Electronic Load Evaluation for Aerospace Power System Verification

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Outline

- History of Use
- Electronic Load Background
- Load Step Transient Verification
- Impedance & Stability Measurement
- Conclusion and Future Work

History of Use (GRC PMAD Branch)

- **Electronic load (e-load) use limited for verification purposes at GRC**
  - Actual loads used to load down the system
  - Step-load transient testing performed with resistive load banks
  - Only allowed for steady-state tests & measurements
- **Use of these loads has produced misleading results**
  - Transient & Impedance results non-repeatable, non-representative
  - Core issues never truly understood
- **Current need to understand the issue**
  - Contractors are proposing use of electronic load banks for verification across projects
  - Use of resistive load banks becomes difficult as time progresses and systems grow to higher power and/or voltages

Electronic Load Background

- **Come in many different flavors**
  - Switched resistive, MOSFET controlled, hybrid, switched (converter)
  - Unidirectional and bidirectional
- **Advantages and disadvantages to each**
- **Goal of this presentation is not to fully evaluate each load type**
- **Goal is to identify possible limitations of electronic loads to be aware of for verification testing**
  - Important since electronic loads are being proposed for use in verification

Electronic Load Background (cont.)

- **Standard spacecraft loads are typically Constant Power (converters) or Resistive (heaters)**
- **E-load standard modes**

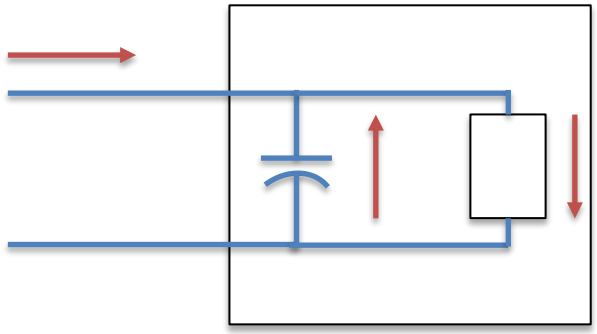
Constant Resistance | Constant Current | Constant Power | Constant Impedance

- **Spacecraft load types can only be represented by e-loads within a limited**
  - Bandwidth
  - Resolution

Load-Step Transient Verification

Evaluate Common Electronic Loads (Load Steps)

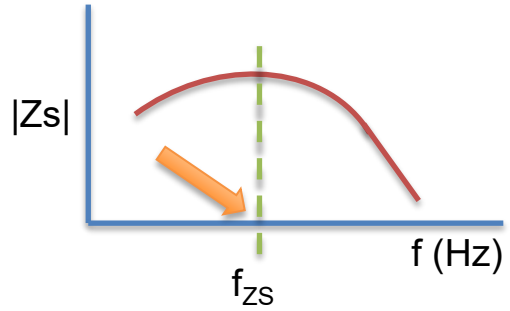
- **Initial thoughts prior to investigation**
  - Standard e-loads not suitable for load-step transients
  - Most e-loads contain input capacitance
    - Capacitor discharges into load-steps
    - Discharge corrupts/mitigates load-step transient response



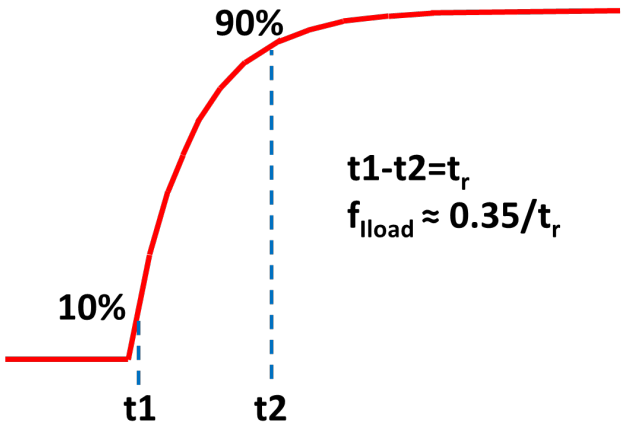
- **When are e-loads acceptable for load-step transient testing?**
  - Strategy is to develop rule of thumb based on EPS performance vs. e-load bandwidth

Definitions and Approach

- **Source Bandwidth**
  - In this presentation, refers to frequency at which the peak source impedance occurs (ignoring leakage inductances)
  - Characterized by source impedance measurement
  - This is not the loop crossover frequency of the converter control loop



- **Load Bandwidth**
  - Refers to the current/power/impedance response 3dB bandwidth
  - Easily characterized based on transient response tests

