150kW Class Solar Electric Propulsion Spacecraft Power Architecture Model

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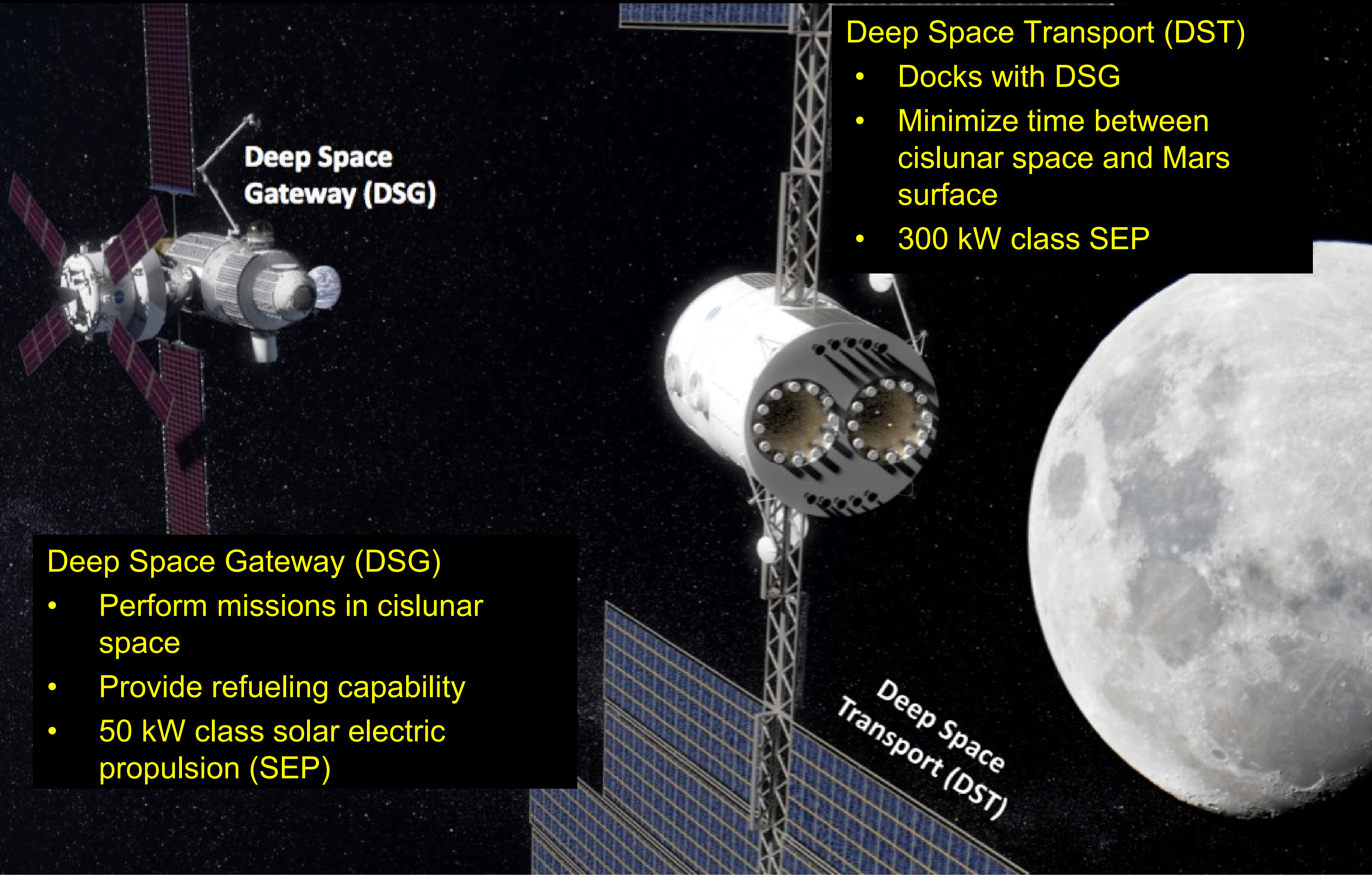
Overview



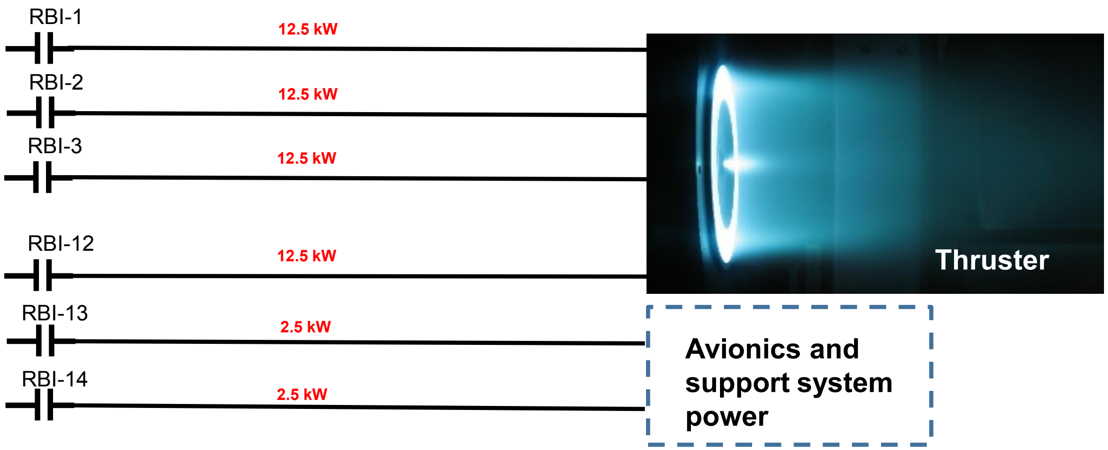
Deep Space Transport (DST)

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

Deep Space Gateway (DSG)

