-segmented.
- This result is consistent regardless of architecture.

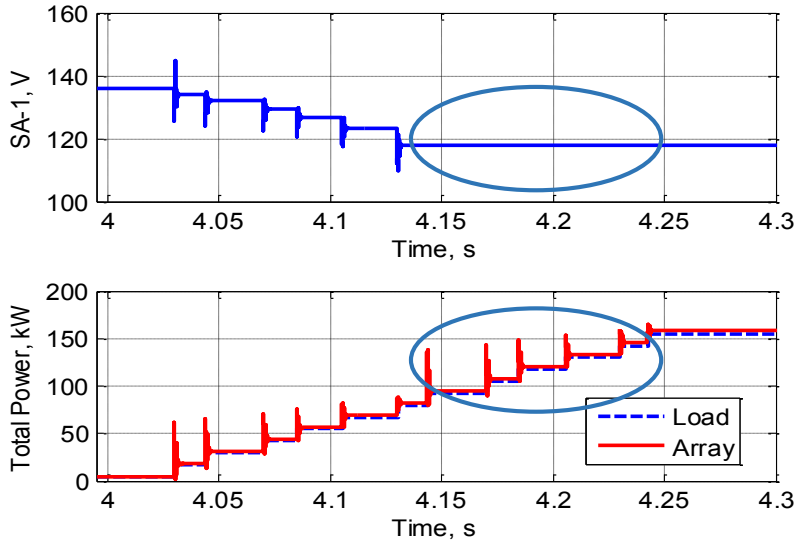


Transient Response to Incremental Commands

1 Millisecond Delay



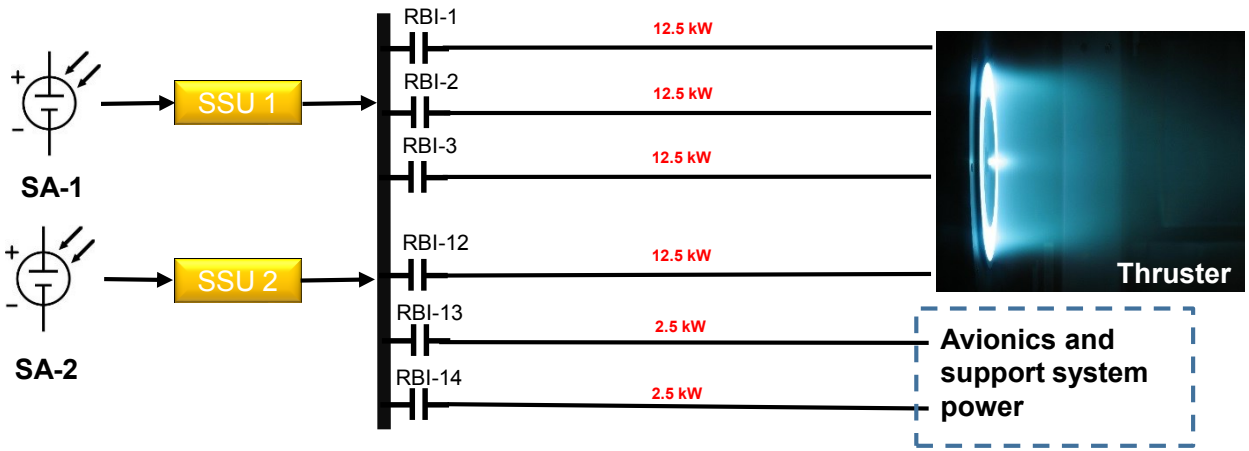
20 Millisecond Delay



Voltage response on SA-2 (would be same as 1 just shifted in time)

- With the 1 millisecond delay, all loads associated with SA-1 are turned on first. Transient peaks are smaller than with the non-segmented.
- Overall, slightly better response than the non-segmented bus architecture.