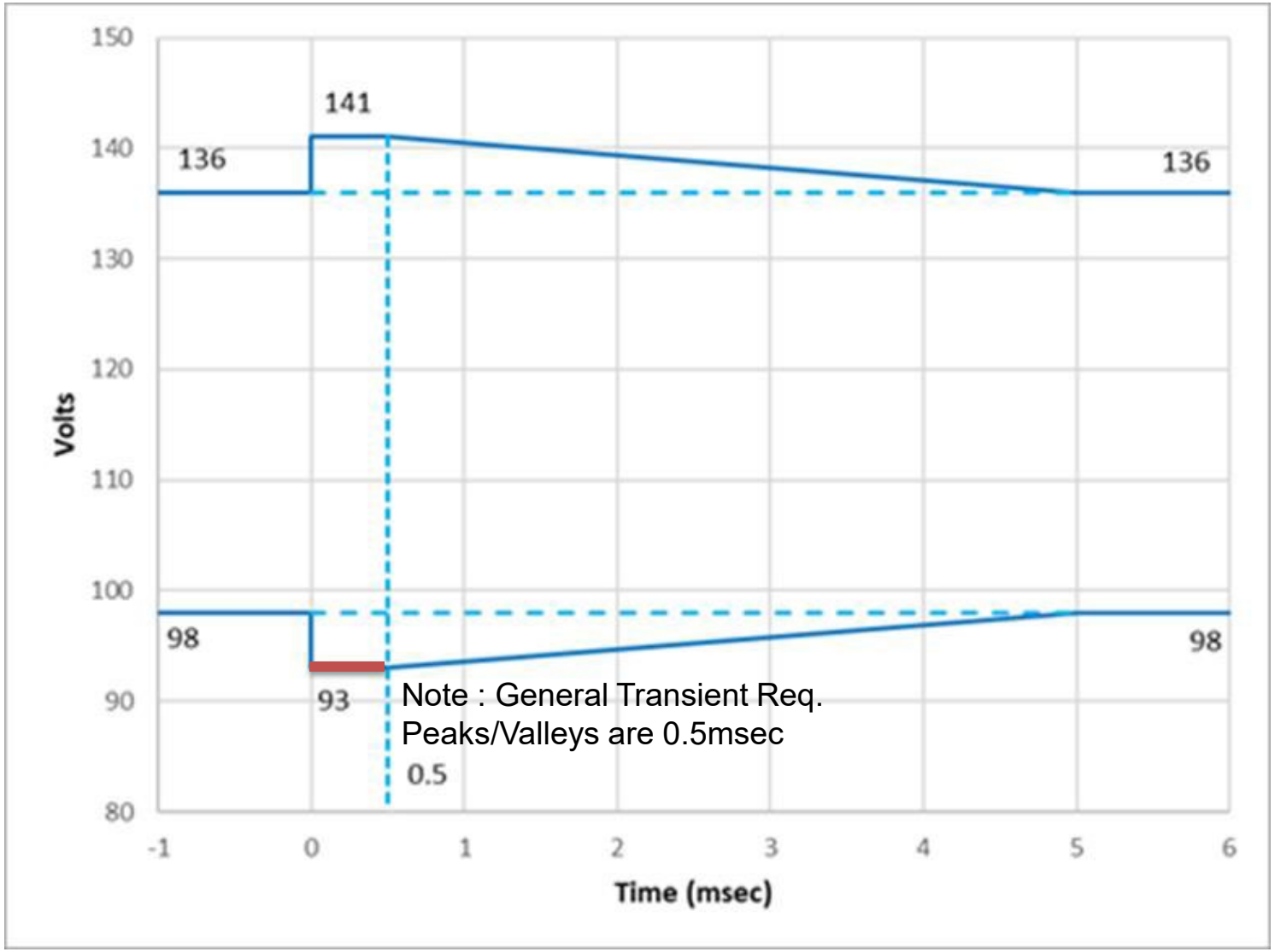


Electronic Load Bandwidth < Source Bandwidth

- **AMPS[1] DDCU[2] as source**
  - COTS[3] e-load and resistive bank (FET switched) step loads
  - 1-2 / 2-1, 1-3 / 3-1 kW load steps, transient tests performed at 120Vdc

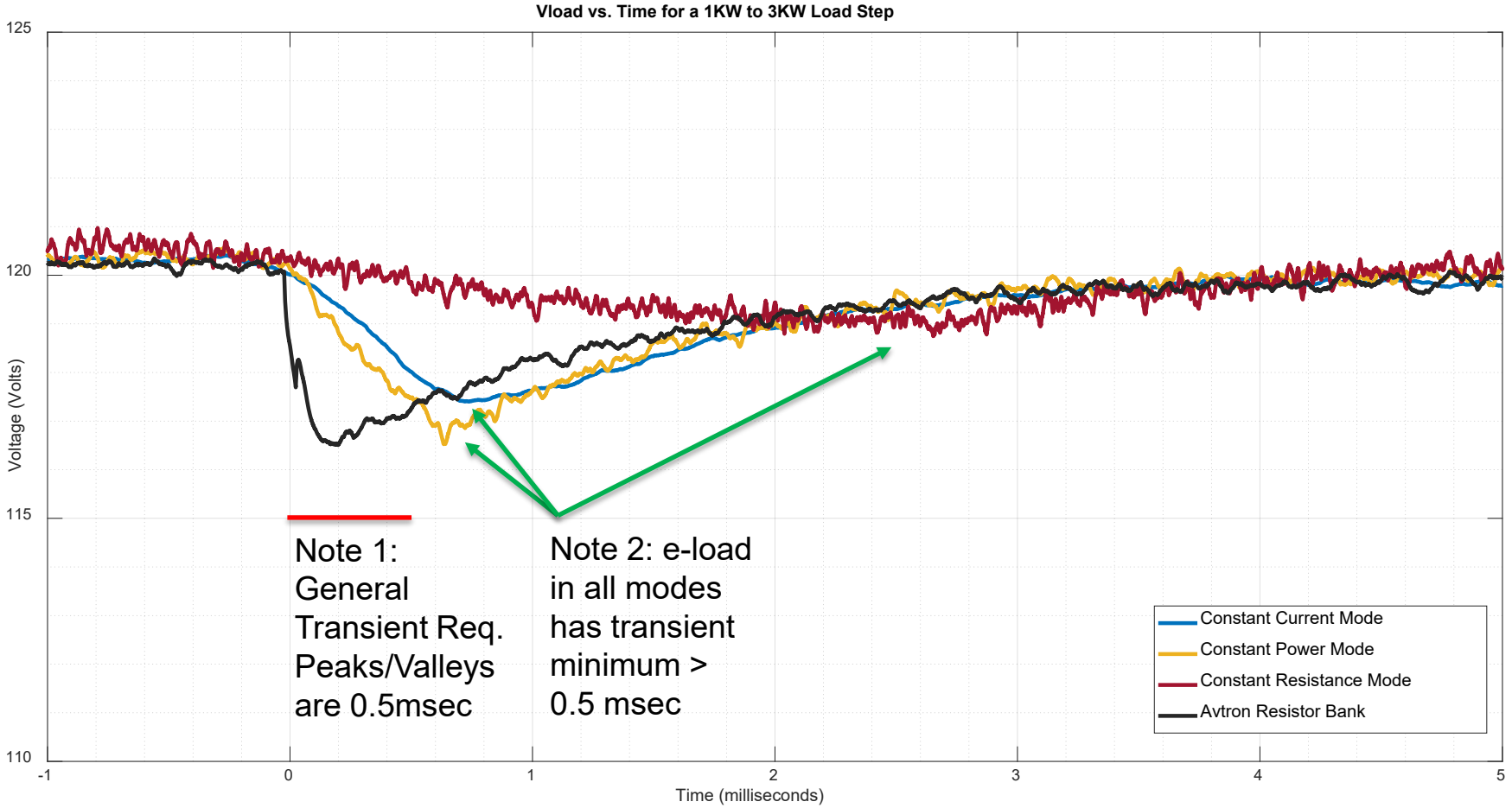
1. AMPS: Advanced Modular Power Systems
2. DDCU: DC-DC Converter Unit
3. COTS: Commercial-of-the-shelf

