# U.S. DOE-NERC Workshop on Fault-Induced Delayed Voltage Recovery (FIDVR) & Dynamic Load Modeling

## Overview

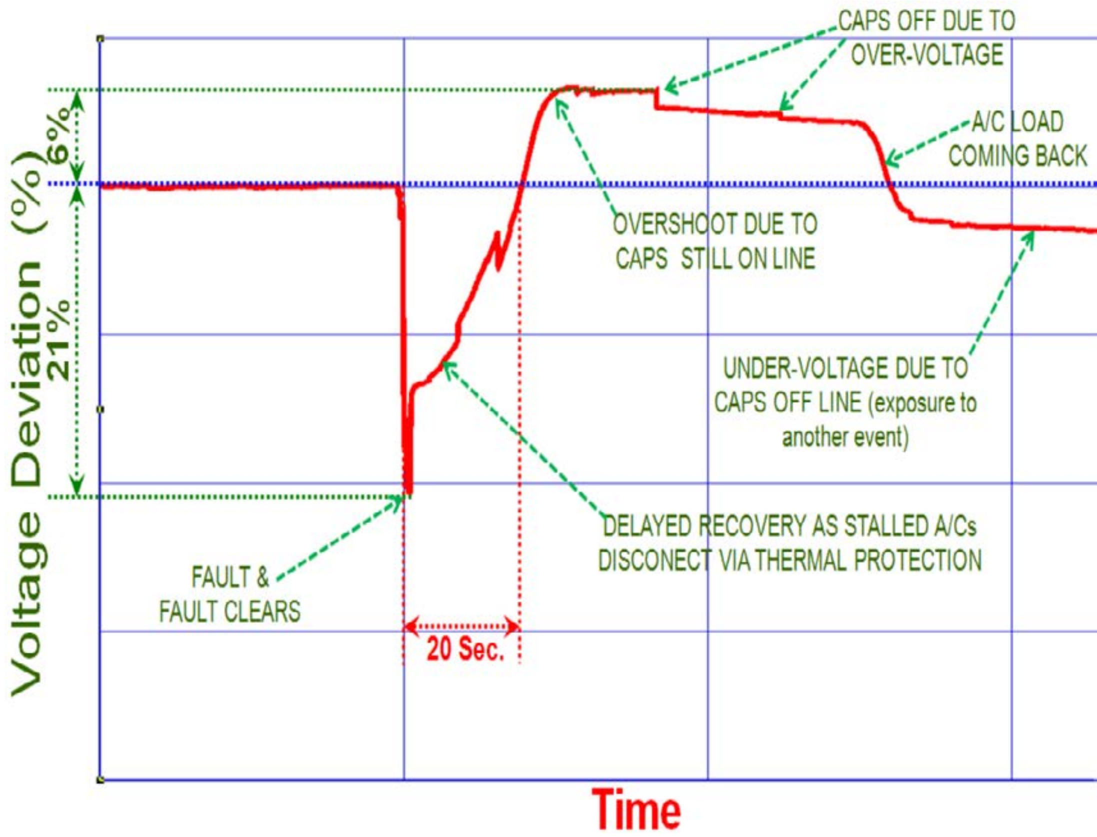
Joe Eto, Lawrence Berkeley National Lab
September 30, 2015
Alexandria, VA

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

# What is FIDVR ?

**Fault-Induced Delayed Voltage Recovery** — a voltage condition initiated by a fault and characterized by:

1) Stalling of induction motors;
2) Initial voltage recovery after the clearing of a fault to less than 90 percent of pre-contingency voltage; and
3) Slow voltage recovery of more than two seconds to expected post-contingency steady-state voltage levels




Source: A Technical Reference Paper: Fault-Induced Delayed Voltage Recovery. Version 1.2. Prepared by: NERC Transmission Issues Subcommittee and System Protection and Control Subcommittee. June 2009

# Agenda

## Wednesday, September 30, 2015

**8:30-9:00** **Welcome & Opening Remarks**
David Meyer, *U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability*
David Till, *North American Electric Reliability Corporation*

**9:00-9:15** **Workshop Overview & Objectives**
Joe Eto, Lawrence Berkeley National Laboratory

**9:15-9:45** **Current State of Load Modeling**
*A landscape overview of dynamic load modeling and FIDVR – where we are today, how we got here, and where we're going.*
Dmitry Kosterev, *Bonneville Power Administration*

**9:45-10:00** **Break**

**10:00-12:00** **Fundamentals, Testing & Modelings of Air-Conditioners**
*A deep dive into the fundamentals of motors, laboratory testing of end-use loads, and modeling efforts. Development of single-phase and equivalent models using field testing and detailed modeling.*
John Undrill, *Independent Consultant*
Dmitry Kosterev, *Bonneville Power Administration*
Steven Robles, *Southern California Edison*
Bernie Leseiutre, *University of Wisconsin*

**12:00-1:00** **Lunch – provided**

ELECTRIC
RATION

# *Agenda*

## Wednesday, September 30, 2015 (continued)

**1:00-2:30** **Manufacturing Perspective, Future Trends & Technologies (Panel Session)**

*Perspectives from the manufacturing community focusing on current and future trends in control design and engineering, end-use requirements, and future technologies.*

John Halliwell, *Electric Power Research Institute*
John Berdner, *Enphase Energy*
Tim Hawkins, *Rheem*
Hung Pham, *Emerson Climate Technologies*

**2:30-2:45** **Break**

**2:45 – 4:30** **Load Model Data**

*The composite load model for transmission planning studies – development, parameter selection, model structure, and data management.*

Ryan Quint, *North American Electric Reliability Corporation*
John Kueck, *Independent Consultant*
Donald Davies, *Western Electricity Coordinating Council*
Dmitry Kosterev, *Bonneville Power Administration*

**4:30-5:30** **Field Measurements**

*Gathering data at the distribution level to better understand the phenomena of FIDVR and load dynamics.*

Kyle Thomas, *Dominion Virginia Power*
Richard Bravo, *Southern California Edison*
John Undrill, *Independent Consultant*

**5:30** **Adjourn**

# *Agenda*

## Thursday, October 1, 2015

**8:30-10:00 Composite Load Modeling & System Studies (Panel Session)**

*Experience using the composite load model for bulk transmission planning studies – lessons learned, technical challenges, identified problems, and solutions. A focus on the development of the model, utilization of the model, and planning around a more detailed load model.*

Noah Badayos, *Southern California Edison*

Dmitry Kosterev, *Bonneville Power Administration*

Rob O'Keefe, *American Electric Power*

Dean LaTulipe, *National Grid*

Scott Ghiocel, *Mitsubishi Electric Power Products, Inc.*

**10:00-10:15 Break**

**10:15-11:30 Reliability Focus (Panel Session)**

*A broad look at reliability aspects related to load modeling and FIDVR, including regulations and policies, system level impacts, history in planning around load-related issues, and fundamental drivers behind reliability of end-use technology changes.*

Bob Cummings, *North American Reliability Corporation* Dmitry Kosterev, *Bonneville Power Administration*

John Undrill, *Independent Consultant*

David Till, *North American Electric Reliability Corporation*

**11:30-12:30 Roundtable Discussion, Summary & Next Steps**

Joe Eto, *Lawrence Berkeley National Laboratory – Moderator*

**12:30 Adjourn**

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

# Contacts for Follow-Up

***fidvr.lbl.gov***

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**jheto@lbl.gov**

Ryan Quint, NERC
**ryan.quint@nerc.net**

# Composite Load Model Development and Implementation

2015 NERC-DOE FIDVR Conference

Presented by

Dmitry Kosterev, BPA

# History Of Load Modeling

1980’s – Constant current real, constant impedance reactive models connected to a transmission bus

Reflected the limitation of computing technologies of that time

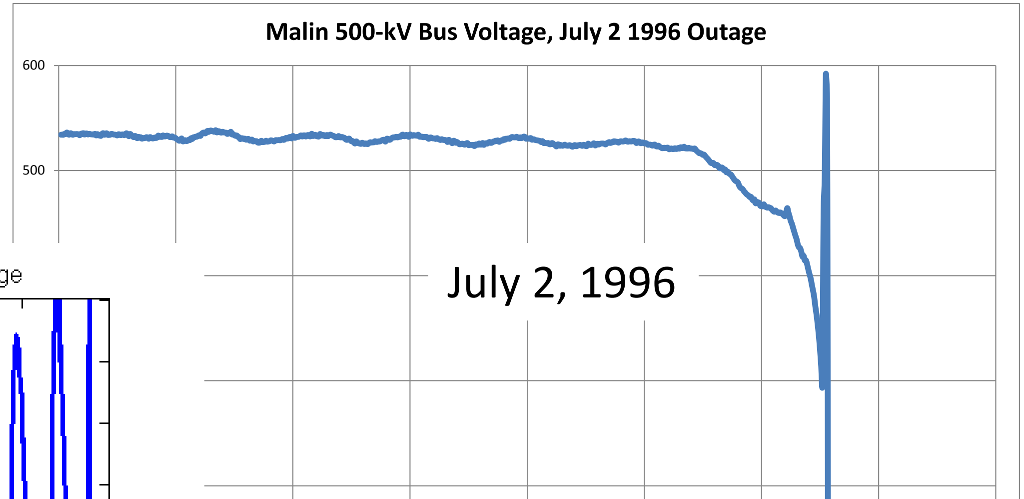
1990’s – EPRI Loadsyn effort

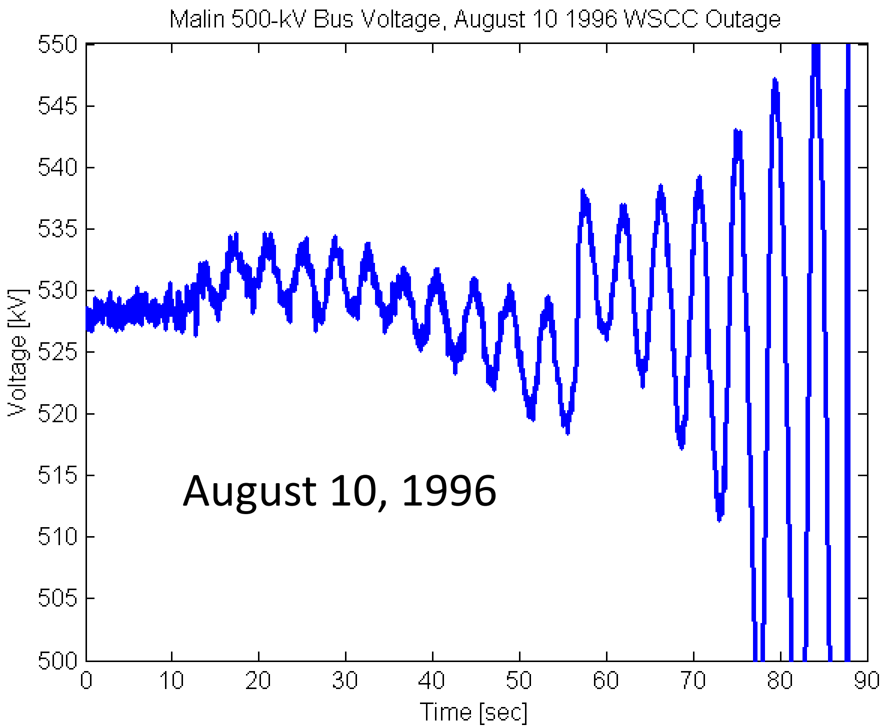
Several utilities use static polynomial characteristics for load representation

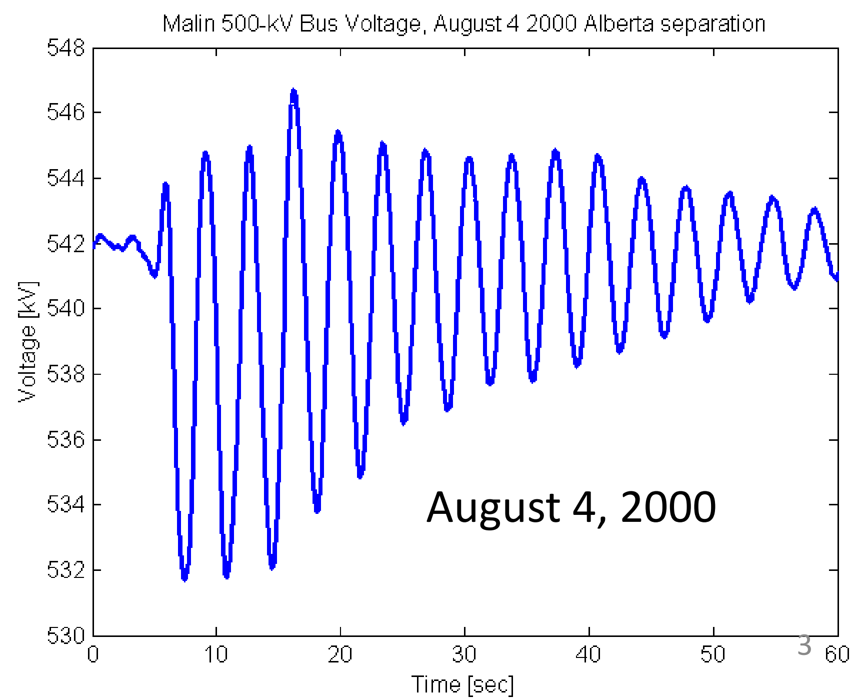
1990’s – IEEE Task Force recommends dynamic load modeling

The recommendation does not get much traction in the industry

# 1996 Large-Scale Outages in the West



# 2001 “Interim” Load Model

## 2001 – WECC “Interim” Load Model:

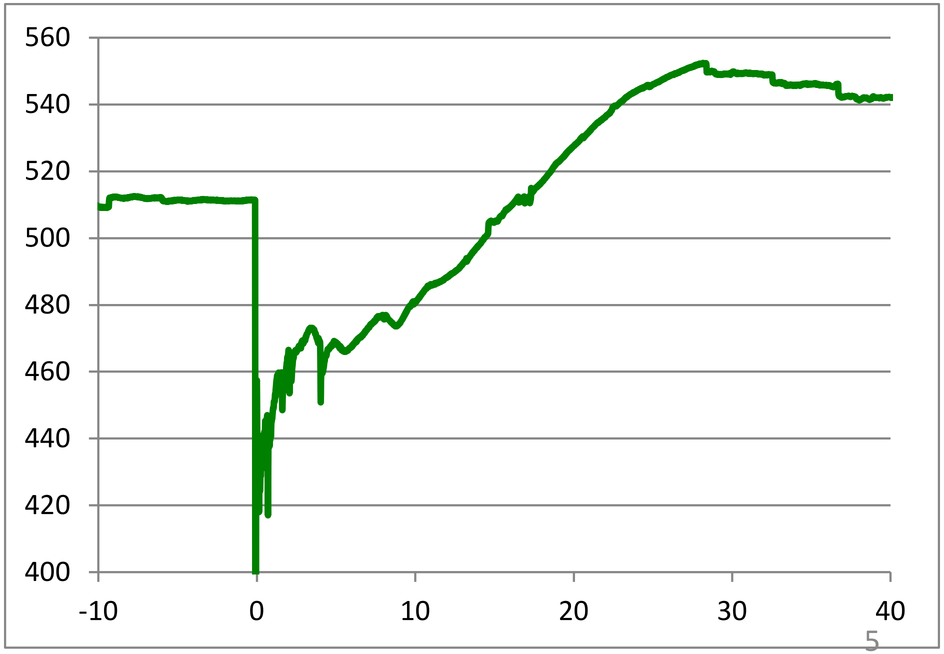
- 20% of load is represented with induction motors, the remaining load is static, mainly constant current active, constant impedance reactive components
- Motors were connected at high voltage bus, data representative of large fan motors (source John Undrill)
- Same percentage was applied to all areas in WECC
- Was the only practical option available in 2001
- “Interim” load model was intended as a temporary solution to address oscillation issues observed at California – Oregon Intertie
- Was in use until 2014 when superseded with composite load model

# Events of Delayed Voltage Recovery in Southern California

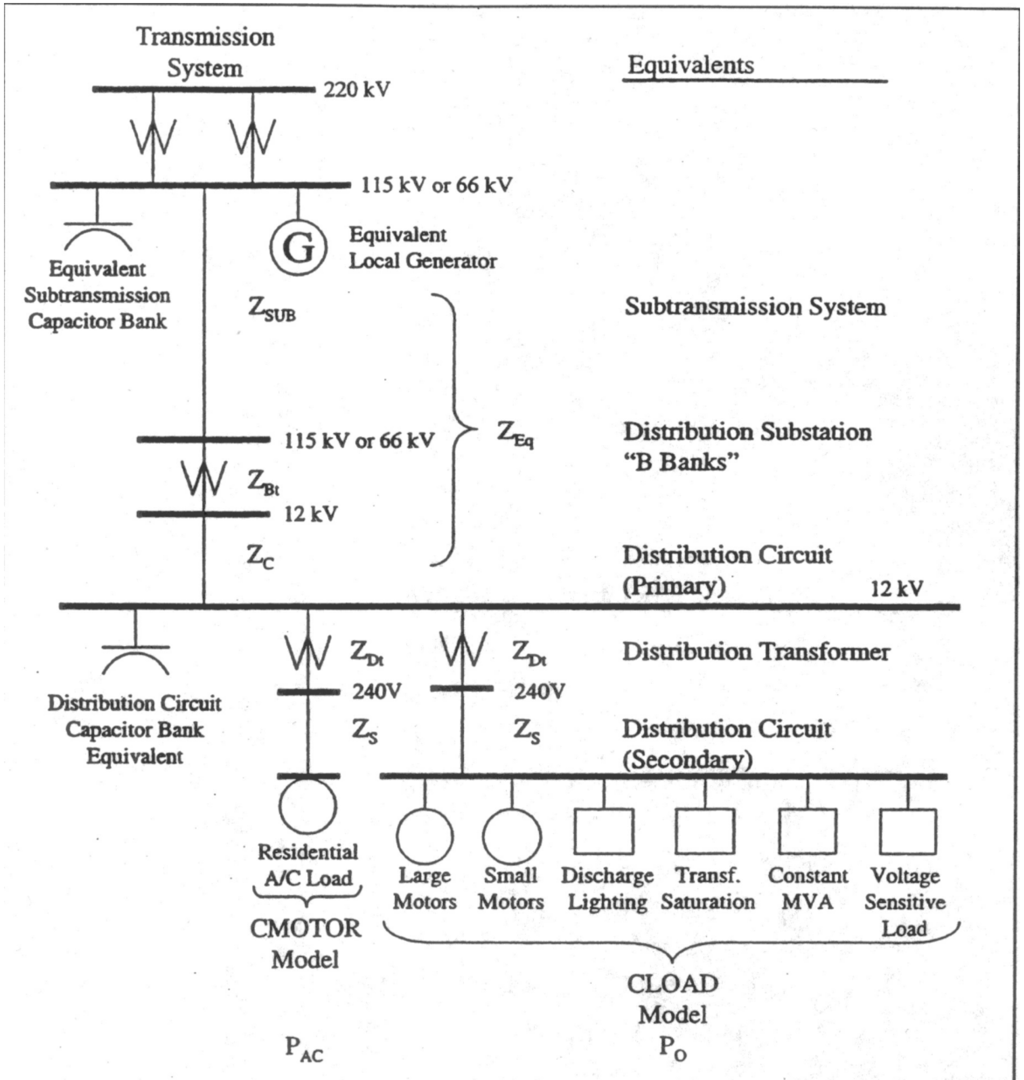
- 1980's – Southern California Edison observed events of delayed voltage recovery attributed to stalling of residential air-conditioners
  - Tested residential air-conditioners, developed empirical AC models

- 1997 – SCE model validation study of Lugo event.

- 2004-06 FIDVR events in Valley area



# Southern California Edison




Need to represent a distribution equivalent

Need to capture diversity of end-uses

Need to have special models for air-conditioning load

# Early Load Modeling Efforts in the East

1994 – Florida Power published an IEEE paper, used a similar load model

1998 – Events of delayed voltage recovery were observed in Atlanta area by Southern Company, the events are analyzed and modeled

Southern Company and Florida Power used approaches similar to SCE's.

The approach was later adopted by WECC in the development of the composite load model…

# WECC Load Modeling Task Force

2005 – WECC developed “explicit” load model:

- Adding distribution equivalent to powerflow case WECC-wide
- Modeling load with induction motors and static loads
- Numerically stable in WECC-wide studies !

2007 – PSLF has the first version of the composite load model (three-phase motor models only)

2006-2009 – SCE-BPA-EPRI testing residential air-conditioners and developing models

2009 – residential air-conditioner model is added to the composite load model

# Implementation Plan for Composite Load Model

## A. Model Structure

Model structure must be implemented in production programs, validated and must be robust and numerically stable in large scale simulations

## B. Data

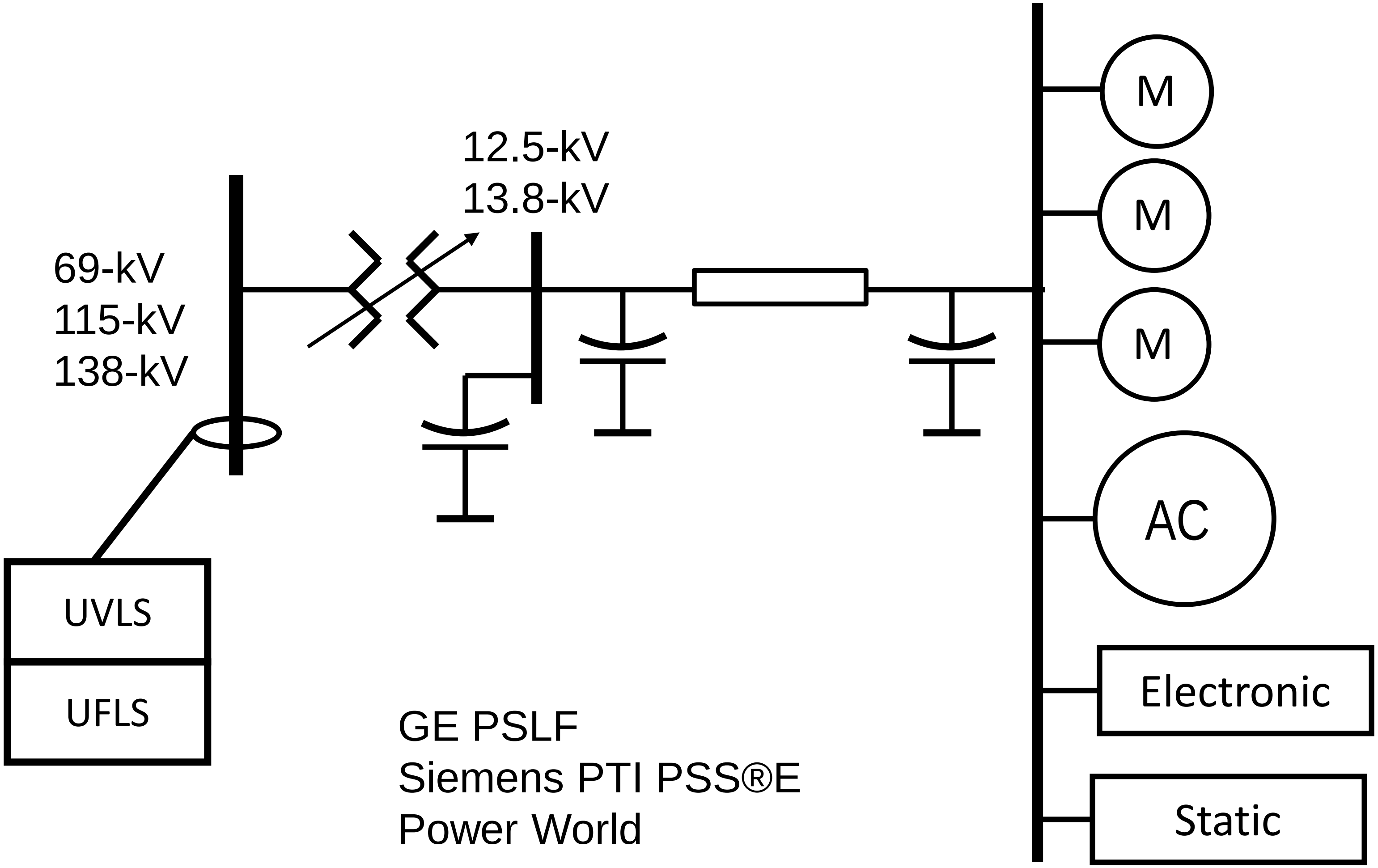
Tools for data management are available
Processes for providing data are established
Default data sets are available

## C. Studies

Model validation studies
System impact and sensitivity studies

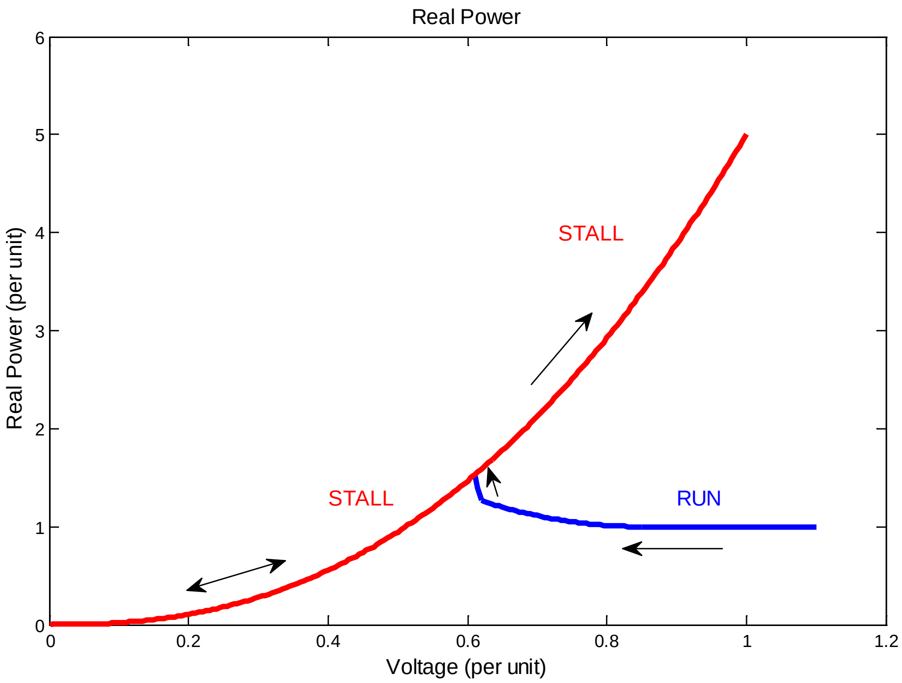
# Composite Load Model Structure

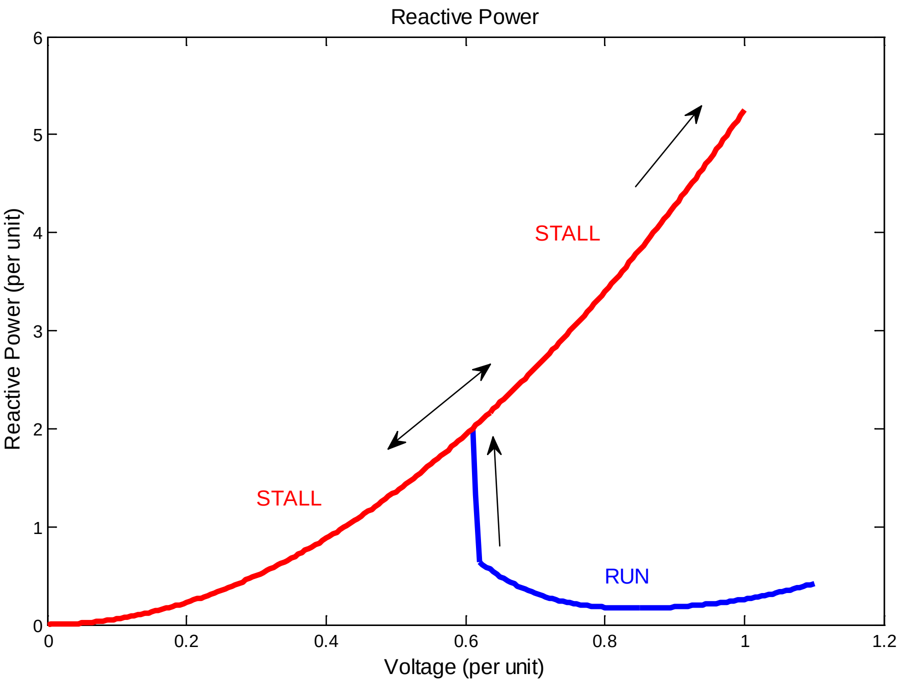
# Composite Load Model Structure




GE PSLF
Siemens PTI PSS®E
Power World

# “Performance Model” for Air-Conditioners



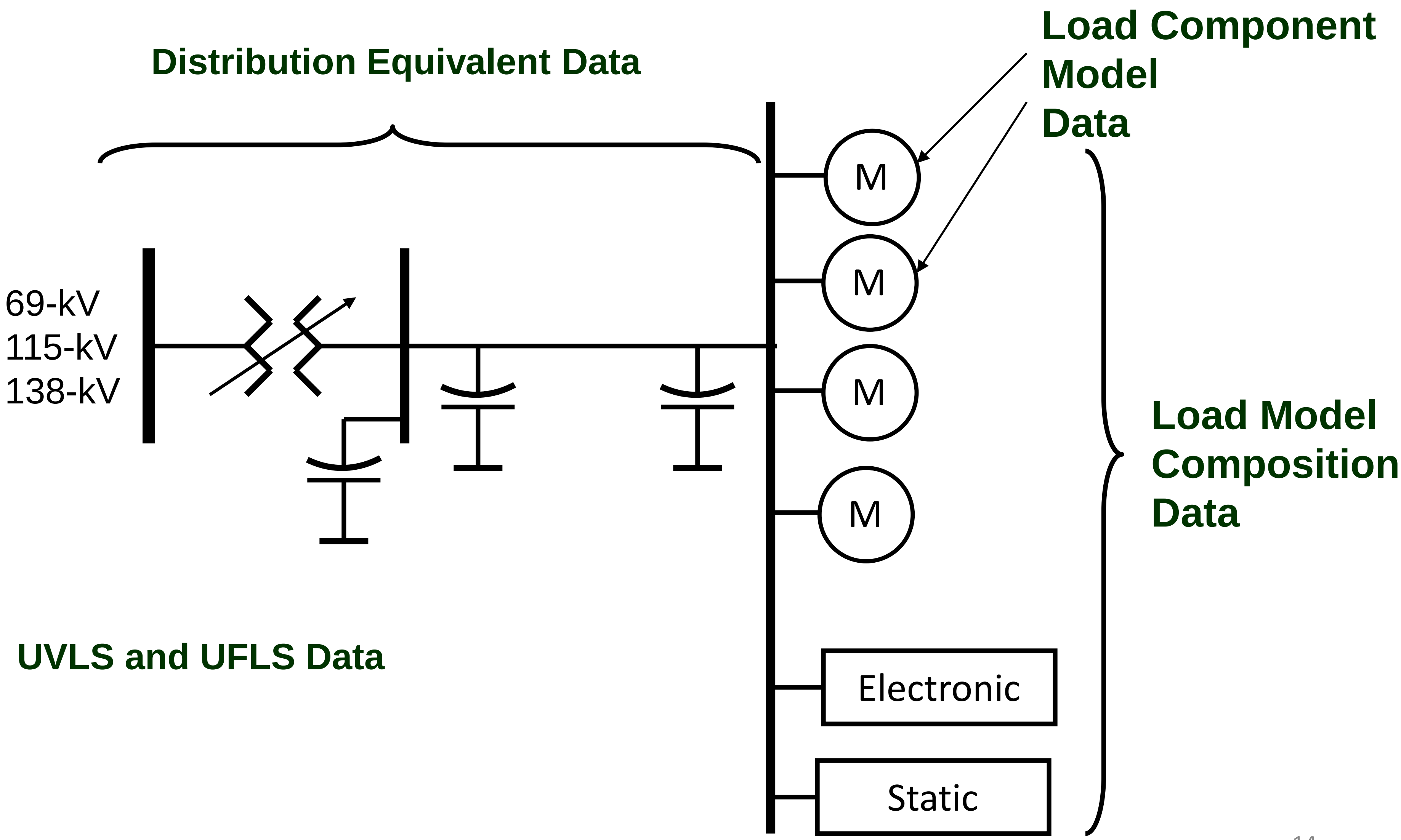

Motors stall when voltage drops below Vstall for duration Tstall

A fraction Frst of the aggregated motor can restart when the voltage exceeds Vrst for duration Trst

Motor thermal protection is modeled

# Data

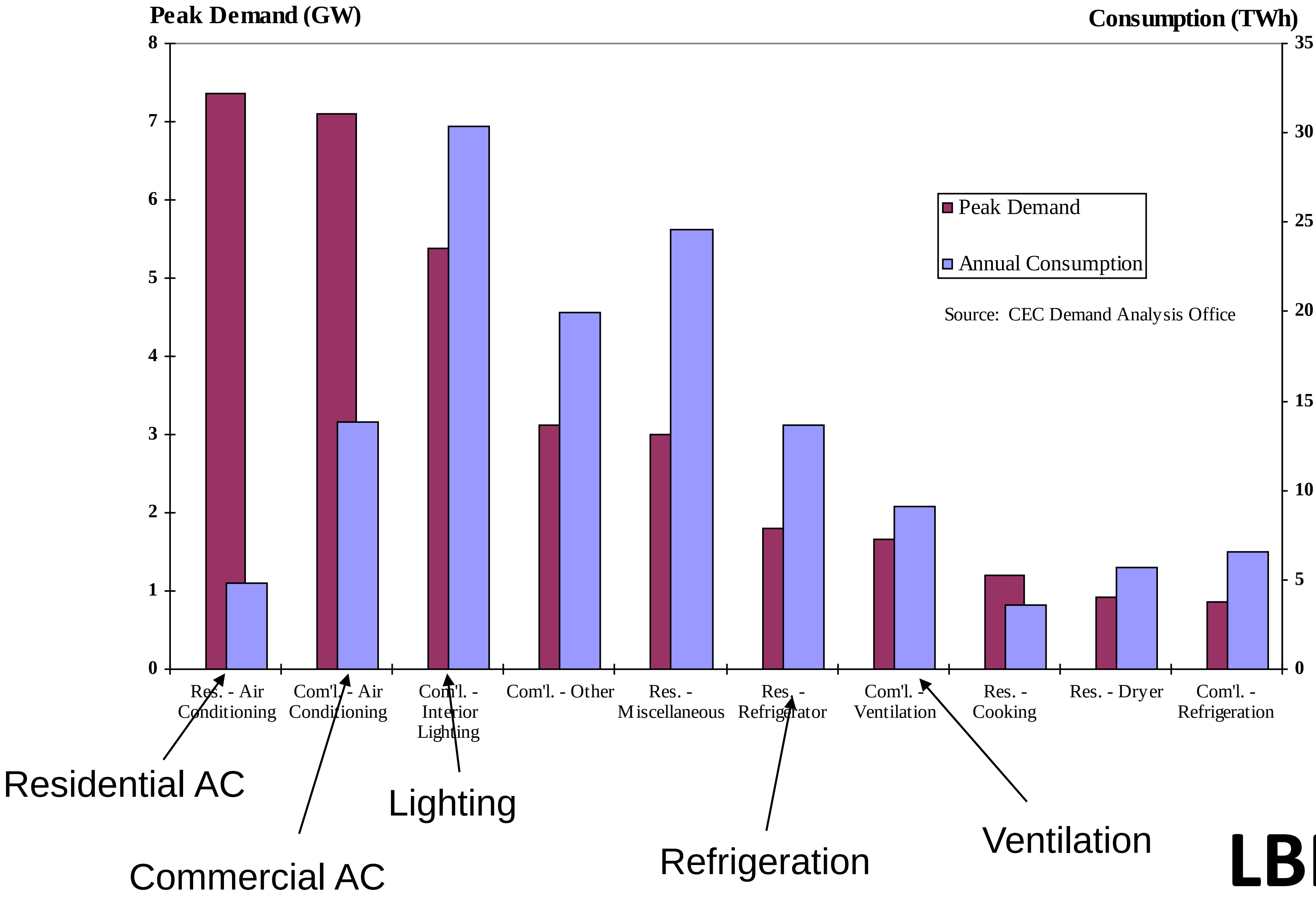
# Load Model Data



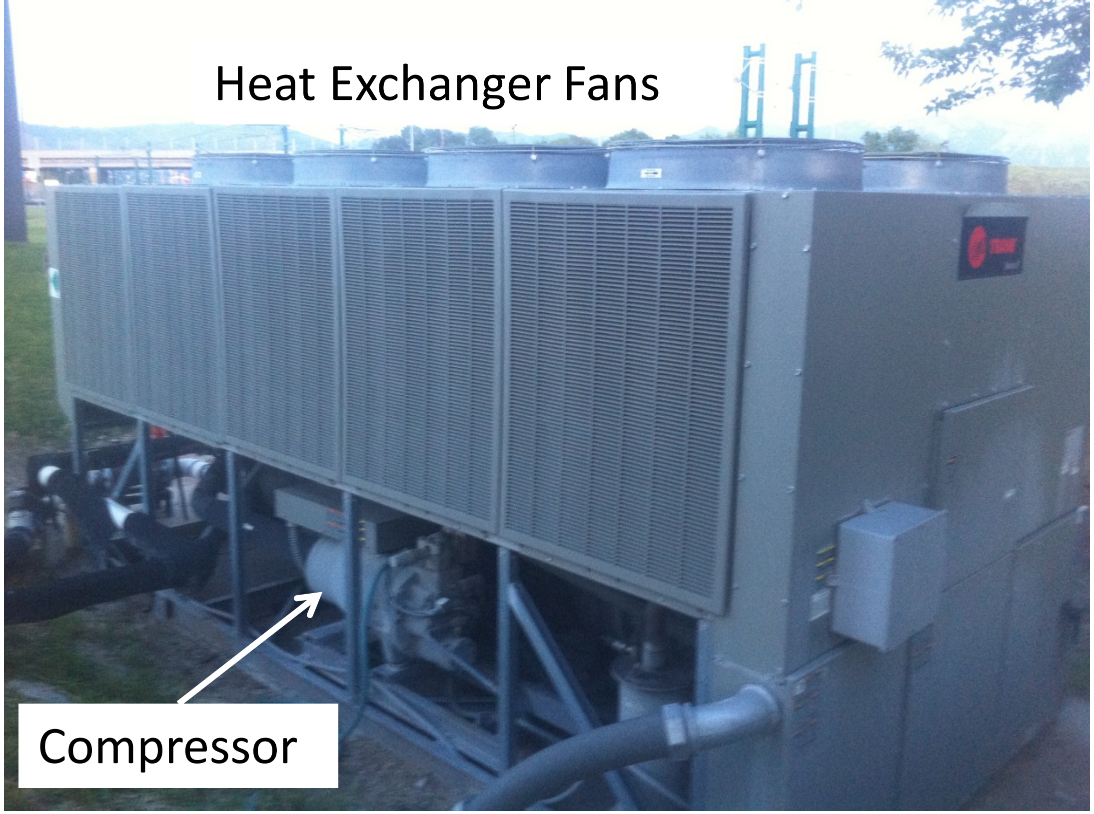
# Load Model Data

- Develop understanding of electrical end uses in various buildings, do not rely solely on consultants with elaborate building models
  - Building models can help develop understanding, but should not be used as the primary source
- When you walk in Whole Foods on hot summer day, do you know how much load is refrigeration / AC / lighting / fans / cooking? Do you know expected size and type of compressor motors? Do you know what building EMS system will possibly do during a fault?
- We need to develop this expertise

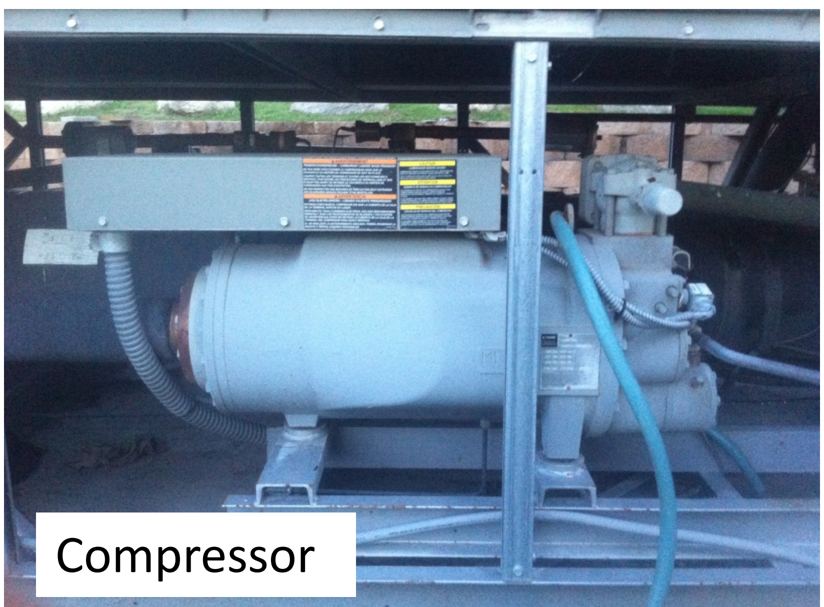
# Summer peak demand in California




LBNL




Hotel in Salt Lake City
125 rooms




**2 Compressor Motors:**

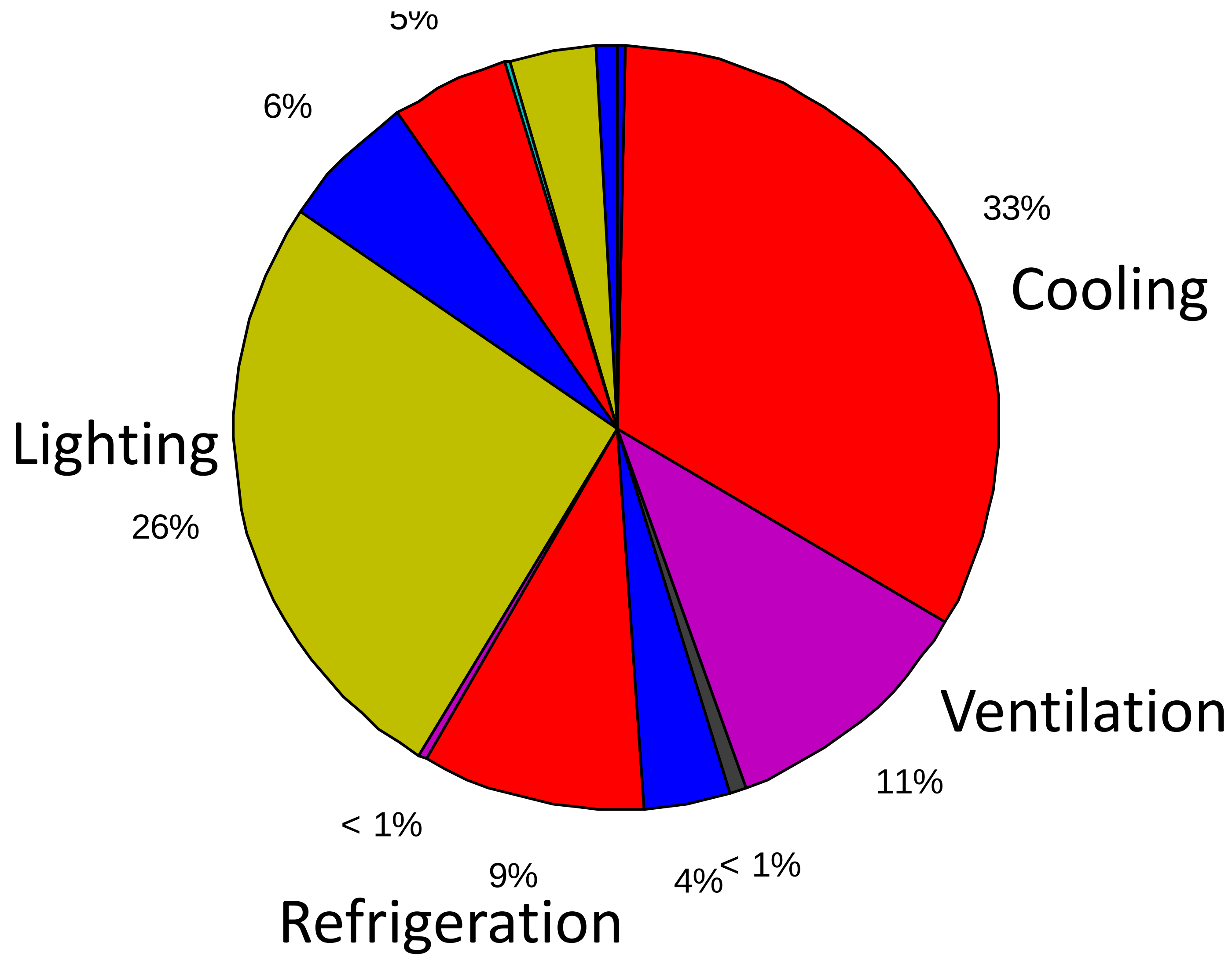
A: 3-ph, 460 V, 139 RLA, ~94kW / 70 hp

B: 3-ph, 460 V, 118 RLA, ~80kW / 60 hp

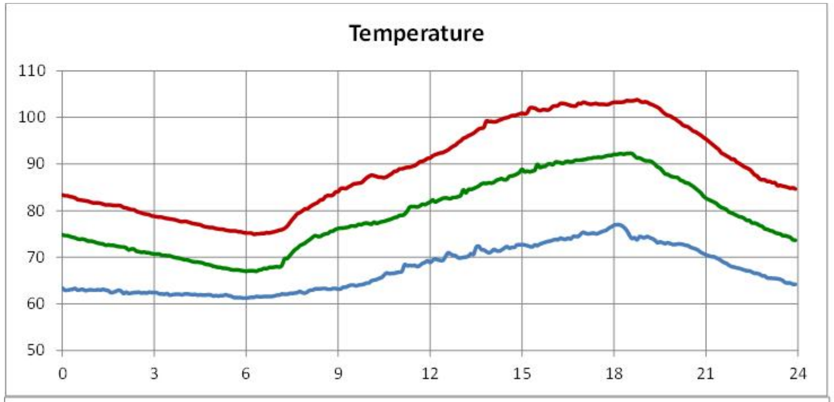
**9 Fan Motors:**

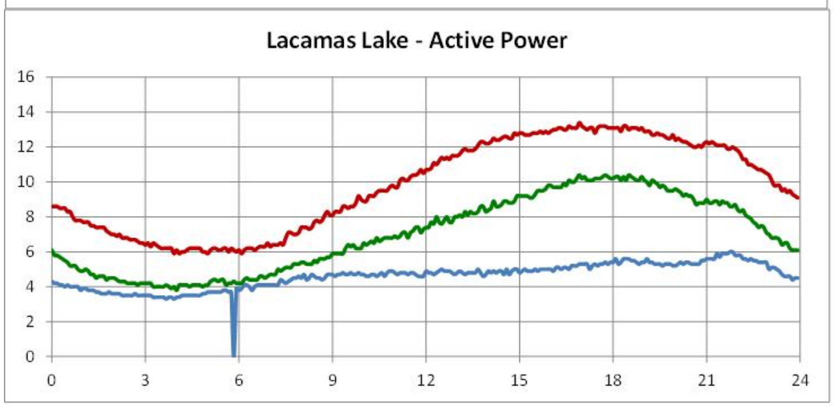
3-ph, 460V, 1.25 hp each

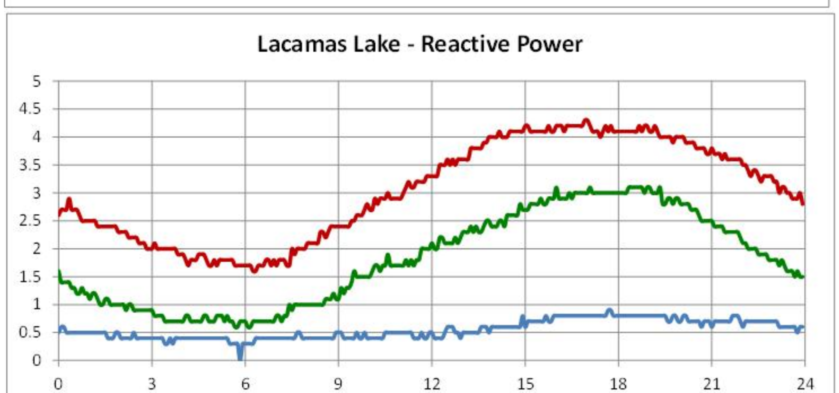
# CEC California Commercial End-Use Survey
# Summer Peak Load



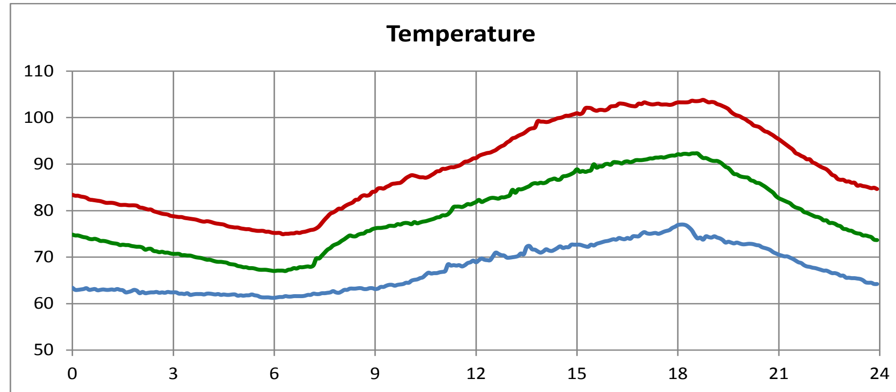
# Residential

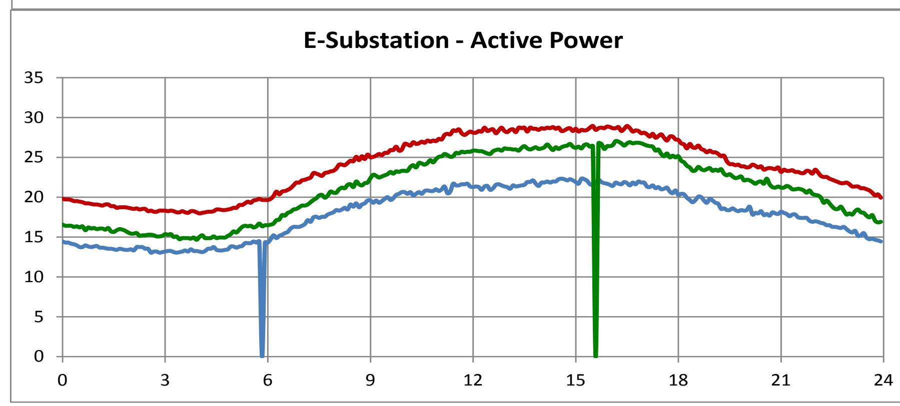


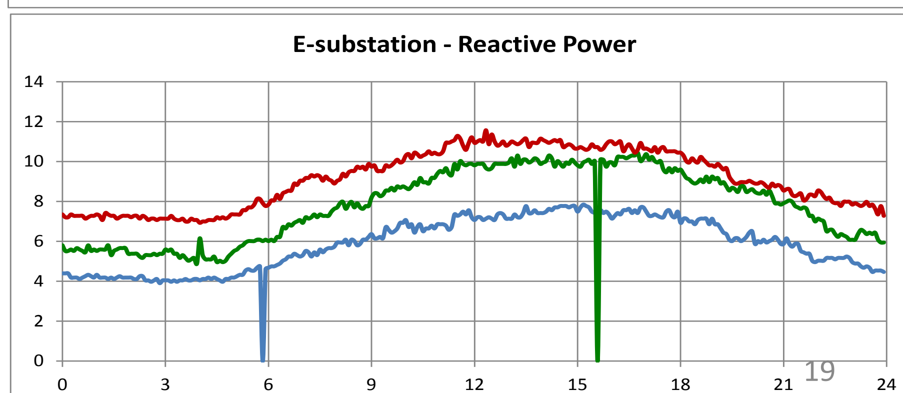



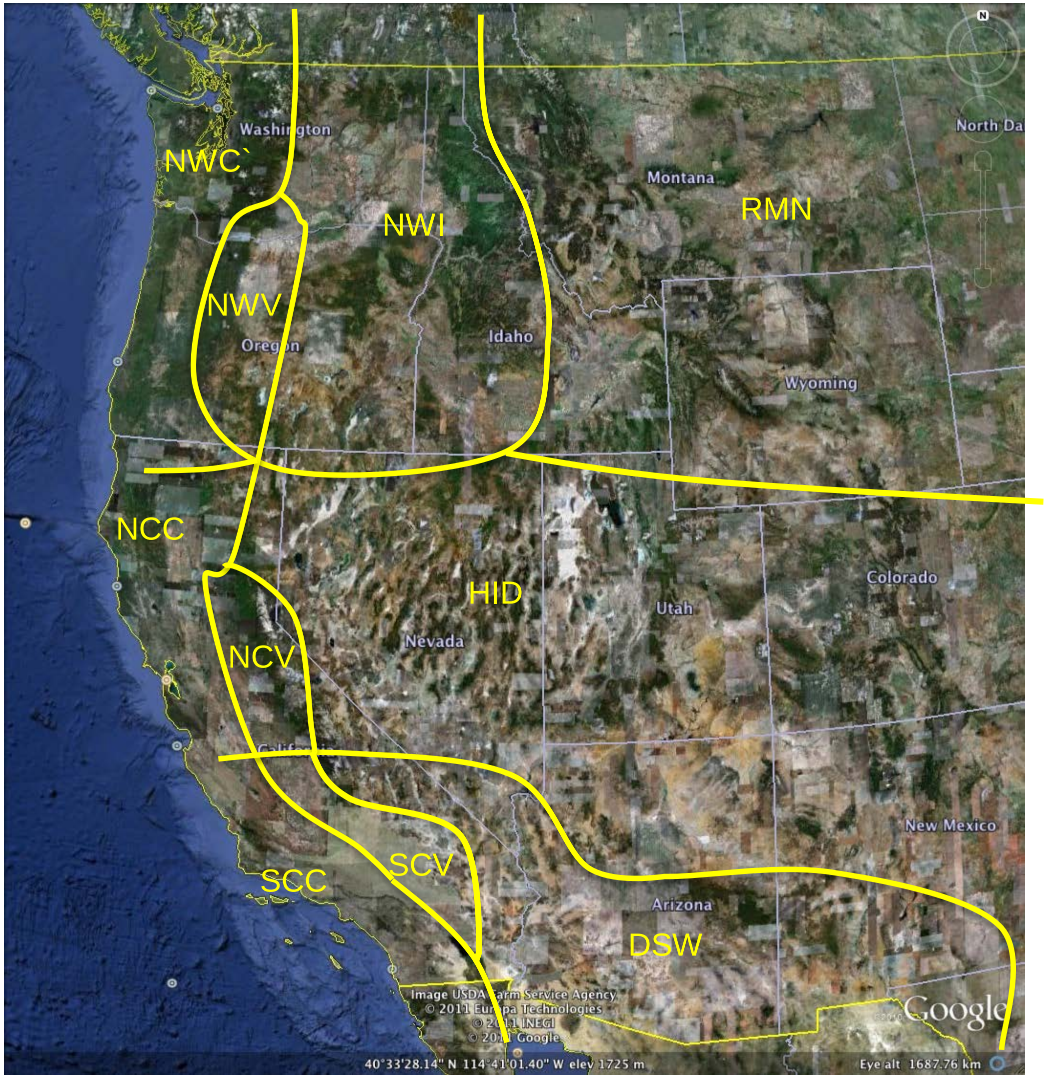

# Commercial



# Climate Zones




NWC – Northwest coast

NWV – Northwest valley

NWI – Northwest inland

RMN – Rocky mountain

NCC – N. Calif. coast

NCV – N. Calif. Valley

NCI – N. Calif. Inland

HID – High desert

SCC – S. Calif. coast

SCV – S. Calif. Valley

SCI – S. Calif. Inland

DSW – Desert southwest

# Substation / Feeder Types

- Residential: typical of your suburban neighborhood
- Commercial: typical of downtown load
- Mixed (default): mix of residential and commercial
- Rural / agricultural
- Several types of industrial loads (petro-chemical, paper mill, steel mill, semiconductor, etc)

Utilities populate base cases with load identifier

(3 characters climate zone)_(3 character type)

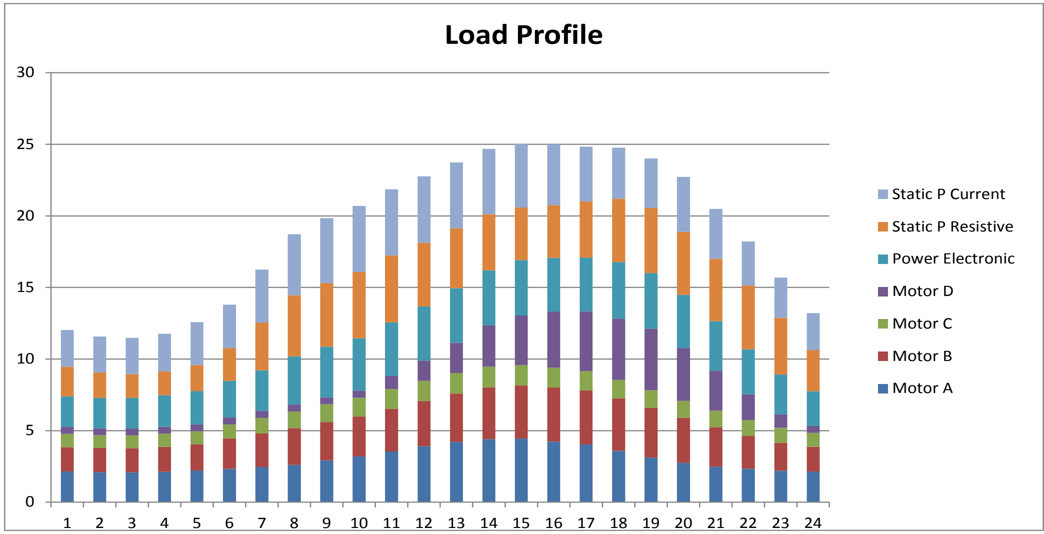
# Load Composition Model

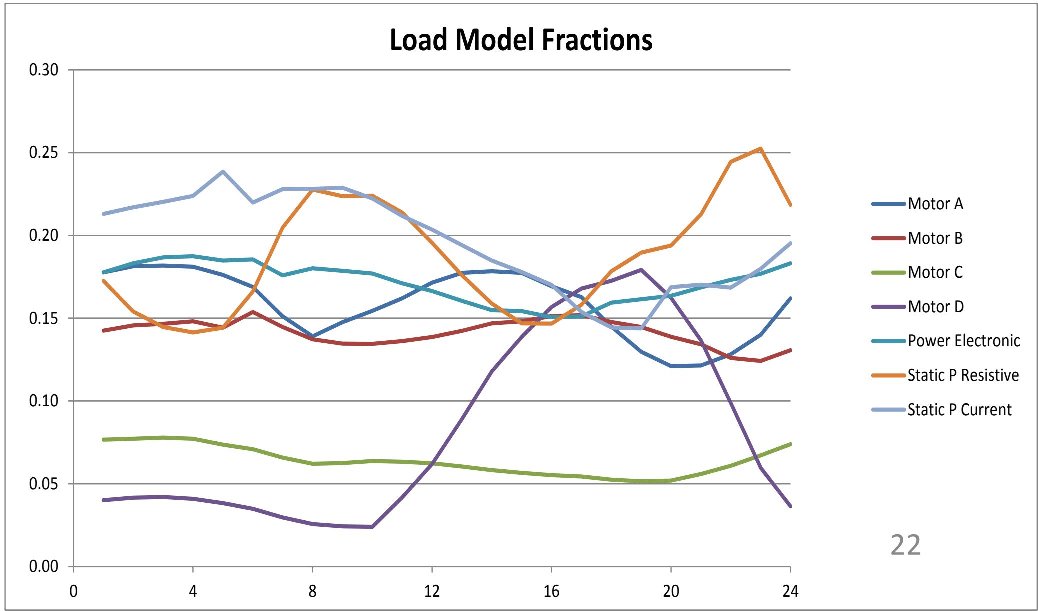
BPA and WECC developed Load Composition Model:

- 12 climate zones X
- 4 feeder types +
- 10 industrial load types

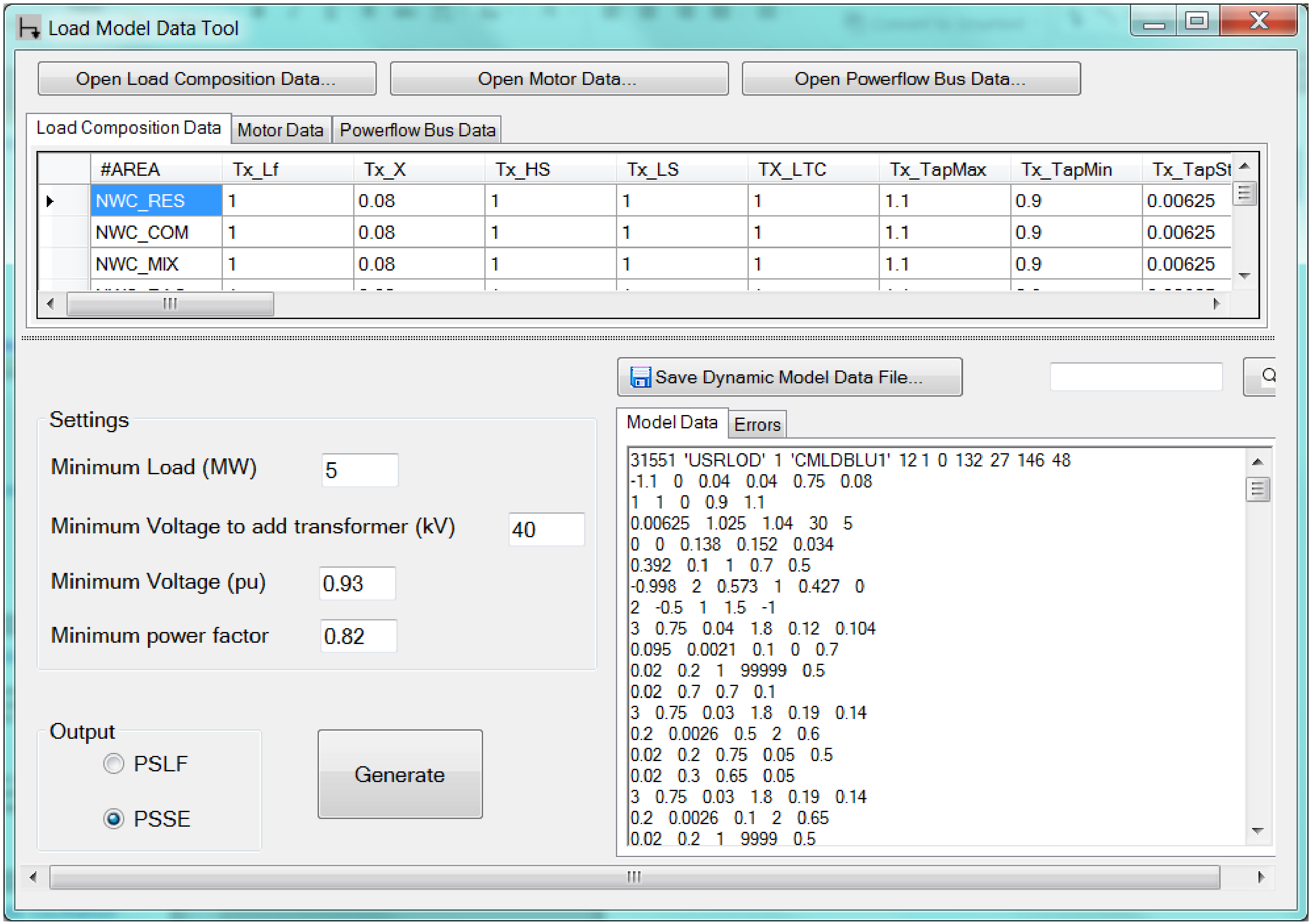
5 seasons

24 hours



# Load Model Data Tool



# Load Model Data Tool

Load Model Data Tool is used to create composite load model records in GE PSLF and PSS®E

Inputs:

- File with load records, including their "load type identifier"
- Load composition data
- Motor and end-use model data

Output:

- PSS®E DYR and PSLF DYD model data records

# Studies

# Model Acceptance and Validation Studies

Tens of thousands runs have been done with composite load model up to date

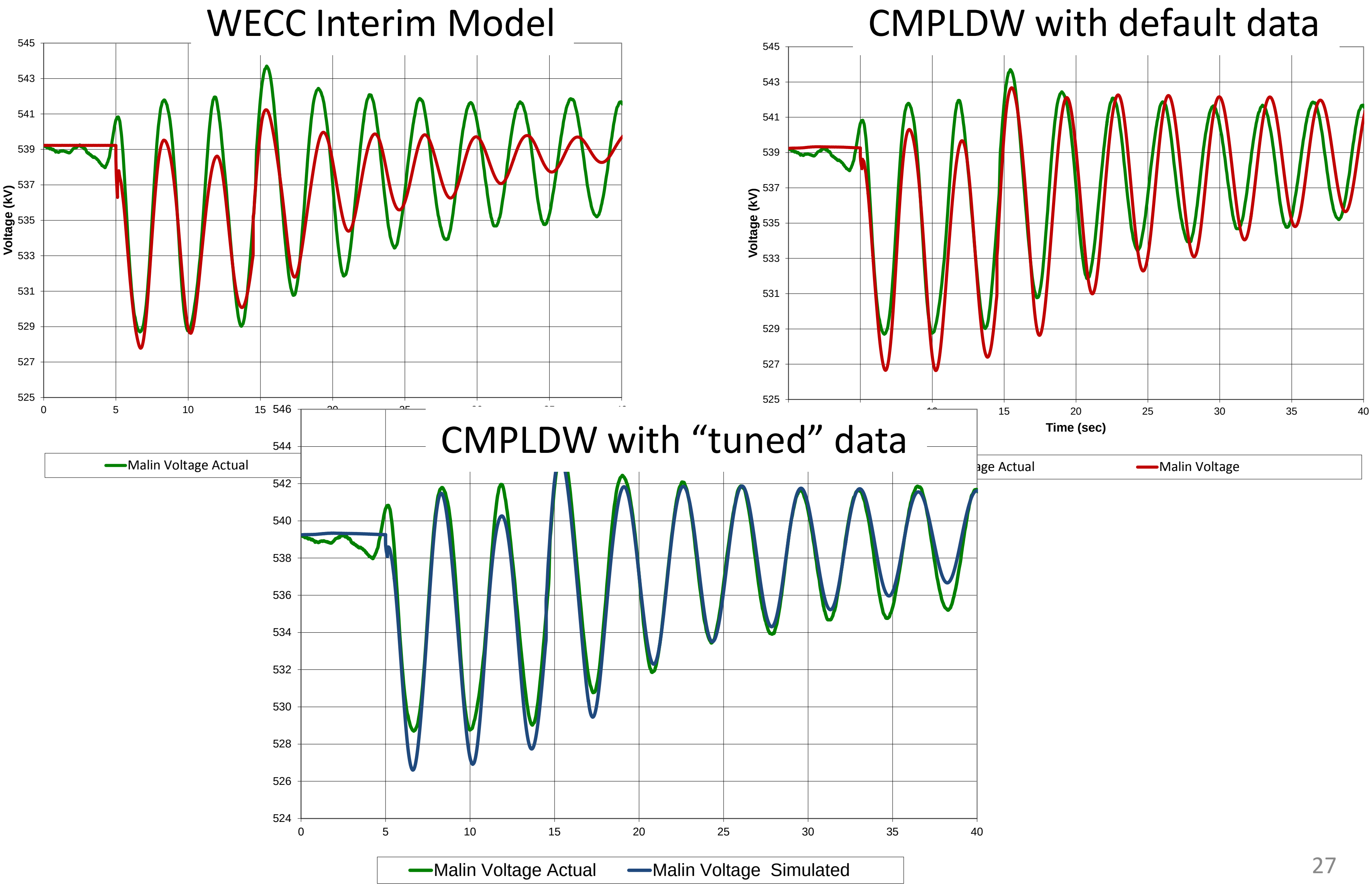
Validate model impact on power system performance:

- Large interconnection-wide disturbances
- Faults that include FIDVR

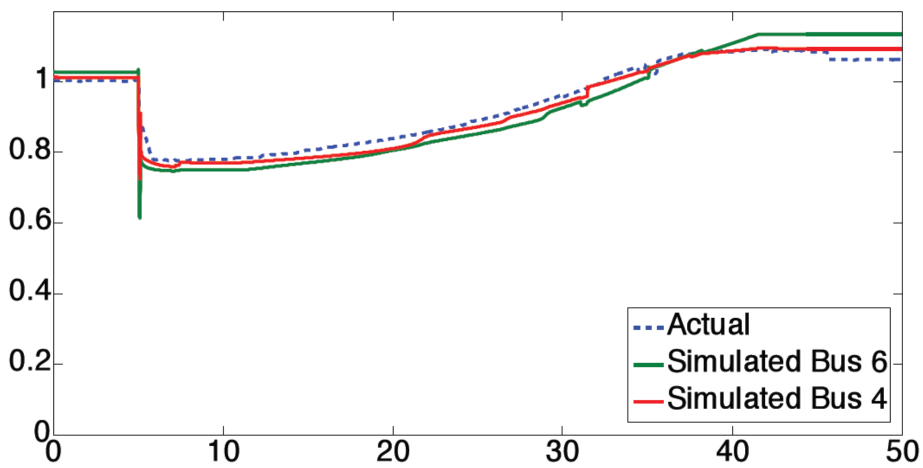
Challenges:

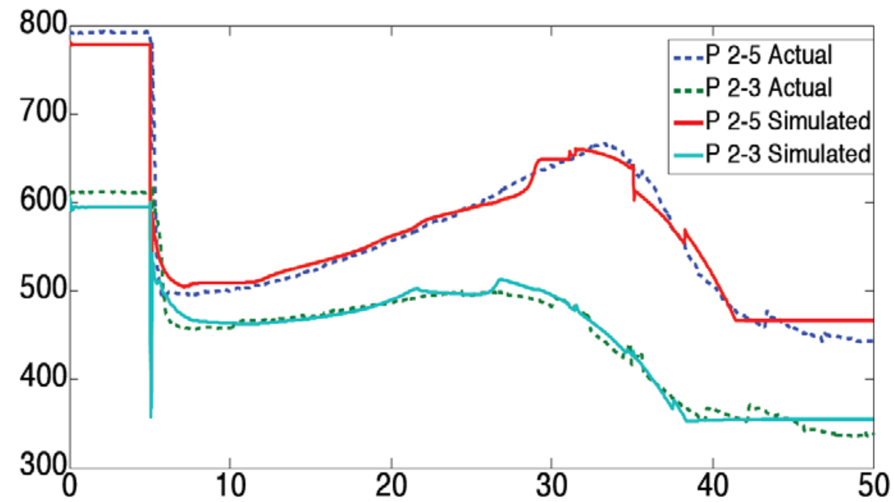
- Load composition varies daily and seasonally
- Lack of disturbance recordings, particularly FIDVR records outside Valley area in Southern California

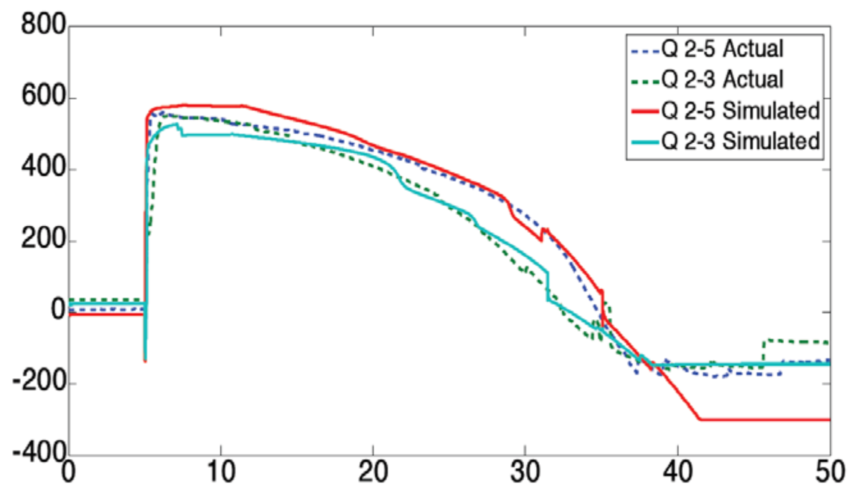
# August 4, 2000 Oscillation



# Reproducing Delayed Voltage Recovery Events with Composite Load Model



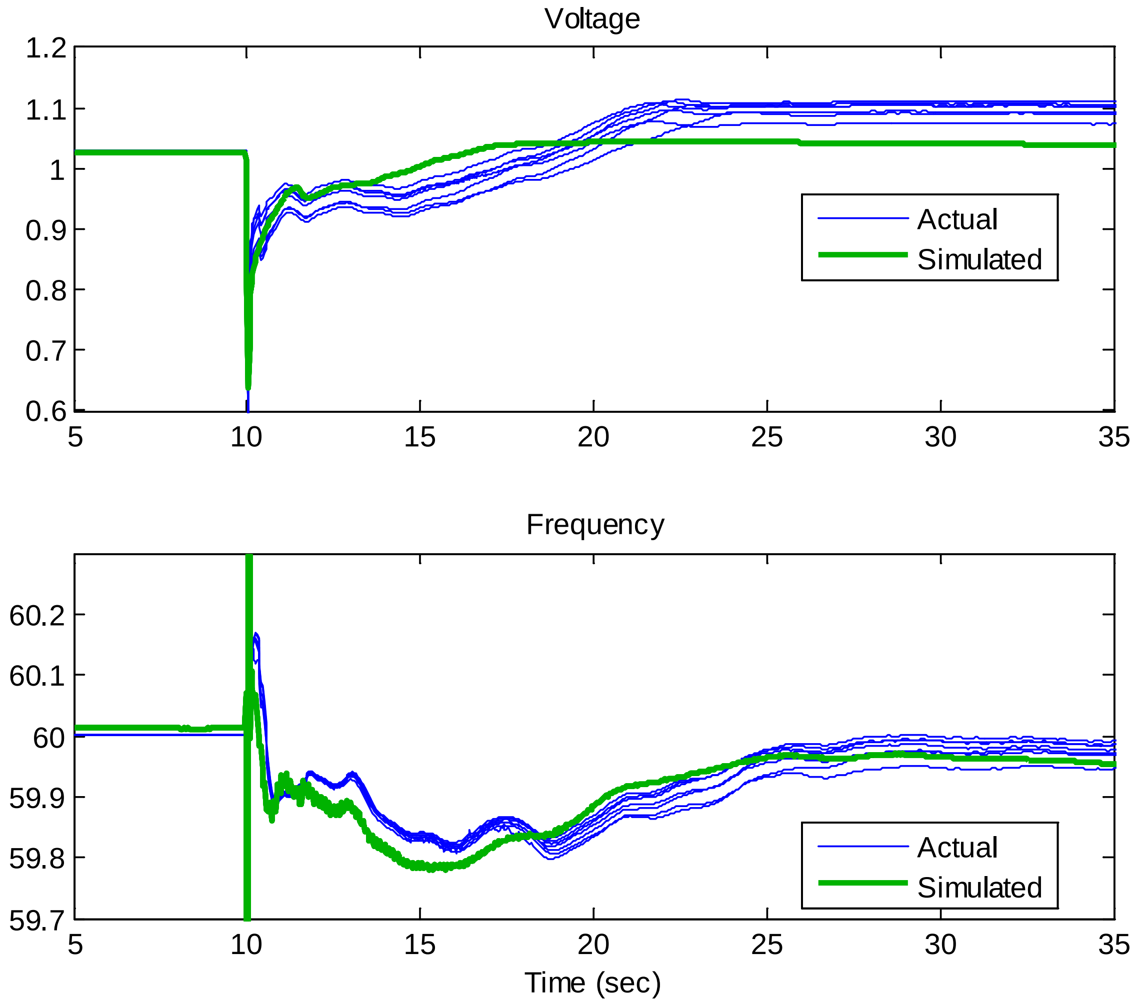




Simulations of delayed voltage recovery event due to air-conditioner stalling
Models can be tuned to reproduce historic events reasonably well

Done by Alex Borden and Bernard Lesieutre at University of Wisonsin

# July 28, 2003
# Hassayampa Fault Sensitivities



# System Impact Studies

- We were able to tune the composite load model to reproduce historic system events

  That said…
- Composite load model was more conservative in simulating the severity of FIDVR events than we expected
- Another concern is high sensitivity of results with respect to stall and motor protection assumptions

  Therefore,
- **WECC adopted phased implementation of composite load model: Phase I – air-conditioner stalling feature is disabled**

# Implementation

# Phased Implementation in the West

2011 WECC approved phased implementation plan:

- Model indicated AC stalling much greater than what experienced in reality outside Valley area in Southern California
- Lack of validation outside Valley area
- WECC voltage dip criteria
- More gradual transition

**Phase I – air-conditioner stalling feature is disabled**

WECC membership performed system impact studies
Model data revisions were implemented
WECC approved composite load model in 2013

Starting 2014, all WECC planning and seasonal operating cases include Phase I composite load model

# Lesson's Learned from Phase I Implementation

Phase I model impacted system performance:

- Damping of inter-area power oscillations
- Transient voltage dip

The impact is observable during large disturbances and close to the operating limit, the impact is less significant during small events

Several utilities voiced concerns about load tripping

# Where we are now …

- Composite load model is implemented in GE PSLF and Siemens PTI PSS®E, similar models exist in Power World, Power Tech TSAT
- Tools are developed for load model data management
- “Default” data sets are prepared
- WECC is taking phased approach for approving the composite load model for TPL compliance studies
  - Phase 1: air-conditioner stalling is disabled by setting Tstall parameter to a large number
  - Phase 2: better understand the reliability implications of delayed voltage recovery due to air-conditioner stalling, develop appropriate reliability metrics

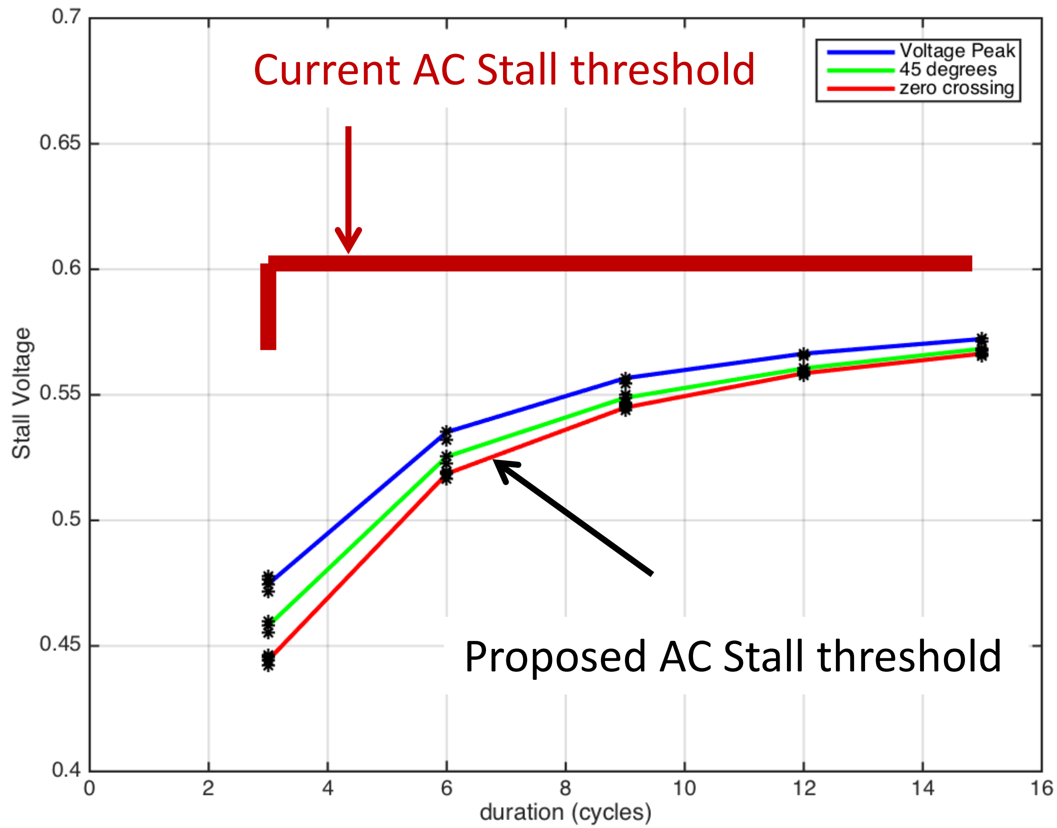
# … Where we are now

- All planning and seasonal operational cases prepared by WECC now have composite load model
- Tens of thousands runs have been done with the composite load model up to date
- WECC studies help to improve model data sets

# Next Steps

# AC Model Revisions

New work by John Undrill, Bernie Lesieutre and BPA suggests that air-conditioners may not stall as easy as previously expected



# Planned Revisions to **Model Structure**

**Flexible model structure**

Electrical end-use characteristics are changing rapidly, as more loads become electronically connected

Modular structure (similarly to generating units)

**Air-conditioner models**

Revise "performance" model to reflect recent test findings

Add MOTORC dynamic model

**Distributed generation**

**Revision of motor protection**

From discrete to more granular

# Model Data

Composite load model is a very powerful.

Deepen our understanding of end-uses.