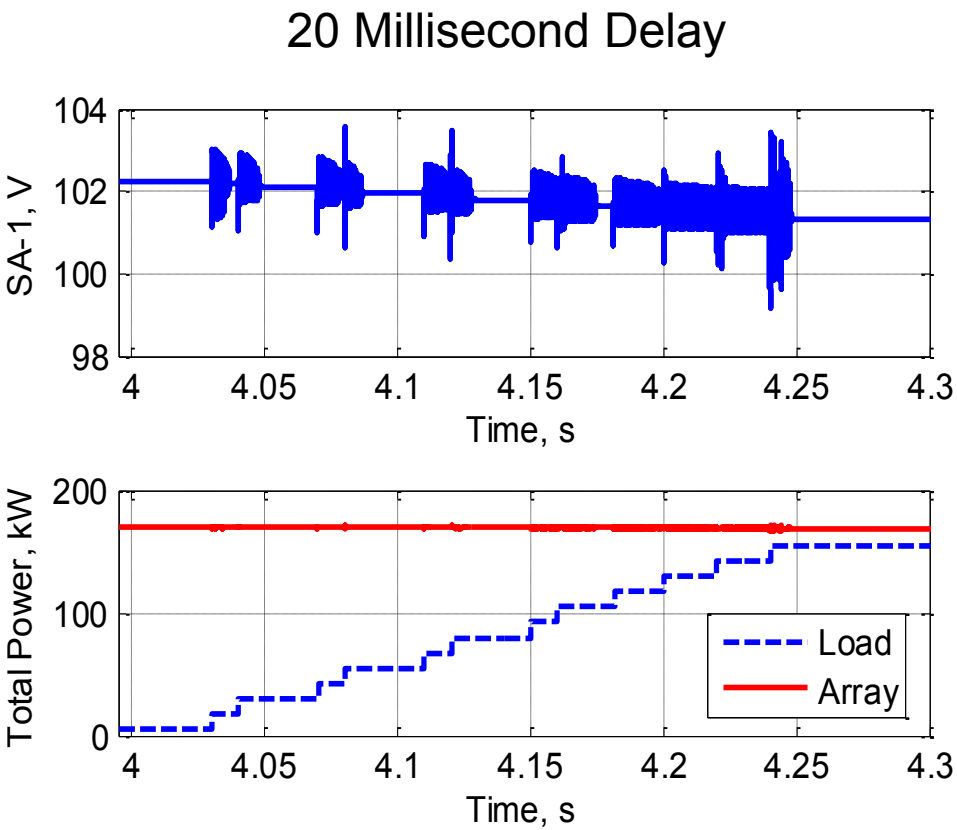
Non-Segmented Regulated Architecture



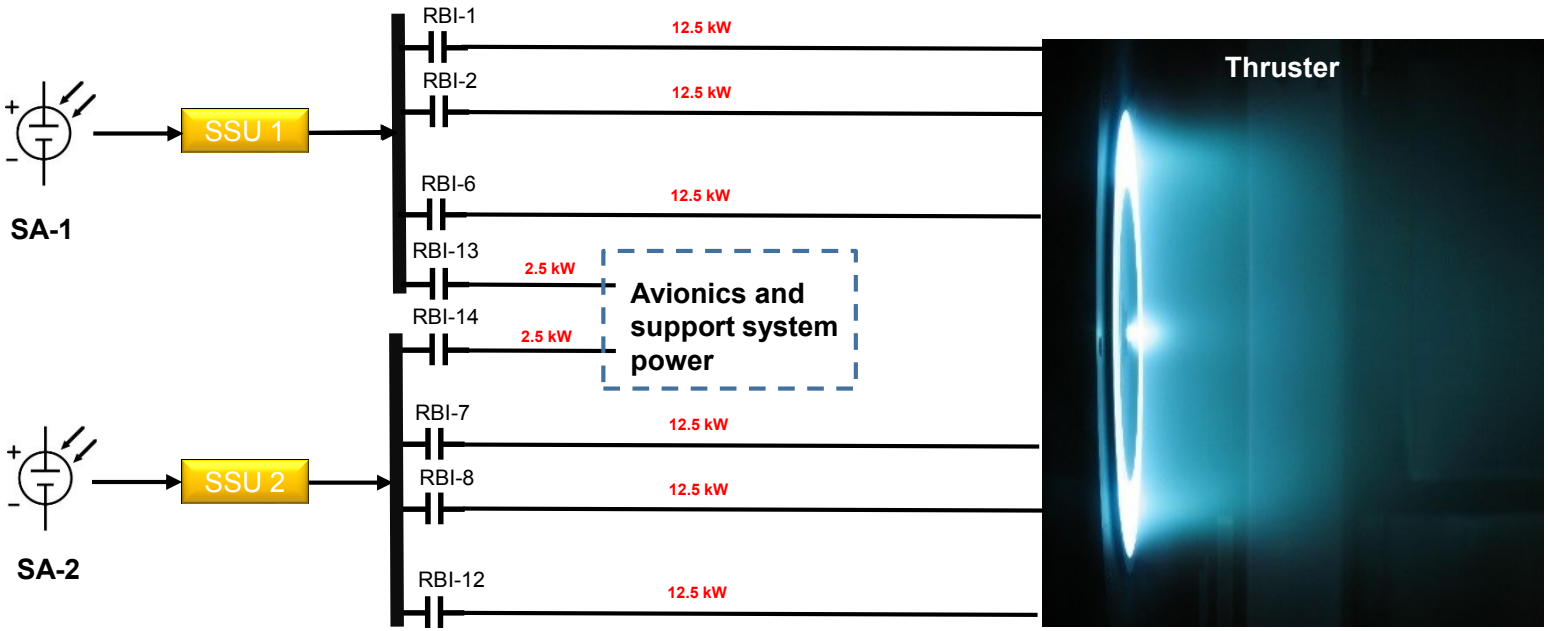
- Common bus architecture
- Sequential shunt unit (SSU) at the output of the solar array
  - SSU regulates the solar array to keep it at a constant voltage and load.