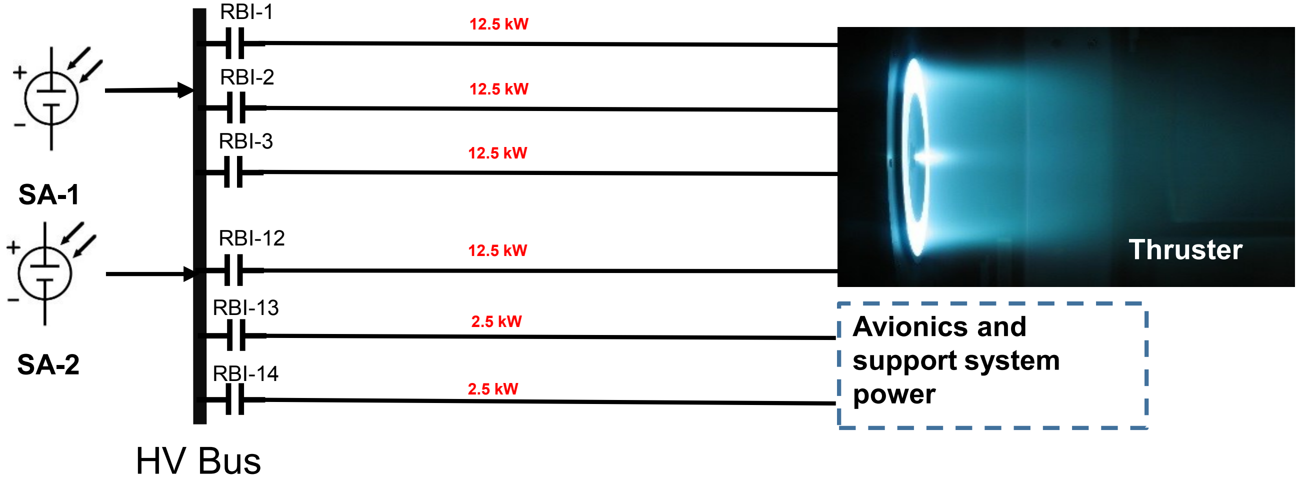
- Perform missions in cislunar space
- Provide refueling capability
- 50 kW class solar electric propulsion (SEP)

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).

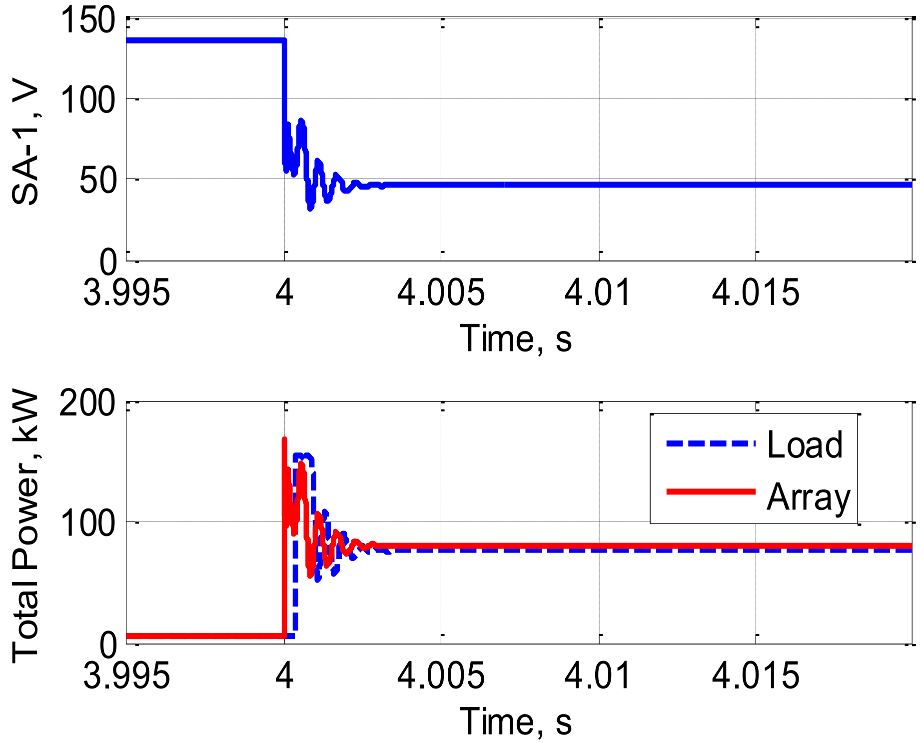
Non-Segmented Architecture



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

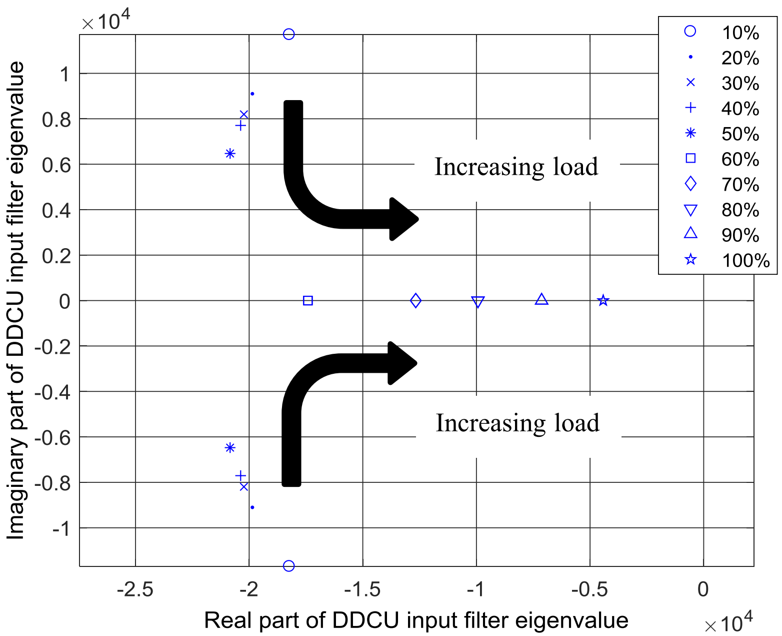
Transient Response – All Loads Turned On

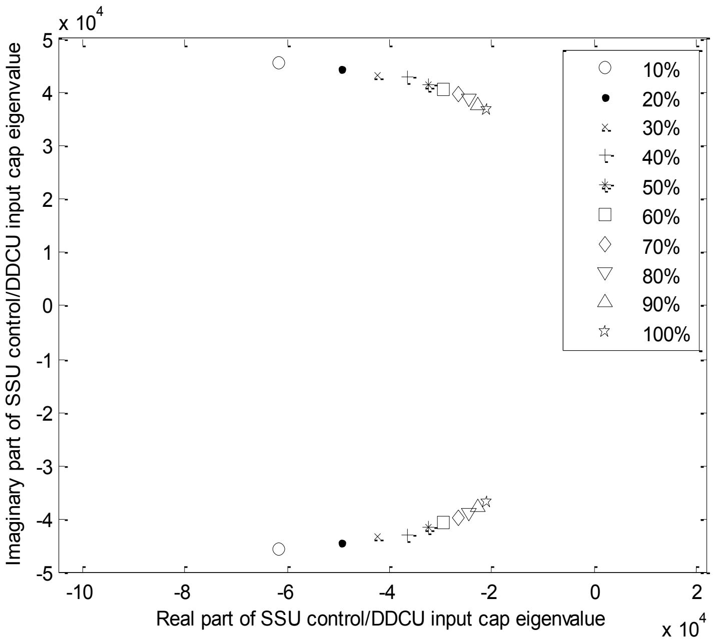
- All propulsion strings RBI's are closed at the same time.
- Solar Array 1 and 2 responses are identical.
- SA voltage reduces from the open circuit voltage (136 V) and reduces to 46 Volts.
- Total power increases from 5k+W to 80 kW. But system should be near 155kW (+losses)