Load Step Transient Windows



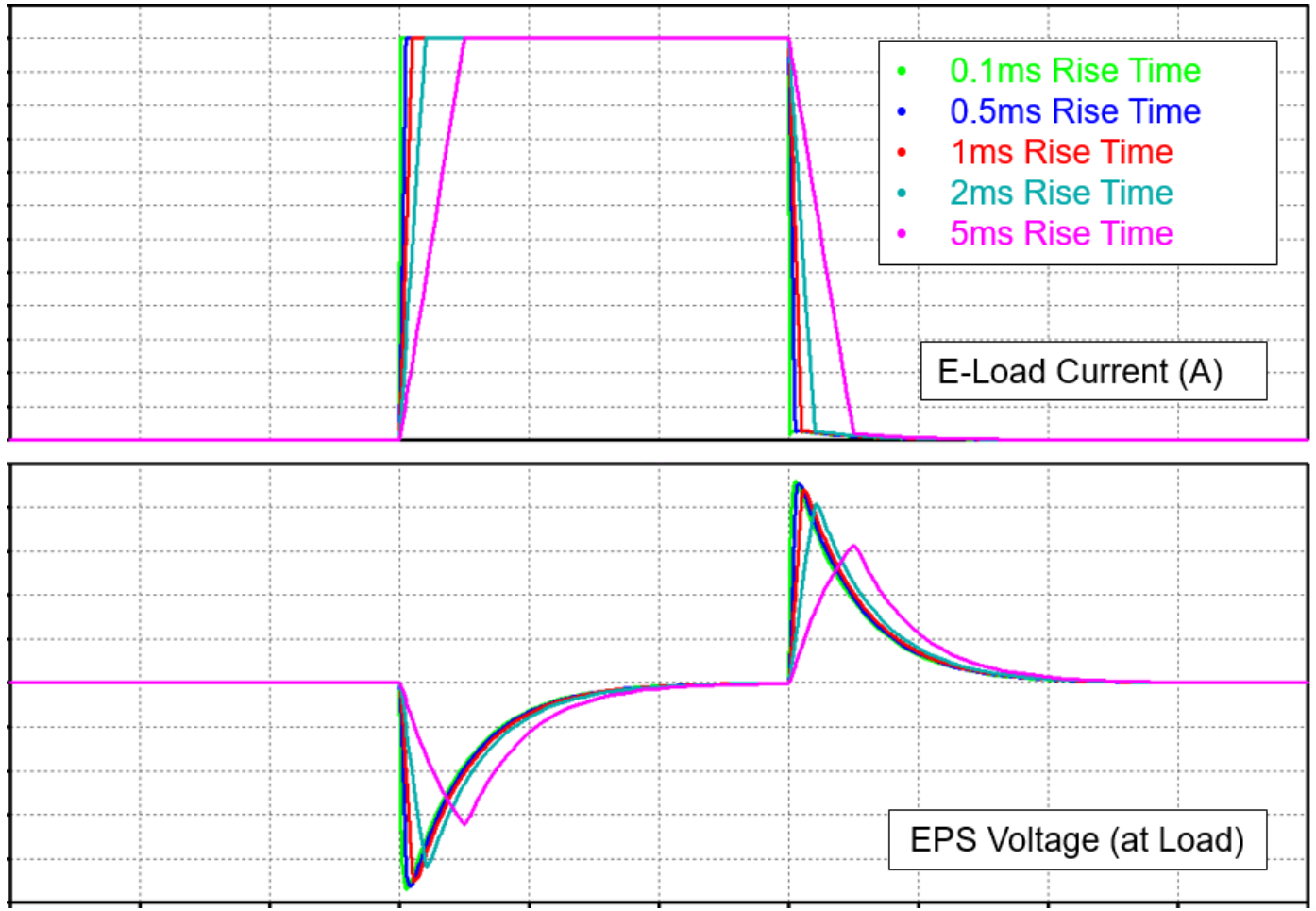
Electronic Load Bandwidth < Source Bandwidth

- **Normalized (~120Vdc) / filtered 1-3kW load steps**
- **COTS e-load is too slow in all modes**



LTSpice Simulation Example of Load Bandwidth Changes

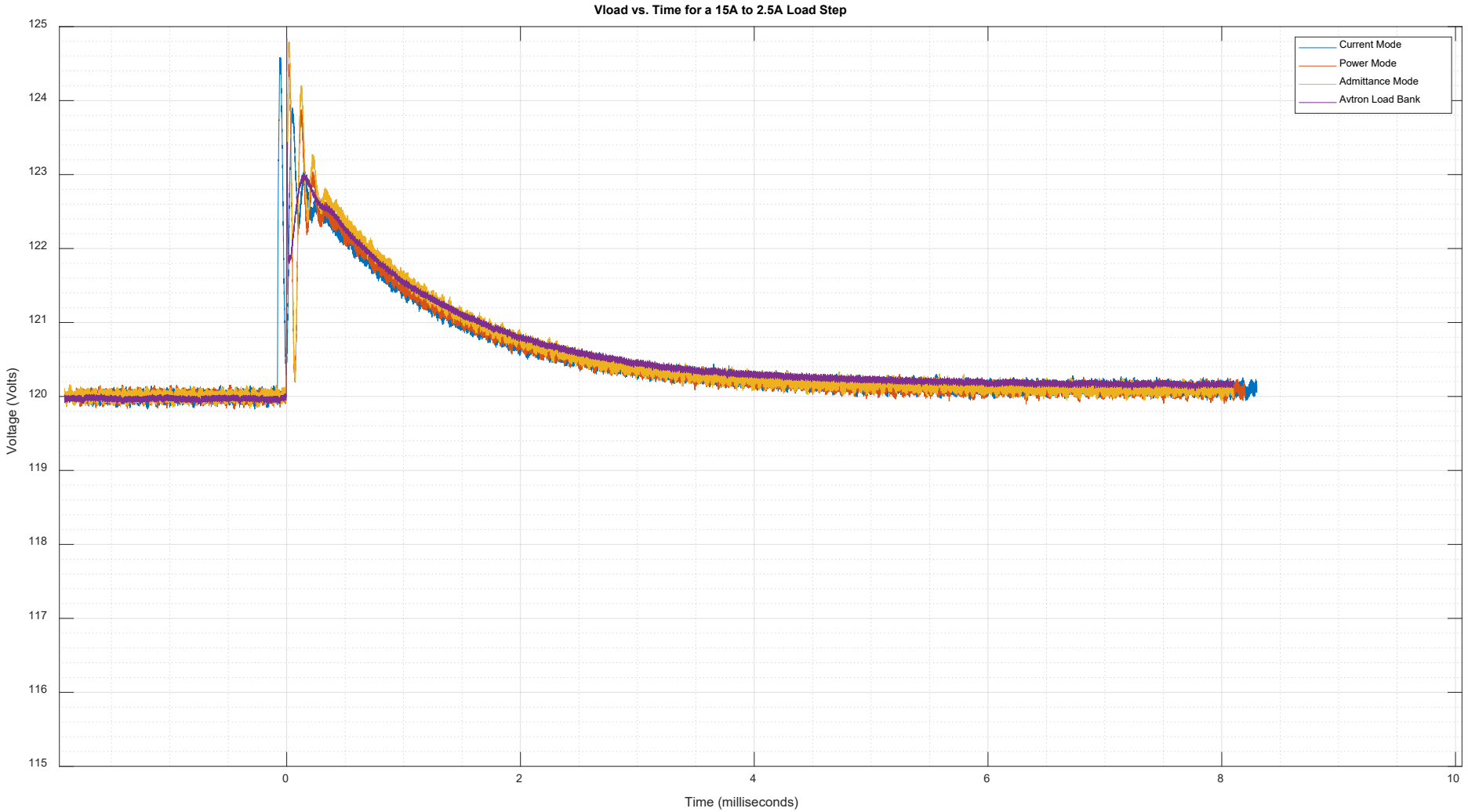
- **Load step transient results with varying rise times**
  - Slow rise times represent bandwidth impacts of electronic loads