Building surveys

- Installed equipment
- Load shapes
- Protection and control

End-use monitoring

Load shape analysis

# Disturbance Monitoring

**We need more recording** of both FIDVR events as well as large faults not causing FIDVR

- Synchronized recordings at transmission and distribution levels

System impact studies for Phase II and sensitivity studies with respect to model parameters

- Continue after model improvements are completed

# Load Modeling – Setting Expectations

We can now achieve the great accuracy with generator models:

- We model physical equipment that is well defined and under our control

We will never be able to achieve a comparable level of accuracy with load models

- Yes, we can tune load models to accurately reproduce and explain past events
- But, Load models is only capable of predicting the future load response only in principle, and not in detail

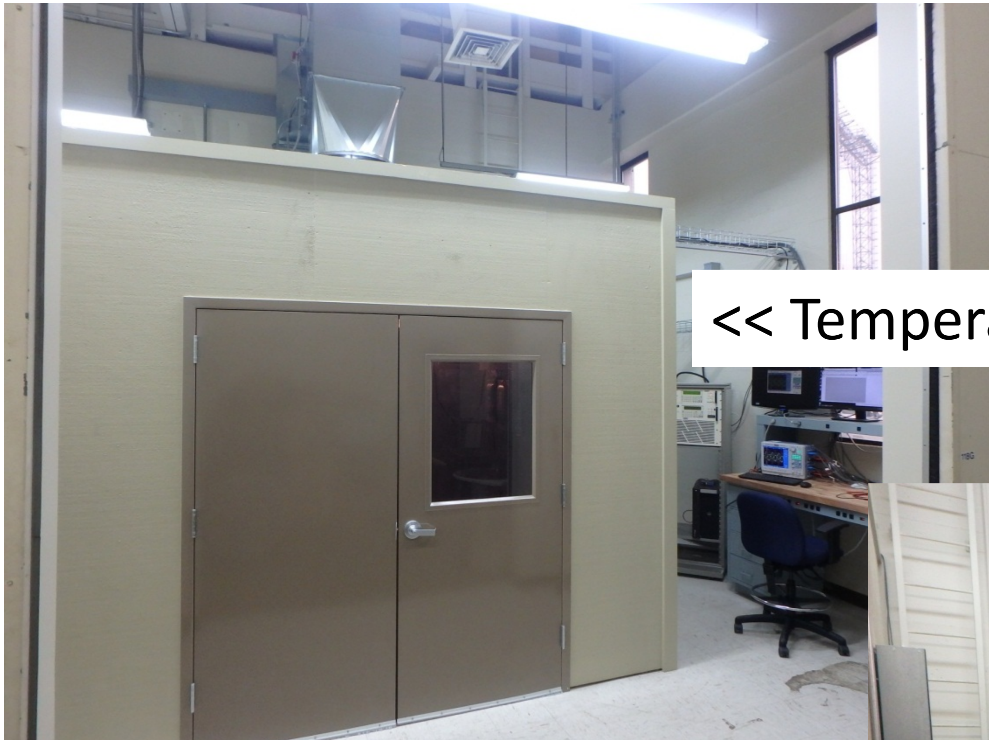
# Thank You

# End-Use Testing at BPA

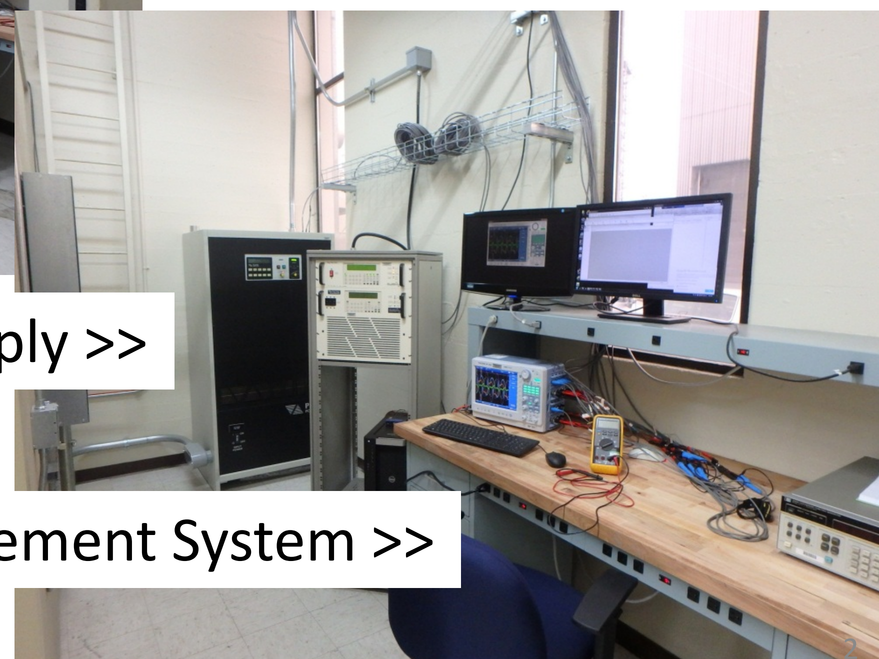
2015 NERC-DOE FIDVR Workshop

Presented by
Dmitry Kosterev and Steve Yang, BPA

# BPA End-Use Testing Lab



<< Temperature controlled chamber



Controllable power supply >>

Measurement System >>

# Residential Air-Conditioner Tests

BPA, SCE and EPRI tested independently a number of single phase air-conditioners

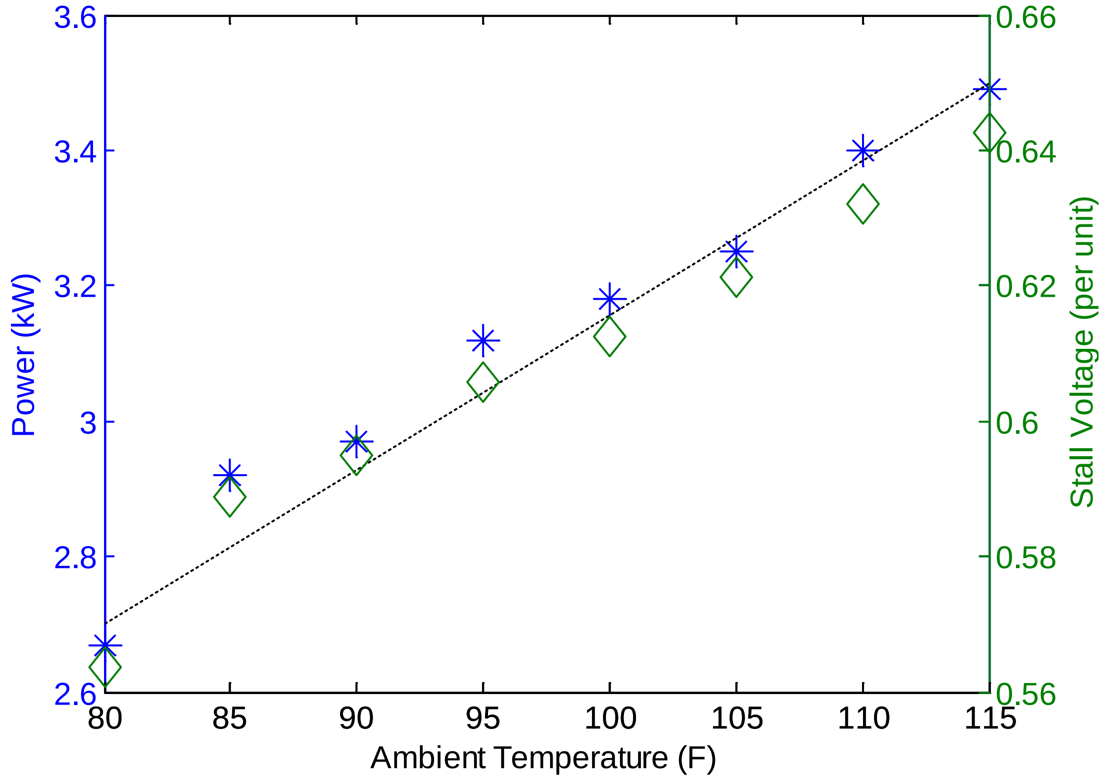
Tests included voltage sags, ramps, oscillations, as well as frequency excursions

Learned in the first round:

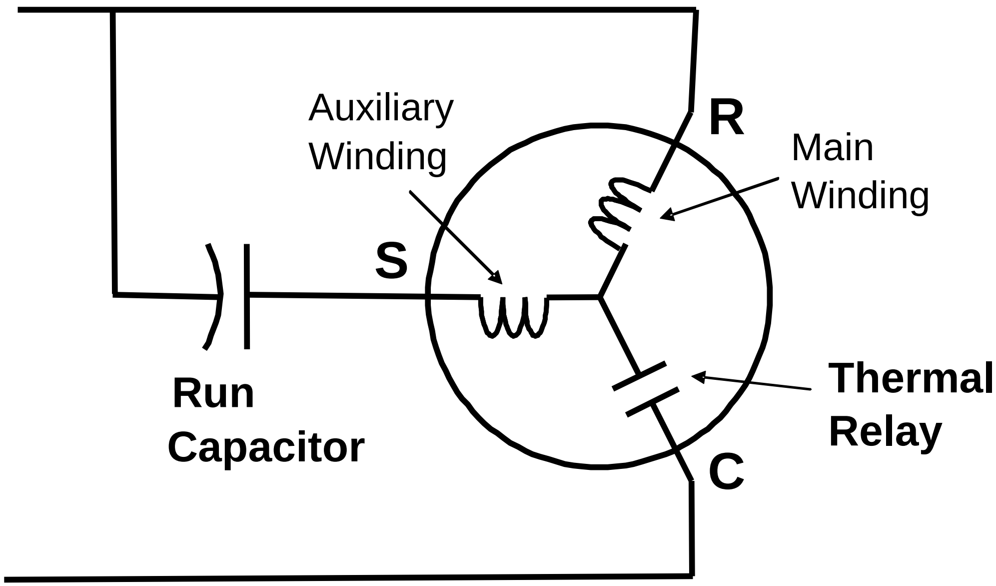
- Residential air-conditioners stall for a sudden drop in voltage to 50%-60% of nominal in less than 3 electrical cycles
- Once stalled, residential air-conditioner remain stalled even when the voltage is recovered, until coolant pressure is equalized
- Thermal protection trips in 5 to 30 seconds

# Test Findings:
# Compressor Motor Steady-State Loading

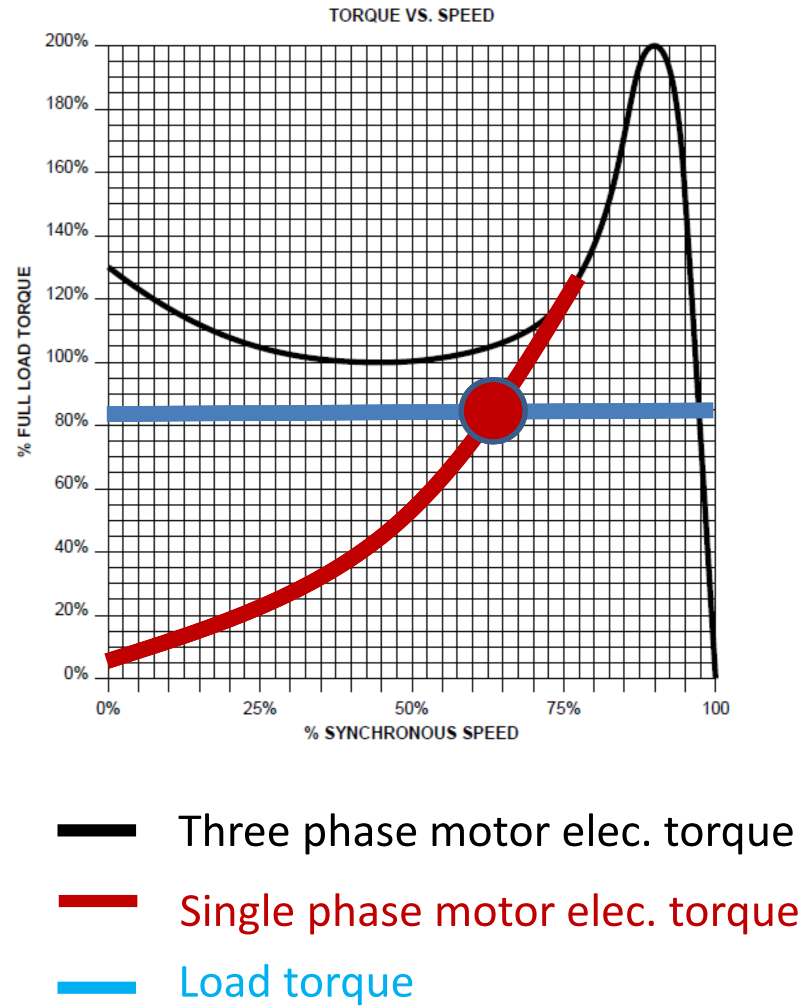
- Compressor loading and stall voltage depend on the ambient temperature
- Compressor motors have high power factor ~0.97 when running



# (a) Torque-Speed Curves




1 phase supply, 2 winding, capacitor-run motor

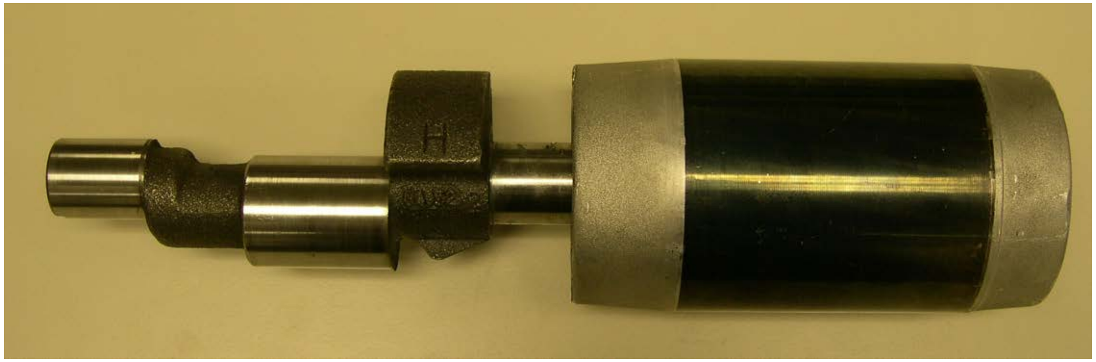


# (b) Compressor Motors Inertia is Very Low

**H = 0.03 – 0.05 seconds**

E.g. 3.5-ton compressor motor:

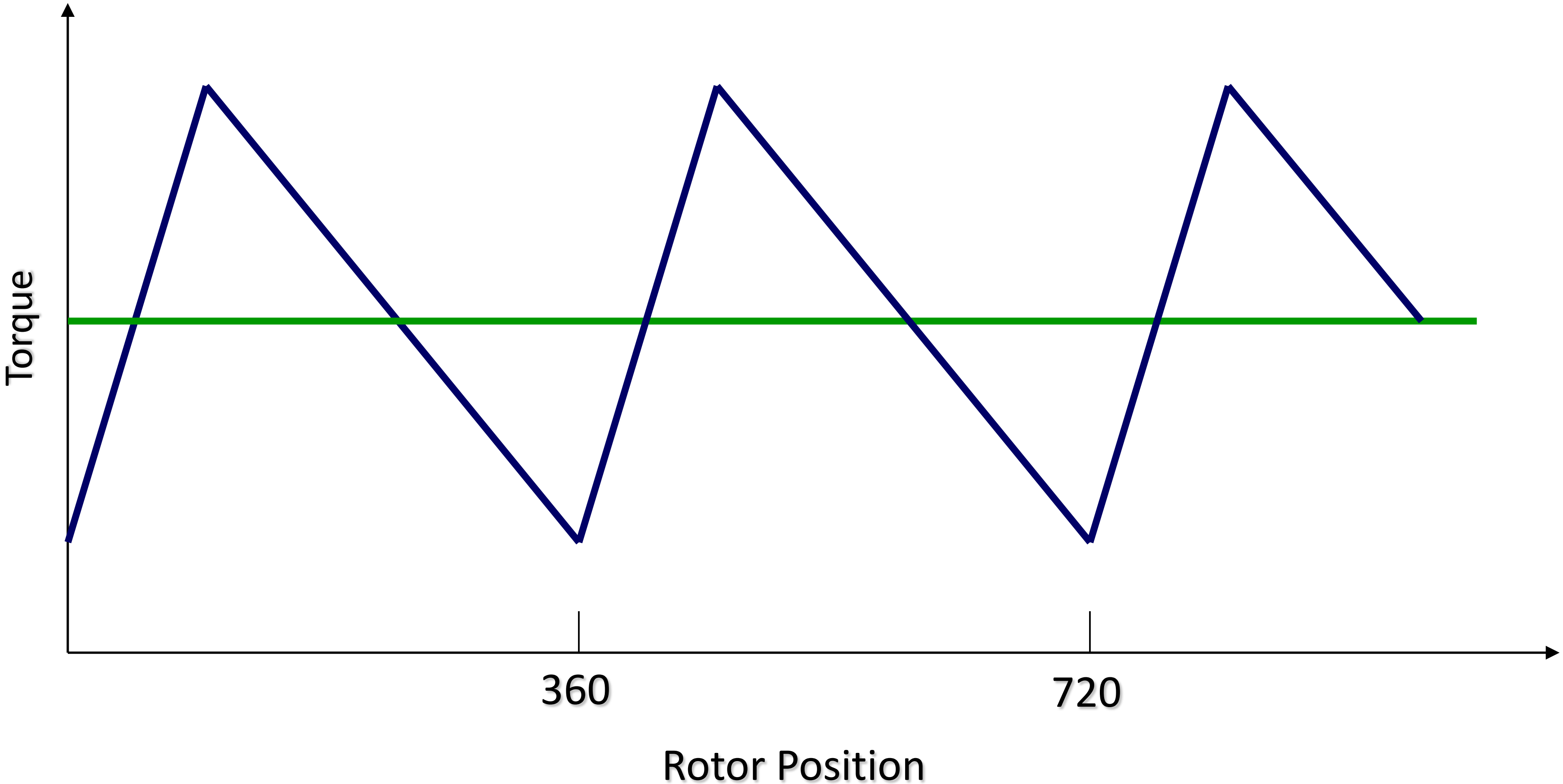
Weight: 4.6 kg




75 mm

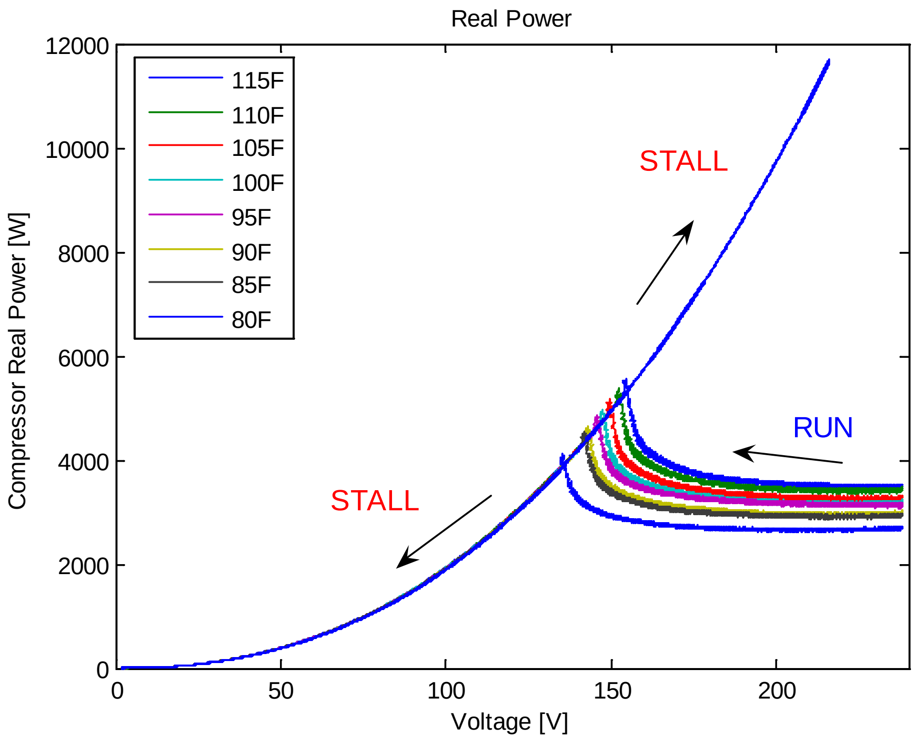
310 mm

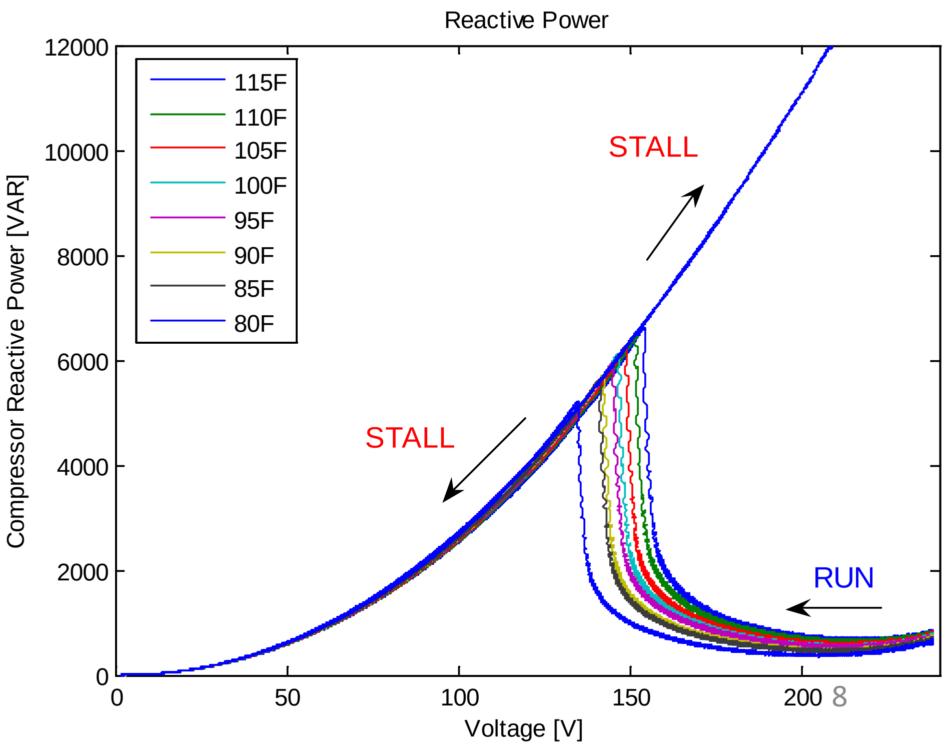
# (c) Compressor Load Torque in very cyclical




It is very possible that the motor stalls at the next compression cycle

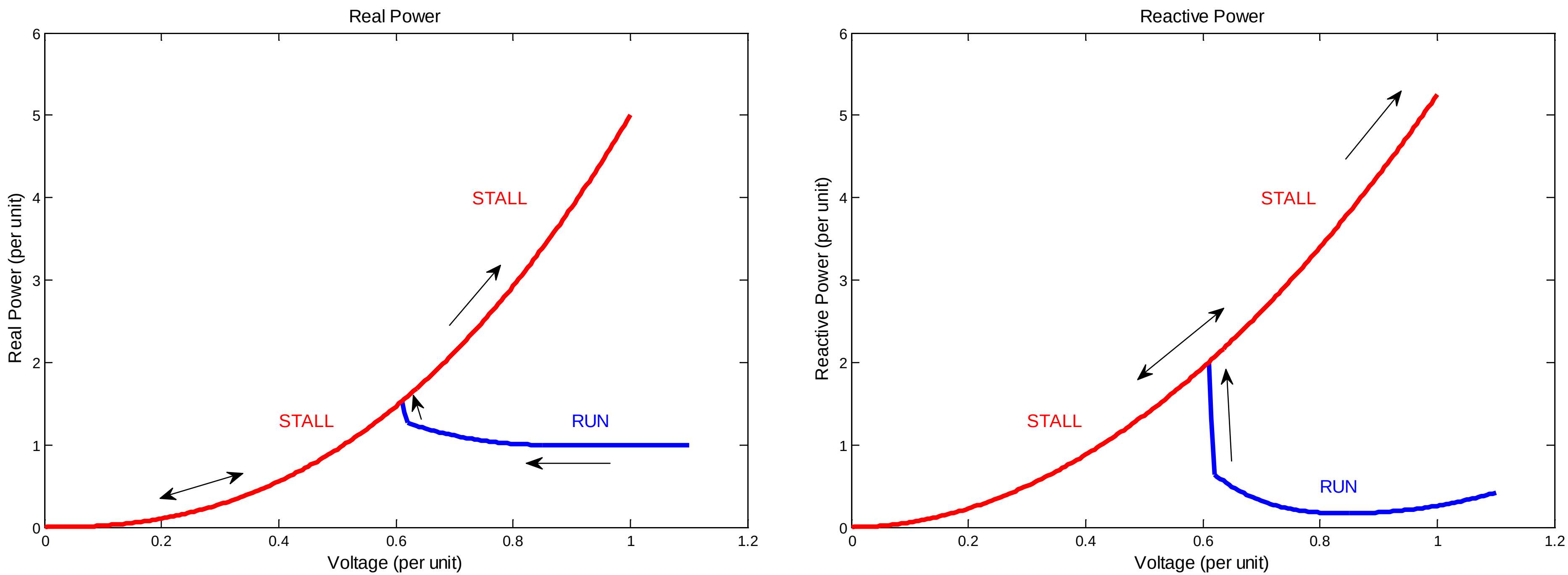
# Compressor Motor Tests – Power-Voltage Trajectories




* note motor load and stall voltage increase with temperature

# "Performance" Model




Motors stall when voltage drops below Vstall for duration Tstall

A fraction Frst of the aggregated motor can restart when the voltage exceeds Vrst for duration Trst

# System Studies

Studies done with developed AC models were much more conservative compared to actual experience: the model indicated greater and wider FIDVR phenomenon compared to actual experiences

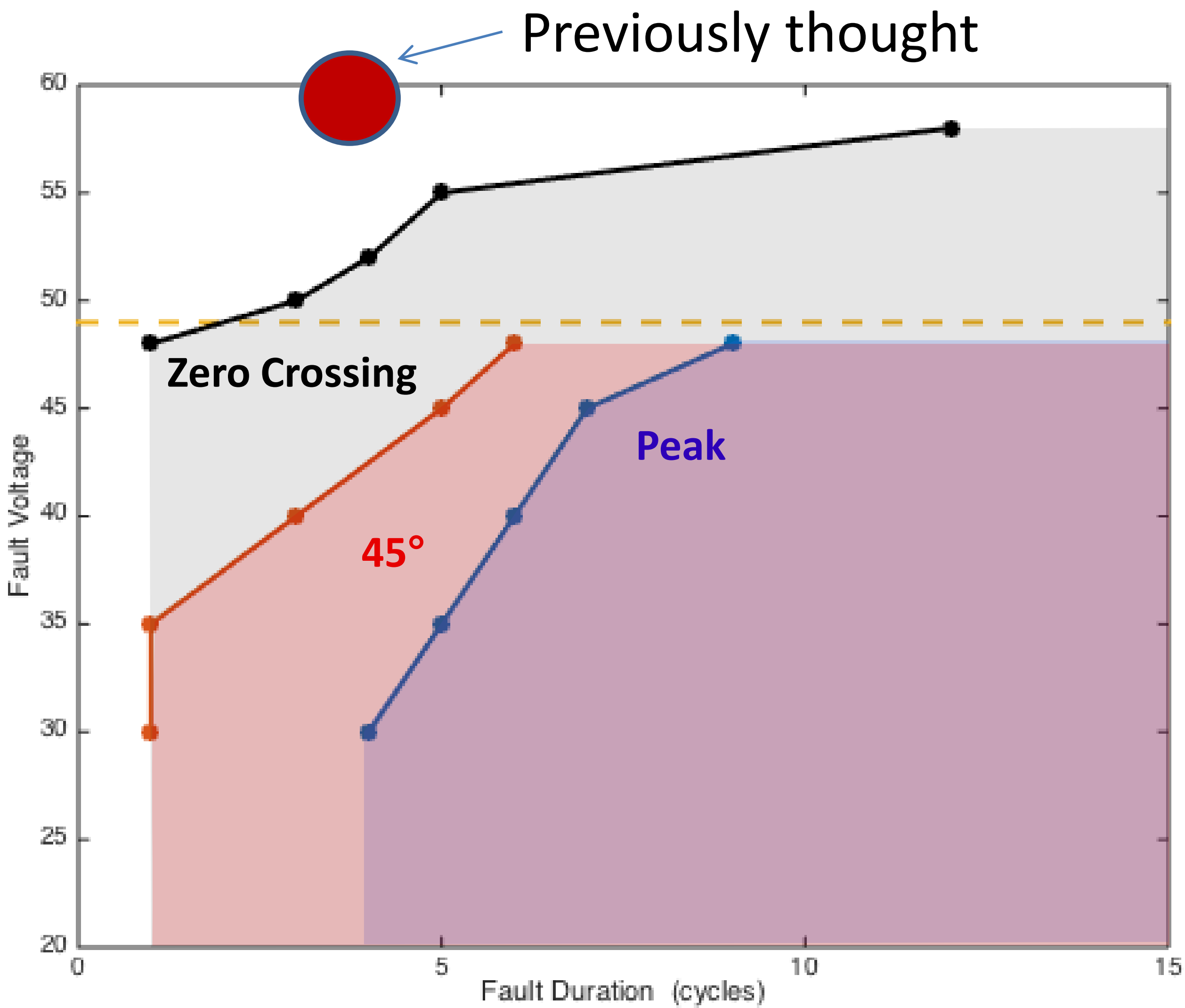
…Back to the drawing board…

# Testing and Modeling – Round 2

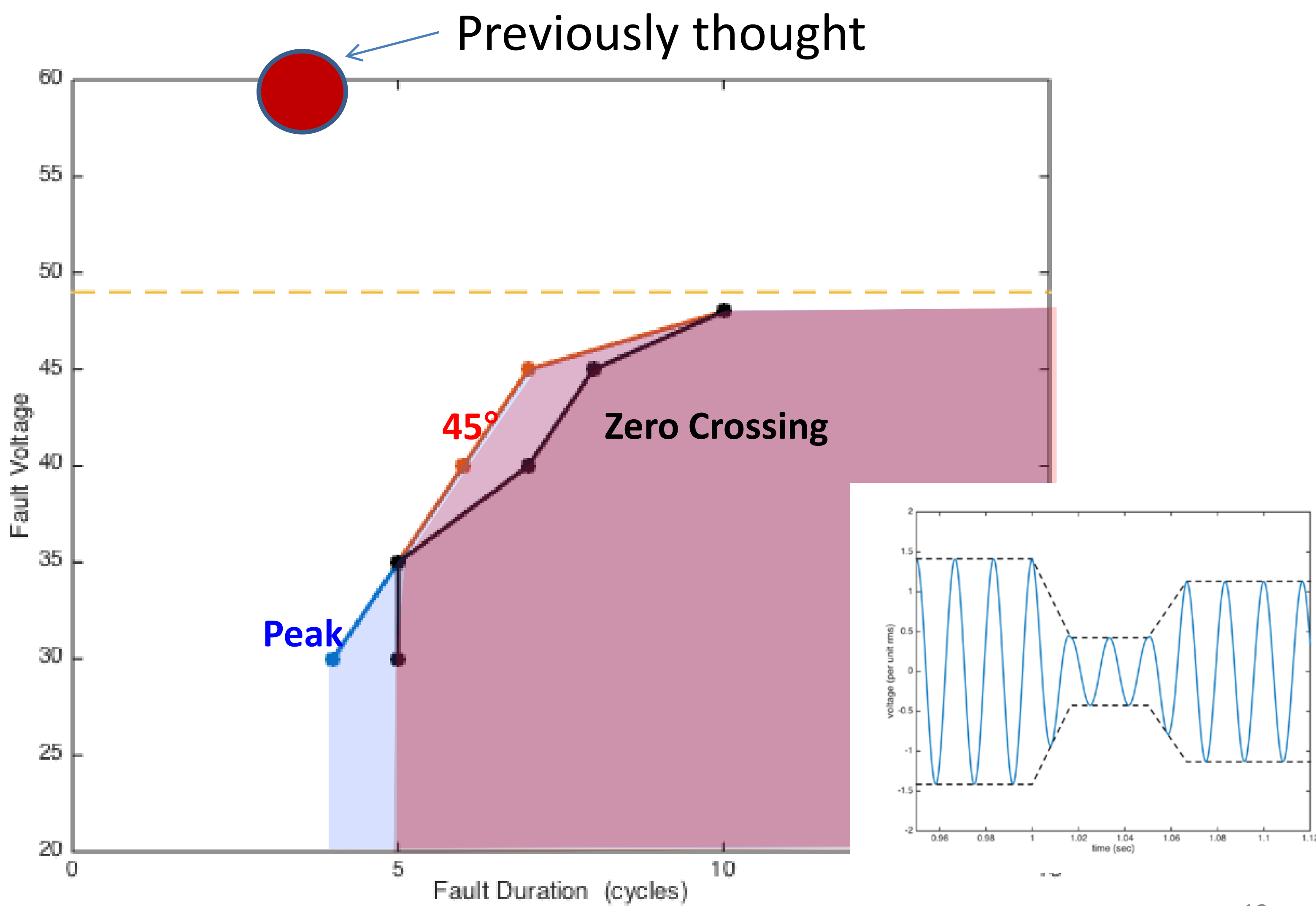
BPA, John Undrill and Bernie Lesieutre found a "common mode failure" mode in SCE-BPA-EPRI testing - **all voltage sags were sudden and applied at voltage waveform zero-crossing**

Additional testing done at BPA in collaboration with John Undrill and Bernie Lesieutre showed that **air conditioners tend to be less prone to stalling when the fault is applied at the waveform peak, or voltage is ramped down** instead of sudden steps down

# AC Stall, Instantaneous Voltage Dip

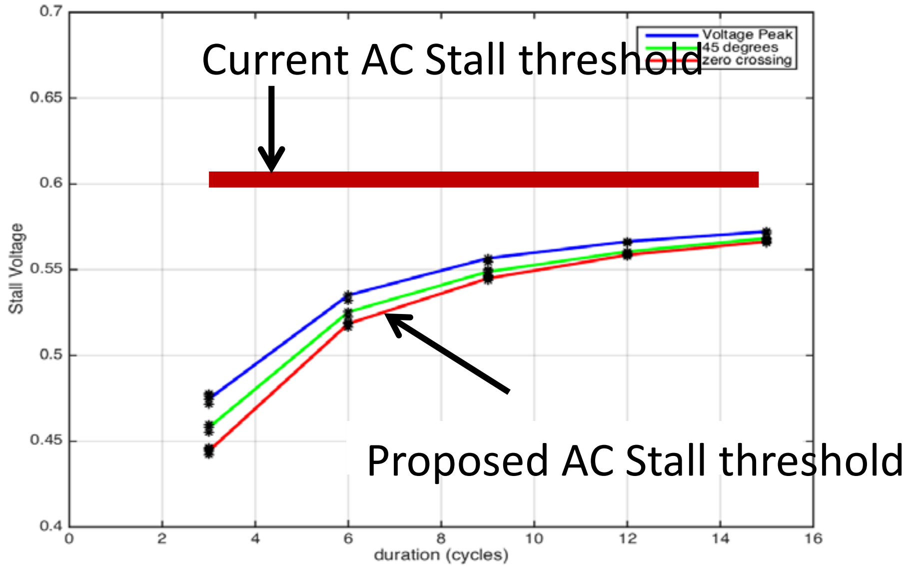


# AC Stall, : 1 Cycle Ramp in Voltage Dip



# Next Steps

1. Update AC "performance" model




2. Add dynamic MOTORC model to composite load model

3. Continue benchmarking positive sequence models (GE PSLF and PSS®E) with point on wave models (PSCAD)

# Thank You

# Simulation Models for Single Phase Compressor Motors

Bernie Lesieutre (UW-Madison, LBNL)

NERC FIDVR and Dynamic Load Modeling Workshop, September 30, 2015.
Support from CERTS and PSERC

# Simulation Models for Compressor Load Models

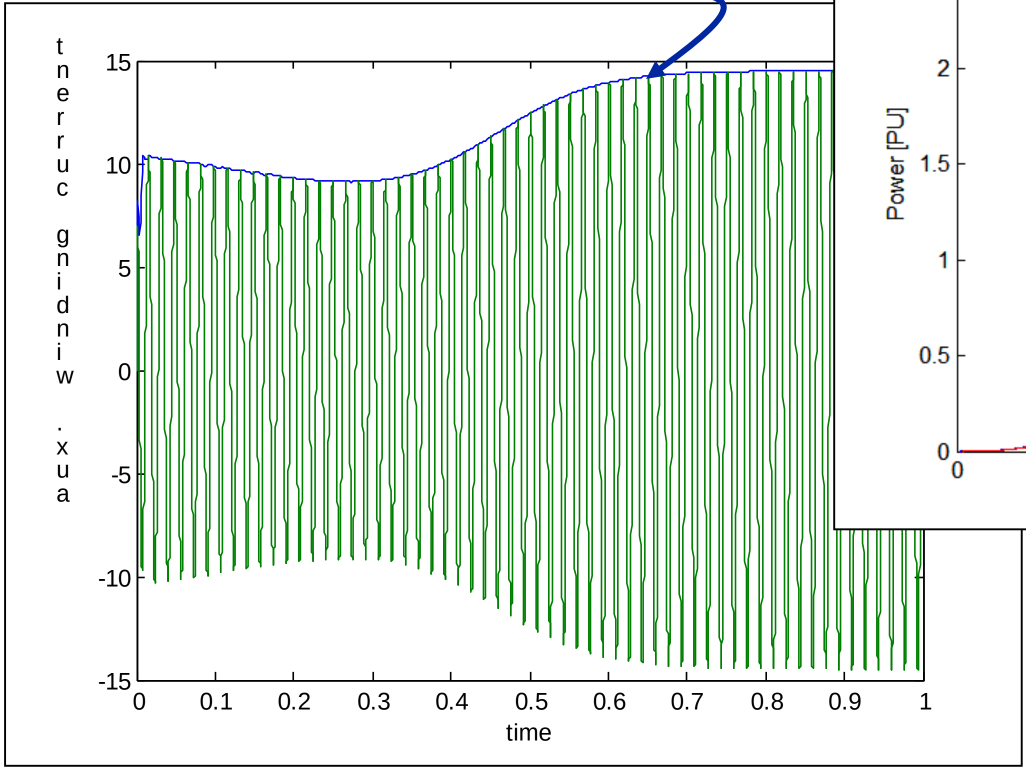
Option 1: Detailed motor models, and single-phase network models. Useful for research, hopefully not needed for grid-scale simulations.

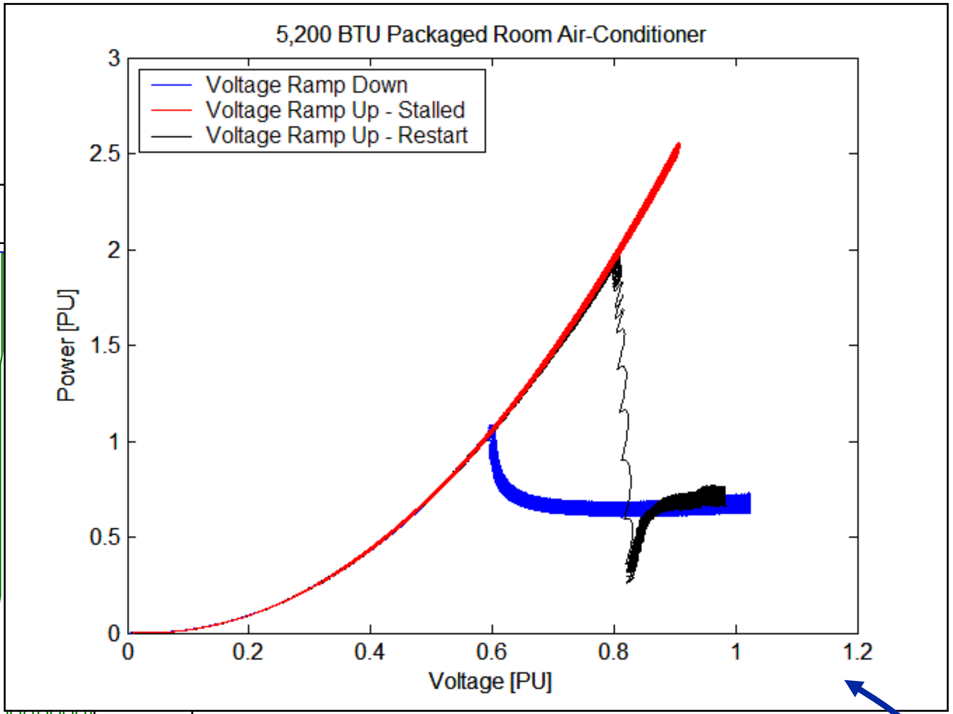
Option 2: Adapt models for grid simulations

- static performance model, current model simplistic, somewhat pessimistic.
- dynamic phasor model, complicated, doesn't capture subcycle influences (yet).

# Single-Phase Motor Models for Grid

“Dynamic Phasor” Model



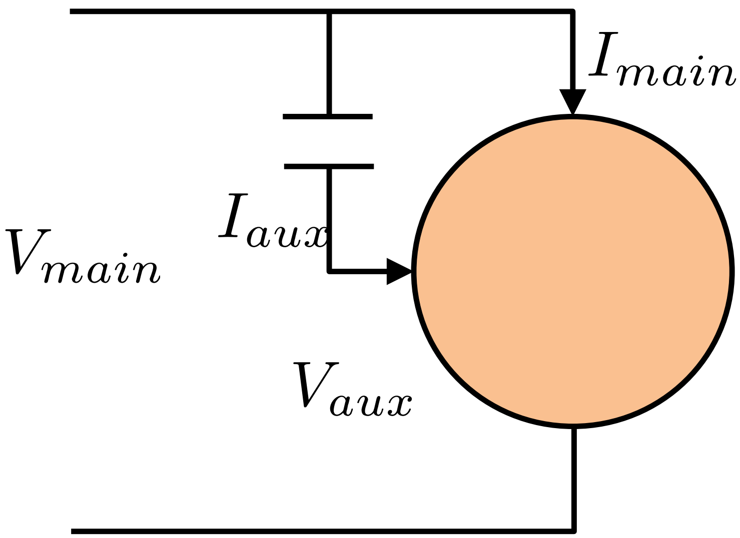

“Performance” Model

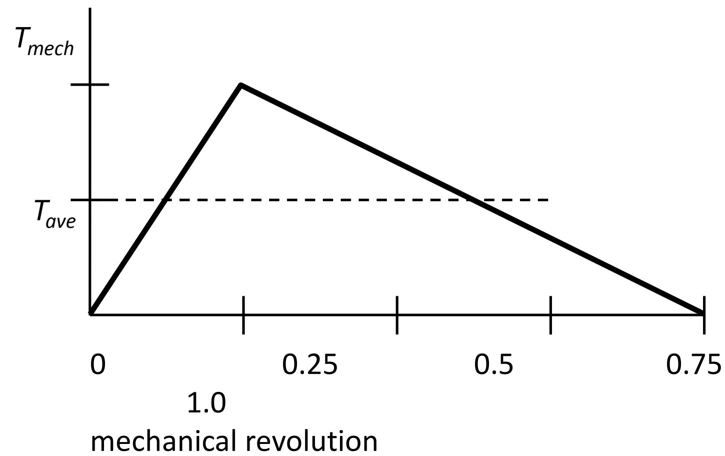
# Important Questions about Grid Simulations

- To what extent do single-phase, point-on-wave effects matter? Examine with single-phase motor simulations and tests.
- To what extent can impacts be aggregated?

Do all motors stall during a FIDVR event?

# Single Phase Compressor Simulation Model

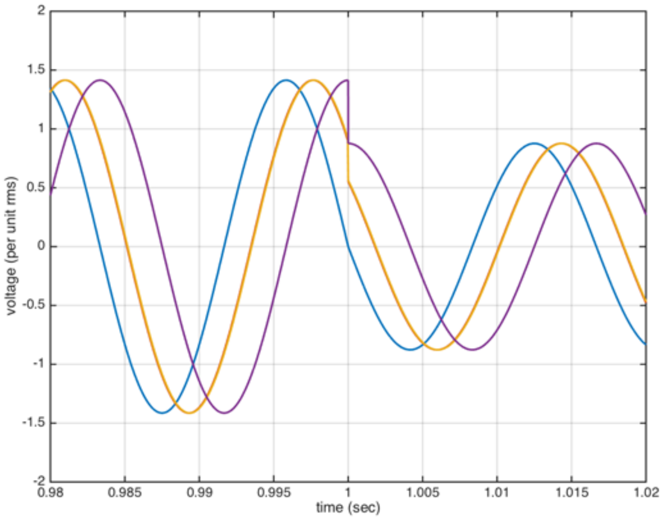



Reciprocating Compressor Mechanical Load

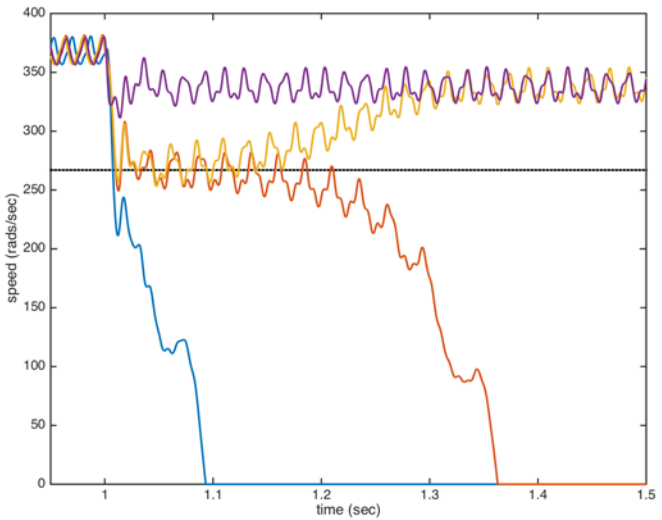
# Point-on-Wave Effects

## Simulations of Single-Phase Compressor Motor




Applied voltage. The disturbance occurs at different points along the sinusoid: peak, zero crossing, in between.

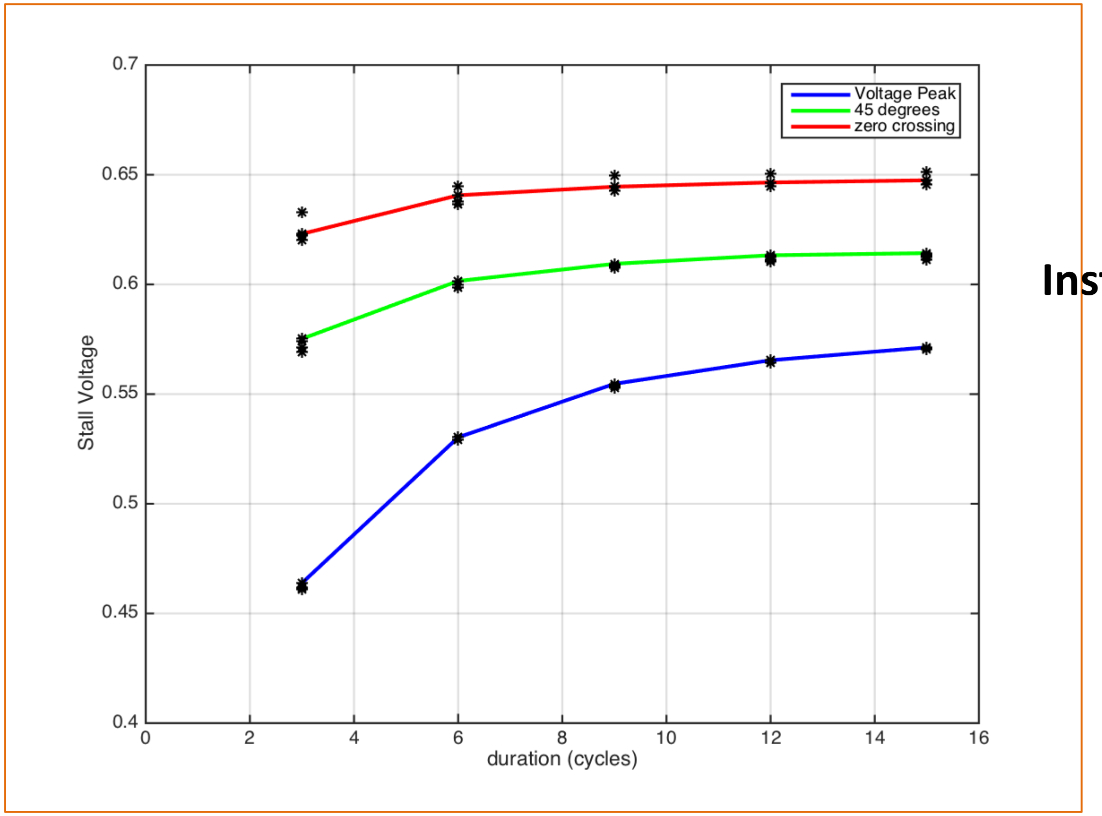
Instantaneous drop to 62% nominal for 3 cycles.




Speed for the different applied voltages. Worst case: zero crossing disturbance.

# Point-on-Wave Effects

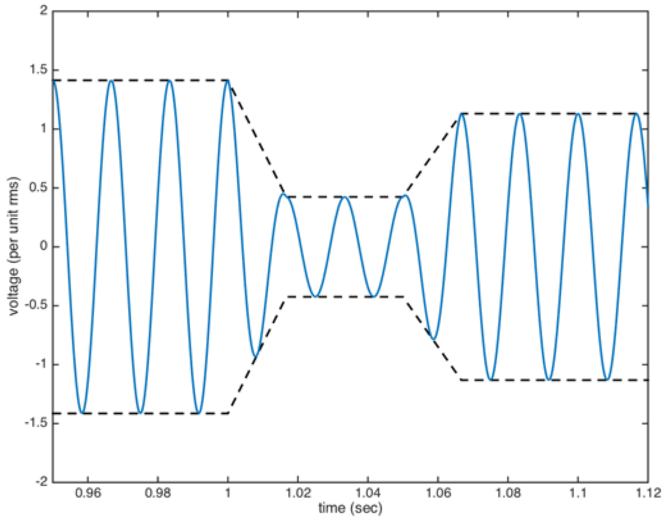
## Stall Voltage vs fault duration, and point-on-wave variation.



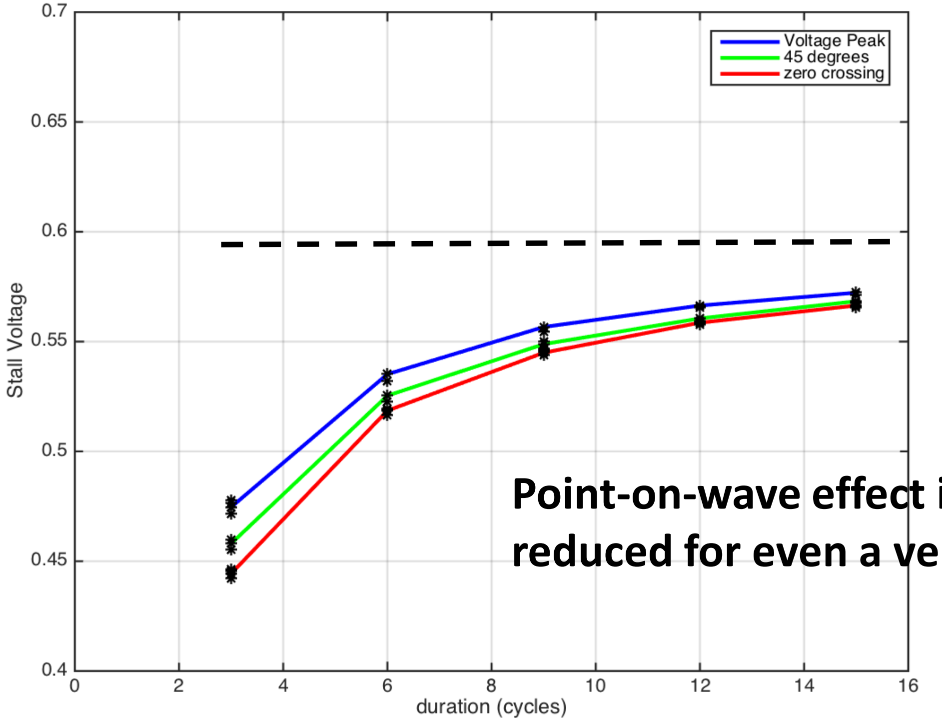

**Instantaneous voltage drop**

# Point-on-Wave Effects

- Ramp Voltage Instead:



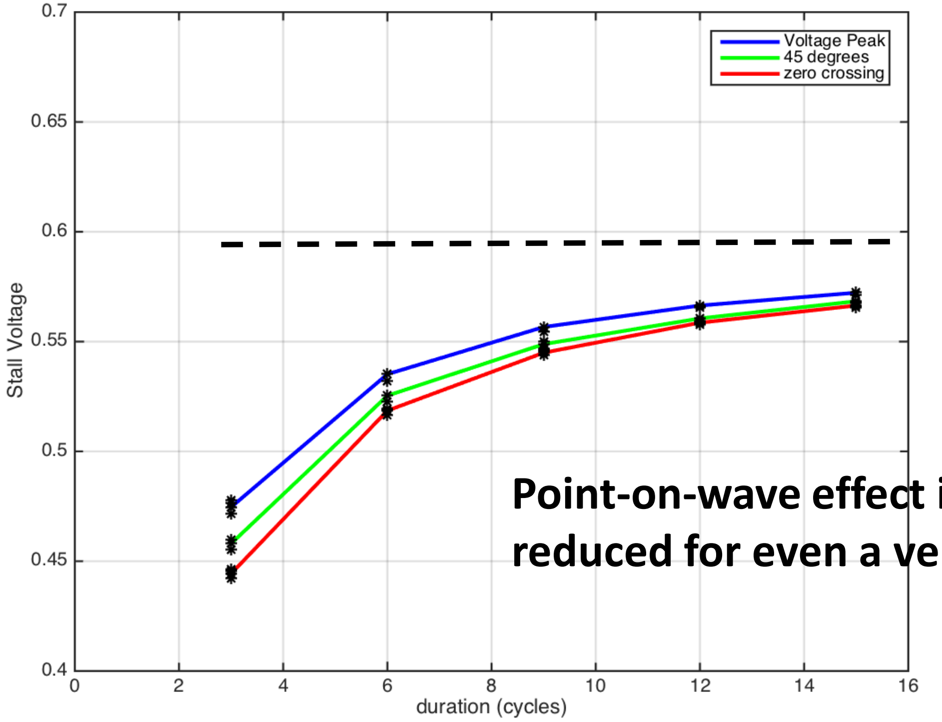

Performance Model Characteristic for reference




**Point-on-wave effect is greatly reduced for even a very short ramp.**

# Point-on-Wave Effects

- These results suggest a reason why FIDVR events don't cascade beyond an event feeder.
- Locally, A/C motors stall in response to event.




**Further away, the filtered voltage may exceed threshold.**

Performance Model Characteristic for reference

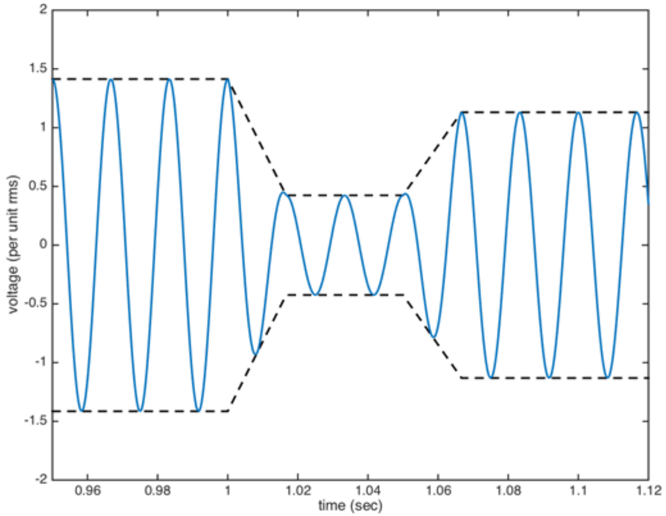
**Point-on-wave effect is greatly reduced for even a very short ramp.**

# Laboratory Tests

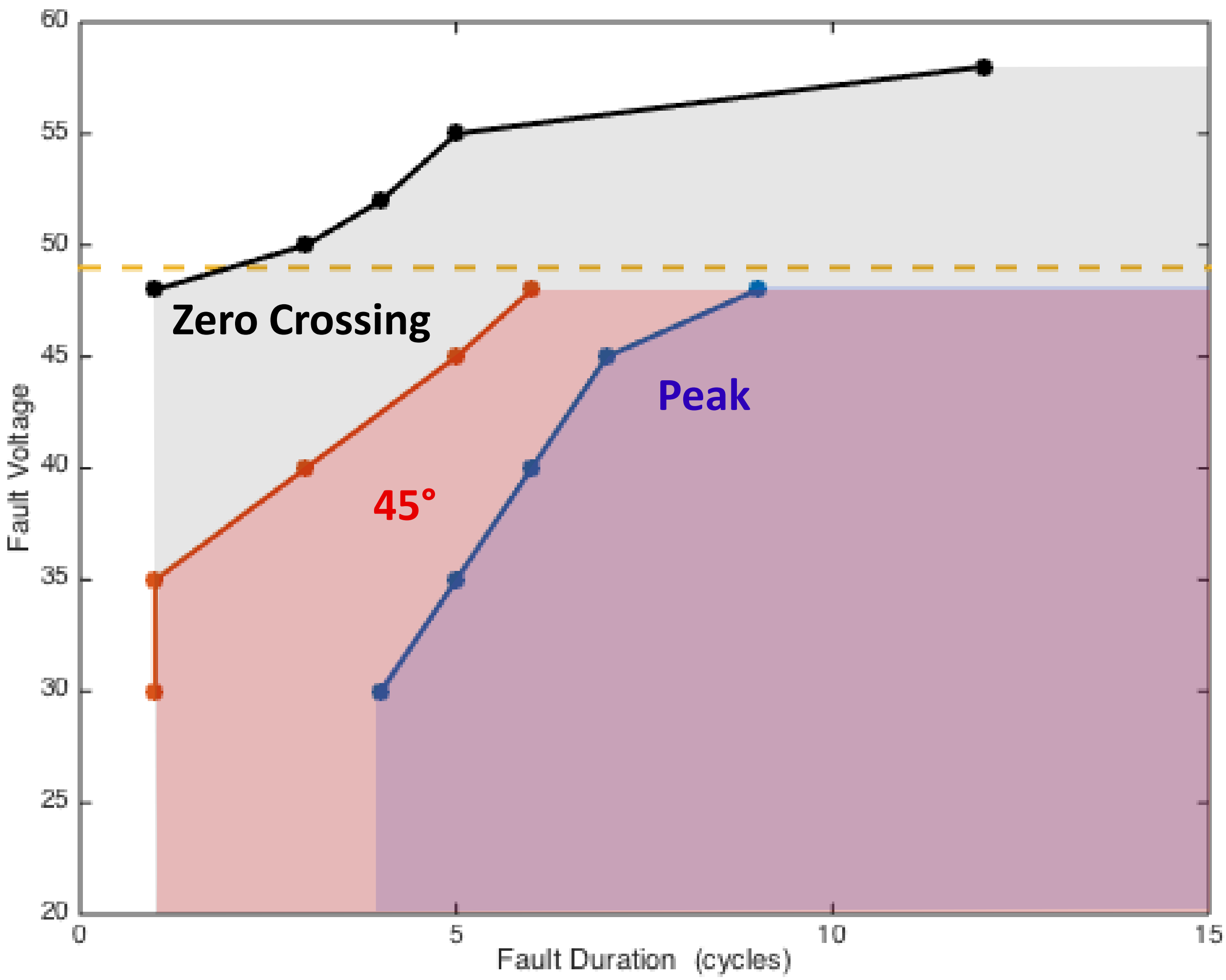
- Air Conditioner Tests at BPA Facility
- Test Point-on-Wave Response, with and without ramp.
- Scroll Compressor

Voltage dip to 48, 45, 40, 35 and 30% nominal
Recovery voltage at 90% nominal.

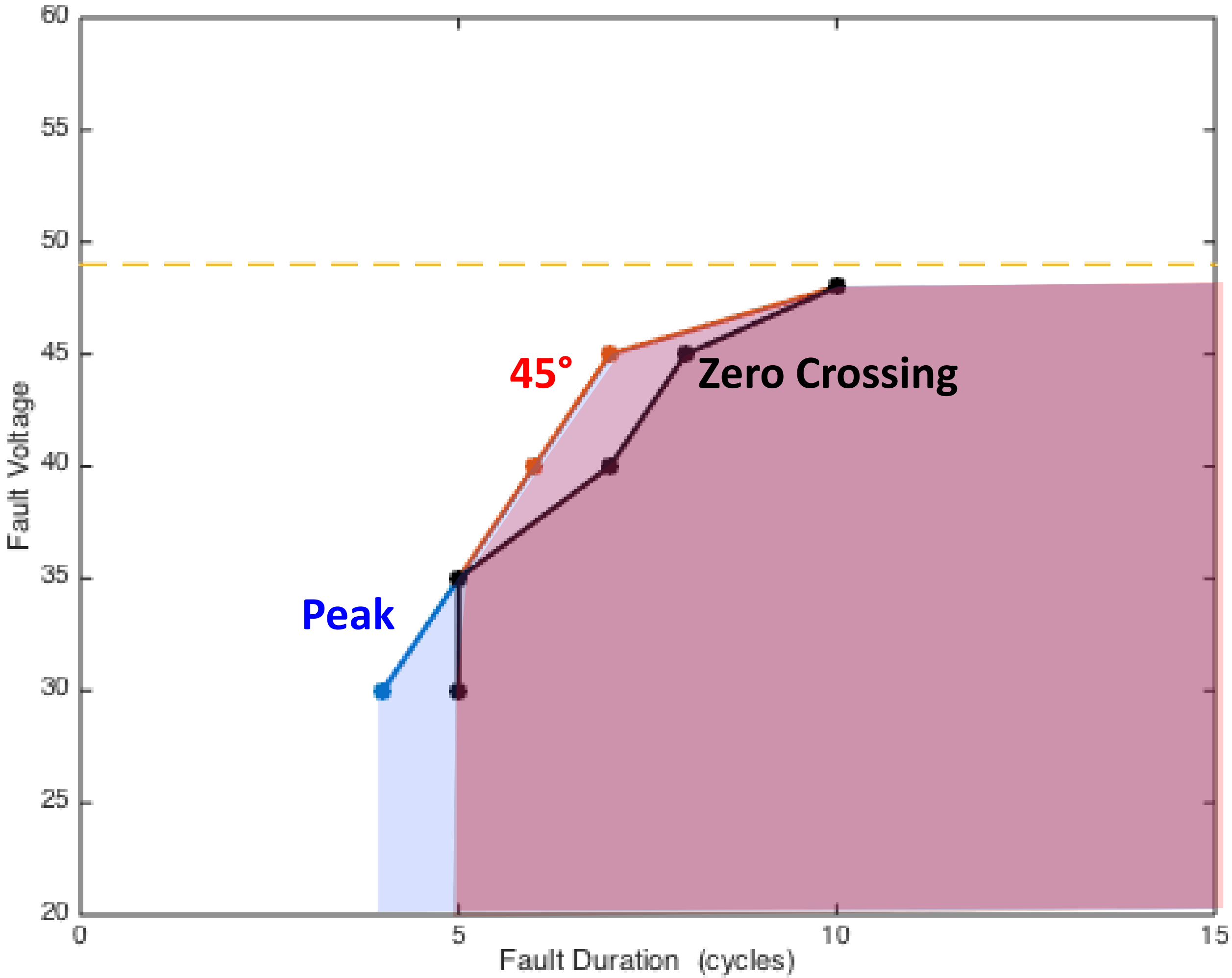
Find fault duration to result in a change in operating characteristic (not stall)



# Fault Regions, Instantaneous Voltage Dip

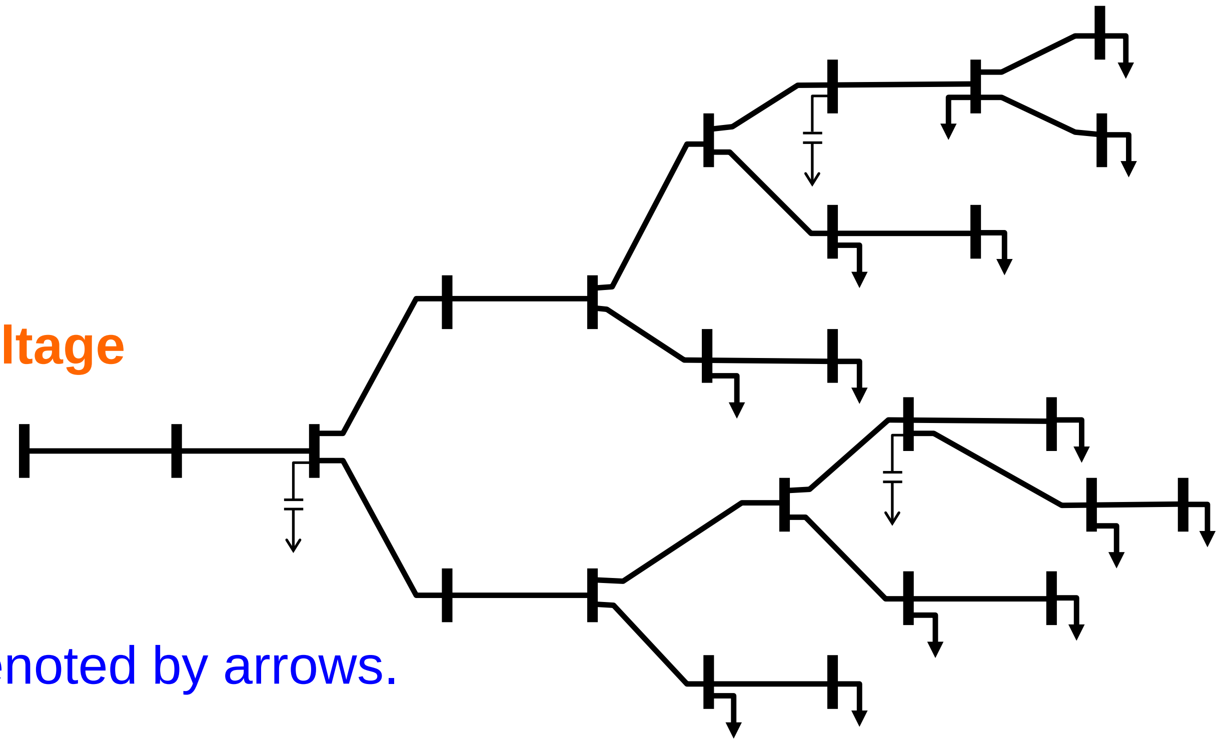


# Fault Region: 1 Cycle Ramp in Voltage Dip



# Do All Motors Stall?

**Grid Voltage**
***V***



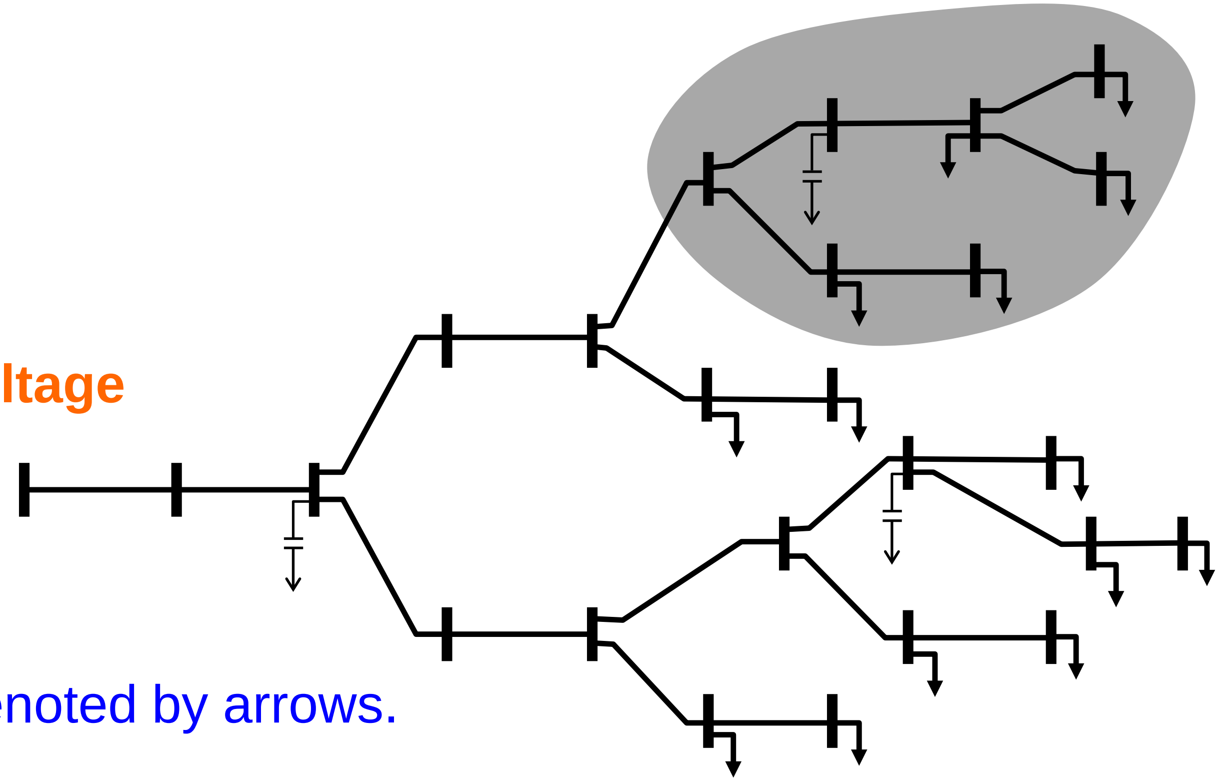
Loads denoted by arrows.

25 Buses, 13 loads, tree distribution network, single connection to the grid.

Is it possible for a fraction of motors to stall in this network without stalling them all?

# Do All Motors Stall?

Grid Voltage
*V*



Loads denoted by arrows.

**100% Compressor Load: They all stall.**

**50% Compressor, 50% Impedance, some may stall.**

(up to 5 maximum in this example)

# Conclusions

A dynamic phasor models may be suitable for grid-scale simulations because

- point-on-wave effects may be naturally mitigated by smoothing in disturbance away from the event location.
- allow aggregation of stall effects.

# Dynamic Phasor Model

$$\left|V_s\right| = \left(r_{ds} + j\frac{\omega_s}{\omega_b}X'_{ds}\right)\left(I^R_{ds} + jI^I_{ds}\right) + j\left(\frac{\omega_s}{\omega_b}\right)\frac{X_m}{X_r}\left(\Psi^R_{dr} + j\Psi^I_{dr}\right)$$

$$\left|V_s\right| = \left(r_{qs} + j\frac{\omega_s}{\omega_b}X'_{qs} + j\frac{\omega_b}{\omega_s}X_c\right)\left(I^R_{qs} + jI^I_{qs}\right) + j\left(\frac{\omega_s}{\omega_b}\right)\frac{nX_m}{X_r}\left(\Psi^R_{qr} + j\Psi^I_{r}\right)$$

$$\begin{bmatrix} \left(\Psi^R_f + j\Psi^I_f\right) \\ \left(\Psi^R_b + j\Psi^I_b\right) \end{bmatrix} = \left(\frac{1}{2}\right)\begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix}\begin{bmatrix} \left(\Psi^R_{dr} + j\Psi^I_{dr}\right) \\ \left(\Psi^R_{qr} + j\Psi^I_{qr}\right) \end{bmatrix} \quad \begin{bmatrix} \left(\Psi^R_{dr} + j\Psi^I_{dr}\right) \\ \left(\Psi^R_{qr} + j\Psi^I_{qr}\right) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}\begin{bmatrix} \left(\Psi^R_f + j\Psi^I_f\right) \\ \left(\Psi^R_b + j\Psi^I_b\right) \end{bmatrix}$$

$$\begin{bmatrix} \left(I^R_f + jI^I_f\right) \\ \left(I^R_b + jI^I_b\right) \end{bmatrix} = \left(\frac{1}{2}\right)\begin{bmatrix} 1 & -jn \\ 1 & jn \end{bmatrix}\begin{bmatrix} \left(I^R_{ds} + jI^I_{ds}\right) \\ \left(I^R_{qs} + jI^I_{qs}\right) \end{bmatrix} \quad \begin{bmatrix} \left(I^R_{ds} + jI^I_{ds}\right) \\ \left(I^R_{qs} + jI^I_{qs}\right) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ j/n & -j/n \end{bmatrix}\begin{bmatrix} \left(I^R_f + jI^I_f\right) \\ \left(I^R_b + jI^I_b\right) \end{bmatrix}$$

$$T'_o\frac{d}{dt}\left(\Psi^R_f + j\Psi^I_f\right) = X_m\left(I^R_f + jI^I_f\right) - \left(sat(\Psi_f, \Psi_b) + j\left(\omega_s - \omega_r\right)T'_o\right)\left(\Psi^R_f + j\Psi^I_f\right)$$

$$\left(\Psi^R_b + j\Psi^I_b\right) = \frac{X_m\left(I^R_b + jI^I_b\right)}{\left(sat(\Psi_f, \Psi_b) + j\left(\omega_s + \omega_r\right)T'_o\right)}$$

$$\frac{2H}{\omega_b}\frac{d\omega_r}{dt} = \frac{X_m}{X_r}2\left(I^I_f\Psi^R_f - I^R_f\Psi^I_f - I^I_b\Psi^R_b + I^R_b\Psi^I_b\right) - T_{mech}$$

$$I_s = \left[\left(I^R_{ds} + jI^I_{ds}\right) + \left(I^R_{qs} + jI^I_{qs}\right)\right]e^{j\phi}$$

# Commercial 3Φ Rooftop and Residential VFD A/C Testing

*DOE-NERC FIDVR Workshop*

*September 30th, 2015*

Steven Robles

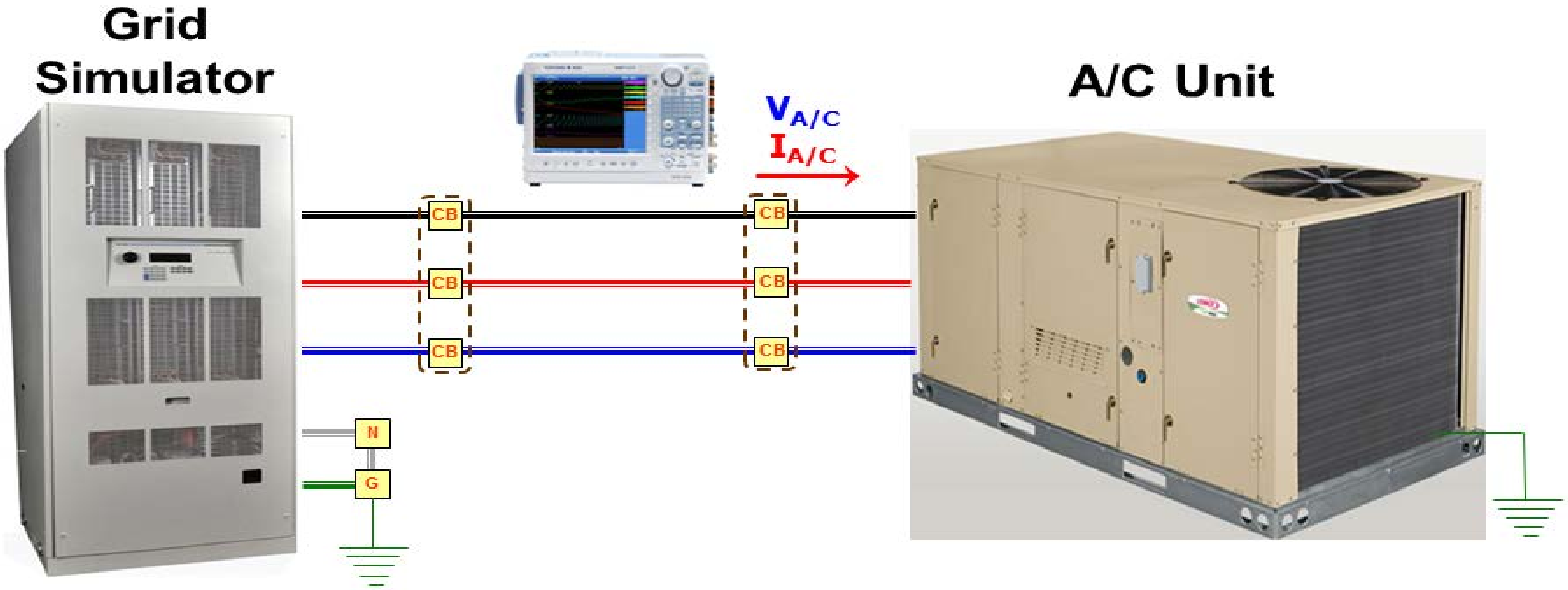
# Objectives

- Assess the performance of air conditioner (A/C) units during typical grid voltage and frequency deviations, including but not limited to:
  - Stalling criteria (or lack thereof)
  - Inrush currents
  - Contactor/relay dropout
  - Harmonics contribution

- A/C performance data can be used to:
  - Build, test, and/or validate load models
  - Identify potential device impacts (Is it "grid friendly"?)
  - Explore potential stalling solutions

# Laboratory Setup

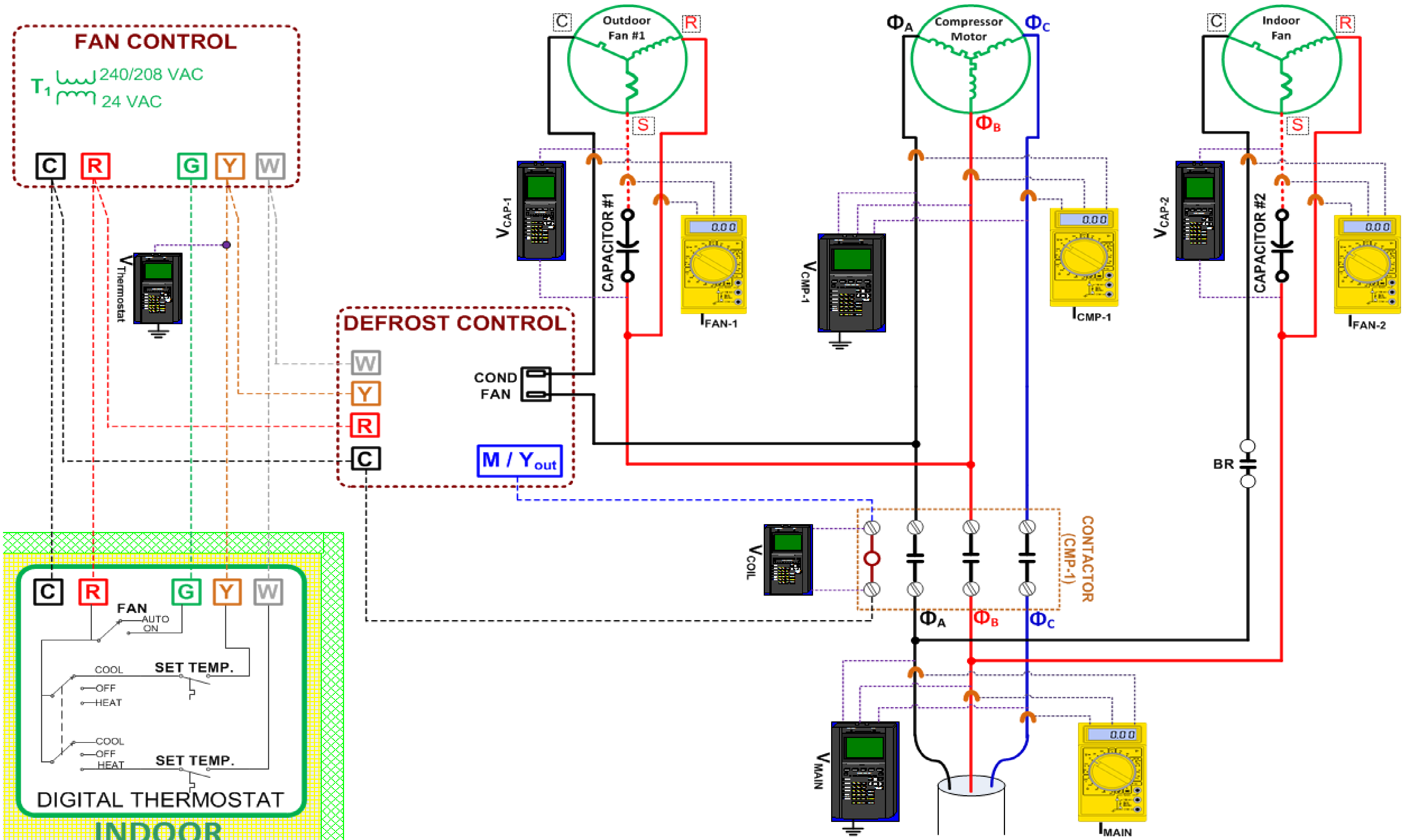
- Grid Simulator
- Equipment under test
  - 3Φ Commercial Rooftop A/C Unit
  - Residential A/C Unit with VFD
- Digital Oscilloscope
  - Voltage Probes
  - Current Transformers (CTs)
  - Thermocouples
  - Accelerometers



# Tests Performed

- Compressor Shutdown
- Compressor Startup
- Balanced Under/Over-Voltage Transients
- Unbalanced Under/Over-Voltage Transients
- Under/Over-Frequency Transients
- Voltage/Frequency Oscillations
- Voltage/Frequency Ramps
- Harmonics
- Conservation Voltage Reduction

# Commercial 3Φ Rooftop A/C Testing



# 3Φ A/C Contactor Dropout Summary

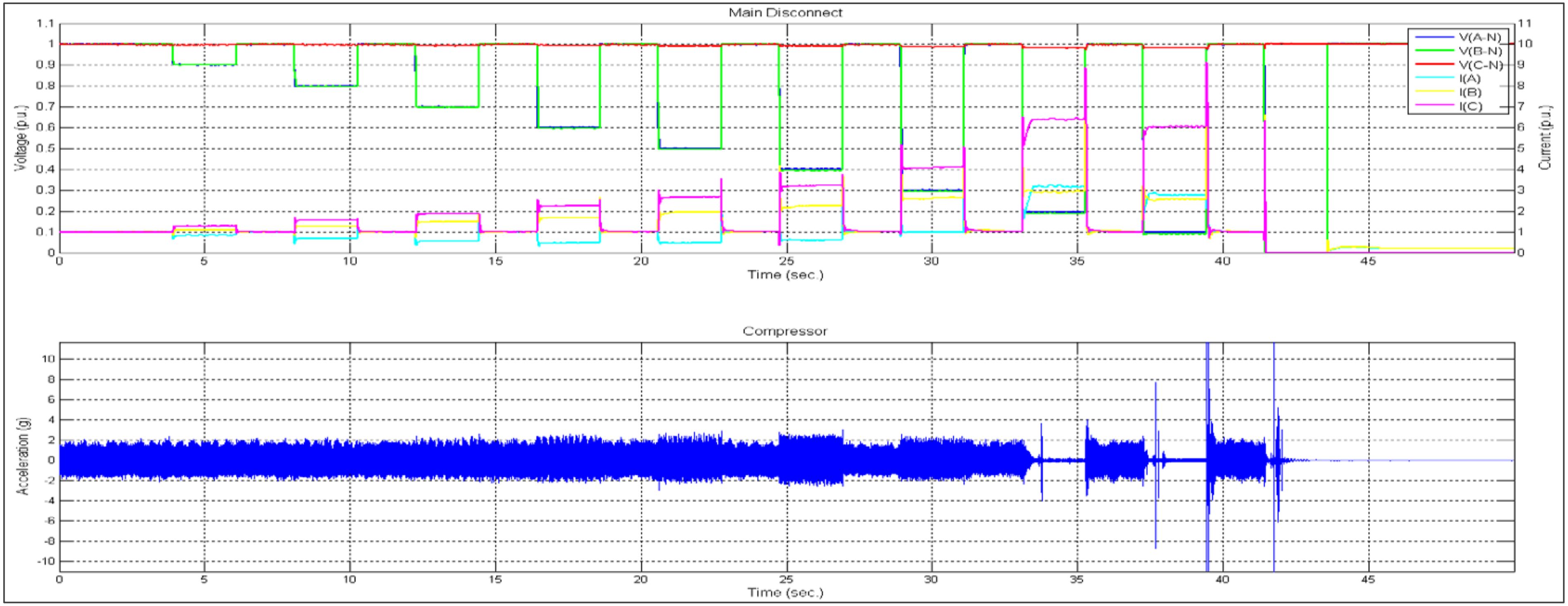
- Dropout is dependent on voltage supplying the A/C unit controls ($V_{\Phi A\text{-}\Phi B}$, $V_{\Phi B\text{-}\Phi C}$, or $V_{\Phi C\text{-}\Phi A}$)
- Dropout generally occurs between 60% - 50% voltage within 2 – 10 cycles
- Contactor often chatters before dropping out
- Contactor normally does not reclose immediately after voltage recover (unit restarts several minutes later)
  - Suggests protective relay on thermostat or local controller

# 3Φ A/C Stalling Results Summary

- Contactor drops out before stalling can occur for 3-phase balanced under-voltage conditions
- Most units (5 of 7) stall during 2-phase unbalanced under-voltages
  - Stalled between 30% - 10% voltage within 10.8 – 60 cycles
  - Stalling occurs quicker at lower voltages
  - Compressor restarts in 5 cycles after voltage recovers
- No stalling is observed during 1-phase unbalanced under-voltages

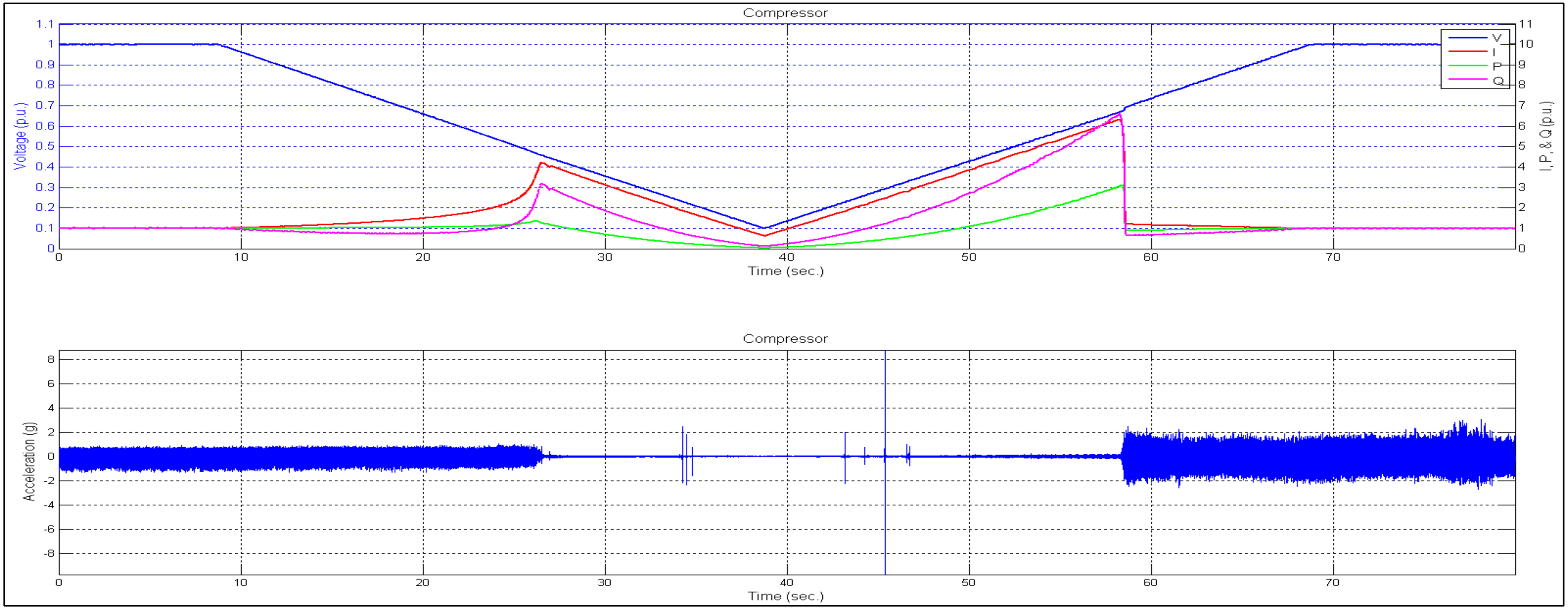
# 3Φ A/C Stalling Results (Sample)

- Compressor performance during unbalanced under-voltage (Phases A & B) transients:
  - Stalled at 20% $V_{L-N}$ in 24 cycles
  - Stalled at 10% $V_{L-N}$ in 12.6 cycles

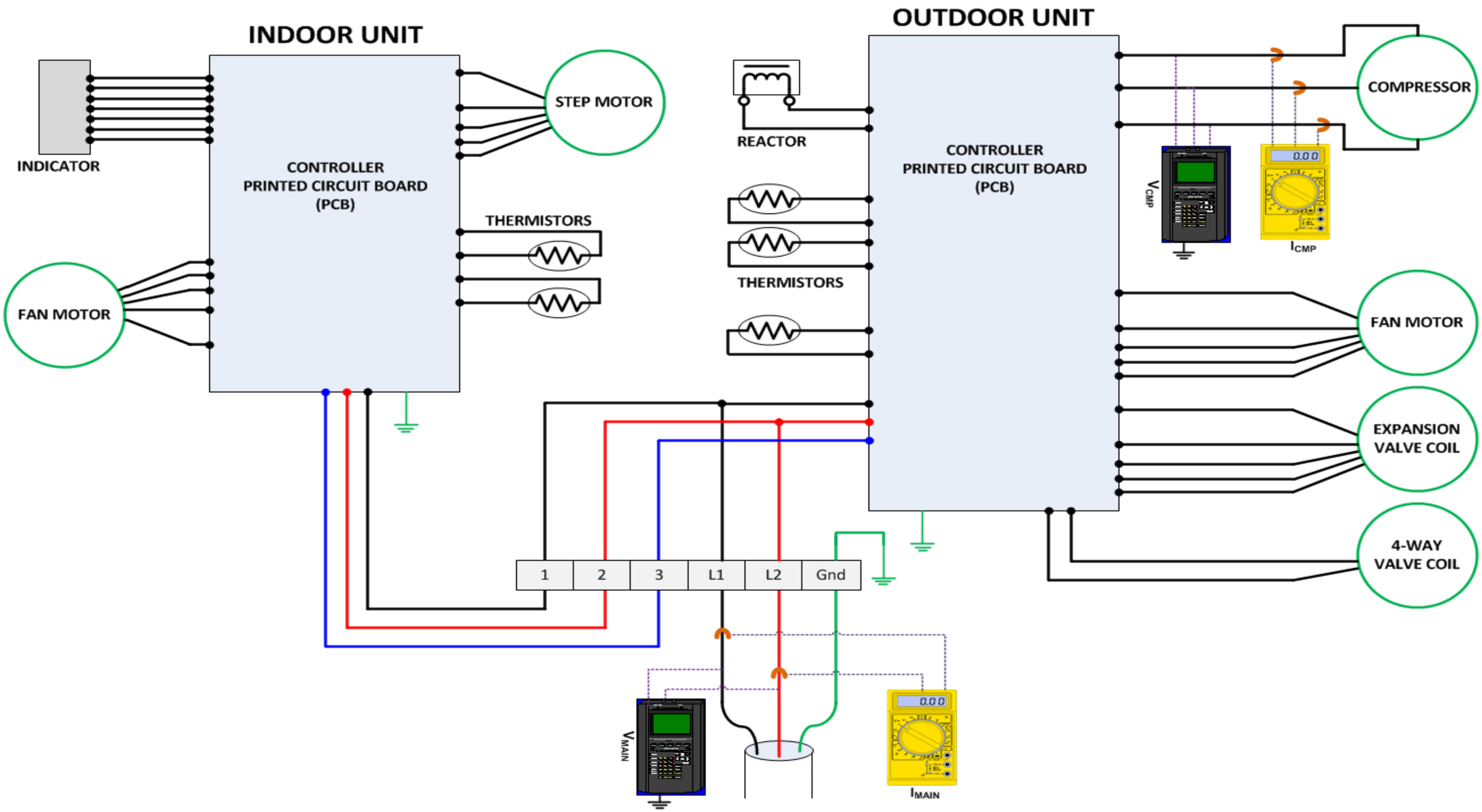


# 3Φ A/C Stalling (Modified Units)

- Units were modified such that controls were powered separately to bypass dropout
- Captured I, P, and Q at different balanced voltage levels, including at the stalling and restarting point



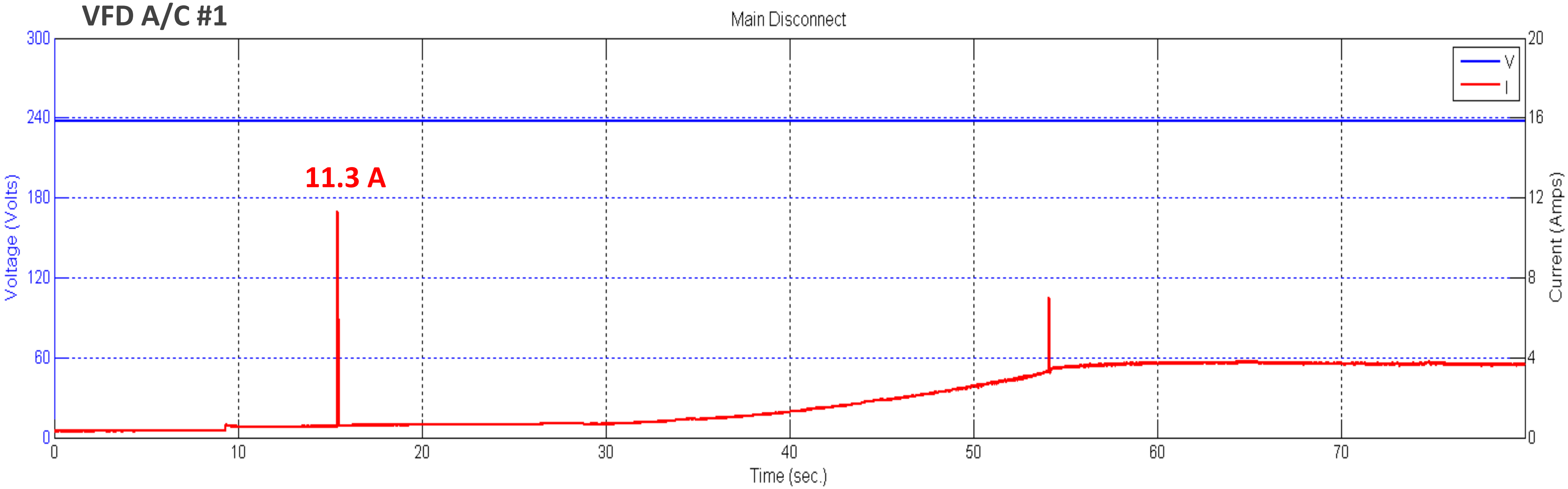
# Residential VFD A/C Testing



# VFD A/C Compressor Startup

- VFD A/C units display low inrush current compared to conventional units
  - Largest inrush current:  11.3 Amps within 1.8 cycles
  - Compressor current ramps up in 20 – 50 seconds
  - Consumption increases periodically to meet temperature demand

**VFD A/C #1**

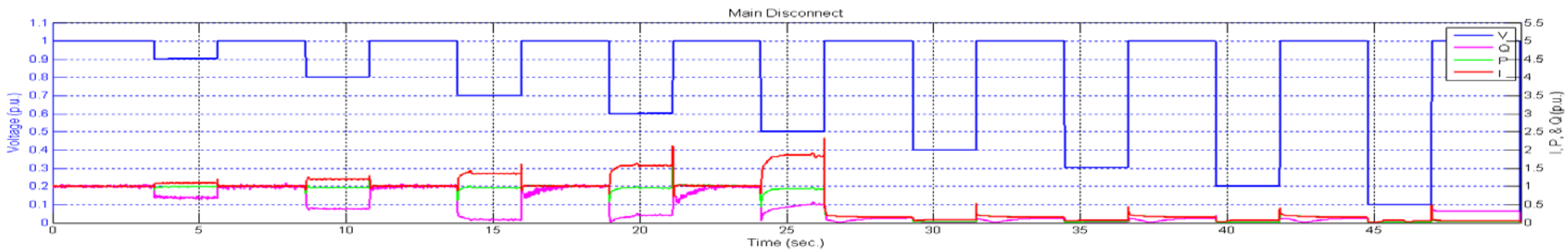


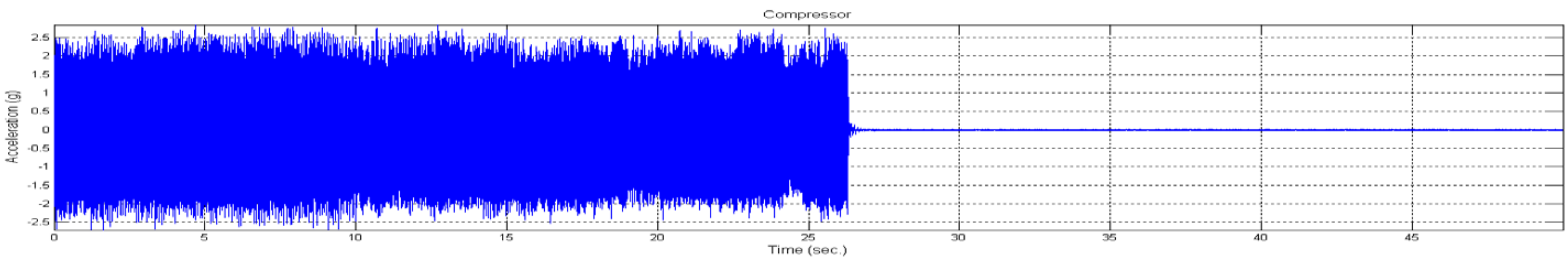
# VFD A/C Controls Dropout Summary

- No stalling behavior was observed
- Compressor usually disconnects at the end of a voltage sag or up to 3 cycles after voltage recovers
  - May be due to inrush of current during voltage recovery
- Compressor rides through shorter sags (down to 0%)
  - Shorter voltage sags range from 1 to 6 cycles
- Compressor does not restart immediately after controls drop out (unit restarts several minutes later)
  - Suggests protective relay on the local controller

# VFD A/C Controls Dropout Summary

| Unit | 130 cycle Transients | | 12 cycle Transients | | 3 cycle Transients | |
|---|---|---|---|---|---|---|
| | $V_{trip / dropout}$ (%) | $t_{trip / dropout}$ (cyc) | $V_{trip / dropout}$ (%) | $t_{trip / dropout}$ (cyc) | $V_{trip / dropout}$ (%) | $t_{trip / dropout}$ (cyc) |
| **VFD A/C #1** | 52% | 15 | 55% | 13.2 | 51% | 3.6 |
| **VFD A/C #2** | 56% | 7.8 | 55% | 9 | N/A | N/A |
| **VFD A/C #3** | 58% | 130.8 | 58% | 12.6 | 59% | 4.2 |
| **VFD A/C #4** | 69% | 130.1 | 49% | 12.9 | N/A | N/A |
| **VFD A/C #5** | 41% | 130.8 | 20% | 12.6 | N/A | N/A |
| **VFD A/C #6** | 81% | 131.1 | 56% | 12.2 | N/A | N/A |
| **VFD A/C #7** | 62% | 129.6 | 60% | 12 | 54% | 4.2 |

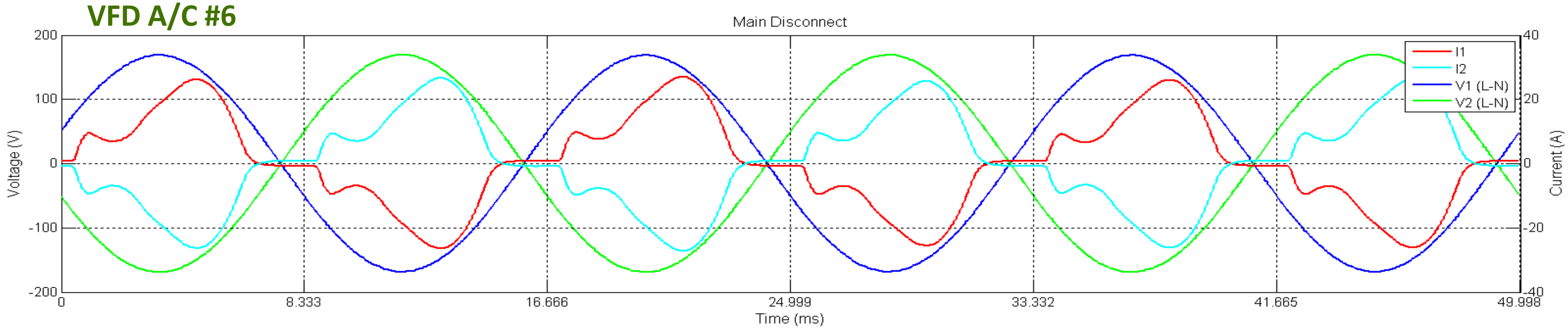


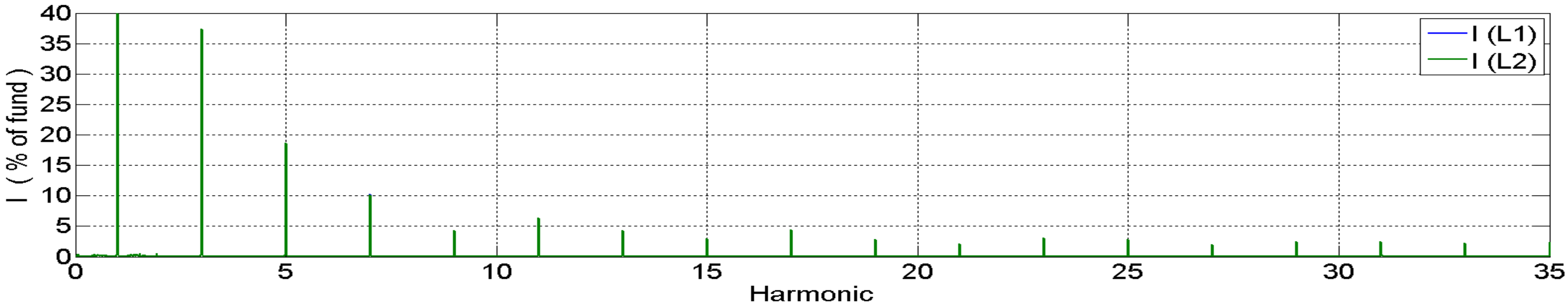



# VFD A/C Harmonics Contribution

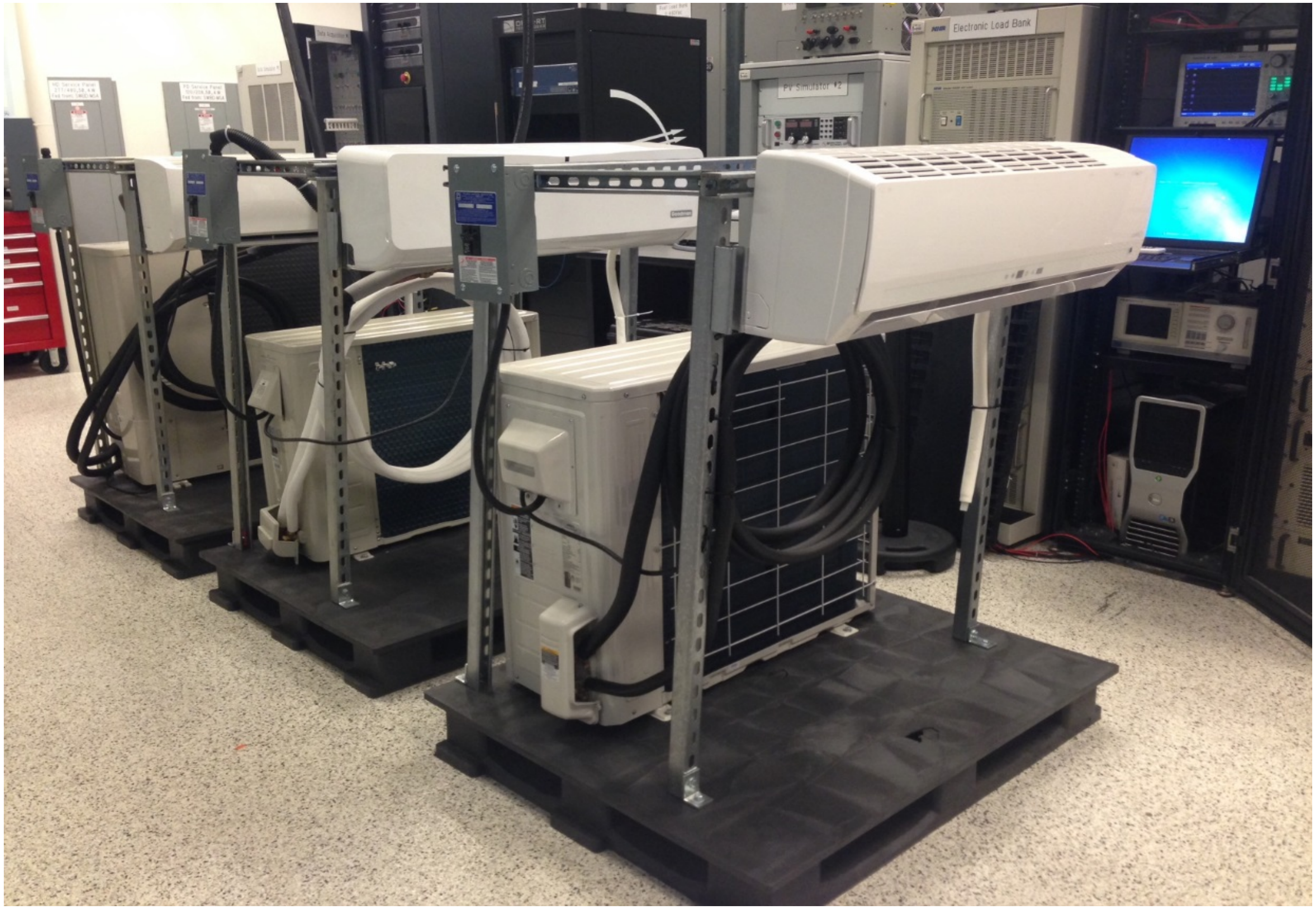
- VFD A/C #1, 4, 5, 7 current THD is 11% - 16.9% of fund.
- VFD A/C #3 current THD is ~29% of fund.
- VFD A/C #2 & #6 current THD is 39% - 47.5% of fund

**VFD A/C #6**



# Thank You.



# FIDVR

## The transient behavior of loads

John Undrill

September 2015

# Load modeling issues

## Load composition

lighting
electronic power supplies
single phase motors
three phase motors

## Static characteristics (for load flow)

constant P,Q    constant I,B    constant G,B    variations on the theme

## Behavior in transients

stay-on/shutdown
slow-down/reaccelerate
run/stall

discharge and LED lighting
miscellaneous motors
residential air conditioners

## Asymptotic behavior

linear dynamics
mode changes

control gain and bandwidth
sensitivity to voltage/frequency conditions

# Load modeling issues

## Incandescent lighting / resistance heating

Was/is reasonable to treat as algebraic function of voltage/frequency

## Discharge and new-technology lighting

We are increasingly concerned that algebraic modeling is reasonable only within narrow voltage/frequency bands