Transient Response to Incremental Commands

- As the load increases in power demand (loads turned on), the SSU adjusts.
- Allows for a much more consistent solar array voltage and helps avoids the large signal stability issues seen prior.
- Previous SA-1 V peak was ~135V. (Non-segmented 20 millisecond delay)



Segmented Regulated Architecture

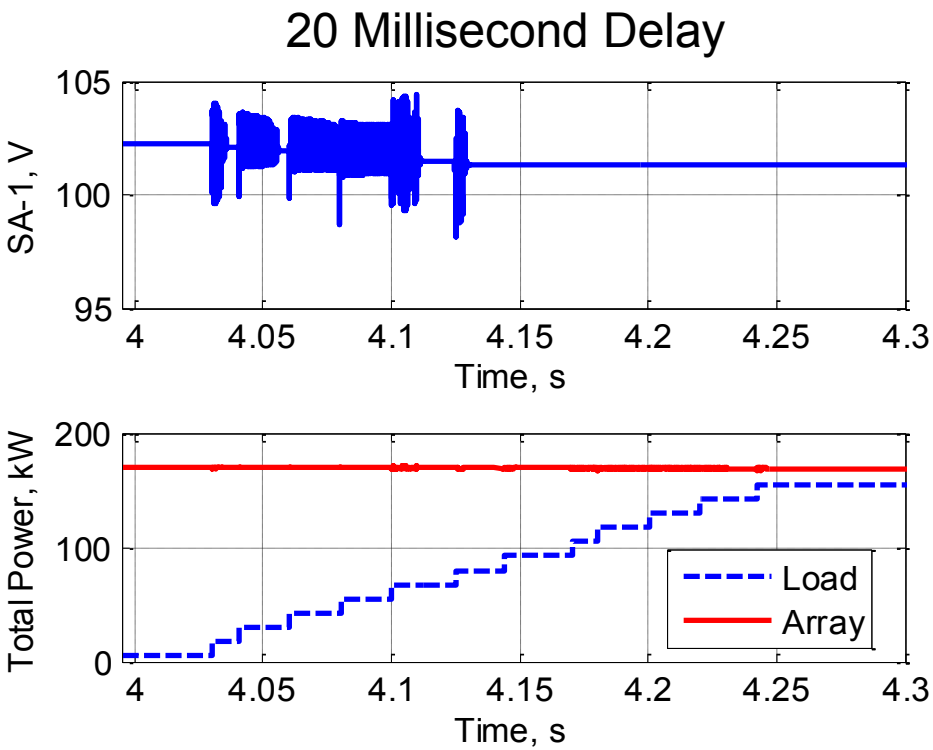


- Segmented bus architecture
- SSU at the output of the solar arrays

Transient Response to Incremental Commands

- Adding the SSU allows for a much more consistent solar array voltage and helps avoids the large signal stability issues seen prior.