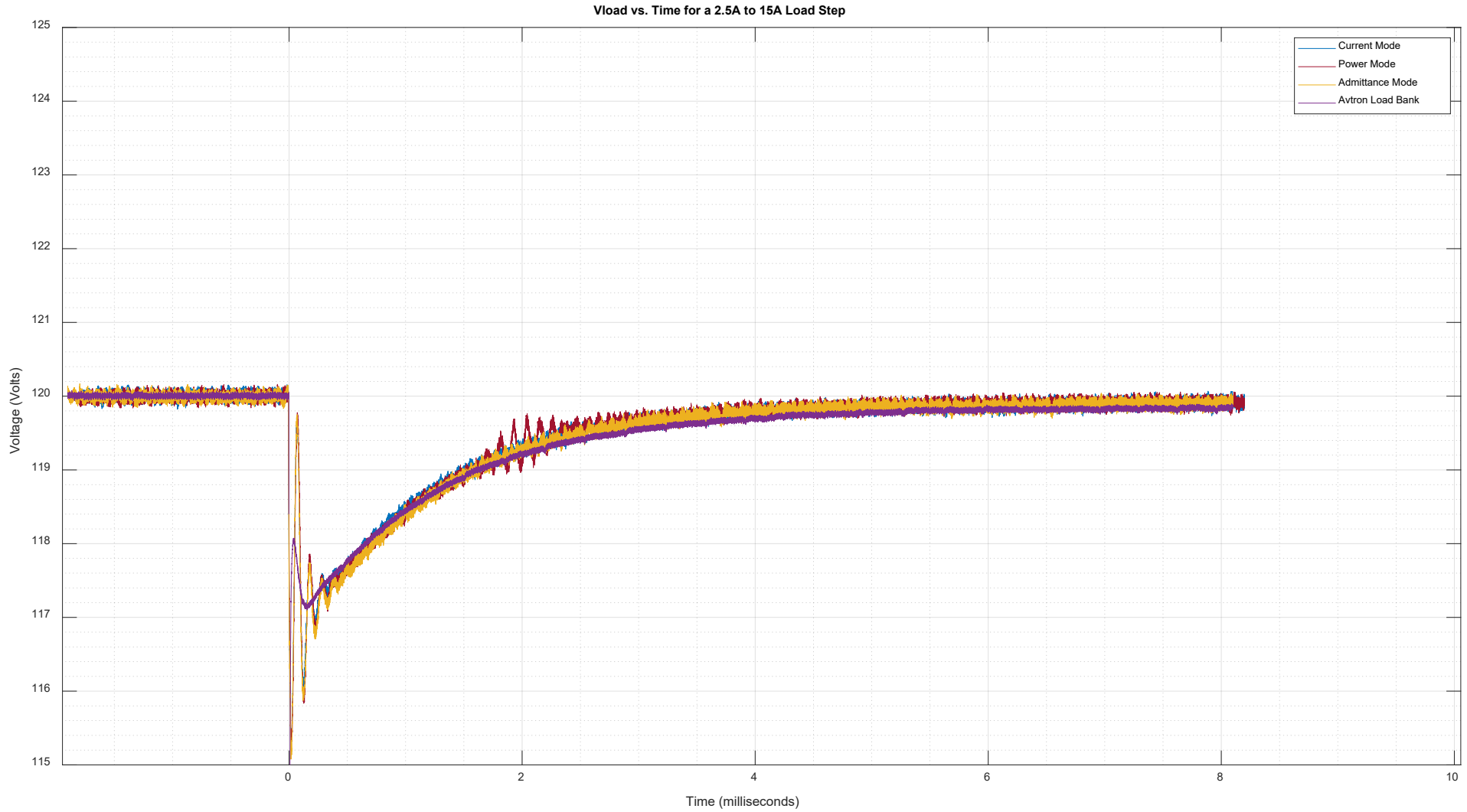
Electronic Load Bandwidth >> Source Bandwidth

- **AMPS DDCU as Source**
  - Fast e-Load, Avtron resistive bank (FET step)
  - Fast e-Load is much faster than AMPS DDCU in all control modes (>x10)

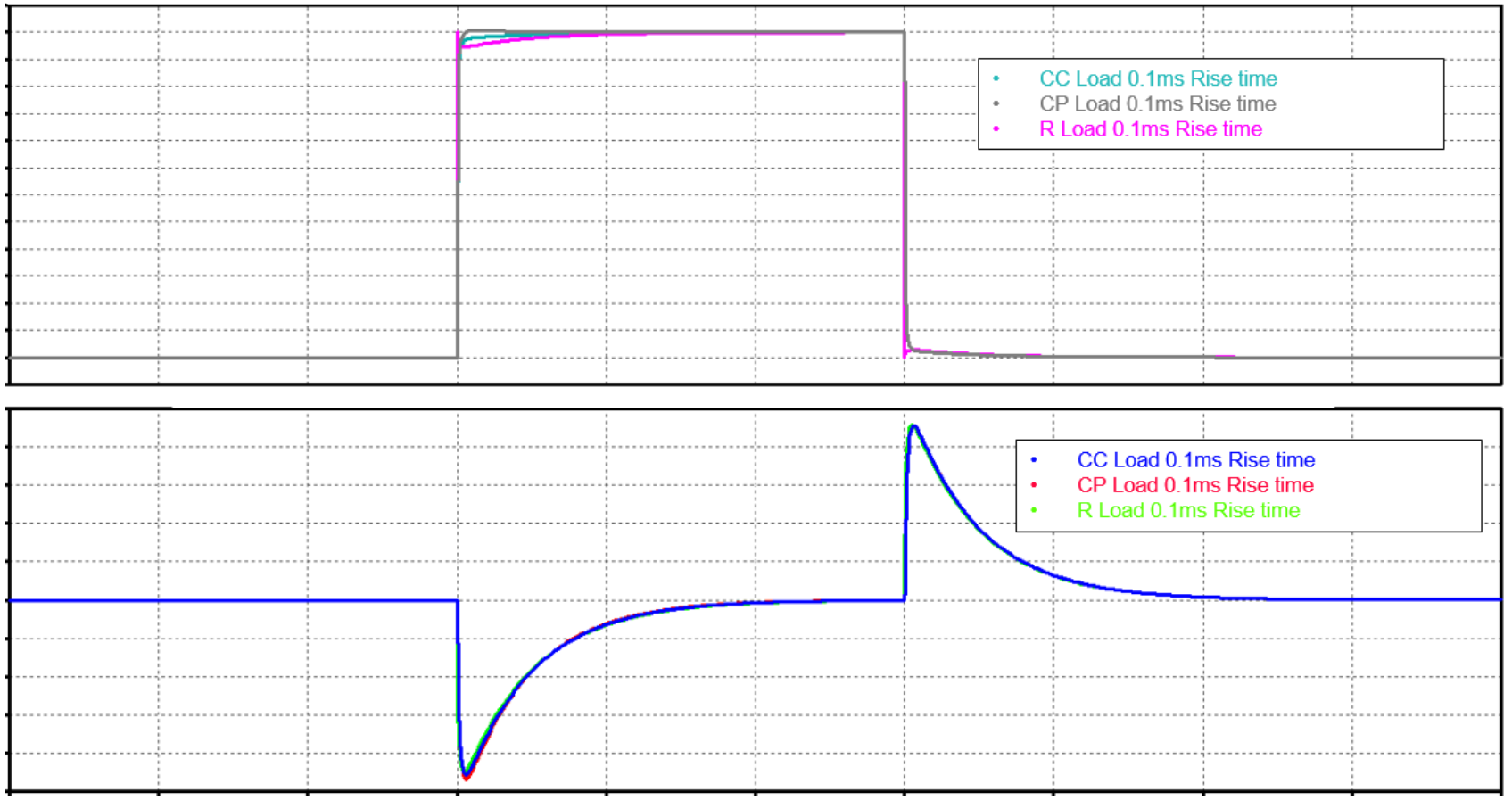
Electronic Load Bandwidth >> Source Bandwidth



Electronic Load Bandwidth >> Source Bandwidth



LTSpice Simulation Results (Match)