## Large rotating machines - generators/motors

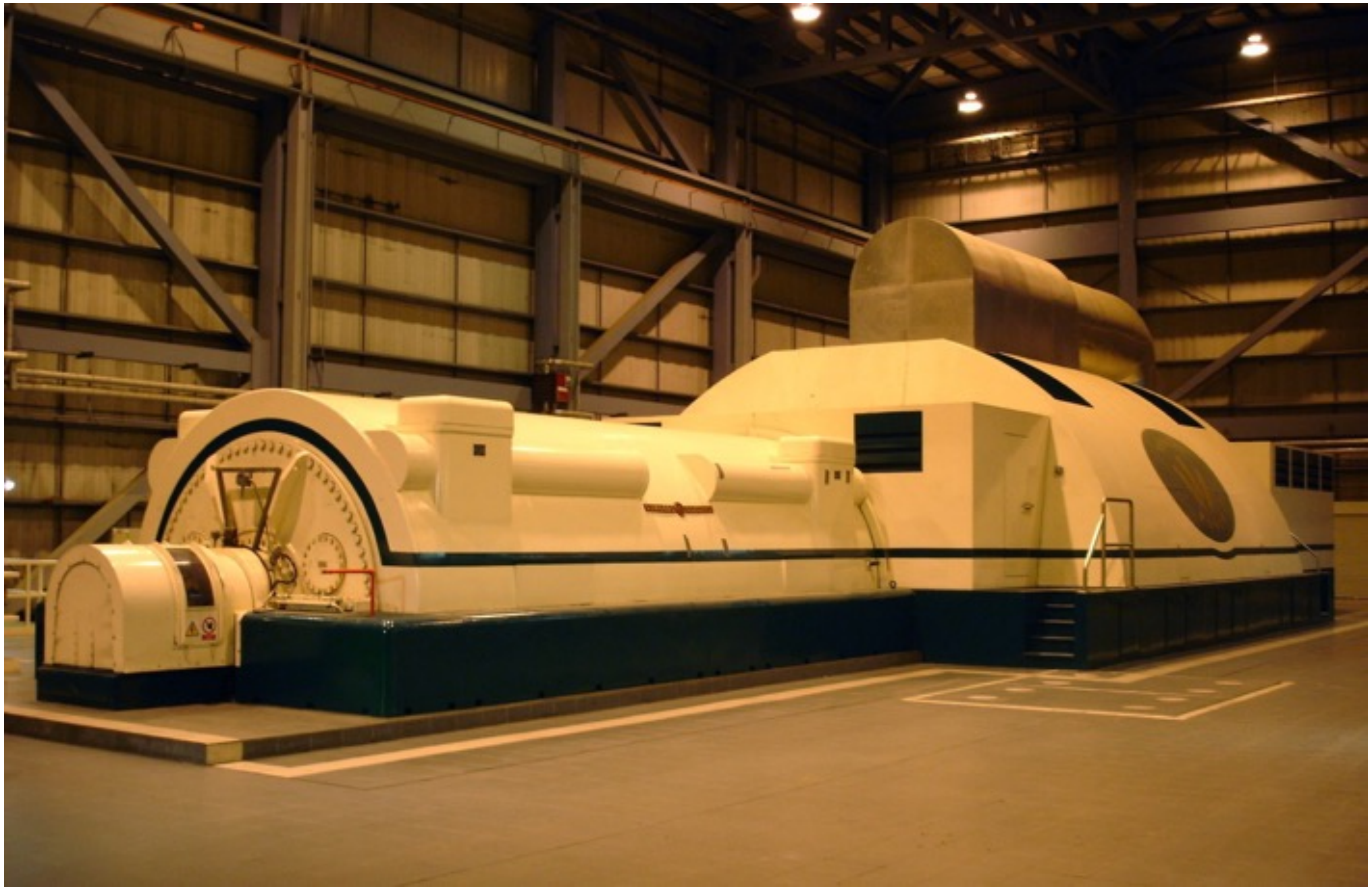
We can model large machines very closely but we are often quite lax about modeling the driven loads

## General population motor loads

Phasor-level modeling can reveal characteristics in steady operation but cannot address behavior in the initiating parts of grid transients

# Turbine generators

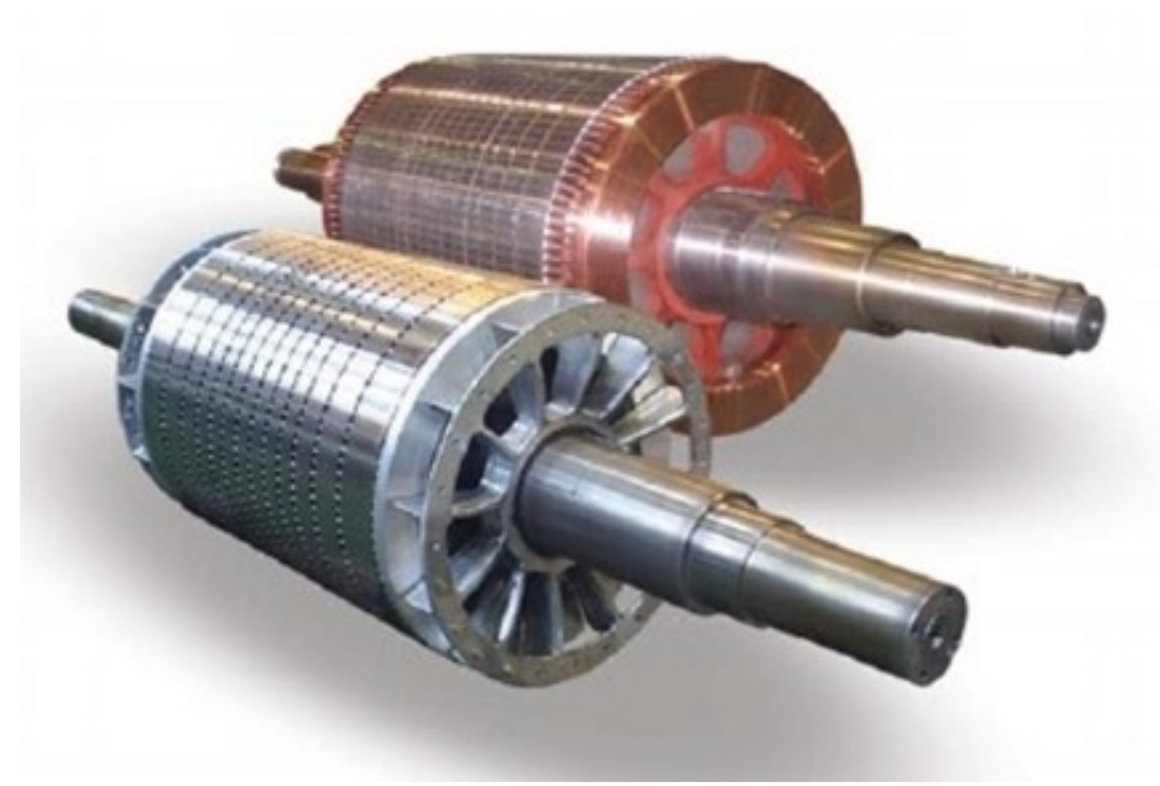
Time scale of 1 - 10 seconds

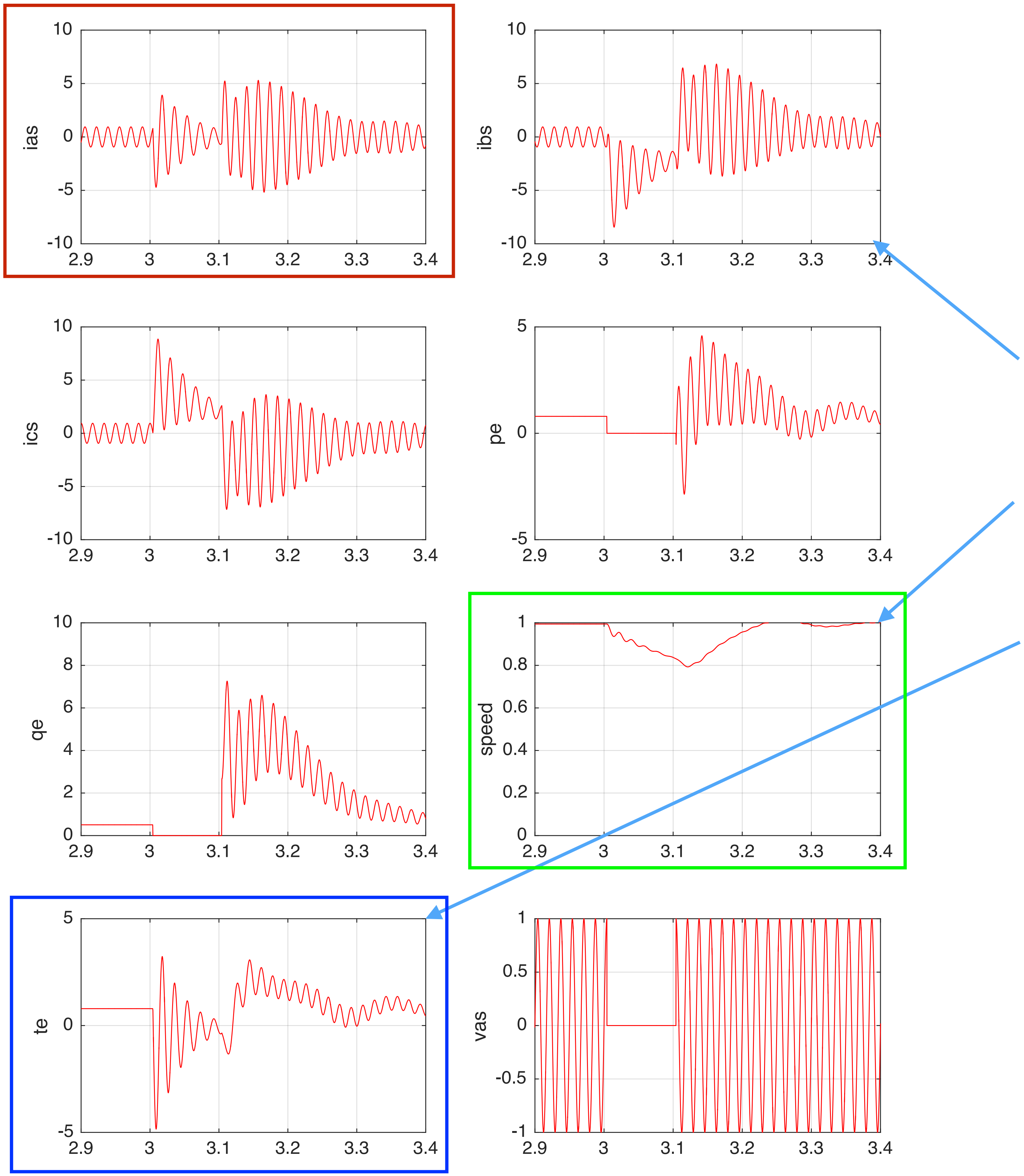


# Industrial motors

Inertia constant ~0.3 sec < H < very large

Time scale of 0.5 - 10 seconds






Short circuit at terminals of 100KW three phase motor driving a pump -

H = 0.3 second

Motor contributes significant short circuit current

Speed dips during fault - reacceleration is decisive

Immediate **negative** peak of torque transient approaches **six times** rated torque

Well understood behavior

Central to circuit breaker rating standards

Voltage dip at terminals of 100KW three phase motor driving a pump -

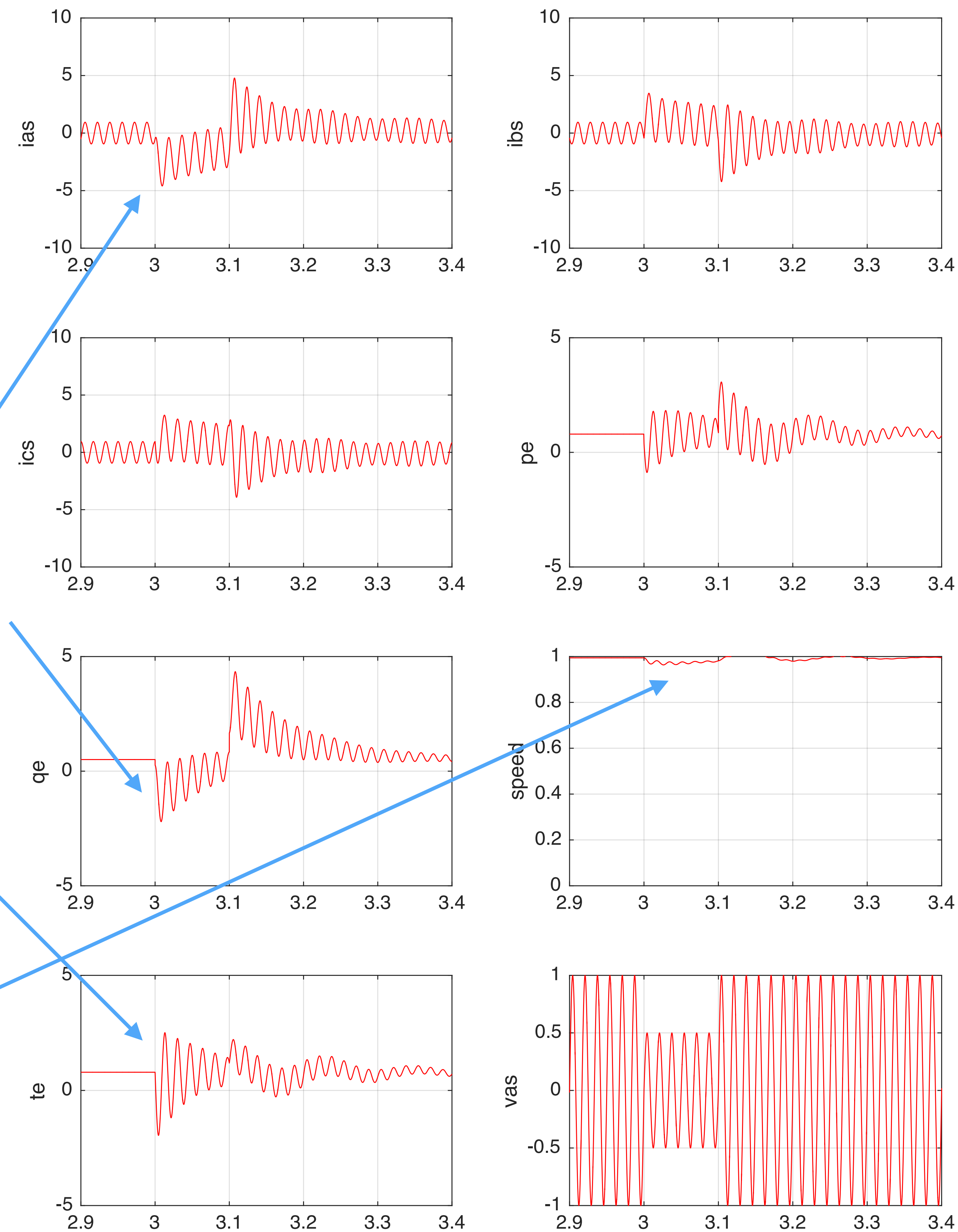
H = 0.3 second

Current contains AC and unidirectional components

Reactive power reverses during voltage dip - motor contributes to support of voltage

Immediate **negative** peak of torque transient approaches **six times** rated torque

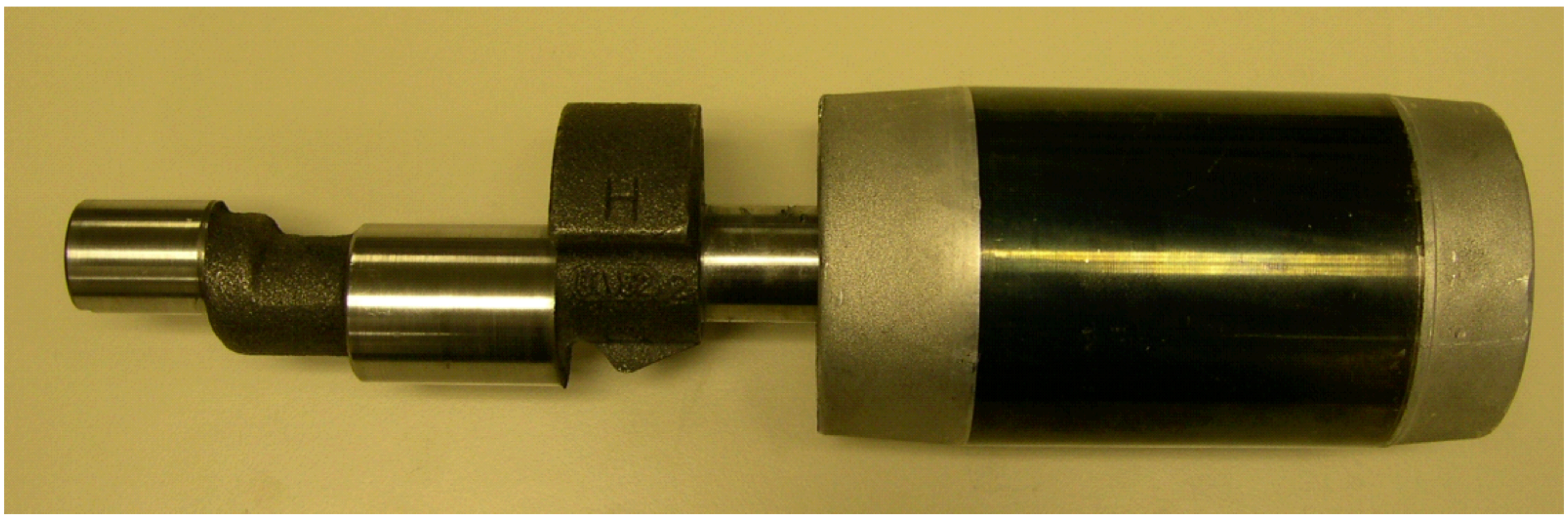
Response to alternating torque is observable in speed transient, but only to minimal extent



# Air conditioner rotor - approximately 5kW

Hmotor ~= 0.05 second

Time scale of tenths of a second



75 mm

310 mm

## Voltage dip at terminals of 5KW single phase motor driving a residential air conditioner

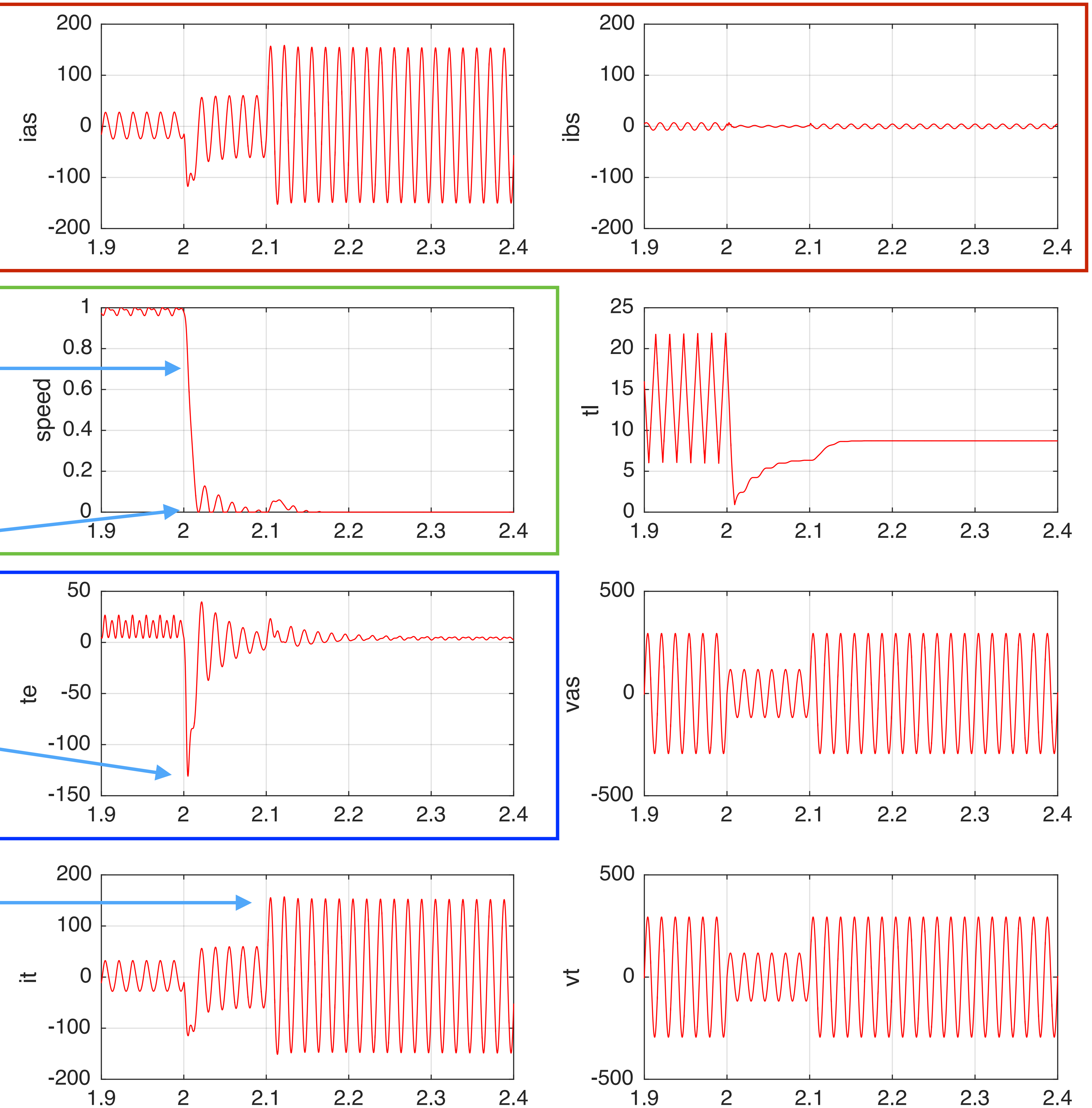
## H = 0.048 second

Speed is pulled down very strongly by the negative electromagnetic torque

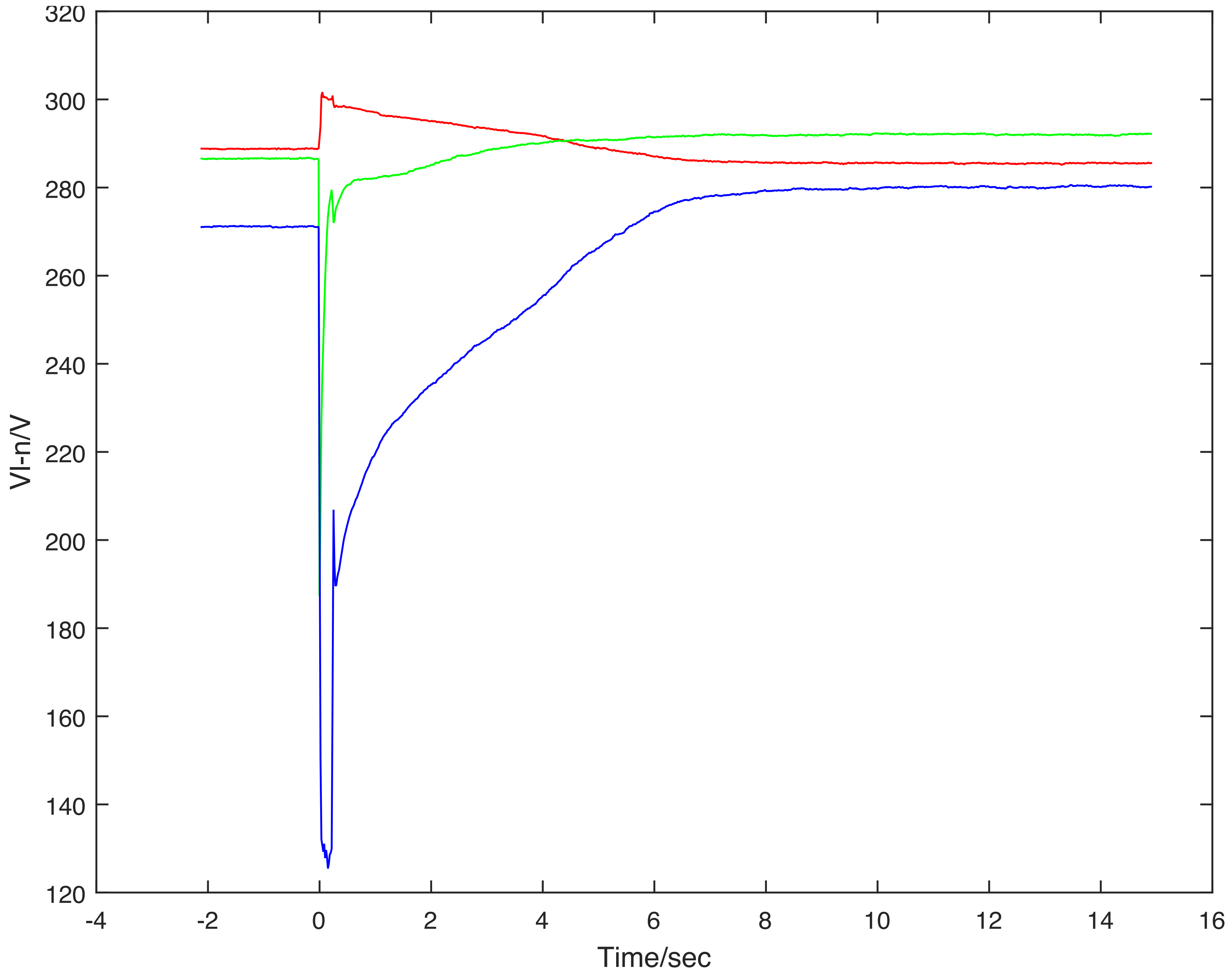
Motor stalls and does not restart

Immediate **negative** peak of torque transient approaches **eight times** rated torque

Current drawn by stalled motor is **five times** normal load current



# FIDVR is not only a positive sequence issue



# Motor behavior is sensitive to

Supply system impedance

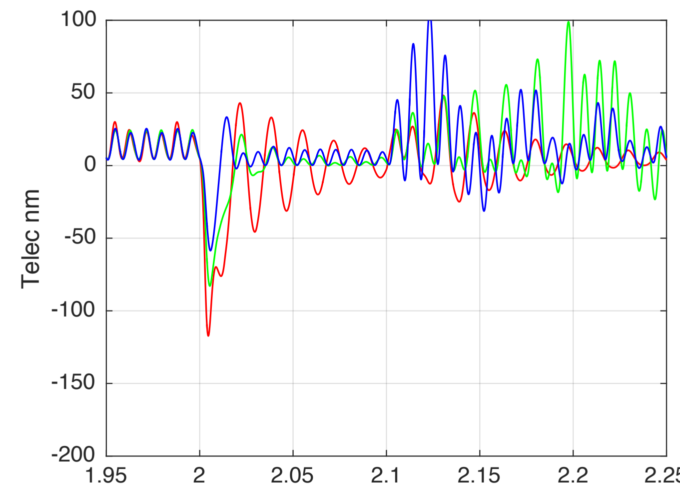
Driven load type and characteristics (torque/speed/angle)

Electrical phase at moment whe voltage dip is initiated

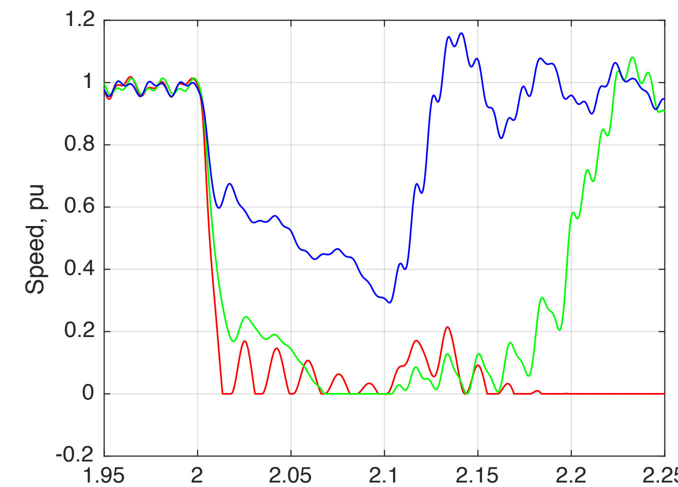
Rate of change of voltage in initiation of voltage dip

Presence of other motors and load on feeders

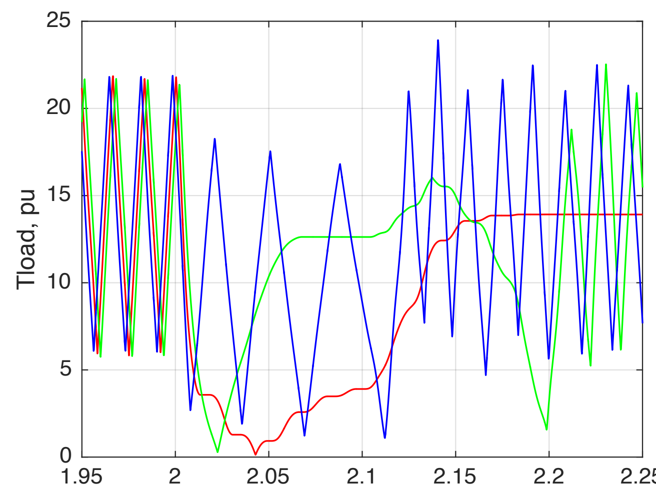
etc.



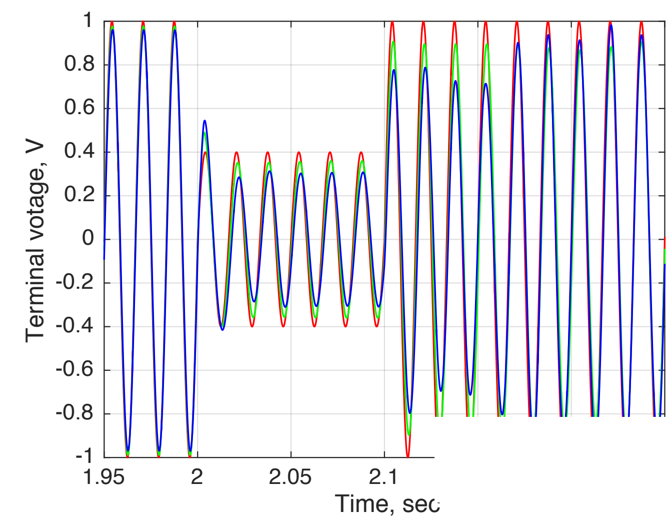
electromagnetic torque



speed



load torque



terminal voltage

What **generators and large rotating equipment** will do depends on things that we can model with phasor calculation and positive sequence networks

What **small motors and electronic equipment** will do depends on things that happen much faster than can be seen by models based on phasor calculation

We cannot see what we want with R + jX

We could, *perhaps,* see a lot if we could use R + Ldi/dt

Even after living through 25 iterations of Moore's law, the computers that I can use are not fast enough or big enough to handle grid-size systems at the di/dt level

When they do become available, the assembly of the required data will be a task of the same scale as we have today

We have to proceed

based on the physical understanding that we have, combined with carefully assembled empirical information

there are practical steps that we should take

End

# Smart Inverters and FIDVR Events

John Berdner

Senor Director of Regulatory and Policy Strategy

DOE / NERC Workshop, Alexandria, VA, Oct 2016

# Presentation Overview

- **Inverter capabilities**
  - Old Inverters
  - Smart Inverters
- **Smart inverter functions defined today**
- **Defining the needed FIDVR response**
  - Normal operation (steady state) versus FIDVR (transient)
- **Conclusions**

# The Old Days (2000 - 2003)

- **Grid tied PV systems were rare**
- **General philosophy was:**
  - Produce unity power factor
  - Get out of the way quickly if anything bad happened
  - Tight trip limits
  - No requirements for ride through
- **Relevant Standards**
  - UL 1741, IEEE 1547, 1547.1

# Today (2014 - 2016)

- **CA rule 21 approves smart inverter functionality. Phase 1 autonomous behaviors (Dec 2015)**
  - Voltage and frequency ride through
  - Real and reactive power control
  - Return to service behaviors / ramp rate control
- **Hawaiian Electric Inc. implements mandatory ride through requirements (Jan 2015)**
- **CA rule 21 Phase 2 in development.**
  - IEC 61850 data model, IEEE 2030.5 / SEP 2.0 Protocol
  - Updates to interconnection handbooks under development
- **Relevant Standards**
  - UL 1741, UL 1741 Supplement A, IEEE 1547, 1547.a,1547.1
  - IEC 61850, IEEE 2030.5
  - UL 1998 (firmware certification)

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# New Regulatory Concepts (in the US)

- **Voltage and frequency ride through**
  - ***Must not trip*** requirements during abnormal excursions
- **Real and reactive power control**
  - Provides frequency stability and voltage regulation
- **Operating regions with differing behaviors**
  - Multiple areas are bounded by pair points of Voltage/time or frequency/time
- **Cease to energize (momentary cessation)**
  - A mode where the DER must cease to energize the area EPS but ***must not trip***.
- **Return to service**
  - The criteria and behaviors required as the DER re-energizes the area EPS following an excursion

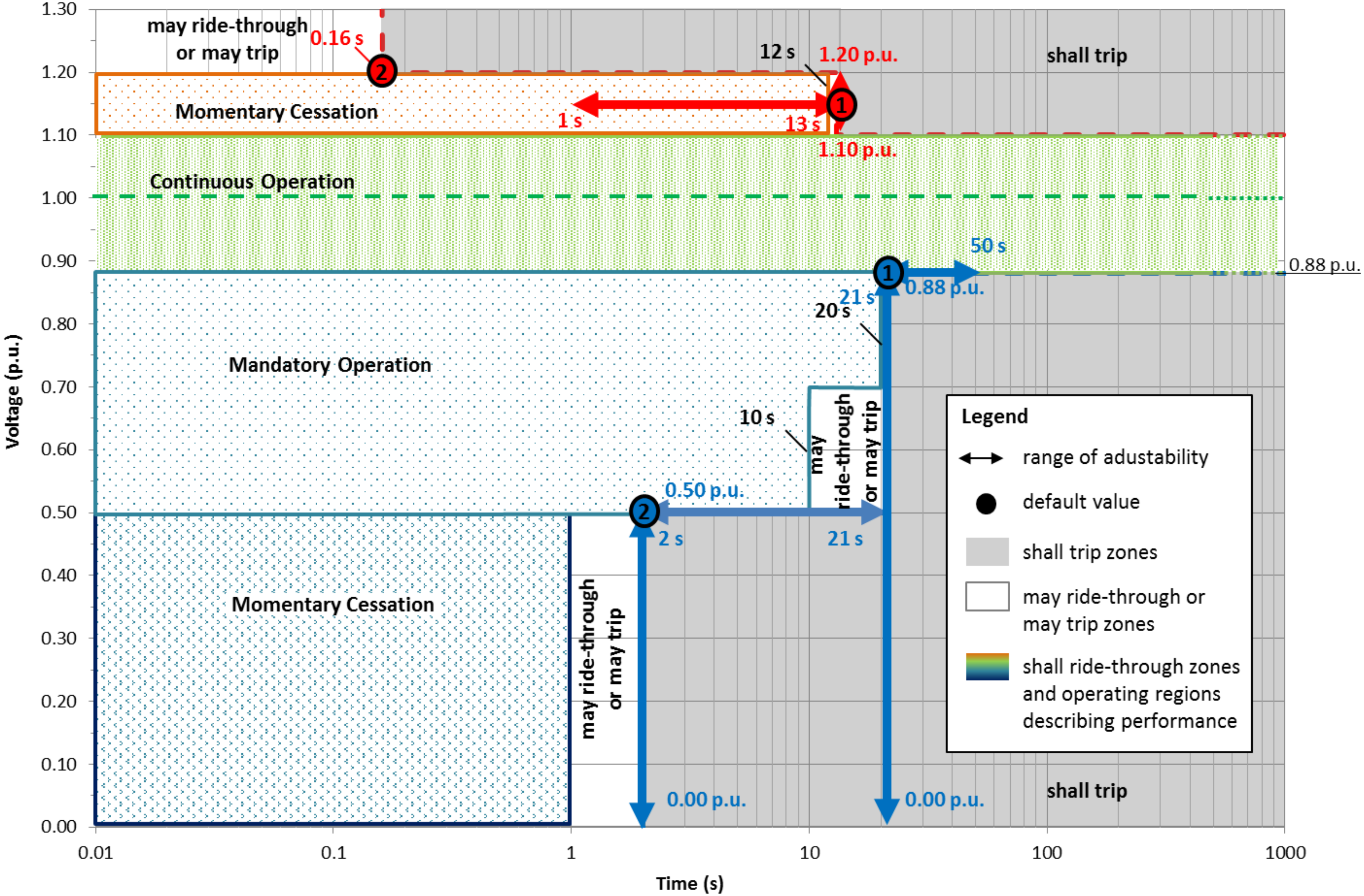
# UL 1741 Supplement A Functions

- **Voltage and frequency ride through**
- **Reactive power control (voltage regulation)**
  - Fixed Power Factor
  - Volt/VAr (voltage droop)
  - Commanded VAr
- **Active power control**
  - Ramp rate control
  - Volt/Watt
  - Frequency/Watt (frequency droop)
  - Commanded maximum power

**➔ FIDVR response is NOT currently addressed**

## Category III Voltage Ride Through

*(based on CA Rule 21 and Hawaii)*



# The Four Quadrants (IEEE sign convention)

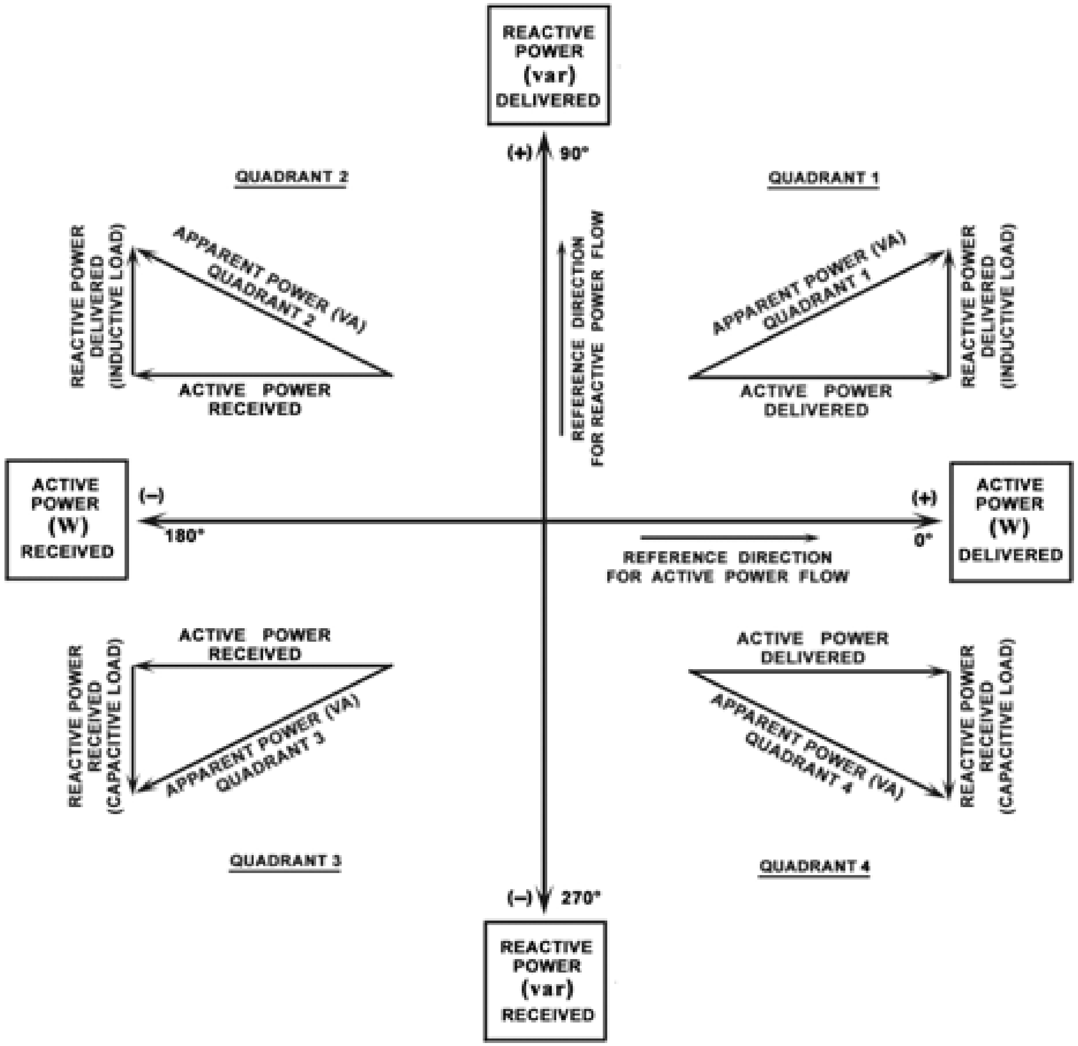
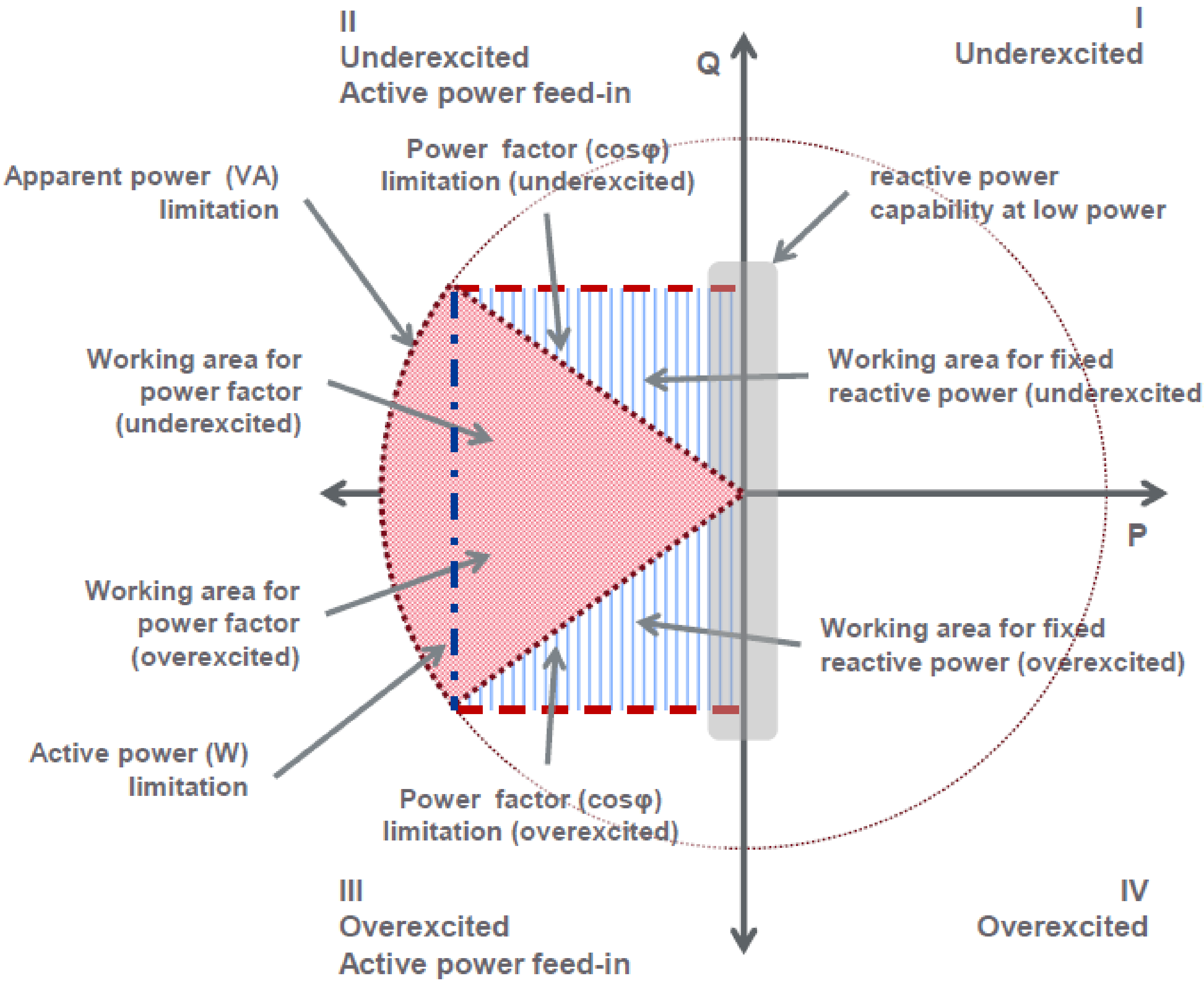


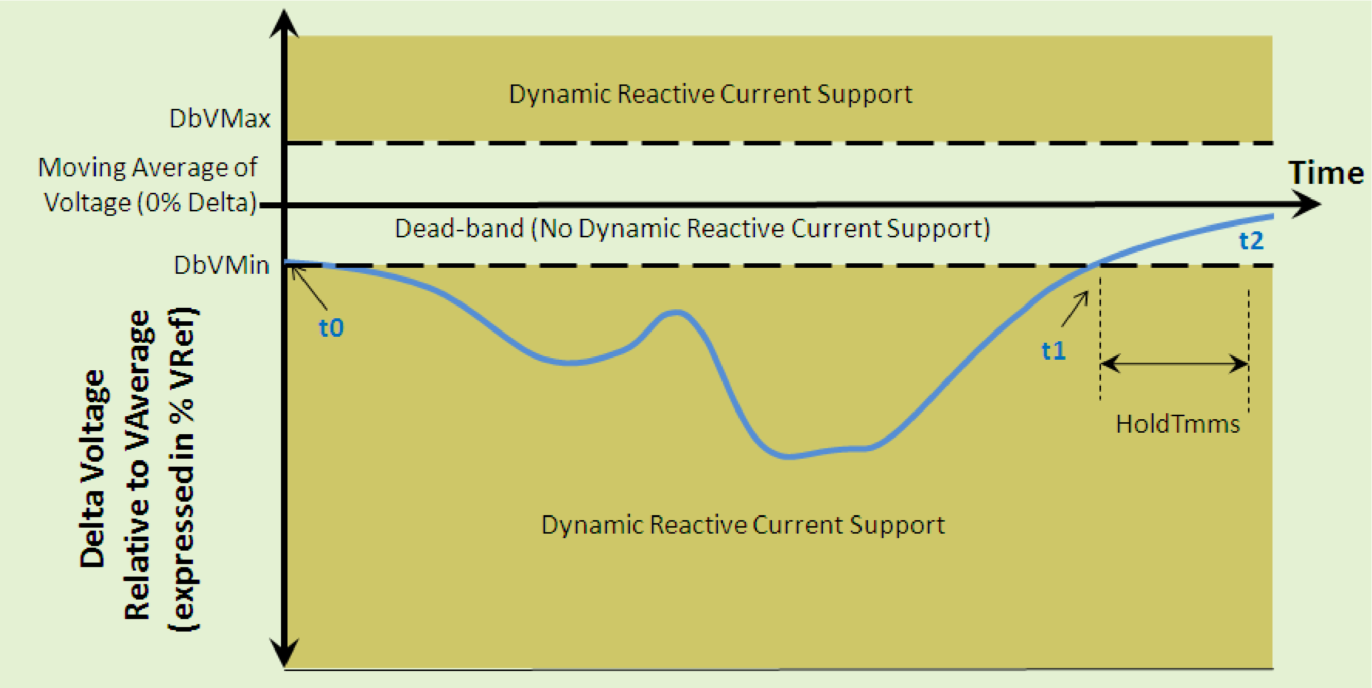

**Figure 1 - Four-quadrant power flow directions**
**(© 1983 IEEE. Reprinted, with permission from the IEEE and R.H. Stevens [B19])**
*(redrawn by McEachern for clarity, 2012)*

# PV Inverter Operating Areas



# Terminology of FIDVR Response

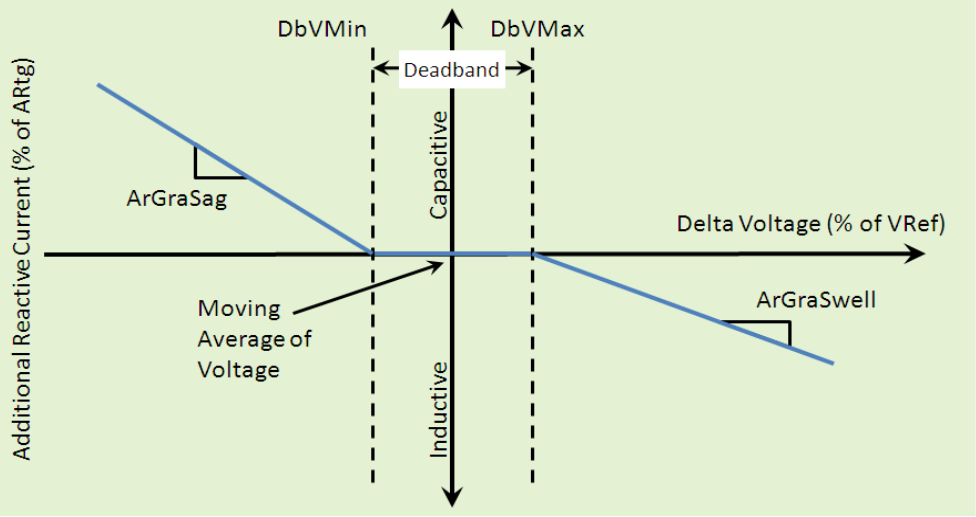
- **“Event based dynamic reactive current support” (EPRI)**
  - Provide capacitive reactive current in response to low voltage
  - Similar to EPRI VV12 but transient in nature
  - Reduce active power to supply reactive power (VAR Priority)




Courtesy of EPRI, *Common functions of smart inverters*, Version 3, Feb, 2014, Brain Seal

# Dynamic Reactive Current Support (EPRI)




- **Dead band default values and ROA's**
  - Default – ANSI Range B (88% to 110% PU) ?
  - ROA's – TBD
- **Gradient default values are TBD**
- **Time domain values are TBD**
- **Detailed modeling needed to establish baselines**

Courtesy of EPRI, *Common functions of smart inverters*, Version 3, Feb, 2014, Brain Seal

# Dynamic Reactive Current Support Variables

| Name | Description |
|---|---|
| **Enable/Disable Dynamic Reactive Current Support Function** | This is a Boolean that makes the dynamic reactive current support function active or inactive. |
| **DbVMin** | This is a voltage deviation relative to Vaverage, expressed in terms of % of Vref (for example -10%Vref). For negative voltage deviations (voltage below the moving average) that are smaller in amplitude than this amount, no additional dynamic reactive current is produced. |
| **DbVMax** | This is a voltage deviation relative to Vaverage, expressed in terms of % of Vref (for example +10%Vref). For positive voltage deviations (voltage above the moving average) that are smaller in amplitude than this amount, no additional dynamic reactive current is produced. Together, DbVMin and DbVMax allow for the creation of a dead-band, inside of which the system does not generate additional reactive current support. |
| **ArGraSag** | This is a gradient, expressed in unit-less terms of %/%, to establish the ratio by which Capacitive % VAR production is increased as %Delta-Voltage decreases below DbVMin. Note that the % Delta-Voltage may be calculated relative to Moving Average of Voltage + DbVMin (as shown in Figure 16-1) or relative to Moving Average of Voltage (as shown in Figure 16-4), according to the ArGraMod setting. |
| **ArGraSwell** | This is a gradient, expressed in unit-less terms of %/%, to establish the ratio by which Inductive % Var production is increased as %Delta-Voltage increases above DbVMax. Note that the % Delta-Voltage may be calculated relative to Moving Average of Voltage<br>+DbVMax (as shown in Figure 16-1) or relative to Moving Average of Voltage (as shown in Figure 16-4), according to the ArGraMod setting. |
| **FilterTms** | This is the time, expressed in seconds, over which the moving linear average of voltage is calculated to determine the Delta-Voltage. |

Courtesy of EPRI, *Common functions of smart inverters*, Version 3, Feb, 2014, Brain Seal

# Optional Variables of DRCS

| Additional Settings (Optional) | |
|---|---|
| **ArGraMod** | This is a select setting that identifies whether the dynamic reactive current support acts as shown in Figure 16-1 or Figure 16-4. (0 = Undefined, 1 = Basic Behavior (Figure 16-1), 2 = Alternative Behavior (Figure 16-4). |
| **BlkZnV** | This setting is a voltage limit, expressed in terms of % of Vref, used to define a lower voltage boundary, below which dynamic reactive current support is not active. |
| **HysBlkZnV** | This setting defines a hysteresis added to BlkZnV in order to create a hysteresis range, as shown in Figure 16-5, and is expressed in terms of % of VRef. |
| **BlkZnTmms** | This setting defines a time (in milliseconds), before which reactive current support remains active regardless of how deep the voltage sag. As shown in Figure 16-5. |
| **Enable/Disable Event-Based Behavior** | This is a Boolean that selects whether or not the event-based behavior is enabled. |
| **Dynamic Reactive Current Mode** | This is a Boolean that selects whether or not Watts should be curtailed in order to produce the reactive current required by this function. |
| **HoldTmms** | This setting defines a time (in milliseconds) that the delta-voltage must return into or across the dead-band (defined by DbVMin and DbVMax) before the dynamic reactive current support ends, frozen parameters are unfrozen, and a new event can begin. |

Courtesy of EPRI, *Common functions of smart inverters*, Version 3, Feb, 2014, Brain Seal

# Priority of Smart Inverter Functions

- **Multiple functions can be running simultaneously**
- **Can lead to conflicting requirements**
  - Example: active power needed during under frequency versus reactive power needed for voltage regulation / FIDVR
- **What is priority of functions during FIDVR event ?**
  - 1) Frequency support of bulk system
    - May cause limitations of reactive power capabilities (W priority)
  - **2) FIDVR response ? (New concept needs discussion)**
  - 3) Steady state voltage regulation (FPF, V/VAr)
  - 4) Commanded active / reactive power
  - 5) Scheduled responses



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# Conclusions

- **Smart Inverters can provide dynamic reactive power in response to FIDVR events**
  - Capability exists today but functional requirements are TBD
- **Regulatory standards are under development now and FIDVR response is "on the agenda"**
  - IEEE 1547 (2016), IEEE 1547.1 (2016/170
  - UL 1741 Supplement A (2015), Full revision (2016)
- **Definition of the desired functionality is needed in order to implement and certify**
  - Inverters are very flexible and behaviors can be complex
  - Inverter models are very complex but will be critical in determining best guesses for initial functionality
- **Remote upgradability of inverters will likely be needed as PV proliferates and understanding evolves**

 

# Thank you for your attention!

For questions contact John Berdner

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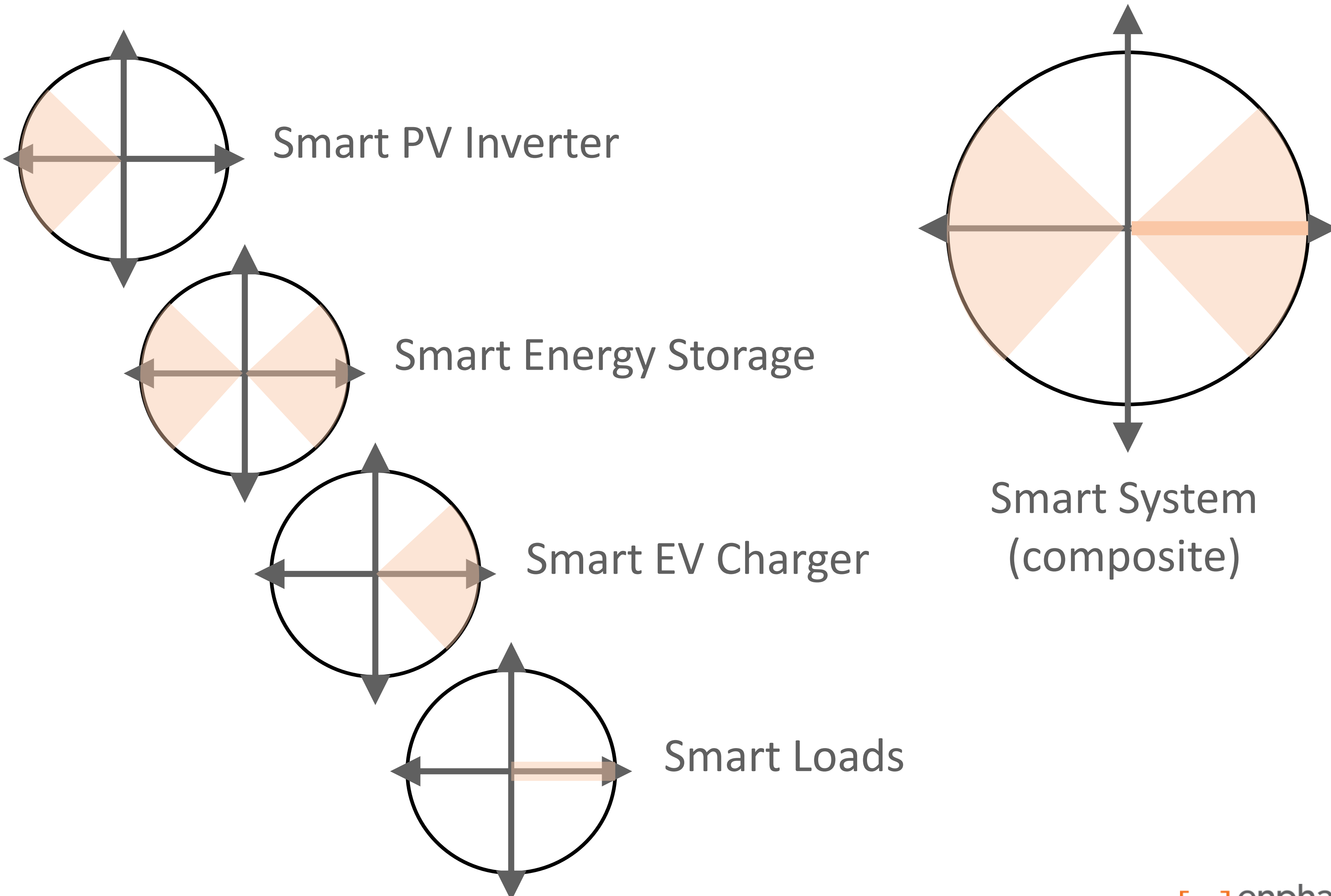
Tel: 530.277.4894

# "Smart System" Operating Areas



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# Plug-in Electric Vehicle Charging
## Characteristics

**John Halliwell**
Principal Project Manager – Electric Transportation

**NERC-DOE FIDVR Workshop**
September 30, 2015

Washington, D.C.

# Outline

- Electric Vehicle Supply Equipment
- Charging System Topologies
- Charging Characteristics
- Vehicle Voltage Response

# Some Electric Vehicle Supply Equipment Samples

Level 1 AC - Cord Set

120V charging



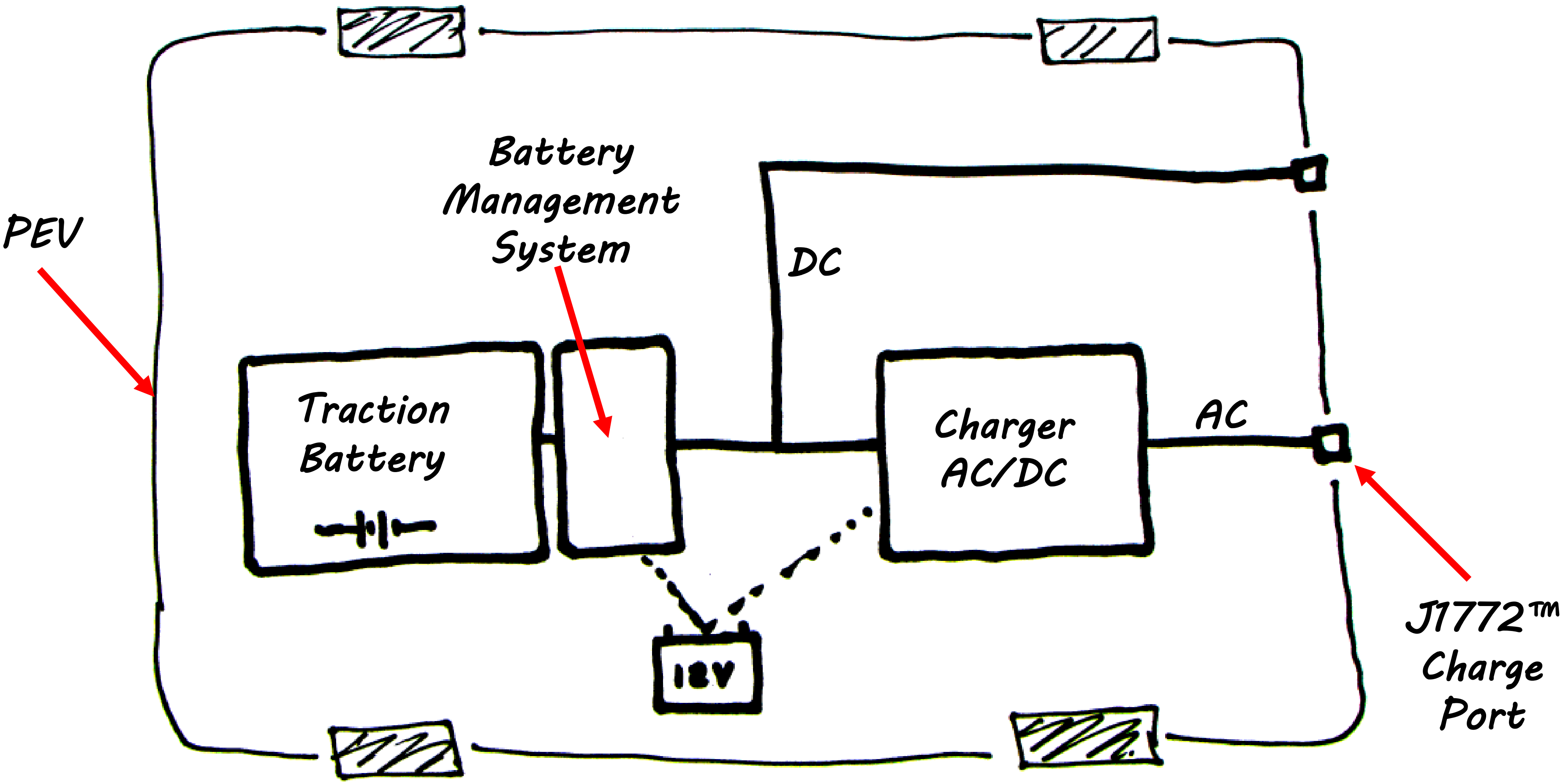
Level 2 AC

208/240V charging

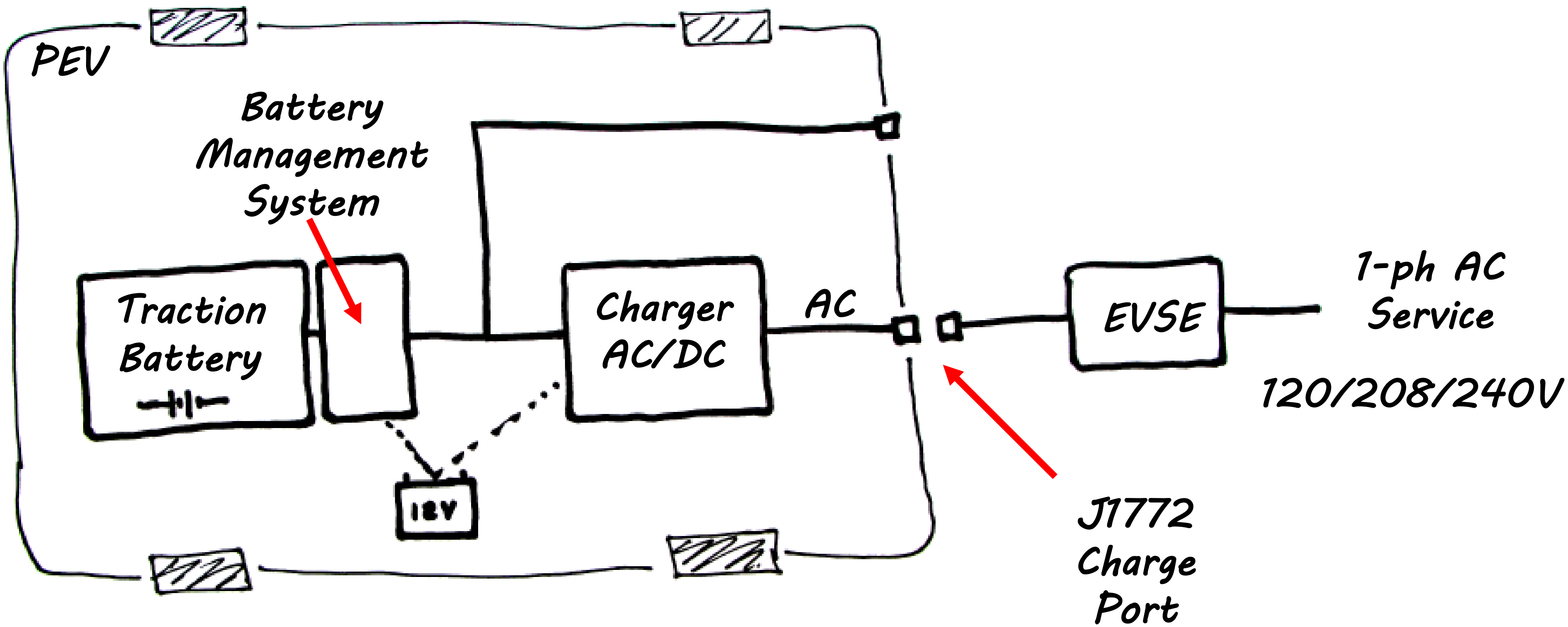

DC Fast

208/480V 3phase input

# Plug-in Vehicle On-board System Topology



# Topology and Nomenclature – AC Charging



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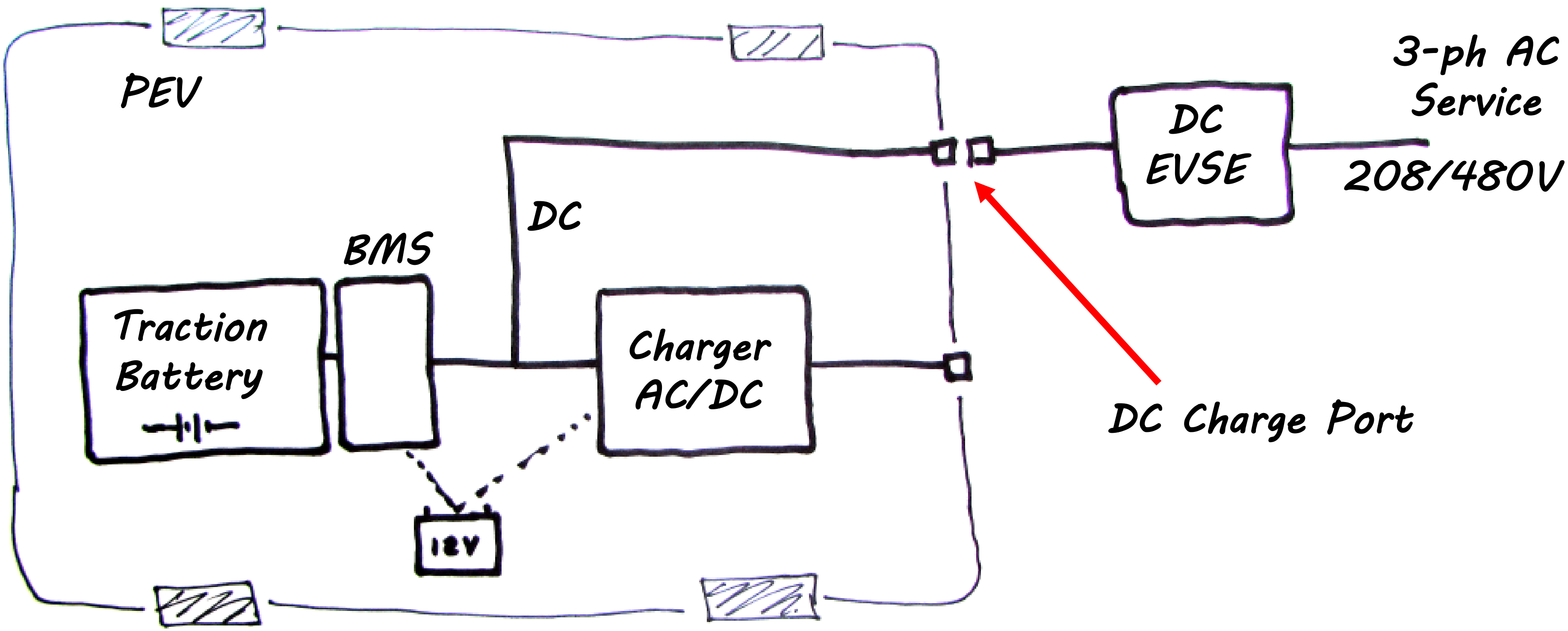
# DC Charging



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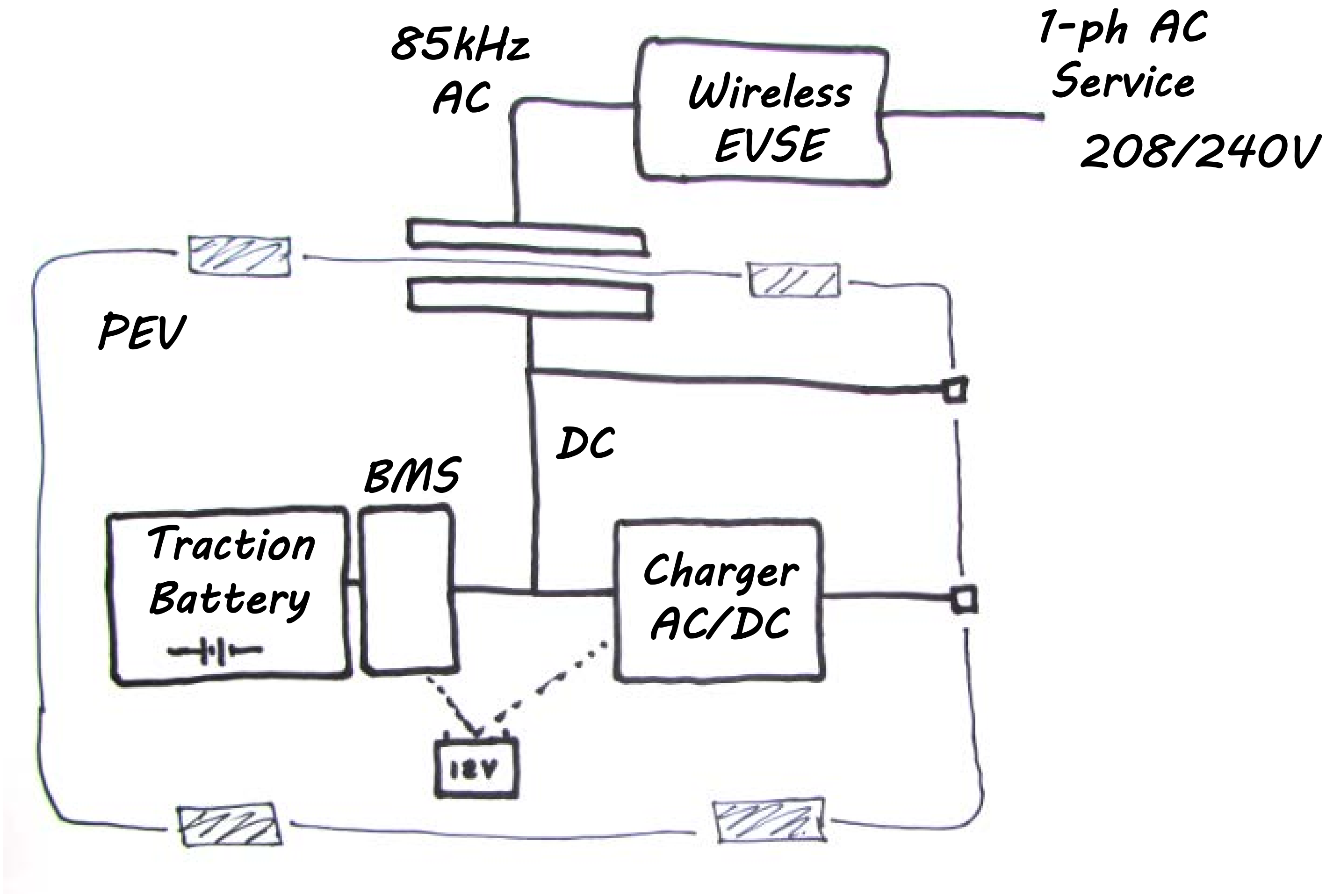
# Wireless Charging





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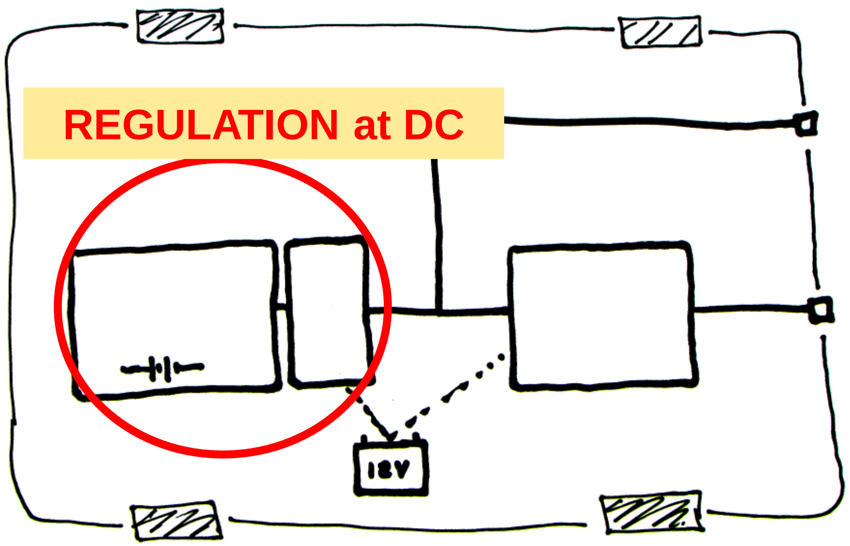
# No Matter the Charging Technology…

- Regulation is at the battery (DC load side)
  - V and I controlled by Battery Management System
  - From AC input, generally looks like a constant power load with a current limit
- Standards, wire sizing, etc..
  - Based on input current
- Response to off-normal conditions mix of:
  - OEM designed charge management
  - Third party charge station design (AC, DC Wireless)





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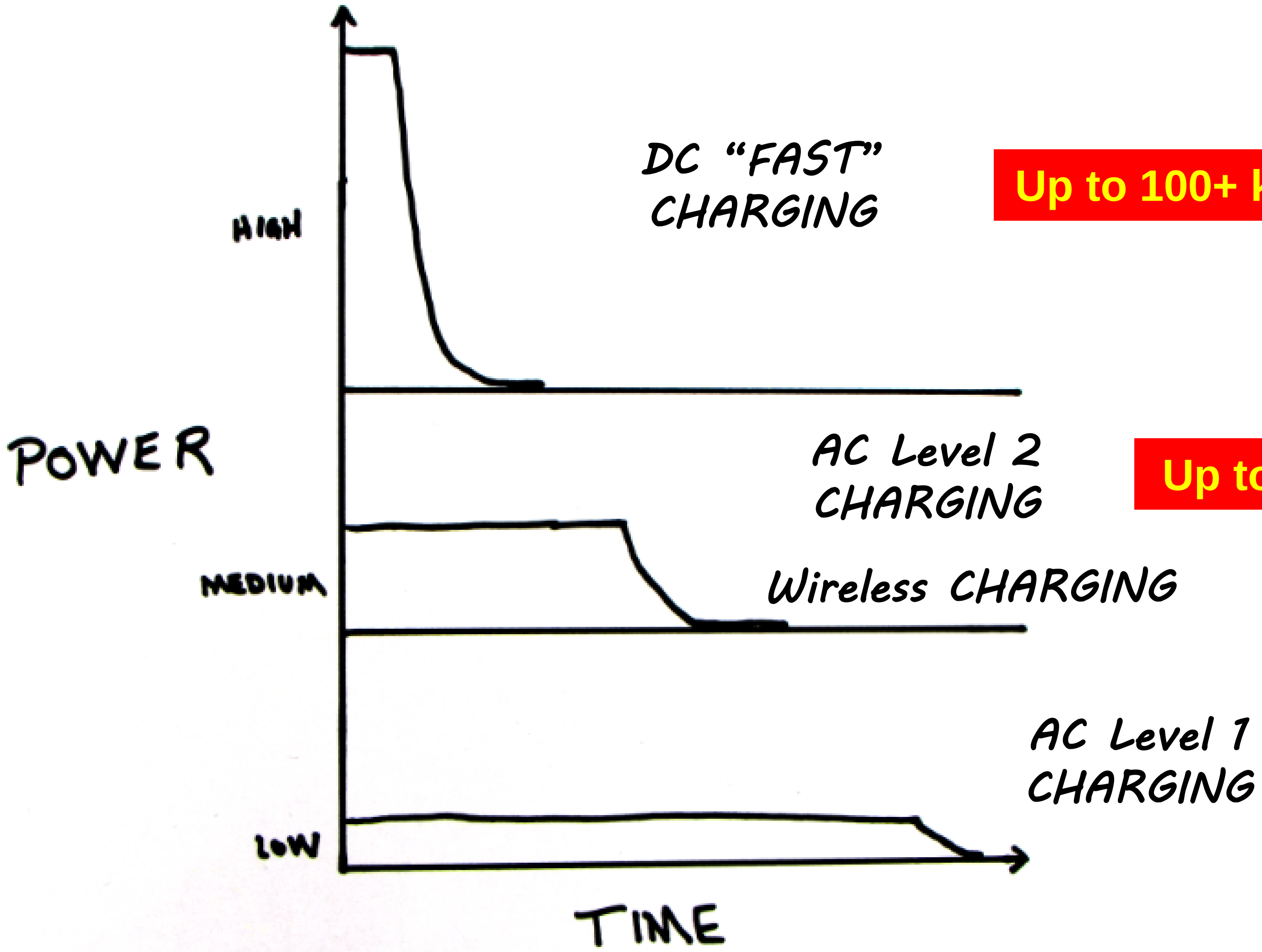
# Power versus Time




**Up to 100+ kW**

**Up to 19.2 kW**

**Up to 2 kW**





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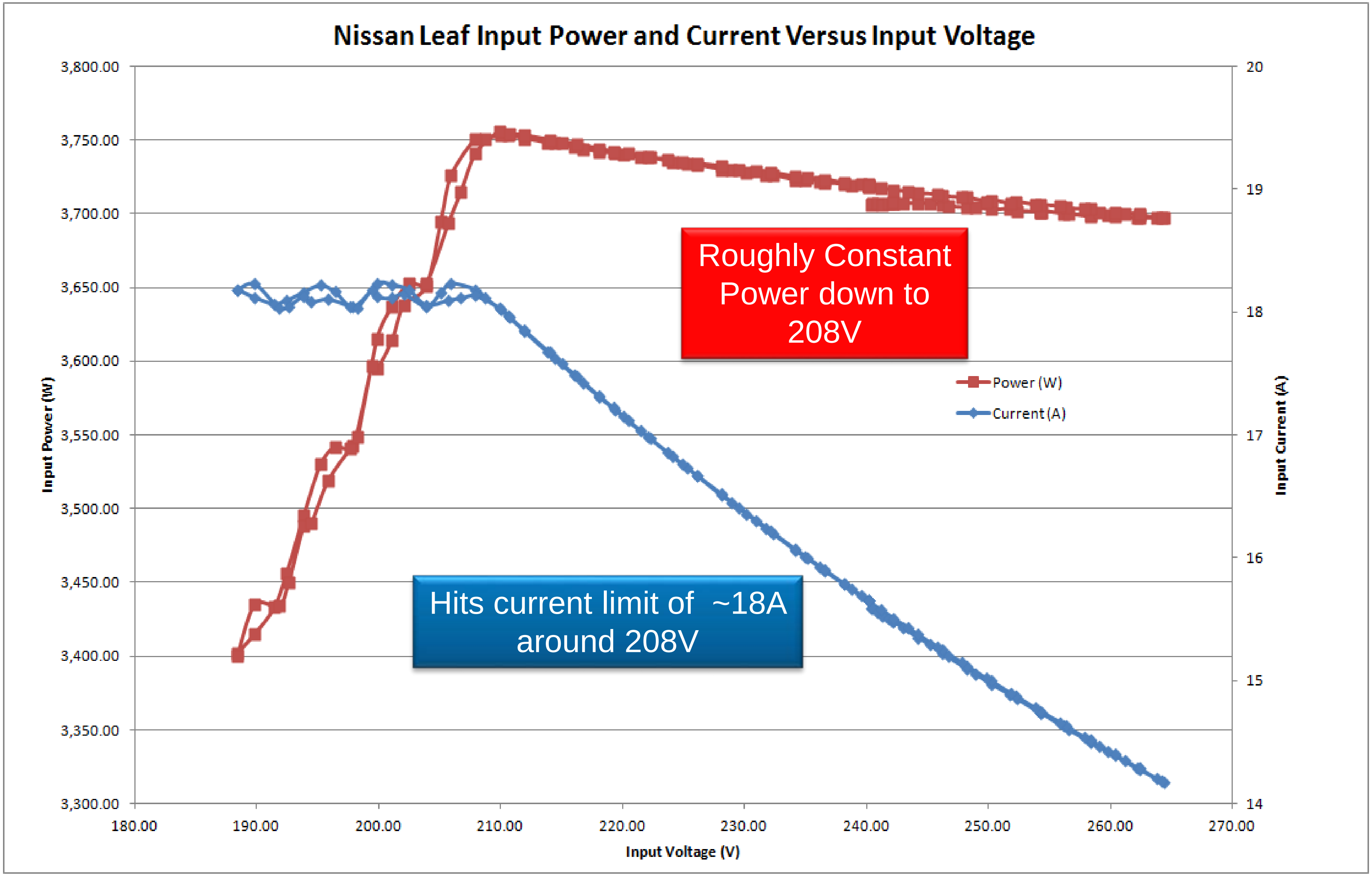
# EPRI 2011 Nissan Leaf Data





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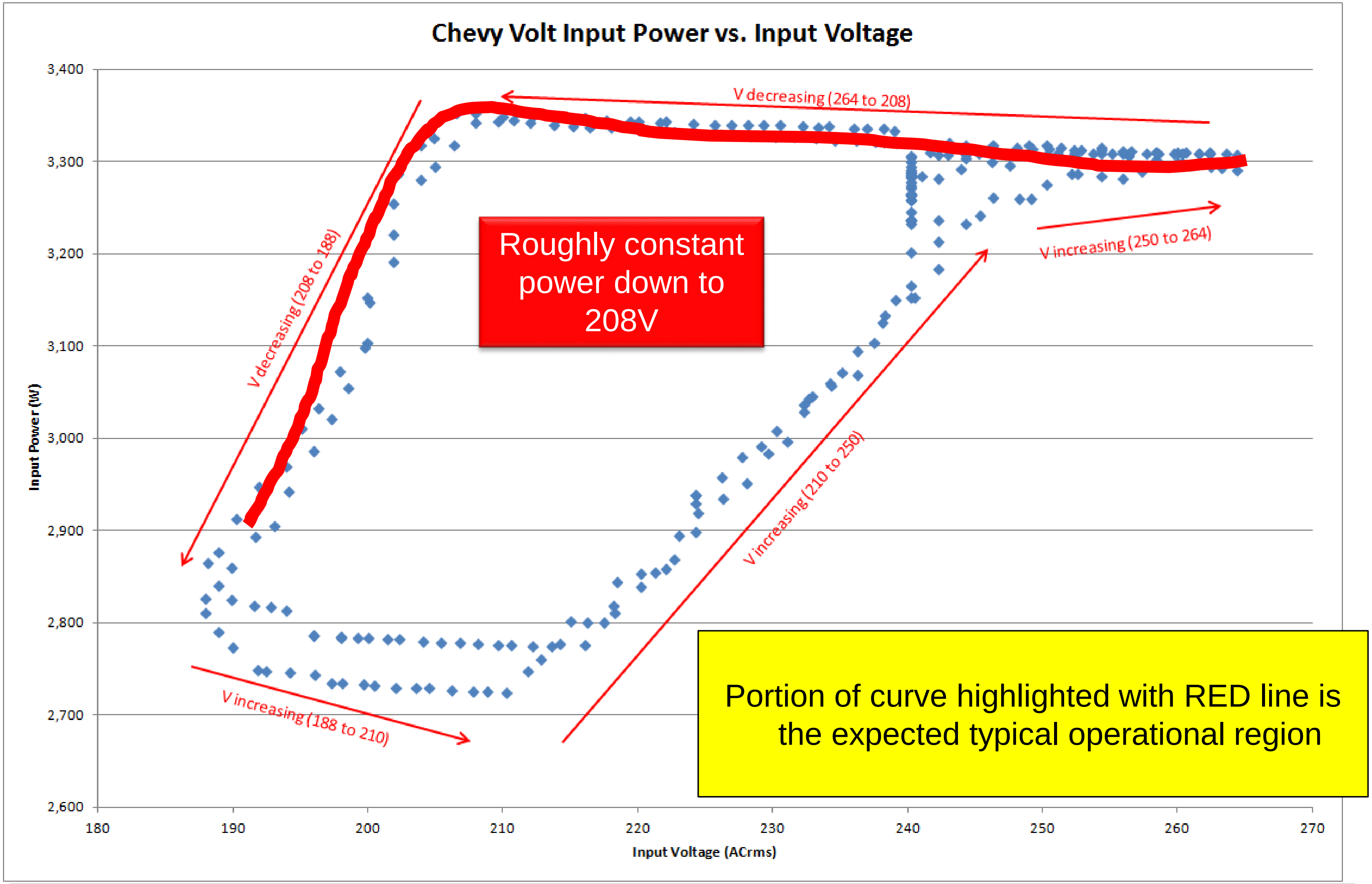
# EPRI 2011 Chevy Volt





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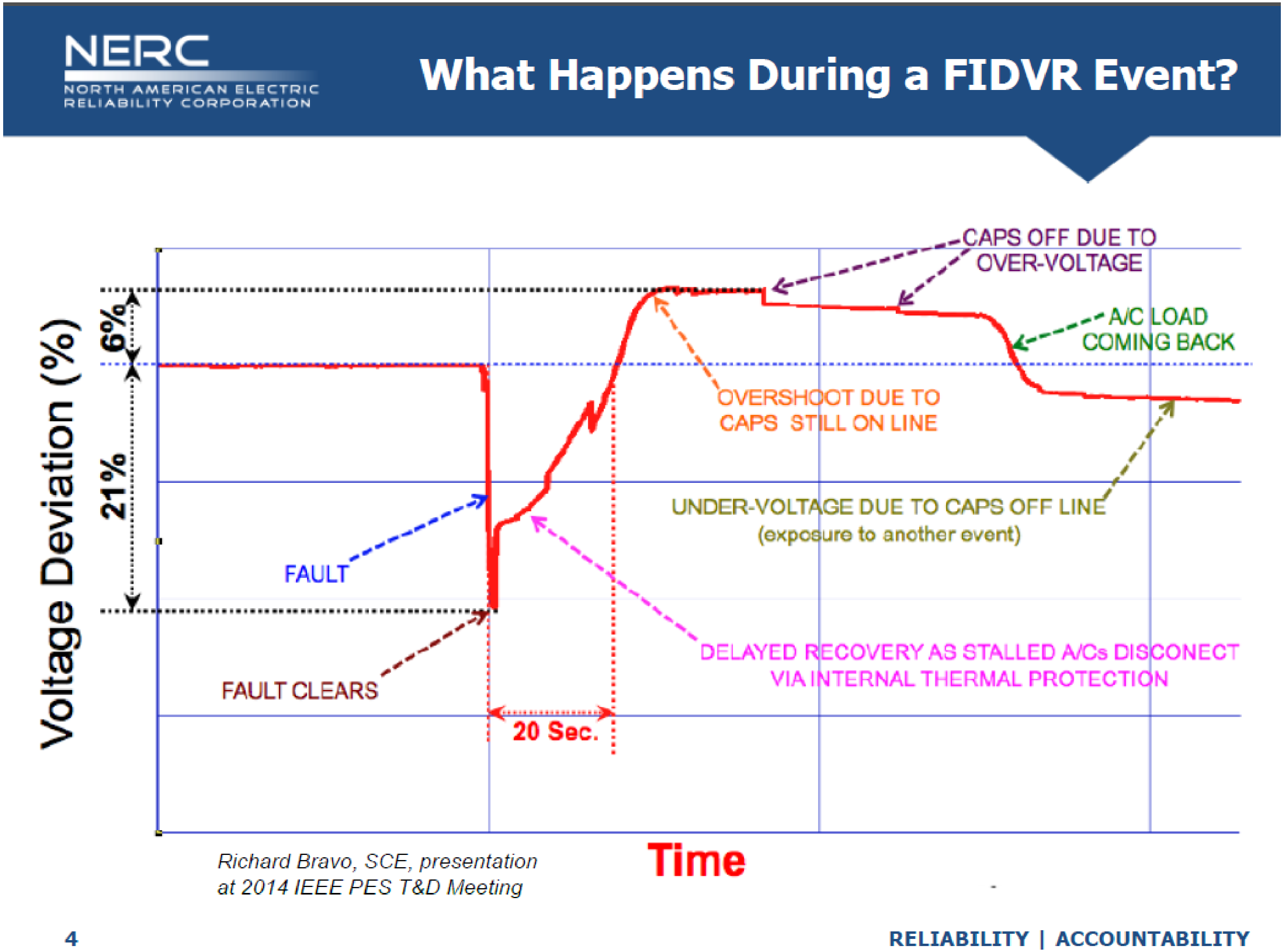
# This Sample Waveform was Used





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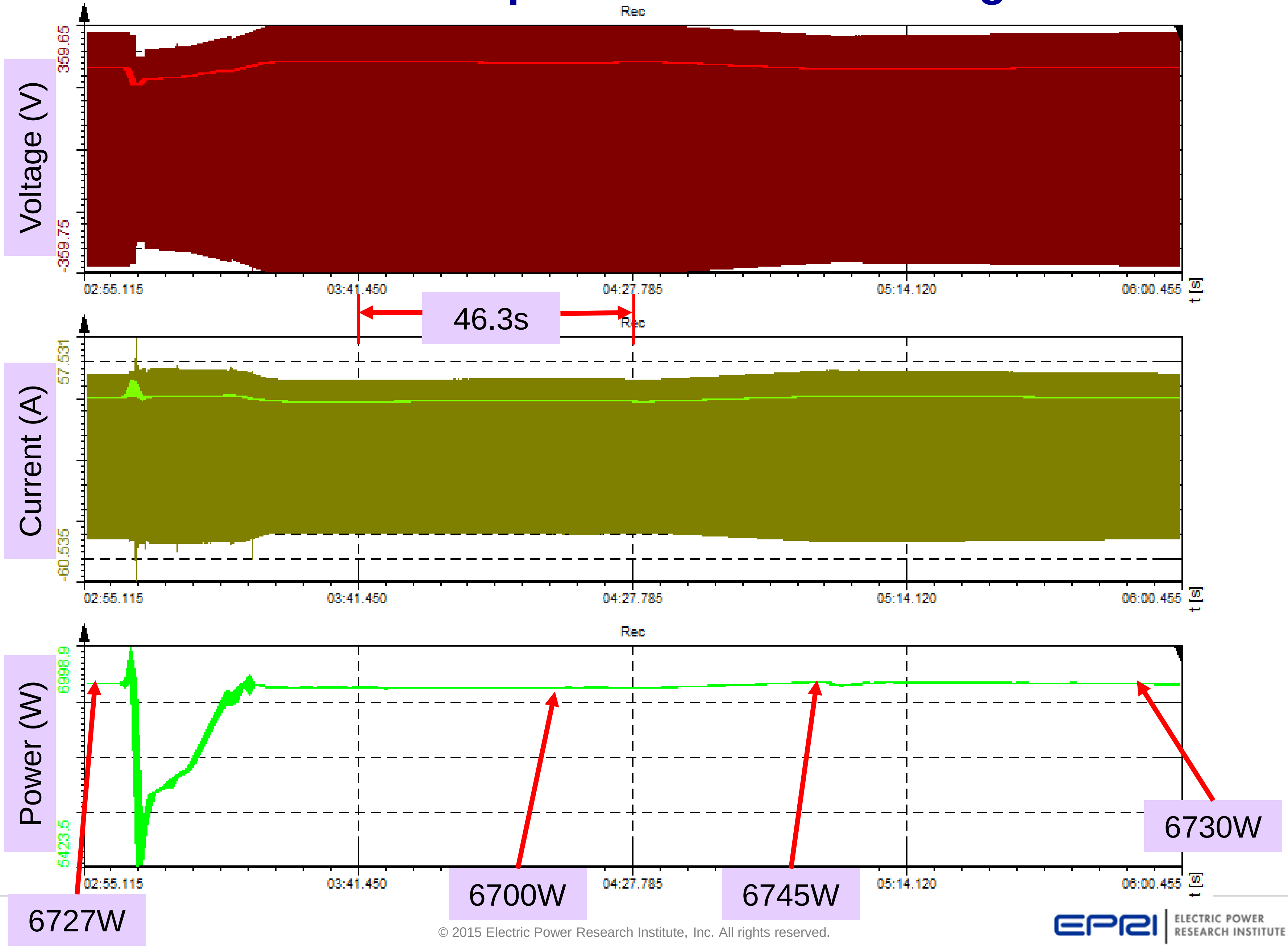
# 2013 Nissan Leaf – Response to FIDVR Voltage Profile





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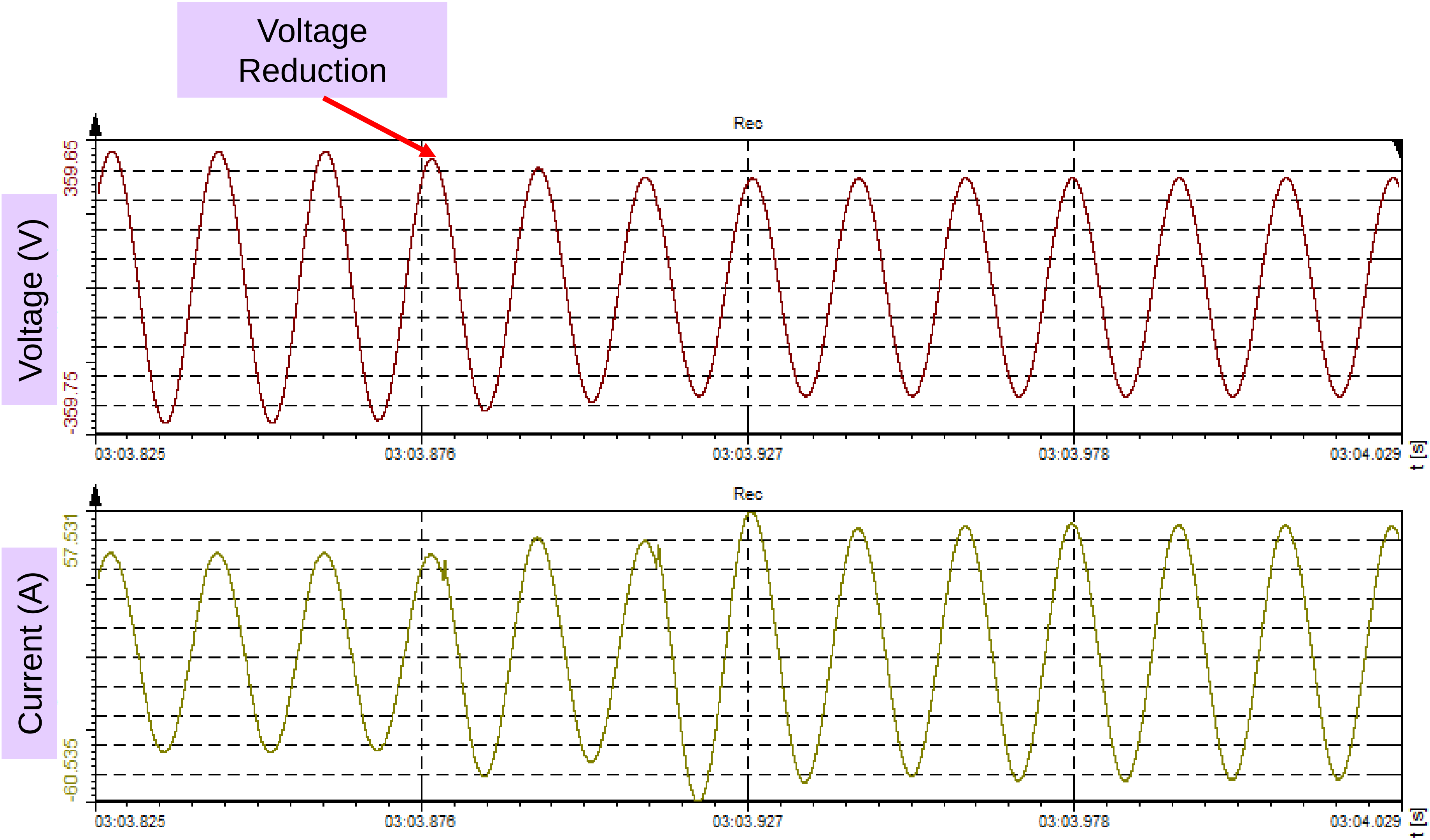
# 2013 Nissan Leaf – Response to FIDVR Voltage Profile - 2





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# Together…Shaping the Future of Electricity





ELECTRIC POWER RESEARCH INSTITUTE

# Load Model Improvements – a Case Study

Donald Glen Davies

Chief Senior Engineer

# Data Management

- Complexity of load modeling
  - Each load has a different composition
  - Load magnitude and composition changes over a day, over a year, and over the years.
- Had to find ways to simplify data management processes
- Other entities will also need to find ways to simplify data management, may wish to consider some of WECC's methods

# Load model addition to a new base case

- Developed a process we use to build composite load models for a given base case.
- Don’t need to worry about all the details for each case.