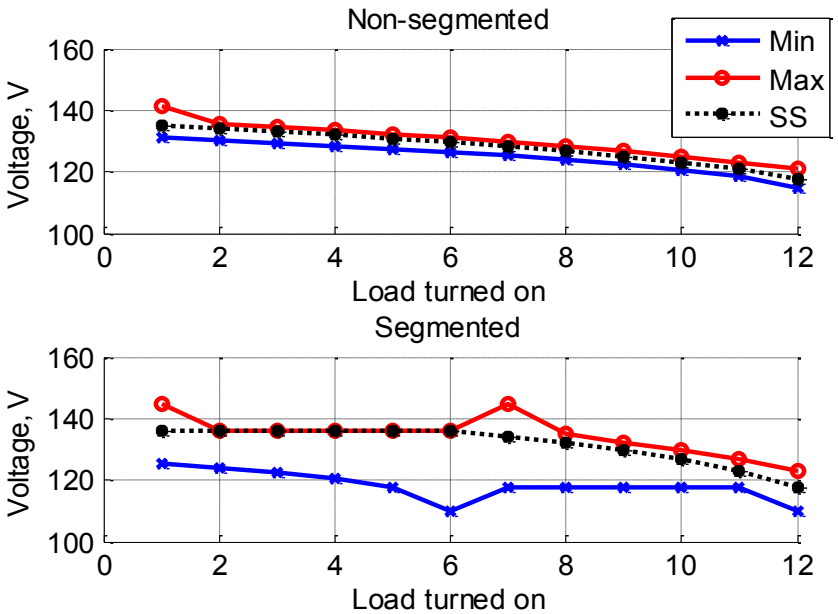
- Previous SA-1 V peak was ~150V. (segmented architecture 20 millisecond delay)



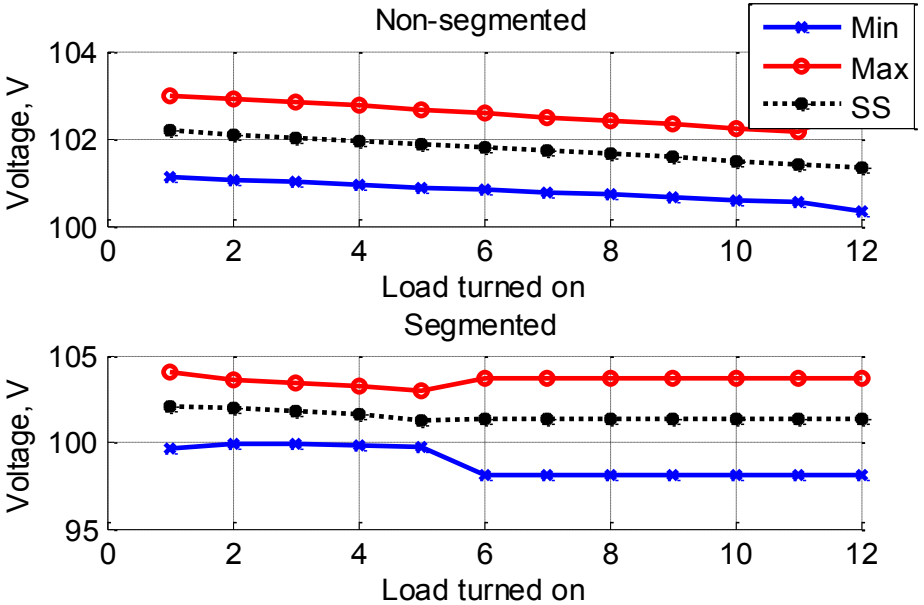
- In terms of peak voltages, the regulated non-segmented bus architecture with 20 millisecond provided the best response. (voltage magnitude)
- The segmented bus architecture (~1 volt higher peak) provided less oscillations, since only have the loads impact each solar array.