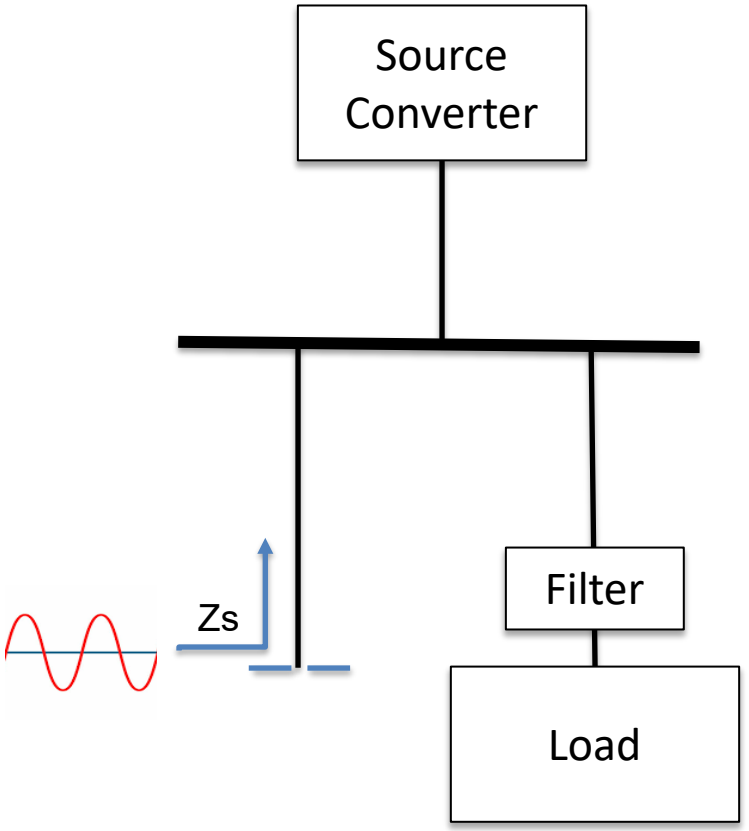
Test Load Suitability for EPS Load-Step Transient Testing

- **What loads are suitable?**
  - Resistive or actual representative load (if known)
    - Resistive worst-case for general purpose interface
  - High bandwidth electronic loads
    - >10x Source Bandwidth General Rule of Thumb
    - 5-9x needs further engineering evaluation
- **Which loads aren't suitable?**
  - Low bandwidth electronic load (relative to source)
  - Loads with input capacitance > spec

Impedance & Stability Verification

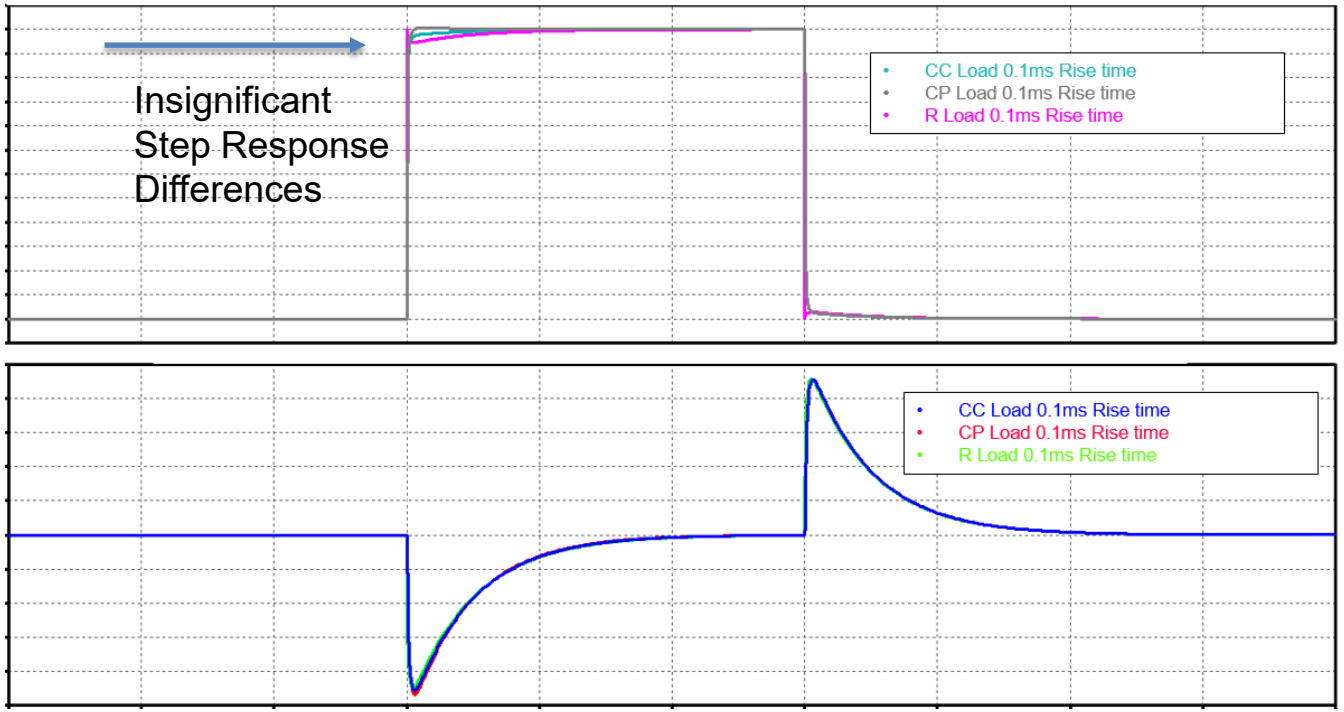
Initial Impedance Thoughts

- **An interface's source impedance is impacted by the impedance of all of the parallel loads attached to that interface.**
- **When using an electronic load in place of actual constant power load, it must perform like the load it is trying to represent.**

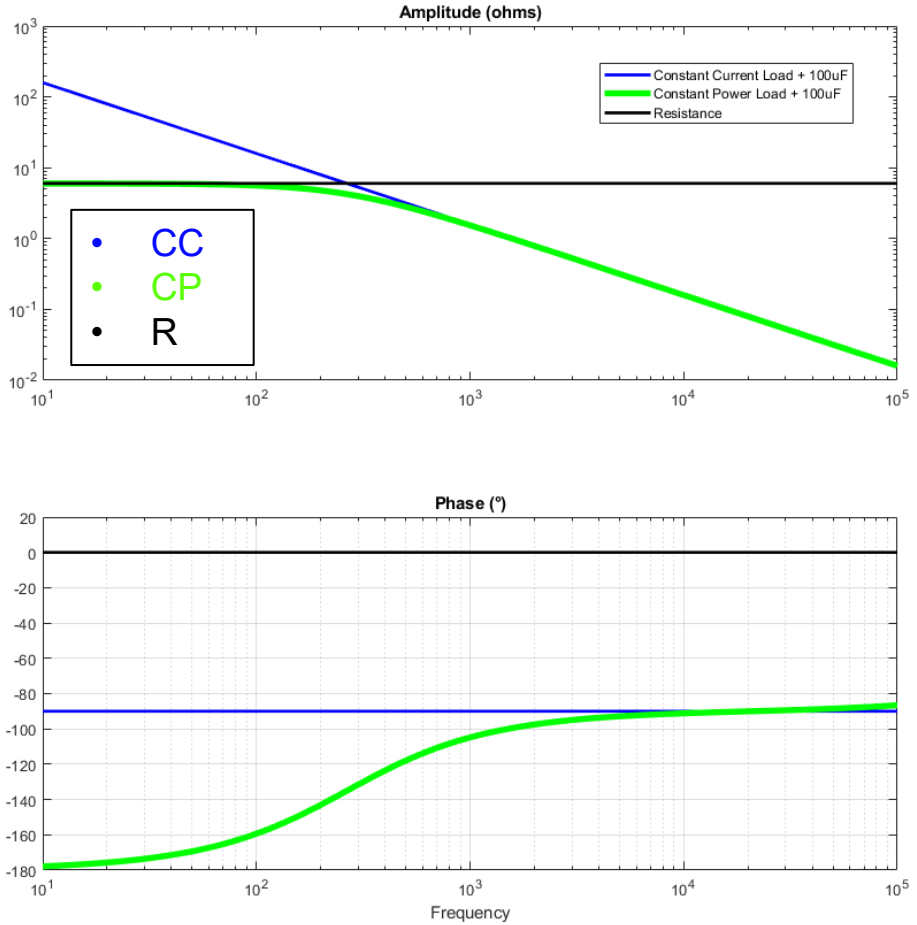


Load Impedance Primer

- **Resistive, Constant Current, Constant Power Loads**
  - Same EPS Transient Response
  - Different impedance characteristics