# CLZONE – “Climate Zone”

Developed by WECC LMTF to categorize similar load patterns and types

WECC has approximately 60 climate zones, formed from combinations of climate areas, feeder types, and industrial load types.

# CLZONE – Climate Areas


NWC – Northwest coast
NWV – Northwest valley
NWI – Northwest inland
RMN – Rocky mountain
NCC – N. Calif. coast
NCV – N. Calif. valley
HID – High desert
SCC – S. Calif. coast
SCV – S. Calif. valley
DSW – Desert southwest

# CLZONE – Climate Areas

## WECC Climate Areas

| ID | Climate Zone | Representative City |
|---|---|---|
| NWC | Northwest Coast | Seattle, Vancouver BC |
| NWV | Northwest Valley | Portland OR |
| NWI | Northwest Inland | Boise, Tri-Cities, Spokane |
| RMN | Rocky Mountain North | Calgary, Montana, Wyoming |
| NCC | Northern California Coast | Bay Area |
| NCV | Northern California Valley | Sacramento |
| NCI | Northern California Inland | Fresno |
| SCC | Southern California Coast | LA, San Diego |
| SCV | Southern California Valley | LA, San Diego |
| SCI | Southern California Inland | LA, San Diego |
| DSW | Desert Southwest | Phoenix, Riverside, Las Vegas |
| HID | High Desert | Salt Lake City, Albuquerque, Denver, Reno |

# CLZONE – Feeder Type

## *Feeder Type*

| ID | Feeder Type | Residential | Commercial | Industrial | Agricultural |
|---|---|---|---|---|---|
| RES | Residential | 80% | 20% | 0% | 0% |
| COM | Commercial | 20% | 80% | 0% | 0% |
| MIX | Mixed | 40% | 40% | 20% | 0% |
| RAG | Rural Agricultural | 40% | 40% | 10% | 10% |

LID code is <3-character climate zone>_<3-character load class>
Or <7-character industrial load ID>

LID is a field located in the load table.

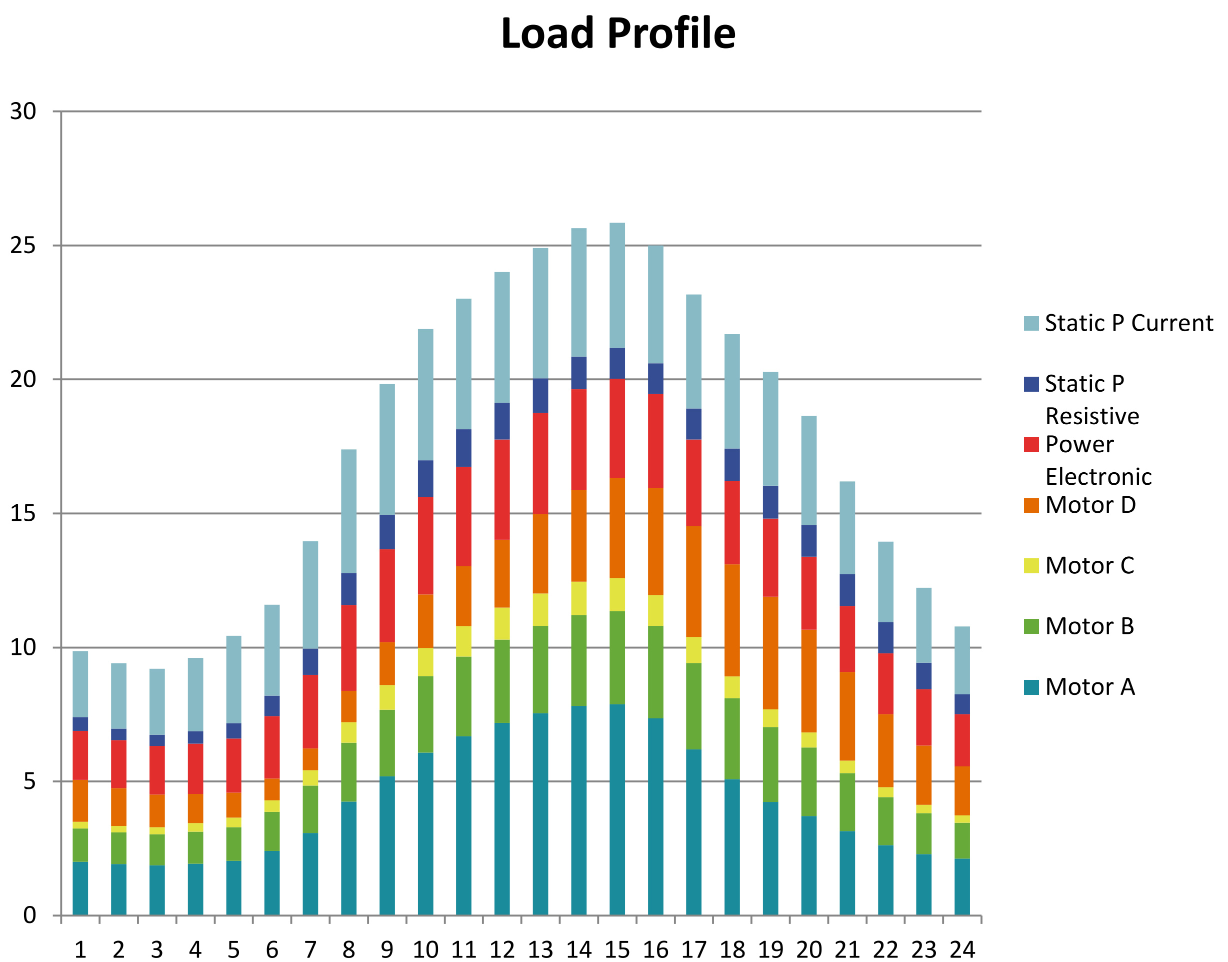
For example:
Commercial load downtown Phoenix with high concentration of commercial loads would be indentified as "DSW_COM"
Rural agricultural load in Moses Lake, WA would be identified as "NWI_RAG"

# CLZONE – Industrial Loads

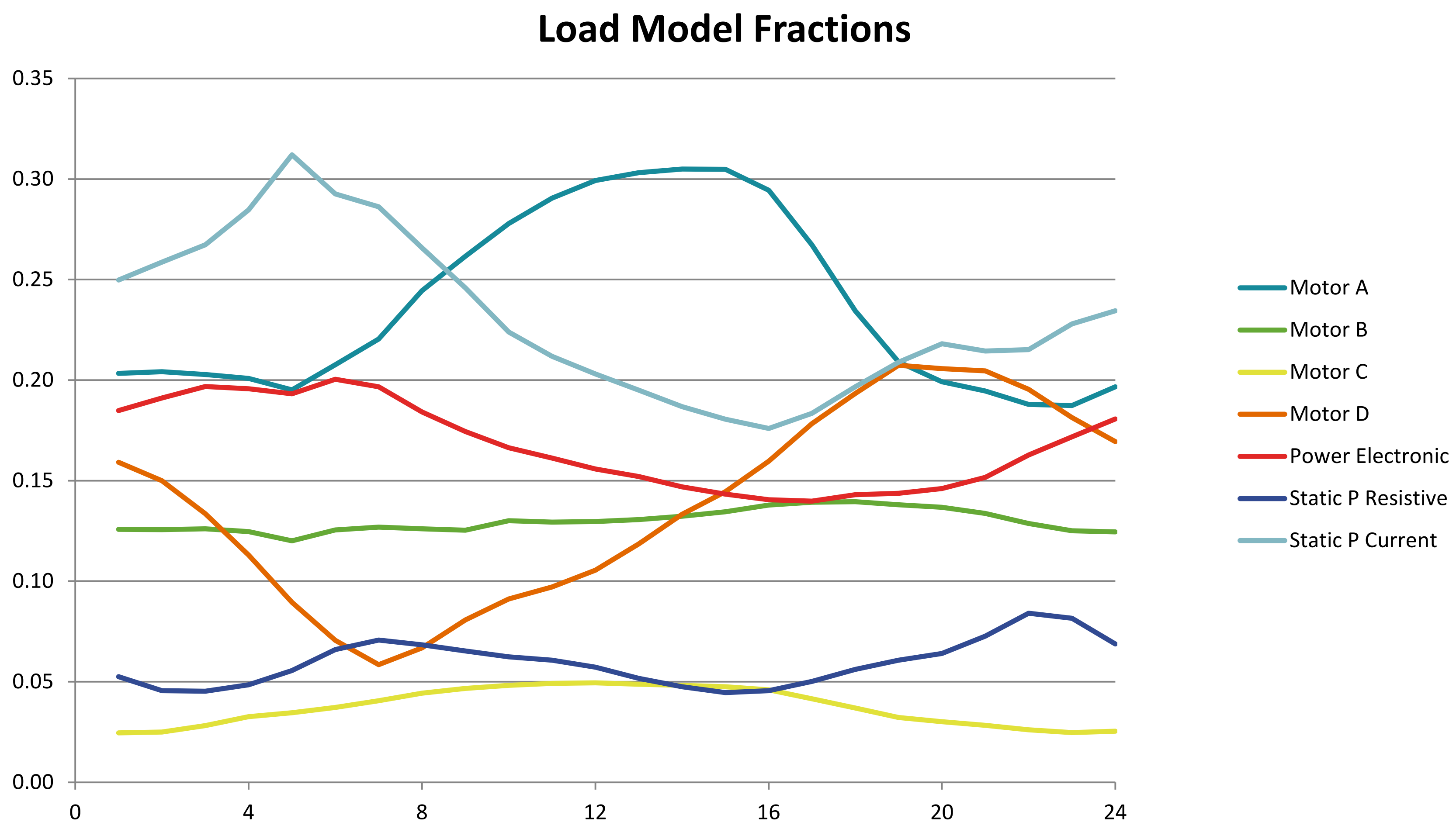
## *Industrial Loads*

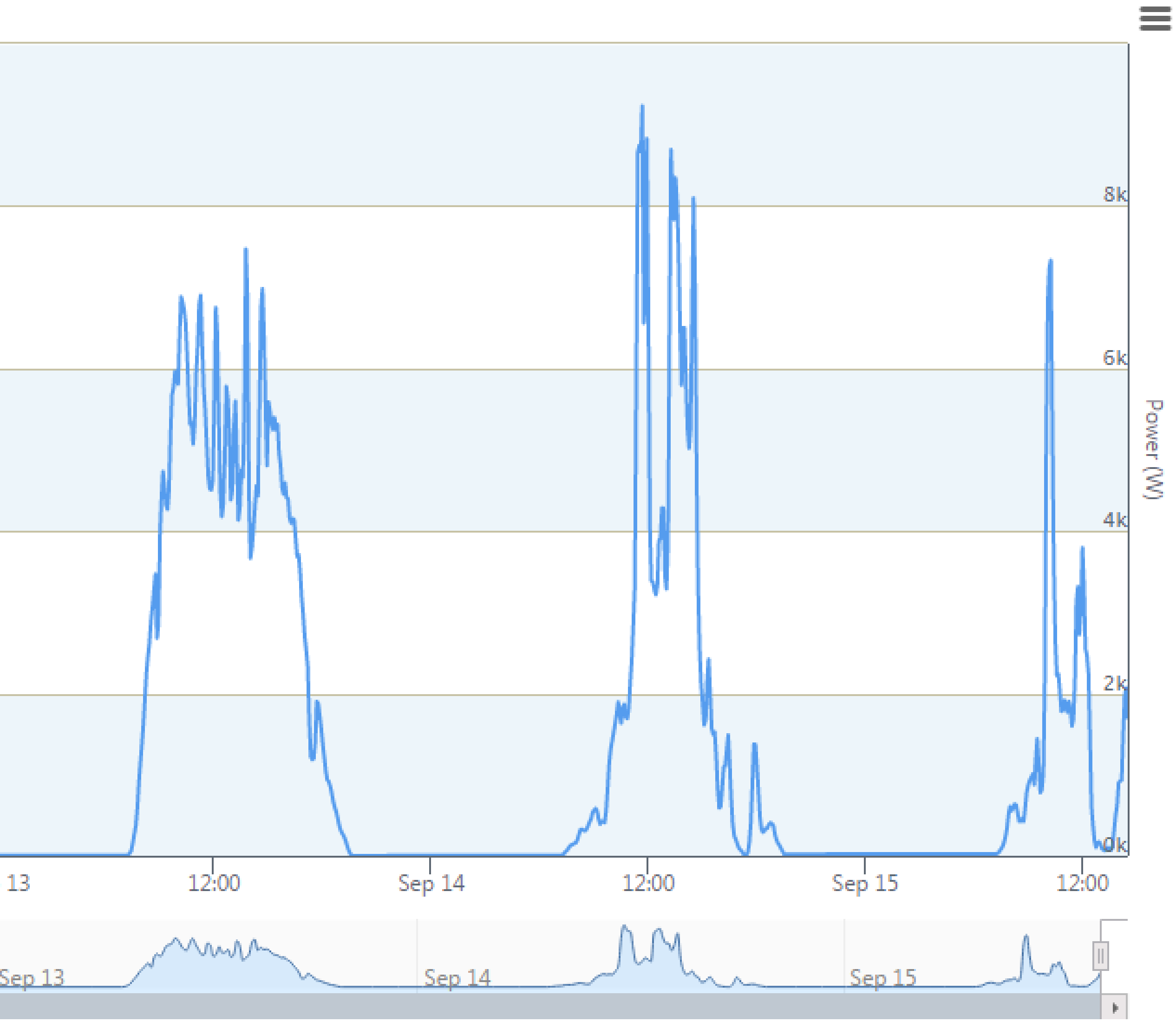
| ID | Feeder Type |
|---|---|
| IND_PCH | Petro-Chemical Plant |
| IND_PML | Paper Mill |
| IND_ASM | Aluminum Smelter |
| IND_SML | Steel Mill |
| IND_SCD | Semiconductor Plant |
| IND_SRF | Server Farm |
| IND_OTH | Industrial – Other |
| PPA | Power Plant Auxiliary |

# Daily Load Shape Example



# Daily Load Shape Example






42 Microinverters
1 Envoy Ethernet
Taylorsville, UT

59°F

System Normal

**Full System**

Energy | Status

**Today**
**10.5** kWh

Peak Power: **7.33** kW at 10:15 AM
Latest Power: **1.70** kW at 2:30 PM

**Past 7 Days**
**335** kWh

**Month To Date**
**797** kWh

**Lifetime**
**19.8** MWh

# Routine Process to add Load model to each base case

1) Transmission Planner (or whoever prepares load data) populates a "Climate Zone" field for each load in their power flow data submittal. They typically do this once, use for all future cases.

2) WECC runs a spreadsheet tool to look up the climate zone definitions for a given power flow case based upon the hour of day and season represented. Spreadsheet dumps a calculated sheet with feeder information, proportion of various motor types in each climate zone to a csv file.

# Spreadsheet Tool

| Enter Day (1=normal summer, 2=hot summer,3=cool summer,4=shoulder,5=winter) | Enter Hour (Pacific Time) |
|---|---|
| 5 | 5 |

Significant effort went into the data in the spreadsheet tool, but that was preparatory . That work does not have to be redone for each case, or by each utility.

The tool computes how much of each motor type, etc. for each climate zone based upon hour of day and type of day.

# Routine Process to add Load model to each base case

3) WECC uses an epcl program (WECC uses PSLF to build cases) that reads the completed power flow case to dump a csv file with needed information including load magnitude, voltage and climate zone for each load bus.

4) WECC runs a tool from PNNL to create the composite load model part of the dynamics data file. The tool reads three files:

- CSV from spreadsheet tool (step 2)
- CSV output from epcl (step 3)
- CSV with predefined motor definitions

The tool can output cmpld model data for PSLF or PSS/E dynamics files

# Implementation Process

- Several rounds of implementation, then trial, then refinement
  - 2 years of studies by individual utility volunteers with the composite load model
  - Additional adjustments were required, especially to the protection model
  - Finally approved for initial inclusion in base cases with a phased approach
    - The new model provides a better match to system events

# Implementation Process

- Phased implementation
  - Currently disabled AC stalling – Phase 1
  - Work continues to better understand AC stalling
  - Hope to continue improving the model – Phase 2

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# Is Load Loss Real ?

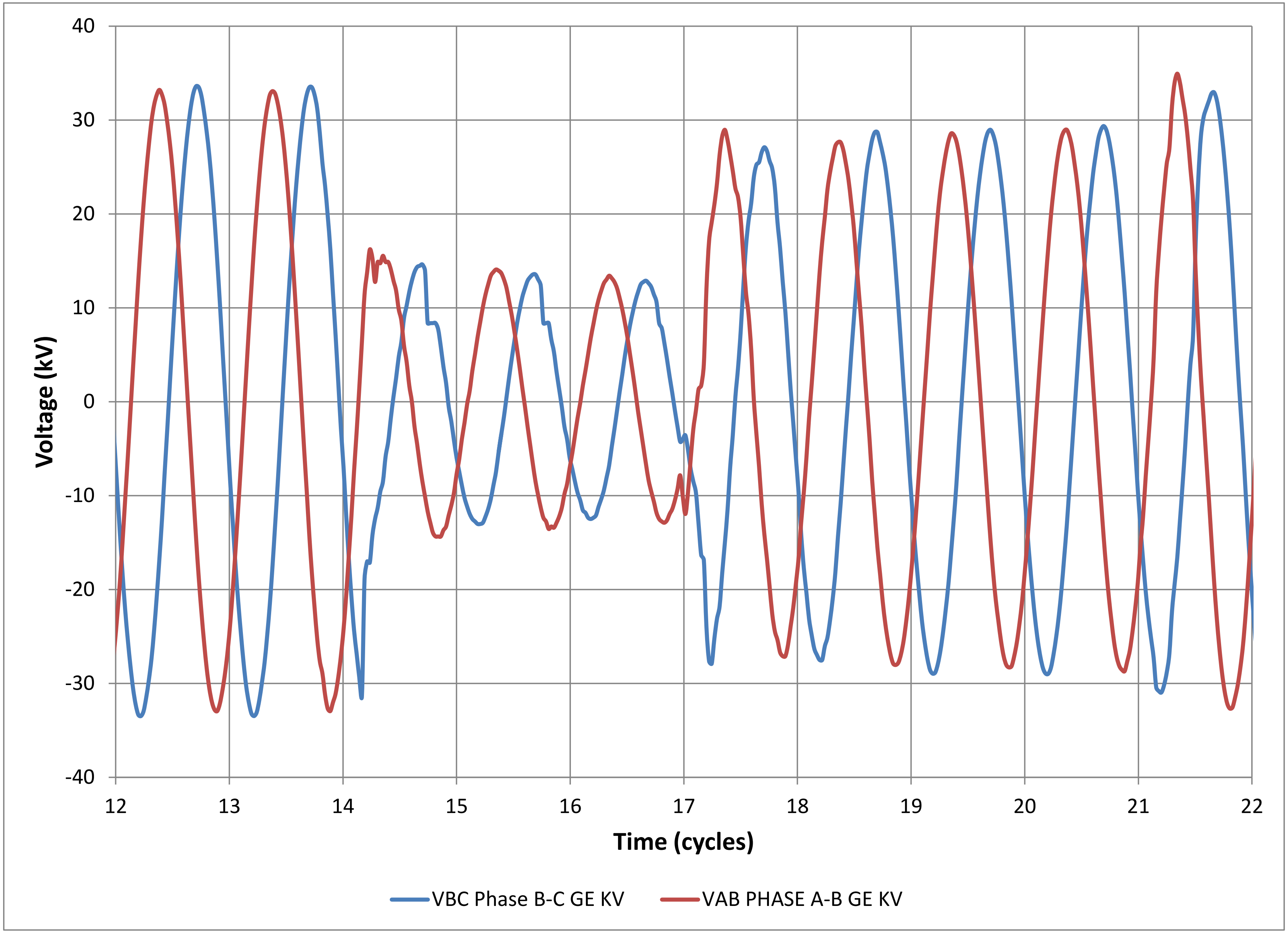
2015 NERC-DOE FIDVR Conference

Presented by

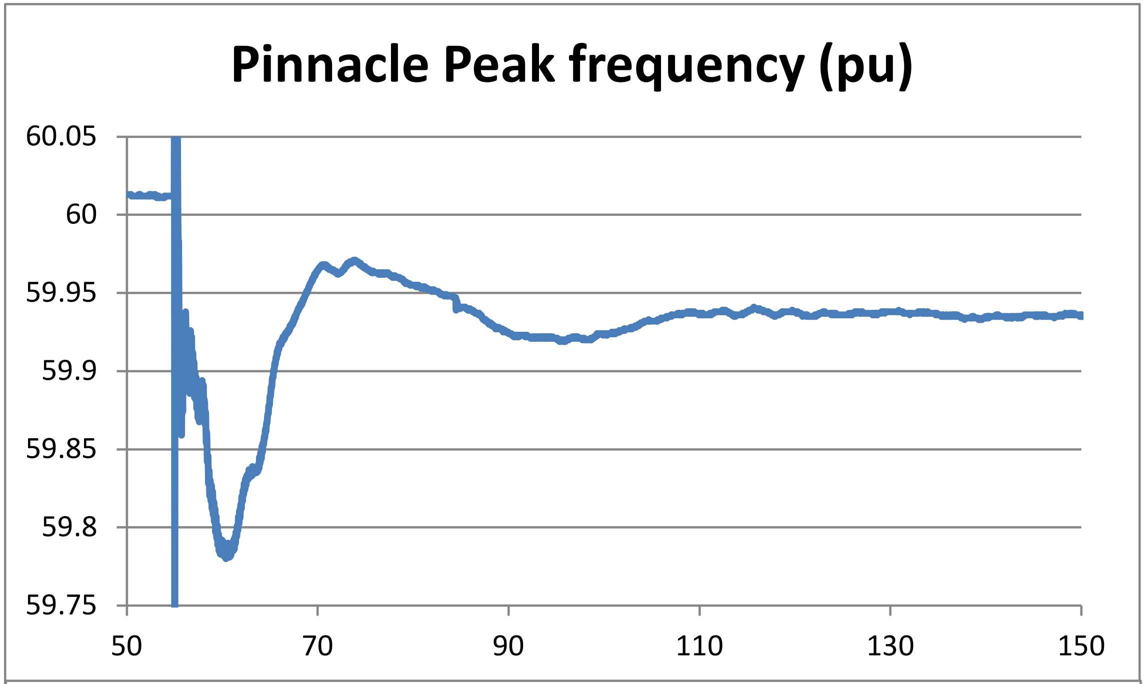
Dmitry Kosterev, BPA

# Hassayampa Event

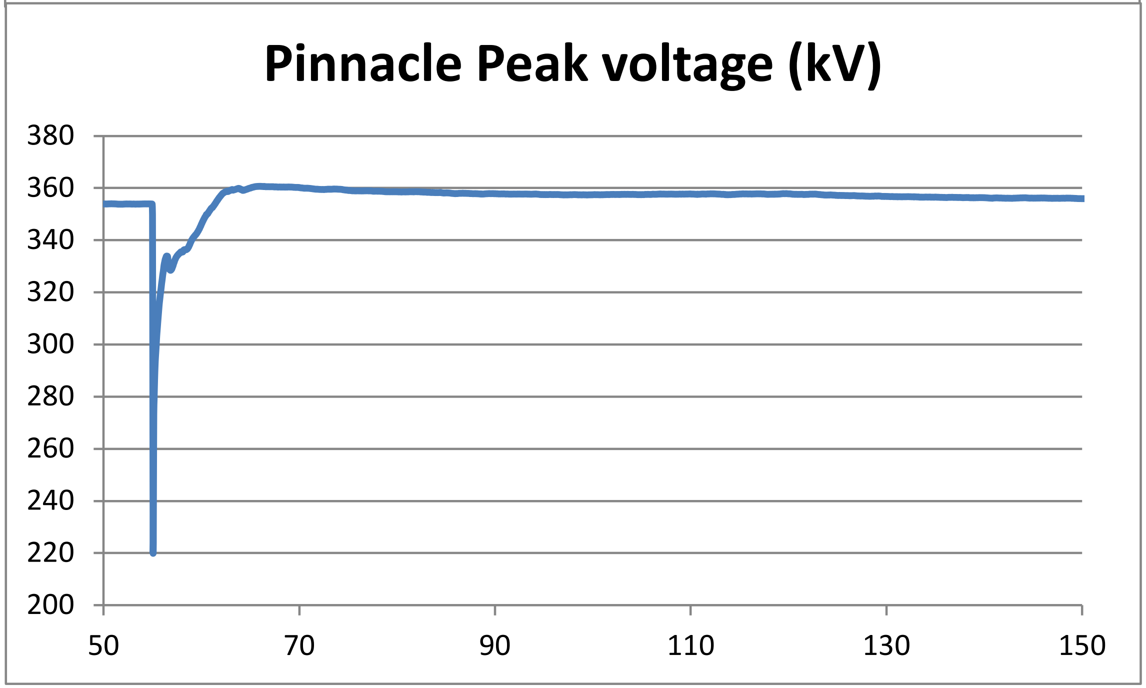
- July 28, 2003 at 18:54
- 3-phase fault at Hassayampa 500-kV substation west of Phoenix, AZ
- 2,685 MW of generation tripped following a fault



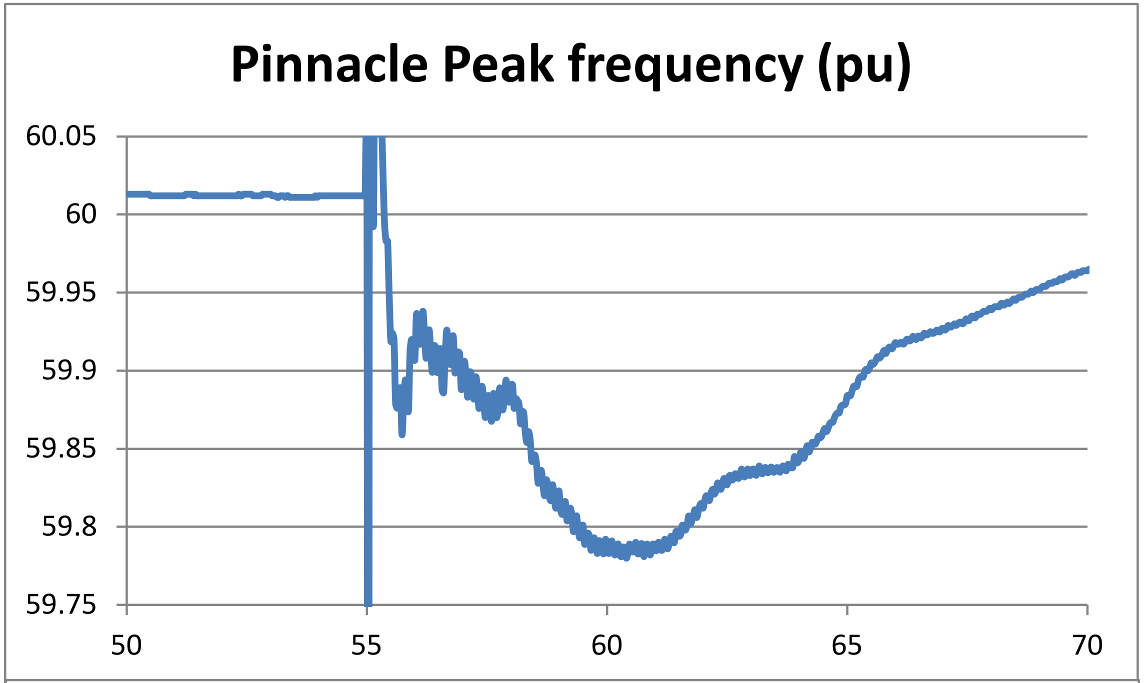
40
30
20
10
0
-10
-20
-30
-40
Voltage (kV)
12
13
14
15
16
17
18
19
20
21
22
Time (cycles)
VBC Phase B-C GE KV
VAB PHASE A-B GE KV



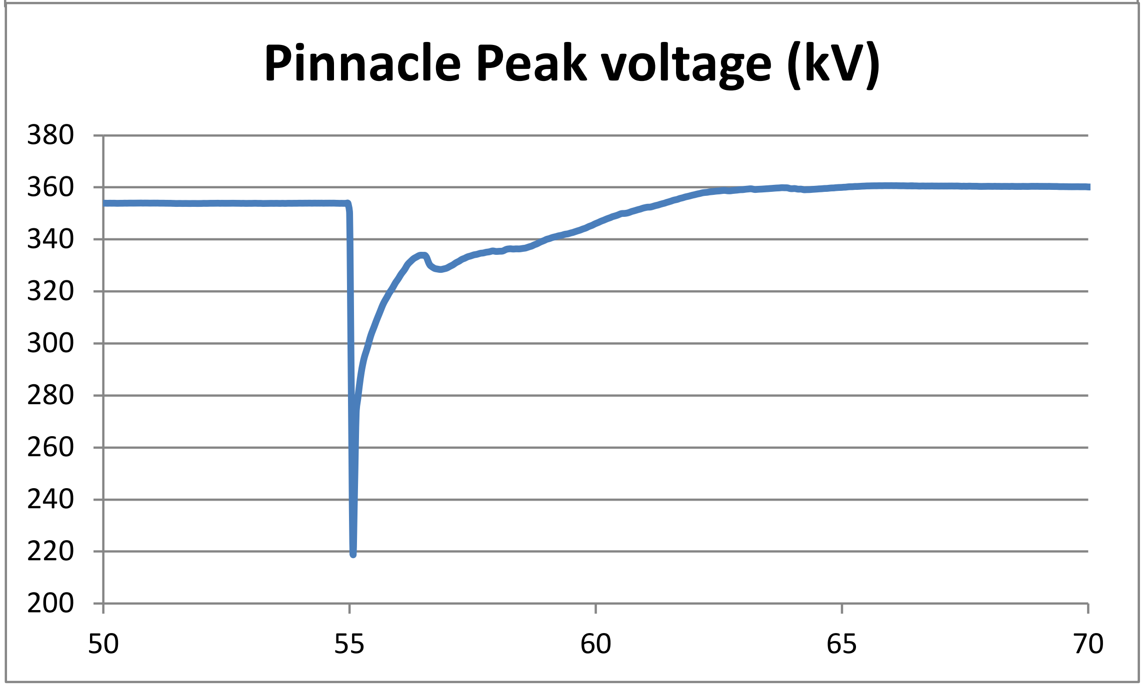
Pinnacle Peak frequency (pu)
60.05
60
59.95
59.9
59.85
59.8
59.75
50
70
90
110
130
150

Pinnacle Peak voltage (kV)
380
360
340
320
300
280
260
240
220
200
50
70
90
110
130
150



Pinnacle Peak frequency (pu)
60.05
60
59.95
59.9
59.85
59.8
59.75
50
55
60
65
70

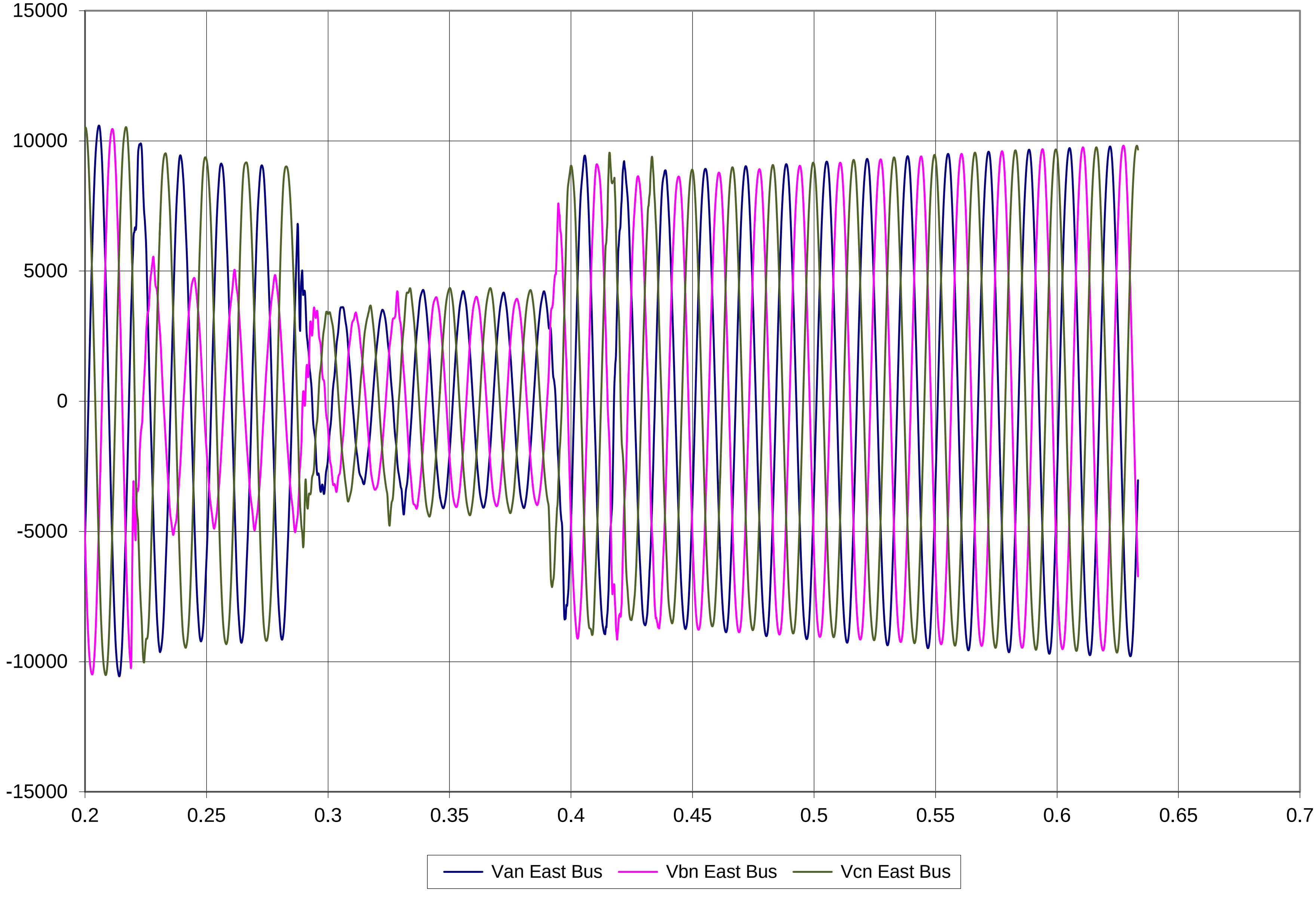
Pinnacle Peak voltage (kV)
380
360
340
320
300
280
260
240
220
200
50
55
60
65
70

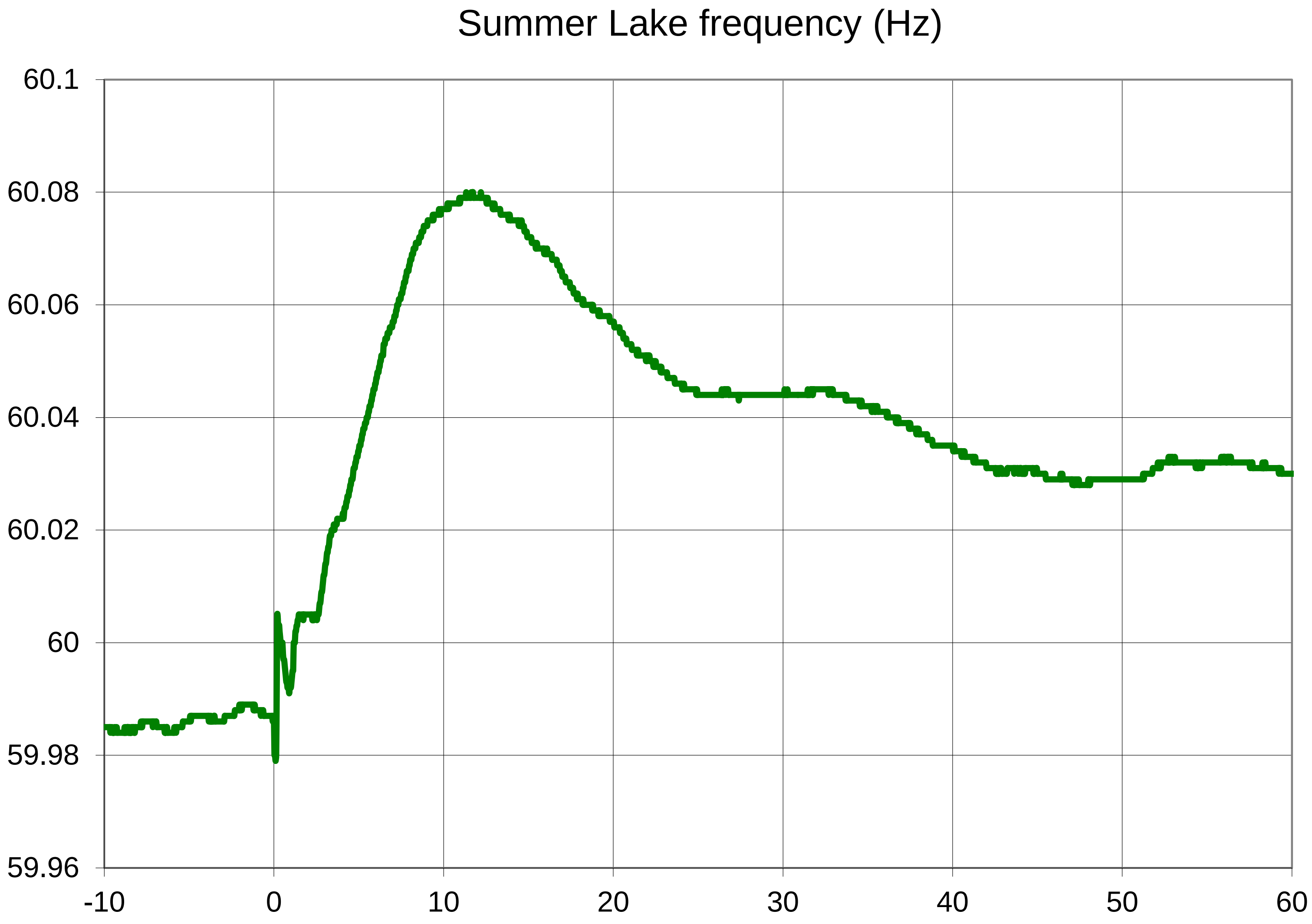
- Delta F = (60.011 – 59.938 )= 0.073 Hz
- WECC Frequency Response is about 1,450 to 1,650 MW per 0.1 Hz (see next page)
- **Estimated Load Loss is 1,480 to 1,620 MW,** calculated as 2,685 – 0.073*10*FRM
- Load loss is due to FIDVR and load tripping during the fault

# Mid-Valley Event

- July 28, 2009 at 21:18
- Mid Valley 138-kV substation, Salt Lake City, UT
- Capacitor bank failure
- Fault initiated as a four cycle single phase to ground fault that evolved into a three phase fault for an additional six cycles. The fault was cleared by action of the capacitor bank's protective relays. Total clearing time was about ten cycles.

- Temperatures were about 80 F

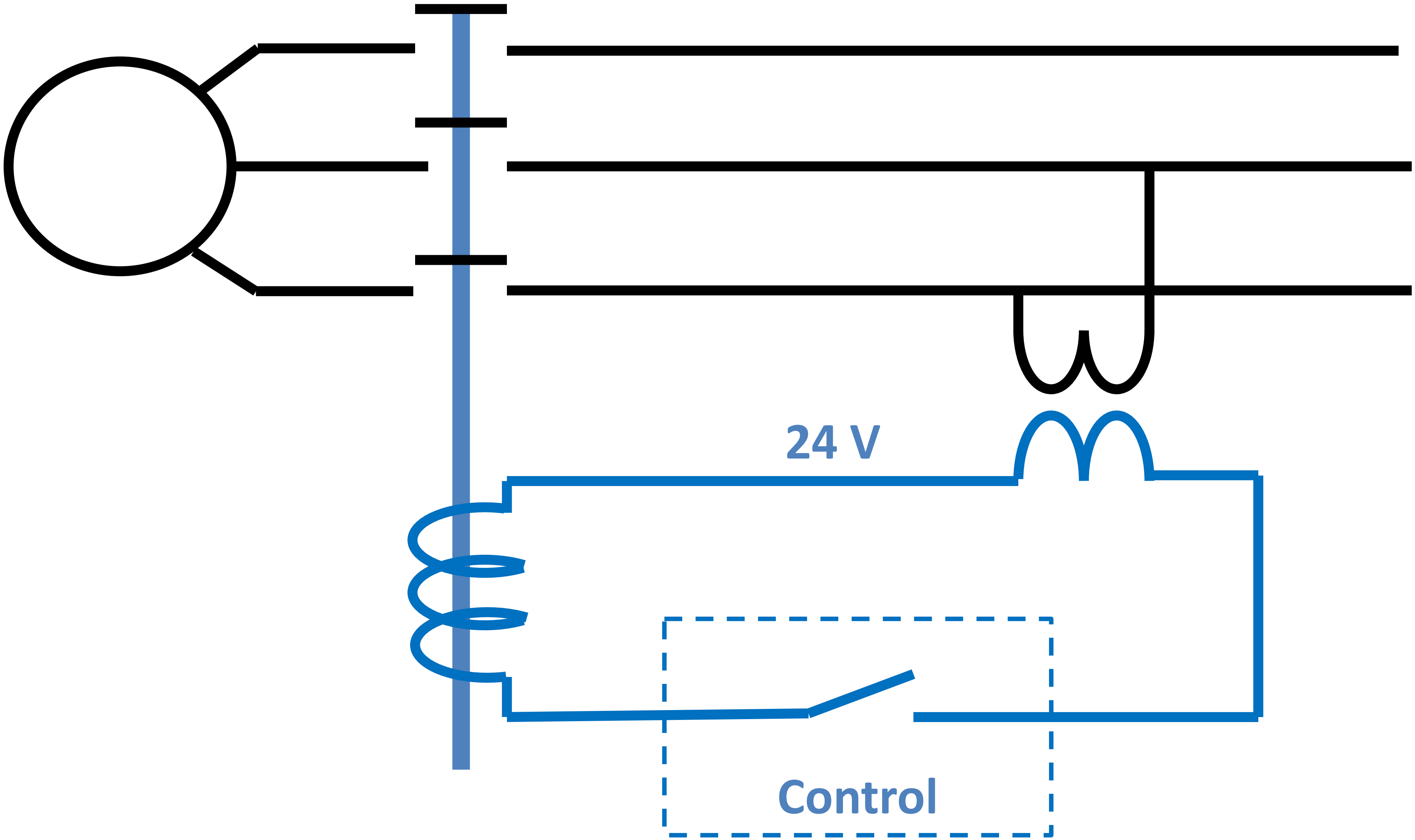

15000
10000
5000
0
-5000
-10000
-15000
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
Van East Bus
Vbn East Bus
Vcn East Bus


Summer Lake frequency (Hz)
60.1
60.08
60.06
60.04
60.02
60
59.98
59.96
-10
0
10
20
30
40
50
60

- Generation loss was about 190 MW

- Total load loss was about **920 MW**
  - 68 MW loss due to fault clearing
  - Loads tripped due to voltage sensitivity during the fault
  - No FIDVR detected

# Modeling


24 V
Control

Commercial / residential loads:

- Motors B and C (fans and pumps)
  - 20% trip at 60% voltage, reclose at 75%
  - 30% trip at 50% voltage, reclose at 65%
- Motor A (compressors)
  - 20% trip at 70% voltage and lock out
  - 70% trip at 50% voltage, reclose at 70%
- Electronics
  - Ramp down linearly as voltage declines from 70% to 50%
  - 20% trip and remain off-line, 80% restart

# Thank You

# Motor Control and Protection

# Effect of Under Voltage Transients in Commercial Buildings

John Kueck, Dan James (PNNL)


# A Study and Report Have Been Completed

- To understand how typical motor protection and control responds to voltage transients.
- A selection of commercial building types was studied.
- Dan James of PNNL has extensive experience with building management systems in a variety of commercial building types and was able to provide expertise on the many different motor types and control systems in today’s commercial buildings.
- We also performed tests of Energy Management Systems at BPA and had discussions with control system manufacturers to review the test results.

# Purpose of Study

- Voltage transient time frames of interest and magnitudes were developed which are used in a set of tables
- Two tables are provided for each building type.
- All motor loads were considered, not just single phase air conditioners.
- In commercial buildings, more and more motors are controlled by computer based building management systems.

# Voltage Transient Time Frames and Magnitudes of Interest

- Voltage transient magnitudes and durations were selected which were typical fault response levels that are of interest to system planners.
  - Dips to 75% of nominal and to 50% of nominal voltage. In general, most motor control equipment will ride through sags down to 75%. In some cases, for larger motors, under voltage protection will trip motors for sags to 80% of nominal for 2 seconds.
  - Dip durations of 5, 10 and 20 cycles, 2 seconds and 3 minutes (3 minutes is really just for interest and for recovery planning.)

# Possible Motor Responses to Voltage Transients

- Motors may ride through, trip, or stall.
- Controls may ride through, drop out, or trip immediately after the event.
- When voltage recovers, motors may re-energize and re-accelerate, or delay for a few minutes, or stay stalled.

# Tables Have Been Developed for the Following Commercial Building Types

- Food Service (Fast Food) (McDonalds)
- Supermarket (Albertson's)
- Other (Hotels, Residential Care)
- Office
- 20k-100k sf office building motor response
- 100k-1m sf office building motor response
- Retail  (Both Big and Small, by square feet)
- 5k sf  Under Retail building motor table (Service Station)
- 15k-40k sf Retail building motor response (Strip Mall)
- 40k-100k sf Retail building Motor Response (big box Stores)
- Warehouse

# Building and Load Characteristics

- Larger, high rise office buildings usually have an EMS. EMS typically consists of a central computer and field controllers which have EPROM memory. The field modules control relays which control contactors.
- Testing at BPA has shown that the EMS can ride though severe voltage sags down to 65% of nominal voltage. Testing has shown even though the EMS can ride through voltage transients below 65% of nominal voltage, the EMS will drop out 2 seconds after the event and then takes 3 seconds to reset.
- Roof top units have motor contactors drop out at 50 to 60% voltage, which is higher than the stall voltage of about 50%. Thus it is unlikely that the three phase motors will be stalling during transients, unlike the single phase compressor motors.

# Sample Table (Office Building Load Square Feet 100,000 to 1,000,000 Voltages between 75% and 50% of nominal)

| Equipment | Motors | Protection | Controls | 5 cycle | 10 cycle | 20 cycle | 2 second | 3 minutes |
|---|---|---|---|---|---|---|---|---|
| **AHUs** | 3-ph Fan Motors | Over voltage, Phase Imbalance, over current | EMS with VFD | EMS remains in control | EMS & VFD operate through event then drops out 2 seconds after event below 65% V but will automatically restart. First fan starts within 5 seconds 2nd fan if applicable re-starts at 30sec | | | |
| **Fan Powered VAVs** | 1-ph Fractional Fan Motors | Fuse & Thermal | EMS with Contactor | EMS remains in control contactor drops out at 50% V and re-energizes after 1 to 8 cycles after event | EMS drops out 2 seconds after event below 65% V but will automatically restart. fan starts within 5 seconds<br><br>Contactors operate through voltage variance but drop out when EMS drops offline 2 seconds after event. Or if the voltage dips below 50% V the contactor will drop and re-energizes 1 to 8 cycles after event. And then drop out again when the EMS drops 2 seconds later.<br><br>Possible thermal trip if the voltage variance is longer than 4-5 seconds and above 65%V | | | |

| | | | | | |
|---|---|---|---|---|---|
| **(DOAS) Dedicated Outside Air System** | **3-ph Fan Motors** | **Over voltage, Phase Imbalance, over current** | **EMS with VFD** | **EMS remains in control** | **EMS & VFD operate through event then drops out 2 seconds after event below 65% V but will automatically restart. First fan starts within 5 seconds 2nd fan if applicable re-starts at 30sec** |
| **Chillers** | 3-ph Compressor Motors | Over voltage, Phase Imbalance, over current | Manufacturer Solid-state Controller tied into EMS | Control Board remains in control contactor drops out at 50% V and re-energizes after 1 to 8 cycles after event | Manufacturer Solid-state Control Board drops out below 65% V but will automatically restart. 300-500sec First Chiller 600sec interstaging delay for each additional chiller if applicable |
| | 3-ph Pump Motors | Over voltage, Phase Imbalance, over current | EMS with VFD | EMS & VFD remains in control | EMS & VFD operate through event then drops out 2 seconds after event below 65% V but will automatically restart. Pump soft starts within 90 seconds |

| Equipment | Motors | Protection | Controls | 5 cycle | 10 cycle | 20 cycle | 2 second | |
|---|---|---|---|---|---|---|---|---|
| Boilers | 1-ph Induced Draft Motor | Fuse & Thermal | Manufacturer Solid-state with contactor, EMS | Control Board remains in control contactor drops out at 50% V and re-energizes after 1 to 8 cycles after event | Manufacturer Solid-state Control Board drops out below 65% V but will automatically restart. 120sec First Boiler 240sec interstaging delay for each additional boiler if applicable<br><br>Possible thermal trip if the voltage variance is long enough and above 50% for 2-3 seconds | | | |
| | 3-ph Motors | Over voltage, Phase Imbalance, over current, & current limiting | EMS with VFD | EMS & VFD remains in control | EMS & VFD operate through event then drops out 2 seconds after event below 65% V but will automatically restart. Pump starts within 90 seconds | | | |
| Cooling Towers | 3-ph Fan Motor | Over voltage, Phase Imbalance, over current, & current limiting | EMS with VFD | EMS & VFD remains in control | EMS & VFD operate through event then drops out 2 seconds after event below 65% V but will automatically restart. First fan starts within 5 seconds 2nd fan if applicable re-starts at 30sec | | | |

# Conclusions

- We have developed a set of load response tables for a range of commercial building types.
- We provide both the "drop out" and recovery characteristic for typical motor loads, for the voltage dips and times of interest, including both protection and control components.
- This is a "next step" in better understanding of commercial building load response to voltage transients.
- http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24468.pdf
- fidvr.lbl.gov

# Additional Info Slides

## VFDs

- Variable Frequency Drives are typically programmed to ride through short duration voltage sags by current limiting the motor.  In cases where only one phase is sagging, and the motor is being operated at partial load, the motor can run for several seconds or more, depending on motor load.
- For 60% voltage and 5, 10 and 20 cycles, the VFD should be able to ride through by current limiting the motor. Depending on motor load, the VFD typically cannot ride through a 2 second or 3 minute loss of voltage unless it is equipped with energy storage.
- In testing, VFDs were noted to ride through sags of up to 2 seconds, or more, in duration, then trip after voltage recovery.

# Additional Info - Chiller Motors

- Large chiller motors in the range of 100 to 700 HP typically have their own proprietary local control board with voltage, overcurrent and unbalance protection.
- Manufacturer under voltage protection is typically set at 80% of nominal voltage for 2 seconds and 60% of nominal voltage for 0.1 seconds.
- If the motor is de-energized on under voltage, it will not restart for 4 to 10 minutes.

# Energy Management System

- The EMS typically consists of a central computer and field controllers which have EPROM memory. The field modules control relays which control contactors.
- Testing at BPA has shown that the EMS can ride though severe voltage sags down to 65% of nominal voltage. Testing has shown even though the EMS can ride through voltage transients below 65% of nominal voltage, the EMS will drop out 2 seconds after the event and then takes 3 seconds to reset.
- It is assumed for the tables that for voltage sag down to 65% of nominal, that the EMS rides through. For sags below 65%, the EMS will drop out the load and then reset by initiating the programed sequences in the controller from the beginning. Some loads and motors will be started relatively quickly while others may take several minutes to reengage the loads.
- Testing performed revealed that the EMS controllers tripped less at voltages above 60% when the control transformer secondary supplying power to the controller was under 50% of its max VA capacity.
- In general, testing showed that voltages variances below 60% resulted in the EMS controller resetting regardless of transformer loading.

# Contactors

- Contactors, in general, will drop out within 5 cycles at 50% voltage. In some cases, voltage may sag to 40% before the contactor drops, and in some cases, it may be 60%, but 50% is a good estimate.
- When the voltage recovers, at 70% of nominal voltage the BPA tests shows contactor reclosed after two cycles. At 65% it took 8.5 cycles to reclose. At 62% it never pulled in, even after multiple seconds.

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# A Look into Load Modeling: The Composite Load Model

Dynamic Load Modeling & FIDVR Workshop

September 30, 2015

Ryan D. Quint, *North American Electric Reliability Corporation*

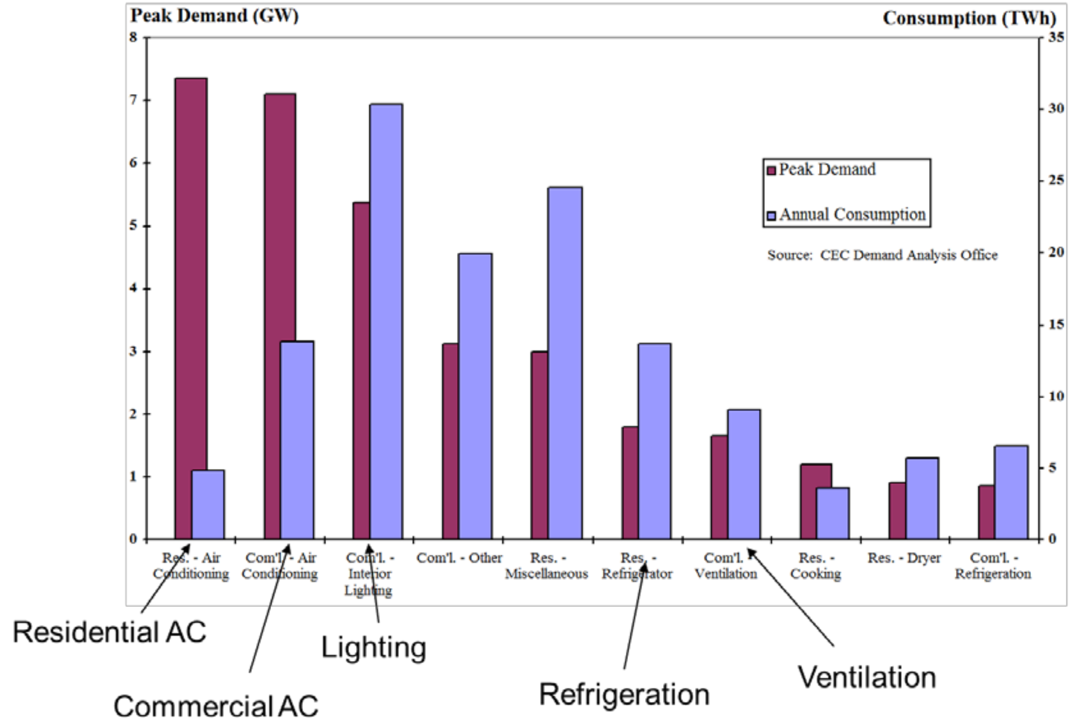
RELIABILITY | ACCOUNTABILITY




# Let's Talk Loads

- Landscape
- Brief History
- Today's State of the Art
- Putting Context to the Comp Load Model
- A Look at Some Key Parameters
- Where We Are & Where We're Going

*Summer peak vs. annual consumption in California*



# Our System Load

*Resistive Cooking*
*Resistive Heating*

*Incandescent Lighting*

*Power Electronics*

*Distributed Generation*

*AC and Heat Pumps*

*Data Centers*

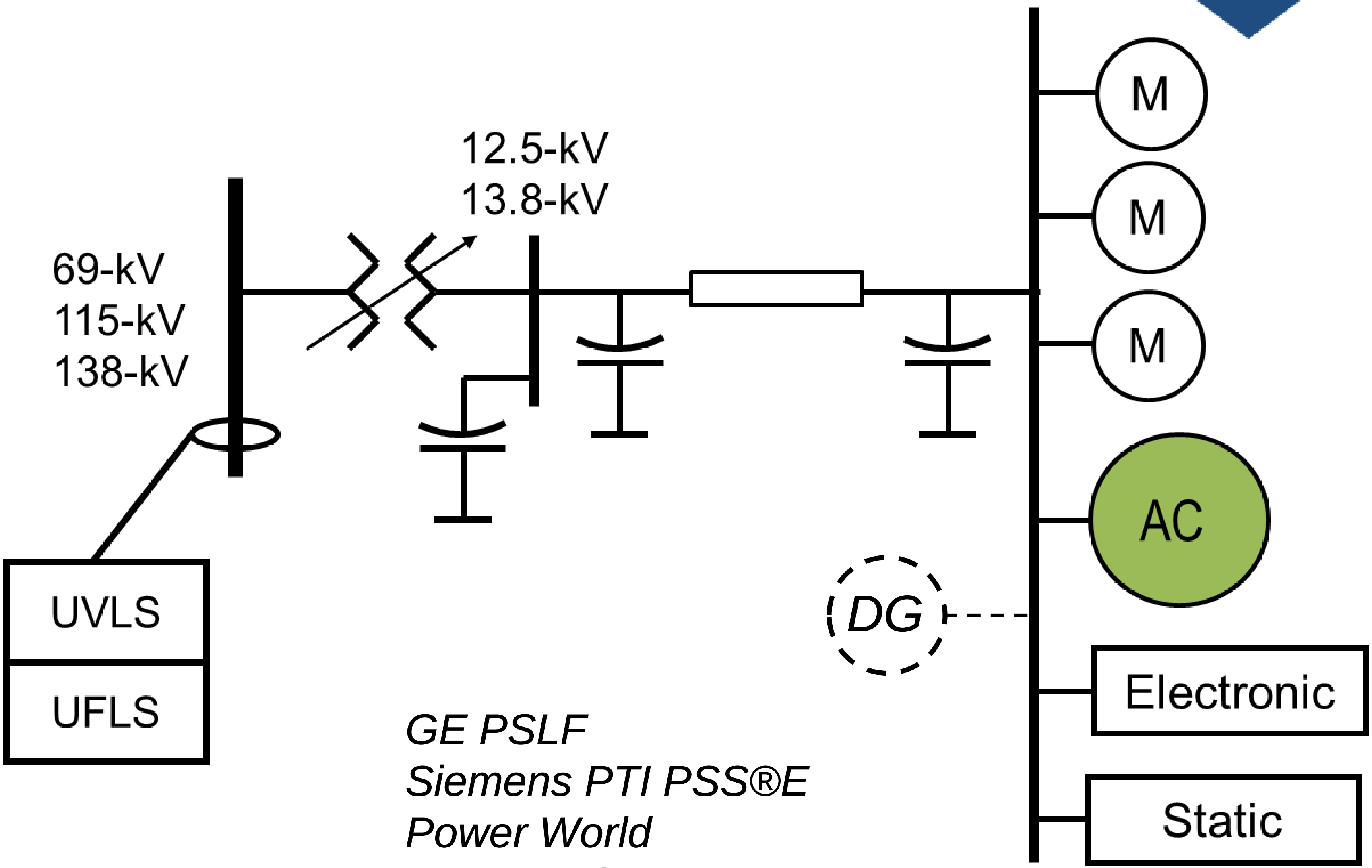
*Electric Vehicles*

*Share of total system load*

# PTI PSS®E & GE PSLF Load Models

| PSS®E Load Models | PSLF Load Models |
|---|---|
| CIM5 – Induction Motor Load | alwscc (b,w,z) – Load Voltage/Frequency Dependence Model |
| CIM6 – Induction Motor Load (WECC) | seccld1 (2,3) – Secondary Load Model with Tap Ration Reset |
| CIMW – Induction Motor Load | apfl (spfl) – Pump/Fan Driven Induction (Synchronous) Motor Load |
| CLOD – Complex Load Model | motorw/x – Single or Double Cage Induction Motor Model |
| EXTL – Extended-Term Reset Load | Ld1pac – Performance-based Model of Single Phase Air Conditioner |
| IEEL – IEEE Load Model | motorc – Phasor Model of Single Phase Air Conditioner |
| LDFR – Load Frequency Model | ldelec (rect) – Electronic (Rectifier) Load |
| ACMT – Single-Phase Air Conditioner | |

# The CMLD (CMPLDW) Model



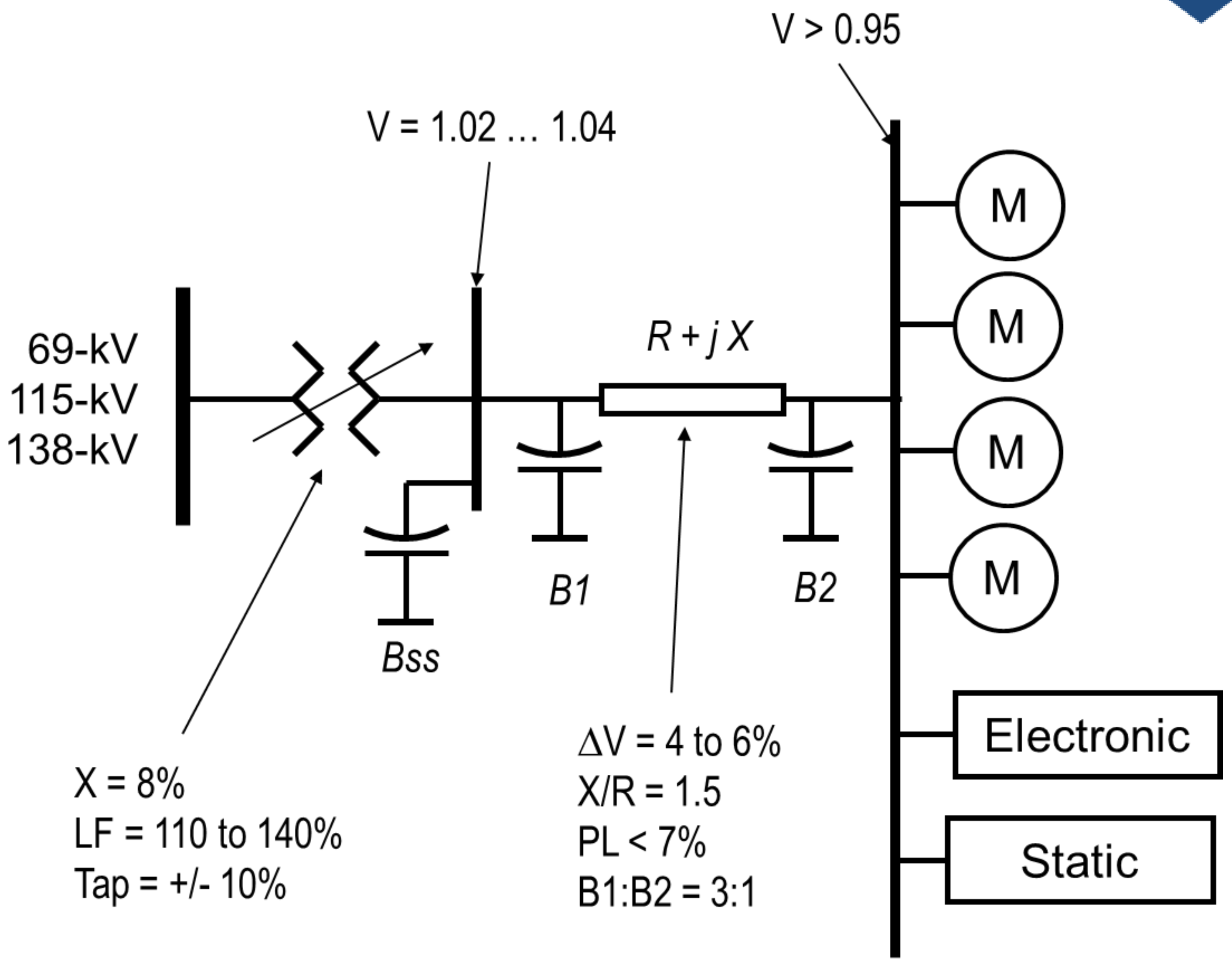

*GE PSLF*
*Siemens PTI PSS®E*
*Power World*
*PowerTech TSAT*

# CMPLDW / CMLD Debunked

- Let us break down the 130+ parameters, contextualize their meaning; begins to come together cohesively.

```
"Bss"    0 "Rfdr" 0.04 "Xfdr" 0.04 "Fb" 0.75/
"Xxf" 0.08 "TfixHS" 1 "TfixLS" 1 "LTC" 0  "Tmin"   0.9 "Tmax" 1.1 "step" 0.00625 /
"Vmin"   1.025 "Vmax" 1.04 "Tdel" 30  "Ttap"   5 "Rcomp" 0 "Xcomp" 0 /
"Fma"    0.239538 "Fmb" 0.156309 "Fmc" 0.064766 "Fmd"   0.206375 "Fel"   0.116908  /
"PFel" 1 "Vd1" 0.7 "Vd2" 0.5 "Frcel" 0.8 /
"Pfs"    -0.994504 "P1e" 2 "P1c" 0.295212 "P2e" 1 "P2c"   0.704788 "Pfreq" 0 /
         "Q1e" 2 "Q1c" -0.5 "Q2e" 1 "Q2c"   1.5 "Qfreq" -1 /
"MtpA" 3  "MtpB" 3  "MtpC" 3  "MtpD" 1 /
"LfmA" 0.75 "RsA" 0.04 "LsA" 1.8 "LpA" 0.12 "LppA"   0.104 /
 "TpoA" 0.095 "TppoA" 0.0021 "HA"   0.1 "etrqA" 0 /
 "Vtr1A" 0.7 "Ttr1A" 0.02  "Ftr1A" 0.2 "Vrc1A" 1 "Trc1A" 99999 /
 "Vtr2A" 0.5 "Ttr2A" 0.02  "Ftr2A" 0.7 "Vrc2A" 0.7 "Trc2A" 0.1 /
"LfmB" 0.75 "RsB" 0.03 "LsB" 1.8 "LpB" 0.19 "LppB"   0.14 /
 "TpoB" 0.2 "TppoB" 0.0026 "HB"   0.5 "etrqB" 2 /
"Vtr1B" 0.6 "Ttr1B" 0.02  "Ftr1B" 0.2 "Vrc1B" 0.75 "Trc1B" 0.05 /
"Vtr2B" 0.5 "Ttr2B" 0.02  "Ftr2B" 0.3 "Vrc2B" 0.65 "Trc2B" 0.05 /
"LfmC" 0.75 "RsC" 0.03 "LsC" 1.8 "LpC" 0.19 "LppC"   0.14 /
"TpoC" 0.2 "TppoC" 0.0026 "HC"   0.1 "etrqC" 2 /
 "Vtr1C" 0.65 "Ttr1C" 0.02 "Ftr1C" 0.2 "Vrc1C" 1 "Trc1C" 9999 /
 "Vtr2C" 0.5 "Ttr2C" 0.02 "Ftr2C" 0.3 "Vrc2C" 0.65 "Trc2C" 0.1 /
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

# The Distribution Equivalent Circuit



# Motor A – Small Commercial

- Represents 3-phase compressor motors in commercial cooling and refrigeration systems
  - Typical of rooftop A/C – Walmart, Whole Foods, Malls, etc.
- Model data representative of 5-15 HP compressor motors
  - Special design motors (not NEMA)
  - Stall at about 40% voltage, restart at about 50-60% voltage
  - Constant torque load (on average)
  - Low inertia
- Motor protection & control:
  - Contactors trip when supply voltage drops to about 40% voltage, reclose at 45-55% voltage
  - Building EMS – no apparent reason to keep equipment out of service

*Roof-Top Direct Expansion HVAC*
*10-25 hp compressor motors*

# Motor A – Large Commercial

- Large commercial buildings have central cooling systems
- Chiller compressors are large motors 200-500 HP
- Motor protection & control:
  - Chillers are sensitive equipment
  - Once tripped, probably require manual restart


*Central Cooling System*
*Chiller 200-250 hp compressors*

# Motor A Model Data

- High initial torque motor
- H = 0.1 sec
- Constant torque load
- 70% of motors trip at 50% voltage, restart at 70% voltage (representing 10-25 HP motors)
- 20% of motors trip at 70% voltage, remain disconnected (representing large chillers)

# Motor B

- Represents fan motors used in residential and commercial buildings
  - Ventilation fans in buildings, air-handler fans
- Model data is representative of 5-25 HP fan motors
  - Usually NEMA B design motors
  - Torque load proportional to speed squared
  - High inertia (0.25 to 1 seconds)
- Motor protection and control:
  - Contactors trip:  ~ 40% voltage;  Reclose:  ~ 45-55% voltage
  - Building EMS – no apparent reason to keep equipment out of service
- Current trend:  Fan motors are being replaced with Electronically Commutated Motors (ECMs)
  - Energy Efficiency Upgrade – DC motors, controllable speed
- Stall at very low voltages

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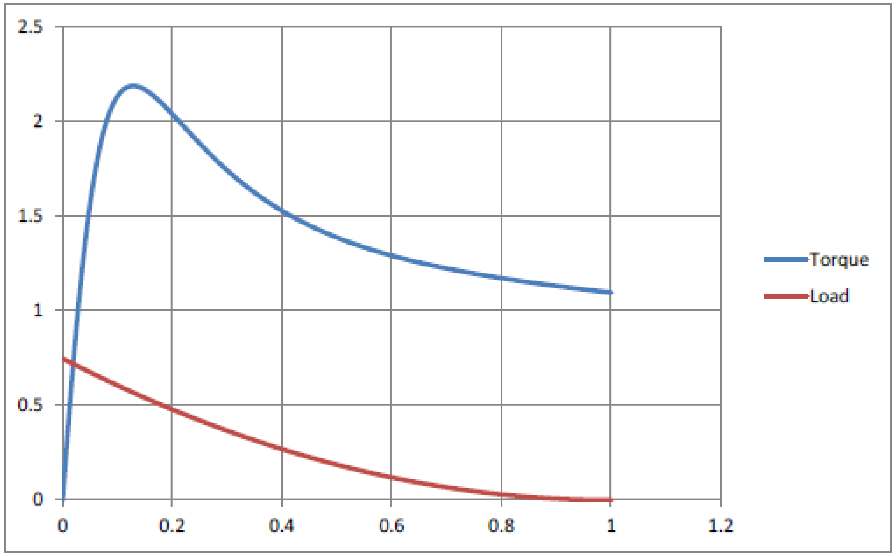
# Motor C

- Represents direct-connected pump motors used in commercial buildings
  - Water circulating pumps in central cooling systems
- Same as Motor B, but with low inertia
- Model data is representative of a 5-25 HP pump motor
  - Usually NEMA B design motors
  - Torque load proportional to speed squared
  - Lower inertia (0.1 to 0.2 seconds)
- Motor protection and control:
  - Contactors trip: ~ 40% voltage; Reclose: ~ 45-55% voltage
  - Building EMS – no apparent reason to keep equipment out of service
- Current trend: Pump motors are being replaced with Variable Frequency Drives (VFDs)
  - EE Upgrade – AC motors, controllable speed

# Motor B and C Model Data

- NEMA B Design Motor
- H = 0.5 sec for fan, H = 0.1 sec for pump
- Load torque proportional to speed squared

| | |
|---|---|
| L | 1.80 |
| L' | 0.19 |
| L" | 0.15 |
| T' | 0.19 |
| T" | 0.0026 |
| D | 2 |
| H (fan) | 0.5 |
| H (pump) | 0.15 |



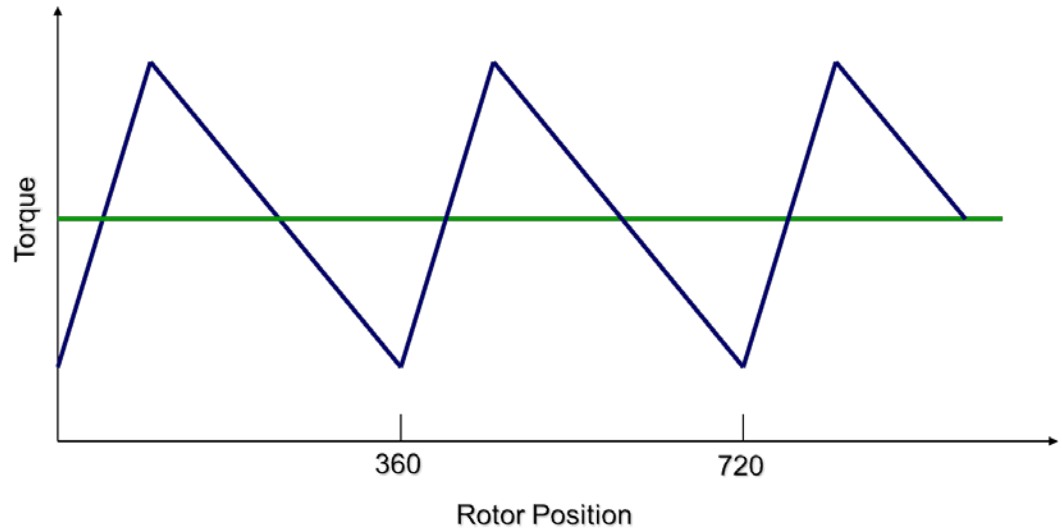
# Motor D – Residential Air Conditioner

# Motor D

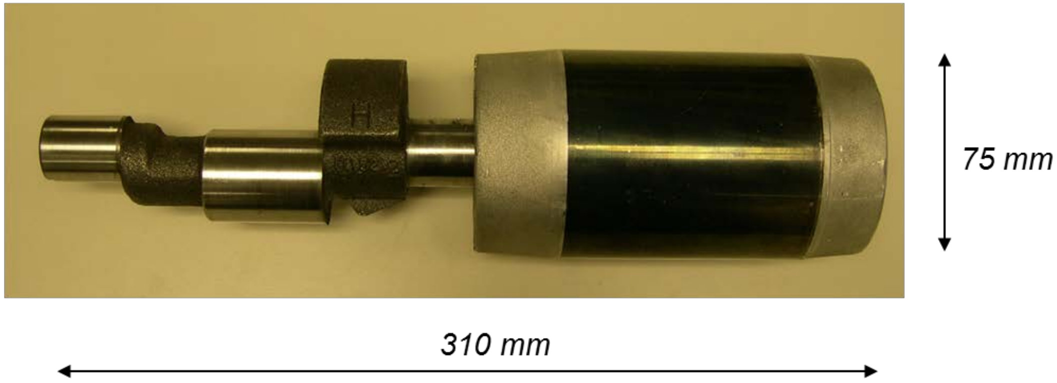
- Single-phase compressor motors in residential and small commercial cooling and refrigeration
- Model data representative of 3-5 HP compressor motors
  - Special design motors (not NEMA)
  - Stall at about 45-60% voltage
  - Constant torque load (on average)
  - Low inertia
- Motor protection and control:
  - Contactors trip: ~ 40-50% voltage; Reclose: ~ 45-55% voltage

# Motor D – Performance

- Compressor Load Torque is very cyclical
- Very possible that motor stalls on next compression cycle




*E.g. 3.5-ton compressor motor:* *Weight: 4.6 kg*




- Compressor Motor Inertia is very low
  - H = 0.03 – 0.05 sec
- Physically small

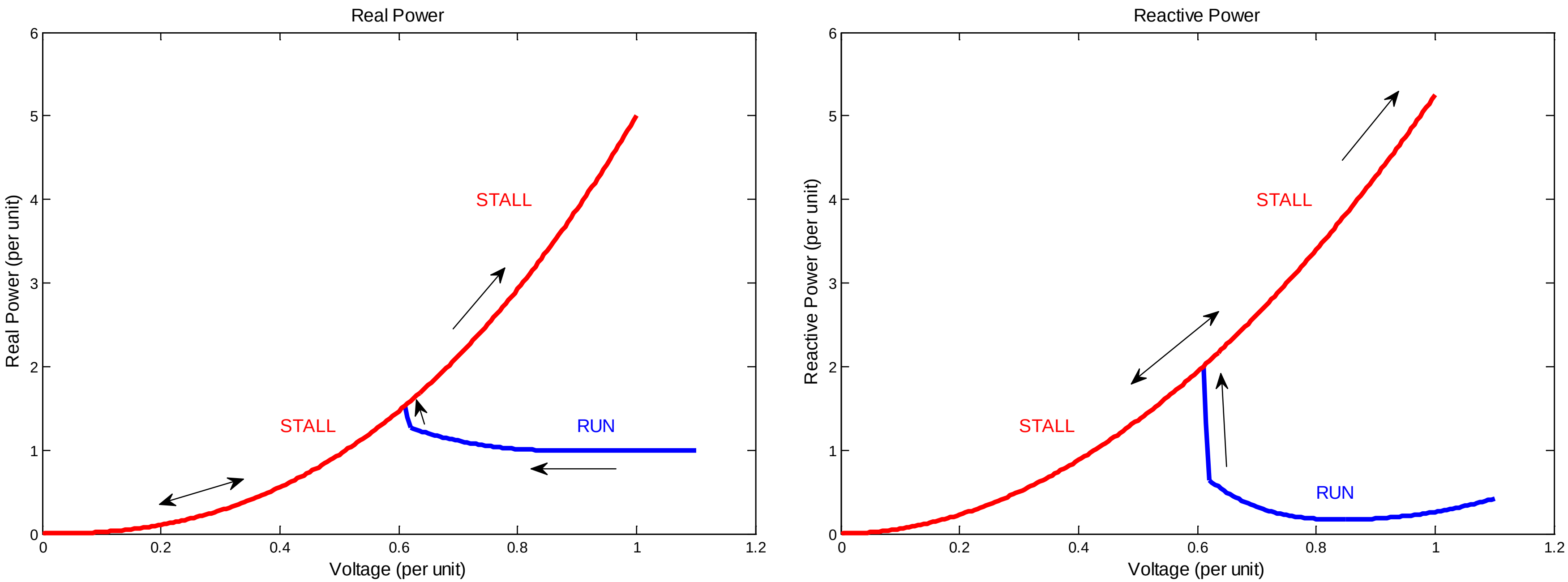
# Motor D Model Representation

- Three-phase motor models cannot represent behavior of single-phase motors with the same datasets
  - Stalling phenomena – 3-phase motors usually stall at much lower voltages
  - P and Q consumption during stalling

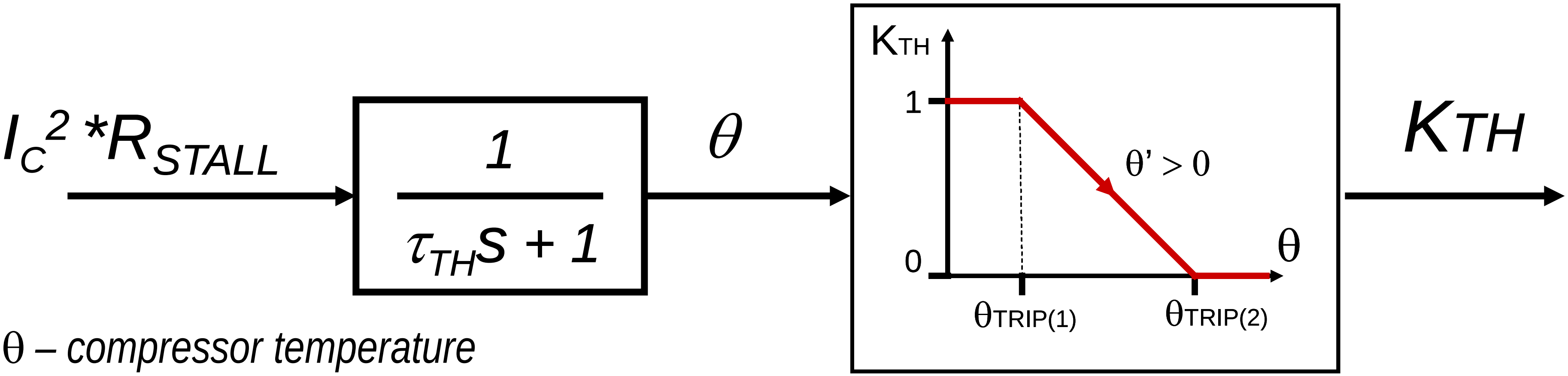
- Single-phase models exist, but not in positive sequence models
  - Research is looking into sensitivities of single-phase motors
    - Point-on-wave
    - Electrical impedance
    - Voltage rate-of-change
    - Voltage and duration

# Motor D Performance Model

- Motors stall when voltage drops below Vstall for duration Tstall
- Fraction Frst of aggregate motor can restart when voltage exceeds Vrst for duration Trst

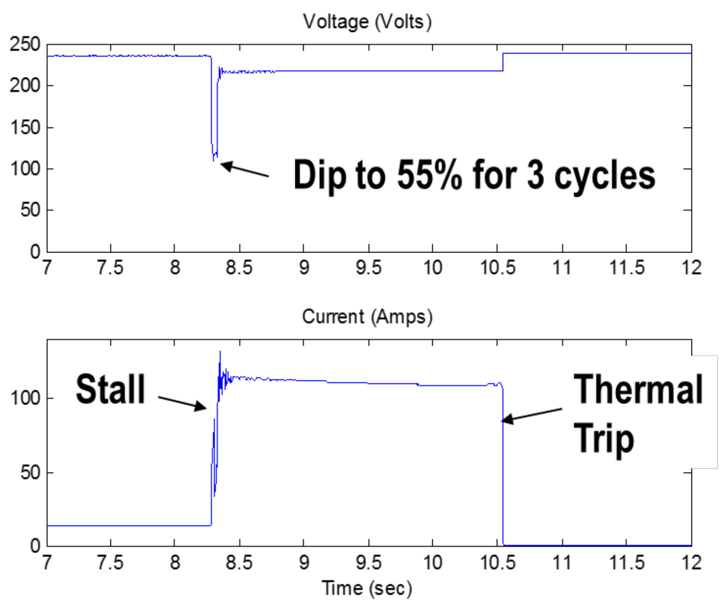


# Thermal Relay Model




$\theta$ – *compressor temperature*

$K_{TH}$ – *fraction of motors that remain connected*




- Thermal trip constant varies by manufacturer, protection requirements
- Thermal relay model accounts for this in linear tripping mechanism

# Motor D

- Electrical response is represented with performance model
  - "Run" and "stall" states based on Vstall and Tstall
  - Fraction of motors allowed to restart (usually scroll compressors)
  - Manufacturers believe scroll-type represents 10-20% of A/C motors
- Thermal protection
  - $I^2t$ characteristic used – a range is used to capture diverse settings
- Contactors
  - Load reduced linearly at 40-50% voltage, reconnect at 50-60% voltage
- Energy Efficiency standards driving greater penetration of scroll compressors – higher efficiency
  - SEER 12 very hard to meet with reciprocating units
- Newer A/C units have power-electronic VFDs – generally smaller ones popular in Europe/Japan for single-room cooling

# Closing Remarks

- The CMPLDW/CMLD model is NOT the “WECC” Model
  - It is generic, and can be used across the interconnections
  - Can provide detailed representation of dynamic load behavior, including induction motor loads
  - Advancements in model structure greatly simplify utilization
  - Must perform sensitivity studies to better understand model parameter impacts on performance
  - Can disable A/C motor stalling by setting Tstall to 9999 (WECC Phase 1)
    - More work to understand software implementation of this
  - Tools available to generate load model records effectively
- These types of models will never capture the level of accuracy of generator modeling.  But they’re a big step in the right direction.
  - Can be tuned to accurately reproduce and explain historical events
  - Seek to predict future events ***in principle***, not in full fidelity

# Questions and Answers

# Appendix: Supplemental Material

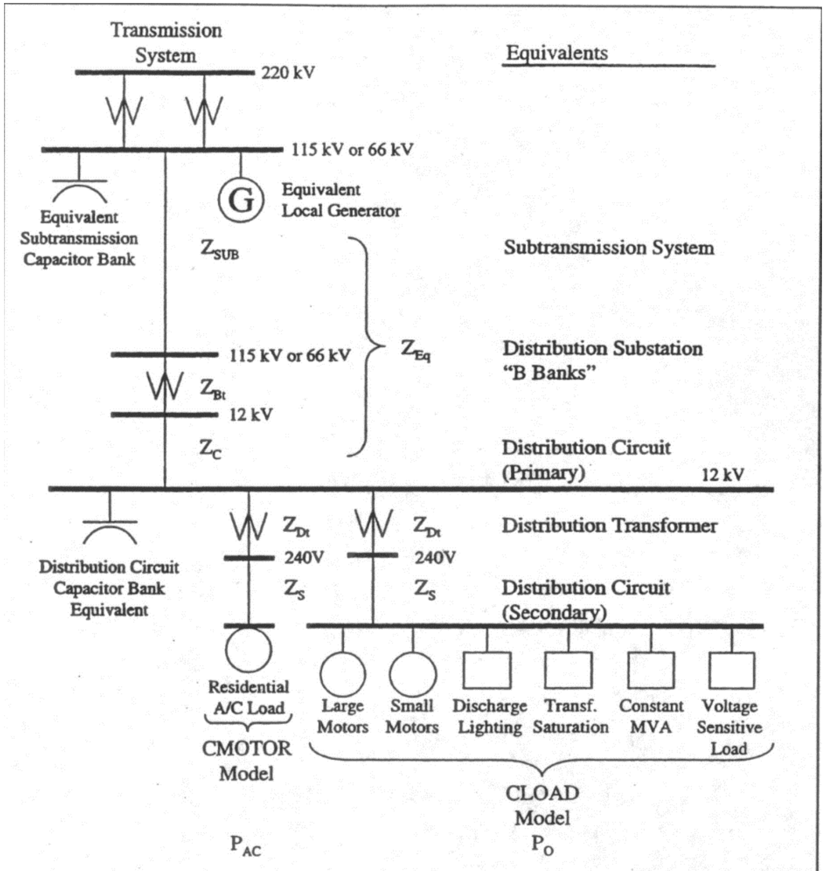
# History of Load Modeling (in WECC)

- 1980s: Constant current real, constant impedance reactive models connected at transmission-level bus
  - ***Limitation of computing technology for that time***
- 1990s: EPRI Loadsyn (static polynomial characteristic to represent load), IEEE Task Force recommends dynamic load modeling
  - ***Failed to get much traction in industry***
- 1996: BPA model validation study for August 10 1996 outage
  - ***Demonstrated need for motor load representation*** in dynamic load models to capture oscillations and voltage instability

# History of Load Modeling (in WECC)

- 2000-2001 – WECC "Interim" Load Model
  - 20% induction motor, remaining static load
  - Was only practical option in 2001
  - Intended as a temporary 'fix' to model oscillatory behavior observed at the California-Oregon Intertie (COI)
  - Model limitations were recognized and need for a better model was clear
  - ***Model was used for 10+ years to plan and operate the Western Interconnection***
  - ***…Many utilities are choosing to use the CLOD model, which is similar to this approach from 2001…!***

# SCE's Observations and Modeling




*Model was used in Southern California for special studies using PTI PSS®E simulator*

- Late 1980s – Southern California Edison observes delayed voltage recovery events, attributed to stalling of residential air conditioners
  - Tested residential A/C units in laboratory, developed empirical AC models
- 1997 – SCE model validation effort of Lugo event
  - ***Illustrated need to represent distribution equivalent***
  - ***Illustrated need to have special models for air conditioning load***

# The East Joins the Party

- 1994 – Florida Power published an IEEE paper, using a similar load model
- 1998 – Delayed voltage recovery event in Atlanta area in Southern Company territory
  - Events were observed, analyzed, modeled, and benchmarked to recreate event
- FPL and Southern Co. used, in principle, similar approaches to SCE and the eventual WECC model

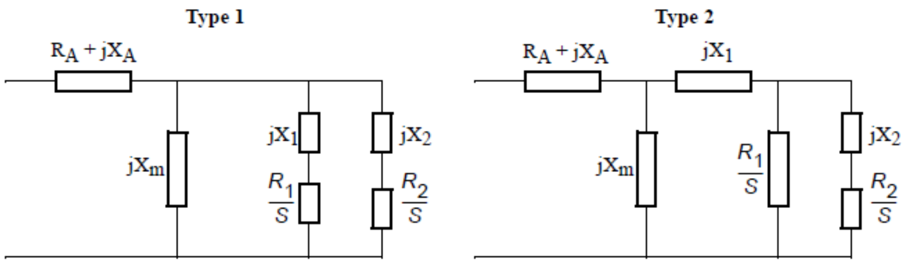
- *These models were used for special studies of local areas, but beginning to get traction*

# WECC Load Modeling Task Force

- 2005 – WECC developed ‘explicit’ model
  - Included distribution equivalent, induction motor and static loads
  - Numerical stability in Interconnection-wide study
    - ***This was a big step 10 years ago. Still unavailable in the East.***
- 2007 – First version of the composite load model in PSLF
  - Three phase motor models only, no single phase represented
- 2006-2009 – EPRI/BPA/SCE testing of residential air conditioners and development of models
- 2009 – 1ϕ air conditioner model added to composite load model
- 2011 – WECC adopts phased approach for composite load model, starts system impact studies
- 2013 – TPL-001-4 requires modeling induction motor load
- 2013-Current – WECC approved use of Phase I composite load models for planning and operational studies

# PTI PSS®E Load Models

- **CIM5 – Induction Motor Load Model**
  - Load Torque represented by $T_{LOAD} = T_{NOM}(1 + n)^D$
  - Single- or double-cage induction motors, including rotor flux dynamics
  - Captures motor start-up



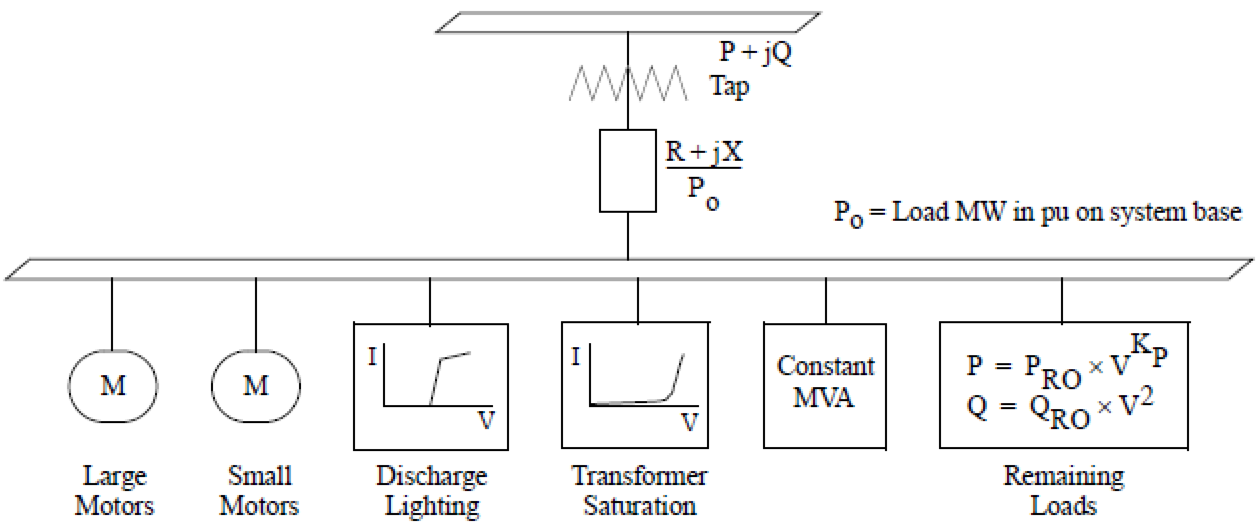

- **CIMW – Induction Motor Load Model (WECC)**
  - Motor load including electromagnetic dynamics (single- or double cage)
  - Load Torque represented by $T_{LOAD} = T_0(A\omega^2 + B\omega + C_0 + D\omega^e)$
- **CIM6 – Induction Motor Load Model**
  - Detailed load torque representation of CIMW
  - Motor starting capability of CIM5



*PSS®E Model Library, Version 32.0.5, Revised October 2010.*

# PTI PSS®E Load Models

- **CLOD – Complex Load Model**
  - Distribution (transformer & circuit) impedance
  - Large & Small 3-ϕ induction motors
  - Discharge lighting
  - Transformer saturation
  - Assumed 0.98 pu loads – tap calculation to obtain V at load bus




*PSS®E Model Library, Version 32.0.5, Revised October 2010.*

# PTI PSS®E Load Models

- **EXTL – Extended-Term Load Reset Model**
  - Simulates general effects of loads being reset to constant MWMVAR in steady-state without specifically modeling equipment (taps, caps, etc.)
- **IEEL – IEEE Load Model**
  - Algebraic representation of load

$$P = P_{load}\left(a_1 v^{n_1} + a_2 v^{n_2} + a_3 v^{n_3}\right)(1 + a_7 \Delta f)$$

$$Q = Q_{load}\left(a_4 v^{n_4} + a_5 v^{n_5} + a_6 v^{n_6}\right)(1 + a_8 \Delta f)$$

- **LDFR – Load Frequency Model**
  - Constant P and constant I components sensitive to system frequency

$$P = P_o\left(\frac{\omega}{\omega_o}\right)^m$$

$$Q = Q_o\left(\frac{\omega}{\omega_o}\right)^n$$

$$I_p = I_{po}\left(\frac{\omega}{\omega_o}\right)^r$$

$$I_q = I_{qo}\left(\frac{\omega}{\omega_o}\right)^s$$

- **ACMT – Single-Phase Air Conditioner Motor Model**
  - Aggregate representation of single-phase A/C load
    - Compressor motor, thermal relay, U/V relays, contactors
  - Representation based on “*Performance Model for Representing Single-Phase Air-Conditioner Compressor Motors in Power System Studies*” developed by WECC Load Model Task Force (LMTF)
  - This is the 1-ϕ A/C motor representation in the CMLD model

PSS®E Model Library, Version 32.0.5, Revised October 2010.

# GE PSLF Load Models

- **Aggregate Load**
  - alwscc (b,w,z) – Load Voltage/Frequency Dependence Model
  - Secld1(2,3) – Secondary Load Model with Reset of Tap Ratio
- **Induction Motor Load**
  - apfl (spfl) – Pump/Fan Driven Induction (Synchronous) Motor Load Model
  - motorw/x – Single or Double Cage Induction Motor Model
- **Single-phase Air Conditioner Load**
  - Ld1pac – Performance-based Model of 1-ϕ Air Conditioner Load
  - motorc – Phasor Model of 1-ϕ Air Conditioner Load
- **Other Loads**
  - Ldelec (rect) – Electronic (Rectifier) Load Model

*PSLF, PSLF User's Manual, Version 19.0_01, Revised July 2015.*

# Substation & Feeder Parameters