Stability Analysis – Small Signal

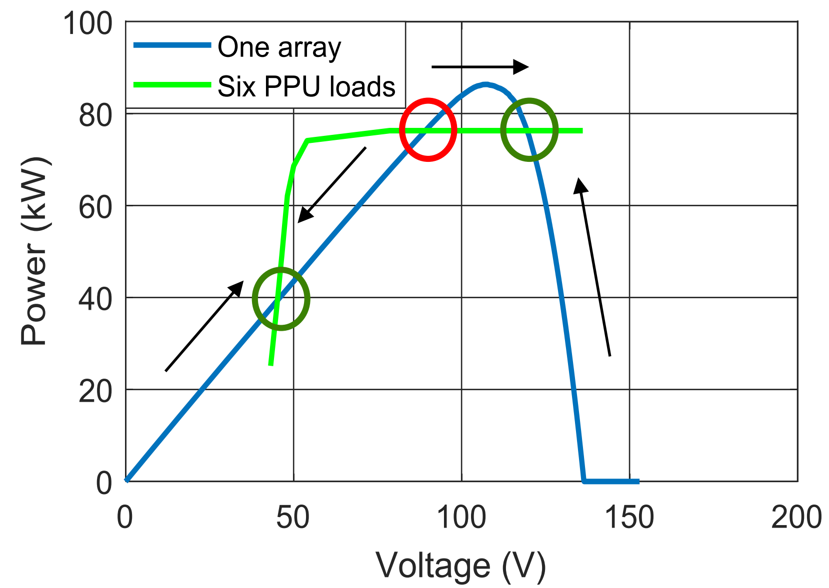
- PCKA developed tool to calculate eigenvalues of the power system
  - ISS Model Library
- Jacobian matrix calculated at 10 load levels in equal steps from 10% to 100% for all 12 PPUs
- Eigenvalue real parts are negative, therefore stability is not of a concern