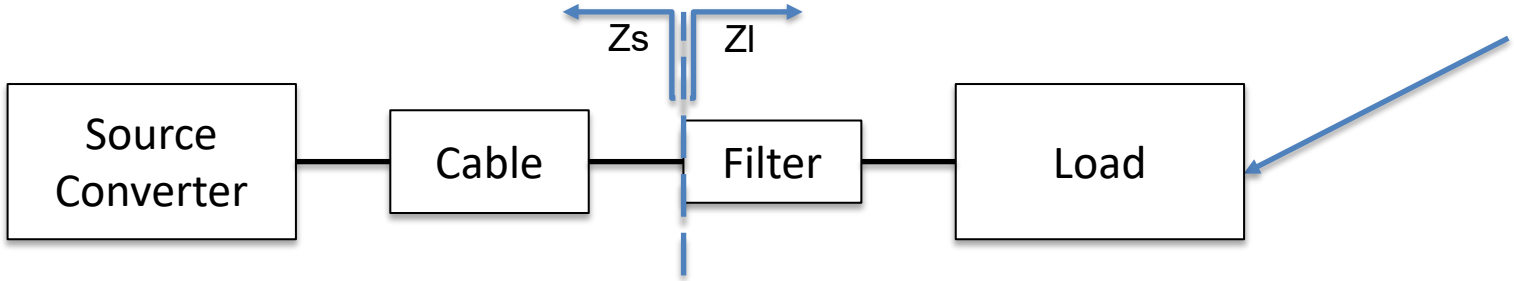


Ideal Load Impedance with 100uF capacitance and no inductance

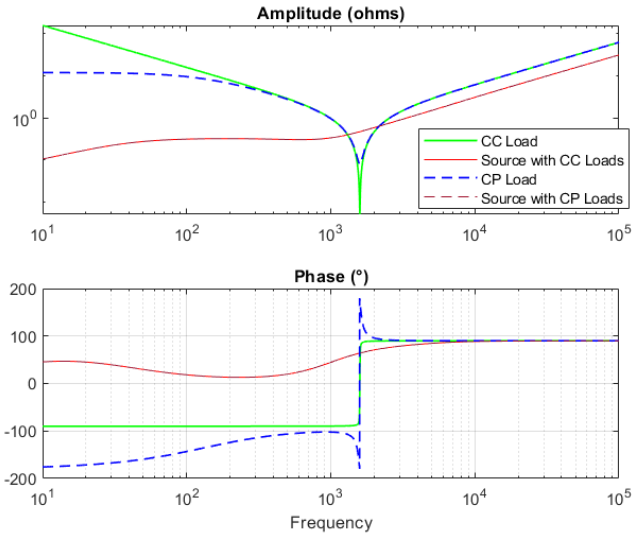


Characterizing an E-Load – Constant Power vs Constant Current

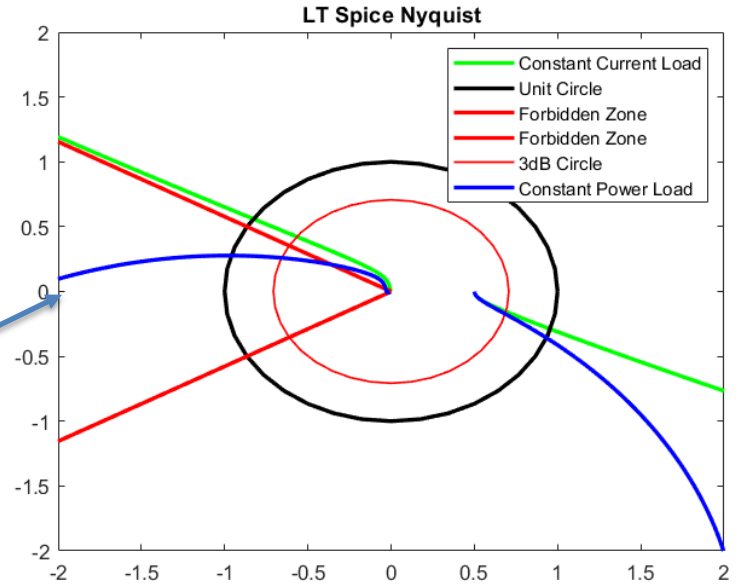
- **When using an e-load in place of a "representative constant power load" it must be characterized correctly and its impedance must match the actual load itself.**
- **Example scenario: The source converter is stable with CC mode load and <u>unstable with CP mode load.</u>**