```
"Bss"    0 "Rfdr" 0.04 "Xfdr" 0.04 "Fb" 0.75/
"Xxf" 0.08 "TfixHS" 1 "TfixLS" 1 "LTC" 0  "Tmin"   0.9 "Tmax" 1.1 "step" 0.00625 /
"Vmin"   1.025 "Vmax" 1.04 "Tdel" 30  "Ttap"   5 "Rcomp" 0 "Xcomp" 0 /
```

| Parameter | Default | Reason |
|---|---|---|
| Load MVA Base | -1.0 to -1.25 | If (-), MVA base = Load MW/Value Specified |
| Bss | 0.0 | Assumed no shunt compensation at bus |
| Rfdr | 0.04 | 4% impedance on load MVA base;<br>1:1 distribution feeder impedance X:R ratio |
| Xfdr | 0.04 | |
| Fb | 0.0 | No shunt compensation, so N/A |
| Xxf | 0.08 | 8% impedance on load MVA base |
| TfixHS | 1.0 | Assumed 1:1 T:D transformer turns ratio |
| TfixLS | 1.0 | |

# T:D Transformer Parameters

```
"Bss"   0 "Rfdr" 0.04 "Xfdr" 0.04 "Fb" 0.75/
"Xxf" 0.08 "TfixHS" 1 "TfixLS" 1 "LTC" 0  "Tmin"   0.9 "Tmax" 1.1 "step" 0.00625 /
"Vmin"   1.025 "Vmax" 1.04 "Tdel" 30  "Ttap"   5 "Rcomp" 0 "Xcomp" 0 /
```

| Parameter | Default | Reason |
|---|---|---|
| LTC | 1 or 0 | Based on whether LTC action enabled |
| Tmin | 0.9 | Based on common ULTC configuration:<br>• 32 steps<br>• +/- 0.1 tap<br>• +/- 1.25% voltage operation bounds |
| Tmax | 1.1 | |
| step | 0.00625 | |
| Vmin | 0.9875 | |
| Vmax | 1.0125 | |
| Tdel | 30-75 | Depends on utility practice for LTC action delay |
| Ttap | 5 | Time duration of LTC adjustment, commonly 5 seconds |
| Rcomp | 0 | Resistance and reactance compensation for LTC; Generally no considered |
| Xcomp | 0 | |

# Load Composition Parameters

```
"Fma"   0.239538 "Fmb" 0.156309 "Fmc" 0.064766 "Fmd"   0.206375 "Fel"   0.116908  /
```

| Parameter | Default | Reason |
|---|---|---|
| Fma | Varies | These parameters are solely dependent on the load composition at the given bus. Many utilities use zonal or regional data when bus-level or feeder-level data is not available. Exact values depend on many factors – season, regional economies, industries, load type, etc. For example, heavy summer case parameters could = A: 25%, B: 15%, C: 5%, D: 15%, PE: 10%. But this is solely dependent on the load composition at the bus. |
| Fmb | Varies | |
| Fmc | Varies | |
| Fmd | Varies | |
| Fel | Varies | |

# Power Electronic Load Parameters

```
"PFel" 1 "Vd1" 0.7 "Vd2" 0.5 "Frcel" 0.8 /
```

| Parameter | Default | Reason |
|---|---|---|
| Pfel | 1.0 | Assumed power electronic load at unity power factor |
| Vd1 | 0.7 | Assume electronic load starts tripping at 70% voltage |
| Vd2 | 0.5 | Assume all electronic load is tripped by 50% voltage |
| Frcel | 0.8 | Assumed 80% of electronic load will automatically reconnect upon acceptable voltage return |

# Static Real Load Parameters

```
"Pfs"    -0.994504 "P1e" 2 "P1c" 0.295212 "P2e" 1 "P2c"   0.704788 "Pfreq" 0 /
          "Q1e" 2 "Q1c" -0.5 "Q2e" 1 "Q2c"   1.5 "Qfreq" -1 /
```

| Parameter | Default | Reason |
| --- | --- | --- |
| Pfs | -0.995 | Rather than specify shunt compensation, assume slight capacitive power factor for static load to account for shunt compensation at substation and on feeder |
| P1e | 2.0 | $P=P_0*(P_{1c}*V/V_0^{P1e} + P_{2c}*V/V_0^{P2e} + P_3) * (1 + P_{frq} * D_f)$ Assume one component varies with square of voltage; 50% remaining static load assigned to this component |
| P1c | 0.5 | |
| P2e | 1.0 | $P=P_0*(P_{1c}*V/V_0^{P1e} + P_{2c}*V/V_0^{P2e} + P_3) * (1 + P_{frq} * D_f)$ Assume one component varies linearly with voltage; 50% remaining static load assigned to this component |
| P2c | 0.5 | |
| Pfreq | 0.0 | Assume real power not frequency dependent |

# Static Reactive Load Parameters

```
"Pfs"   -0.994504 "P1e" 2 "P1c" 0.295212 "P2e" 1 "P2c"   0.704788 "Pfreq" 0 /
         "Q1e" 2 "Q1c" -0.5 "Q2e" 1 "Q2c"   1.5 "Qfreq" -1 /
```

| Parameter | Default | Reason |
|---|---|---|
| Q1e | 2.0 | $Q=Q_0*(Q_{1c}*V/V_0^{Q1e} + Q_{2c}*V/V_0^{Q2e} + Q_3) * (1 + Q_{frq} * D_f)$<br>Assume one component varies with square of voltage; 50% remaining static load assigned to this component; Inversely related to voltage relationship |
| Q1c | -0.5 | |
| Q2e | 1.0 | $Q=Q_0*(Q_{1c}*V/V_0^{Q1e} + Q_{2c}*V/V_0^{Q2e} + Q_3) * (1 + Q_{frq} * D_f)$<br>Assume one component varies linearly with voltage. |
| Q2c | 1.5 | |
| Qfreq | -1.0 | Assume Q inversely frequency dependent |

# Motor Type Definition Parameters

```
"MtpA" 3  "MtpB" 3  "MtpC" 3  "MtpD" 1 /
```

| Parameter | Default | Reason |
|---|---|---|
| MtpA | 3 | Constant torque loads (e.g. commercial air conditioners and refrigerators) |
| MtpB | 3 | Torque speed squared loads with high inertia (fans) |
| MtpC | 3 | Torque speed squared loads with low inertia (pumps) |
| MtpD | 1 | Single-phase induction motors (residential A/C) |

# Motor A Model Parameters

```
"LfmA" 0.75 "RsA" 0.04 "LsA" 1.8 "LpA" 0.12 "LppA"   0.104 /
 "TpoA" 0.095 "TppoA" 0.0021 "HA"   0.1 "etrqA" 0 /
 "Vtr1A" 0.7 "Ttr1A" 0.02  "Ftr1A" 0.2 "Vrc1A" 1 "Trc1A" 99999 /
 "Vtr2A" 0.5 "Ttr2A" 0.02  "Ftr2A" 0.7 "Vrc2A" 0.7 "Trc2A" 0.1 /
```

| Parameter | Default | Reason |
|---|---|---|
| LfmA | 0.75 | Load MVA = MW/MVA Rating |
| RsA | 0.04 | These are 'generic' motor parameters for this type of load, based on laboratory testing |
| LsA | 1.8 | |
| LpA | 0.12 | |
| LppA | 0.104 | |
| TpoA | 0.095 | |
| TppoA | 0.0021 | |
| HA | 0.1 | Majority of these motors are small – low inertia |
| etrqA | 0* | $T_{mech} = T_{mech,0} * \omega^{Etrq}$ - Constant Torque |

**3φ motors driving constant torque loads (commercial air conditioner compressors and refrigeration)*

# Motor A Protection Parameters

```
"LfmA" 0.75 "RsA" 0.04 "LsA" 1.8 "LpA" 0.12 "LppA"   0.104 /
 "TpoA" 0.095 "TppoA" 0.0021 "HA"   0.1 "etrqA" 0 /
 "Vtr1A" 0.7 "Ttr1A" 0.02  "Ftr1A" 0.2 "Vrc1A" 1 "Trc1A" 99999 /
 "Vtr2A" 0.5 "Ttr2A" 0.02  "Ftr2A" 0.7 "Vrc2A" 0.7 "Trc2A" 0.1 /
```

| Parameter | Default | Reason |
|---|---|---|
| Vtr1A | 0.7 | Assumed performance of these motors:<br>• This set represents the higher performance motors – large commercial building chillers/air handlers<br>• First trip level at 0.70 pu voltage, trip time < 2 cycles<br>• 20% of these motors have this type of protection<br>• Manual reconnection |
| Ttr1A | 0.02 | |
| Ftr1A | 0.2 | |
| Vrc1A | 1.0 | |
| Trc1A | 9999 | |
| Vtr2A | 0.5 | Assumed performance of these motors:<br>• This set represents the majority of ‘brute’ motors – standard design, rugged, automated<br>• Trip level at 0.50 pu voltage, trip time < 2 cycles<br>• 70% of these motors have this type of protection<br>• Auto-reconnect – 0.7 pu within 100 ms. |
| Ttr2A | 0.02 | |
| Ftr2A | 0.7 | |
| Vrc2A | 0.7 | |
| Trc2A | 0.1 | |

# Motor B Model Parameters

```
"LfmB" 0.75 "RsB" 0.03 "LsB" 1.8 "LpB" 0.19 "LppB"   0.14 /
 "TpoB" 0.2 "TppoB" 0.0026 "HB"   0.5 "etrqB" 2 /
"Vtr1B" 0.6 "Ttr1B" 0.02  "Ftr1B" 0.2 "Vrc1B" 0.75 "Trc1B" 0.05 /
"Vtr2B" 0.5 "Ttr2B" 0.02  "Ftr2B" 0.3 "Vrc2B" 0.65 "Trc2B" 0.05 /
```

| Parameter | Default | Reason |
|---|---|---|
| LfmB | 0.75 | Load MVA = MW/MVA Rating |
| RsB | 0.03 | These are 'generic' motor parameters for this type of load, based on laboratory testing |
| LsB | 1.8 | |
| LpB | 0.19 | |
| LppB | 0.14 | |
| TpoB | 0.2 | |
| TppoB | 0.0026 | |
| HB | 0.5 | Large inertia commercial/industrial fan motor loads |
| etrqB | 2* | $T_{mech} = T_{mech,0} * \omega^{Etrq}$ - Torque ∝ Speed-Squared |

**3φ motors driving load proportional to speed-squared relationship with high inertia (large fans)*

# Motor B Protection Parameters

```
"LfmB" 0.75 "RsB" 0.03 "LsB" 1.8 "LpB" 0.19 "LppB"   0.14 /
 "TpoB" 0.2 "TppoB" 0.0026 "HB"   0.5 "etrqB" 2 /
"Vtr1B" 0.6 "Ttr1B" 0.02  "Ftr1B" 0.2 "Vrc1B" 0.75 "Trc1B" 0.05 /
"Vtr2B" 0.5 "Ttr2B" 0.02  "Ftr2B" 0.3 "Vrc2B" 0.65 "Trc2B" 0.05 /
```

<table>
<tr><th>Parameter</th><th>Default</th><th>Reason</th></tr>
<tr><td>Vtr1B</td><td>0.6</td><td rowspan="5">Assumed performance of these motors:<br>• First trip level at 0.60 pu voltage, trip time < 2 cycles<br>• 20% of these motors have this type of protection<br>• Auto-reconnect – 0.75 pu voltage within 50 ms</td></tr>
<tr><td>Ttr1B</td><td>0.02</td></tr>
<tr><td>Ftr1B</td><td>0.2</td></tr>
<tr><td>Vrc1B</td><td>0.75</td></tr>
<tr><td>Trc1B</td><td>0.05</td></tr>
<tr><td>Vtr2B</td><td>0.5</td><td rowspan="5">Assumed performance of these motors:<br>• Trip level at 0.50 pu voltage, trip time < 2 cycles<br>• 30% of these motors have this type of protection<br>• Auto-reconnect – 0.65 pu within 50 ms<br>• Emulates staggered tripping and reconnection – diversity of motor load</td></tr>
<tr><td>Ttr2B</td><td>0.02</td></tr>
<tr><td>Ftr2B</td><td>0.3</td></tr>
<tr><td>Vrc2B</td><td>0.65</td></tr>
<tr><td>Trc2B</td><td>0.05</td></tr>
</table>

# Motor C Model Parameters

```
"LfmC" 0.75 "RsC" 0.03 "LsC" 1.8 "LpC" 0.19 "LppC"   0.14 /
"TpoC" 0.2 "TppoC" 0.0026 "HC"   0.1 "etrqc" 2 /
 "Vtr1C" 0.65 "Ttr1C" 0.02 "Ftr1C" 0.2 "Vrc1C" 1 "Trc1C" 9999 /
 "Vtr2C" 0.5 "Ttr2C" 0.02 "Ftr2C" 0.3 "Vrc2C" 0.65 "Trc2C" 0.1 /
```

| Parameter | Default | Reason |
|---|---|---|
| LfmC | 0.75 | Load MVA = MW/MVA Rating |
| RsC | 0.03 | These are ‘generic’ motor parameters for this type of load, based on laboratory testing |
| LsC | 1.8 | |
| LpC | 0.19 | |
| LppC | 0.14 | |
| TpoC | 0.2 | |
| TppoC | 0.0026 | |
| HC | 0.1 | Large inertia commercial/industrial pump motor loads |
| etrqC | 2* | $T_{mech} = T_{mech,0} * \omega^{Etrq}$ - Torque ∝ Speed-Squared |

**3φ motors driving load proportional to speed-squared relationship with low inertia (pump loads)*

# Motor C Protection Parameters

```
"LfmC" 0.75 "RsC" 0.03 "LsC" 1.8 "LpC" 0.19 "LppC"   0.14 /
"TpoC" 0.2 "TppoC" 0.0026 "HC"   0.1 "etrqc" 2 /
 "Vtr1C" 0.65 "Ttr1C" 0.02 "Ftr1C" 0.2 "Vrc1C" 1 "Trc1C" 9999 /
 "Vtr2C" 0.5 "Ttr2C" 0.02 "Ftr2C" 0.3 "Vrc2C" 0.65 "Trc2C" 0.1 /
```

| **Parameter** | **Default** | **Reason** |
|---|---|---|
| Vtr1C | 0.65 | Assumed performance of these motors:<br>• First trip level at 0.65 pu voltage, trip time < 2 cycles<br>• 20% of these motors have this type of protection<br>• Manual reconnection |
| Ttr1C | 0.02 | |
| Ftr1C | 0.2 | |
| Vrc1C | 1.0 | |
| Trc1C | 9999 | |
| Vtr2C | 0.5 | Assumed performance of these motors:<br>• Trip level at 0.50 pu voltage, trip time < 2 cycles<br>• 30% of these motors have this type of protection<br>• Auto-reconnect – 0.65 pu within 100 ms |
| Ttr2C | 0.02 | |
| Ftr2C | 0.3 | |
| Vrc2C | 0.65 | |
| Trc2C | 0.1 | |

# Motor D Model Parameters

```
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

| Parameter | Default | Reason |
|---|---|---|
| LfmD | 1.0 | Load MVA = MW/MVA Rating |
| CompPF | 0.98 | Assumed slightly inductive motors load |
| Vstall | 0.60 | Stall voltage (range) based on laboratory testing |
| Rstall | 0.1 | Based on laboratory testing results of residential air-conditioners |
| Xstall | 0.1 | |
| Tstall | 0.03 | Stall time (range) based on laboratory testing |
| Frst | 0.2 | Captures diversity in load; also based on testing. |
| Vrst | 0.95 | Reconnect when acceptable voltage met |
| Trst | 0.3 | Induction motor restart time is relatively short |

**1φ induction motor load (residential air-conditioner compressors)*

# Motor D Protection Parameters

```
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

| Parameter | Default | Reason |
|---|---|---|
| fuvr | 0.1 | Assumed most A/C units have undervoltage relaying |
| vtr1 | 0.6 | Undervoltage relay |
| ttr1 | 0.02 | |
| vtr2 | 1 | No second level undervoltage tripping specified. |
| ttr2 | 9999 | |
| Vc1off | 0.5 | Stall time (range) based on laboratory testing |
| Vc2off | 0.4 | Based on laboratory testing results |
| Vc1on | 0.6 | Reconnect when acceptable voltage met |
| Vc2on | 0.5 | Induction motor restart time is relatively short |

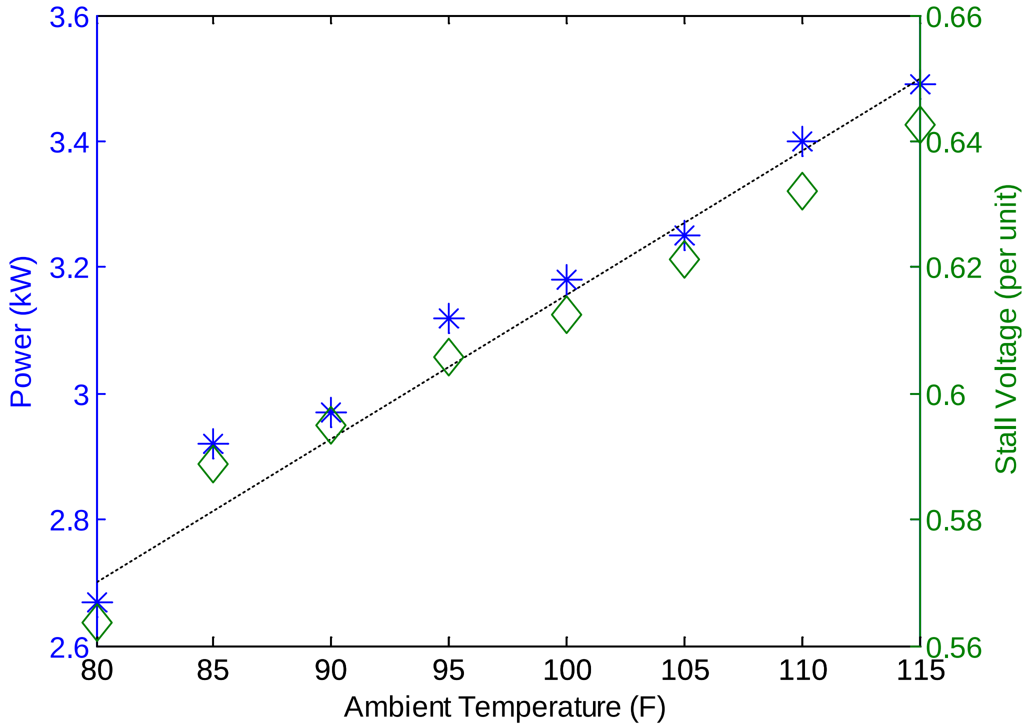
# Motor D Protection Parameters