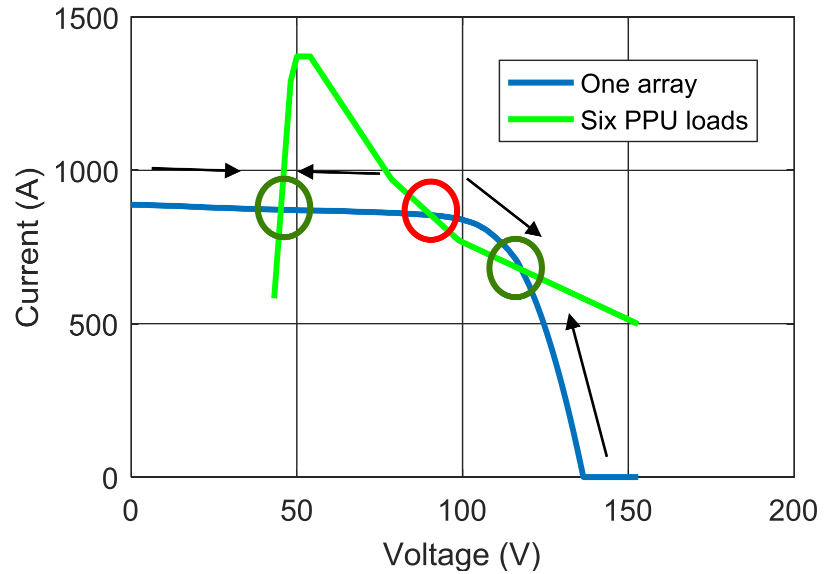




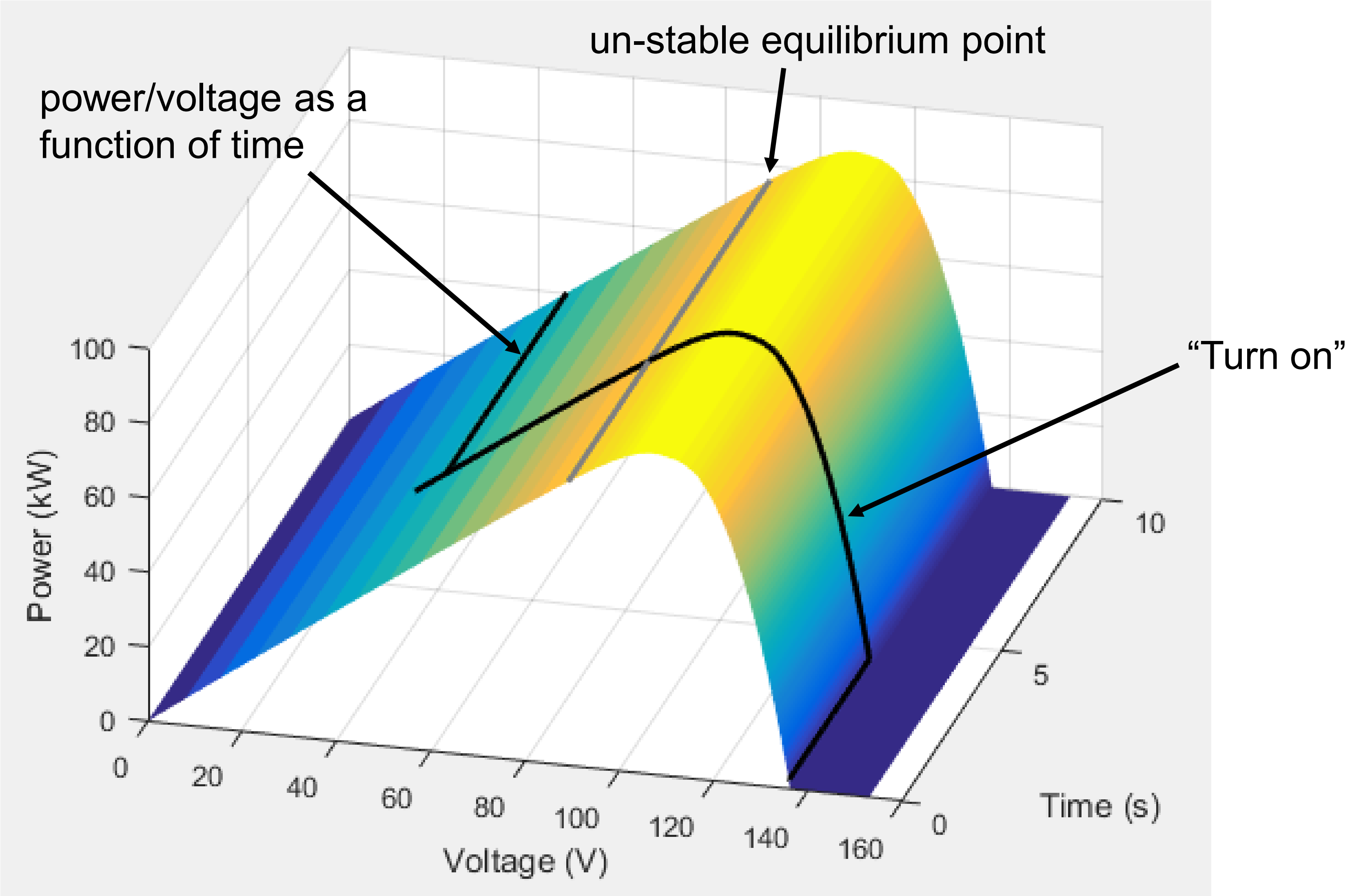
Stability Analysis – Large Signal

- 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



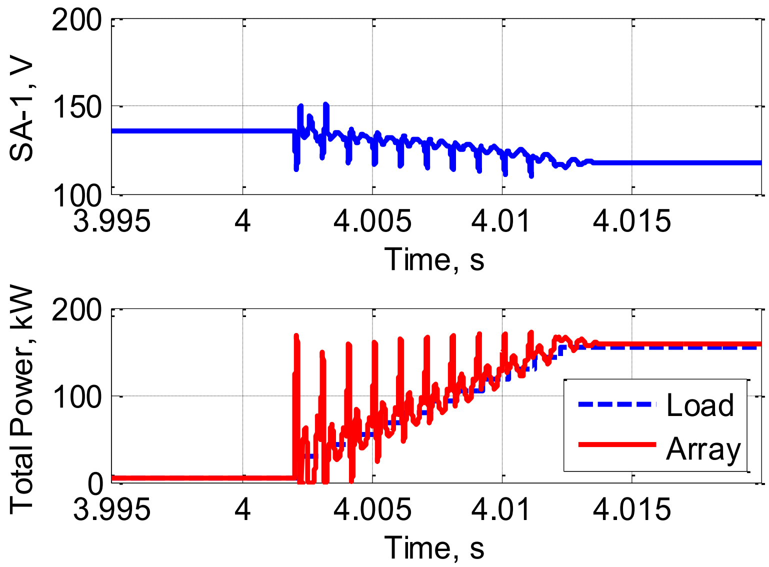


Power/Voltage Curve Vs Time

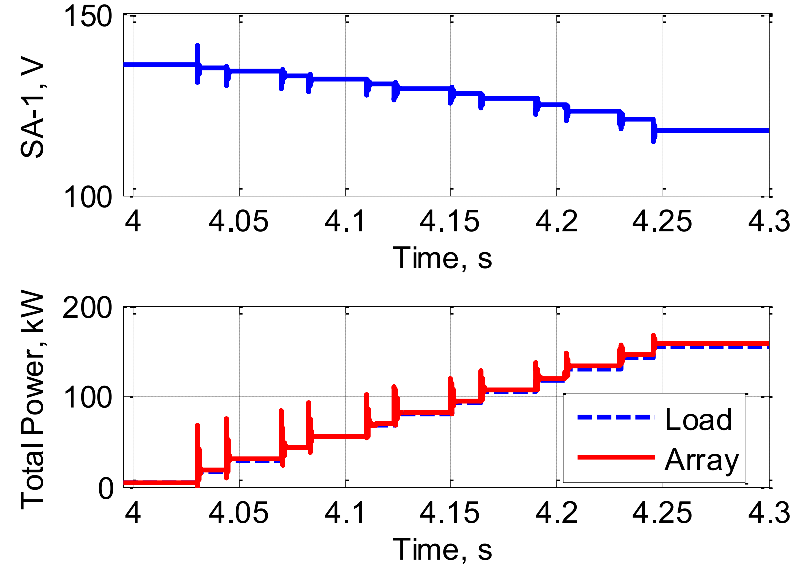


Transient Response to Incremental Commands

1 Millisecond Delay

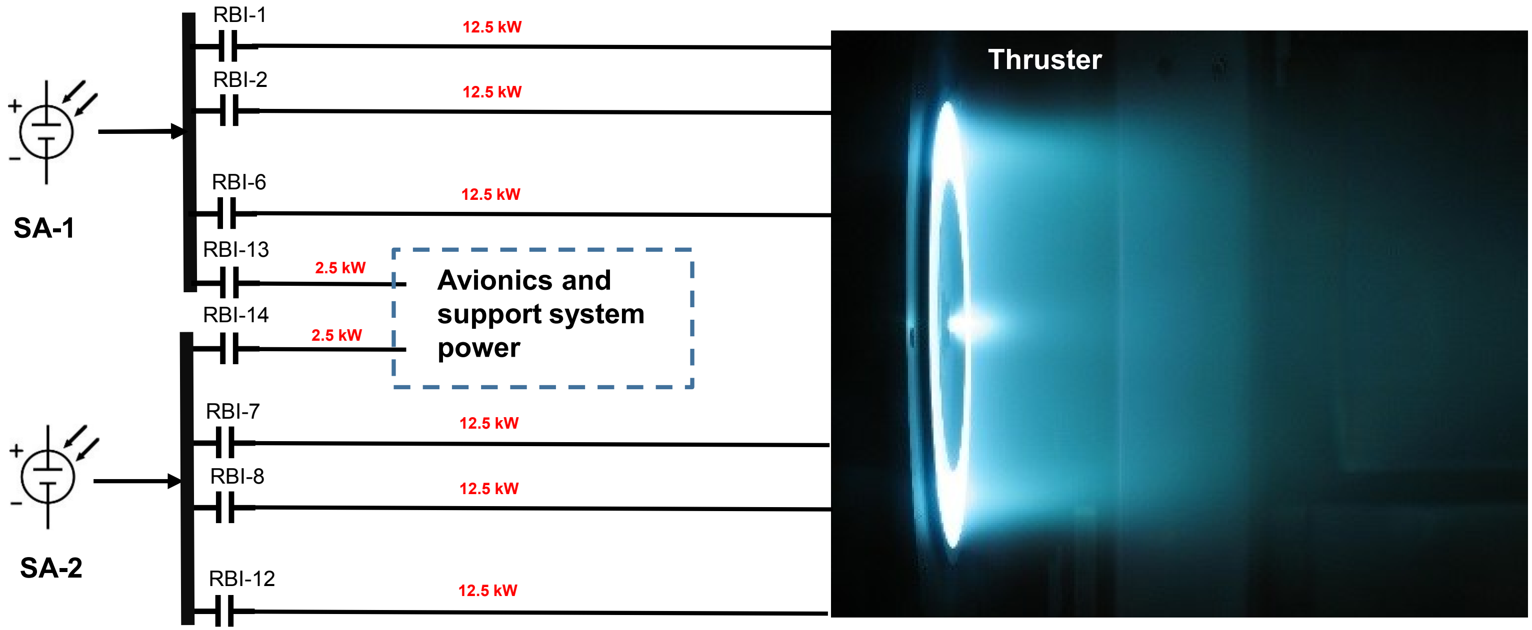


20 Millisecond Delay



- 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.