Ideal CP or CC E-Load

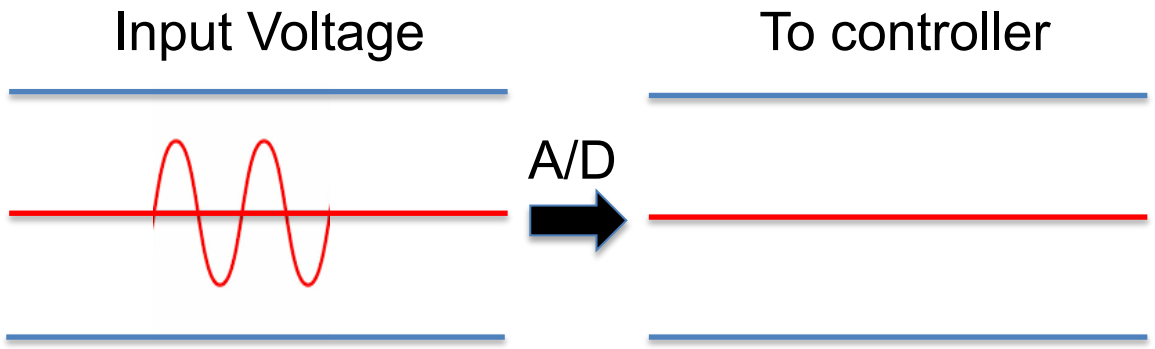


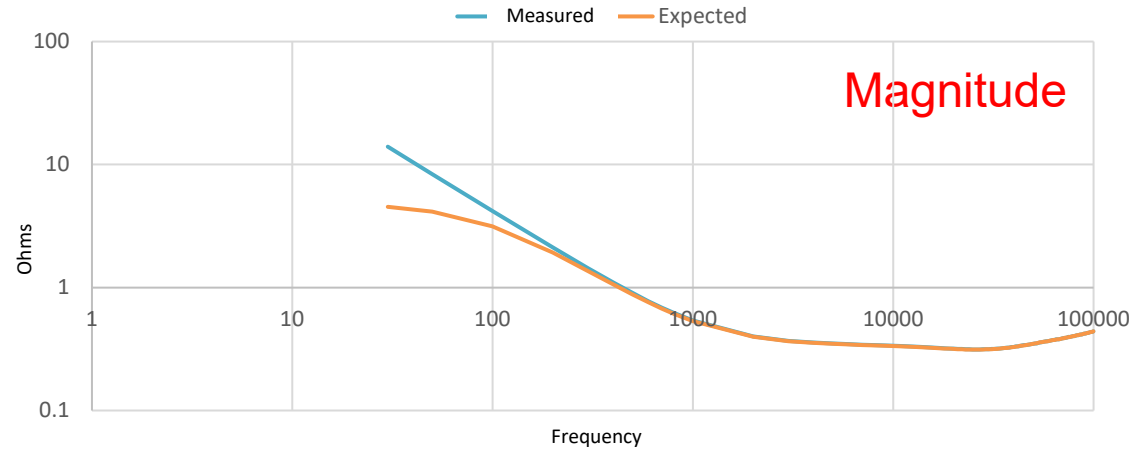
System unstable with CP load

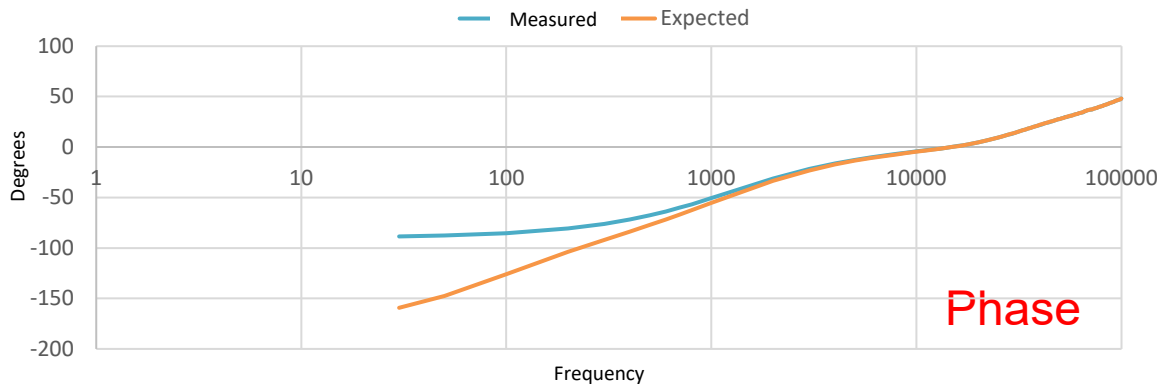


Electronic Load Quantization

- **A/D's on digital loads can change the appearance of the load**
  - Occurs at 'very small signal' level within Quantization window(s)
  - CP load looks like a CC Load

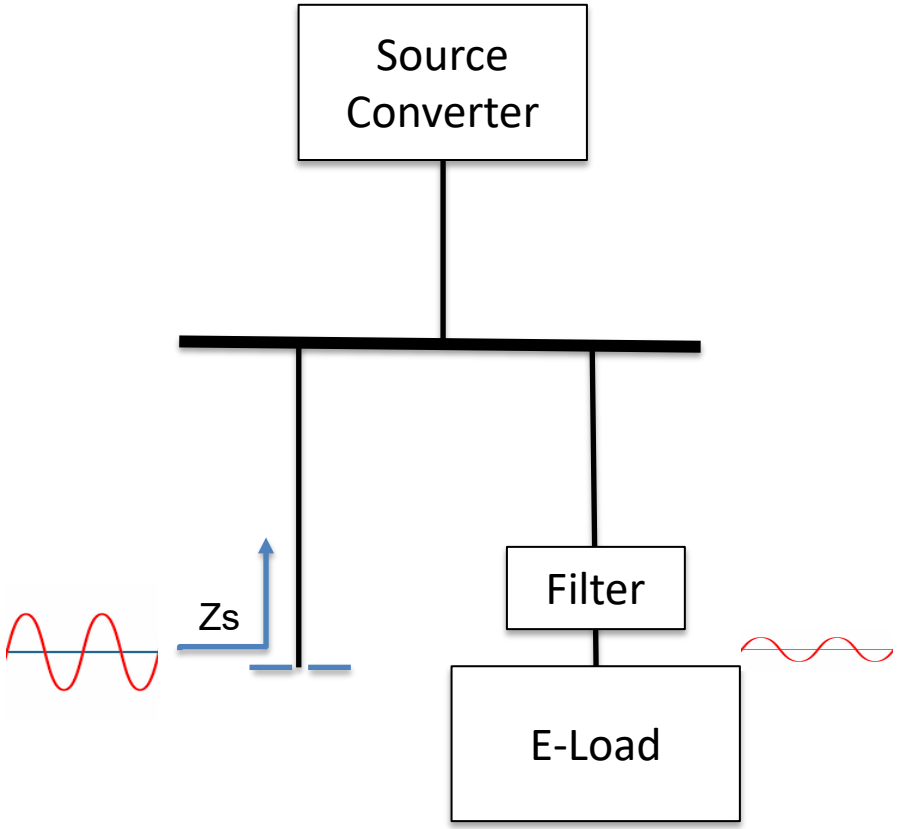






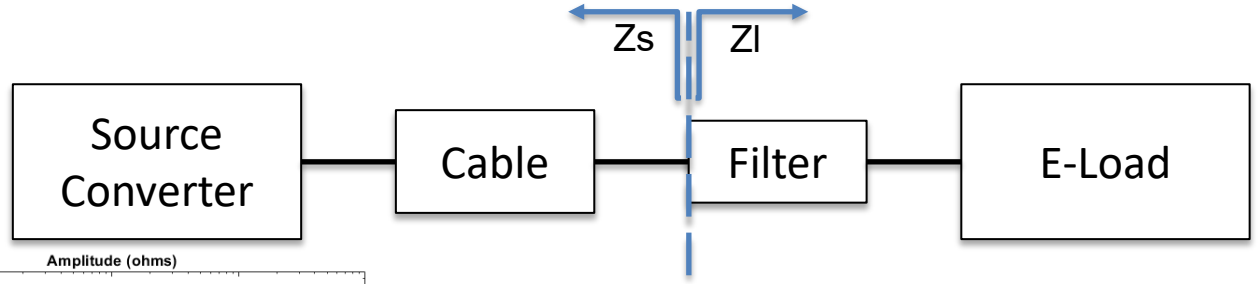
Electronic Load Quantization

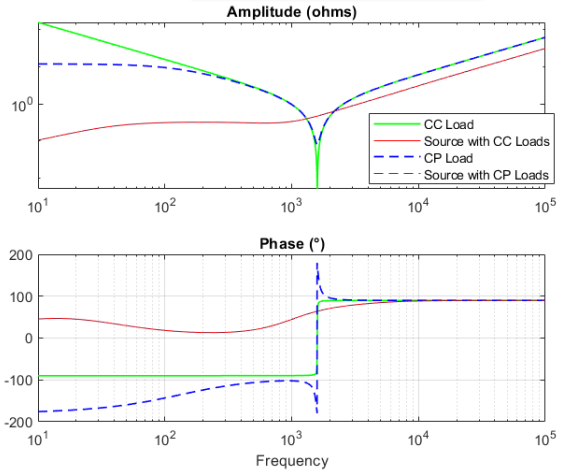
- **So what? We are talking mV…**
  - mV is all some e-loads may see
  - Source impedance can be generalized as upstream parallel combination of all upstream sources and loads
- **Incorrect impedance measurements can occur due to e-load quantization effects**