```
"LfmD"  1 "CompPF" 0.98 /
"Vstall" 0.6 "Rstall" 0.1  "Xstall" 0.1 "Tstall" 0.03  "Frst" 0.2 "Vrst" 0.95 "Trst" 0.3 /
"fuvr" 0.1 "vtr1" 0.6 "ttr1" 0.02 "vtr2" 1 "ttr2" 9999 /
"Vc1off" 0.5 "Vc2off" 0.4 "Vc1on" 0.6 "Vc2on" 0.5 /
"Tth" 15 "Th1t" 0.7 "Th2t" 1.9 "tv" 0.025
```

| Parameter | Default | Reason |
|---|---|---|
| Tth | 15 | Varies based on manufacturer – sensitivity analysis required; based on range of external factors |
| Th1t | 0.7 | Assumed tripping starting at 70% temperature, with all tripped at 190% temperature |
| Th2t | 1.9 | |
| tv | 0.025 | Assumed generic transducer time lag |

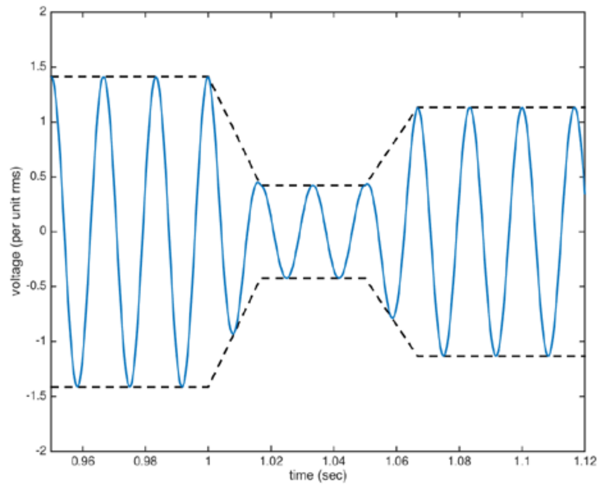
# Motor D – Sensitivity to Ambient Temp

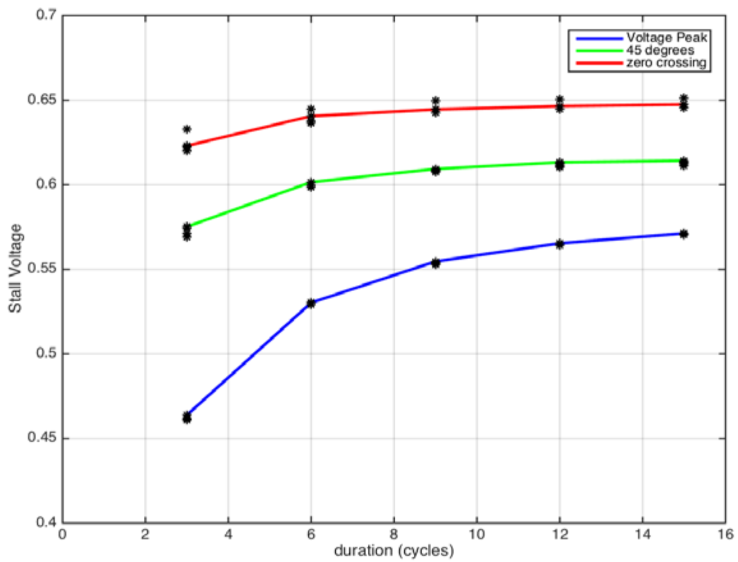
- Compressor loading and stall voltage depend on ambient temperature
- Compressor motors have high power factor when running
  - Approximately 0.97 pf

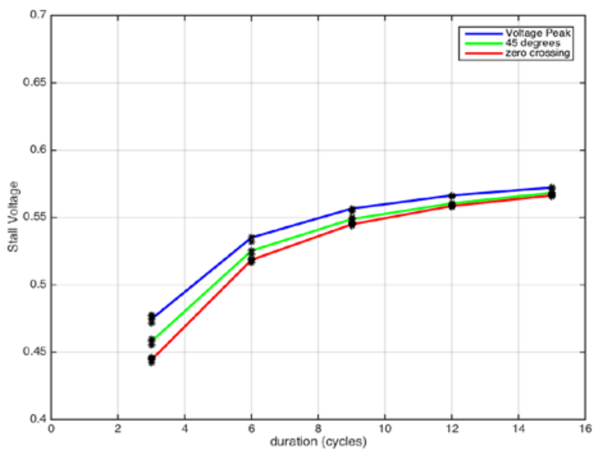


# Current R&D Efforts

- Point-on-wave sensitivity
- Voltage sag rate-of-change sensitivity
  - Distribution recordings show sag is not instantaneous
  - At least 1 cycle for voltage to sag – motor back-feed
  - Vstall numbers lower than previously thought



# Distribution FIDVR Monitoring

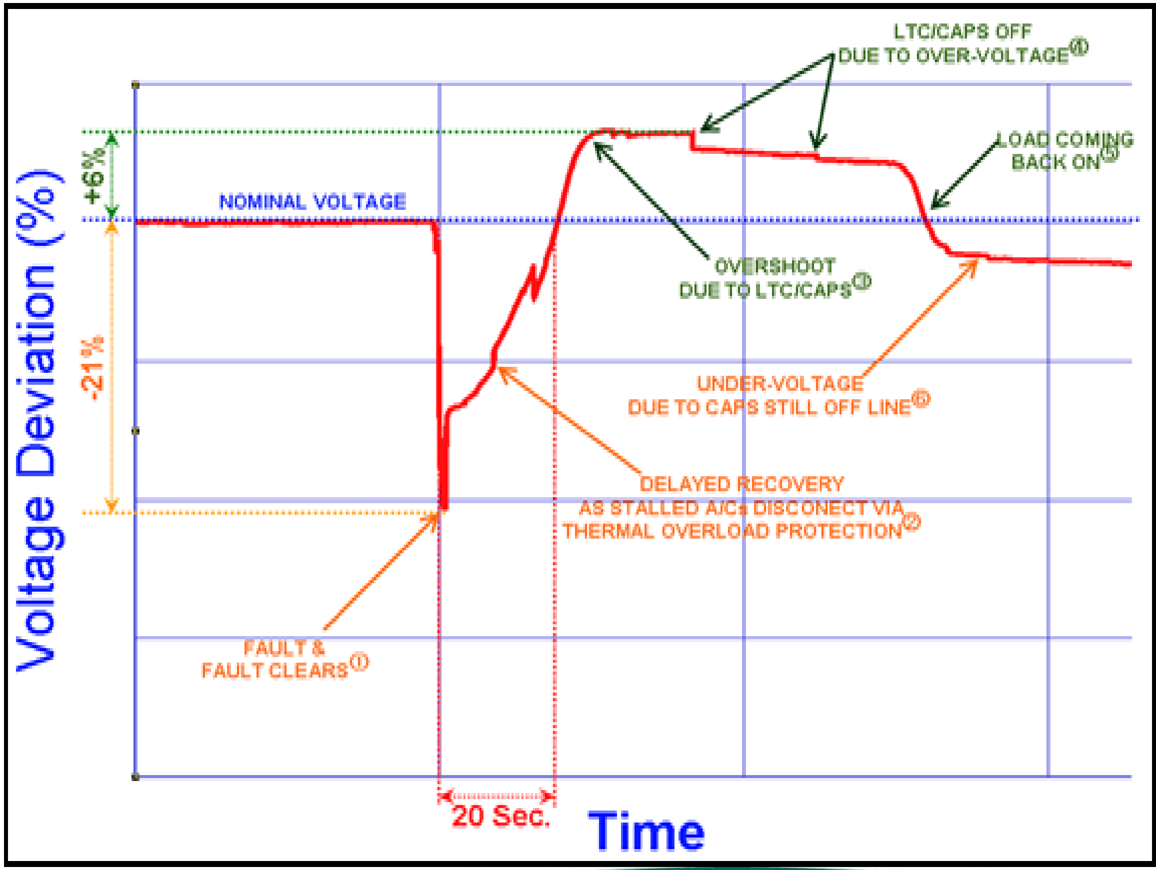
DOE-NERC FIDVR Workshop

Richard Bravo

# FIDVR Events

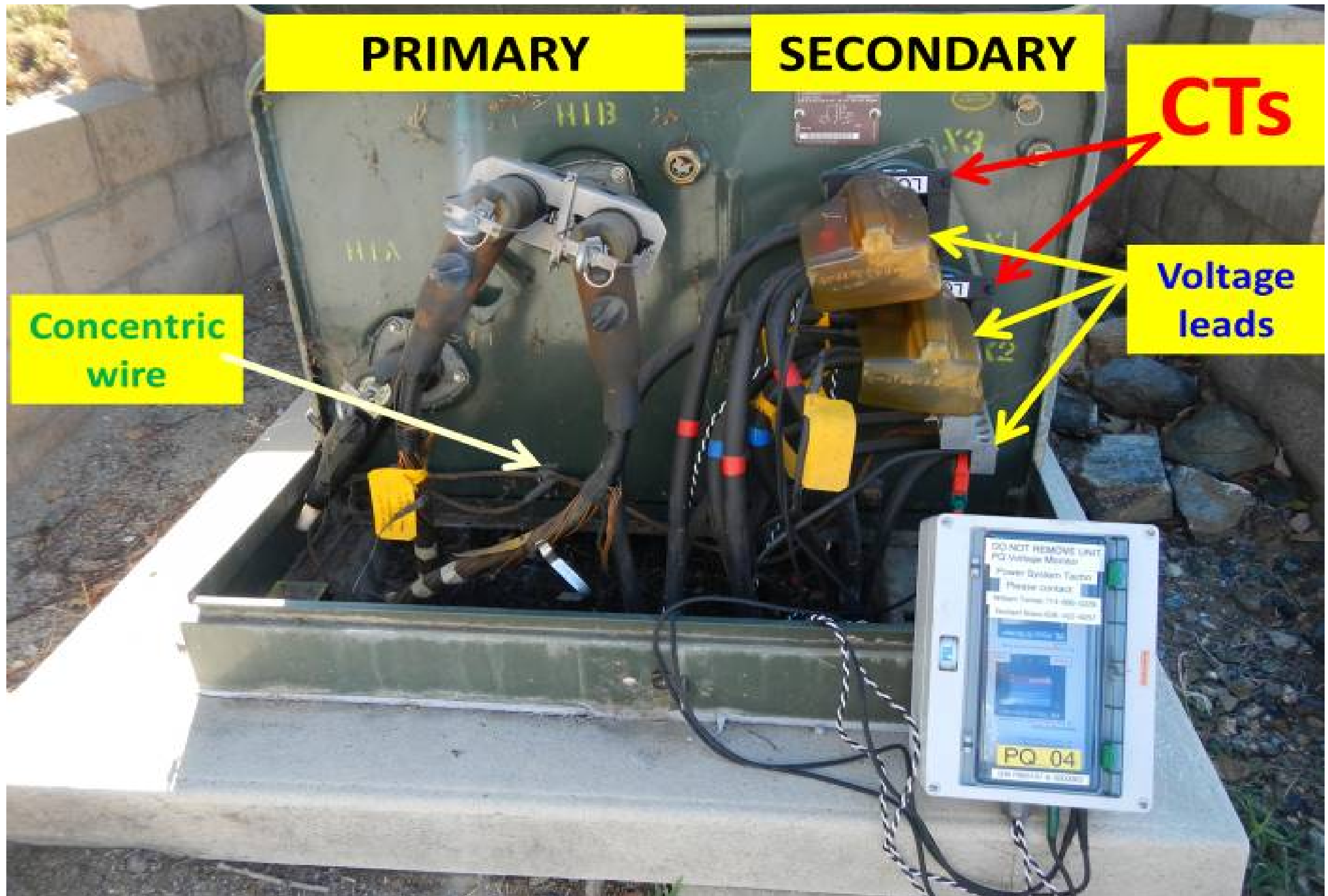


- PMUs has been recording FIDVR events for many years
- Limited information on how FIDVR events evolve in distribution system
- Distribution FIDVR events details needed to assess:
  - Spreading behavior
  - Voltage levels at T&D
  - Time of events
  - Real and reactive power demands



# PQ Monitors on Residential Xmers

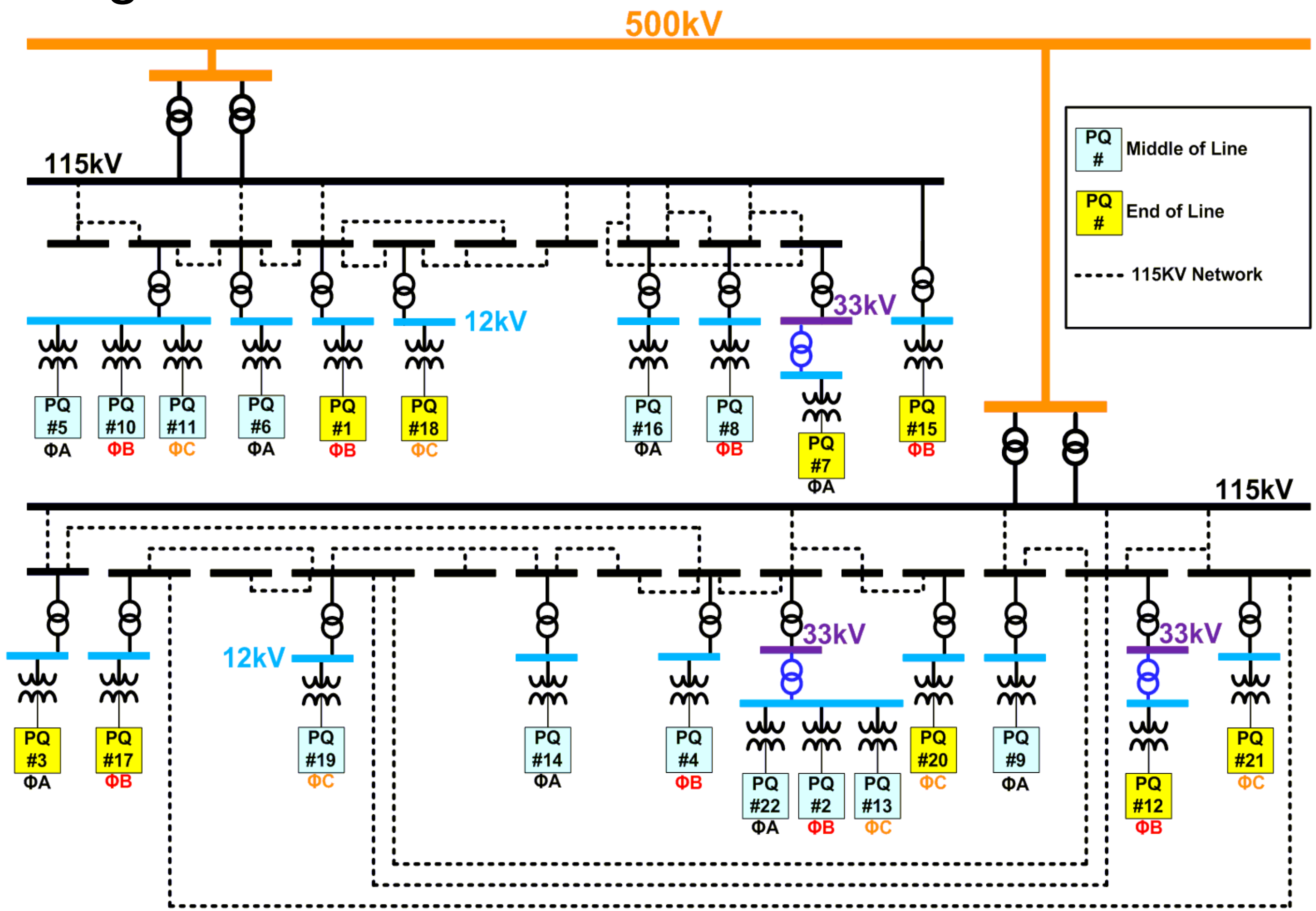
- Installed in pad-mount residential xmers secondary side: 240V
- Record residential loads aggregated behavior
- Record: V & I
  - Line to ground voltage
  - Line current (aggregated)



# PQ Monitors Installations



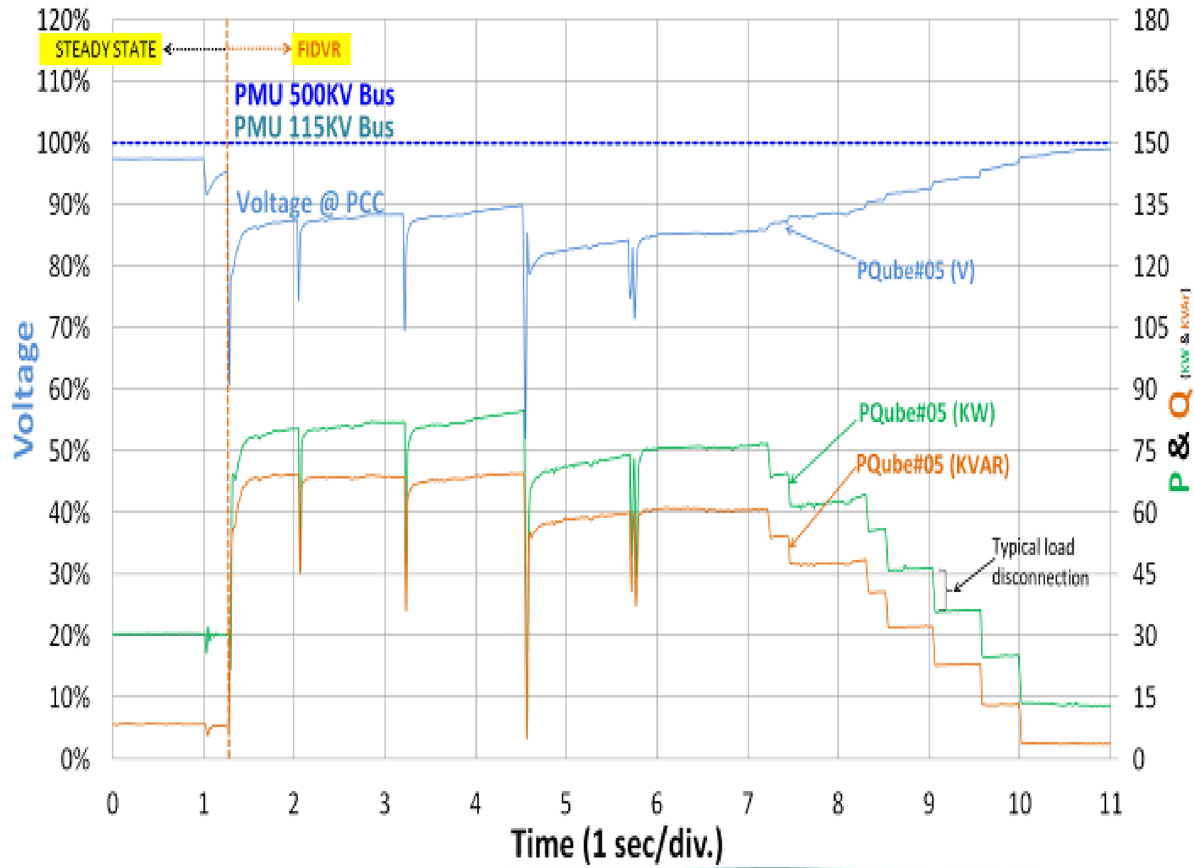
- Installed in Valley system dist. circuits (1,500 MW peak load)
- PQ threshold settings:
  - UV triggers at 80%
  - OV triggers at 110%
  - Capture event
    - RMS
    - sinusoidal waveforms



# Event #1 (RMS)

Leading the Way in Electricity℠

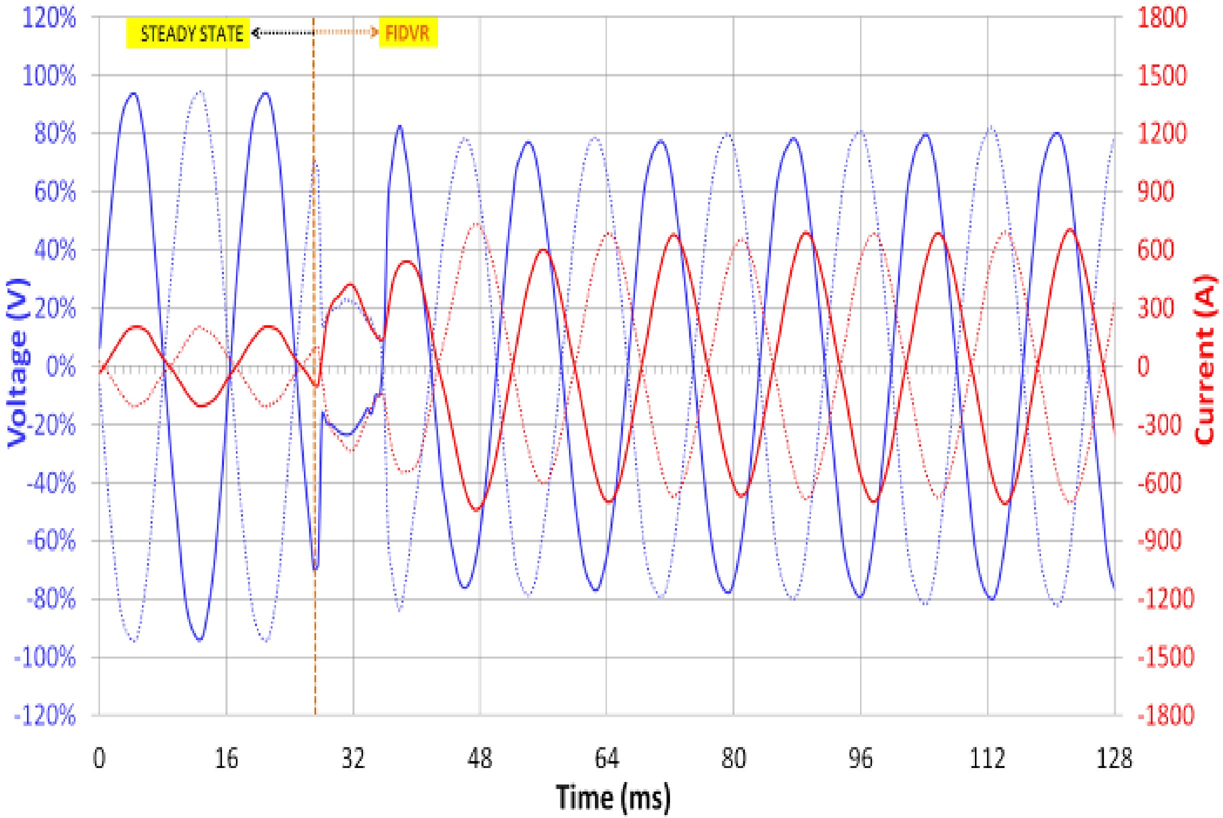
- Multiple lightning strikes caused multiple distribution faults recorded by <u>the PQ devices</u>, <u>but not by transmission PMU</u>
  - P & Q increased during FIDVR
    - P=2.6 p.u. at V=90%
    - Q=7 p.u. at V=90%
  - FIDVR lasted 9 sec
  - TOPs open disconnecting loads after seven (7) second mark
- FIDVR recorded only in distribution system



# Event #1 (sinusoidal)



- Fault initiated at ~70 degrees of voltage waveform
- Fault must have been in adjacent circuit
- Fault cleared fast but not fast enough to prevent A/C stalling
- Stalling prevented voltage from recovering
  - Current waveform (red) increases significantly 200A → 700A
  - Voltage hold at 80%
  - Current lagging behavior increases significantly during the event

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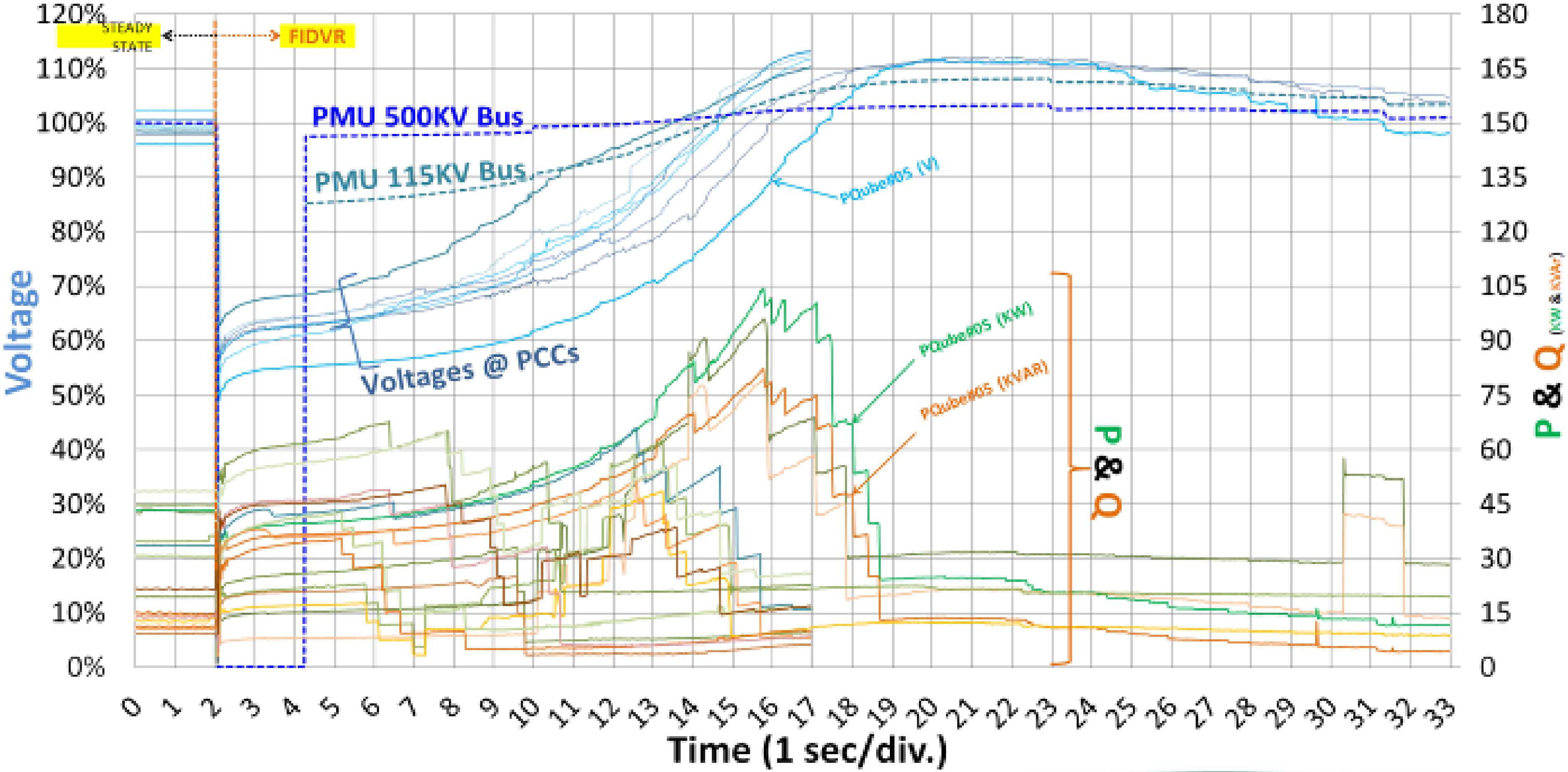
# Event #6



- Lightning causes FIDVR event recorded by BOTH distribution PQ devices and transmission PMU

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# DER Proposed VRT

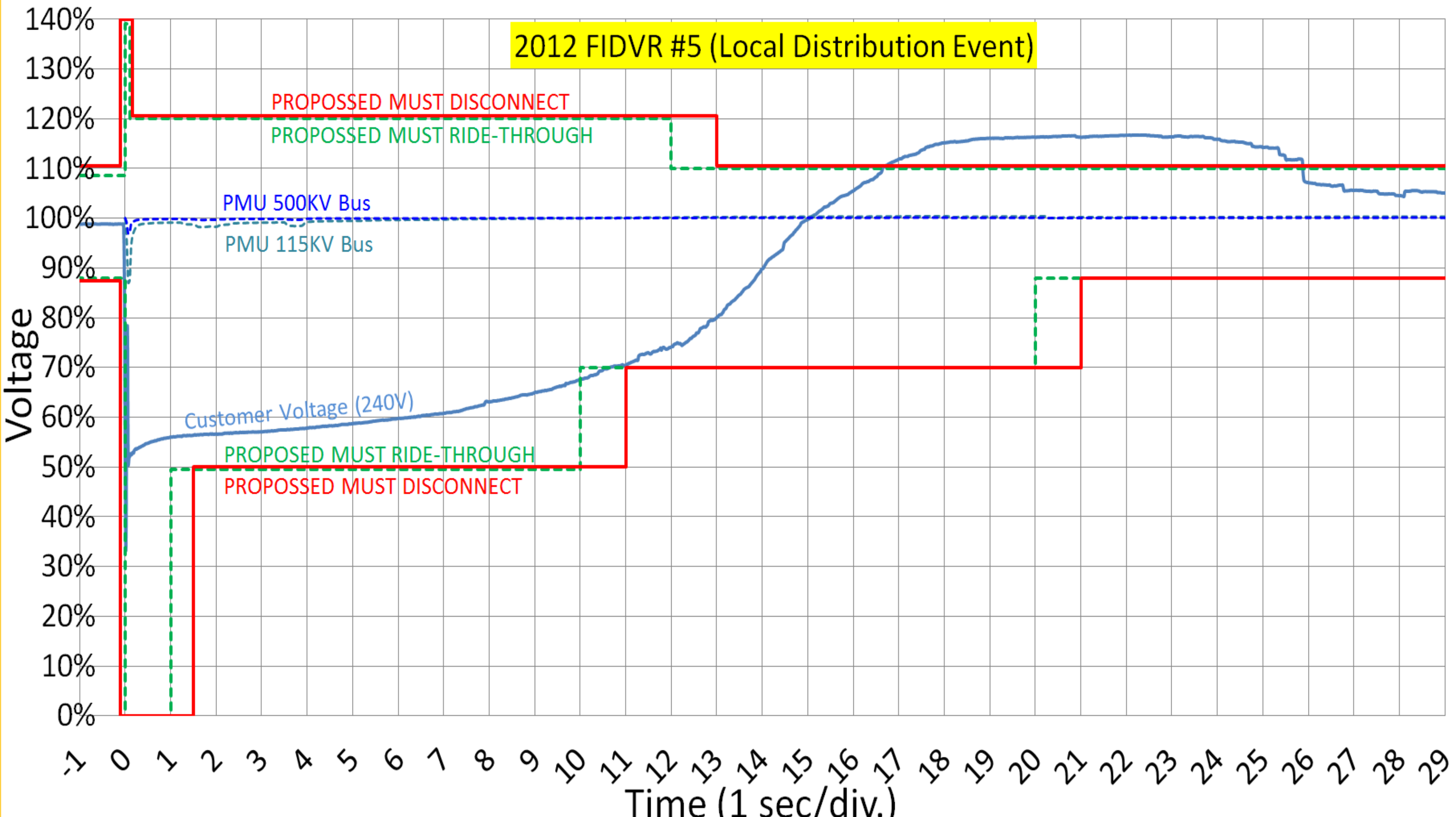


- DER penetration is increasing significantly and may become a major generating part of the grid during certain times
- Standards are being revised to allow voltage ride through

| VOLTAGE (p.u.) | RIDE-THROUGH (seconds) | OPERATION | MUST DISCONNECT (seconds) |
|---|---|---|---|
| >1.2 | none | Disconnect | 0.16 |
| 1.1 ~ 1.2 | 12 | Momentary Cessation | 13 |
| 0.88 ~ 1.10 | | Continuous Operation | |
| 0.70 ~ 0.88 | 20 | Mandatory Operation | 21 |
| 0.5 ~ 0.7 | 10 | Mandatory Operation | 11 |
| 0 ~ 0.5 | 1 sec | Momentary Cessation | 1.5 |

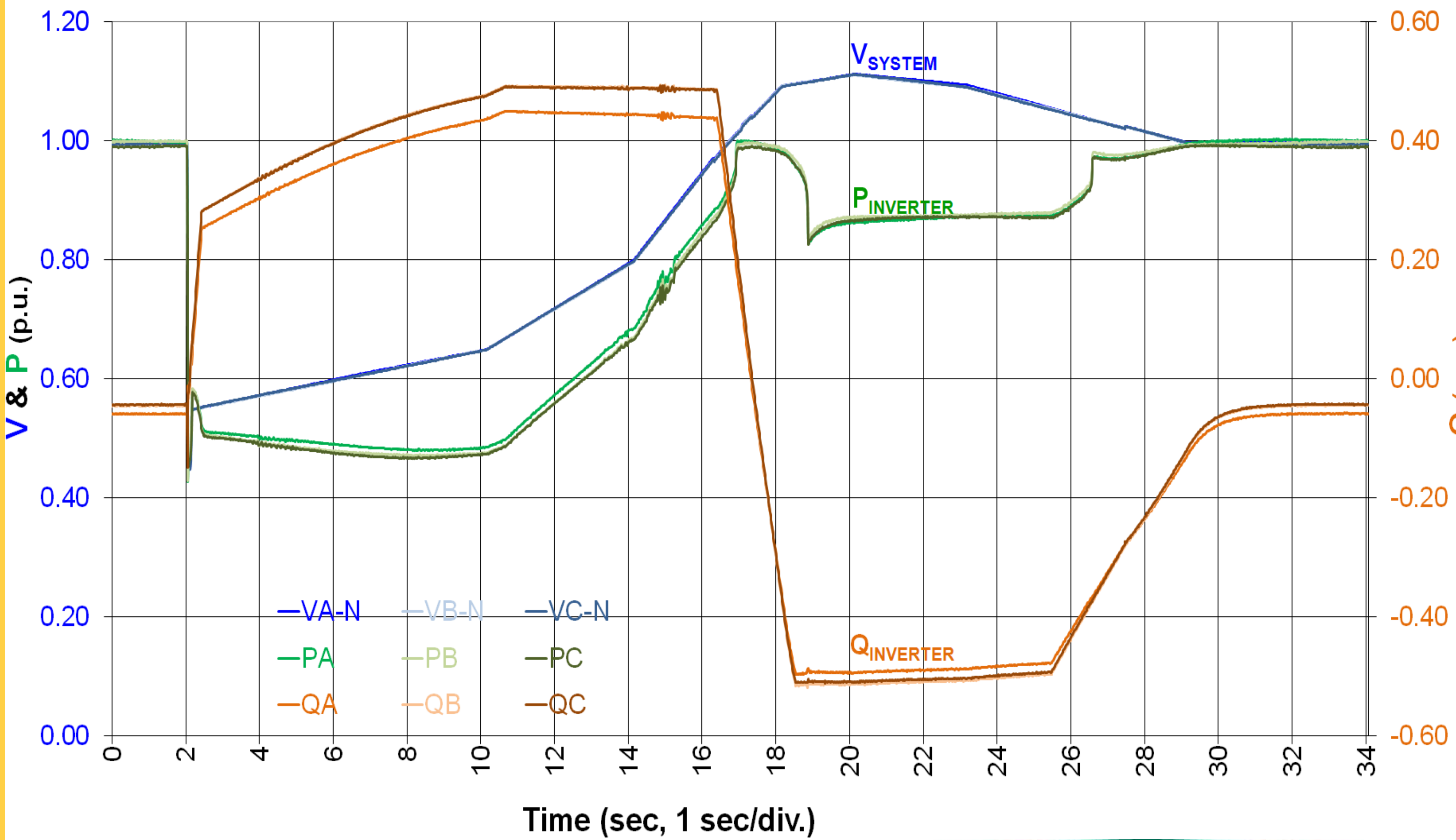
# Ride Through Grid Voltage Events





# DER Can Provide Grid Support



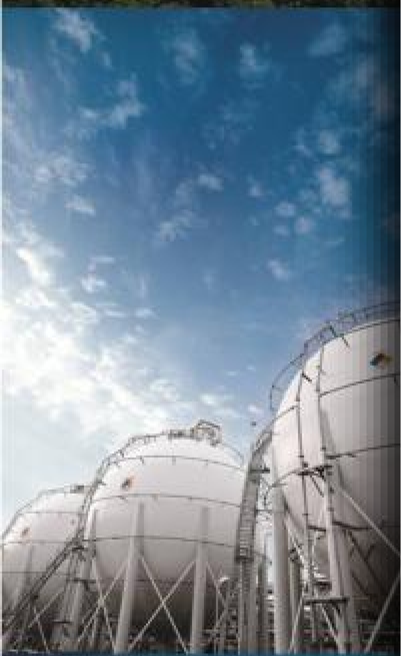


# Conclusion



- No linear relationship between T&D voltages during FIDVR
- Faults at any point in the waveform can provoke FIDVR if there is large induction motor load
- Stalling happens very quick within 2 cycles
- DER should ride through voltage events
- DER should supply VARs to support the voltage during voltage events
- Voltage support typically less than 30 seconds so minimum impact to generation revenew





# Distribution Data for FIDVR & Load Modeling

*Kyle Thomas*
*ET Operations Engineering*
*Dominion Virginia Power*

Dominion®

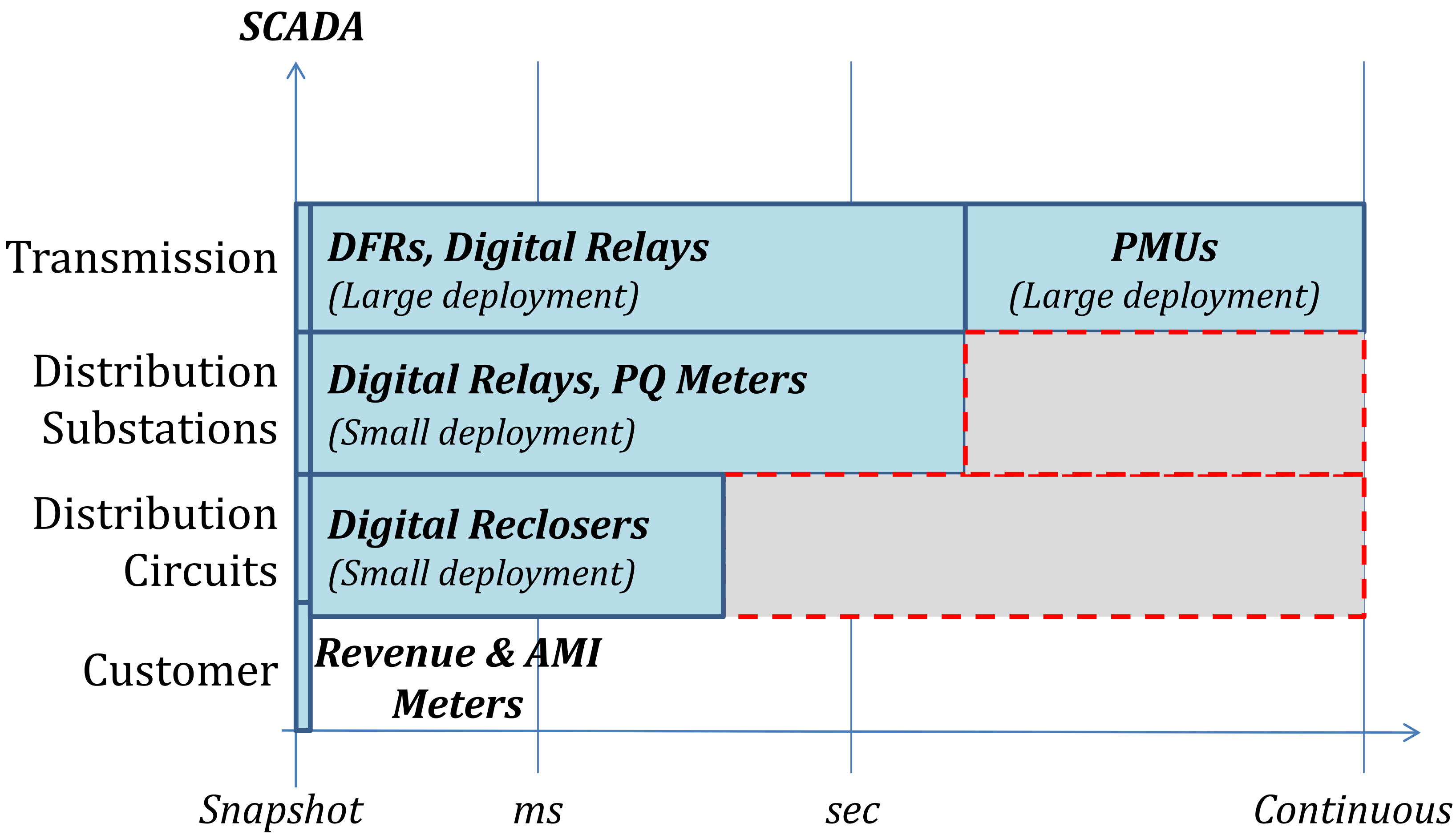
*September 30, 2015*


# Initial Motivation

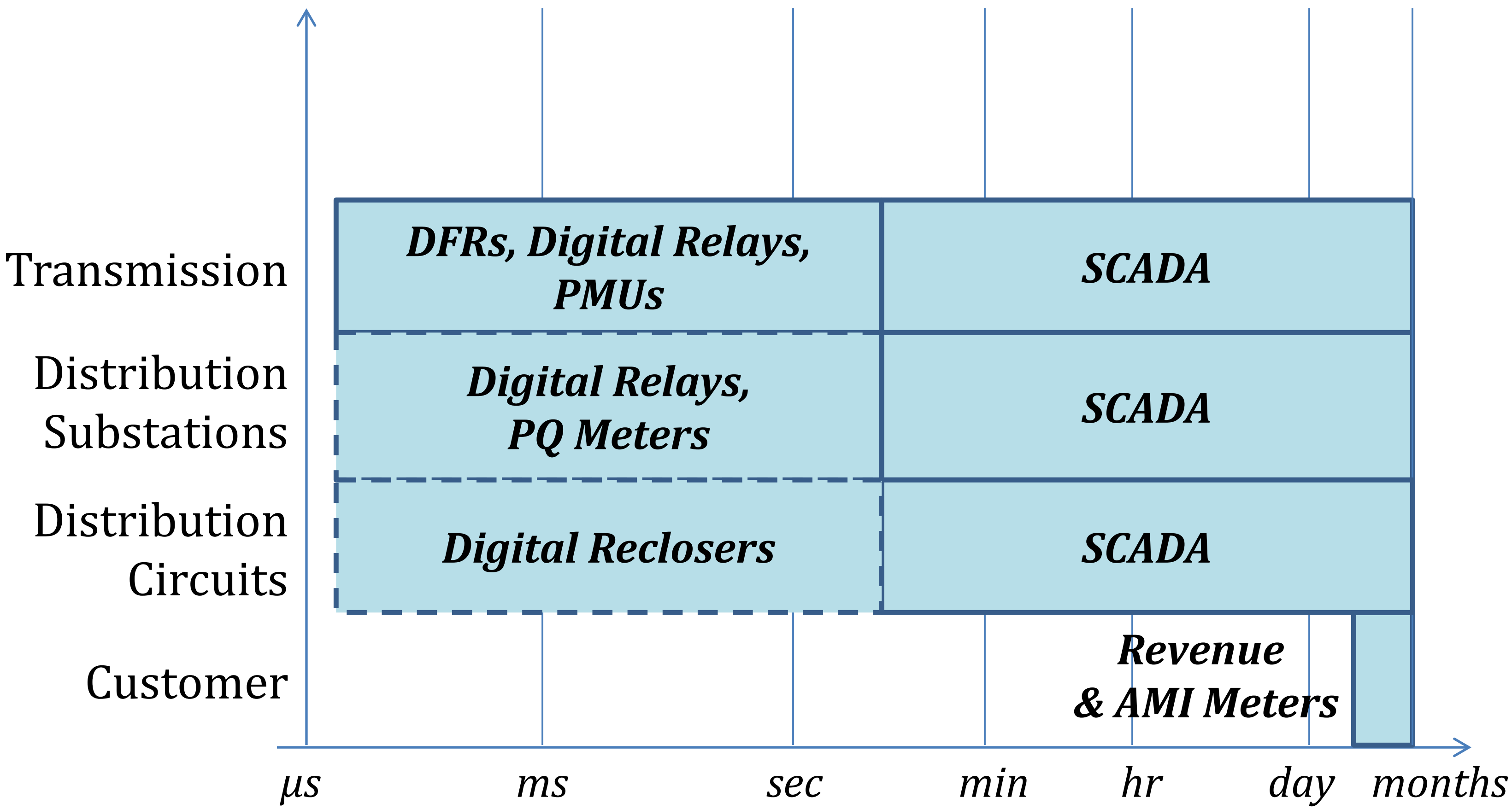
2011 Timeframe

- **NERC TPL-001**
  - Addition of dynamic load model requirement in planning studies expected/planned
- **Initial Simulation Observations**
  - Simulations using composite load model with best guess load composition parameters show widespread FIDVR on Transmission system
  - Actual Transmission level monitoring shows little to no widespread FIDVR
- **Goal:**
  - Improve distribution level monitoring capability
  - Use captured data to understand phenomena & model parameters
  - Use improved model parameters to perform better informed studies

# Distribution Data Gap – Capture Duration



# Distribution Data Gap – Monitoring Resolution



# Initial Field Installations

2012-2014

## – Portable Digital Fault Recorders (DFRs)

- 3 Portable DFRs purchased