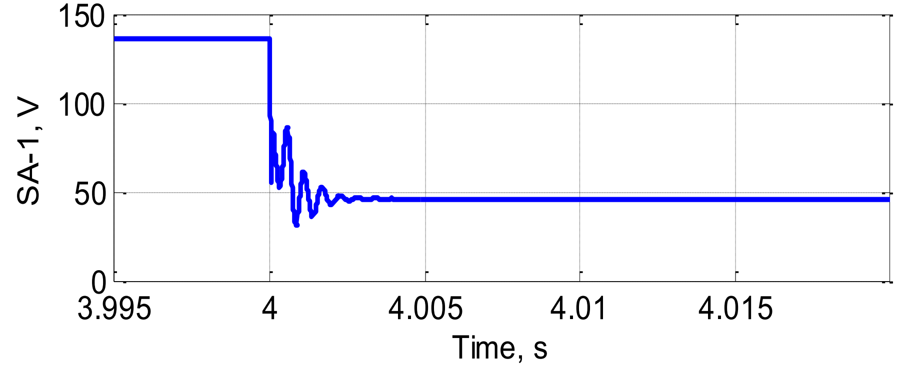
Segmented Architecture

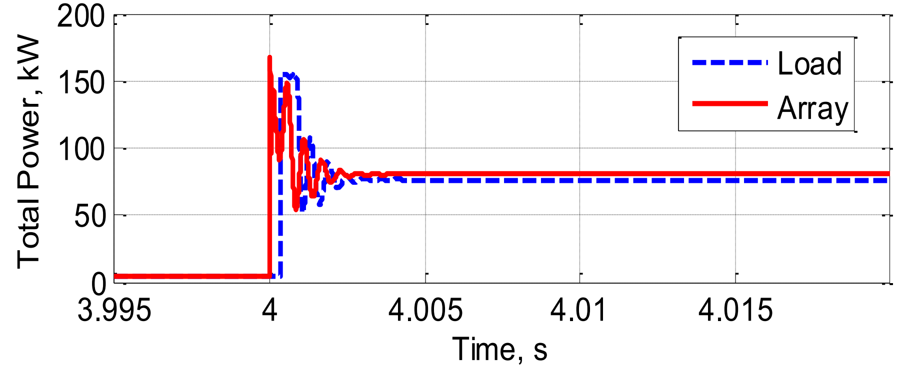


- Segmented bus architecture – each solar array powers a single bus with +77.5kW of power
- Each bus provides power to 6 propulsion strings, 75kW + losses, and 1 string of avionics 2.5kW.

Transient Response – Turning on Loads

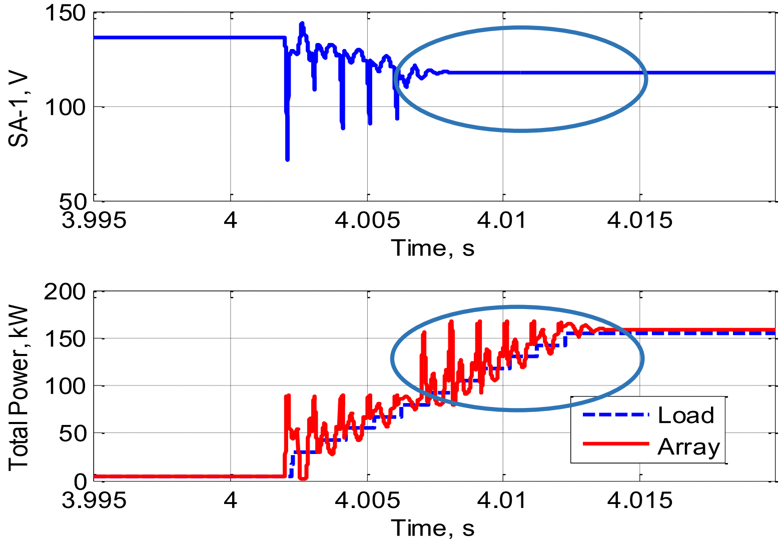
- Turning on all loads at the same time with the segmented bus at the same time has the same response as the non-segmented.
- This result is consistent regardless of architecture.



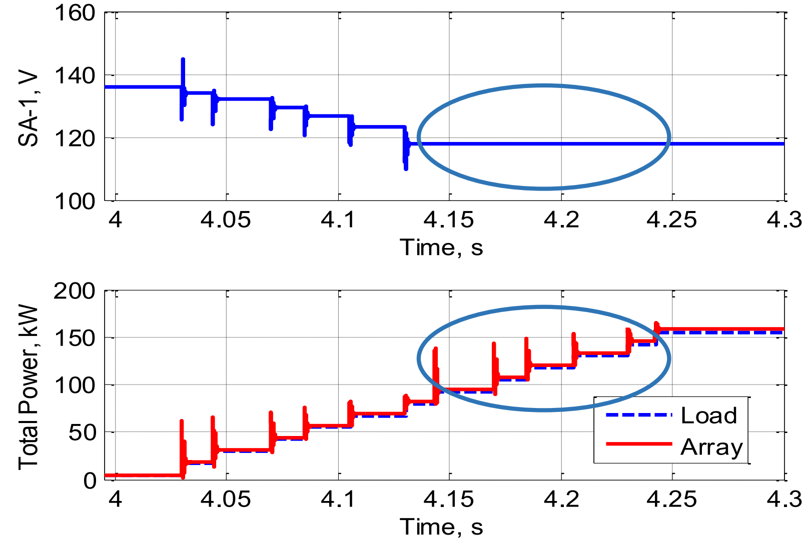


Transient Response to Incremental Commands

1 Millisecond Delay



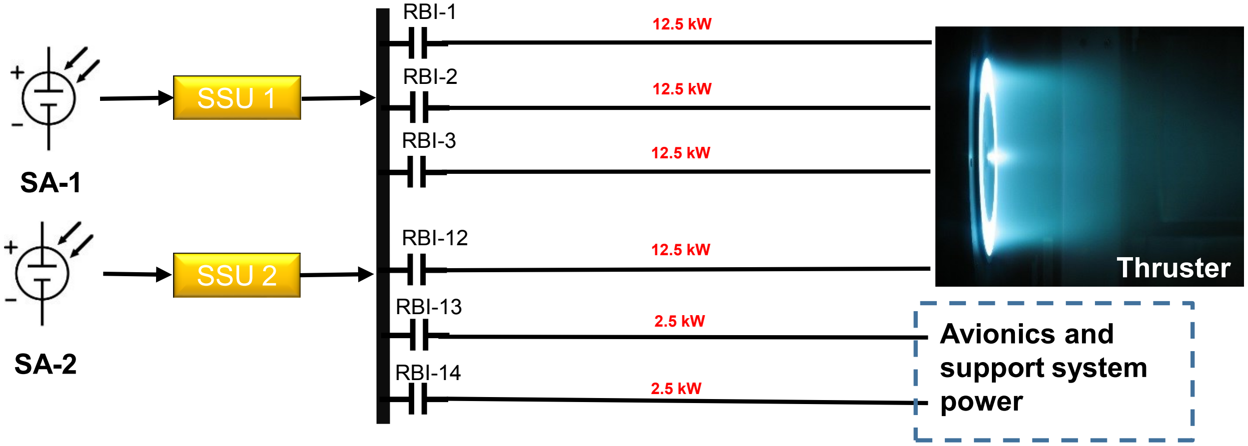
20 Millisecond Delay



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.