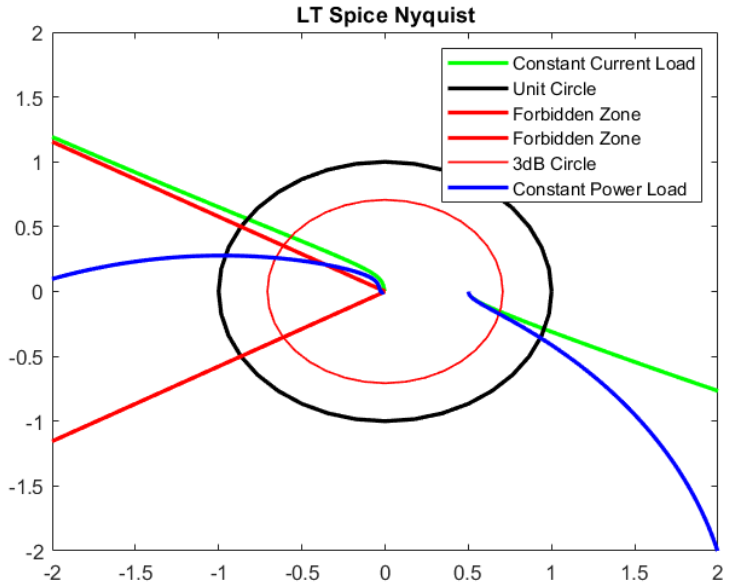


Characterizing an E-Load – Constant Power vs Constant Current

- **When using an e-load in place of a "representative constant power load" it must be characterized correctly and its impedance must match the actual load itself.**
  - A load must be perturbed with a large enough injection signal during impedance measurements
    - The "quantized state" of some CP e-loads may give the appearance of a constant current load at very small signal
    - Voltage does not respond to the change in current because the change is too small
- **Example scenario: The source converter appears stable with CC mode load, but is <u>unstable with CP mode load.</u>**

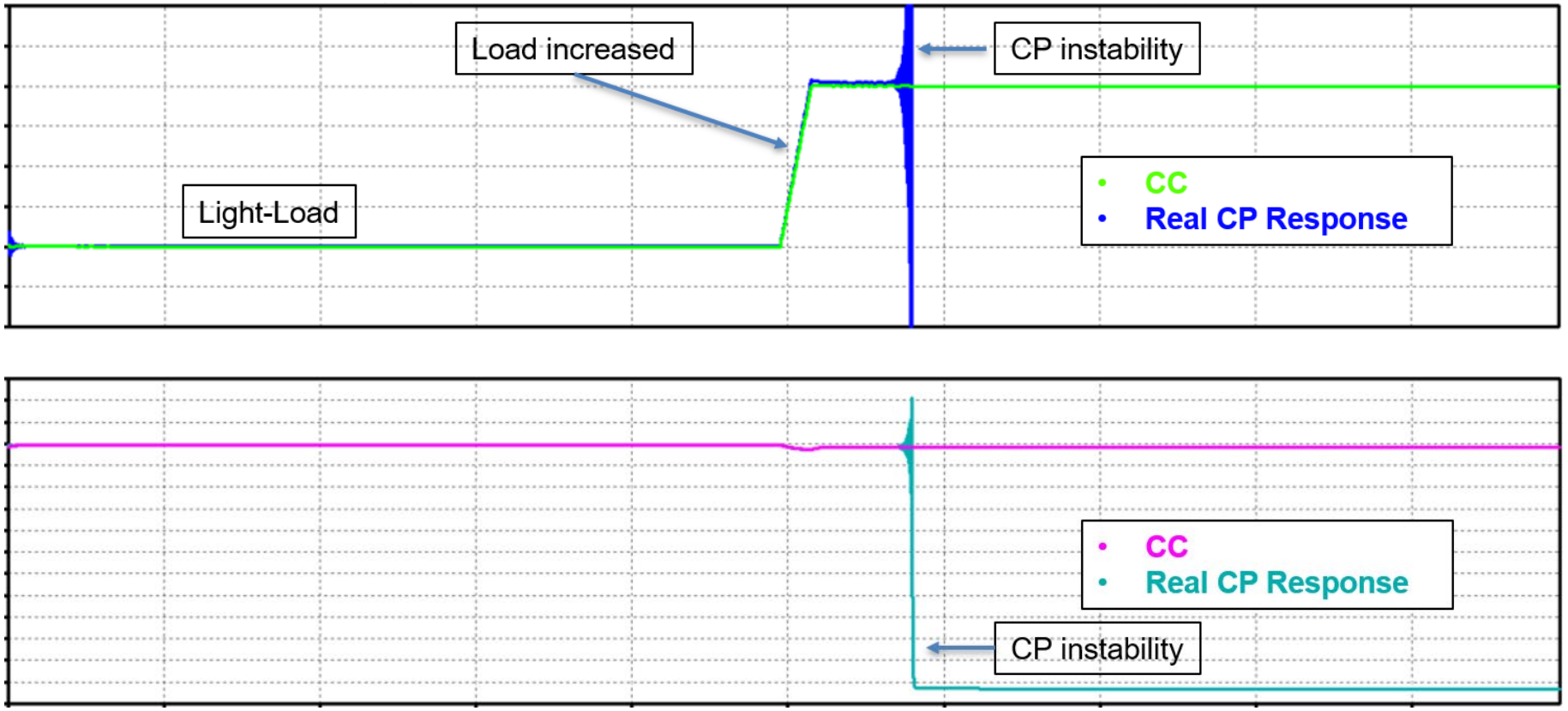






Source and Load may be Stable in Steady-State!

- **Furthermore, without proper load impedance characterization a false sense of stability may be achieved for this electronic load + source combination**
  - With light-loading this system is stable
  - With high-loading this system is unstable



Test Load Suitability for Stability Assessments

- **What loads are suitable?**
  - Actual representative load (if known)
    - Using standard DC-DC converters
    - Representative Filters
  - CP e-Loads with analog control circuitry (requires eng. evaluation)
- **Which loads have questionable suitability?**
  - Digital CP electronic loads
    - Quantization effects will impact measurements, CP loads may look like CC loads
    - Have inherent risk. Steps have to be taken to mitigate risk (follow on work/discussion).
- **Which loads aren't suitable?**
  - CC electronic loads
    - Will inherently mask instability problems
  - Any load without representative filtering

Conclusion and Future Work

- **Detailed analysis and consideration must be taken into account when using e-loads for power system validation and verification**
  - General rule of thumb: e-Loads 10x faster than source for transient verification
  - CC loads cannot be used interchangeably with CP loads
  - A/D's on digital e-loads can affect appearance of the load at very small-signal levels
- **Detailed publication planned covering:**
  - Source converter loop-gain considerations vs. e-load bandwidth constraints
  - Varying test results
  - Simulation results with varying sources

Acknowledgement

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