- Placed in distribution substations throughout our system
- Can monitor 3-phase voltages and 3-phase currents at two distribution feeders
- High resolution oscillography
- Continuous RMS
- Synchrophasors
- Local storage and communications

# Initial Field Installations

2012-2014

# Initial Field Installations

2012-2014

- **High quality data captured over 3 summers**
  - Moved the Portable DFRs around every summer
- **Devices never failed**
- **Communications had high uptime, local storage a perfect backup**

- **Excellent service to customers**
  - No significant events captured!
    - Very few events occurred at all
    - The couple of events occurred at very end of the circuits

# Distribution PQ Meter Data

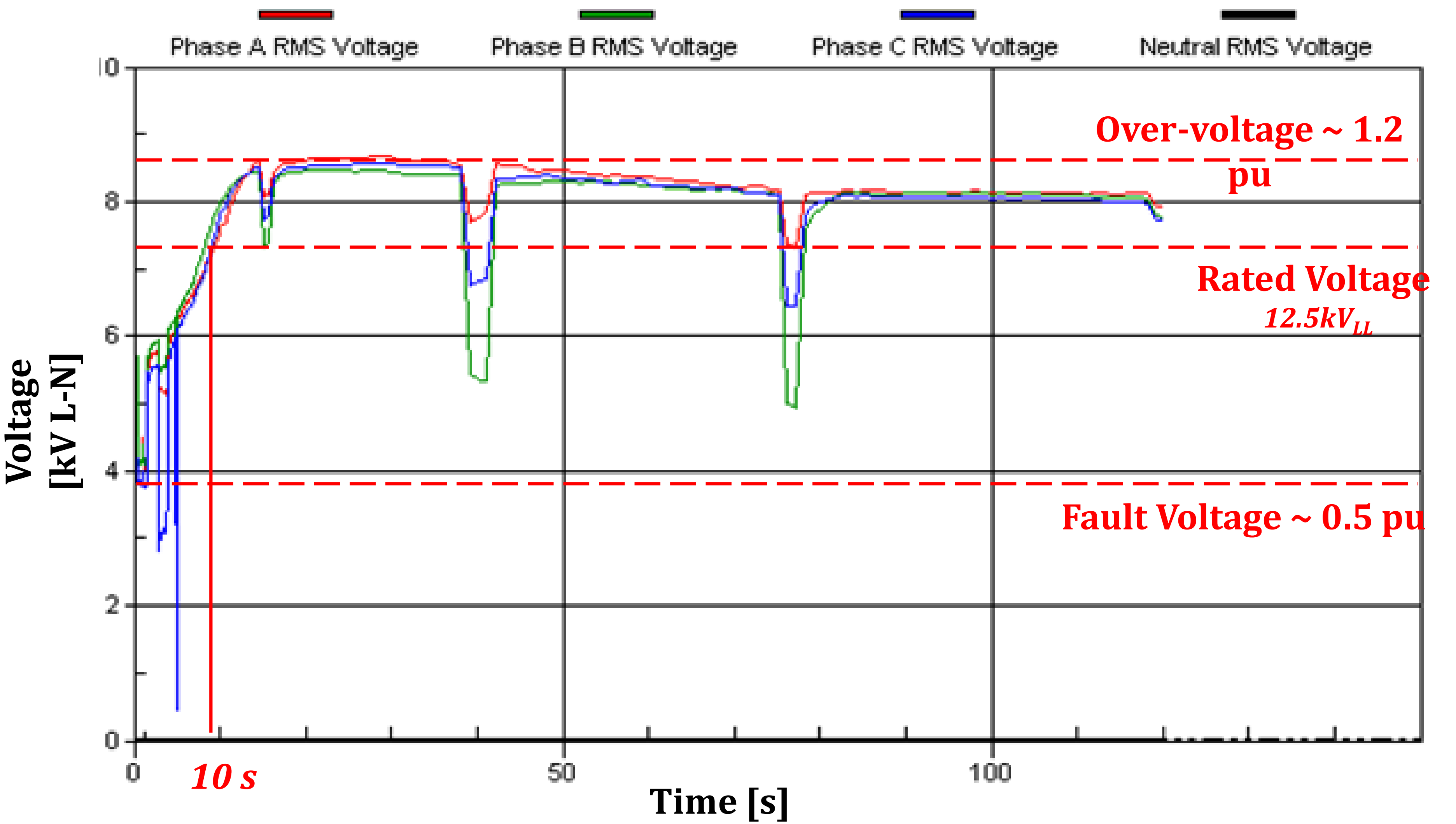
2013 and on

- **Power Quality meters installed on low-side of Distribution Transformers**
  - Primary purpose for helping with customer service issues

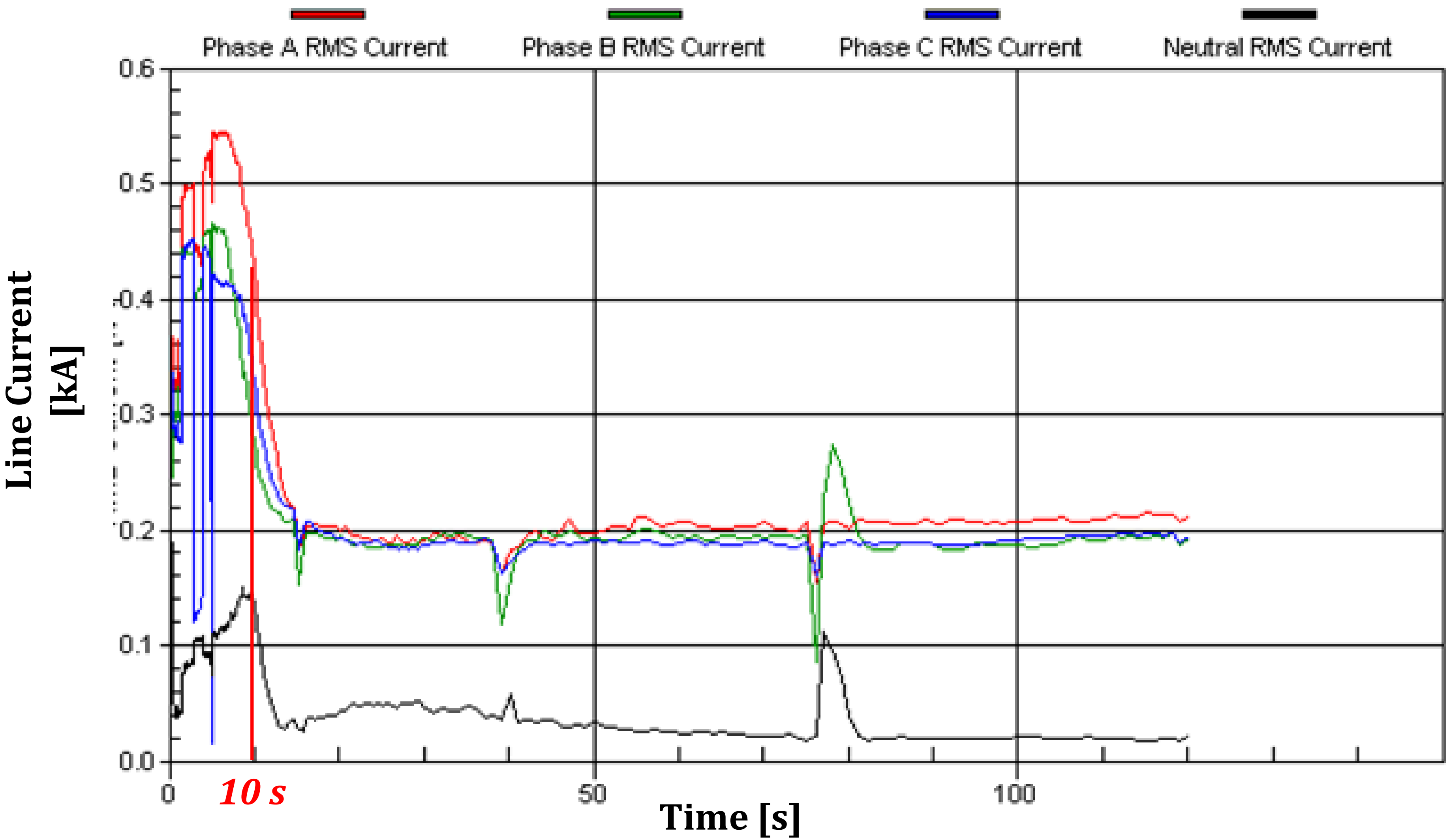
- **PQ data automatically collected via network and dial-up**

- **Historical data going back to 2005**

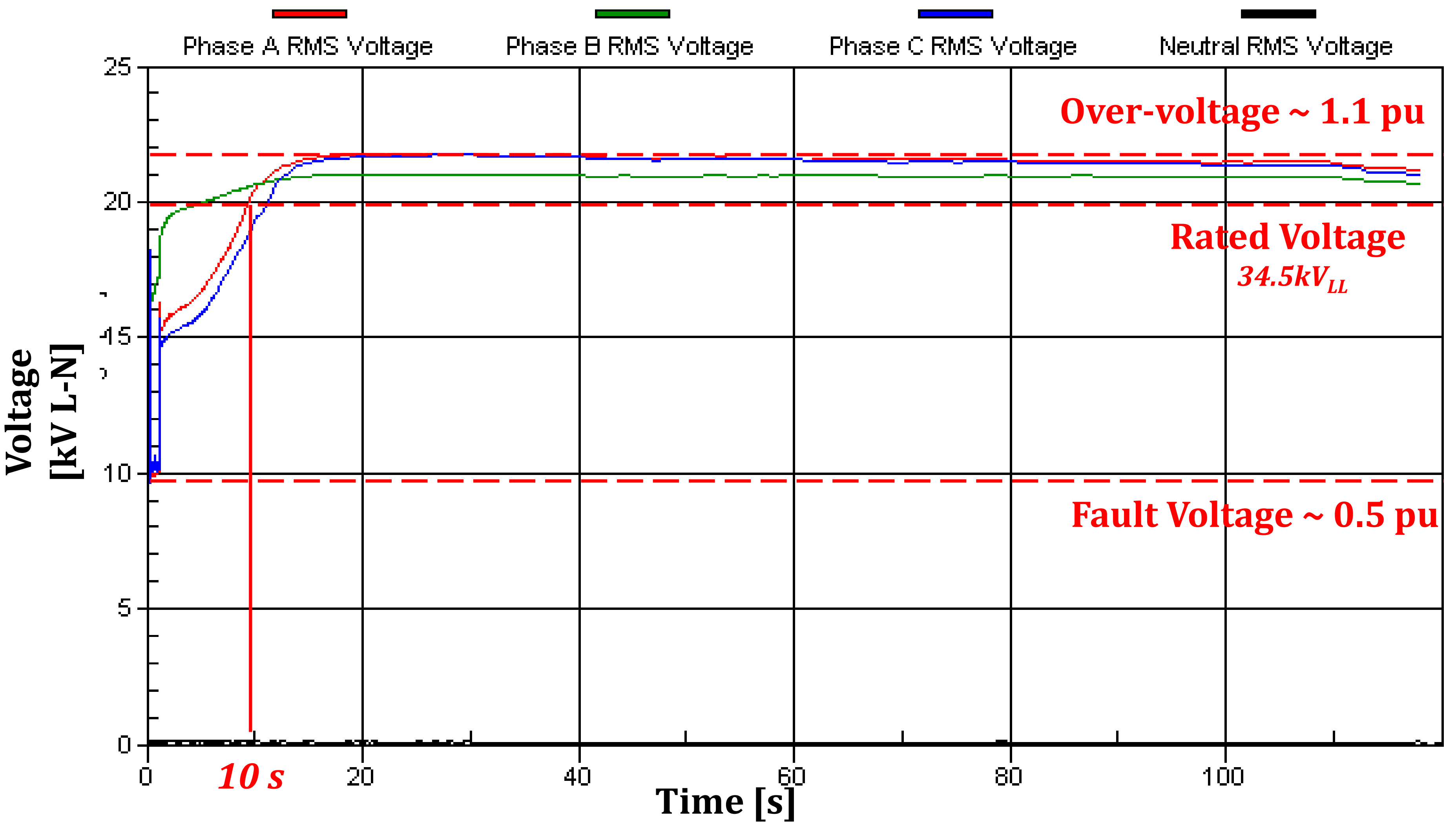
# Example 1 – July 2006 4pm



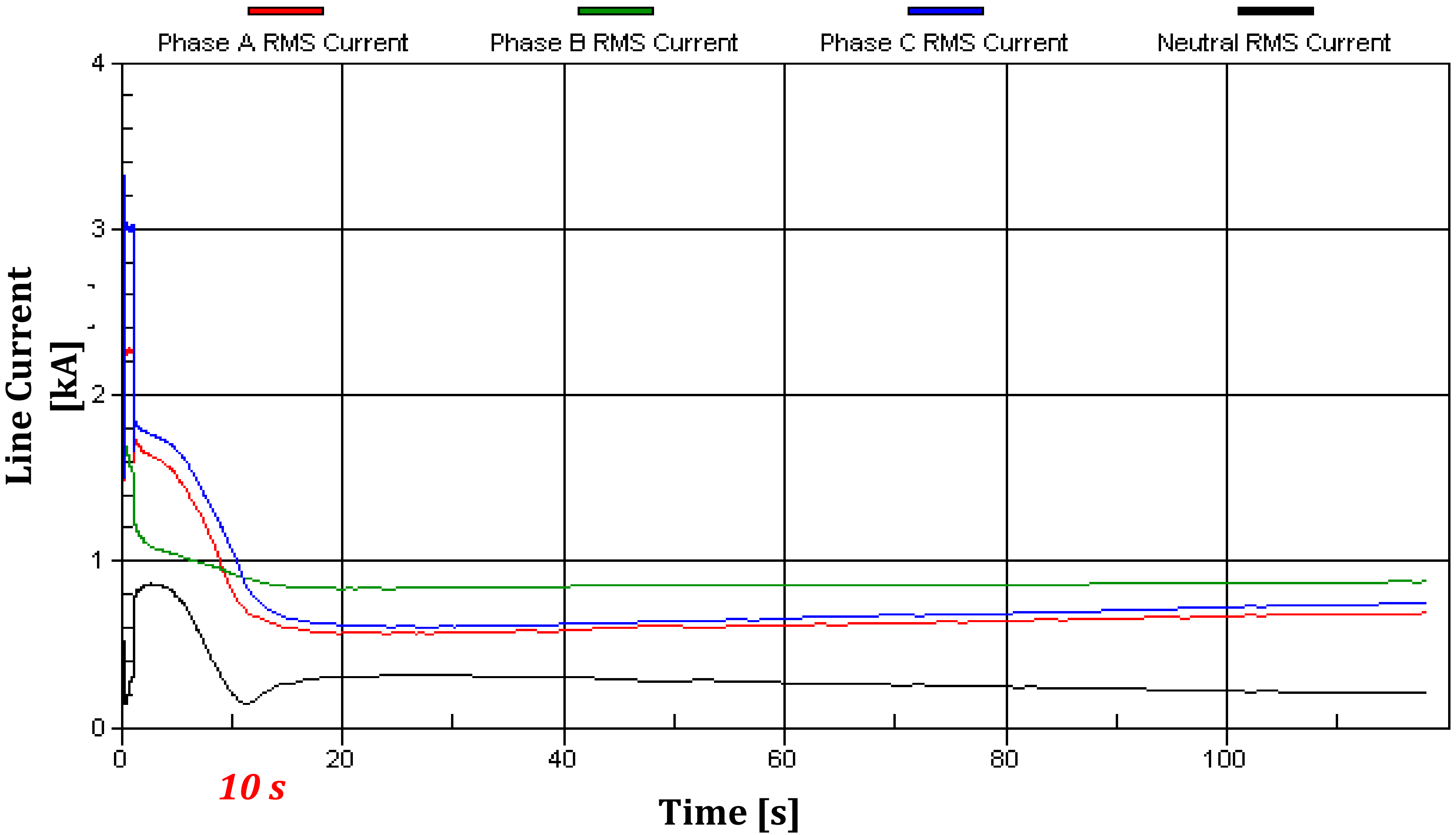
# Example 1 – July 2006 4pm



# Example 2 – August 2006 6pm



# Example 2 – August 2006 6pm



# PQ Meter Settings

- **Did not find any FIDVR events in the PQ meter network since the 2006-2008 timeframe**
  - Problem solved?

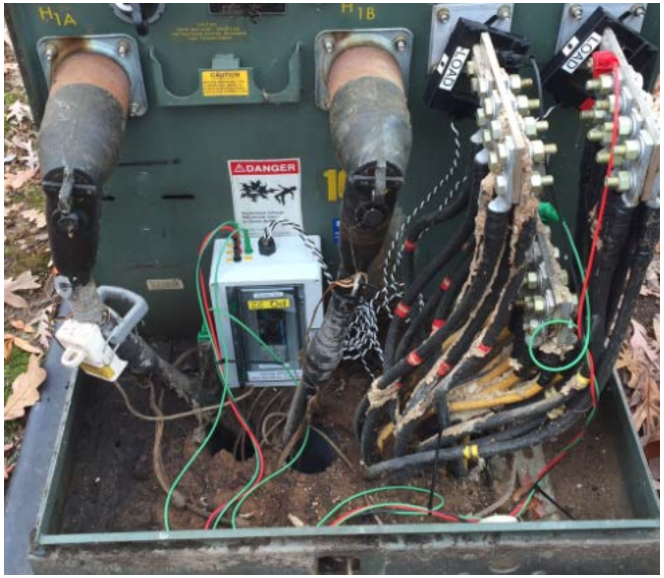
- **Past: Magnitude trigger with duration setting**
  - Can capture longer term dynamics following faults

- **Current: Trigger on V < 0.9 pu, stop capture upon recovery back to 0.9 pu**
  - Very useful for fault analysis, but not for longer dynamics such as A/C motor stalling

# Latest Field Installations

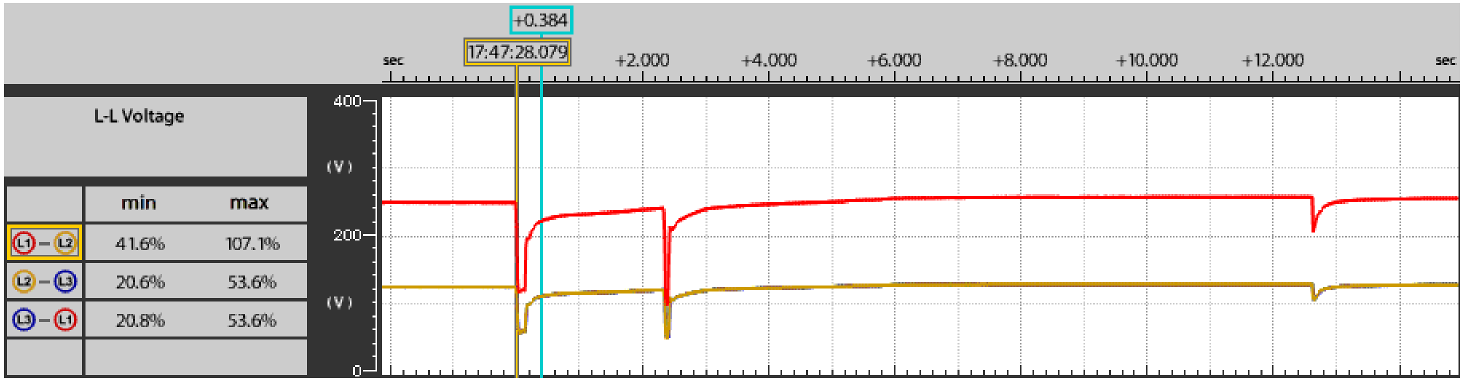
Summer 2015

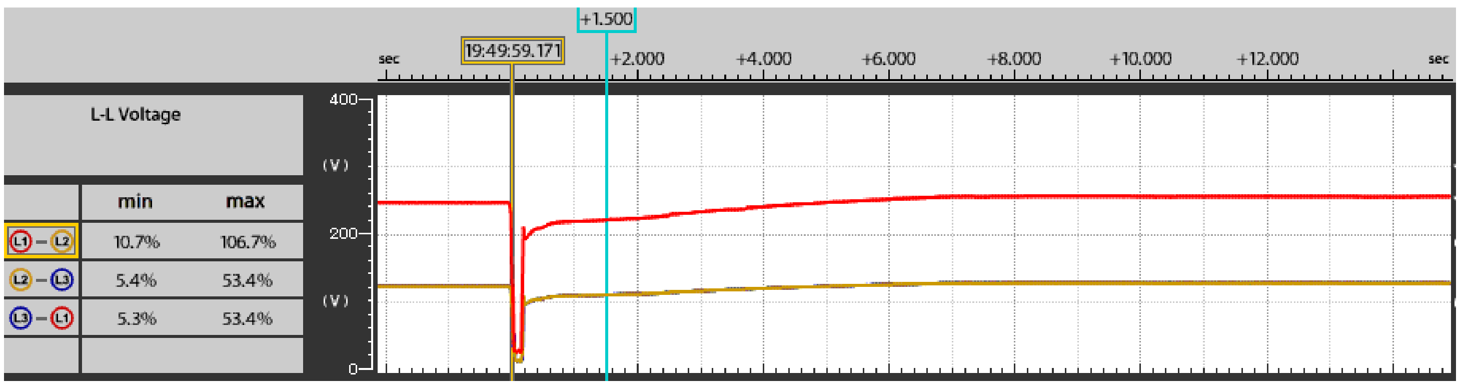
- 10 PQube devices from Joe Eto & Richard Bravo
- Installed on pad mount transformers around our territory
- Selected circuits with portable DFRs and/or digital relays on distribution feeder
- Data being collected at this time

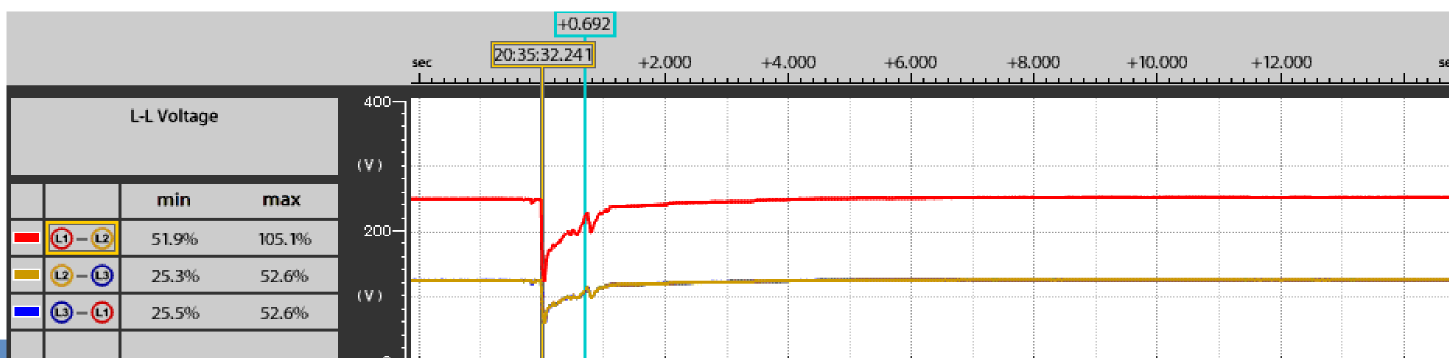



# Latest Field Installations

Summer 2015



# Going Forward

Standardization = Proliferation

- **Transmission PMUs as % of Total Capital Expenditure =< 0.1%**
  - $1M/yr expected on PDC infrastructure & architecture
- **Distribution Substation Hurdles**
  - Use 300-series SEL relays (387/351) w/o PMU capability
  - Use Power Quality meters (SEL 734/735) w/o PMU capability
  - Adding PMU functionality to these devices will proliferate PMU technology into Distribution
- **Fix/standardize meter and relay settings**
- **Automate data/file collection**
- **Distributed Generation increasing need/push for high resolution data on distribution (ex: PMUs)**

Dominion®

# FIDVR
## Voltage Dip Recordings

John Undrill, Weijia Wang
September 2015

PQube power quality recorders placed at 10 locations in Centerpoint distribution system in 2011

1830 events recorded in 2011 - 2013

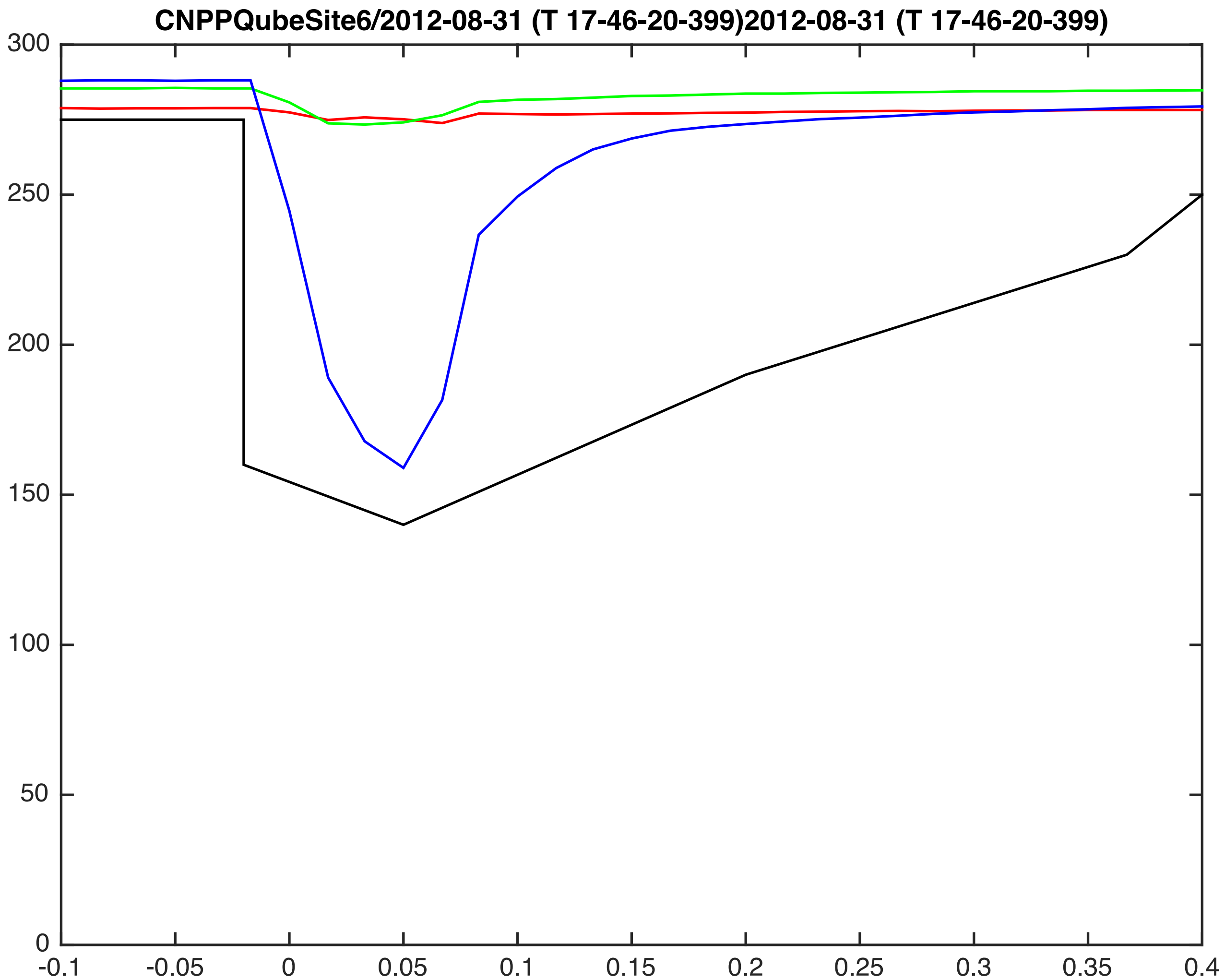
Many events are not of interest with regard to FIDVR

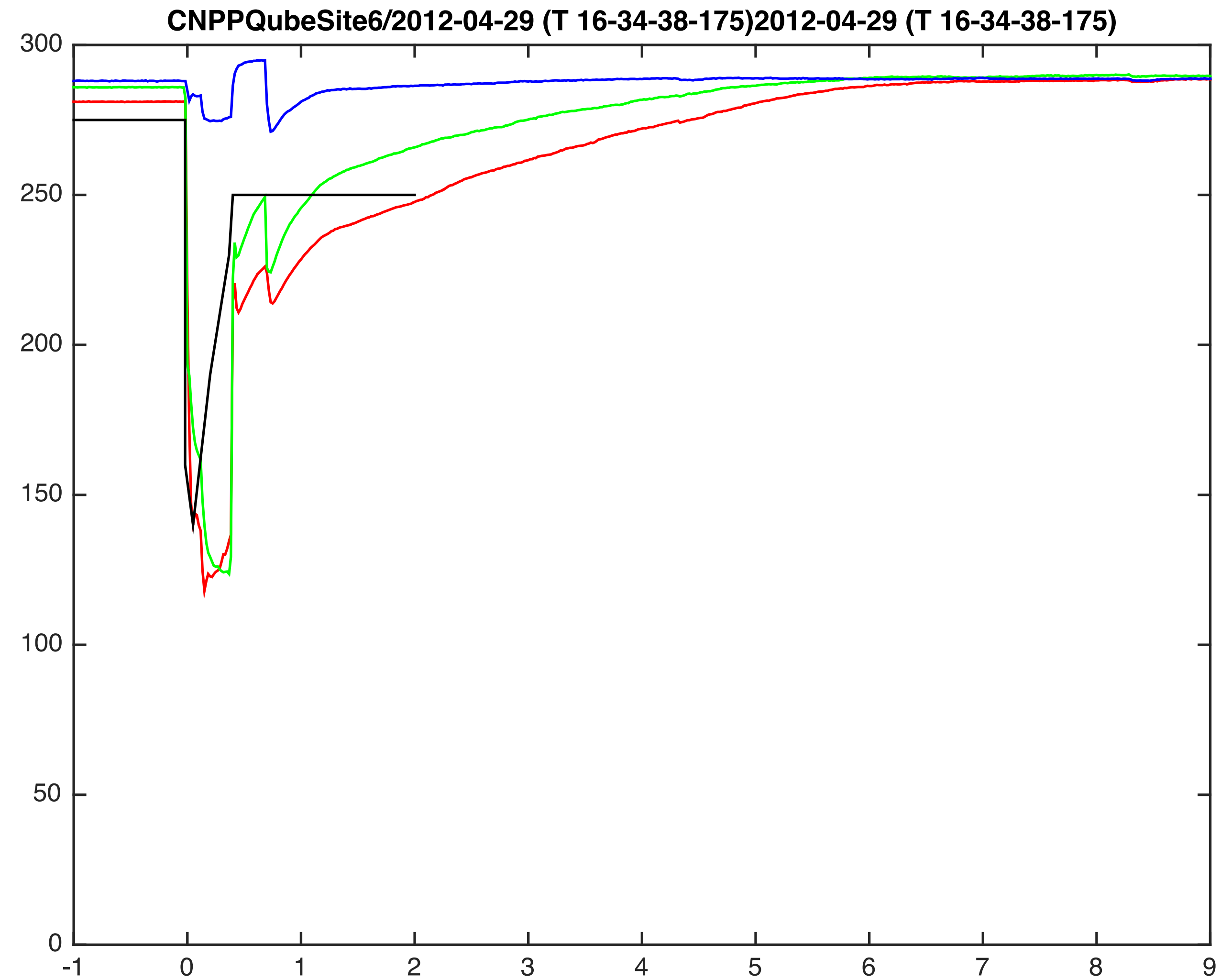
- single point data dropouts
- noise spikes
- normally cleared fault events

# Not of interest

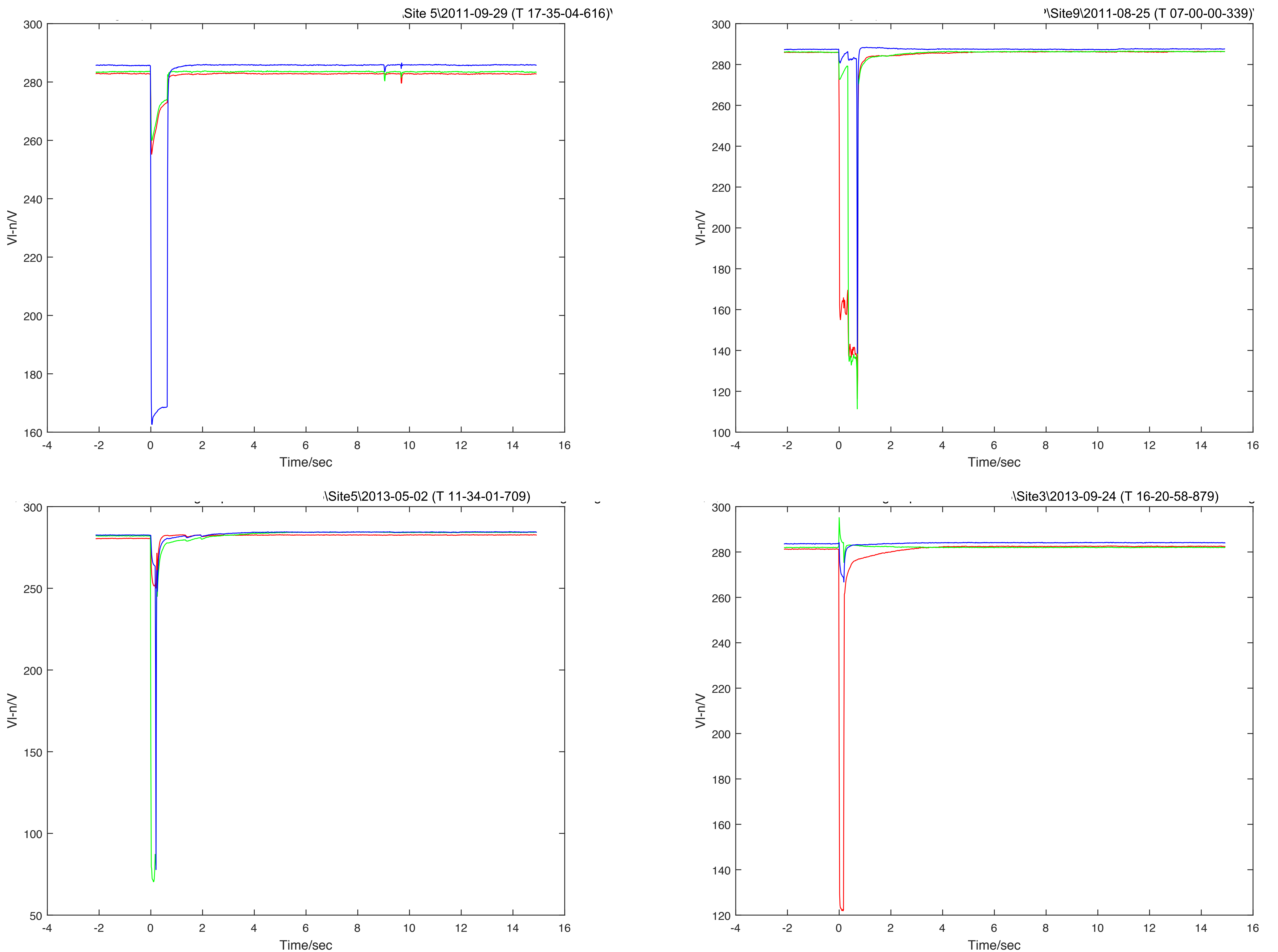
# Selected

first pass filtering
selected 317 events

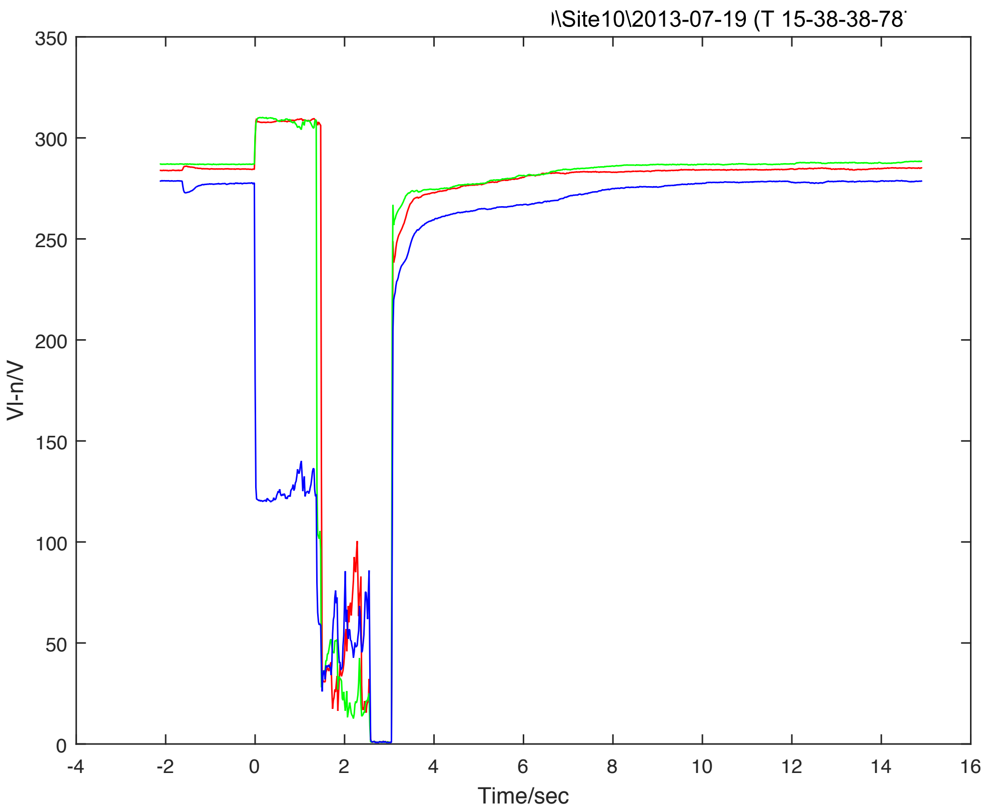


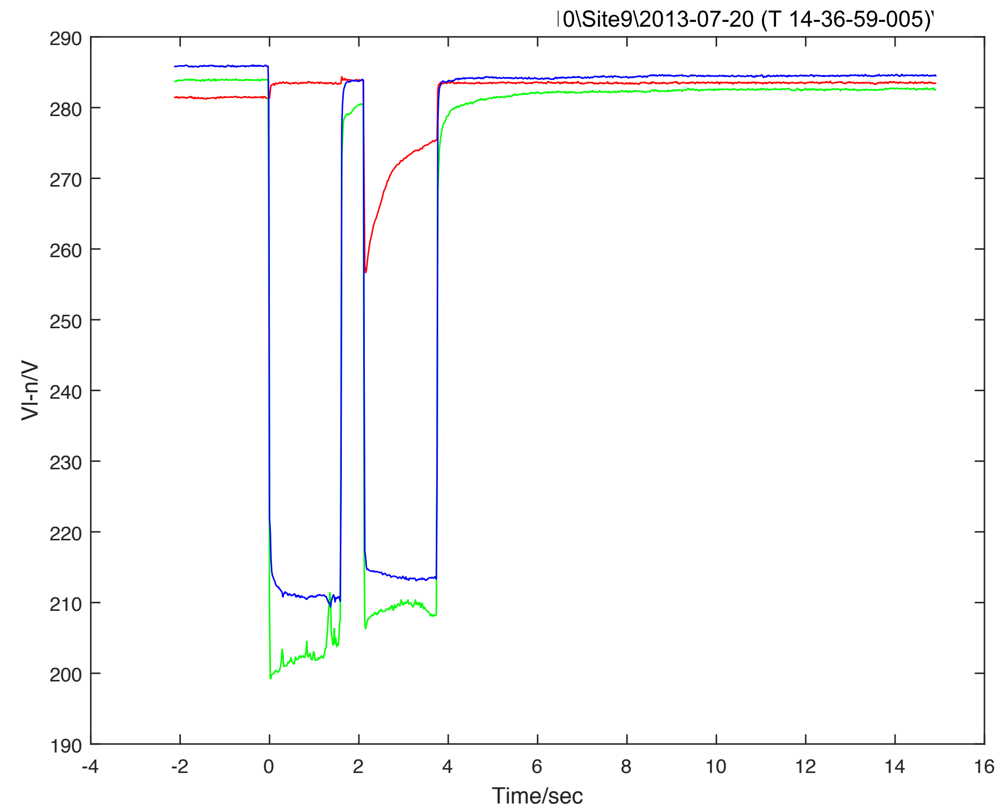



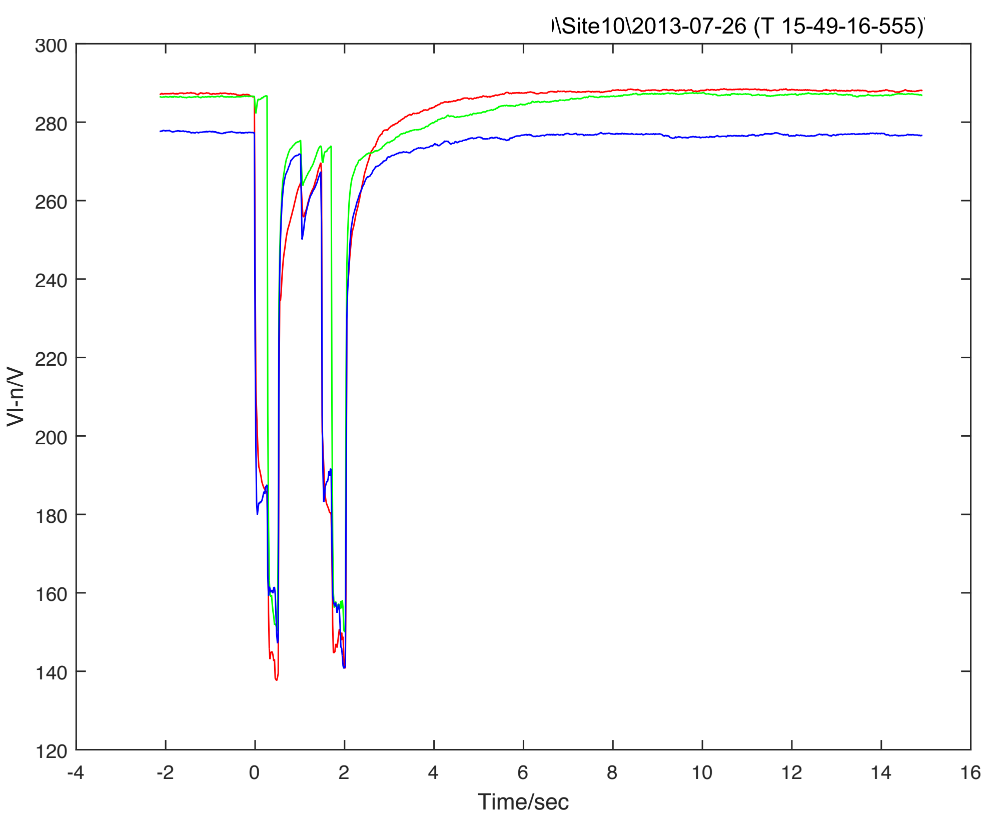
# Non-FIDVR events

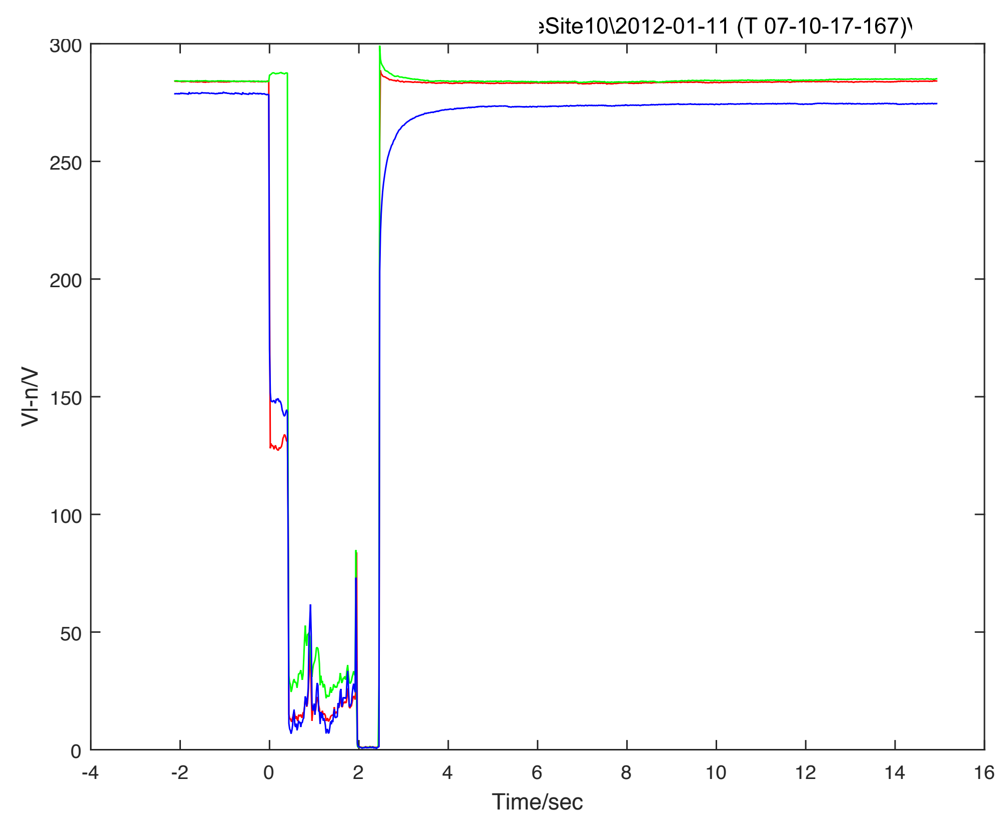


# Complicated events

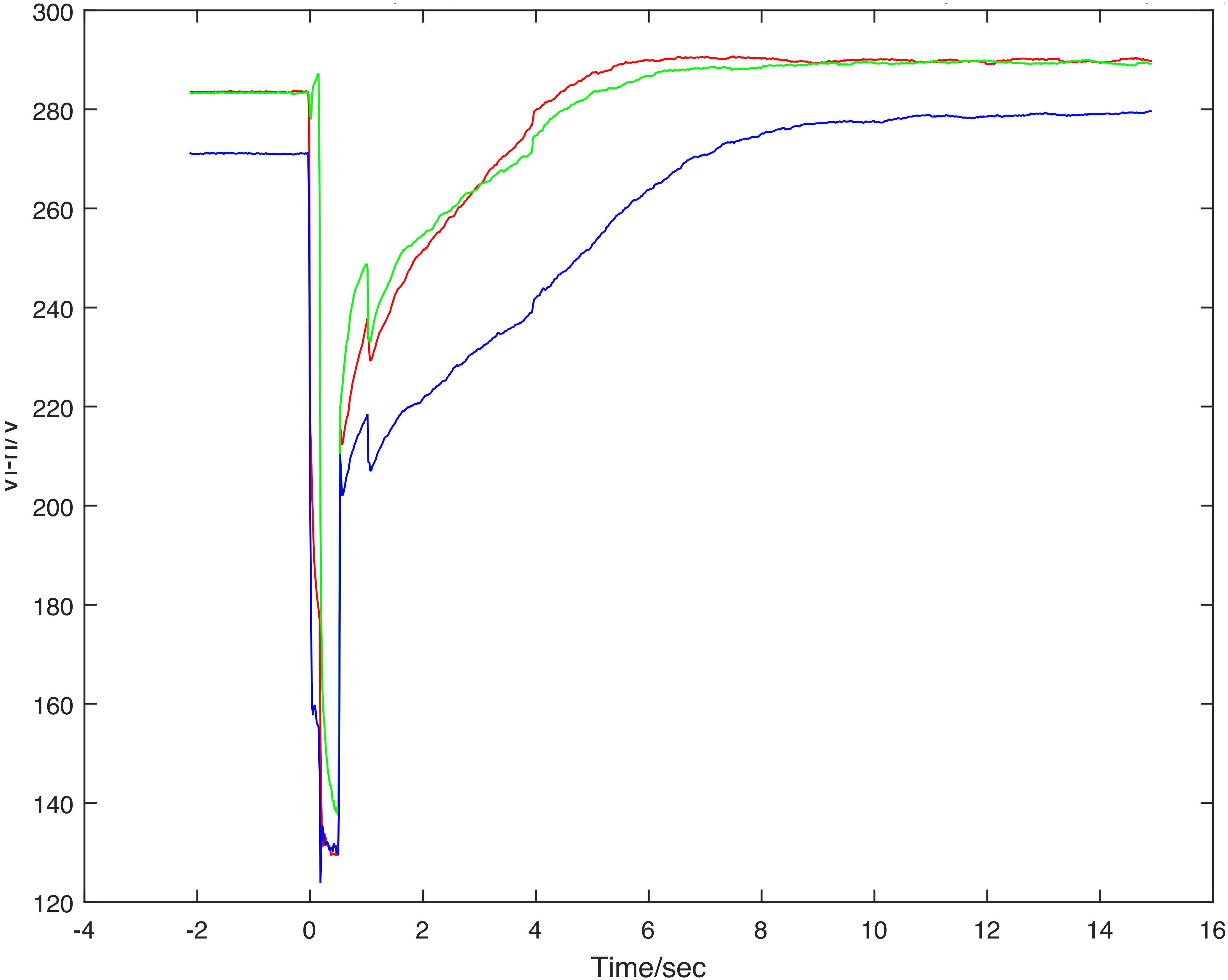


# Events of interest



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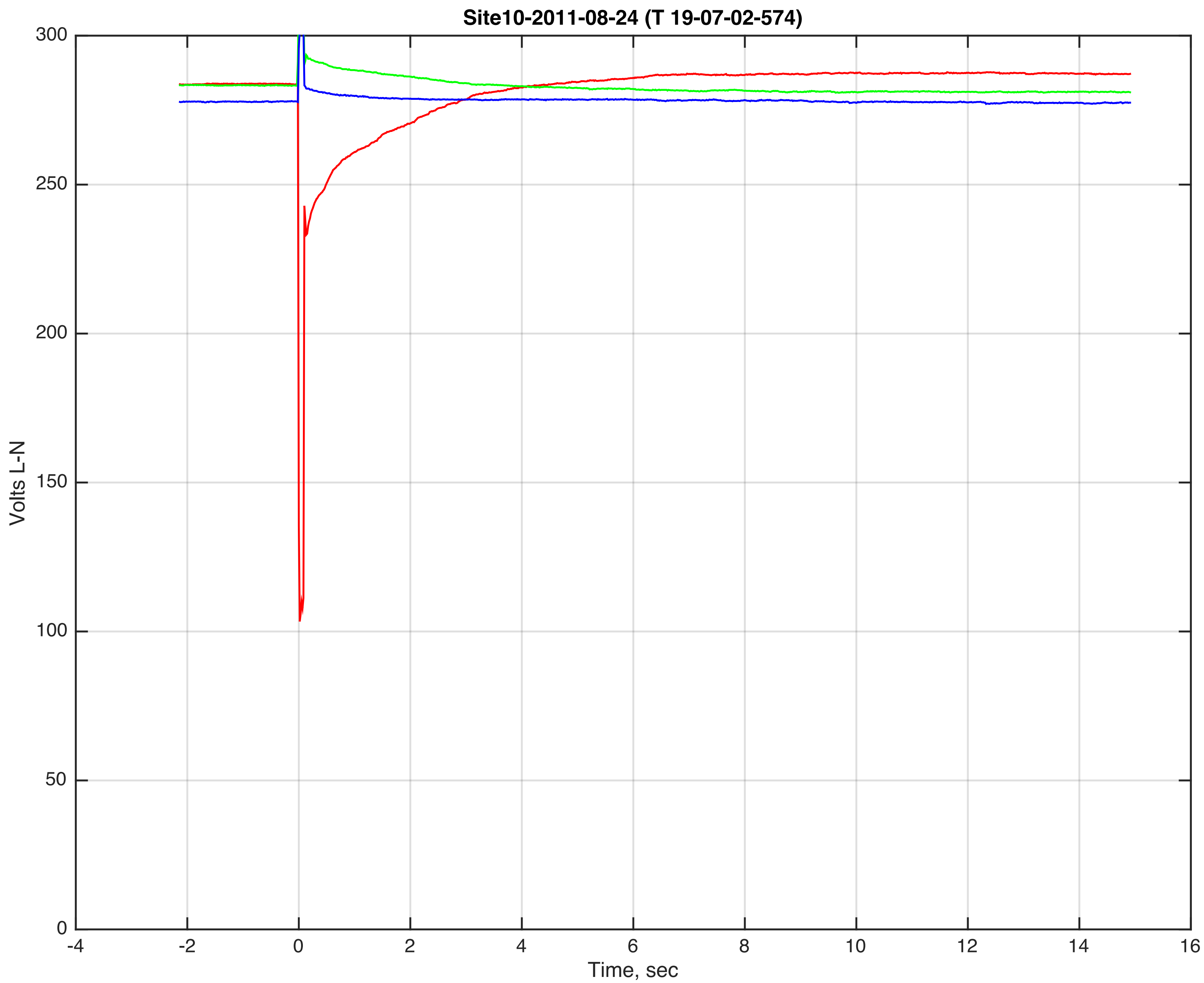
Time/sec

Event 291
Dip Duration 0.117 second (7 cycles)
Initial voltage a,b,c 283.7 283.3 277.8
Final voltage a,b,c 287.4 281.1 277.7

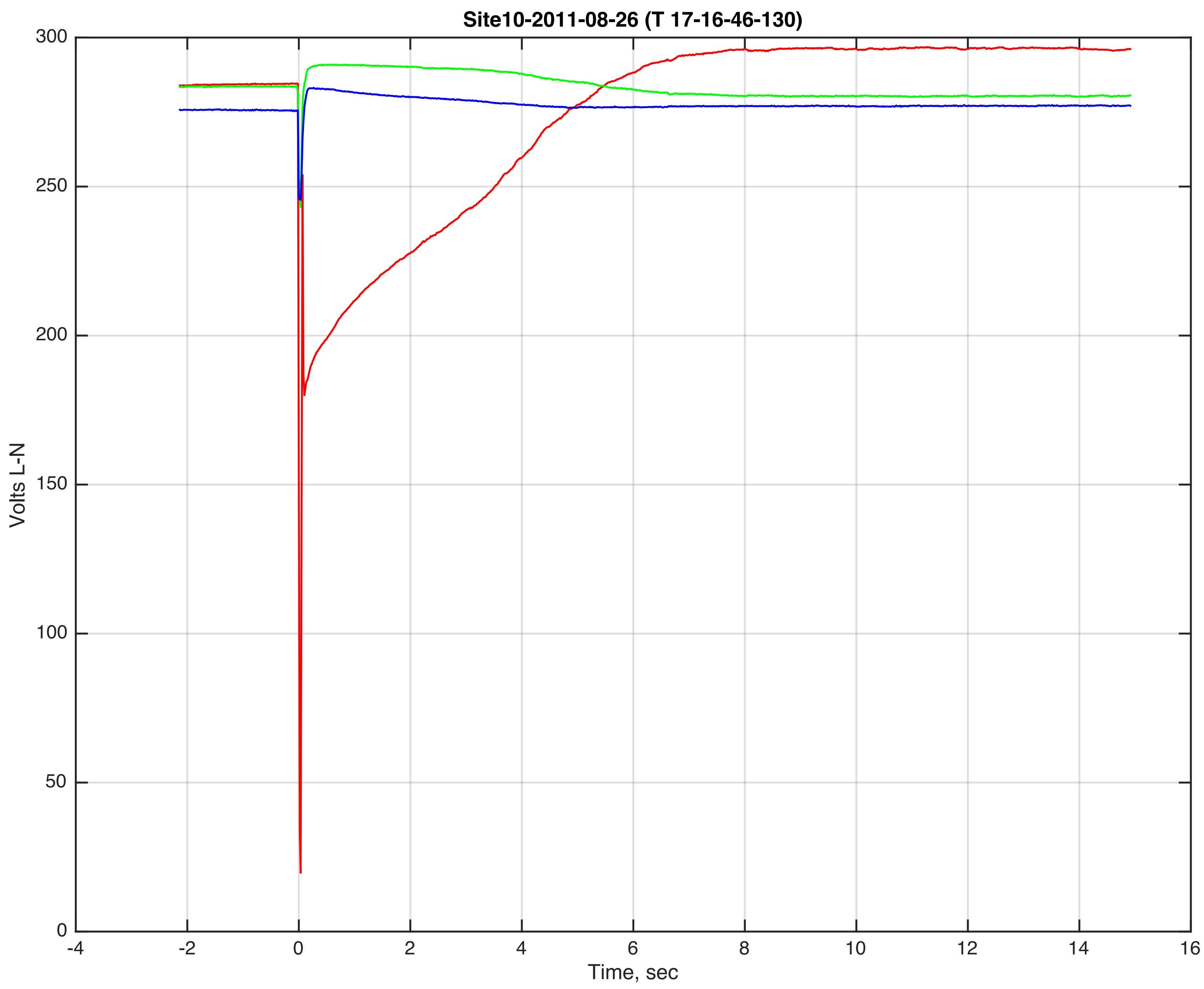


Event 265

Dip Duration 0.067 second (4 cycles)

Initial voltage a,b,c 284.5 283.7 275.4

Final voltage a,b,c 296.4 280.3 277.7

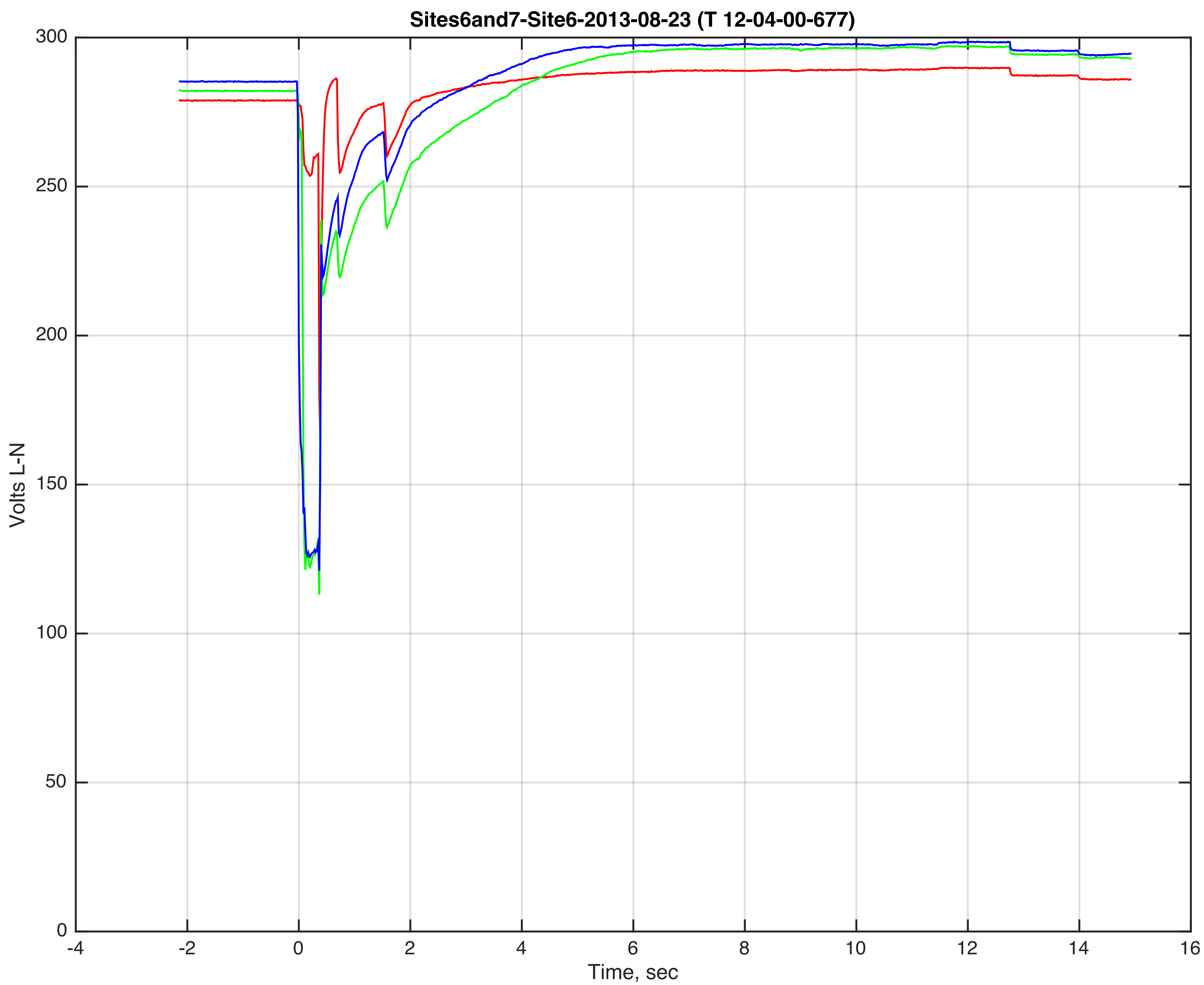


Event 55

Dip Duration 0.4 second (24 cycles)

Initial voltage a,b,c 278.9 282.1 285.2

Final voltage a,b,c 289.2 296.9 298.5

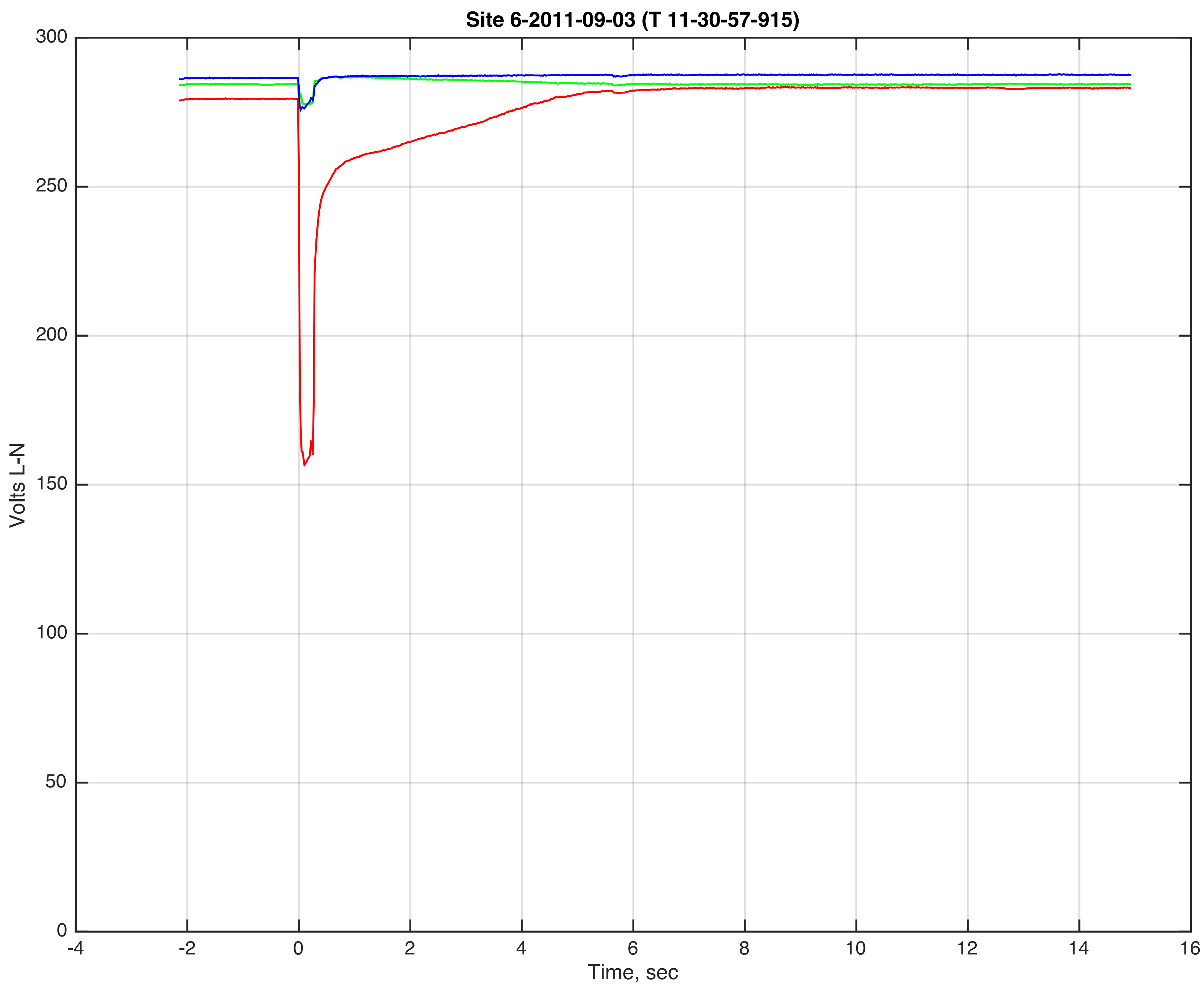


Event 243

Dip Duration 0.3 second (18 cycles)

Initial voltage a,b,c 279.4 284.5 286.5

Final voltage a,b,c 283.1 284.3 287.6

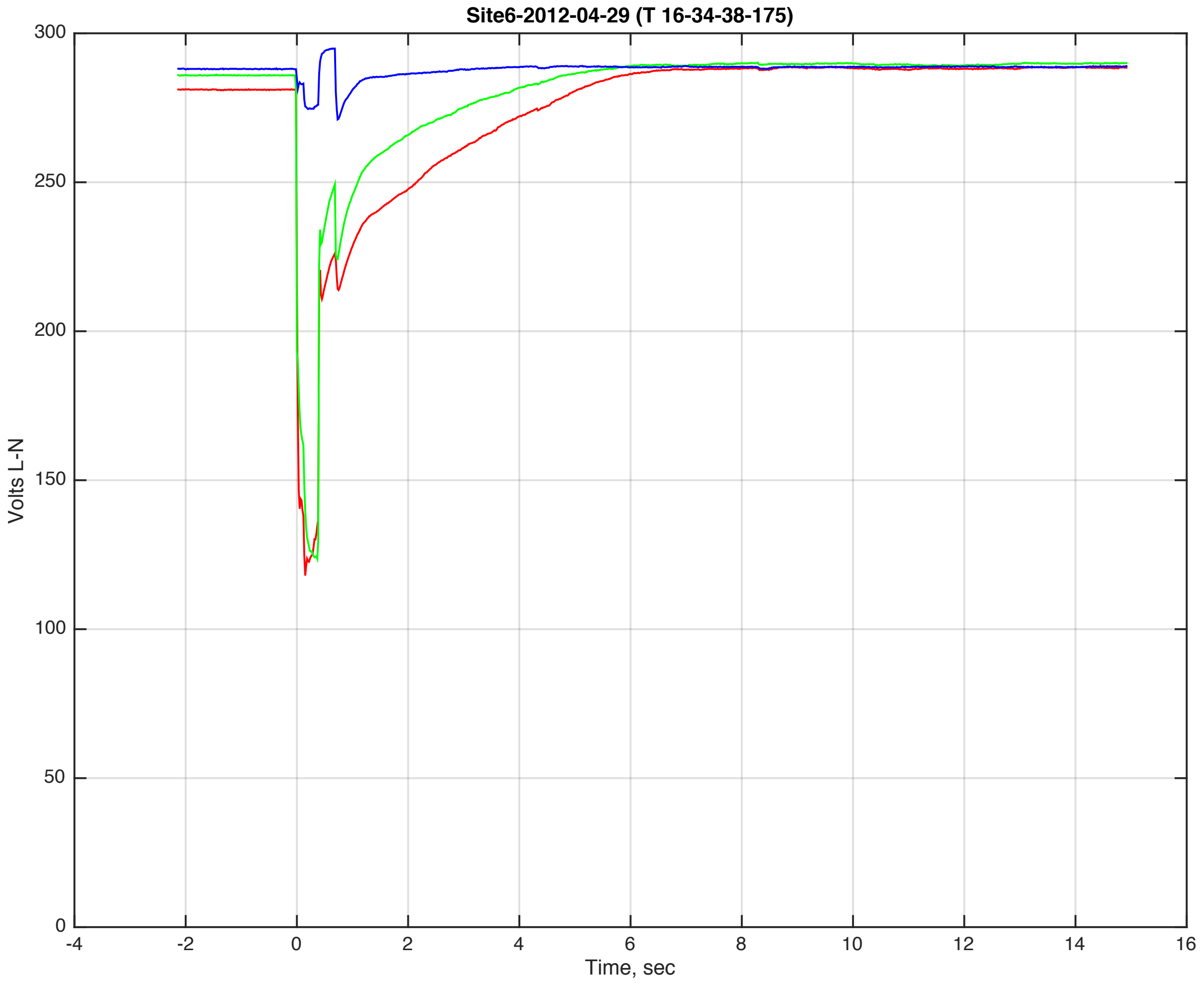


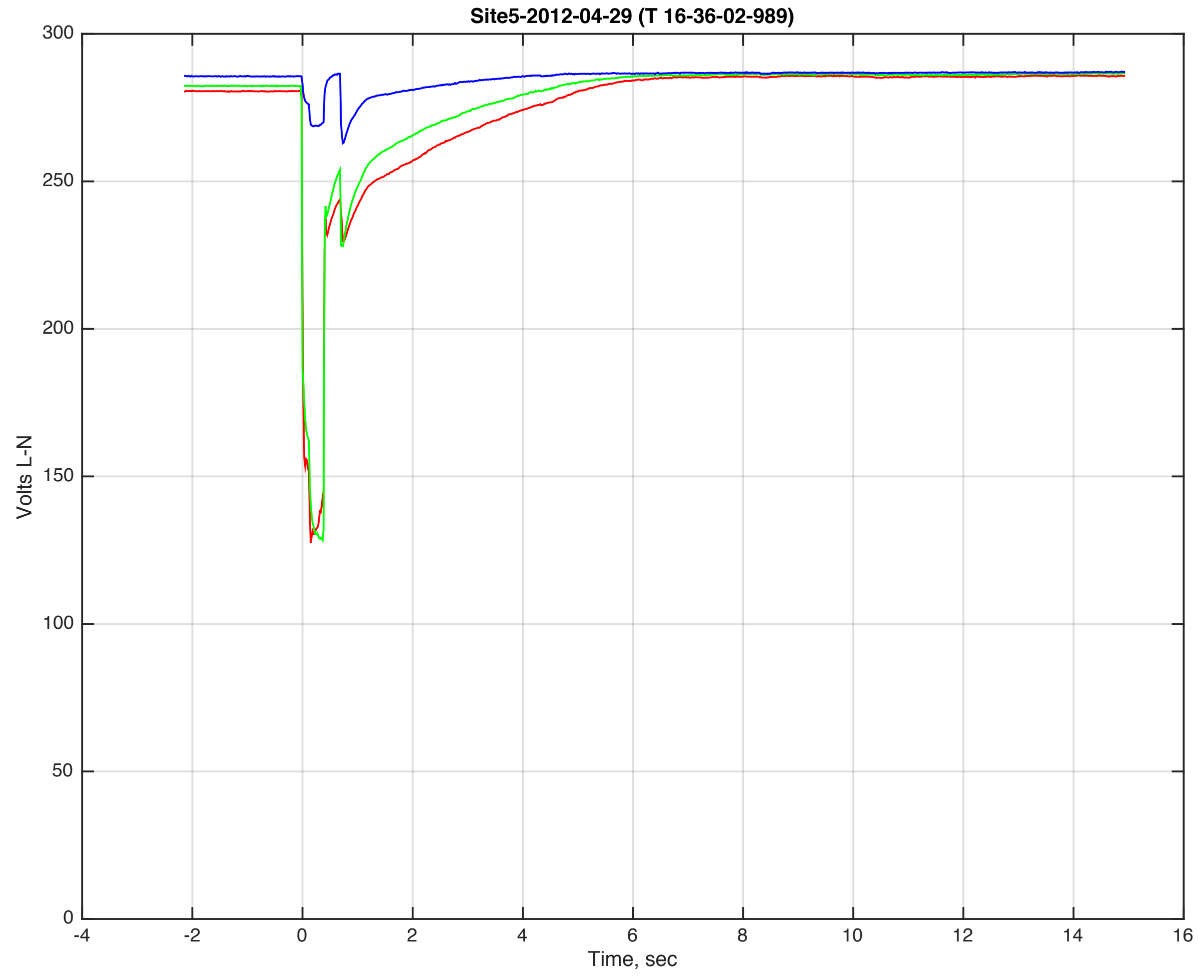
# Events 126 and 139

## Dip Duration 0.4 second (24 cycles)

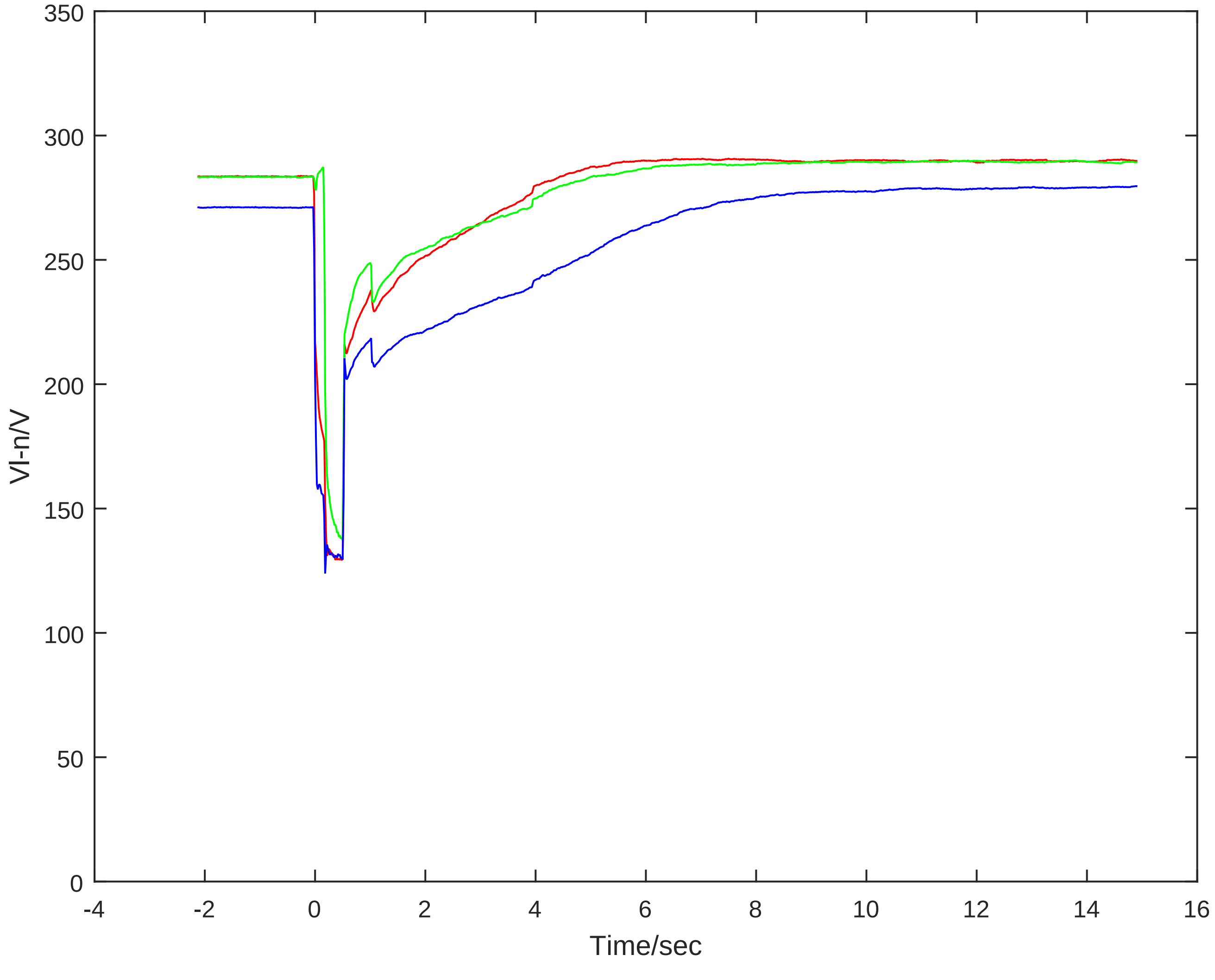
Init a,b,c 281.1 285.8 288.0
Final a,b,c 288.7 288.7 288.7

Init a,b,c 280.5 282.3 285.5
Final a,b,c 285.2 286.4 286.9



Thanks to Centerpoint Energy



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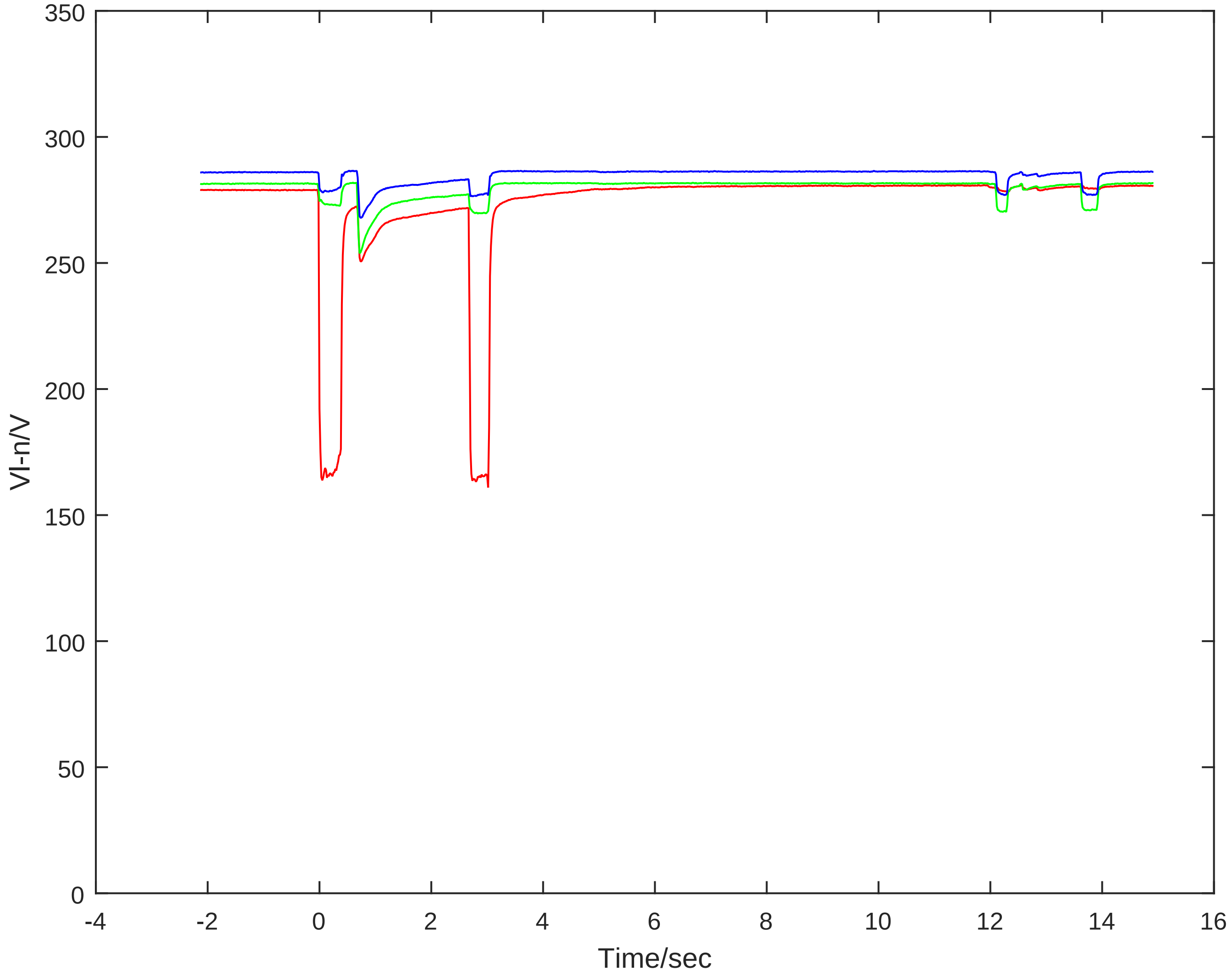

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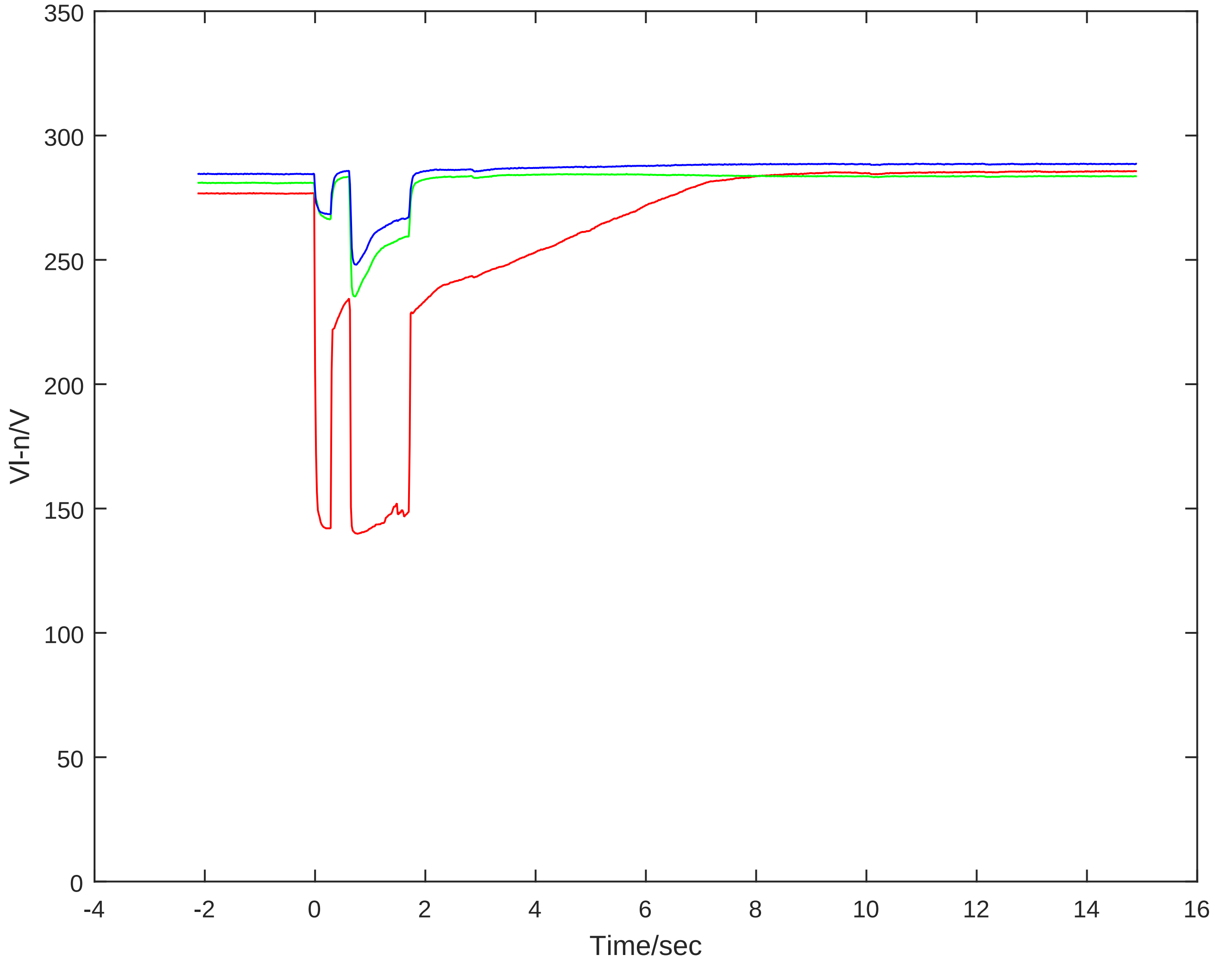

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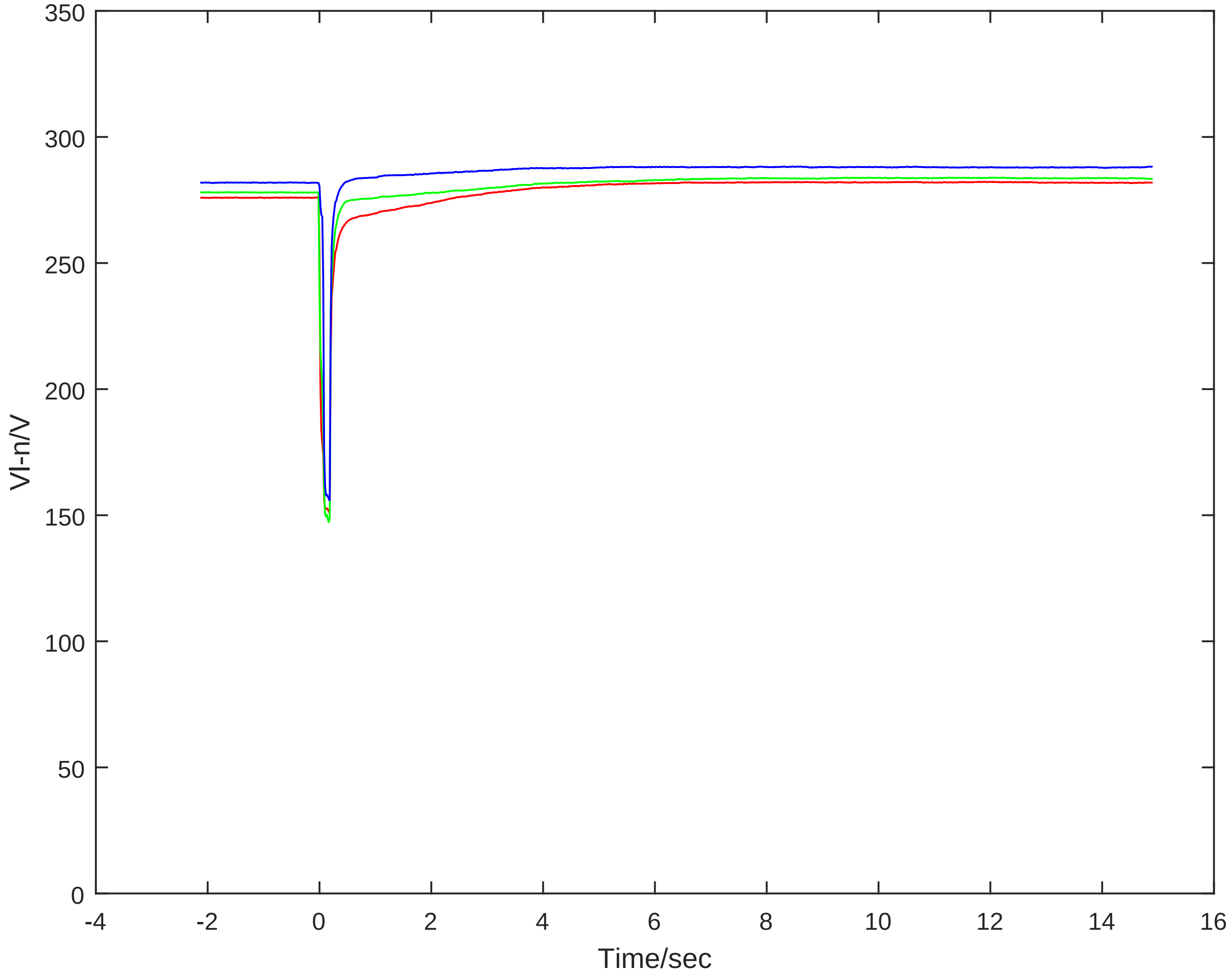
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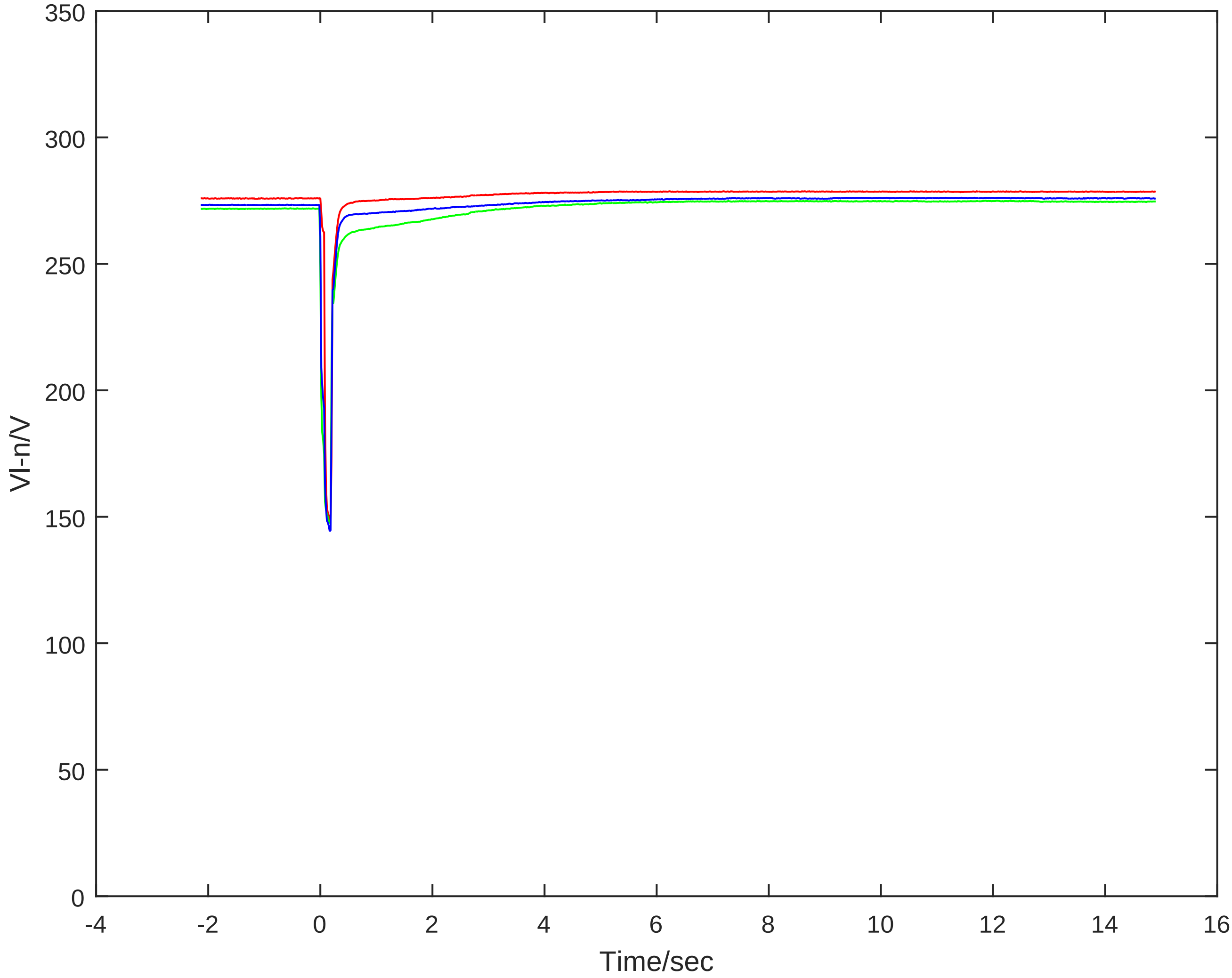

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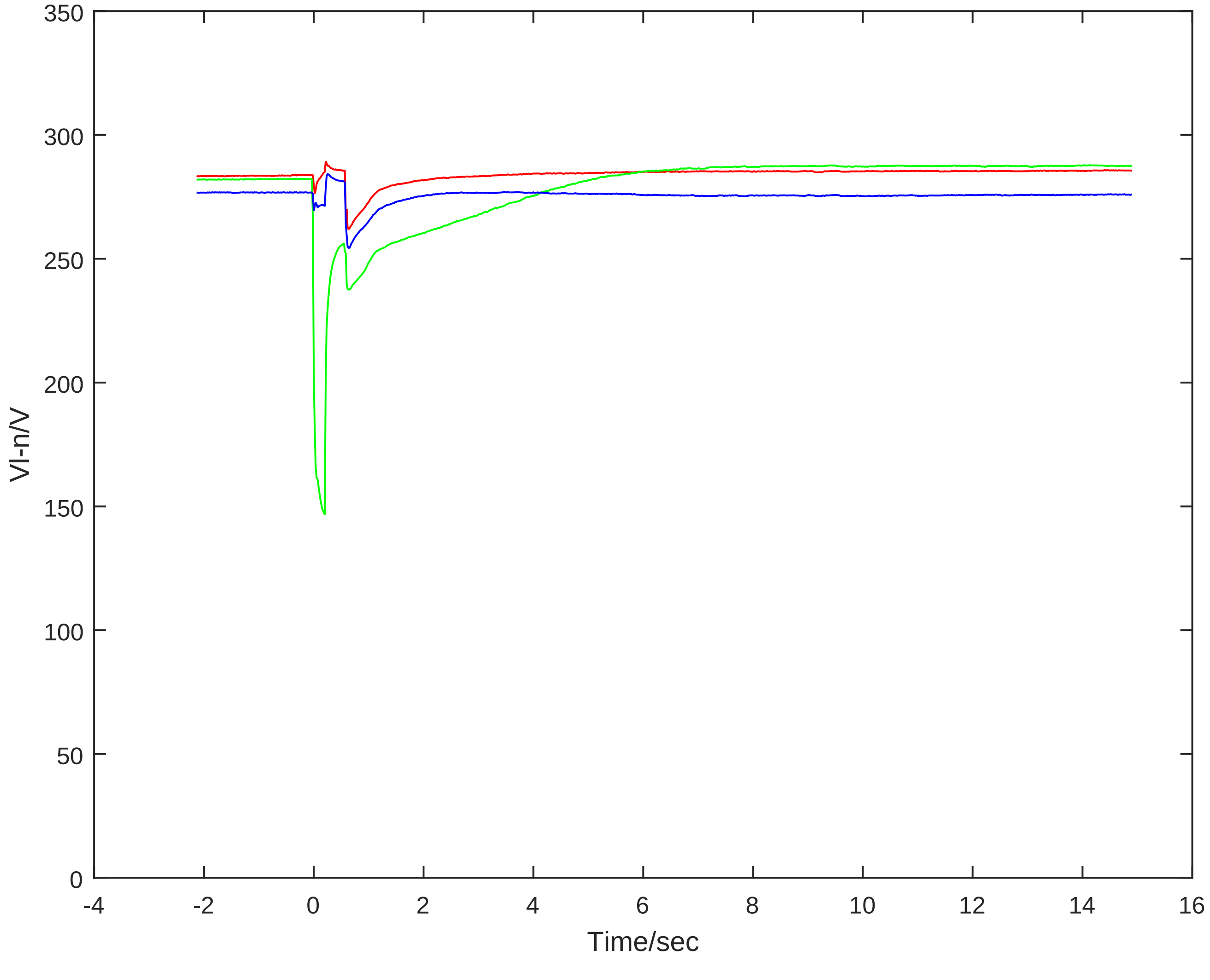

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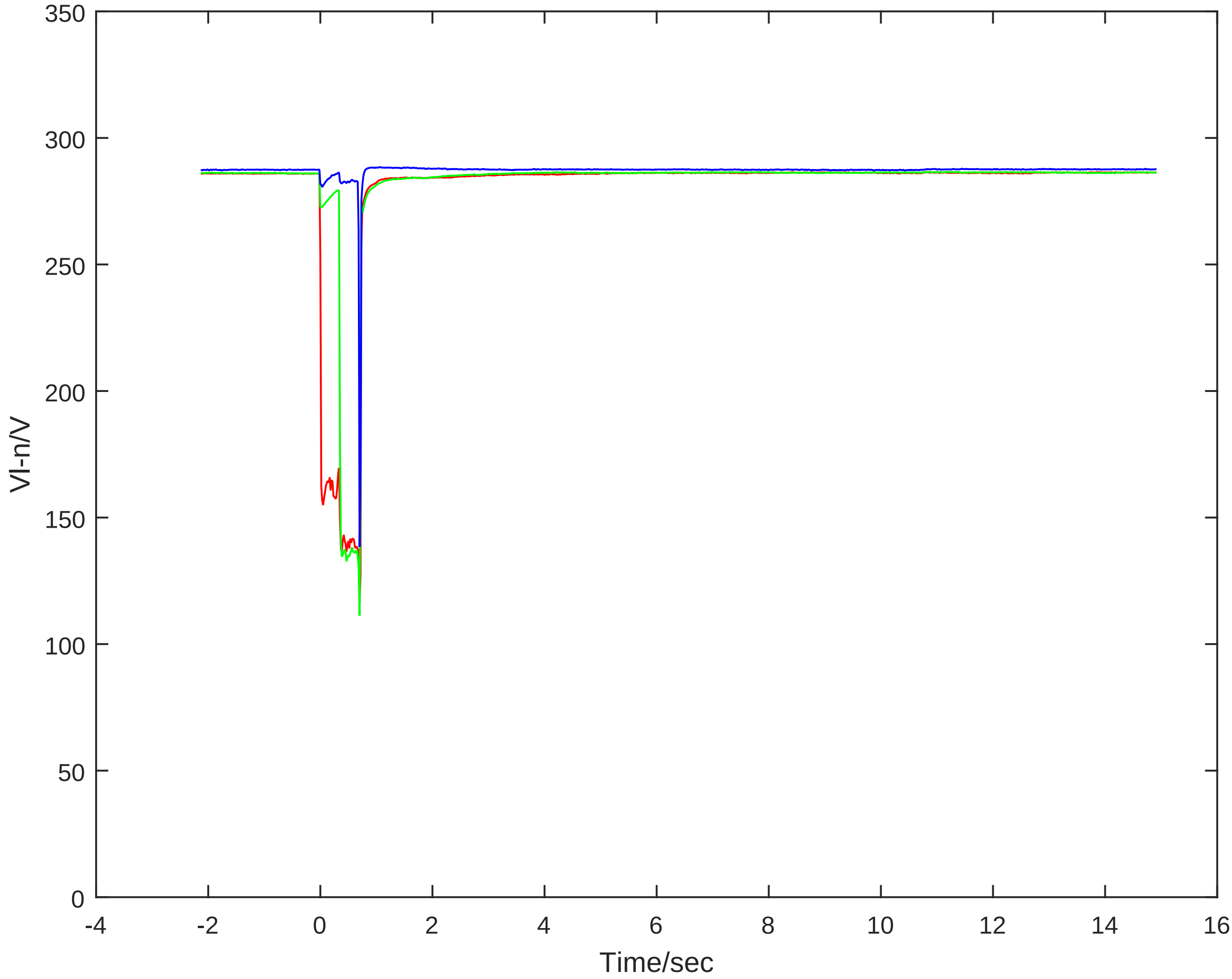
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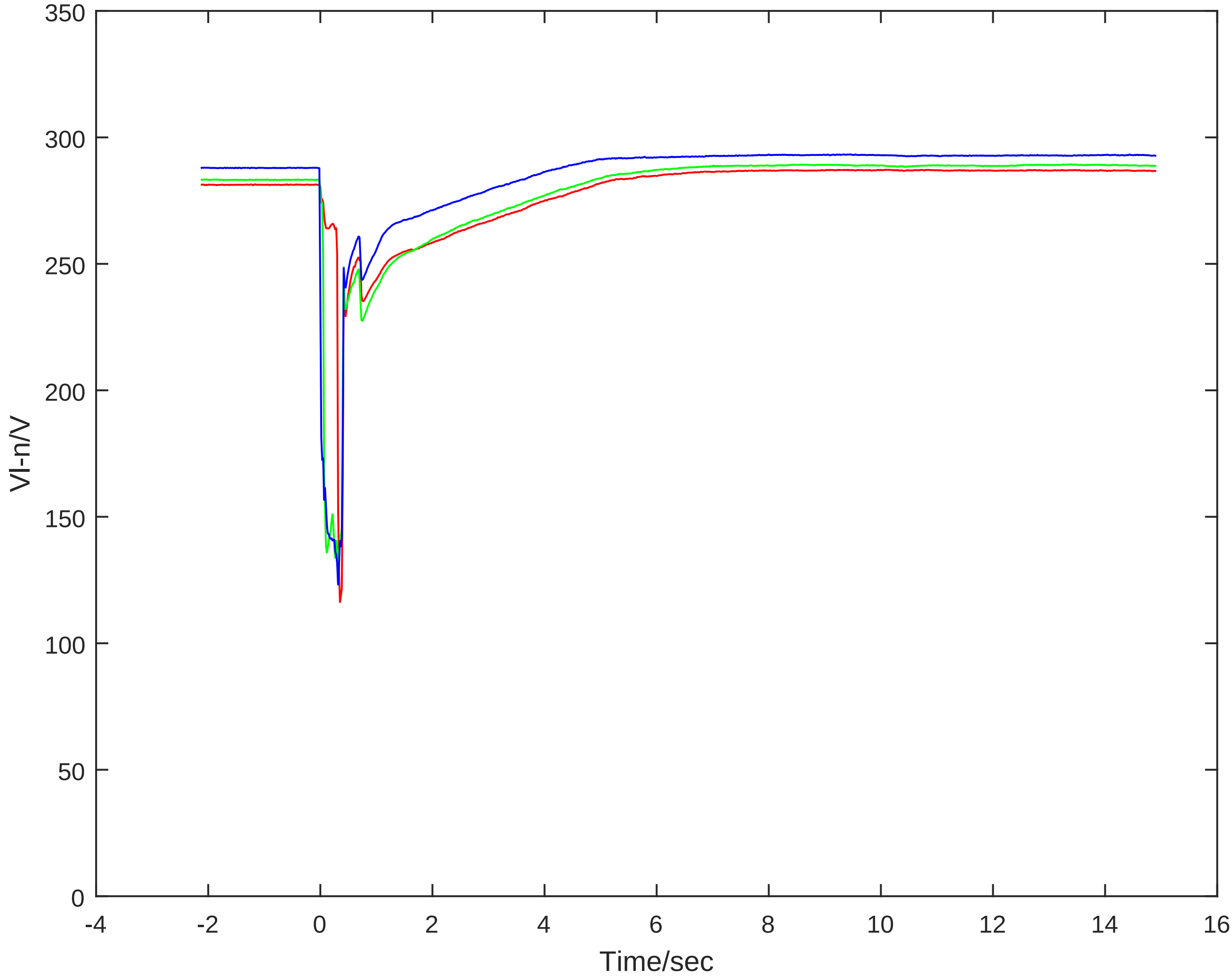

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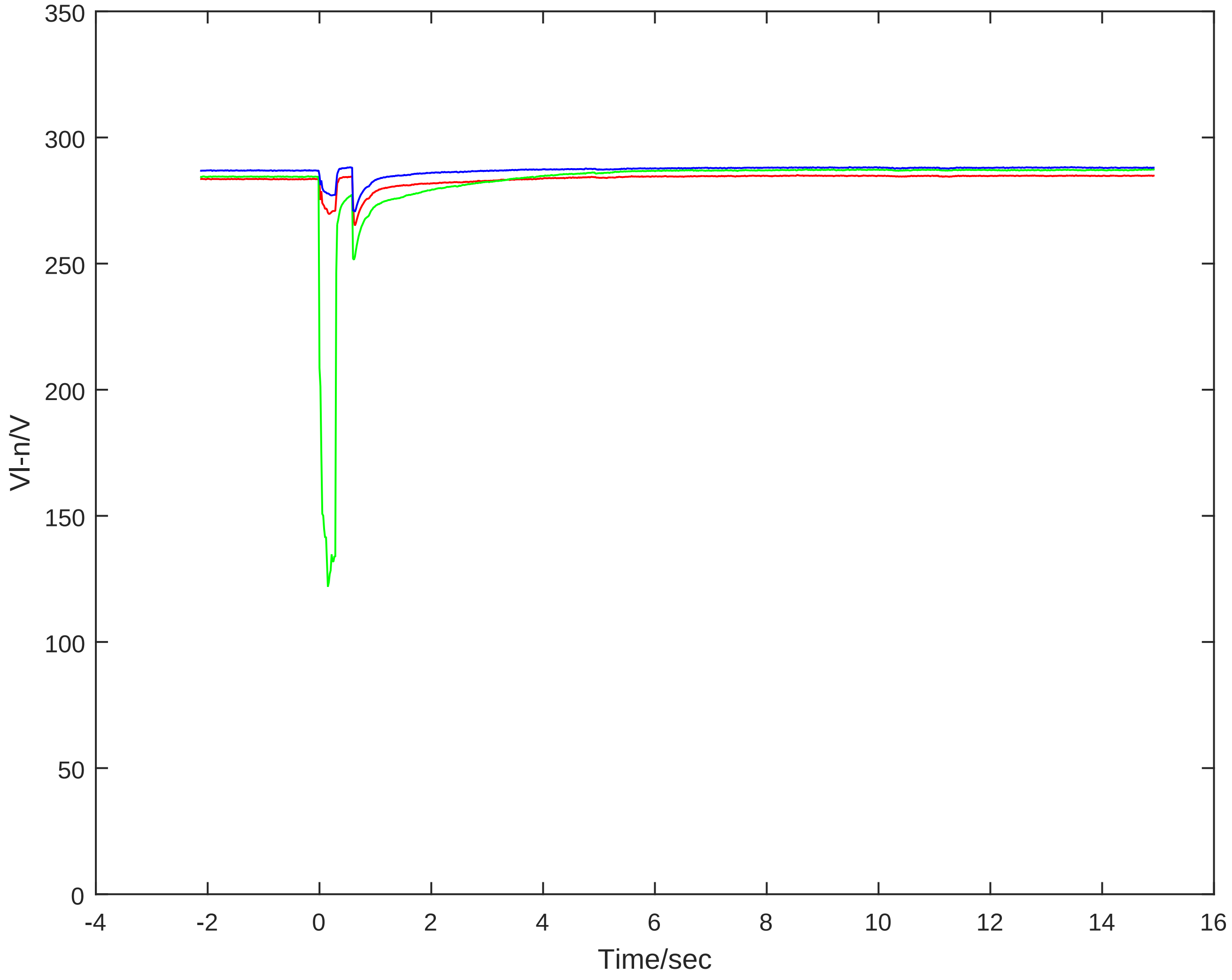