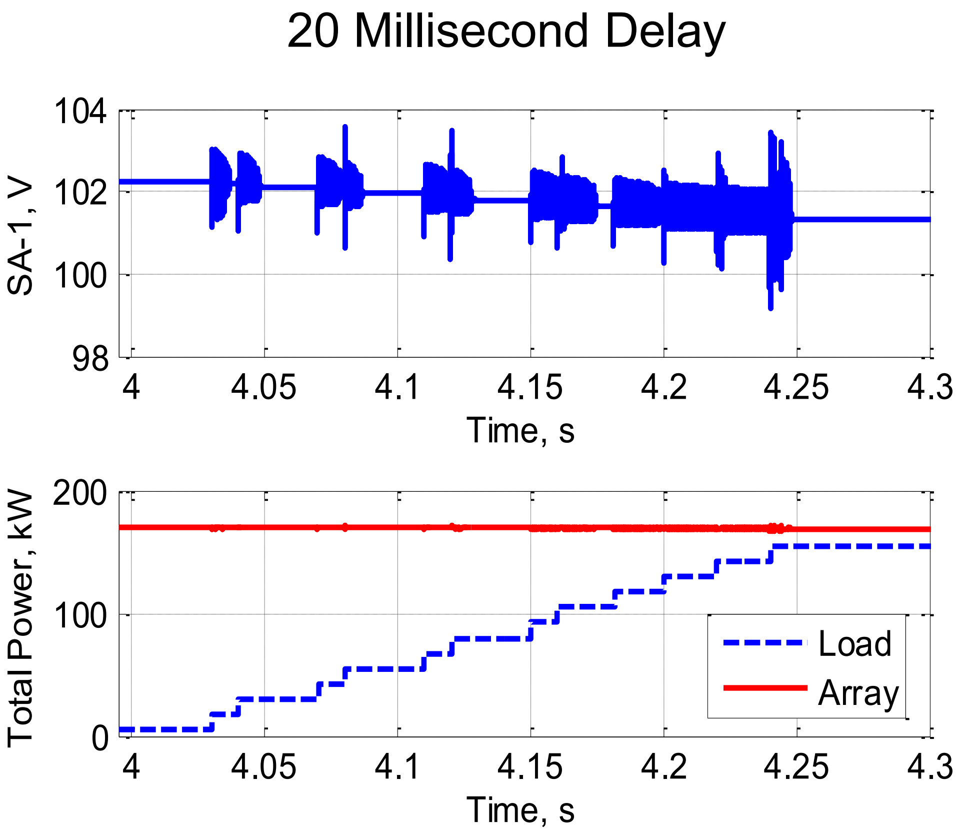
Non-Segmented Regulated Architecture



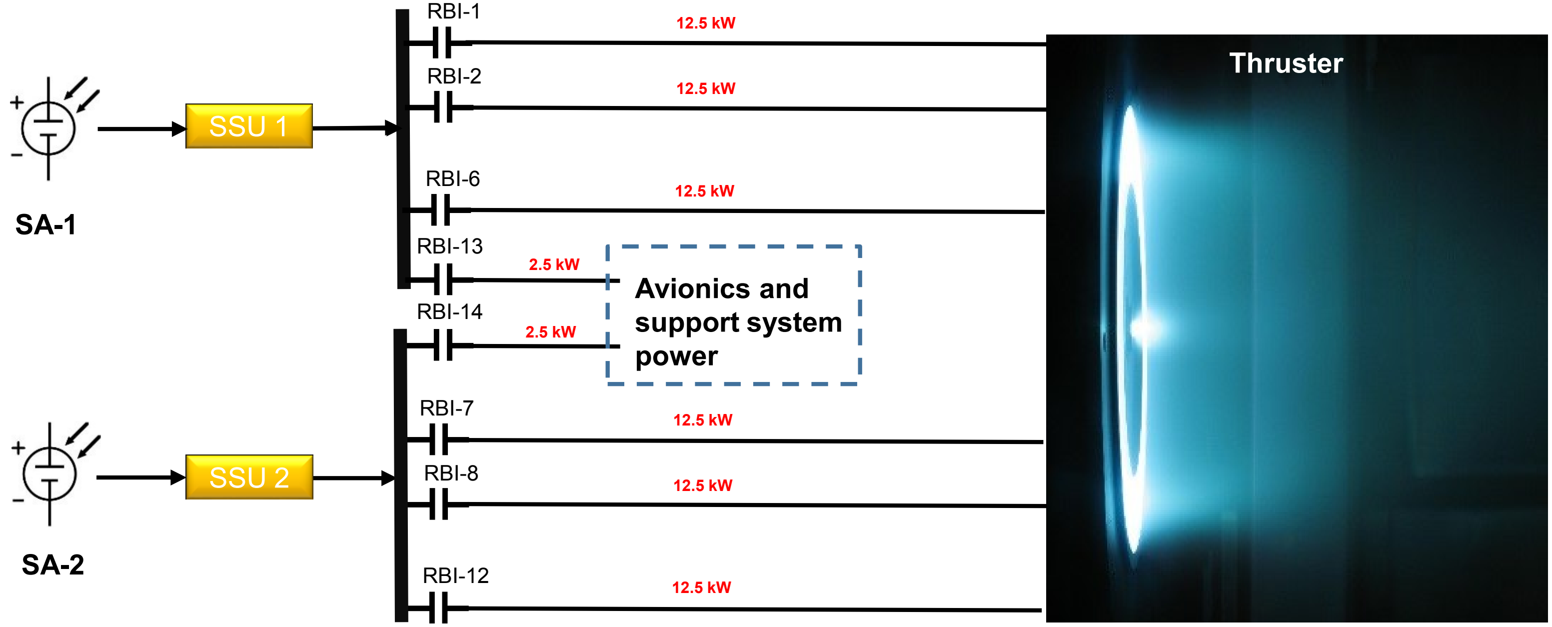
- Common bus architecture
- Sequential shunt unit (SSU) at the output of the solar array
  - SSU regulates the solar array to keep it at a constant voltage and load.