Voltage Response Comparison

Un-Regulated

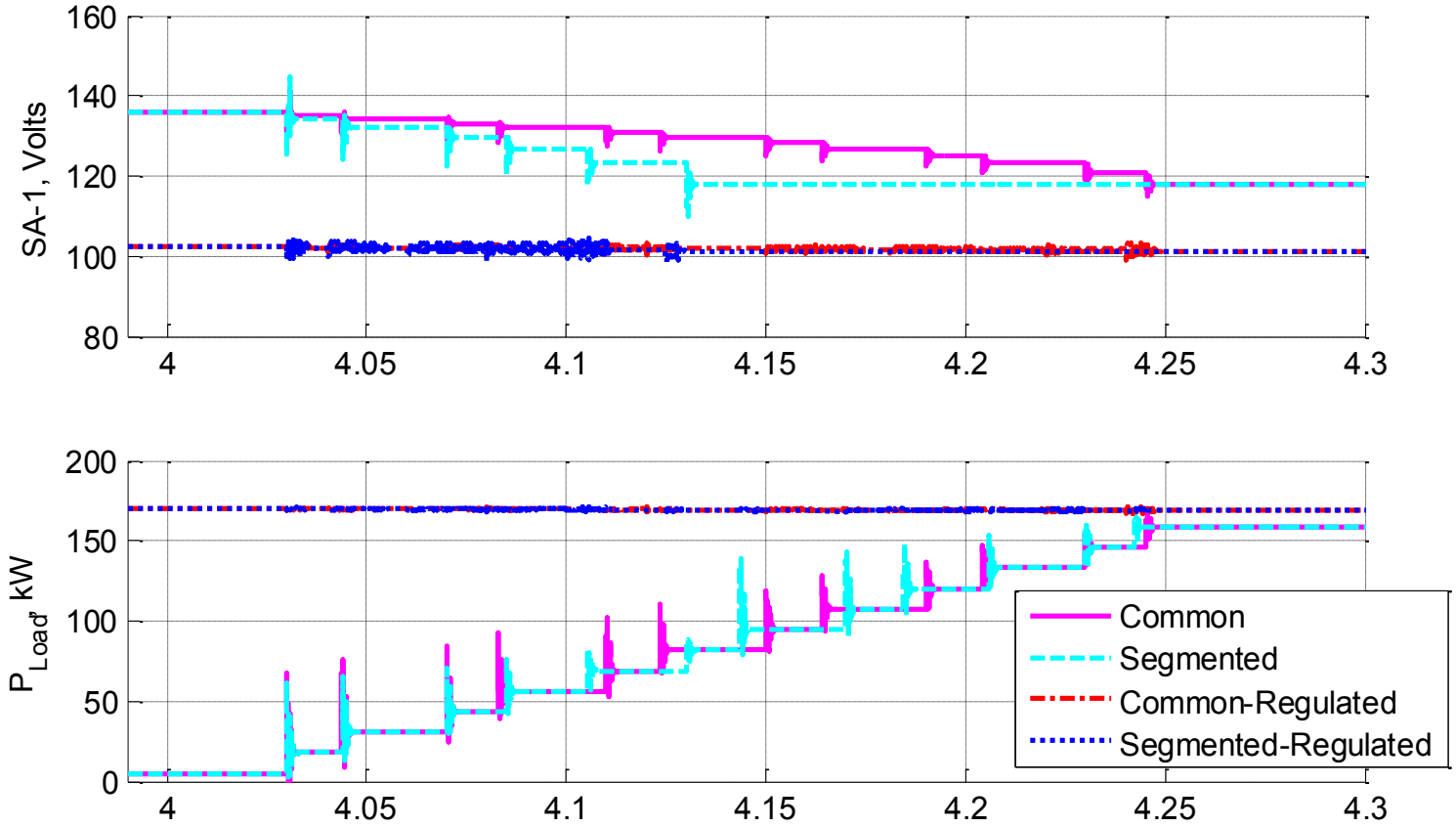


Regulated

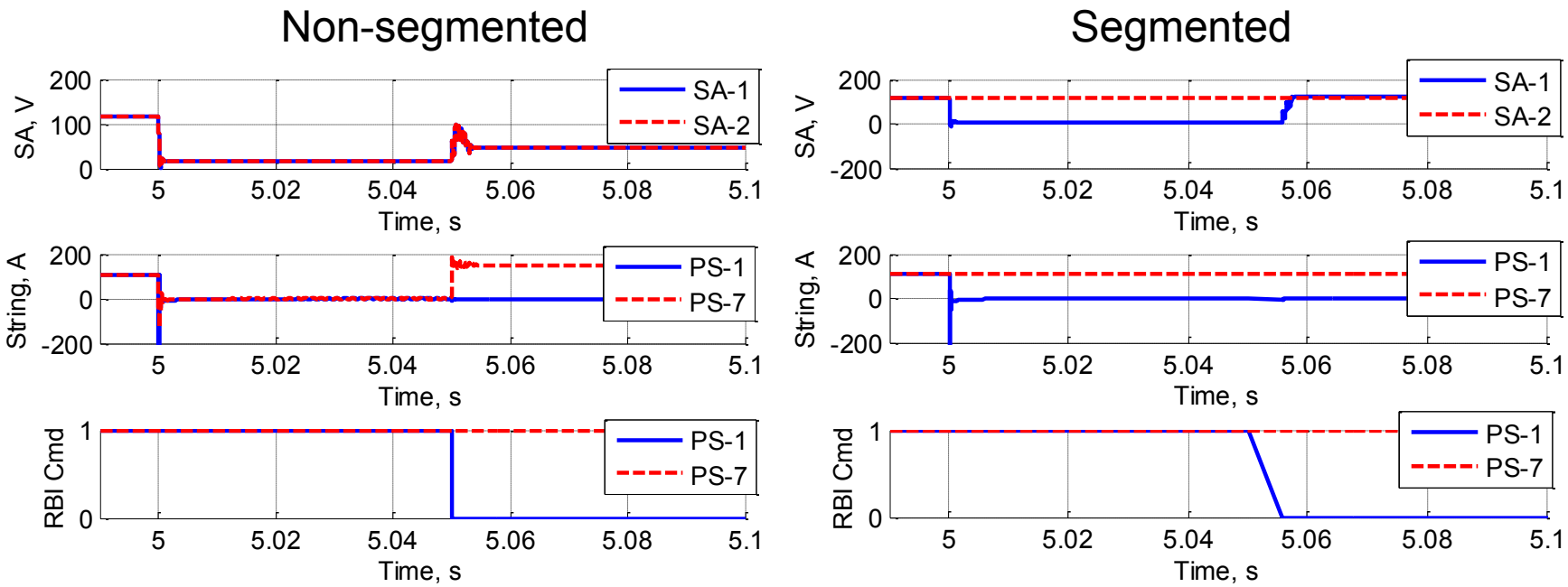


- Maximum, Minimum, and new steady-state voltage recorded as each load is turned on.
- Regulated limits the voltage range (max,min) and the steady-state operating voltage of the solar array and bus.

Voltage Transient Response - Incremental



Fault Response (non-regulated)



- Fault with non-segmented causes array voltage to drop and both SA voltages decrease past unstable equilibrium point (settle at the lower stable voltage).
- The segmented architecture allows the SA not on the fault to remain operational (un-impacted by fault).

Conclusion

- The stability of the solar electric power system can be greatly affected by how high power loads are applied to the system:
  - Attempting to turn on all the loads instantaneously will for the solar array to operate below the unstable equilibrium point further decreasing the solar array voltage.
  - Turning on the loads incrementally with small delay (20ms) provided adequate results.
    - This could also be done in hardware by adding capacitors or limiting in-rush current.

- Regulating the bus voltage resulted in the smallest transient power swings.

- Segmenting the bus (1 solar array per bus) provided additional fault protection by not impacting the non-faulted propulsion strings.

Future Work

- Refine the existing 50 kW class model to reflect the Power and Propulsion Element notional reference architecture
- Expand the model to evaluate 300 kW class systems

Thank you!
Any Questions