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)



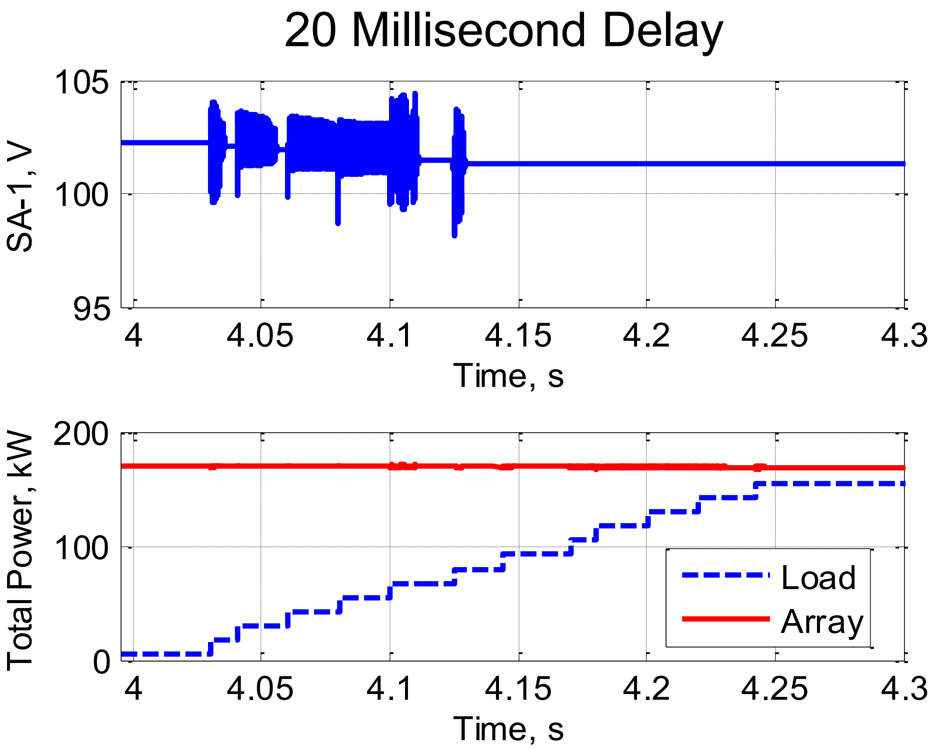
Segmented Regulated Architecture



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

Transient Response to Incremental Commands

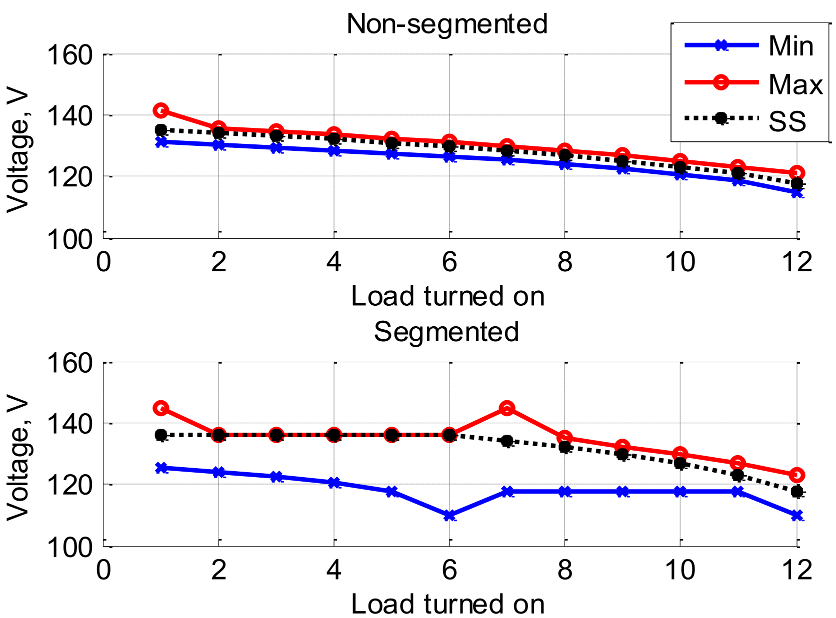
- Adding the SSU allows for a much more consistent solar array voltage and helps avoids the large signal stability issues seen prior.
- Previous SA-1 V peak was ~150V. (segmented architecture 20 millisecond delay)



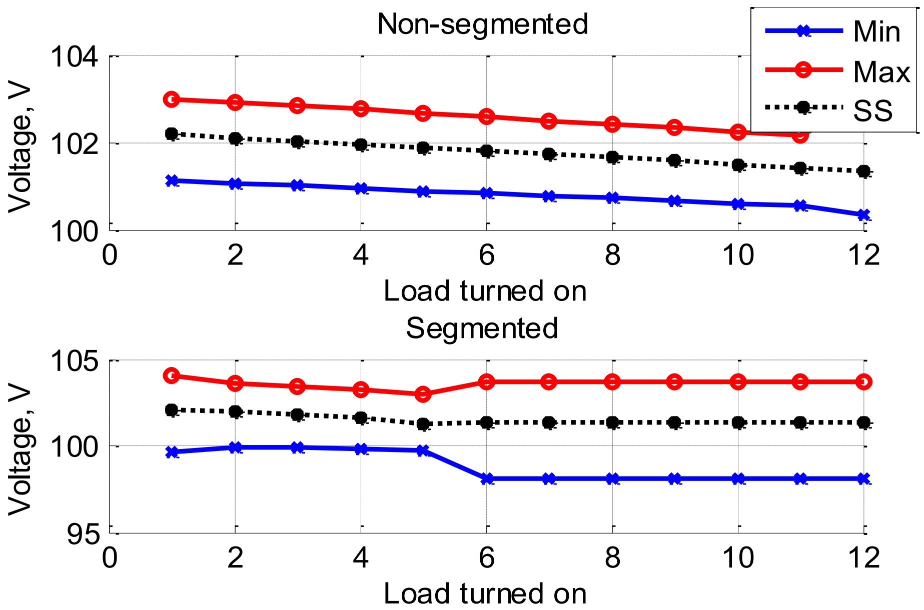
- In terms of peak voltages, the regulated non-segmented bus architecture with 20 millisecond provided the best response. (voltage magnitude)
- The segmented bus architecture (~1 volt higher peak) provided less oscillations, since only have the loads impact each solar array.

Voltage Response Comparison

Un-Regulated

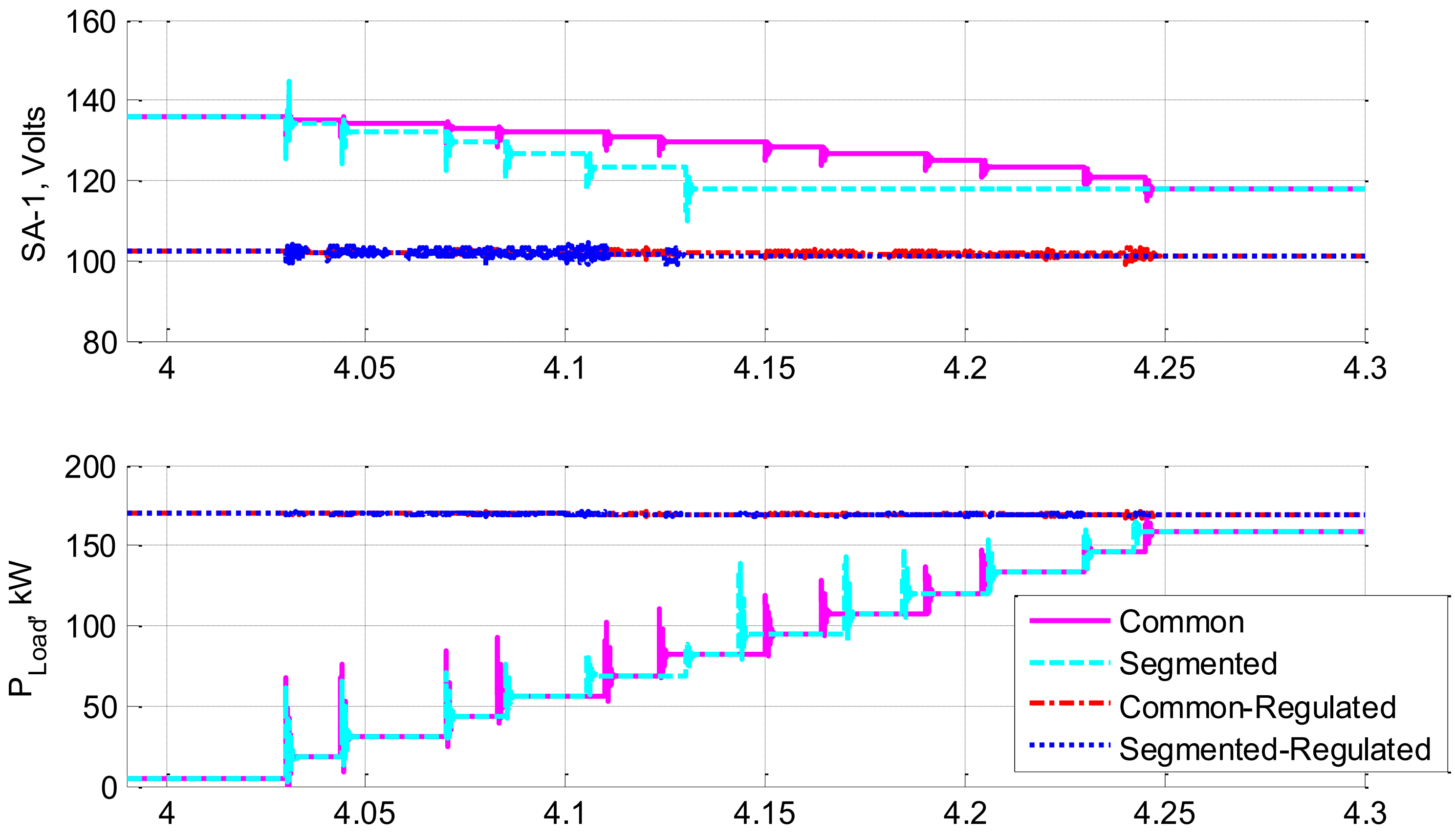


Regulated



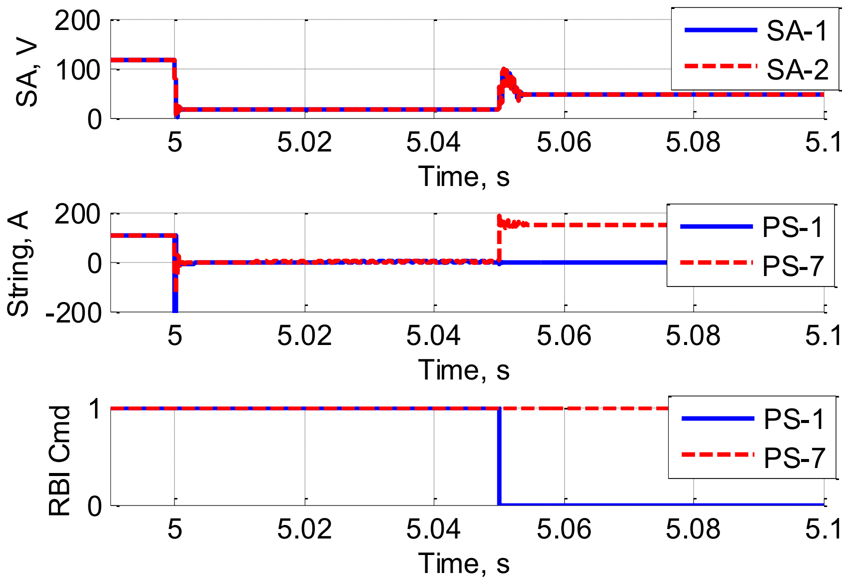
- Maximum, Minimum, and new steady-state voltage recorded as each load is turned on.
- Regulated limits the voltage range (max,min) and the steady-state operating voltage of the solar array and bus.

Voltage Transient Response - Incremental

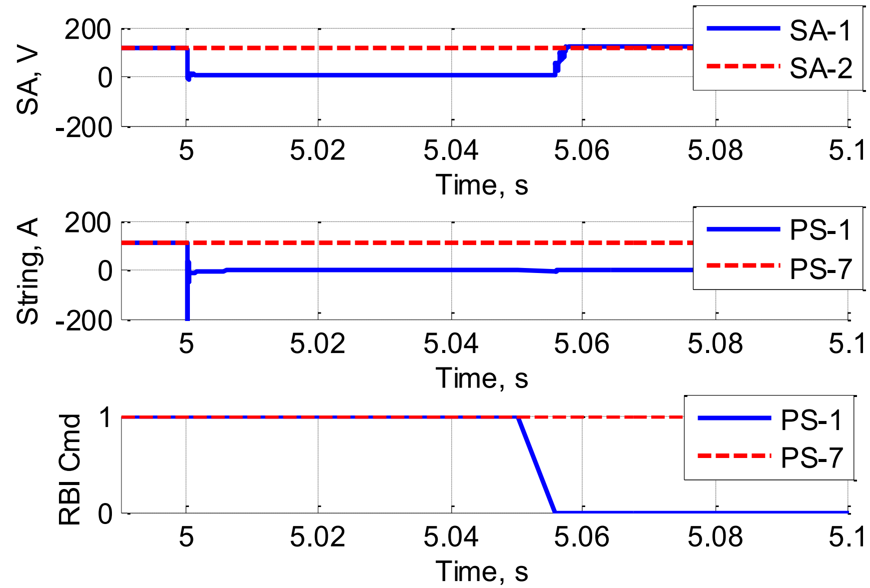


Fault Response (non-regulated)

Non-segmented



Segmented



- 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

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