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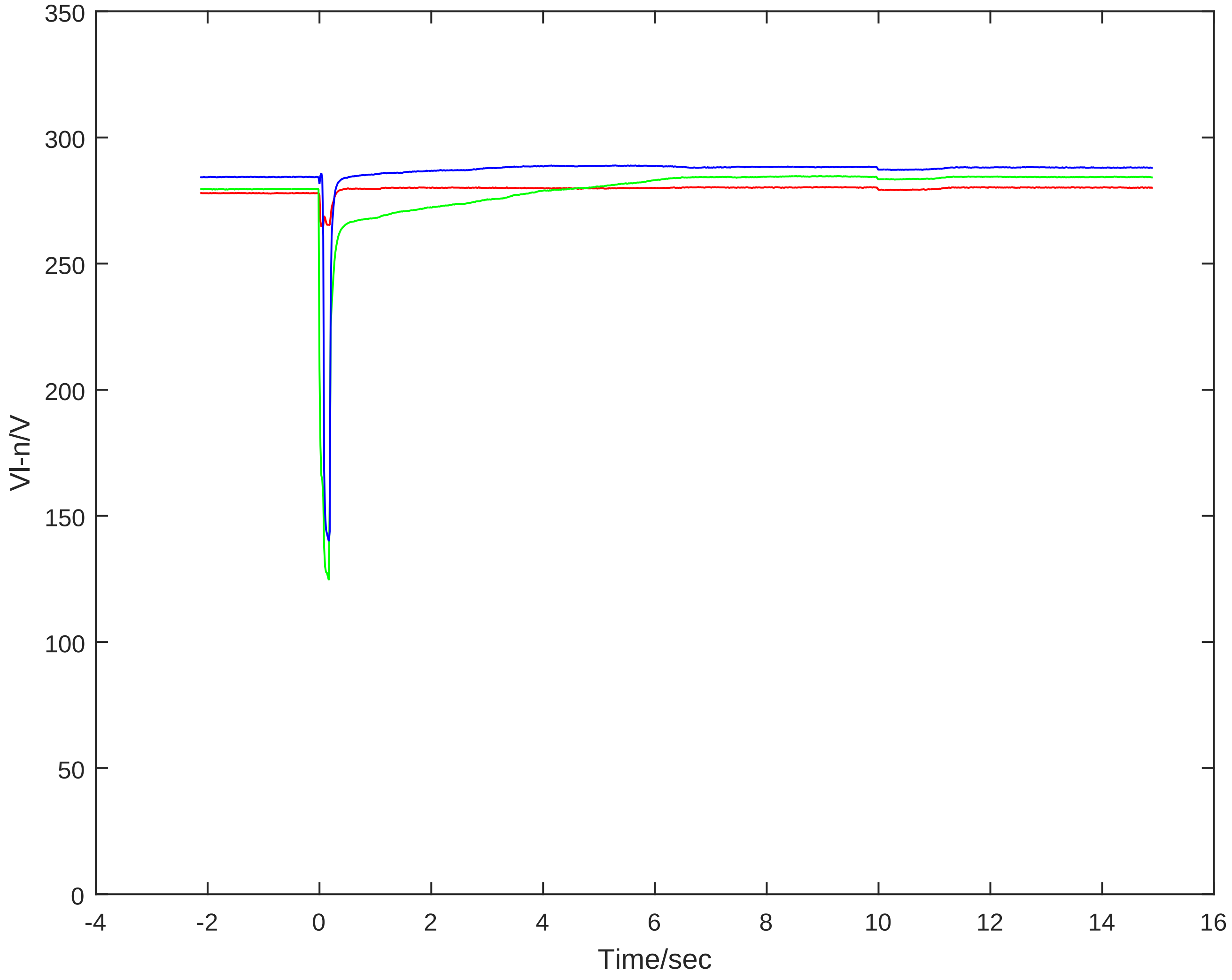

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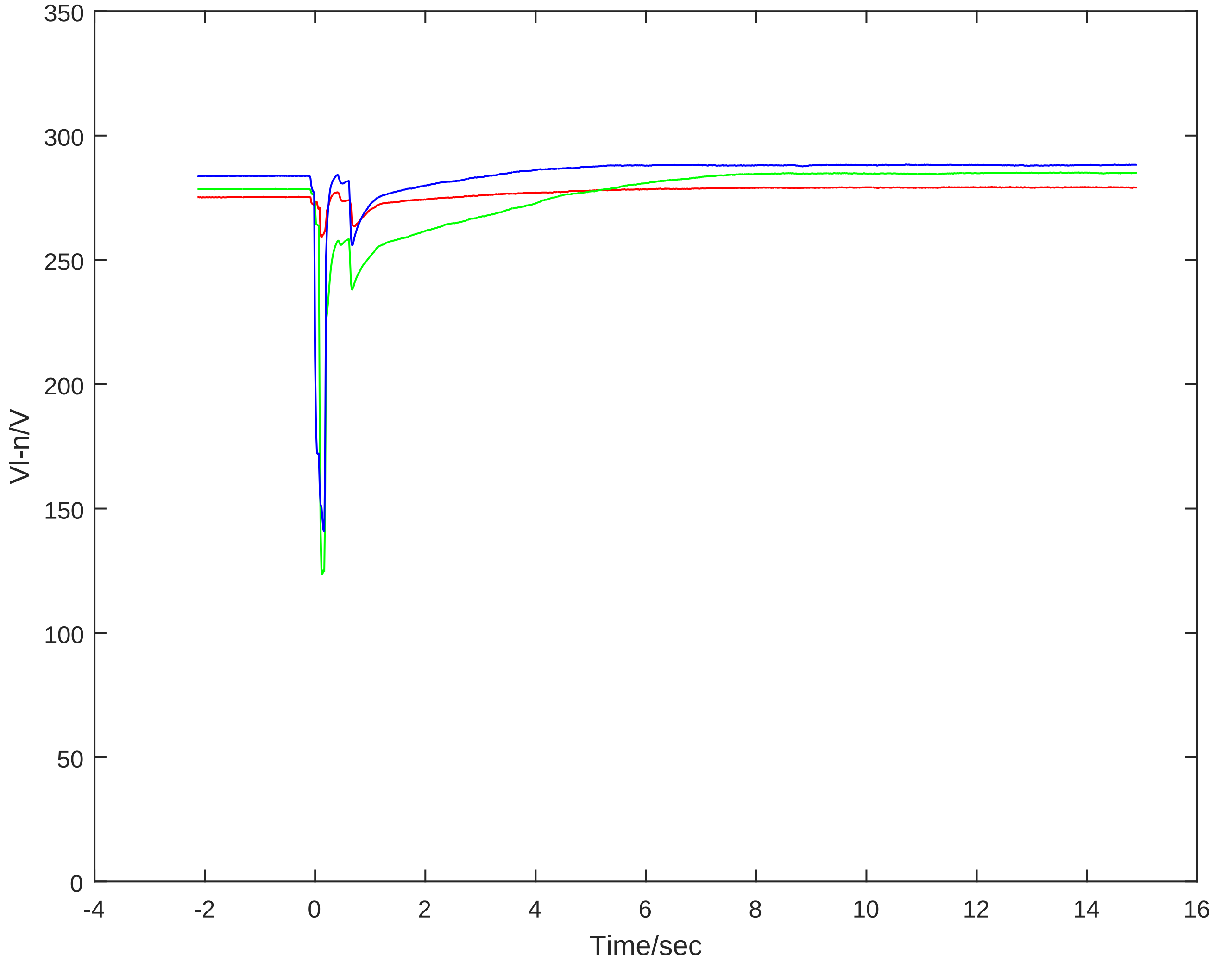

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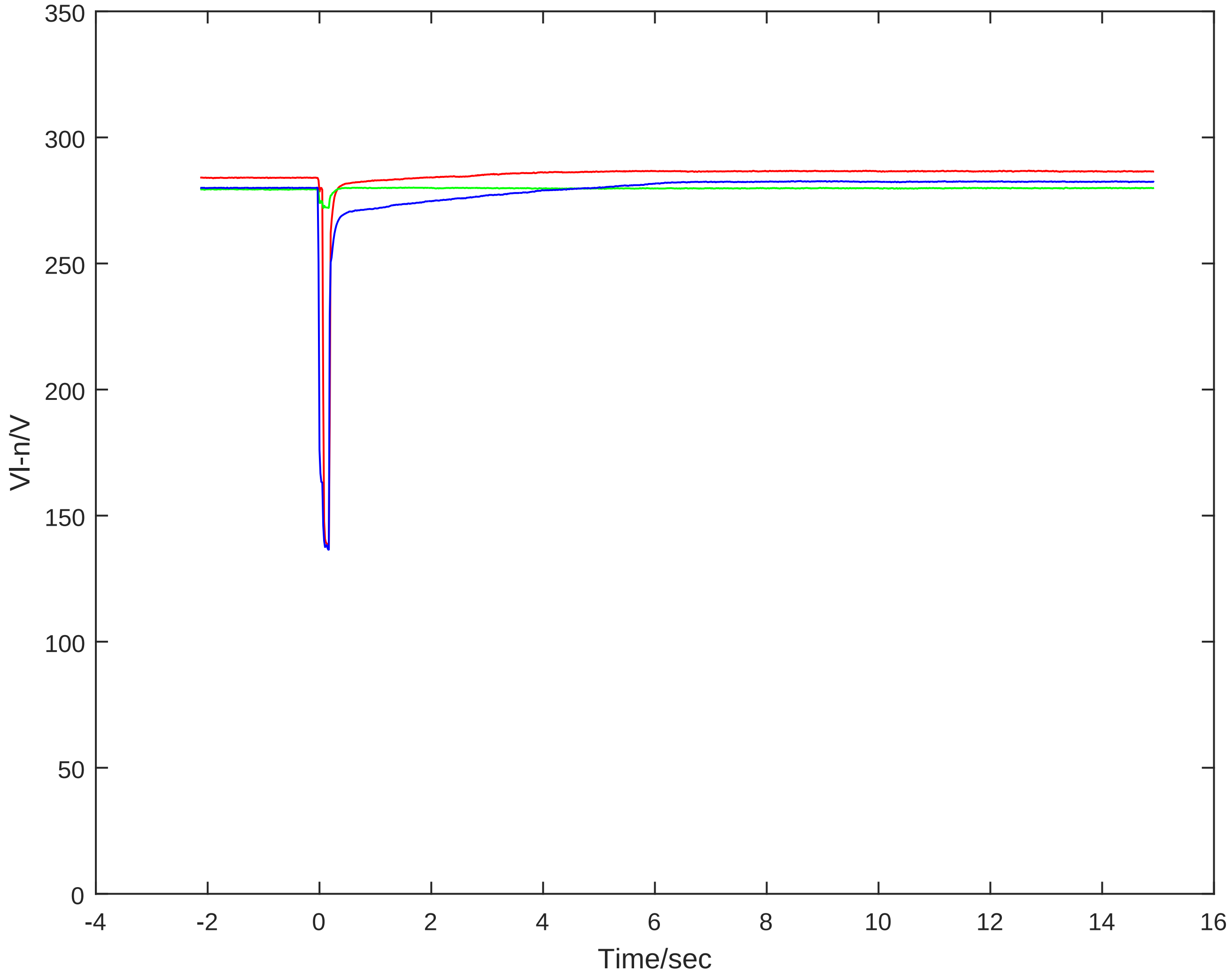
Time/sec



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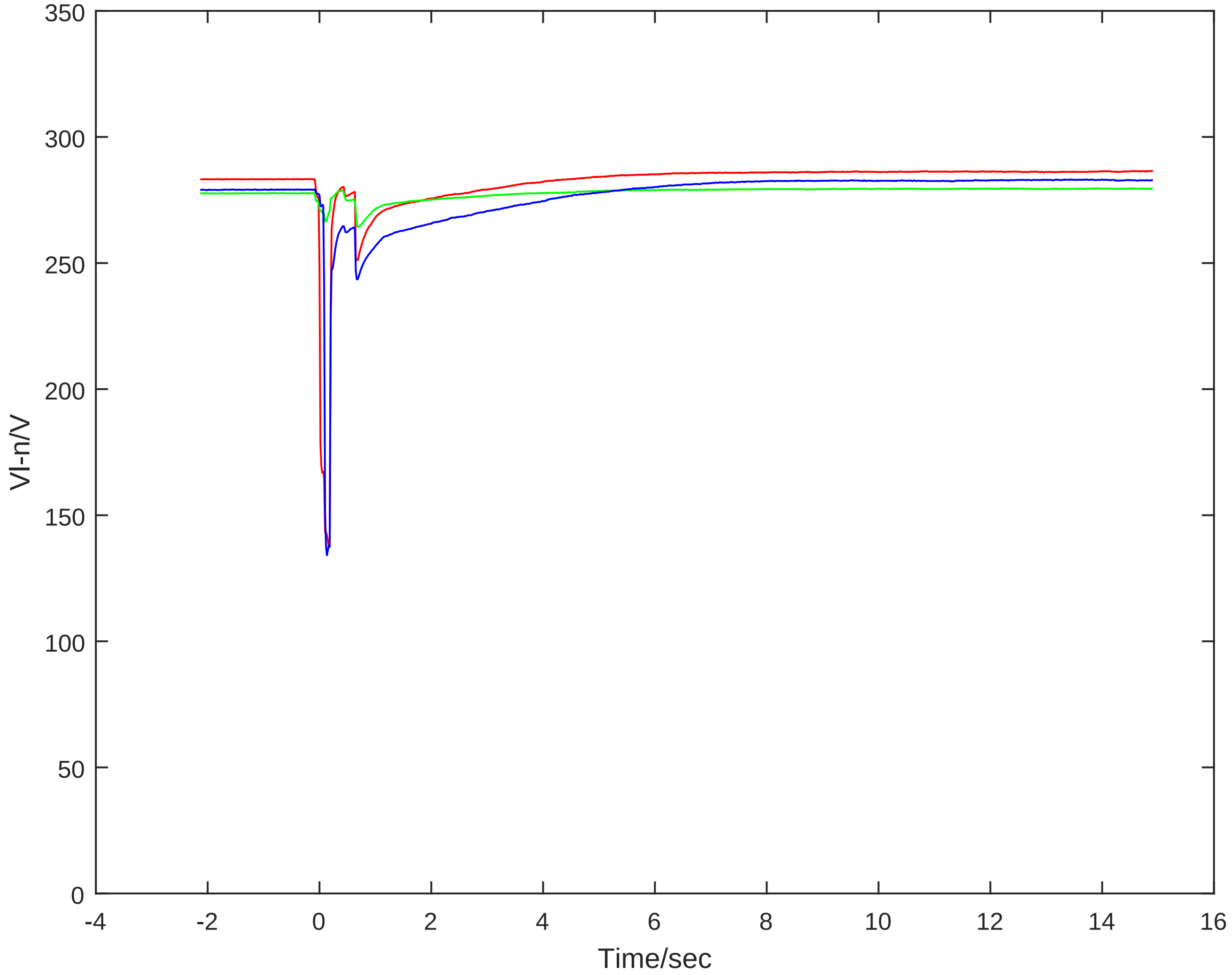
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Time/sec
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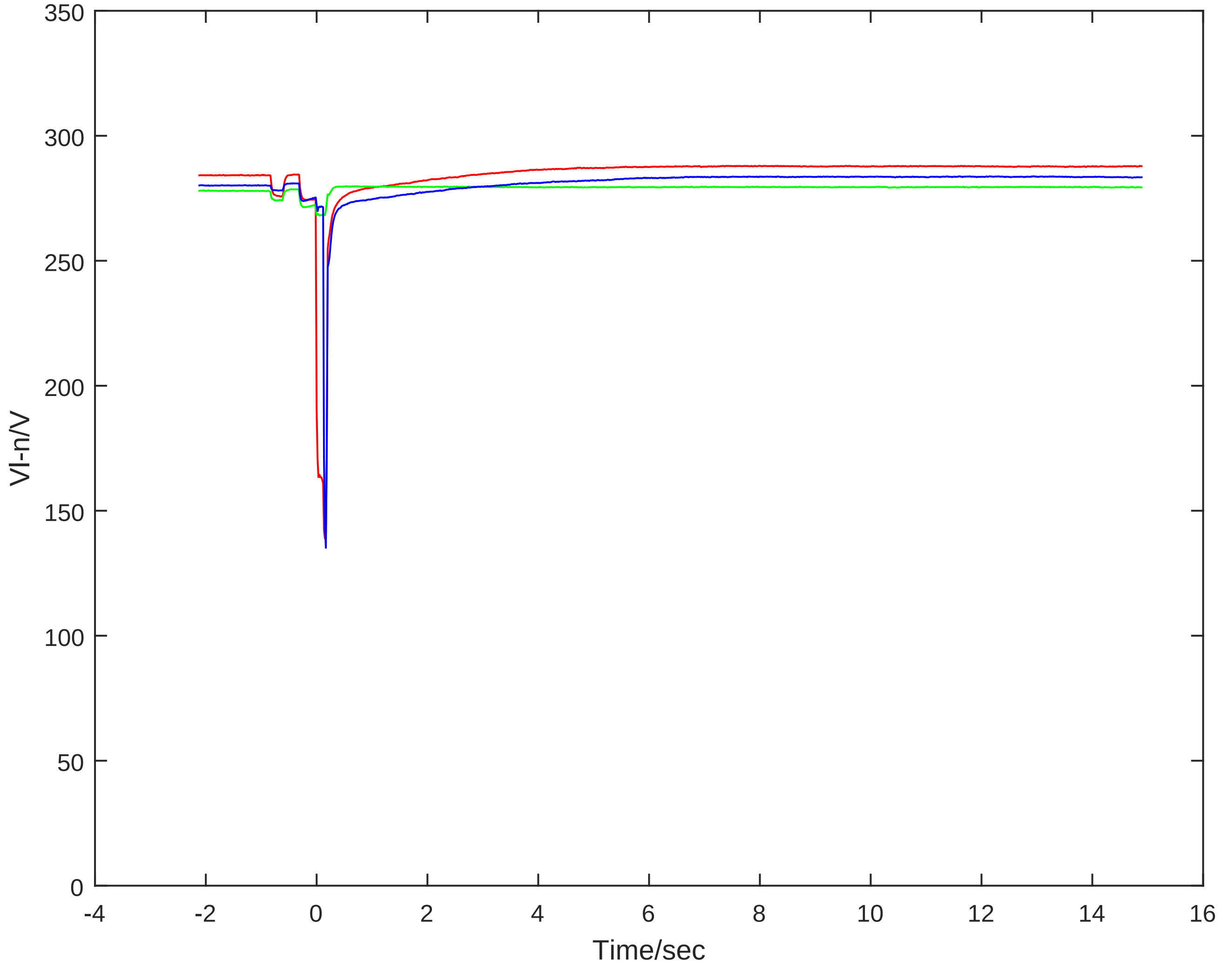

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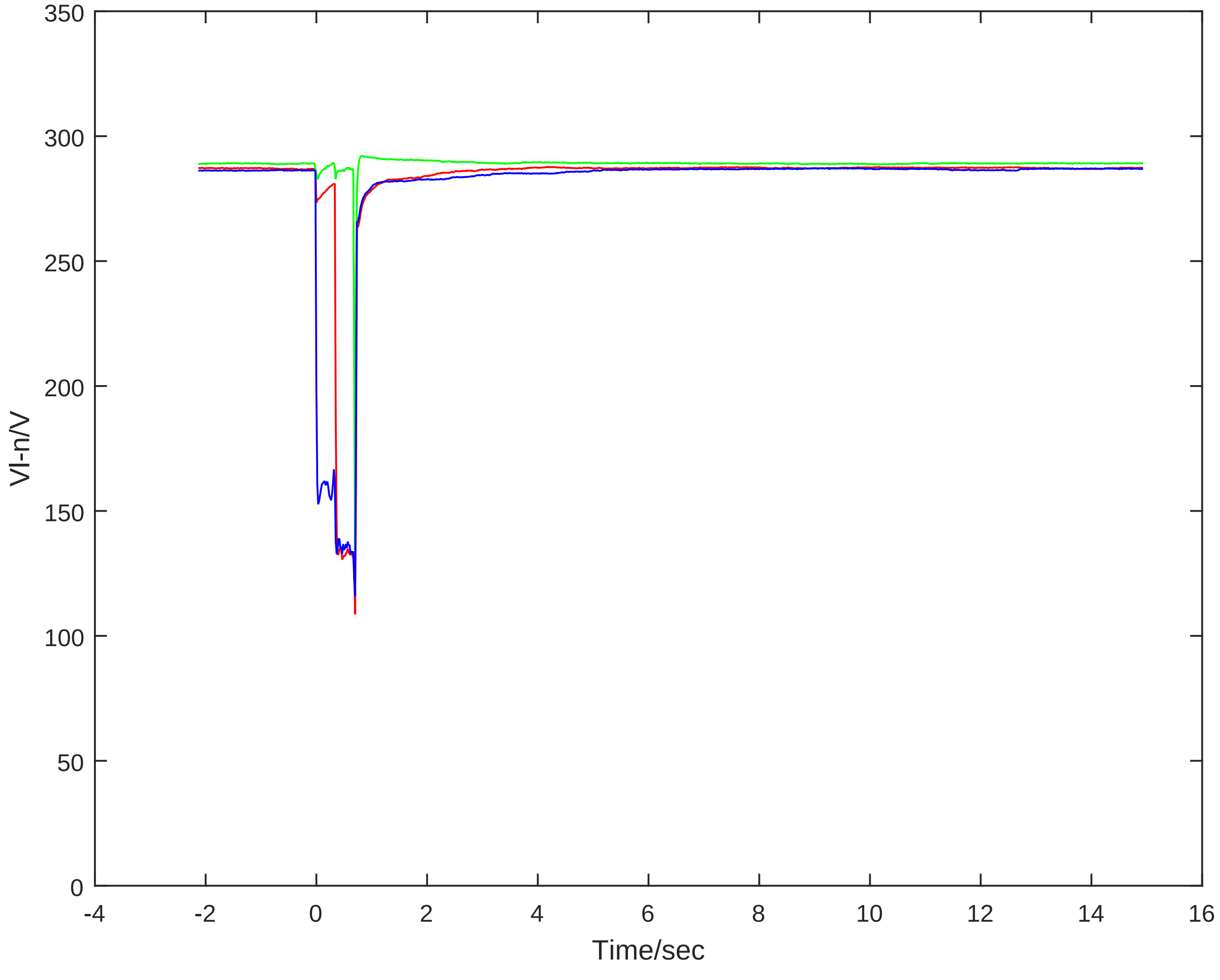

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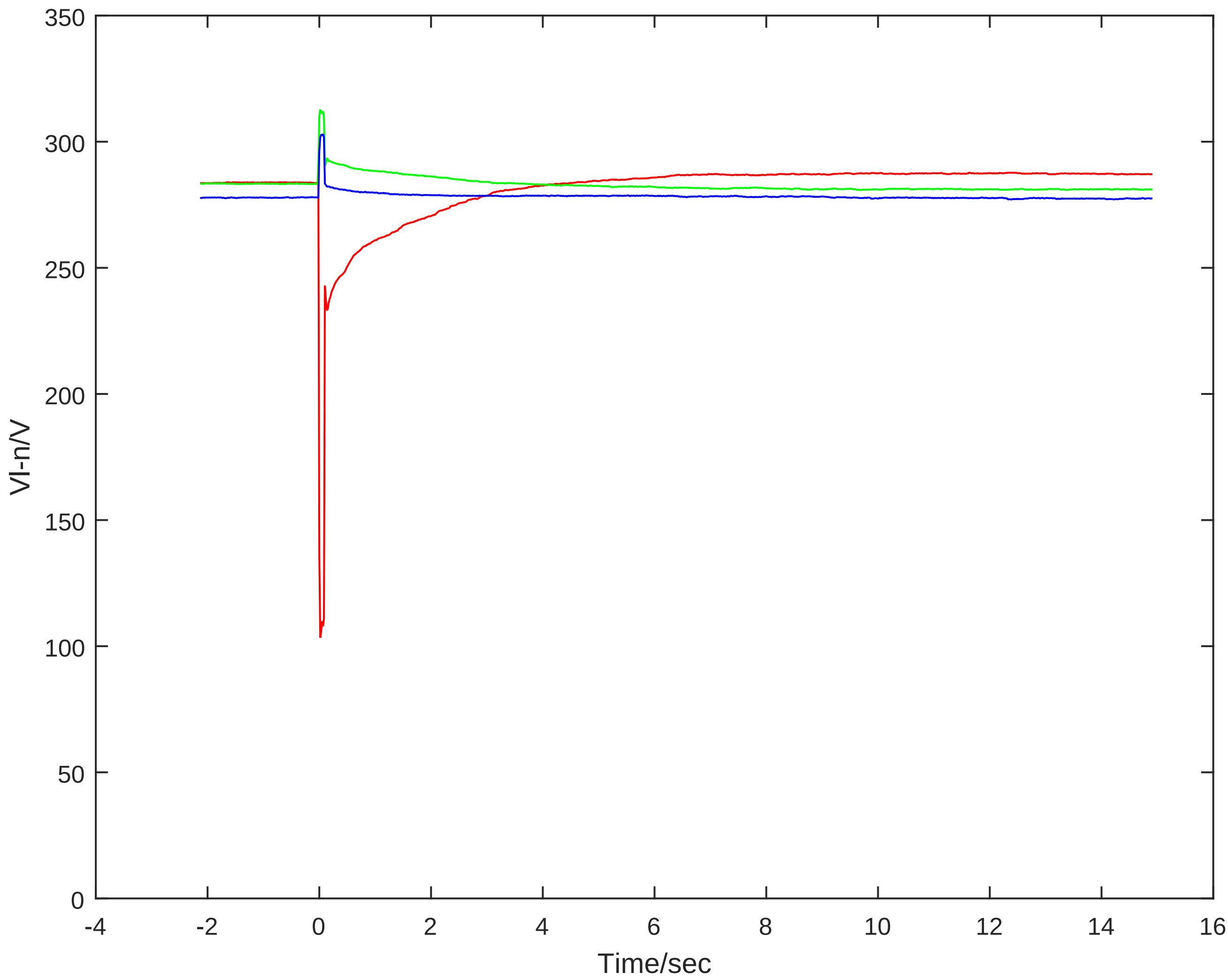

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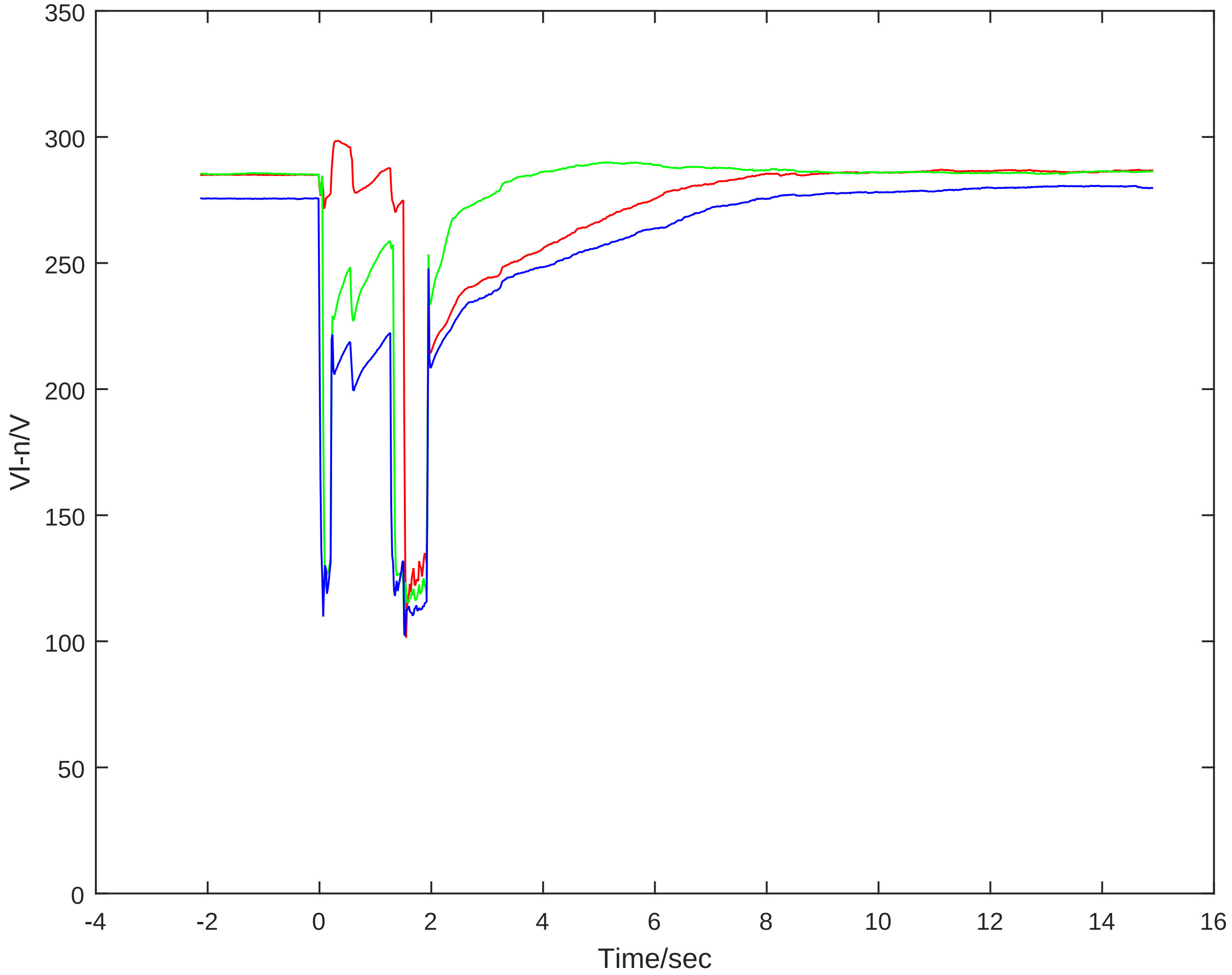

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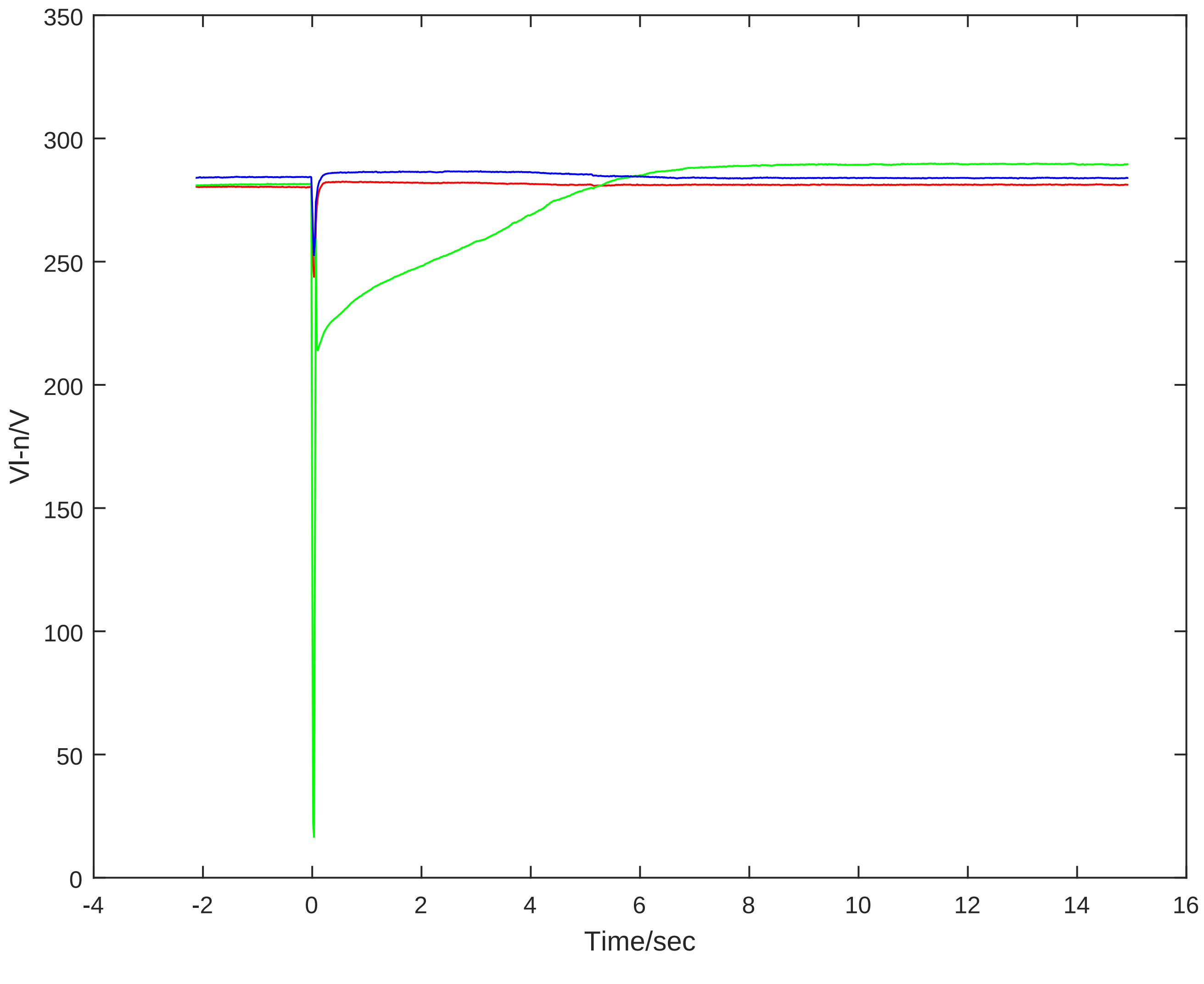

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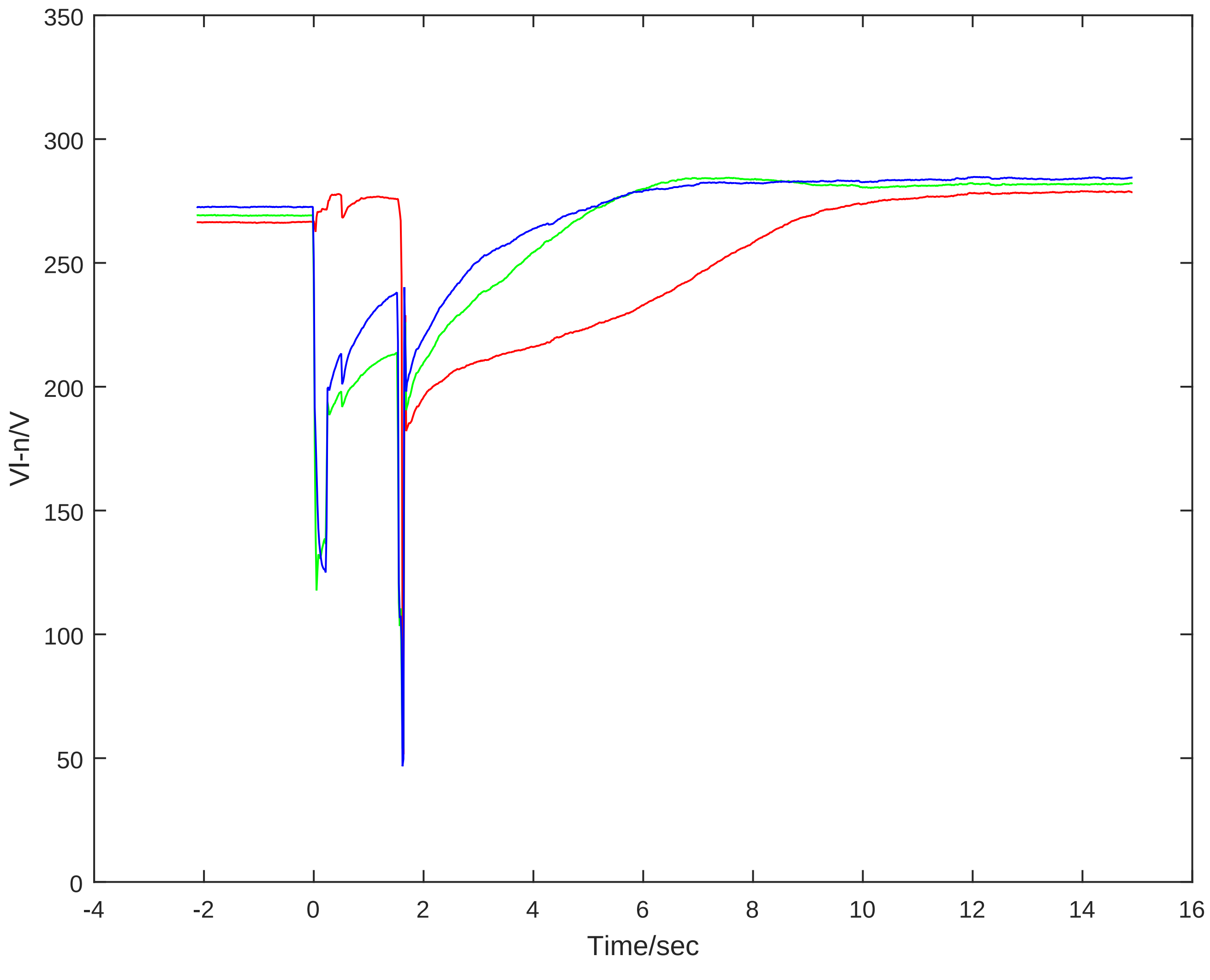
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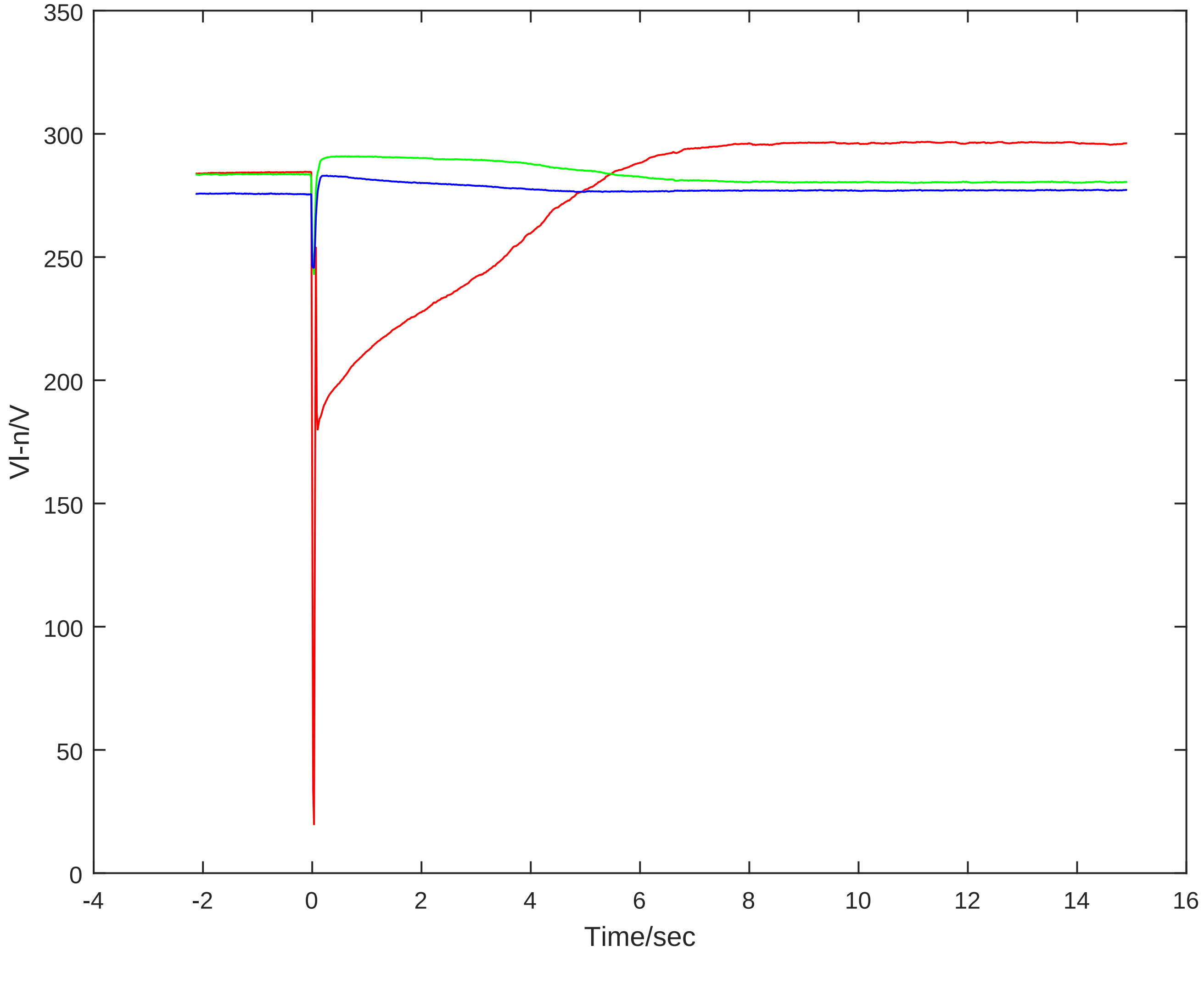
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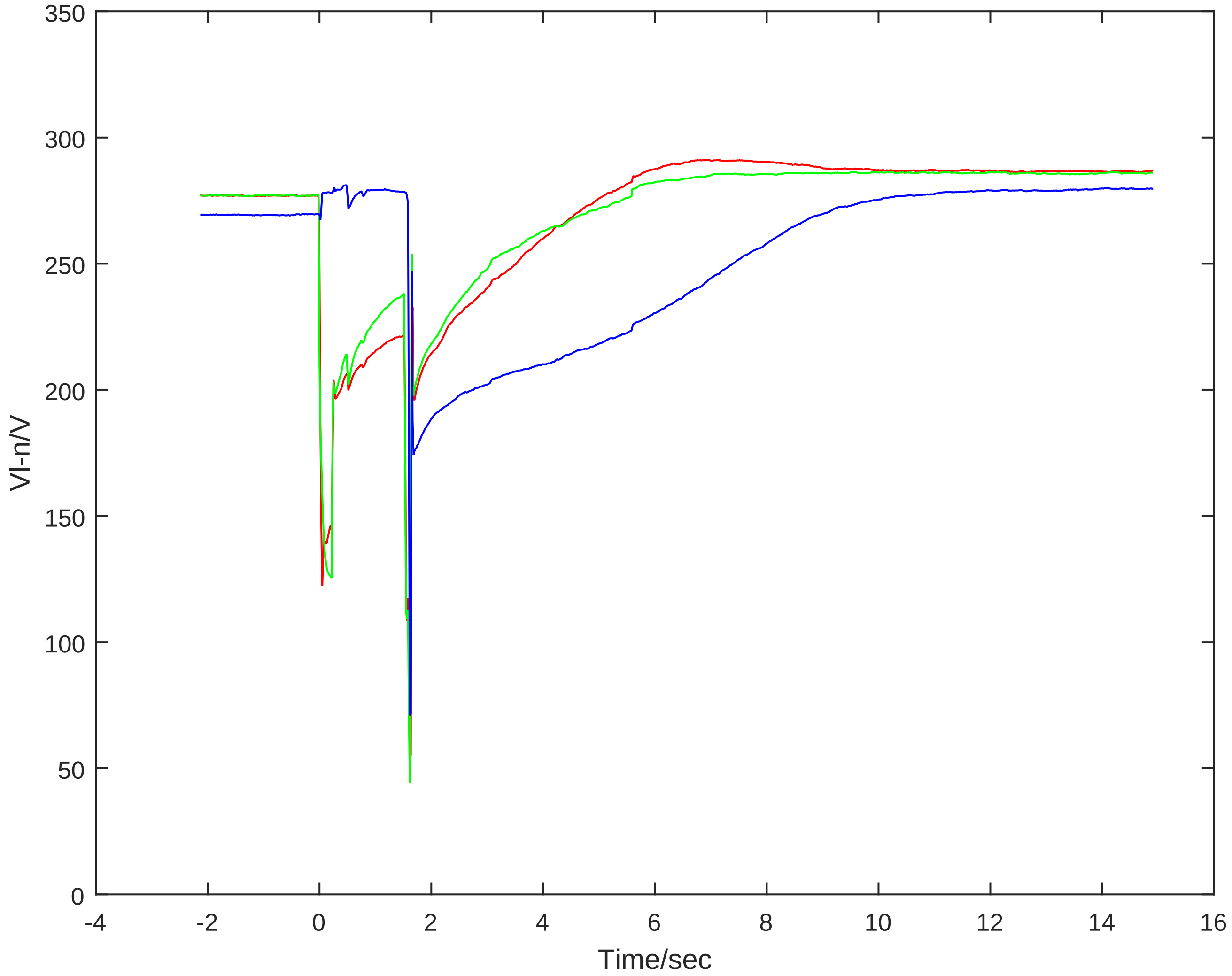

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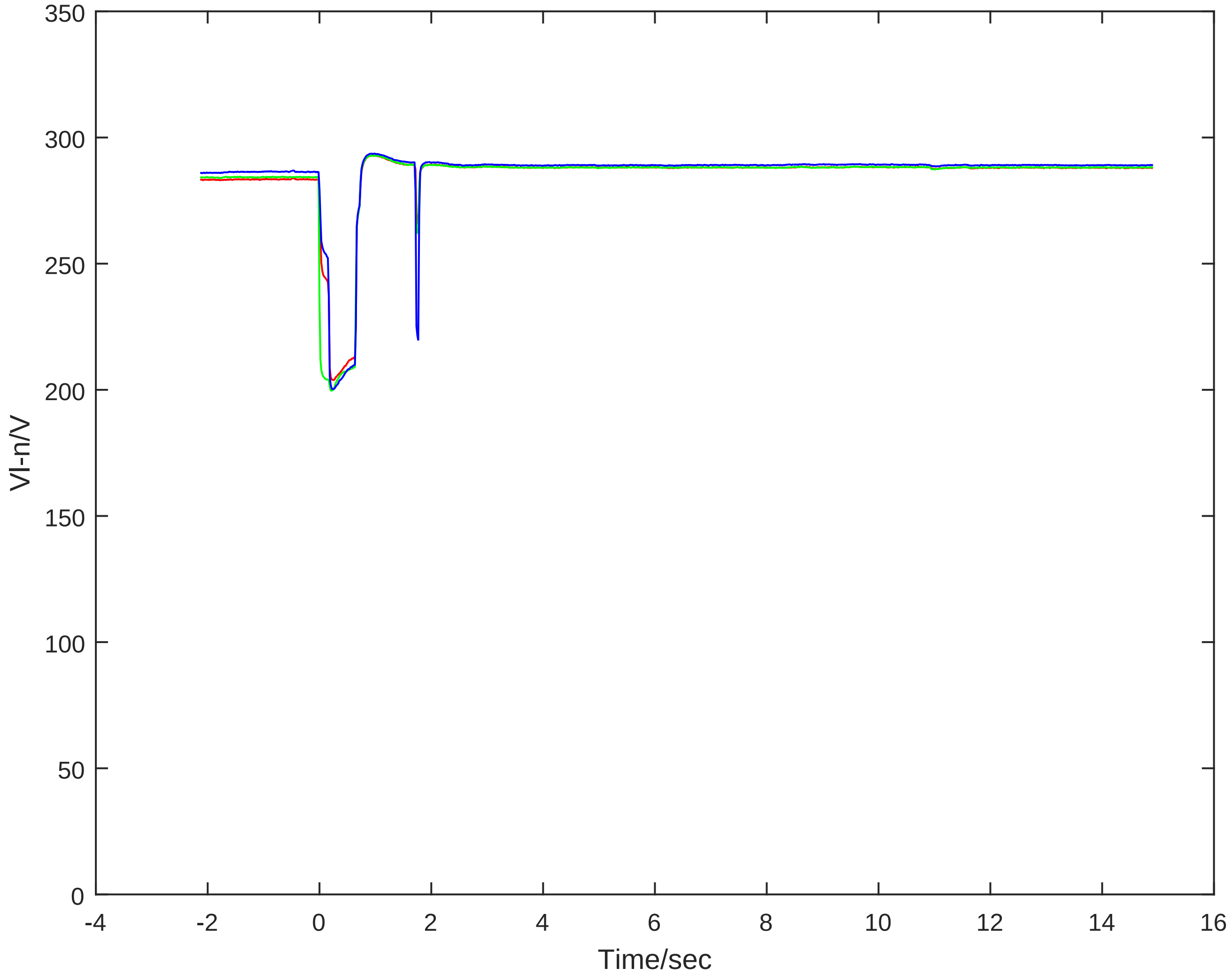

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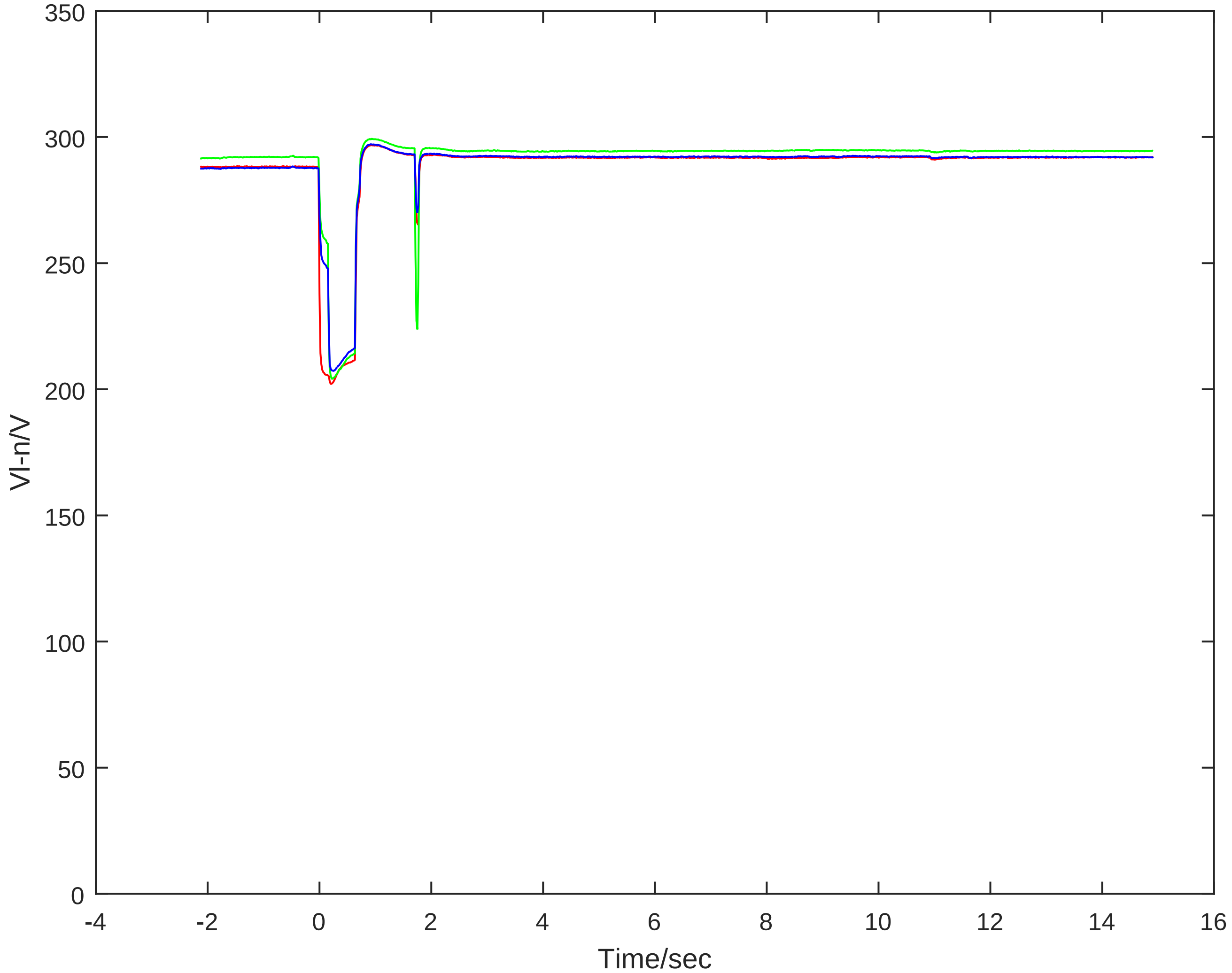

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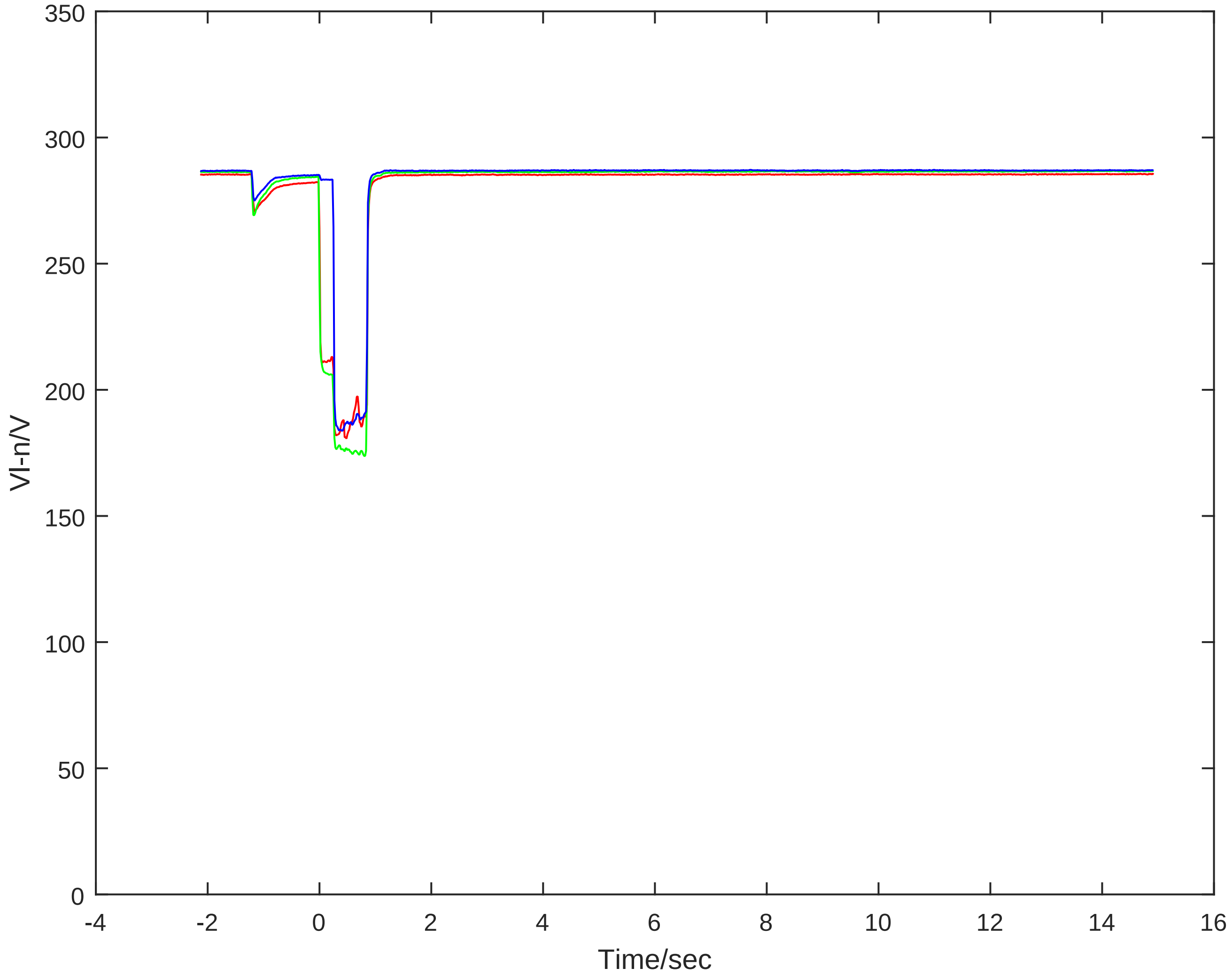

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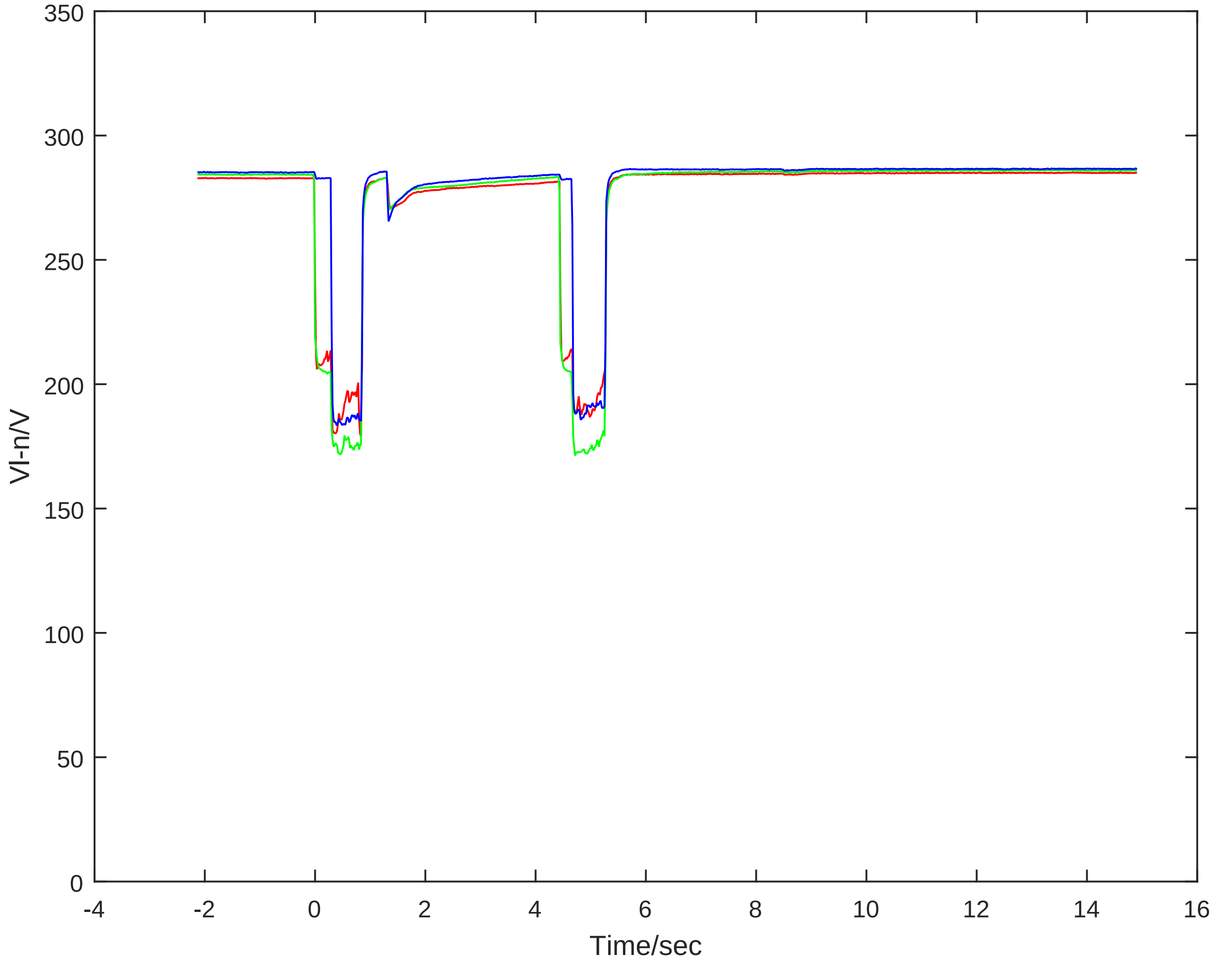

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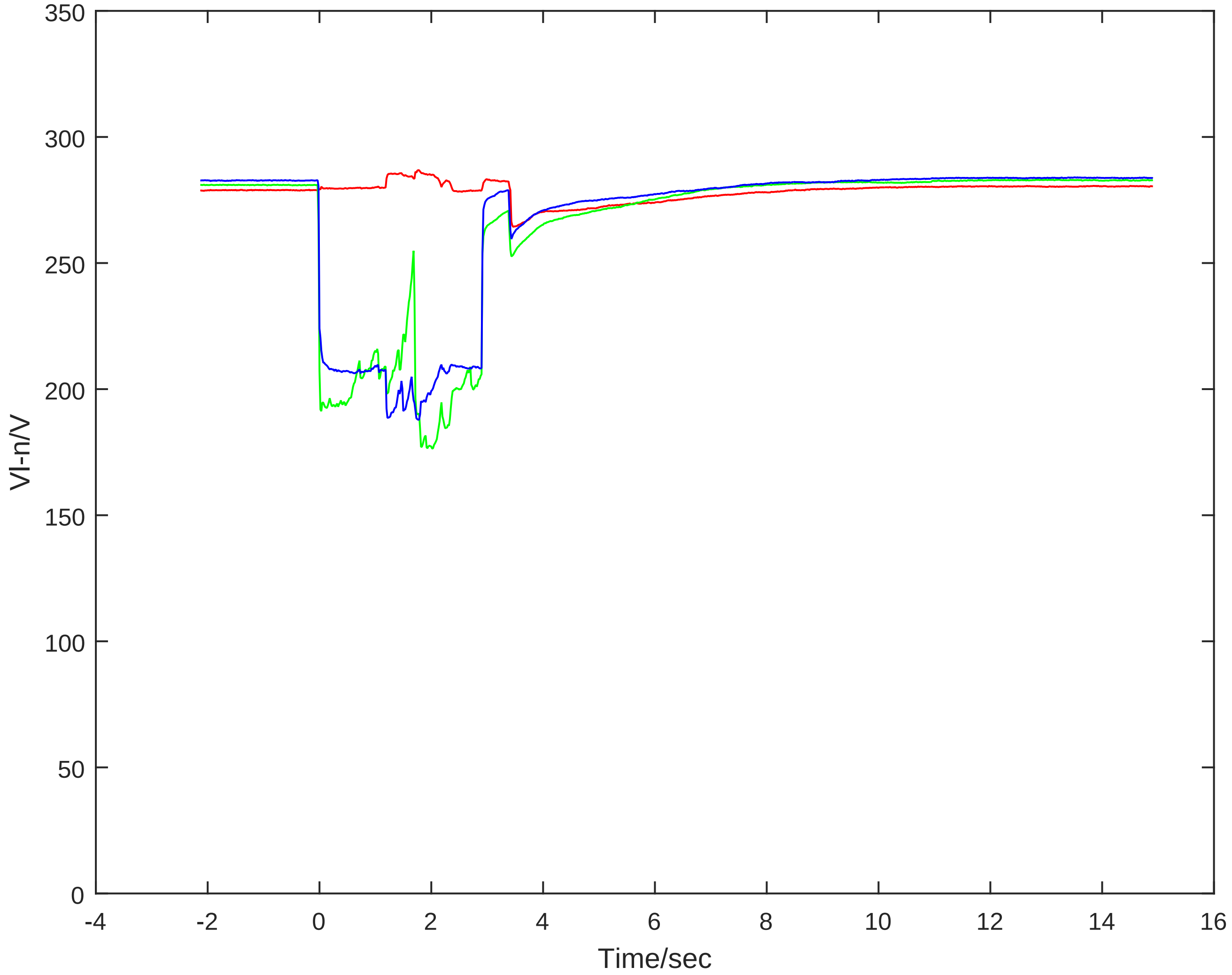

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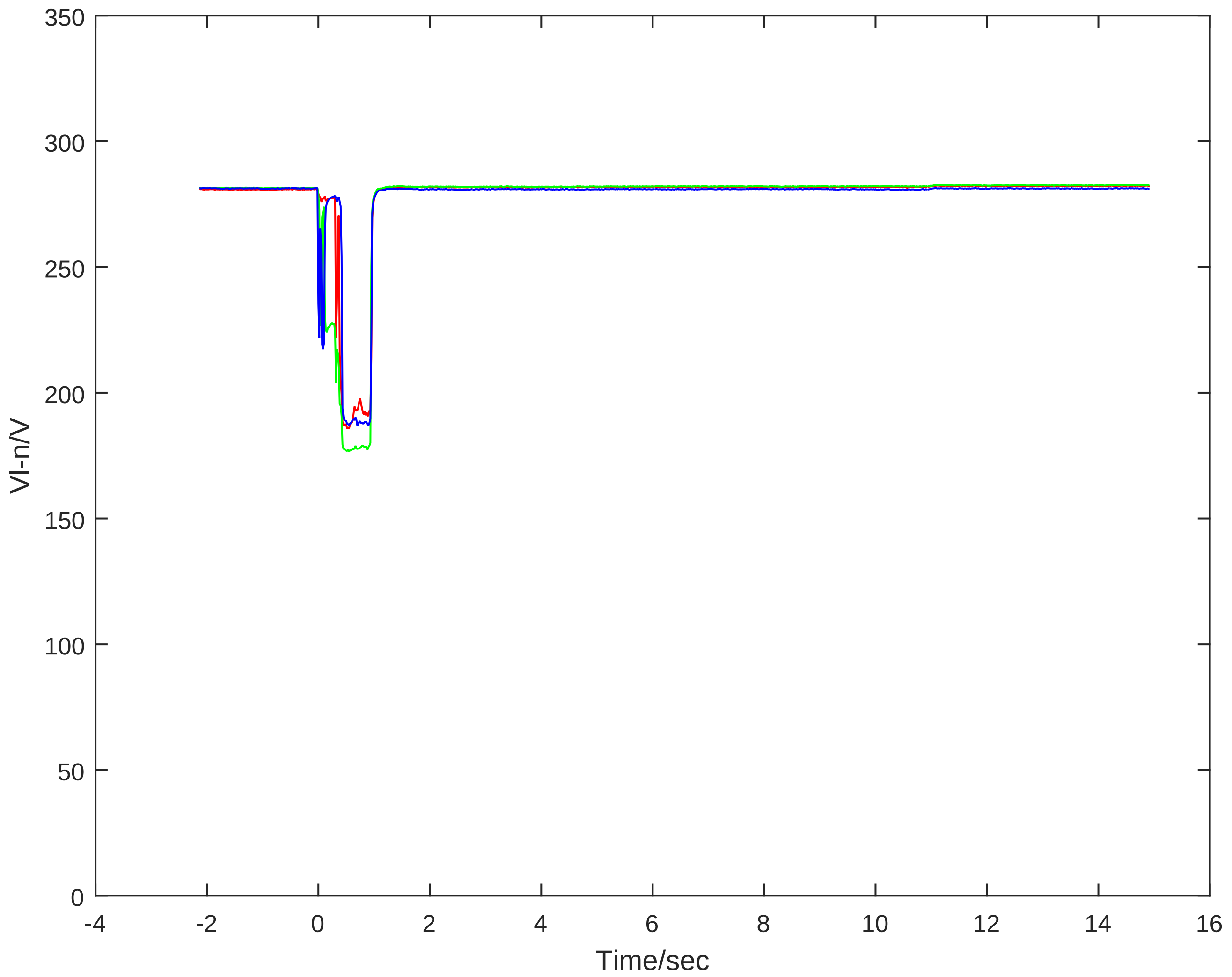

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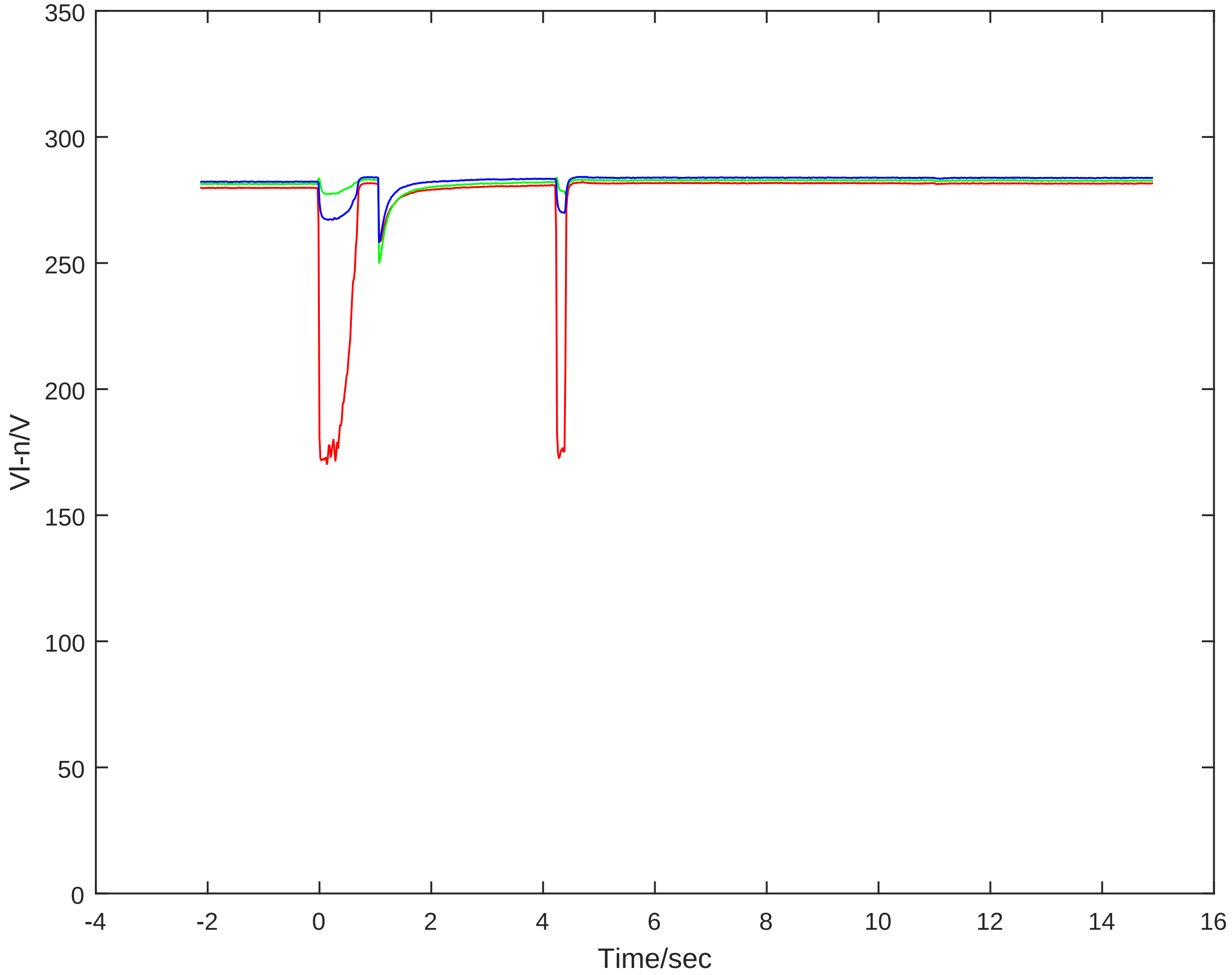

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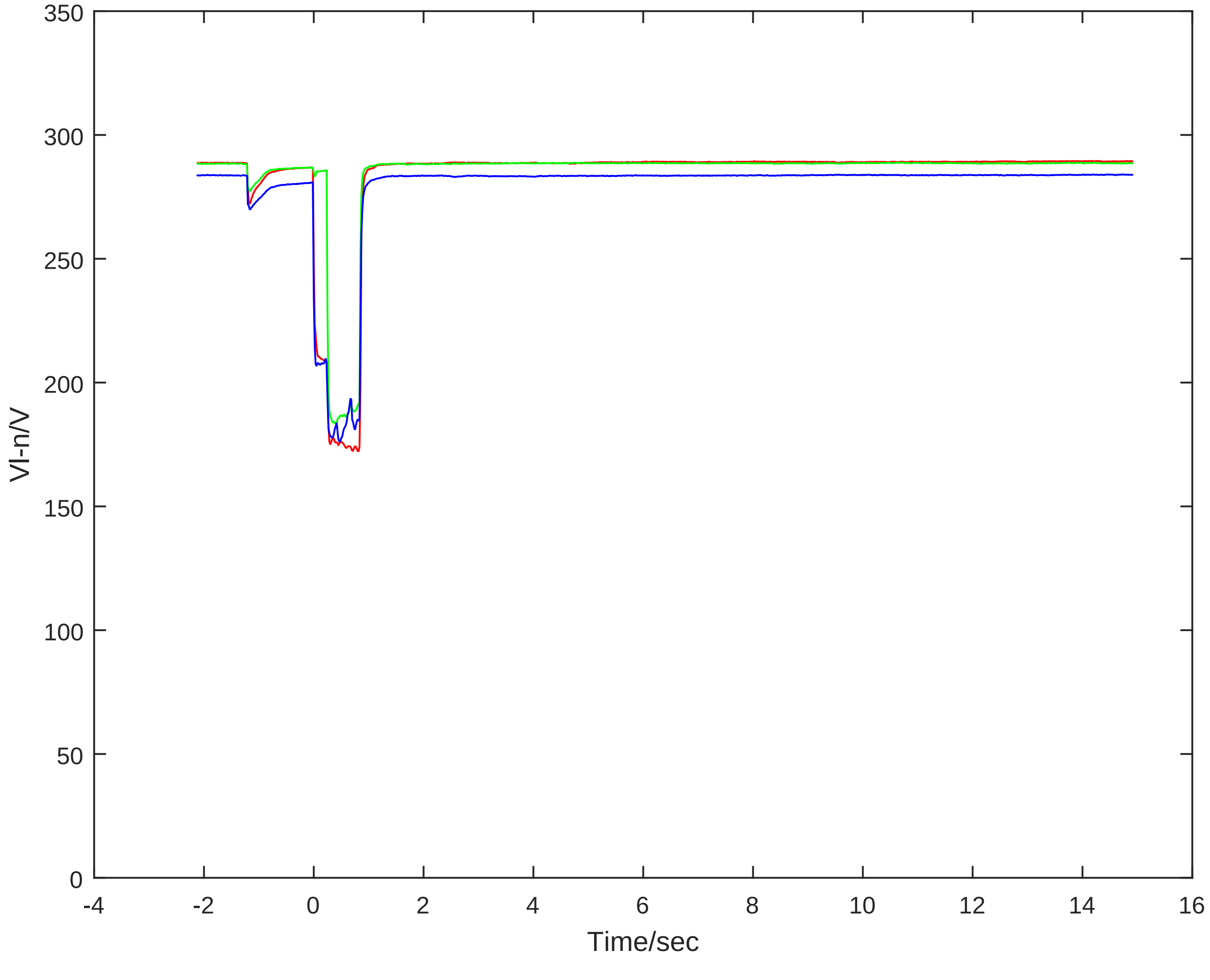

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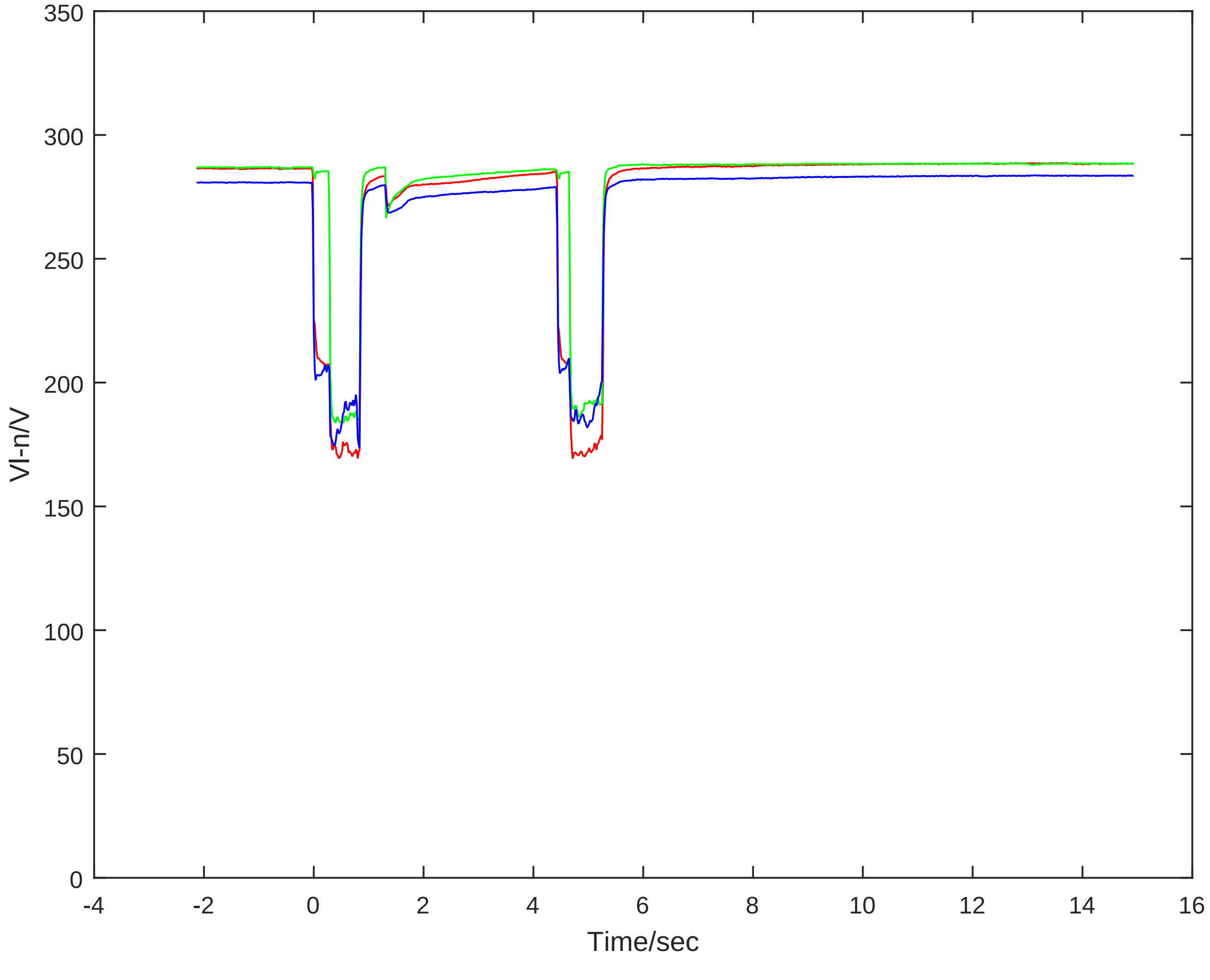

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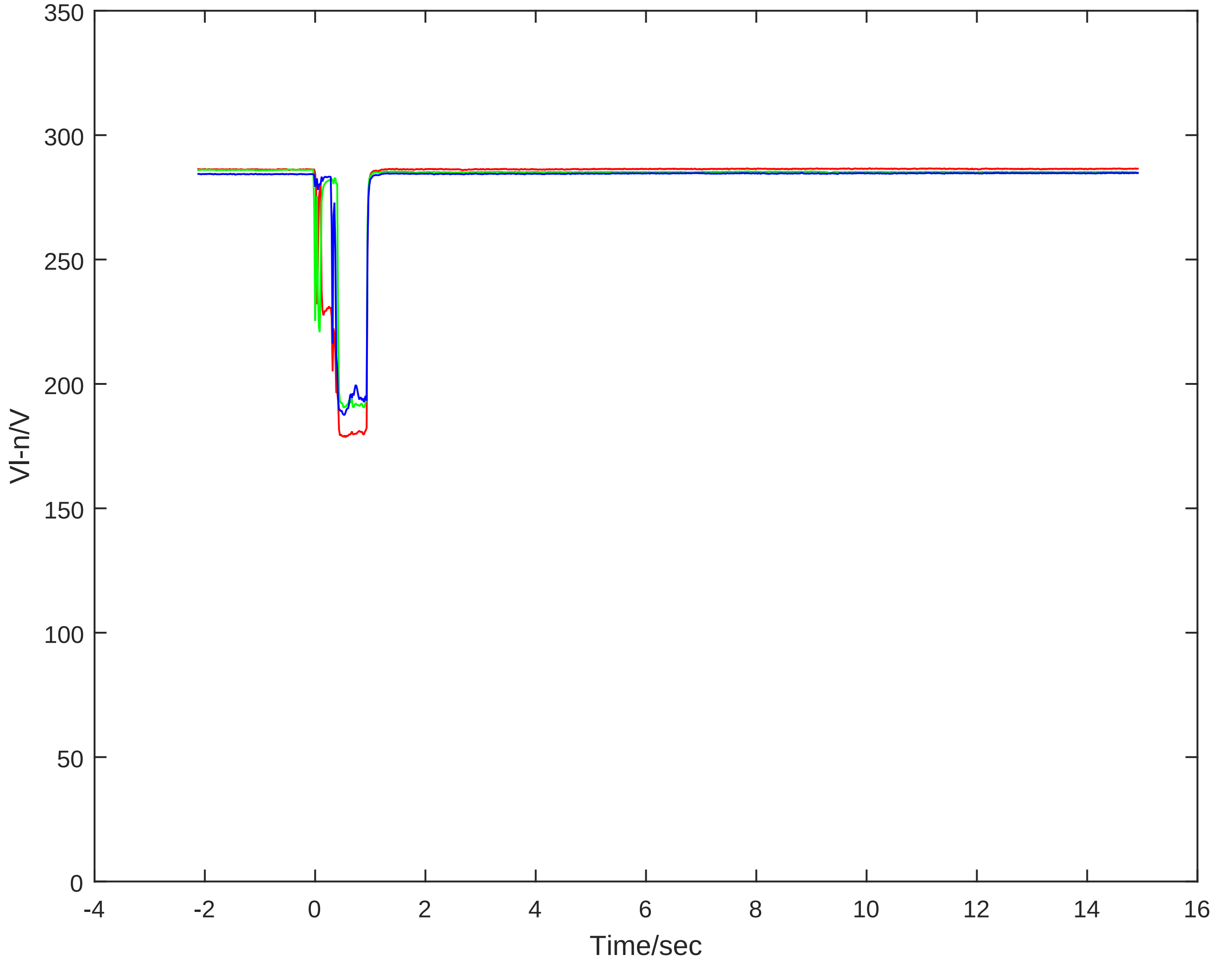

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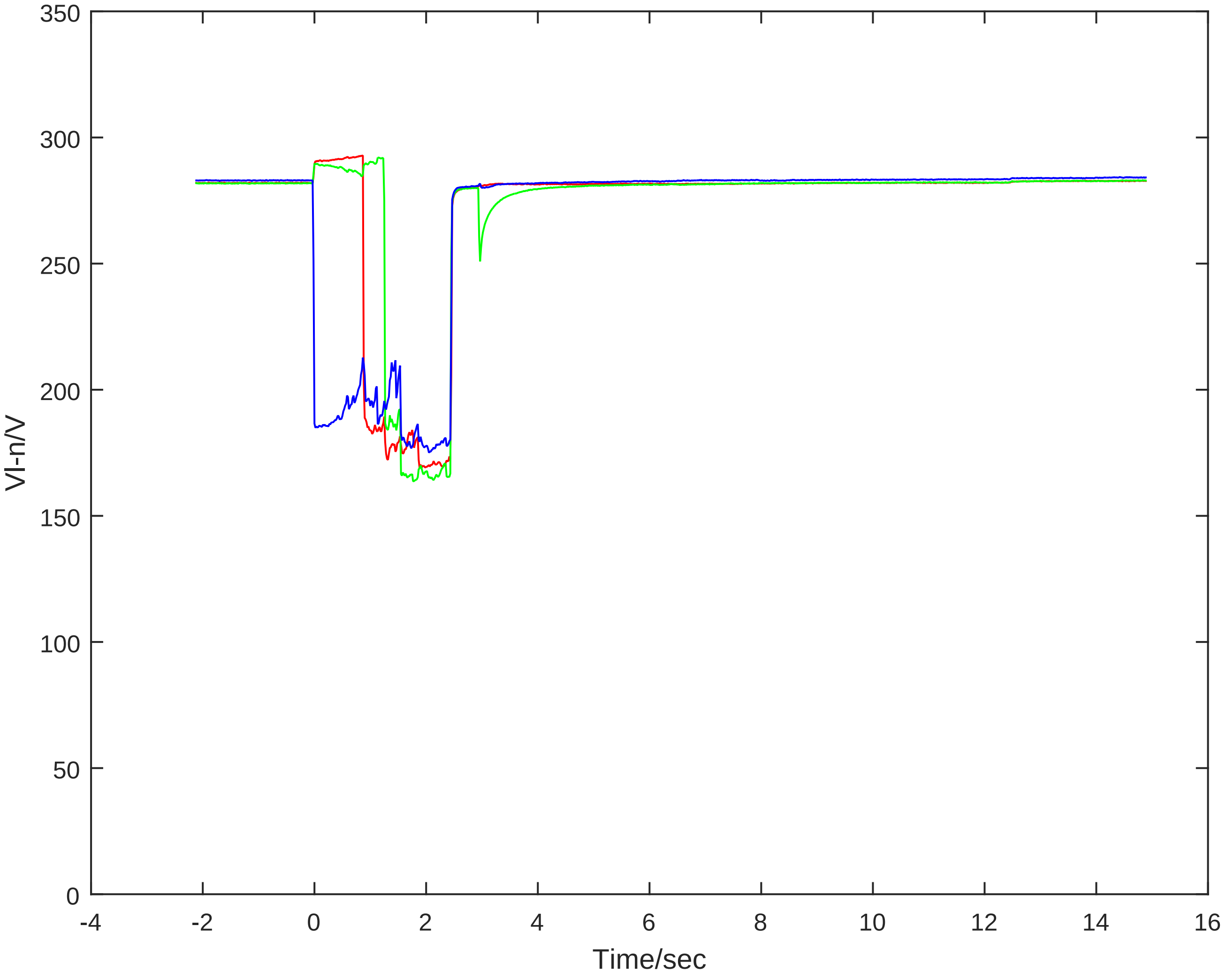

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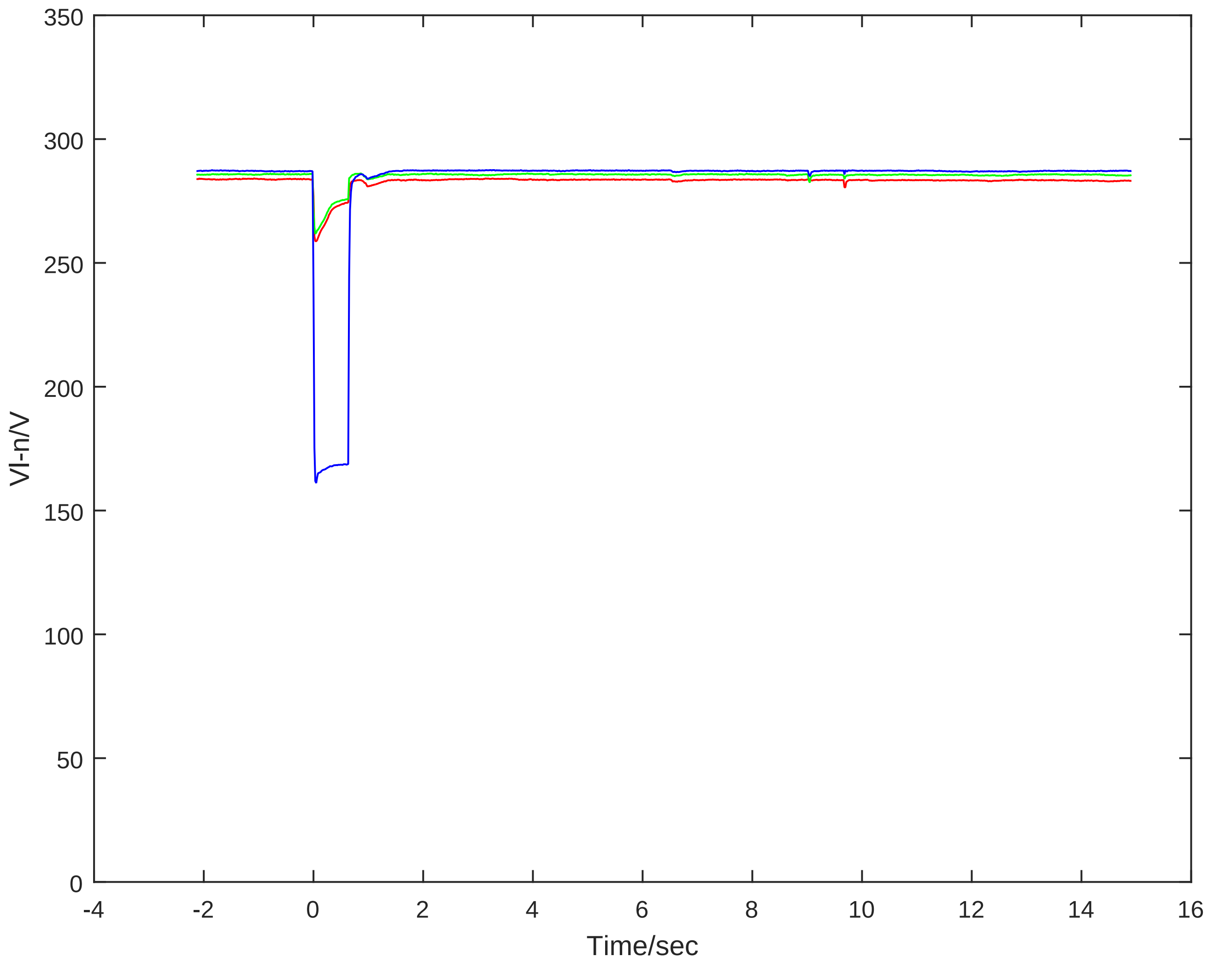

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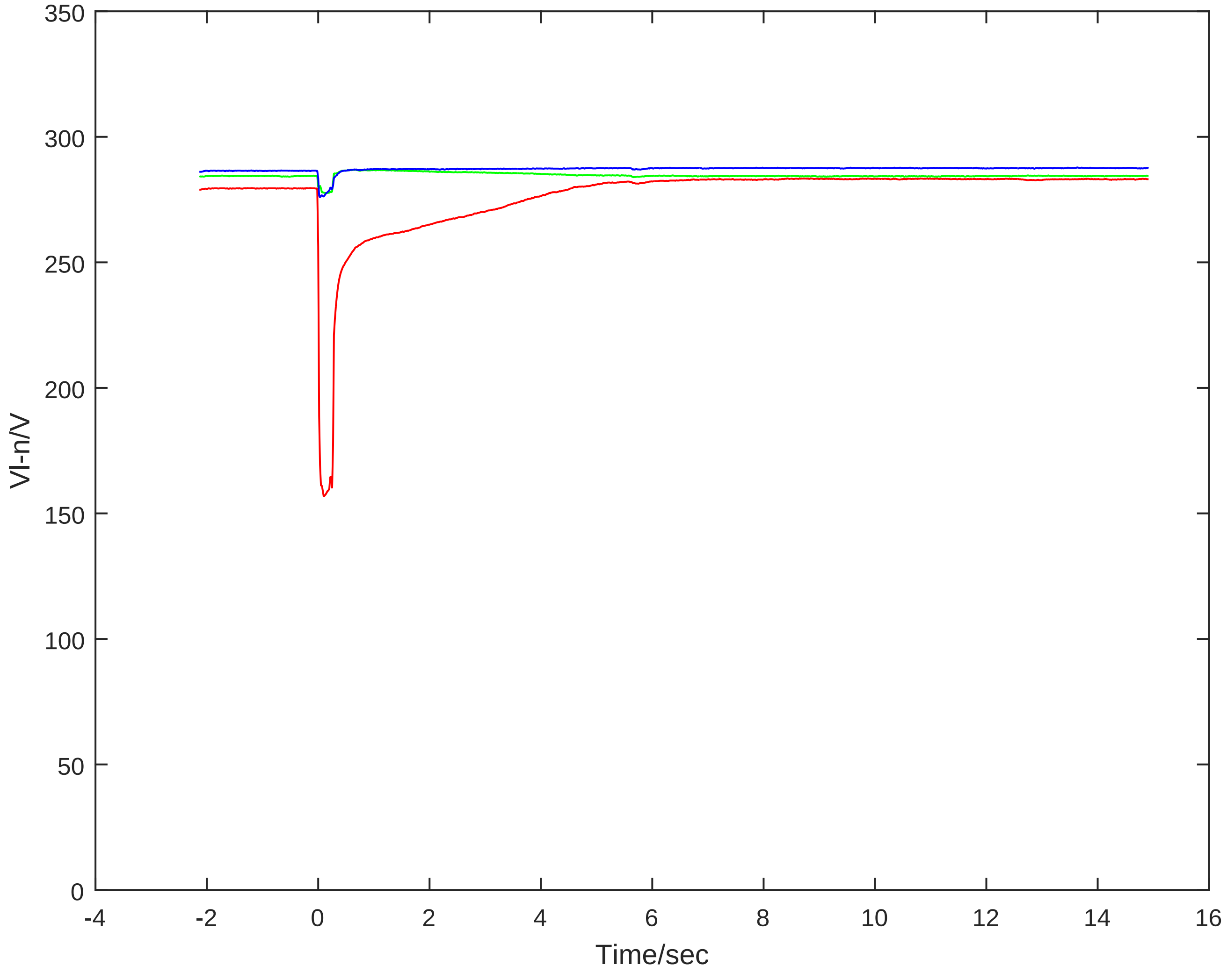

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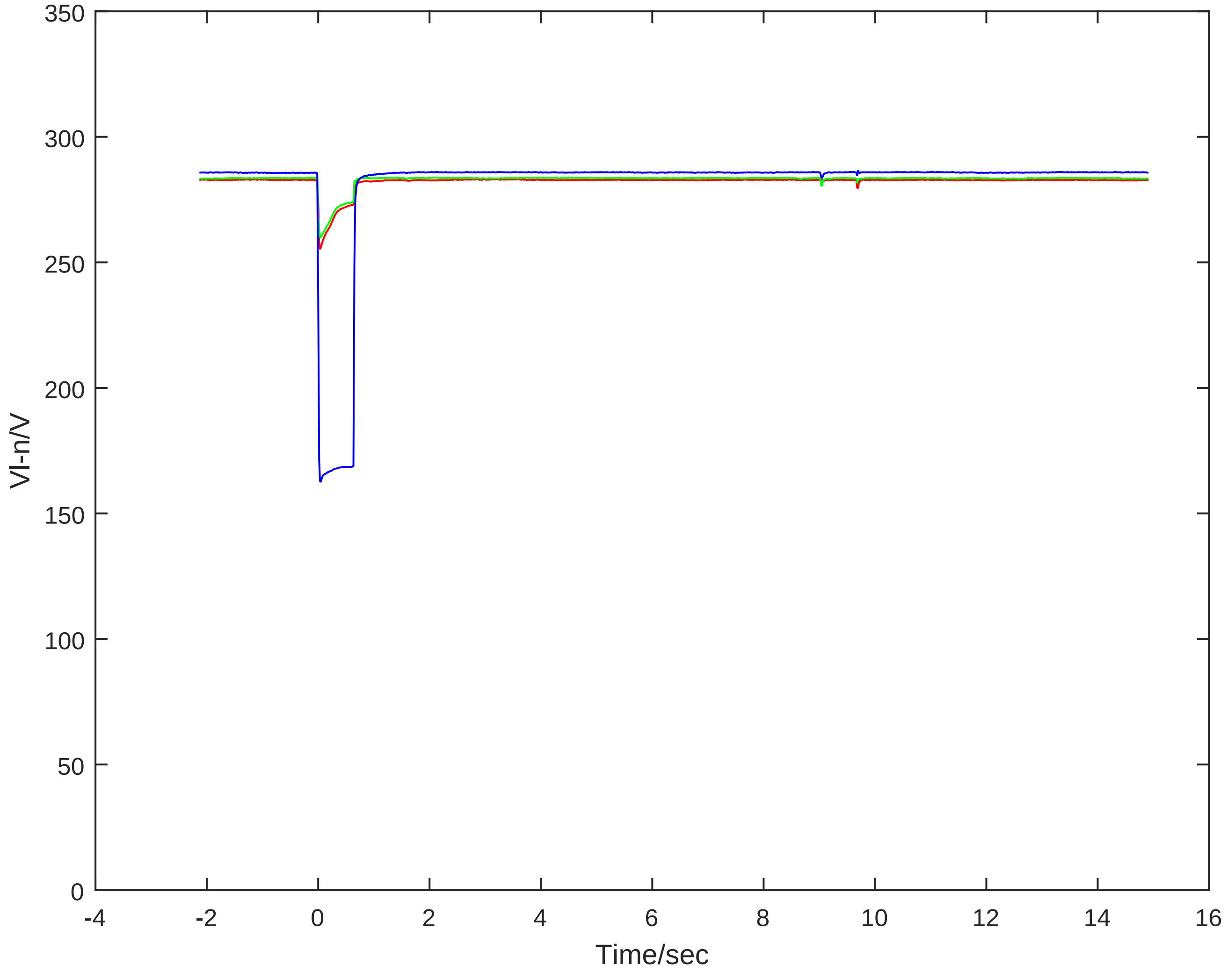

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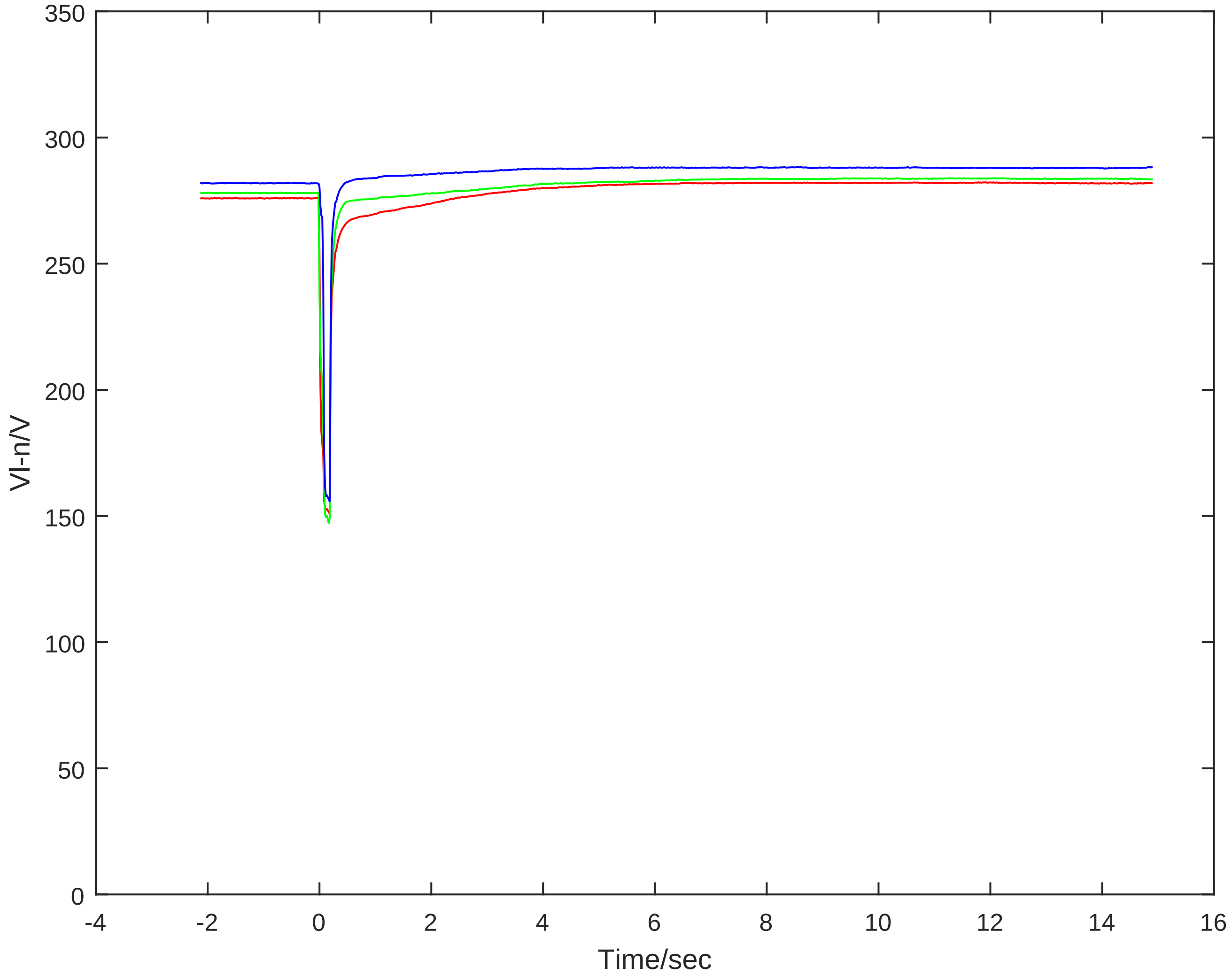

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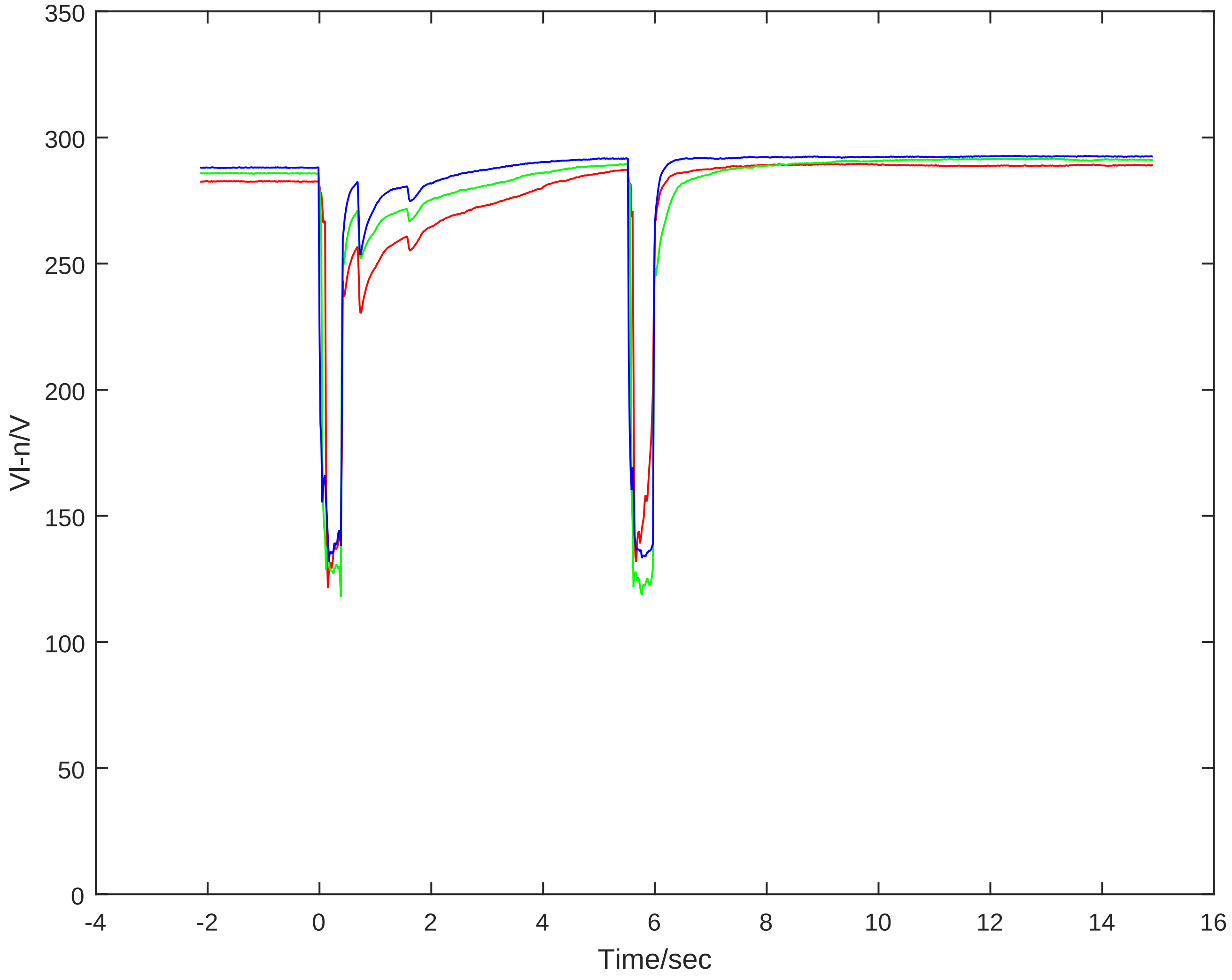

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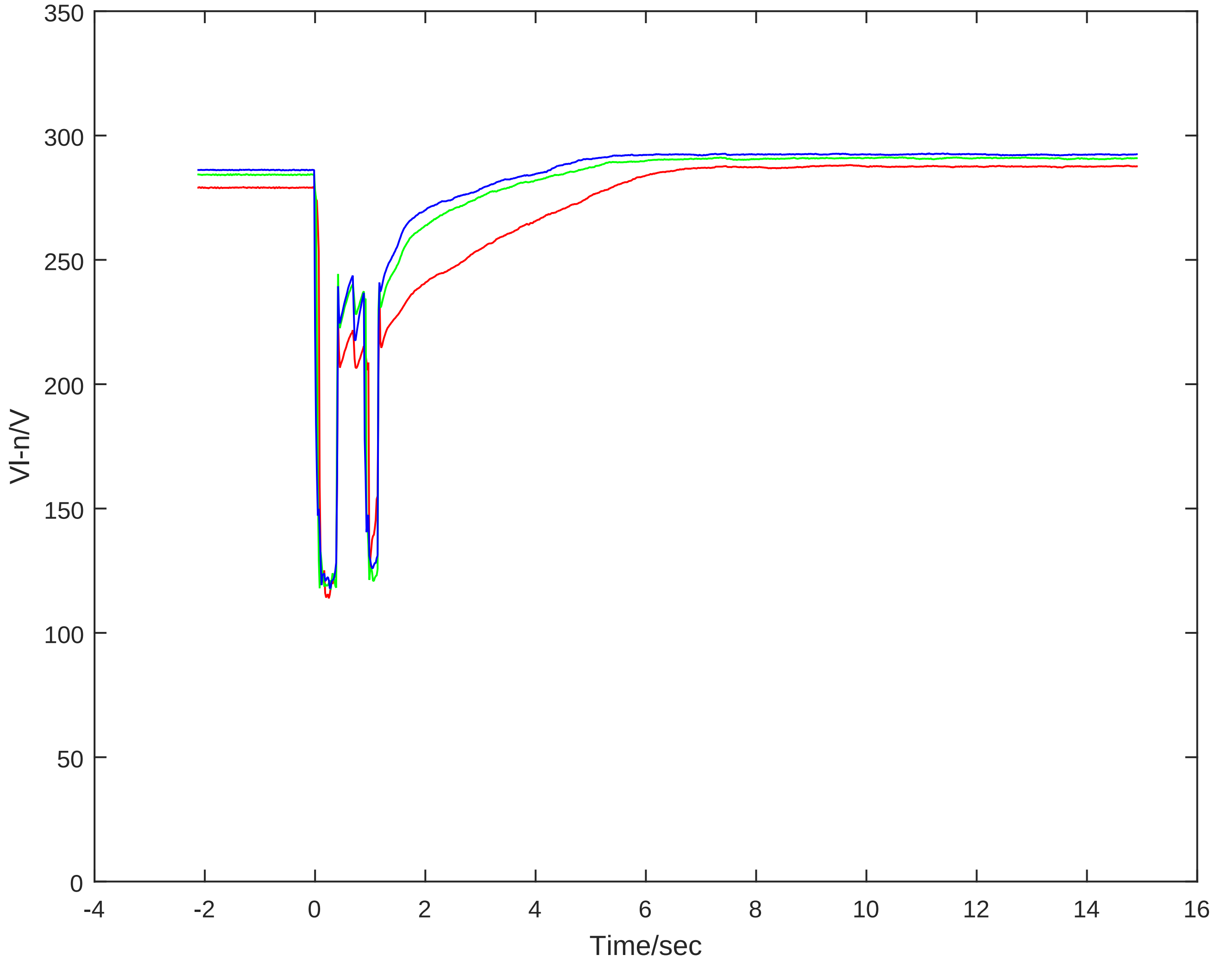

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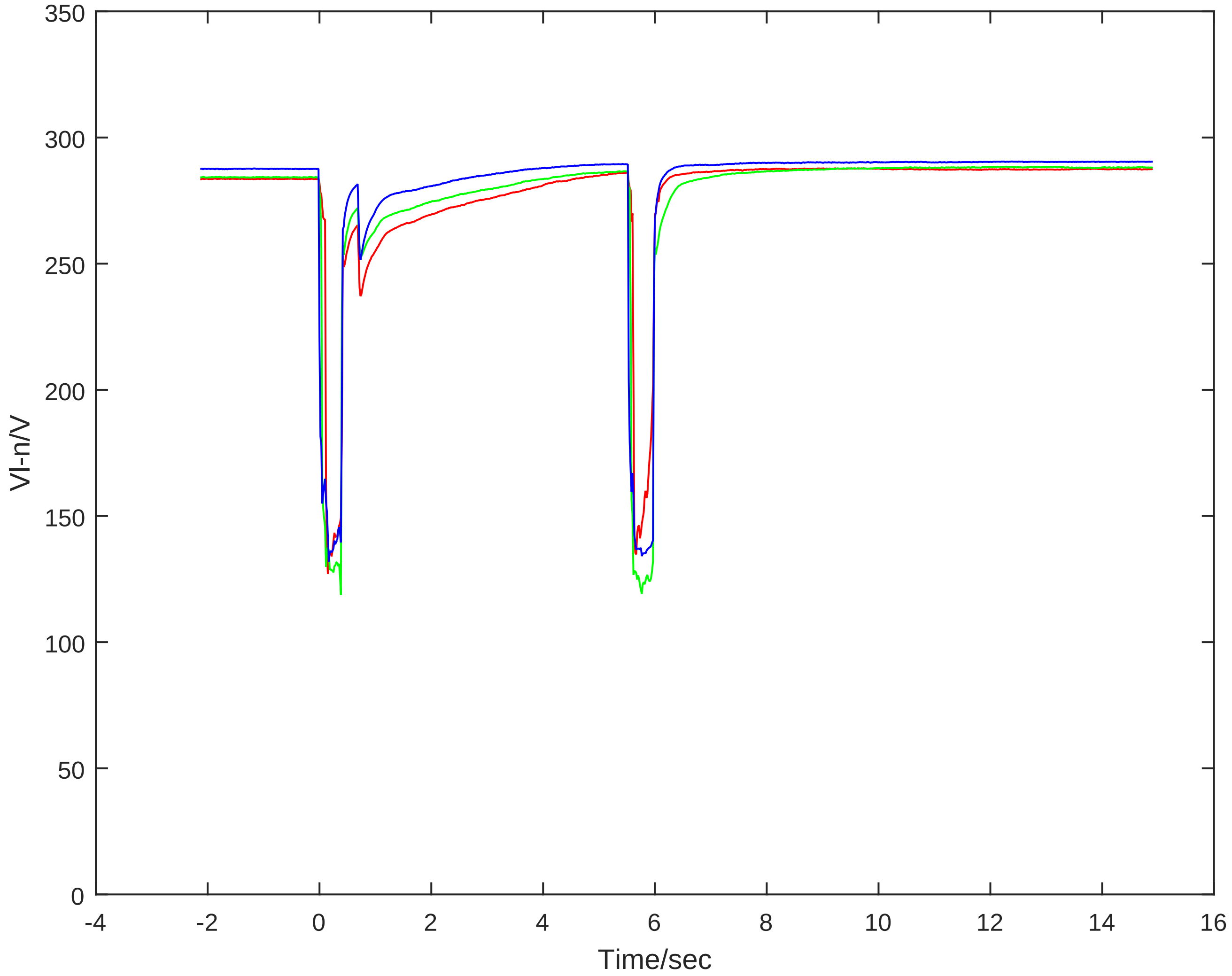

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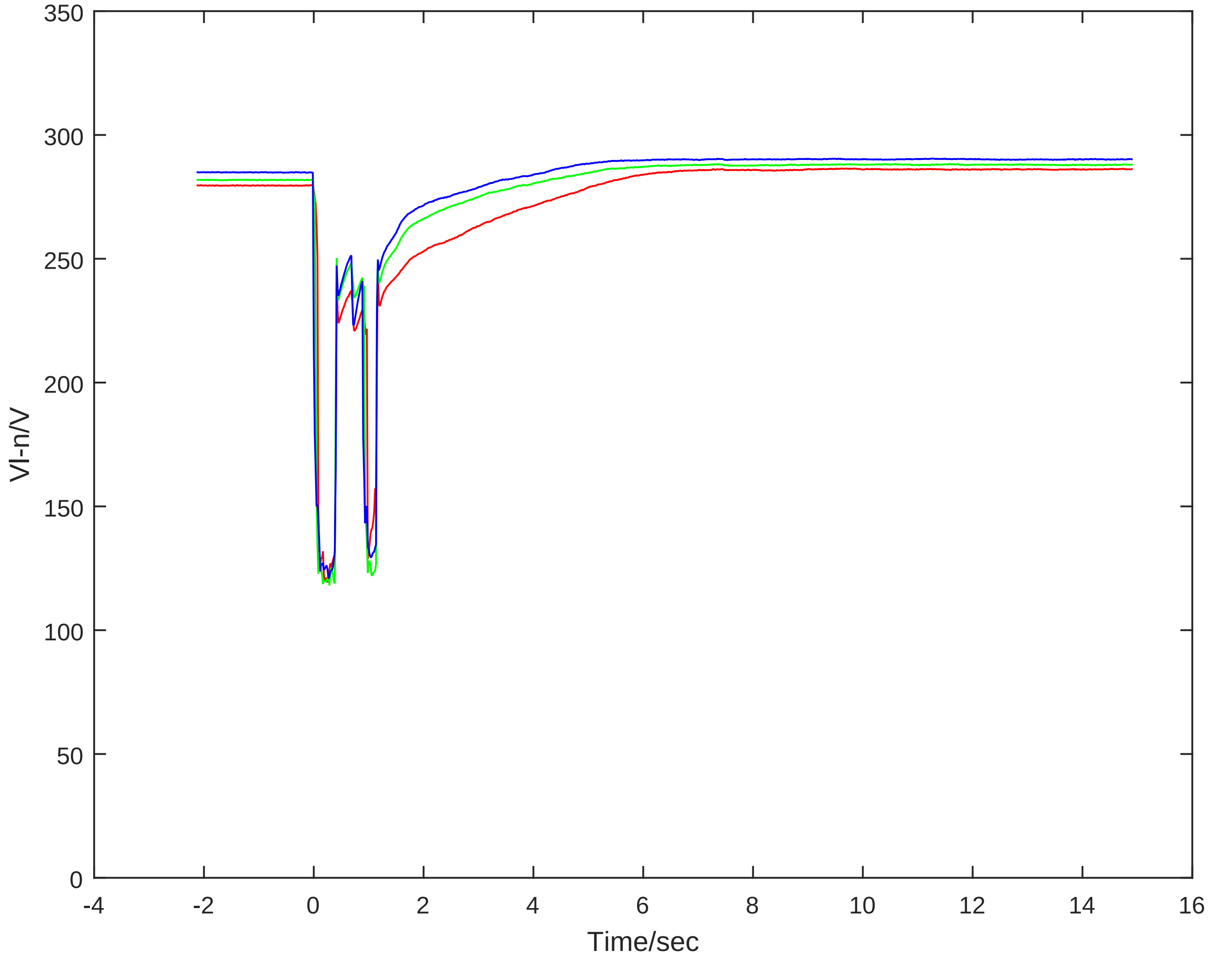

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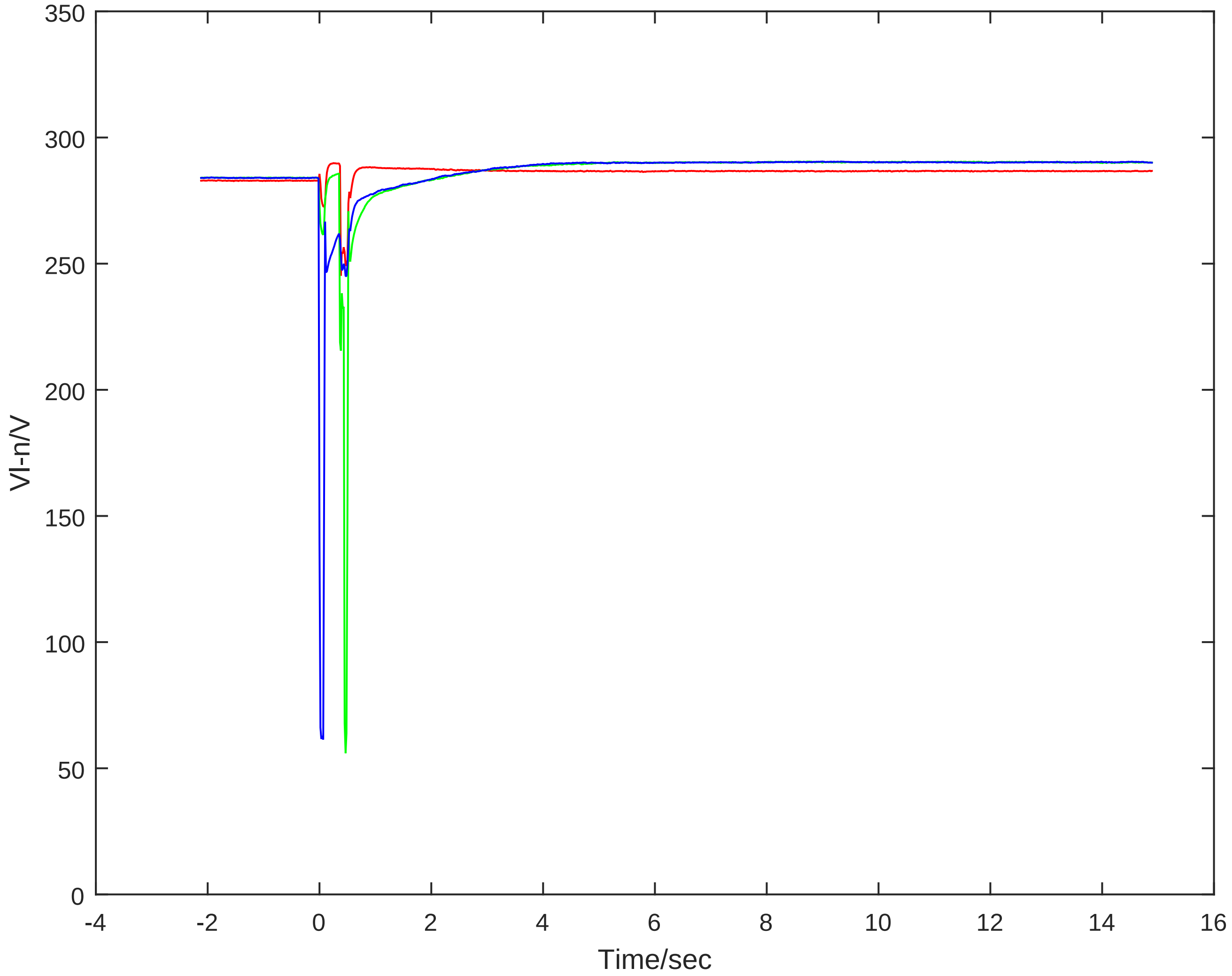

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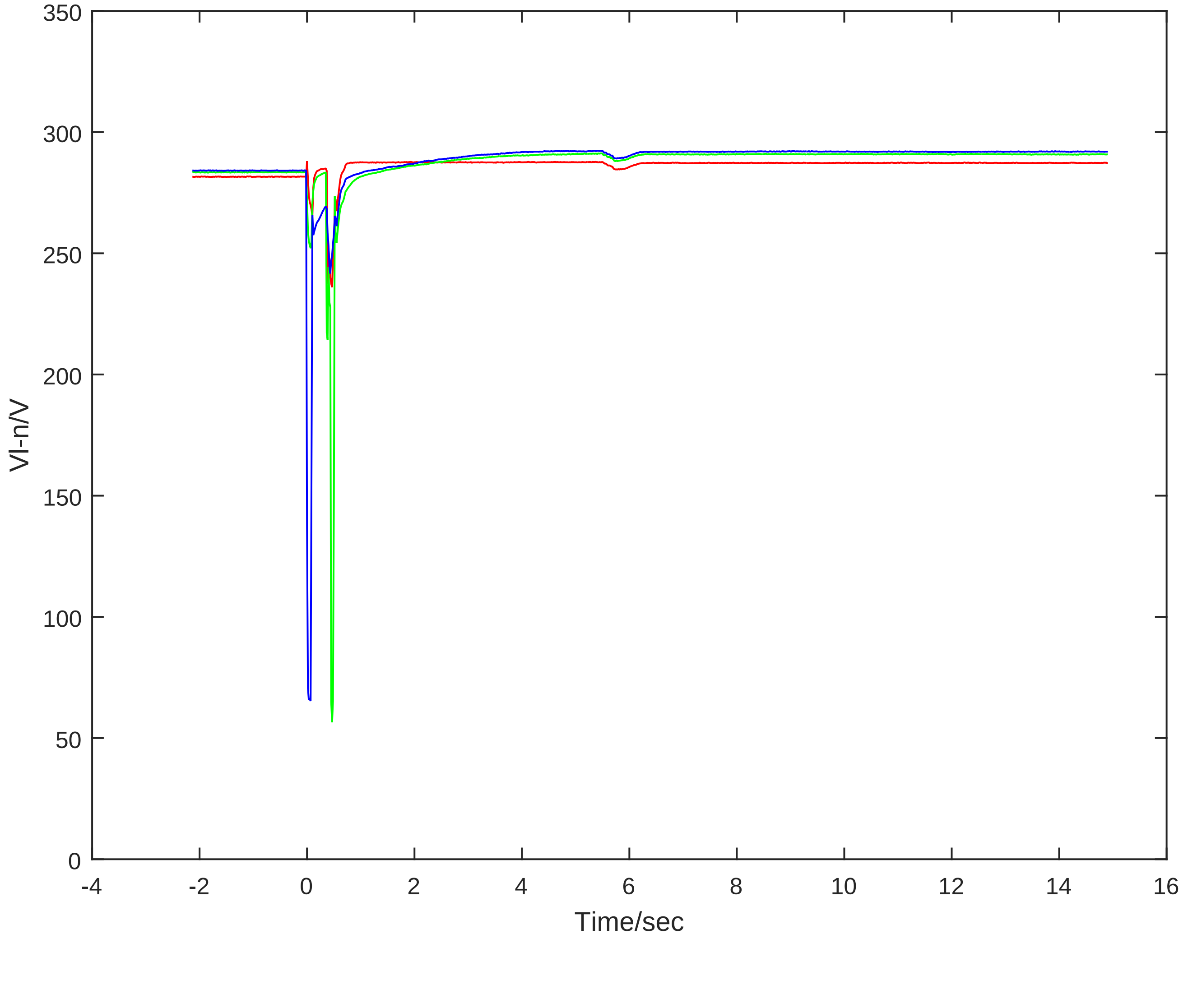

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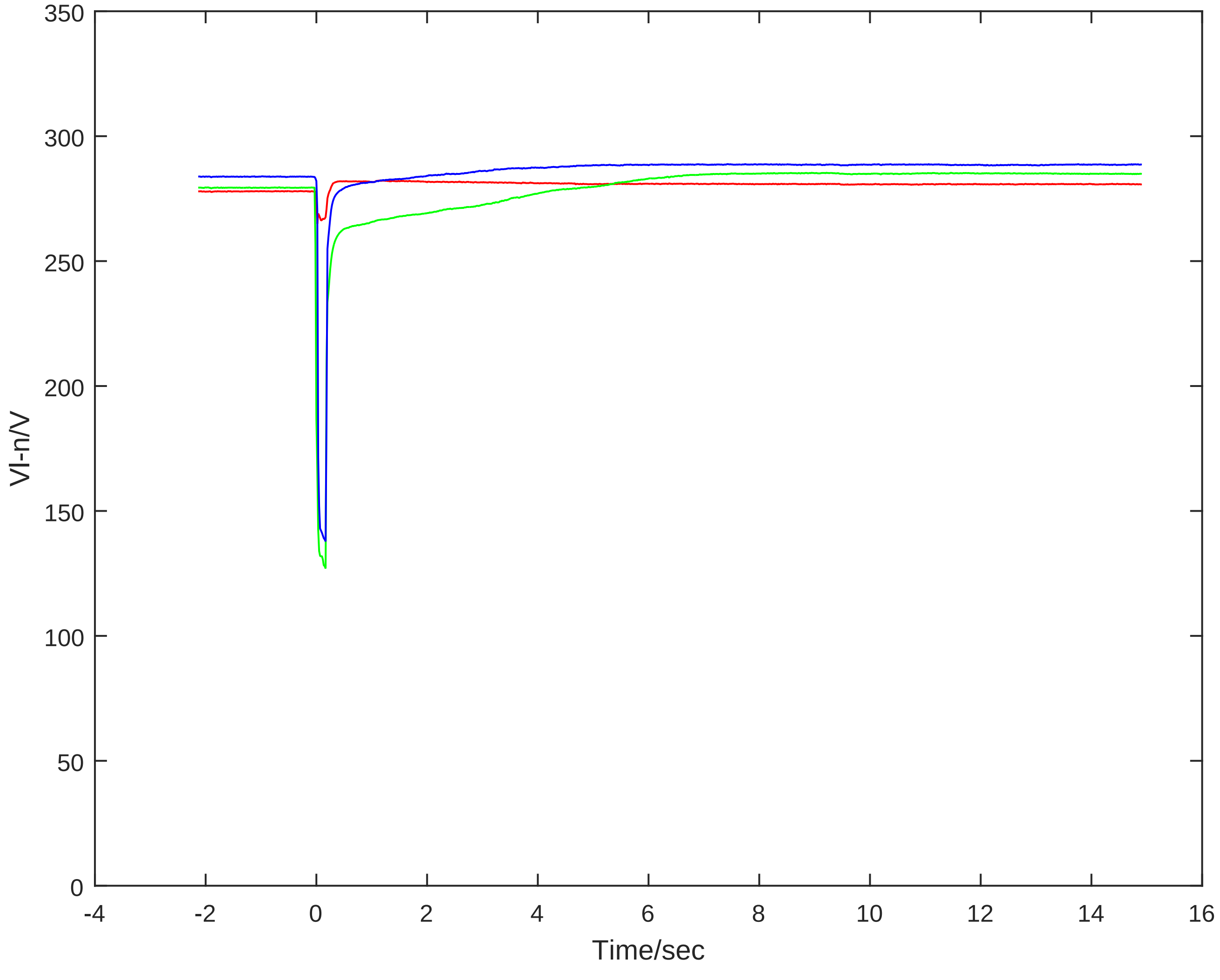

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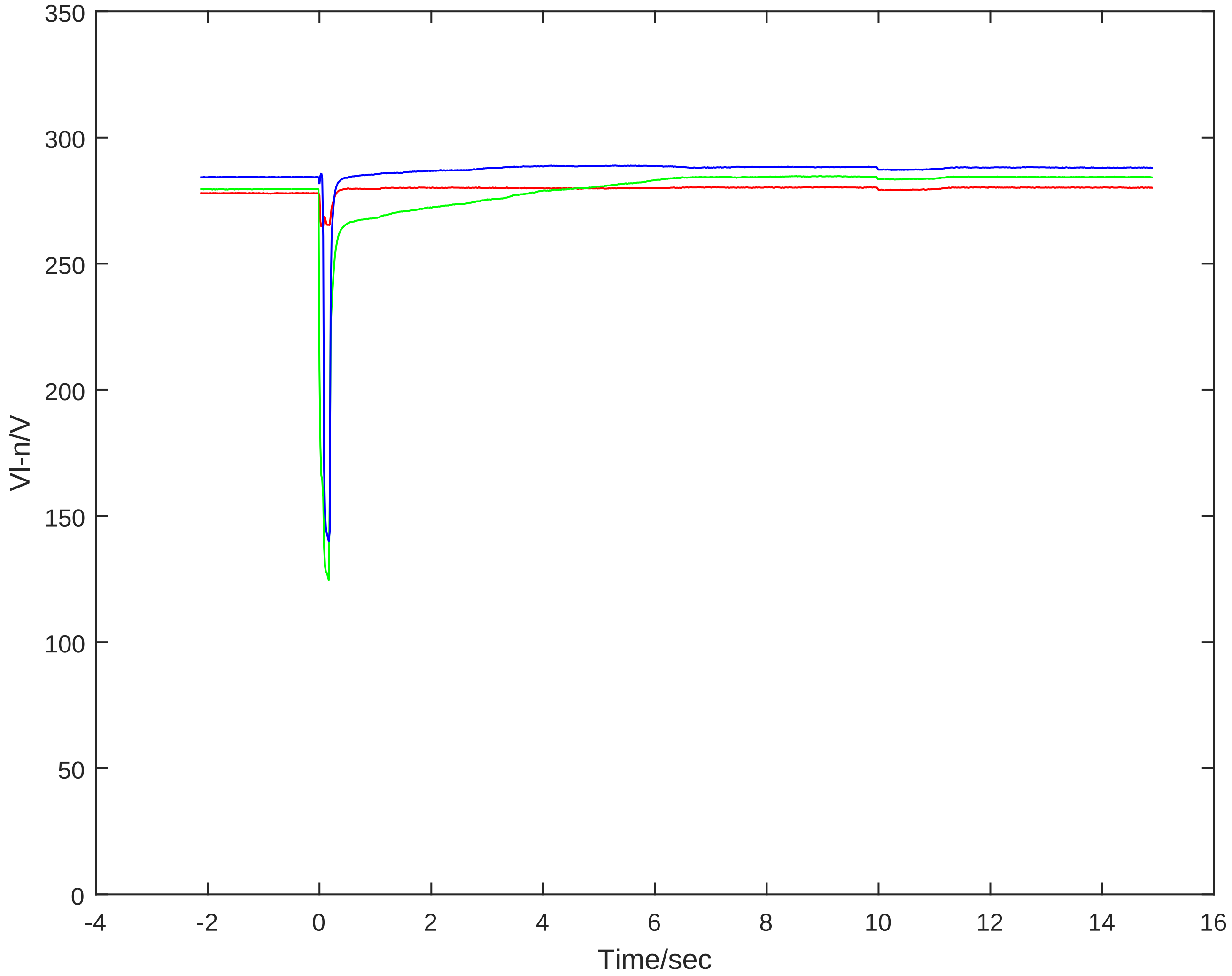

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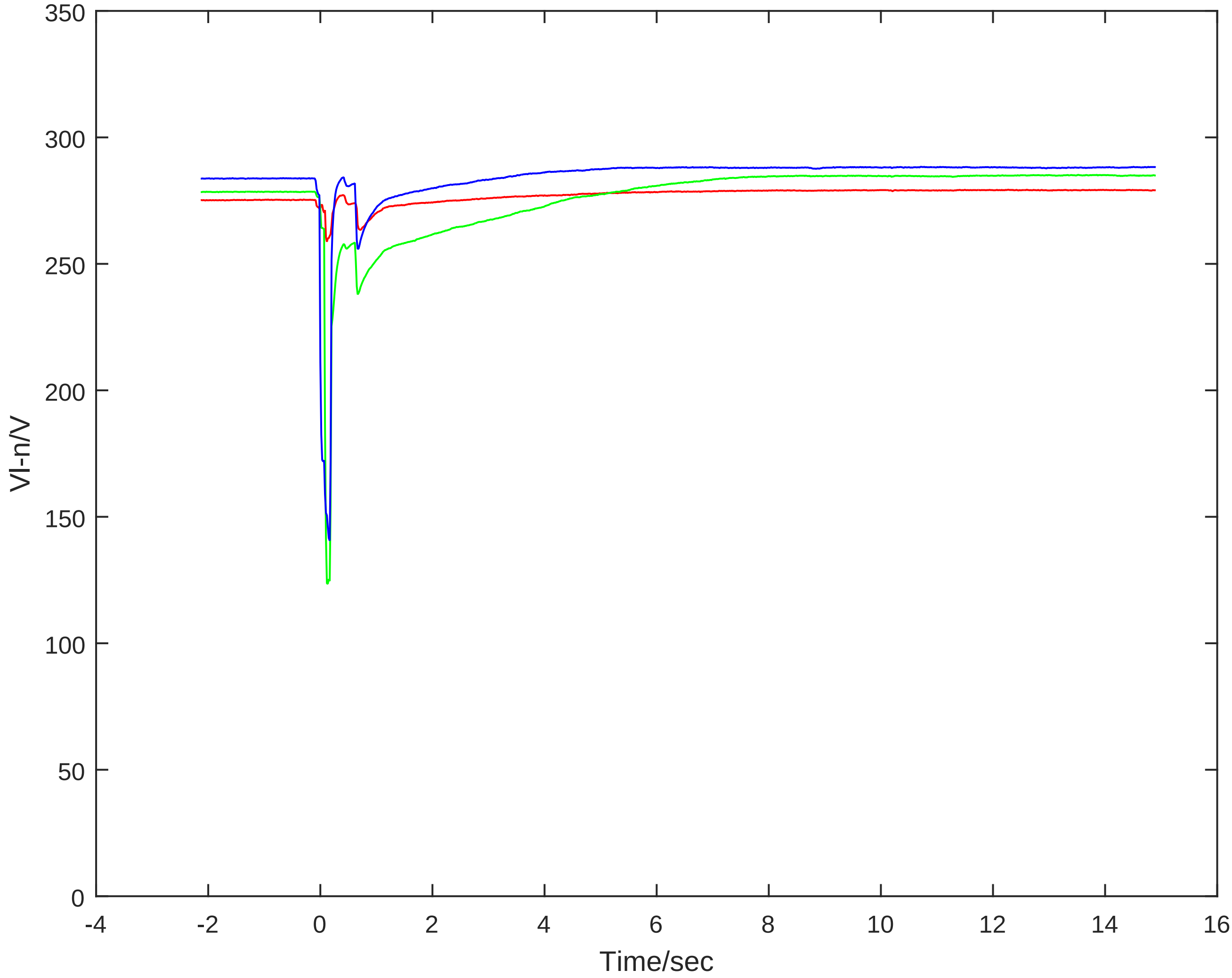

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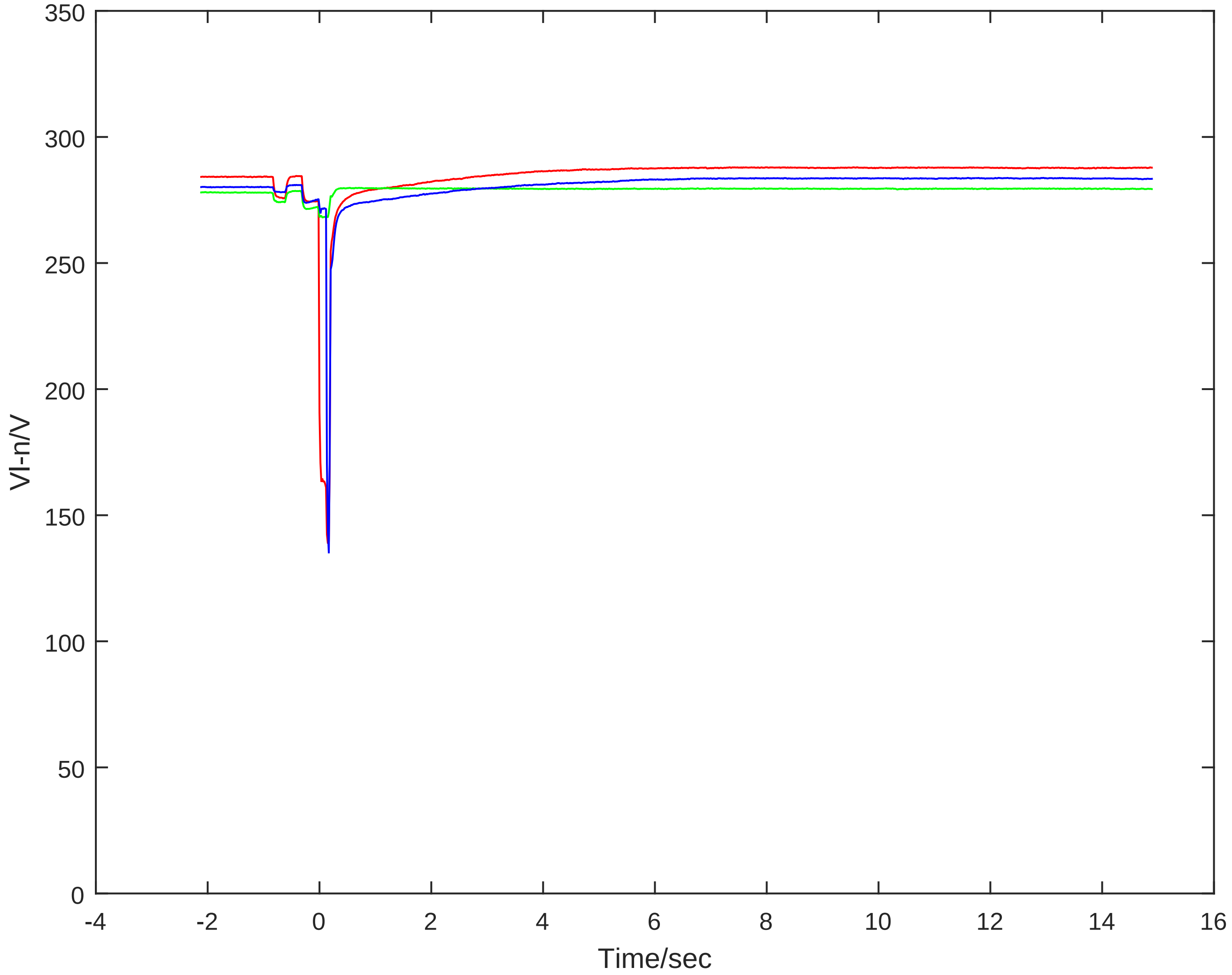

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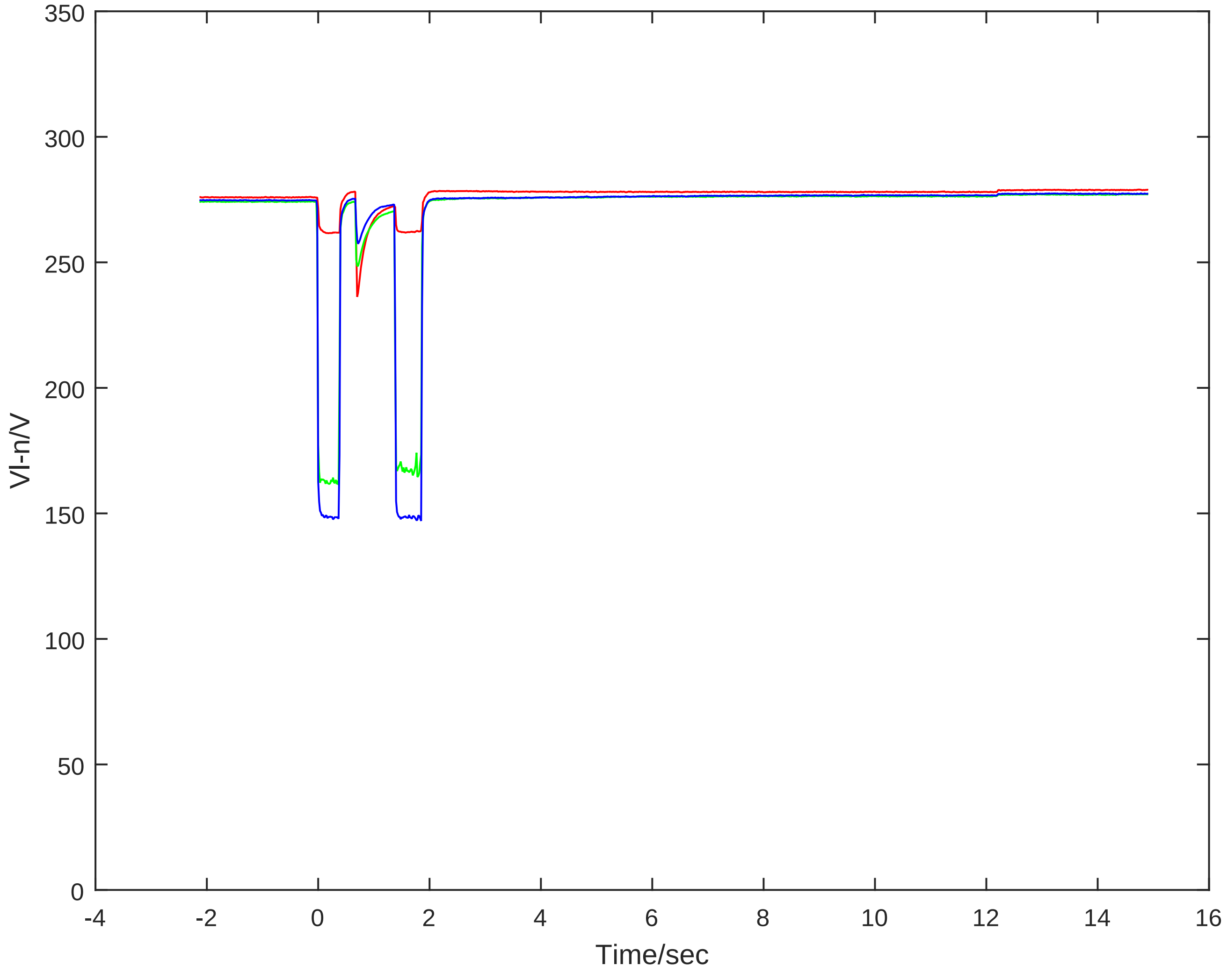

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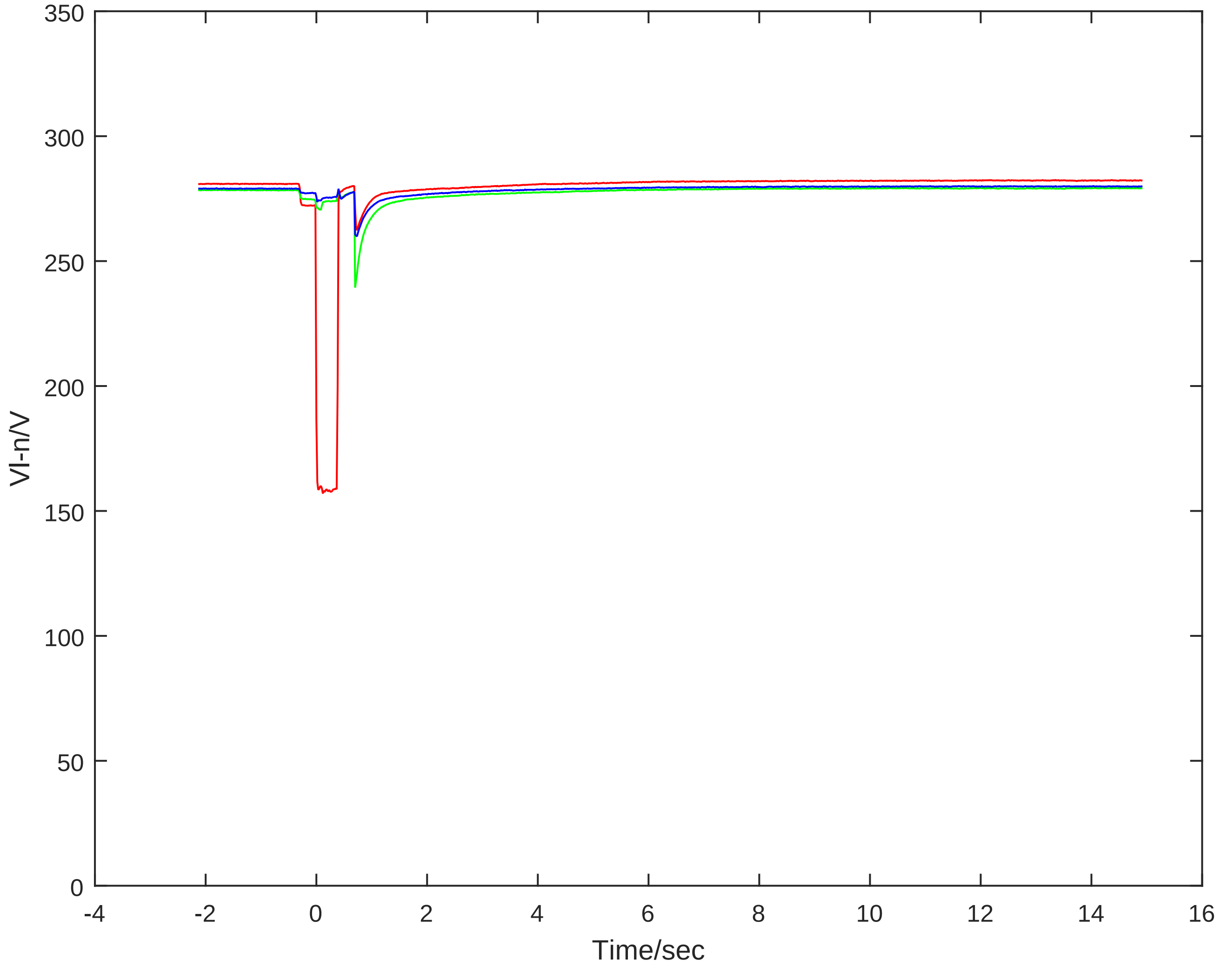

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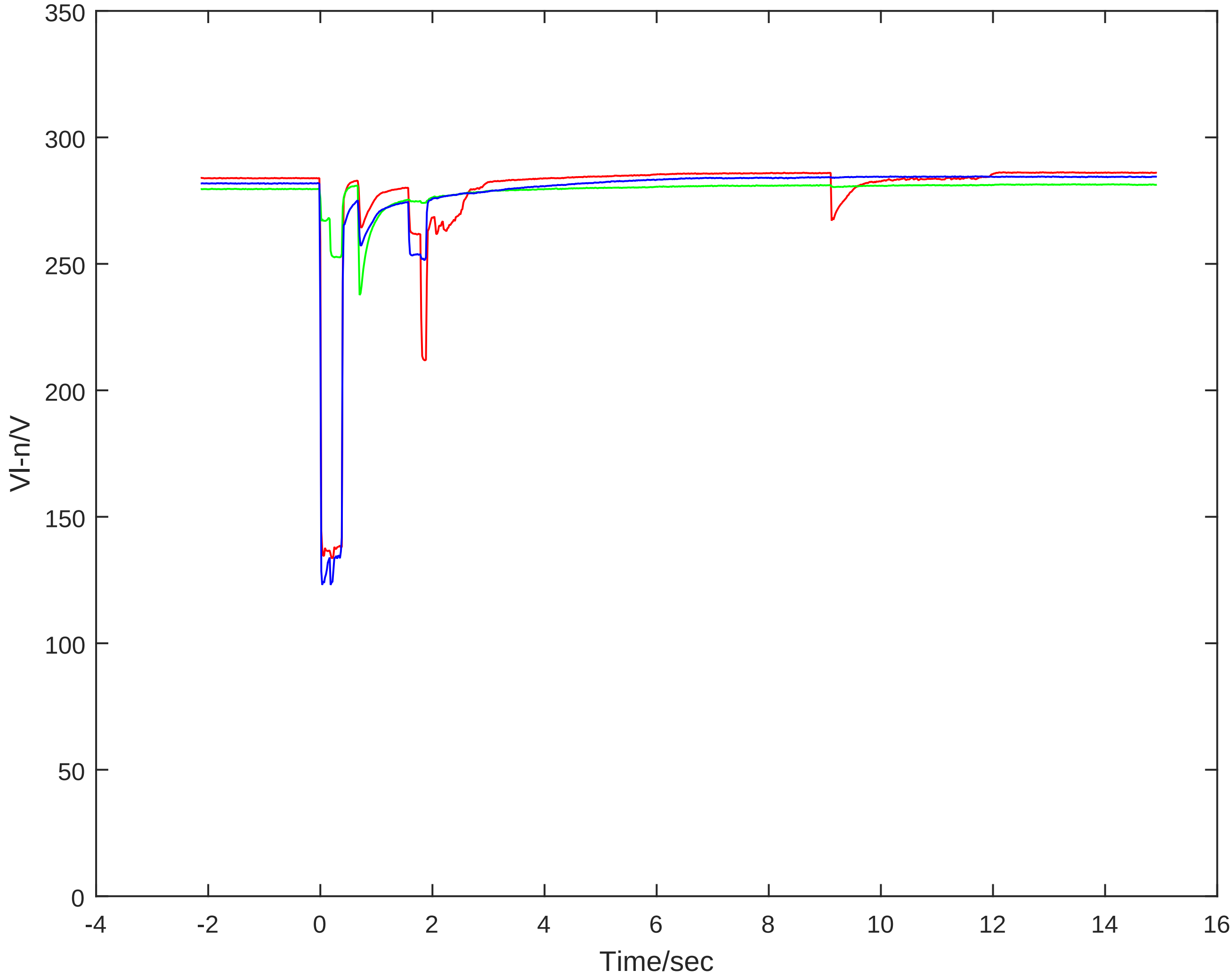

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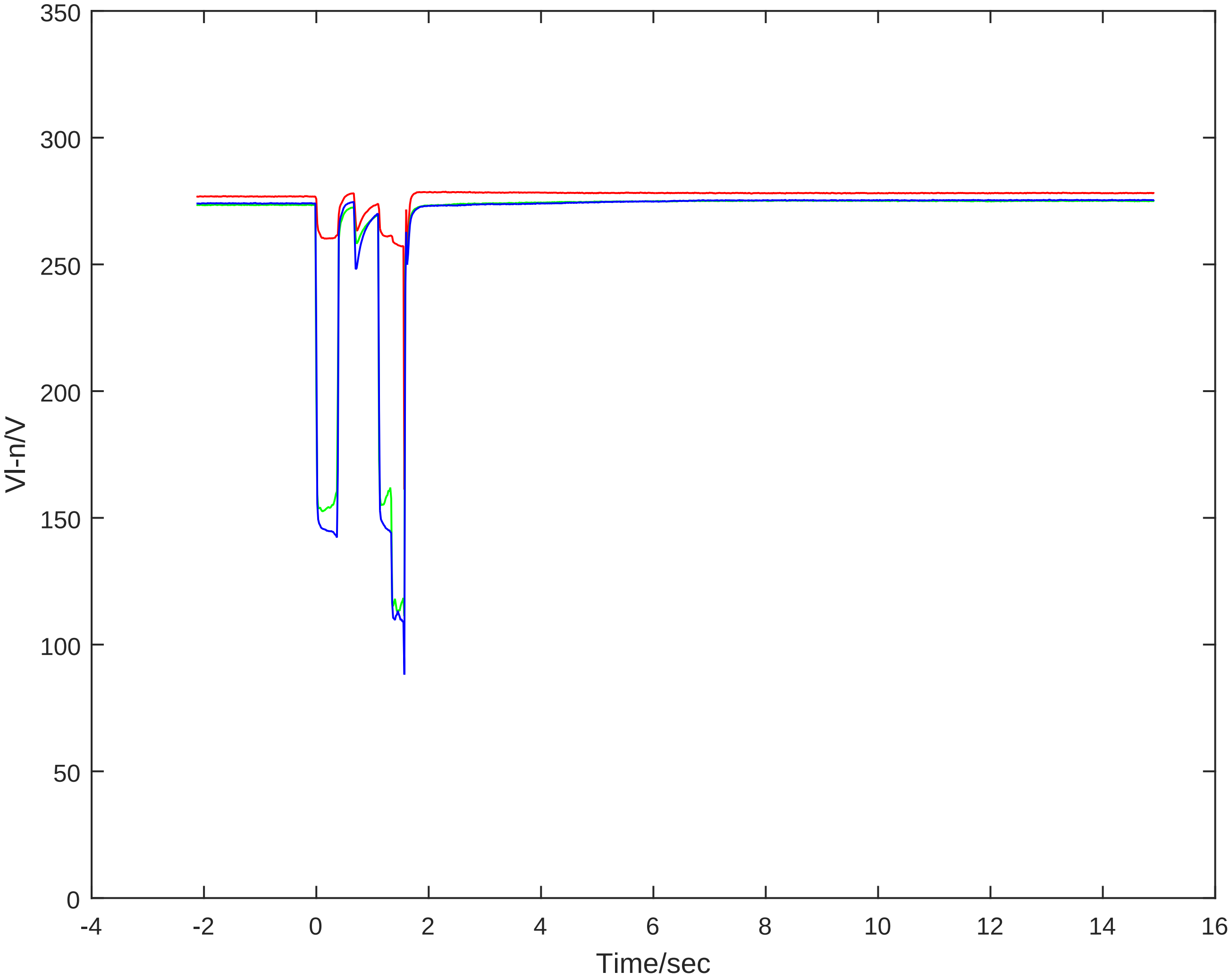

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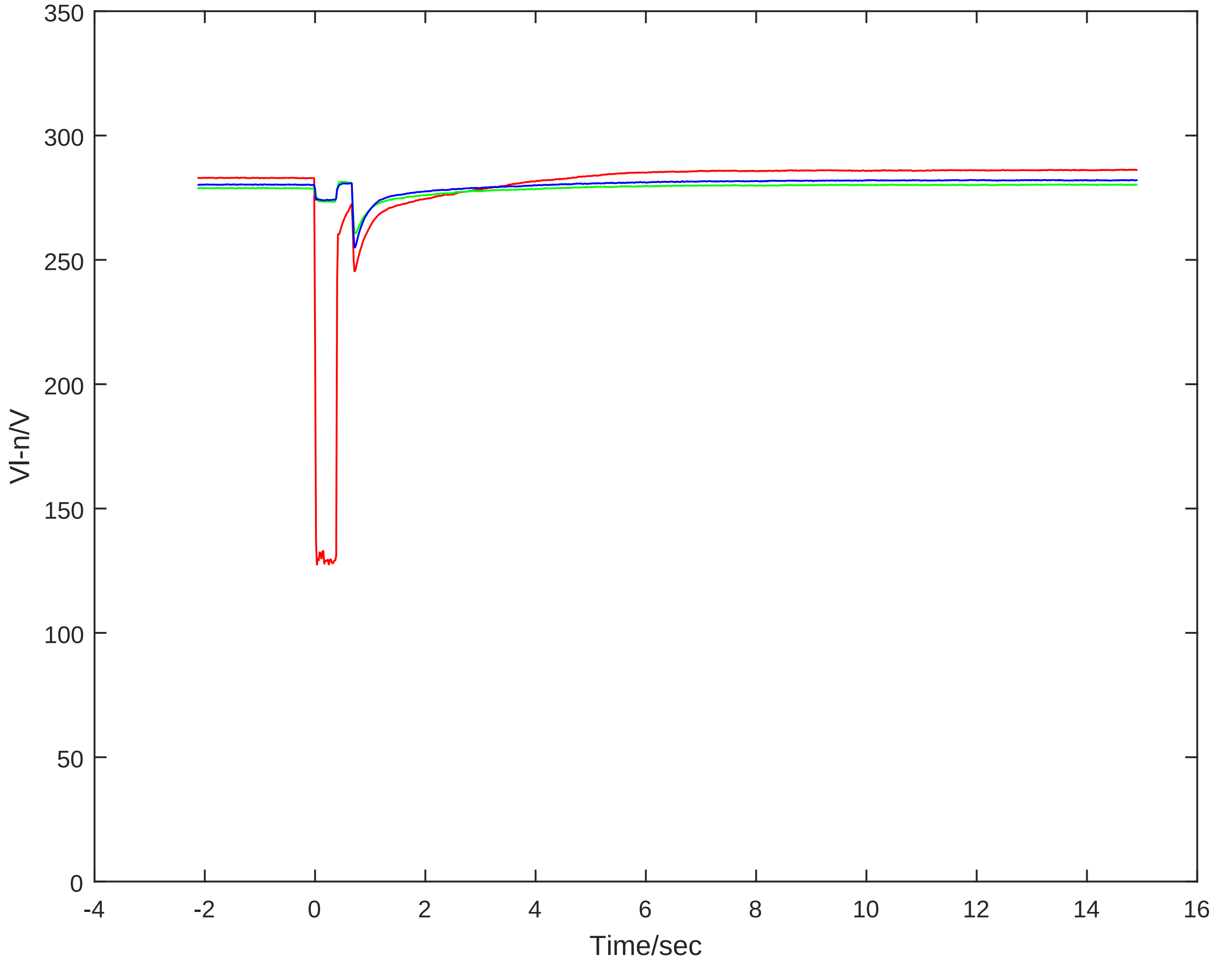

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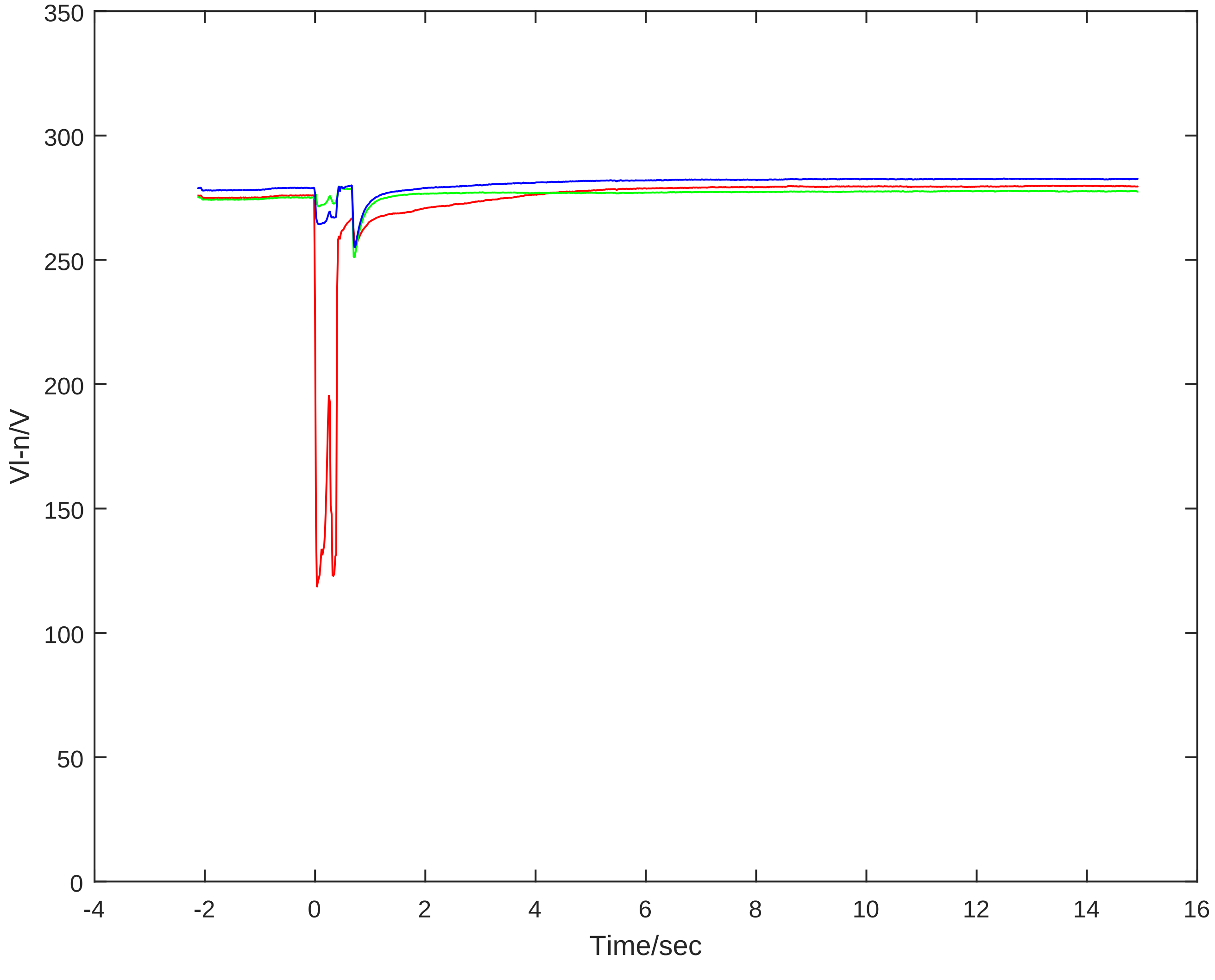

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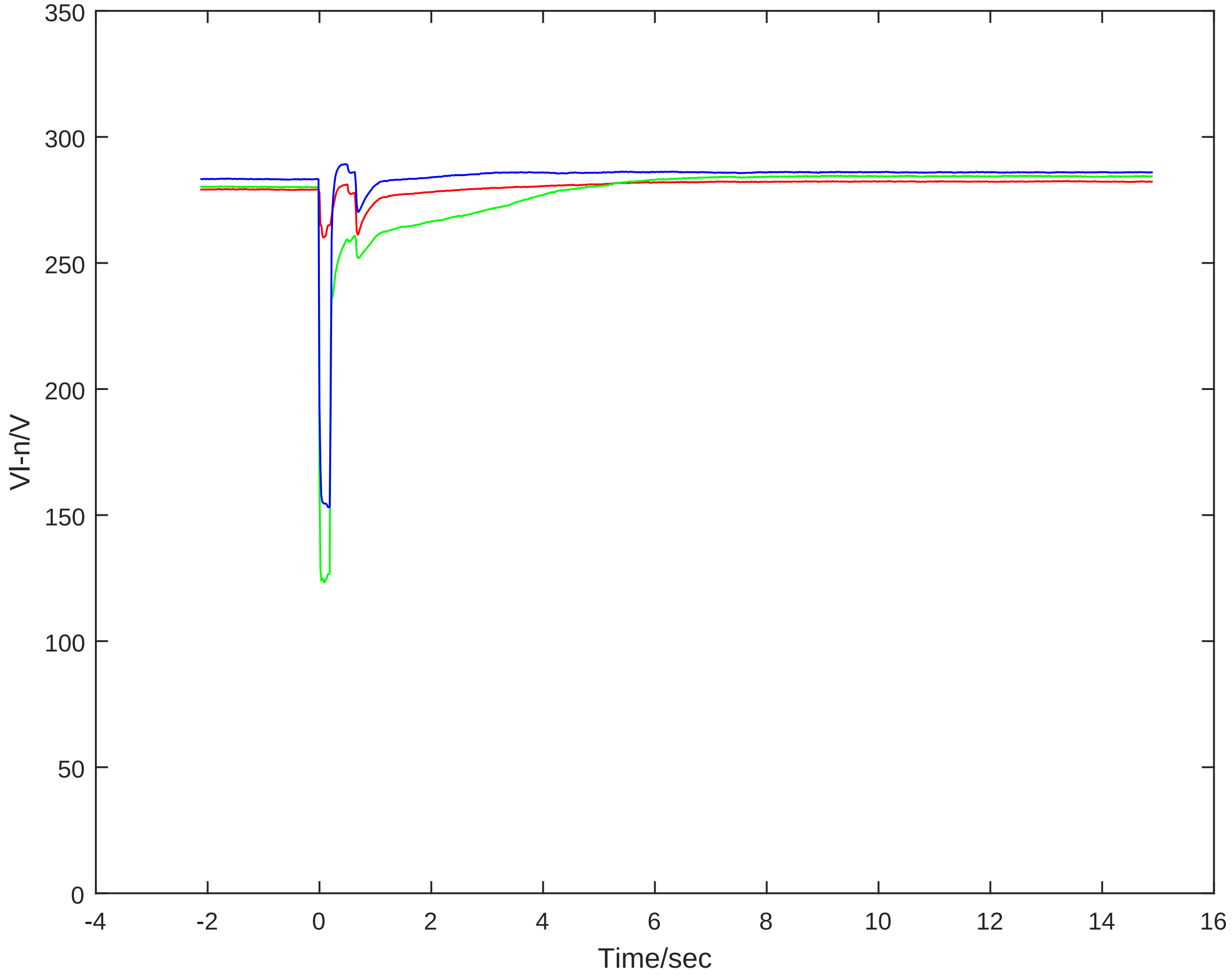

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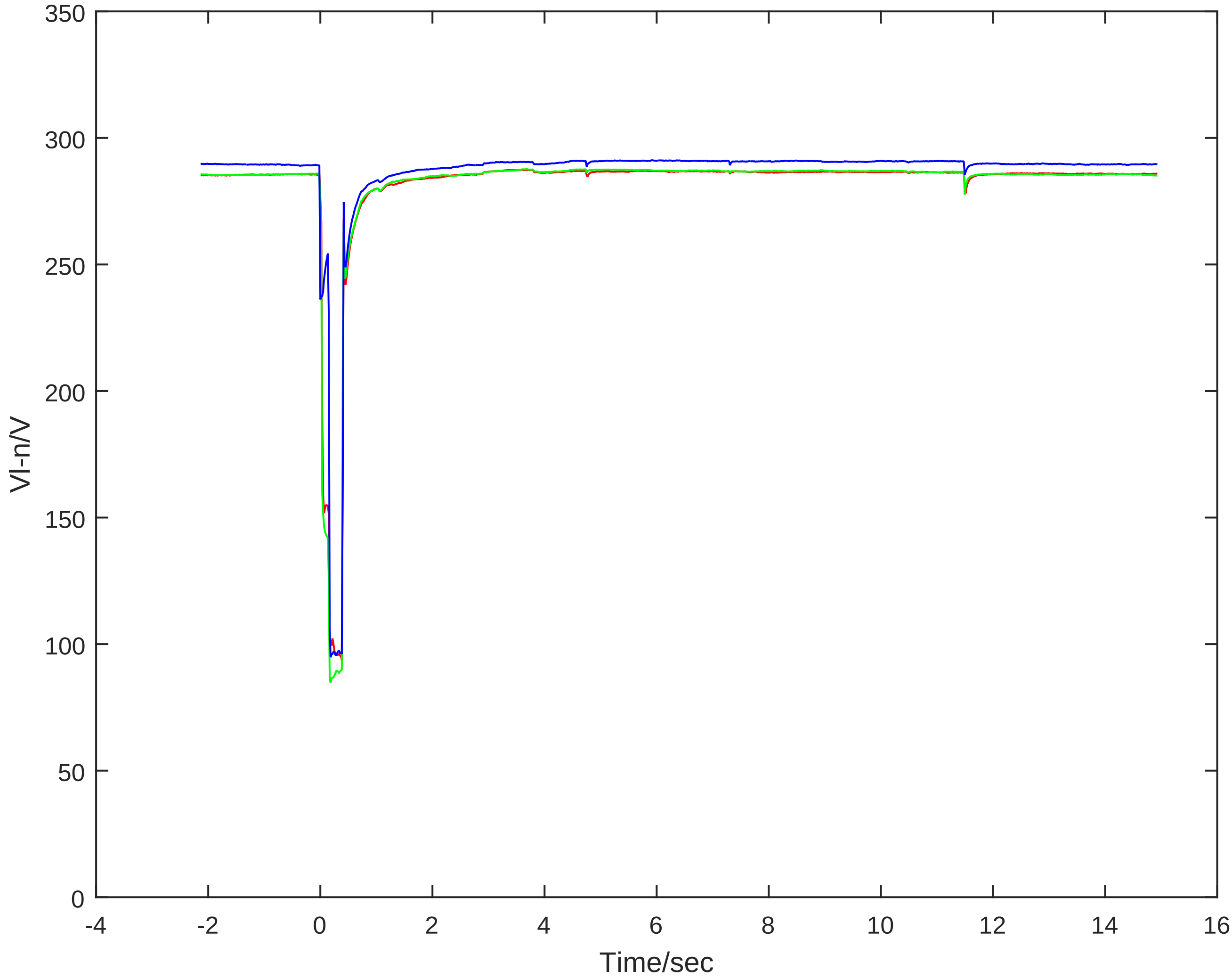

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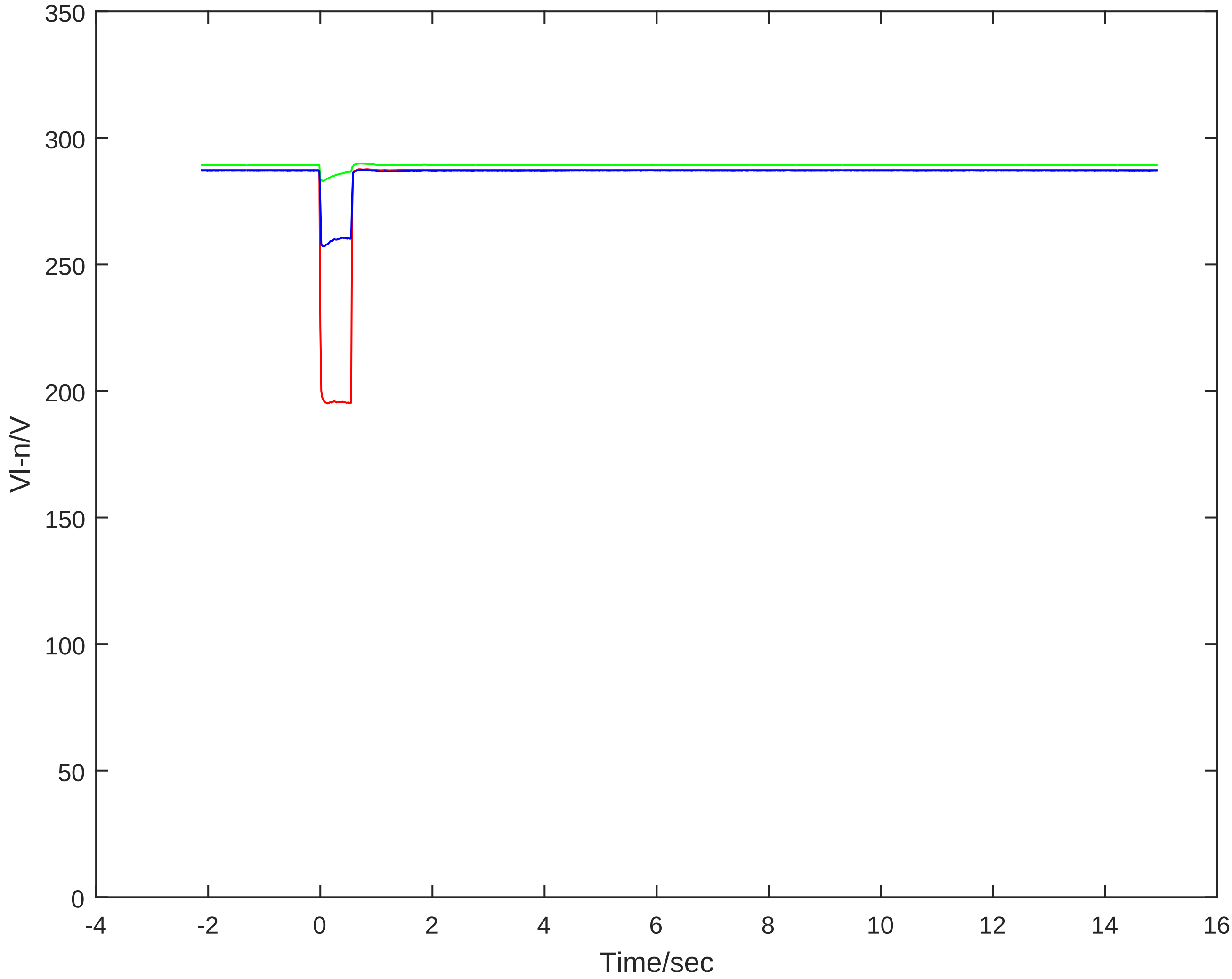

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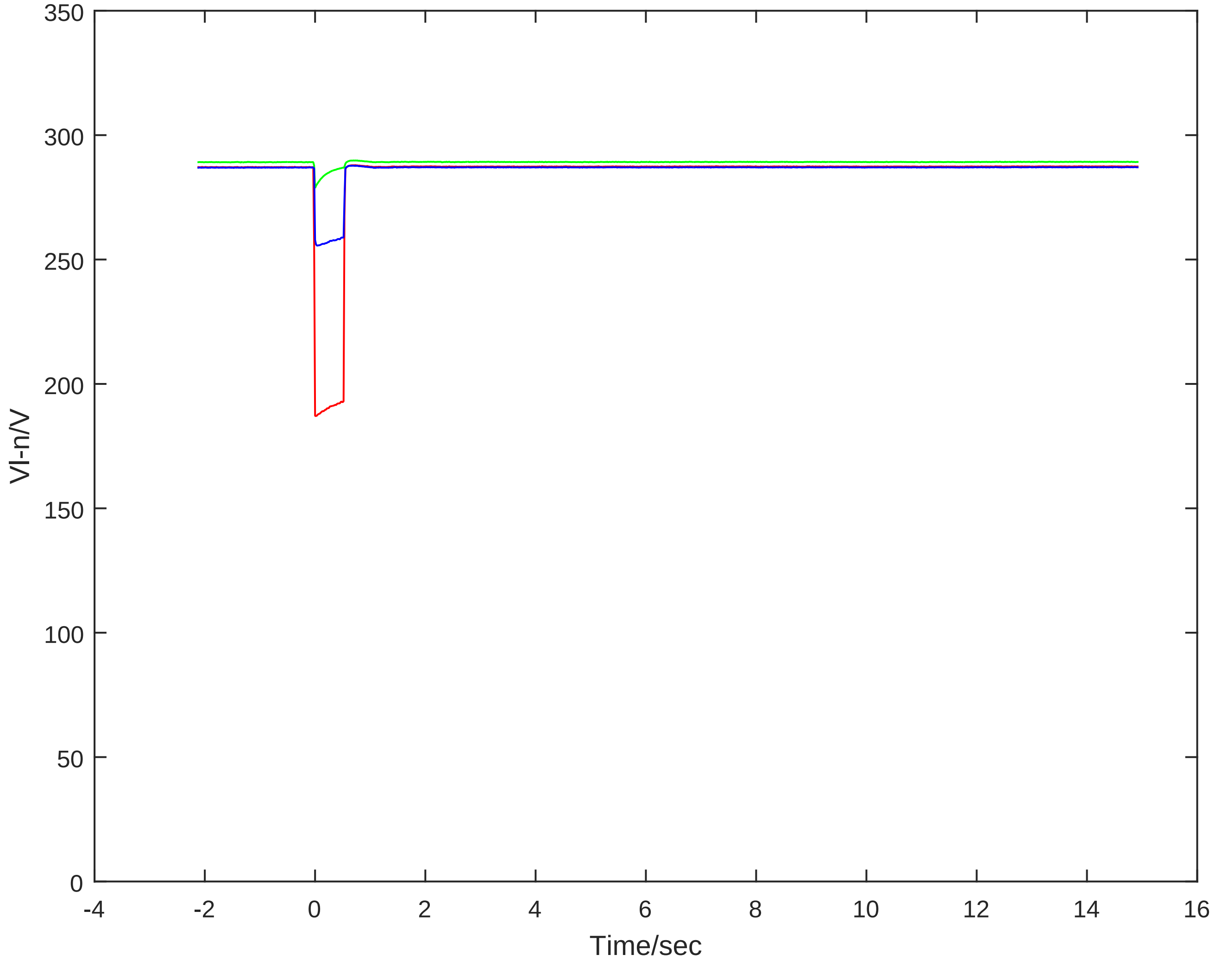

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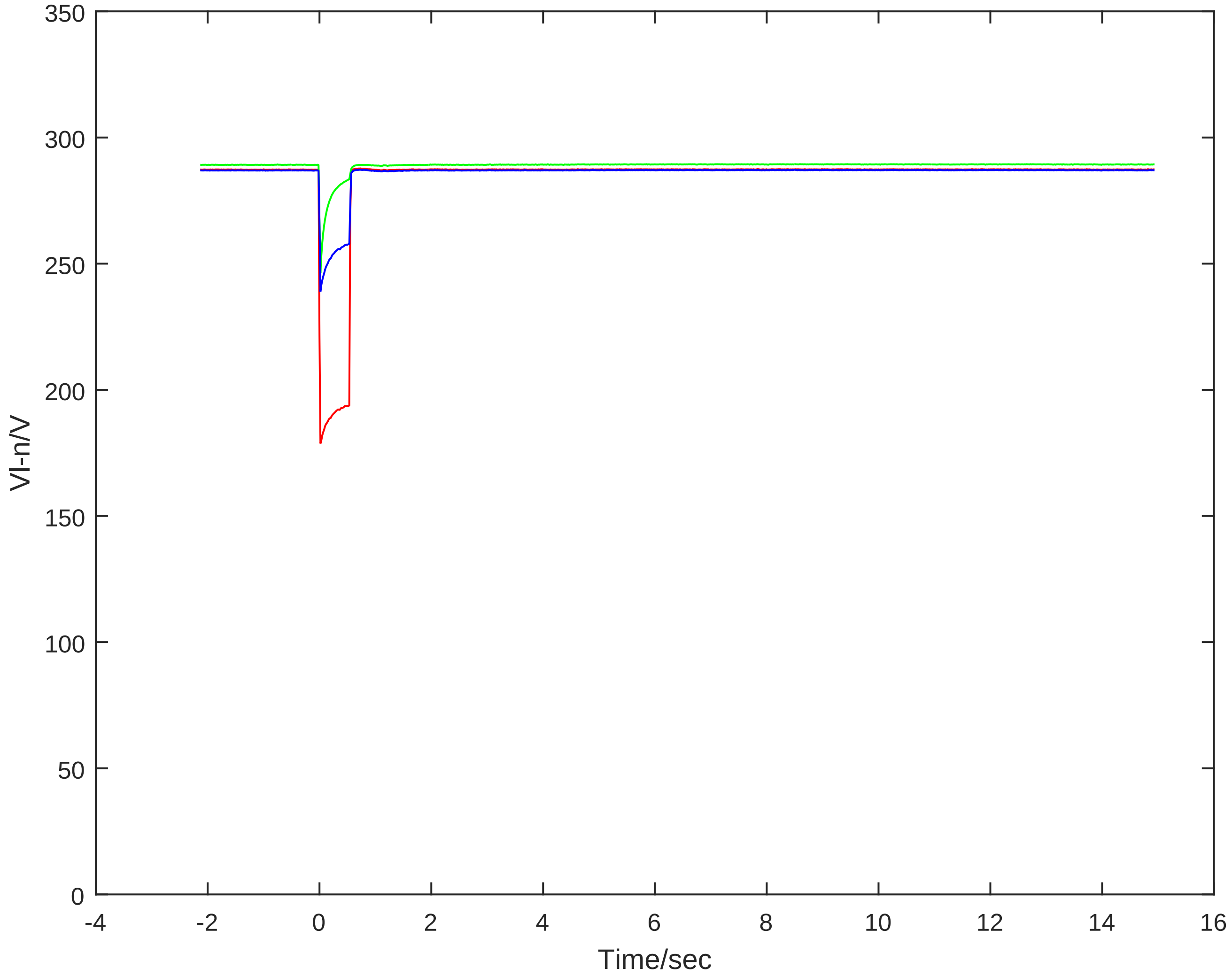

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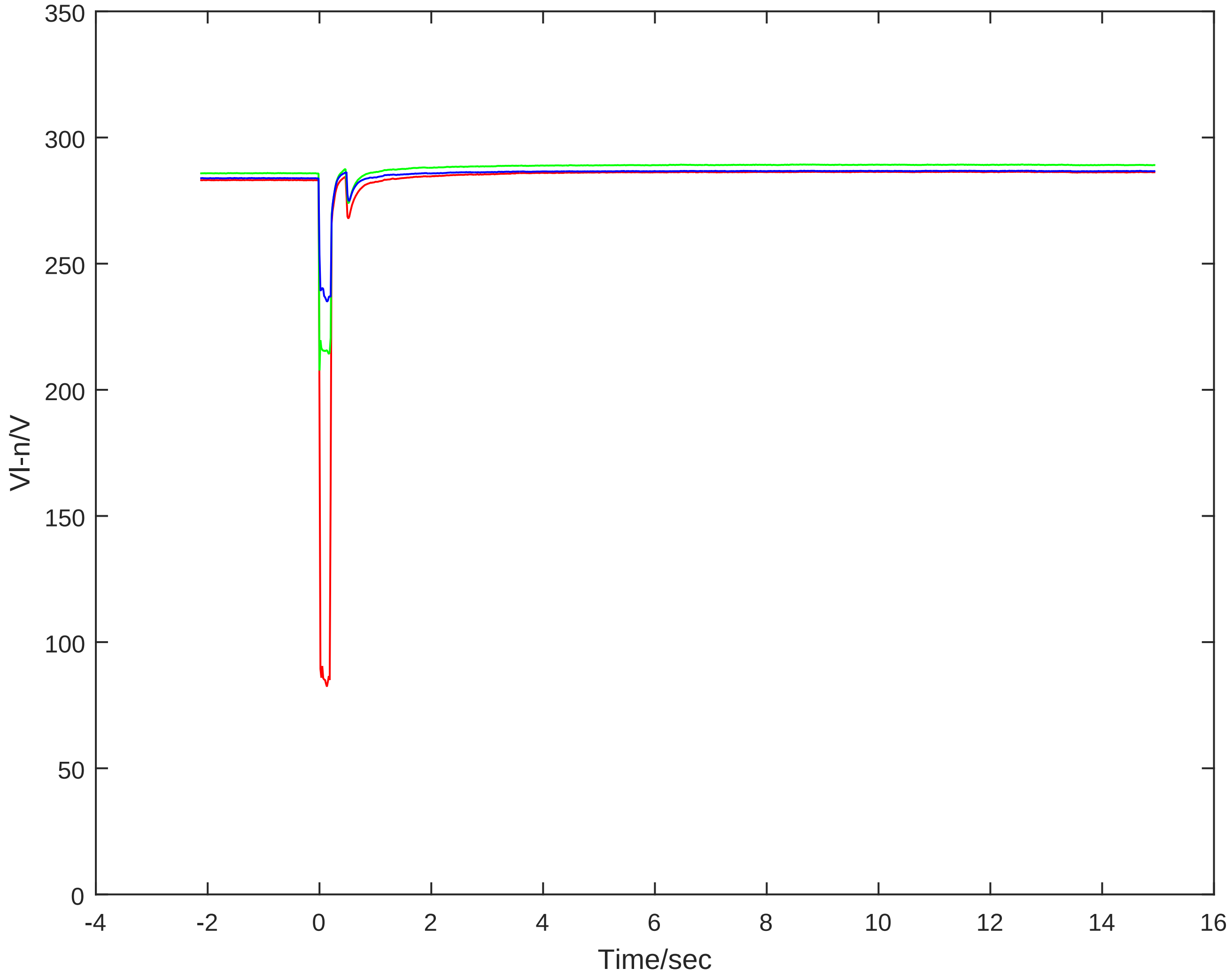

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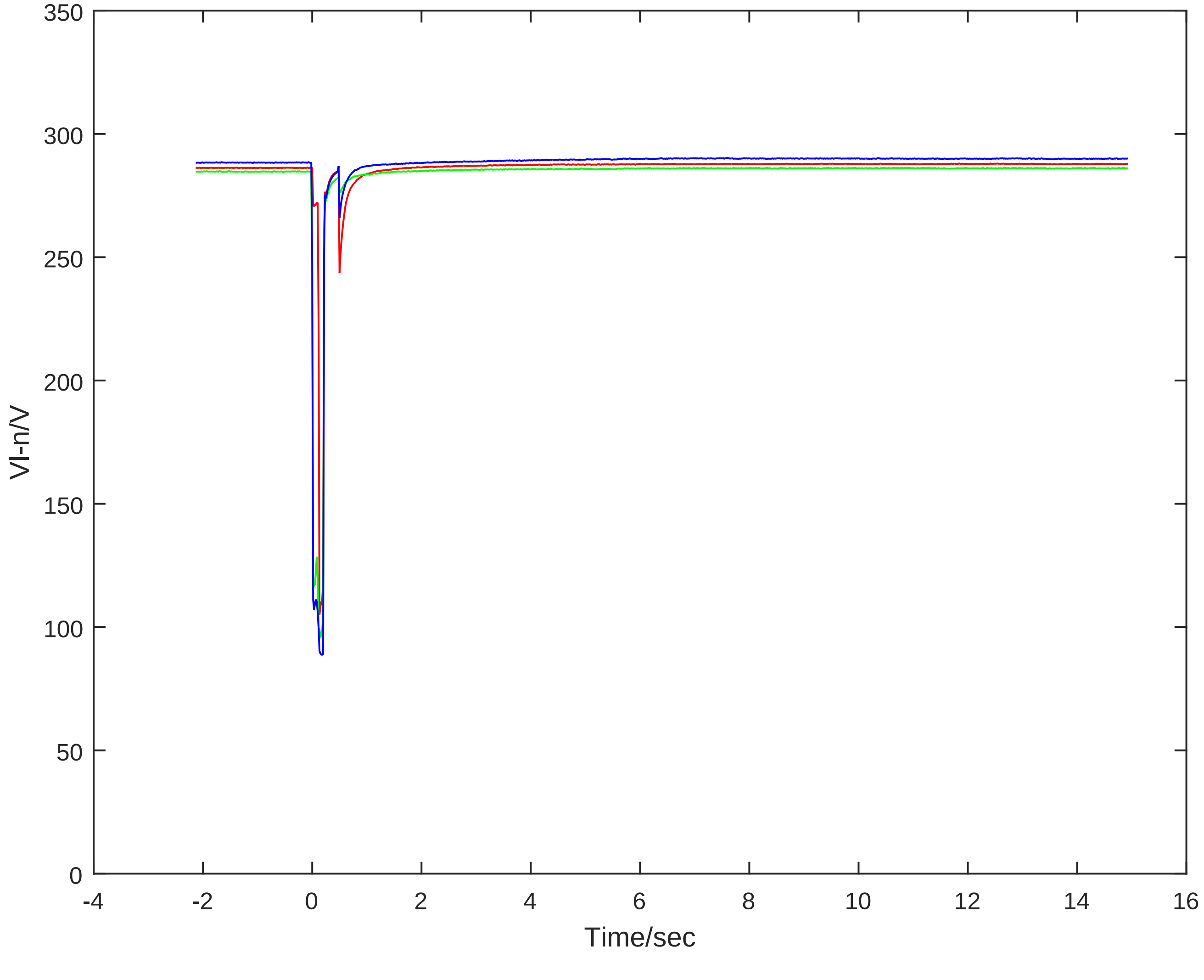

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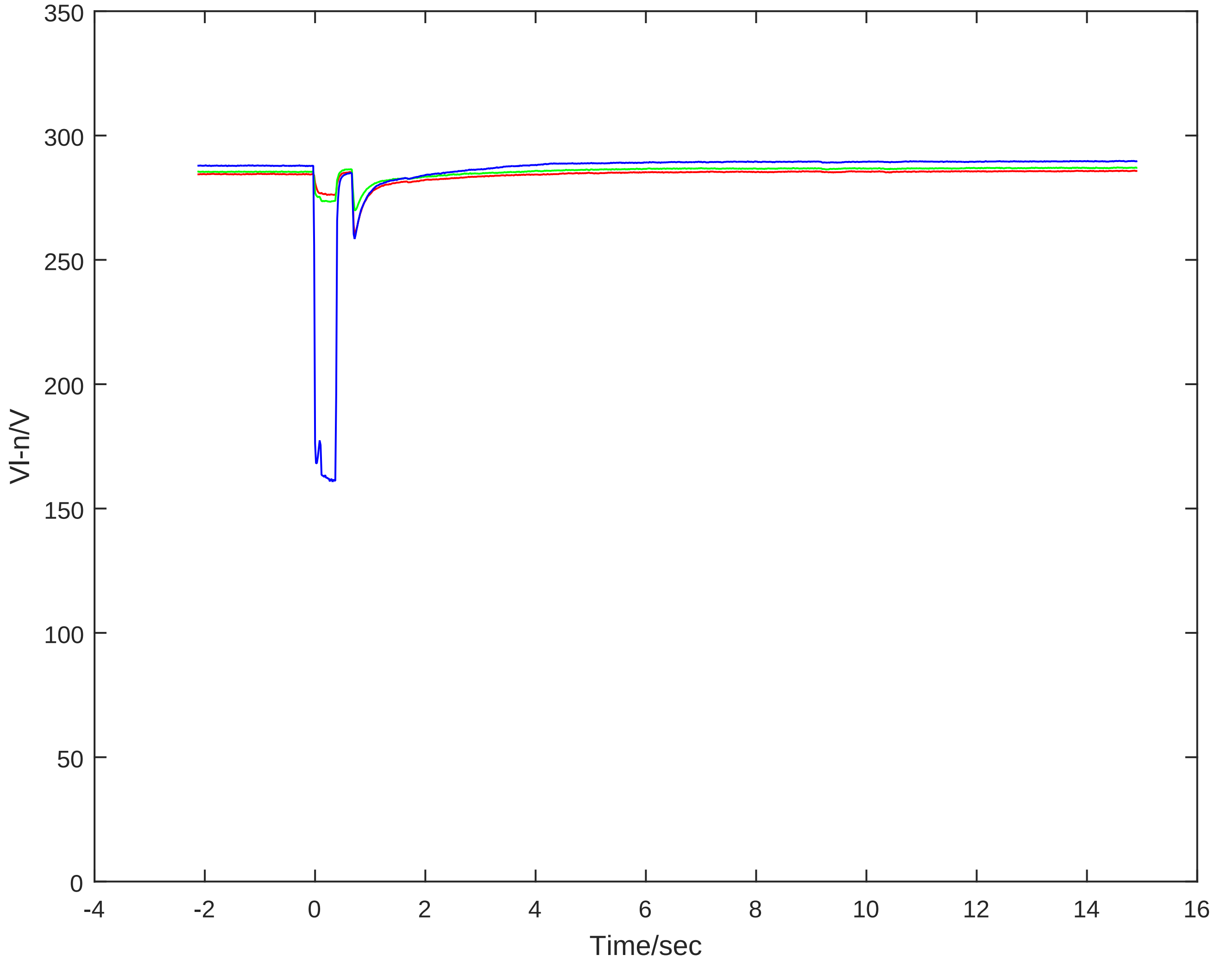

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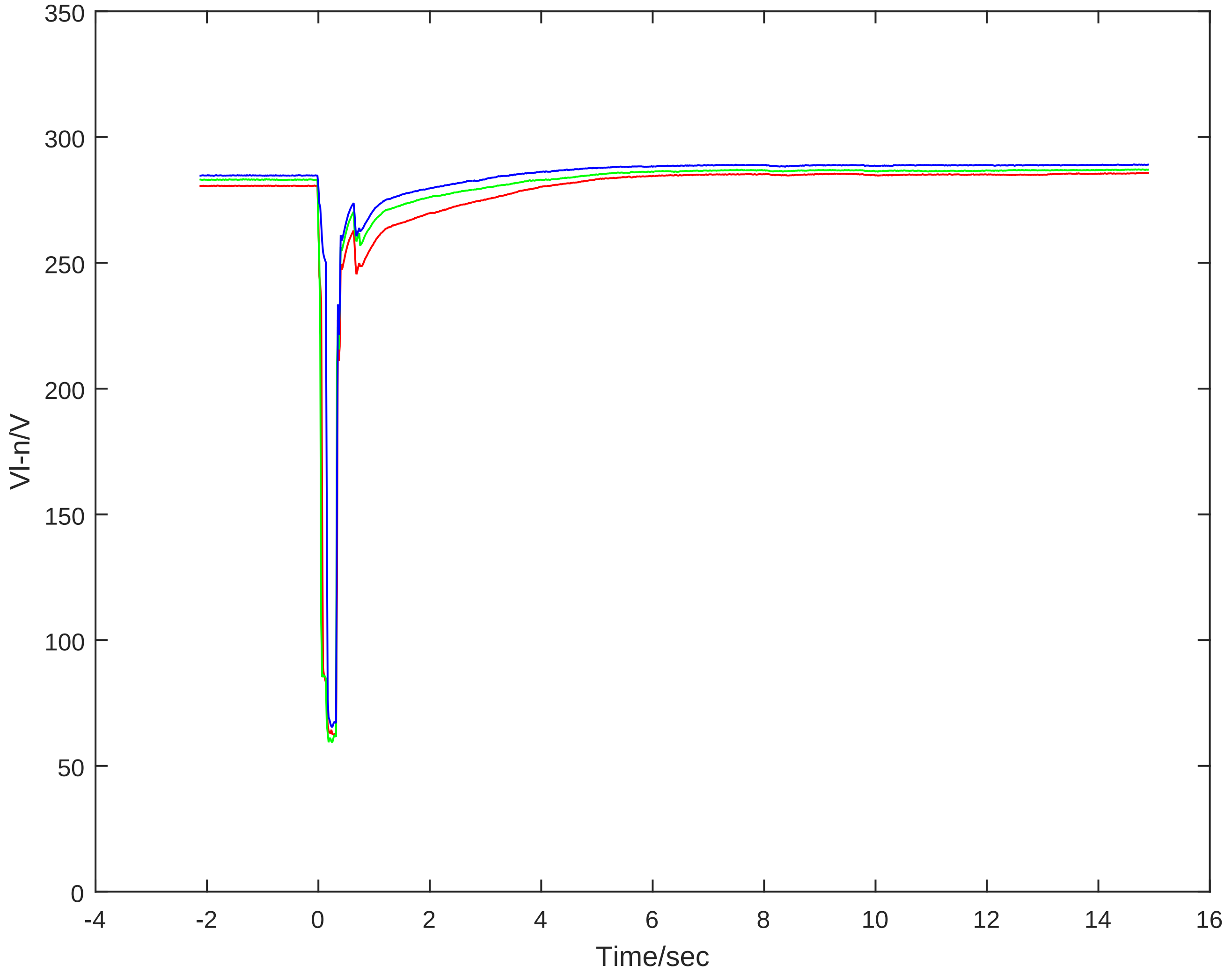

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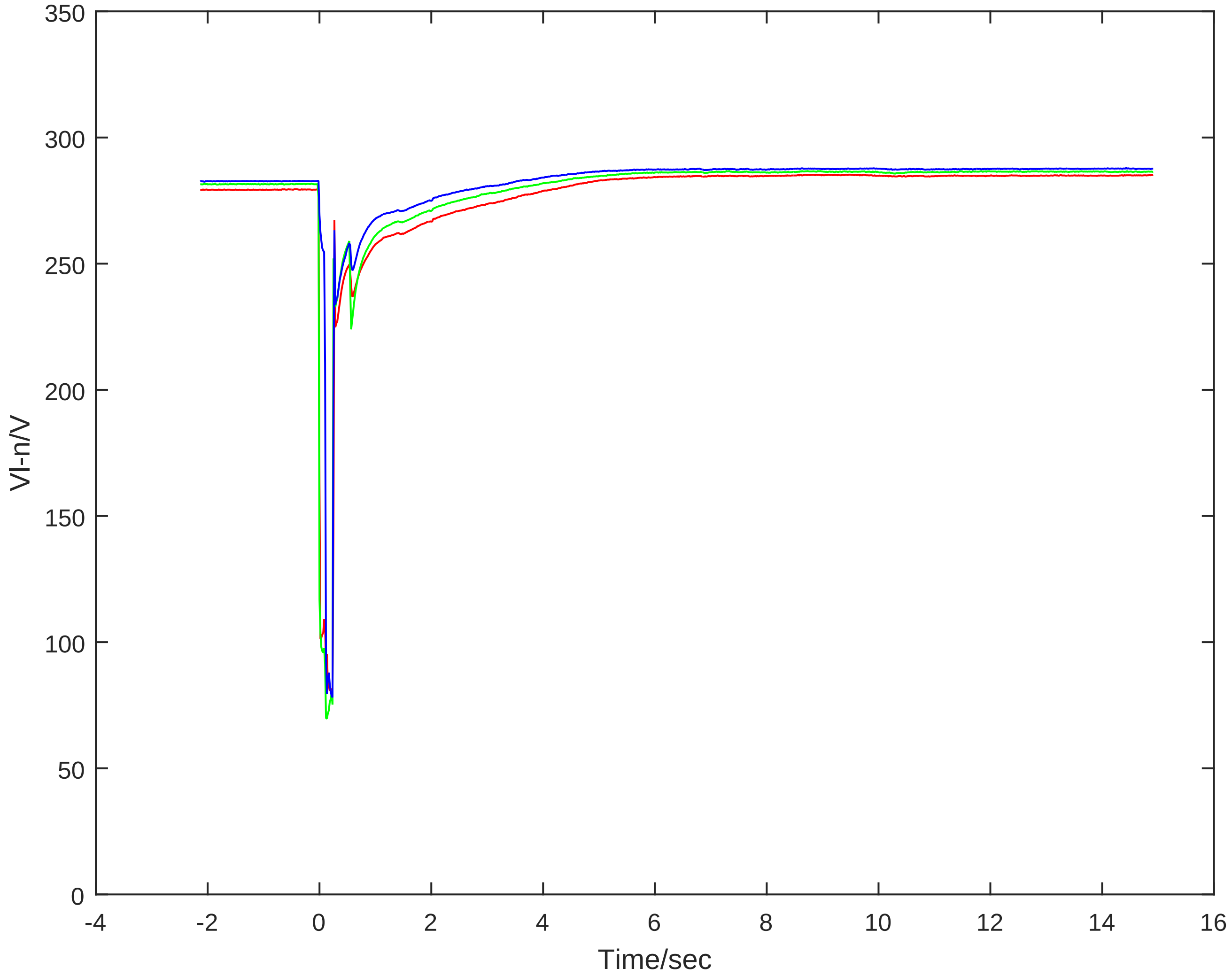

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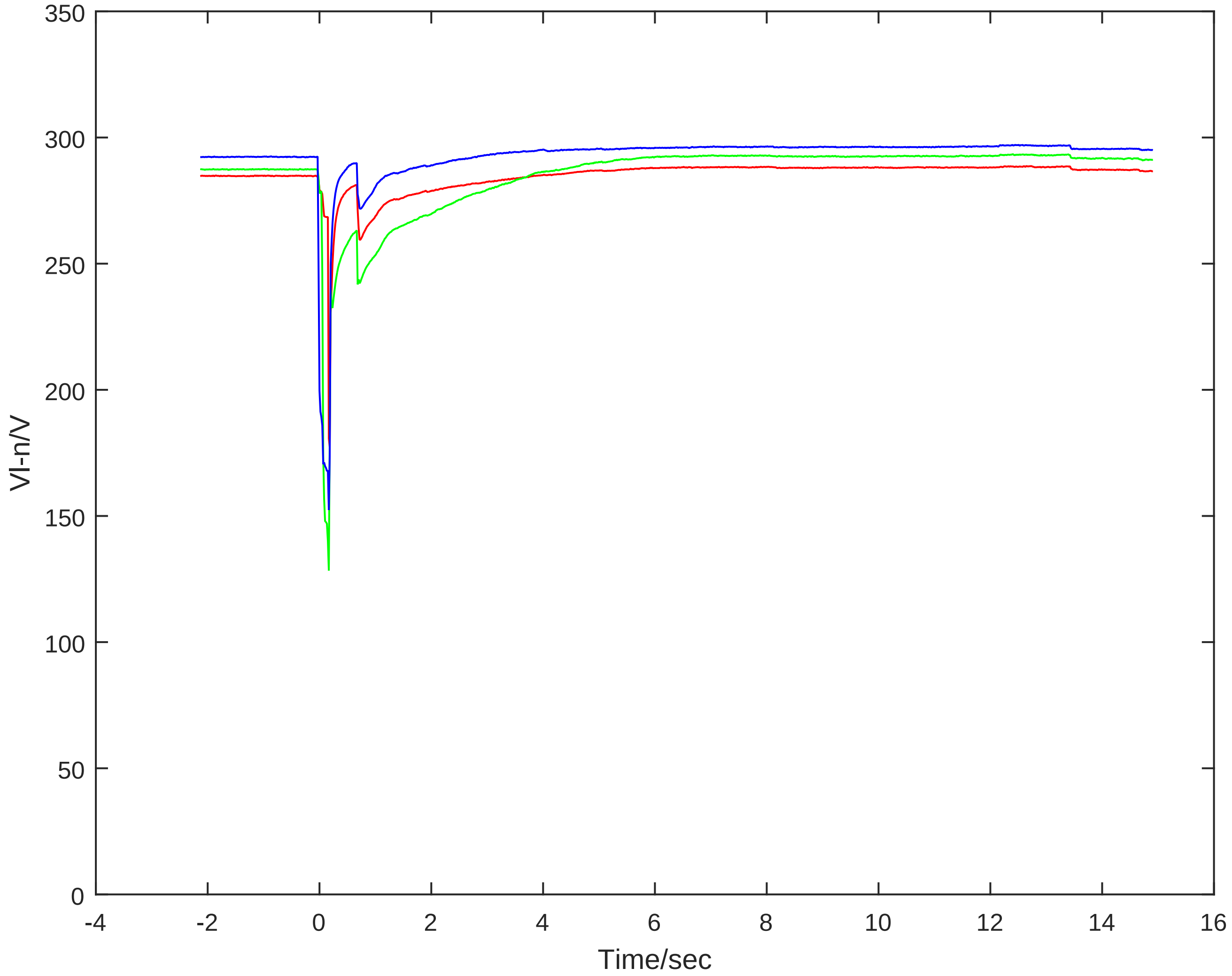

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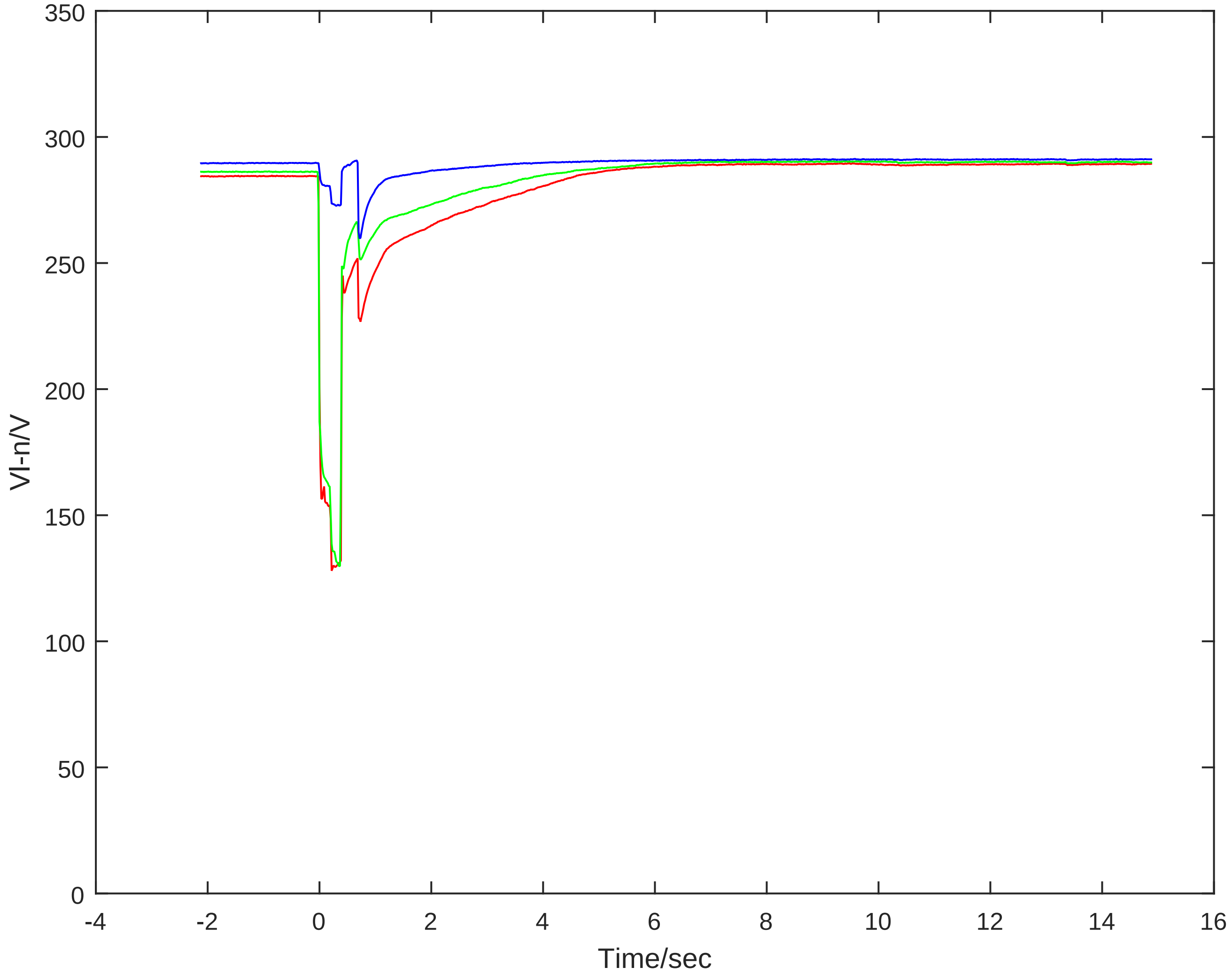
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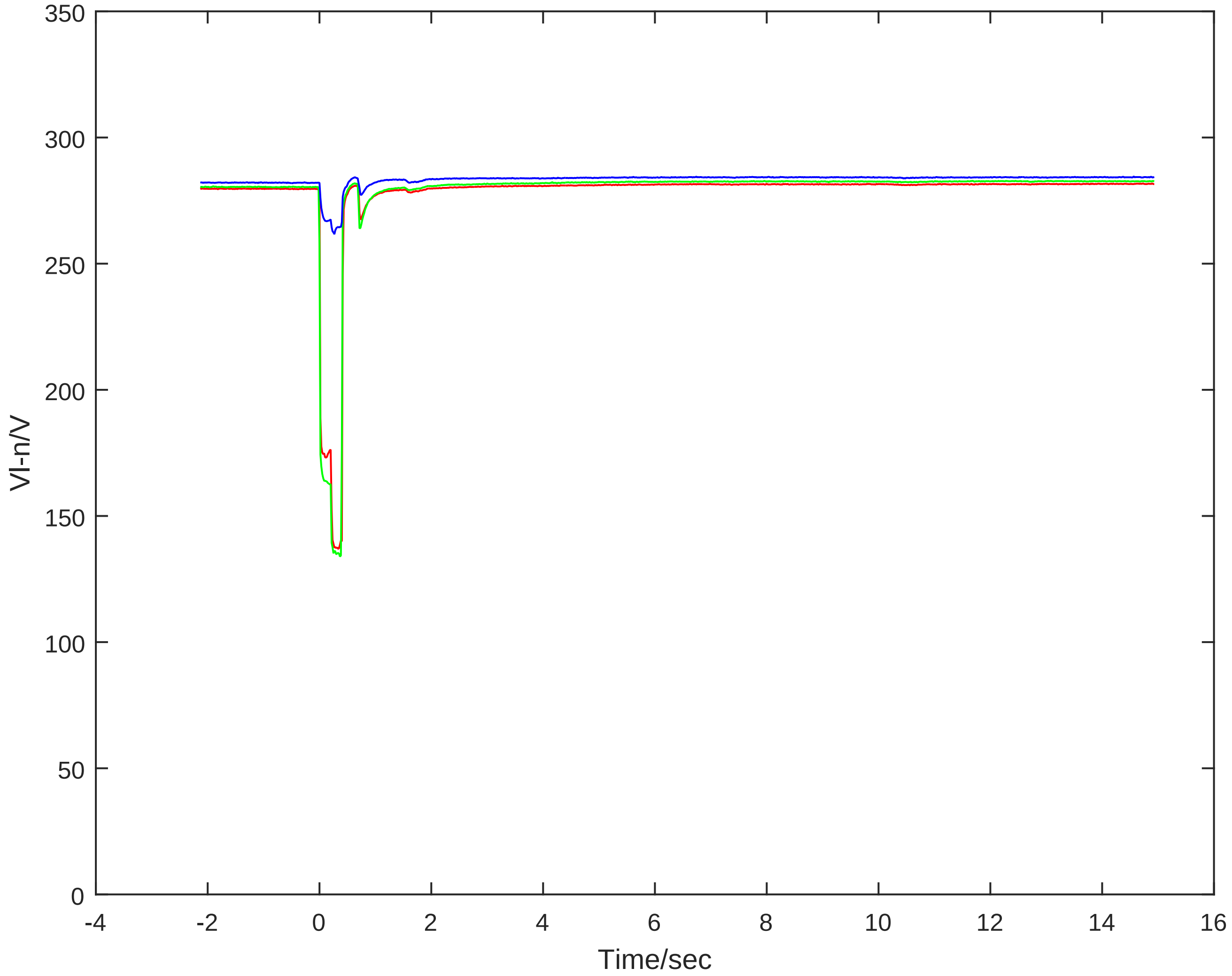
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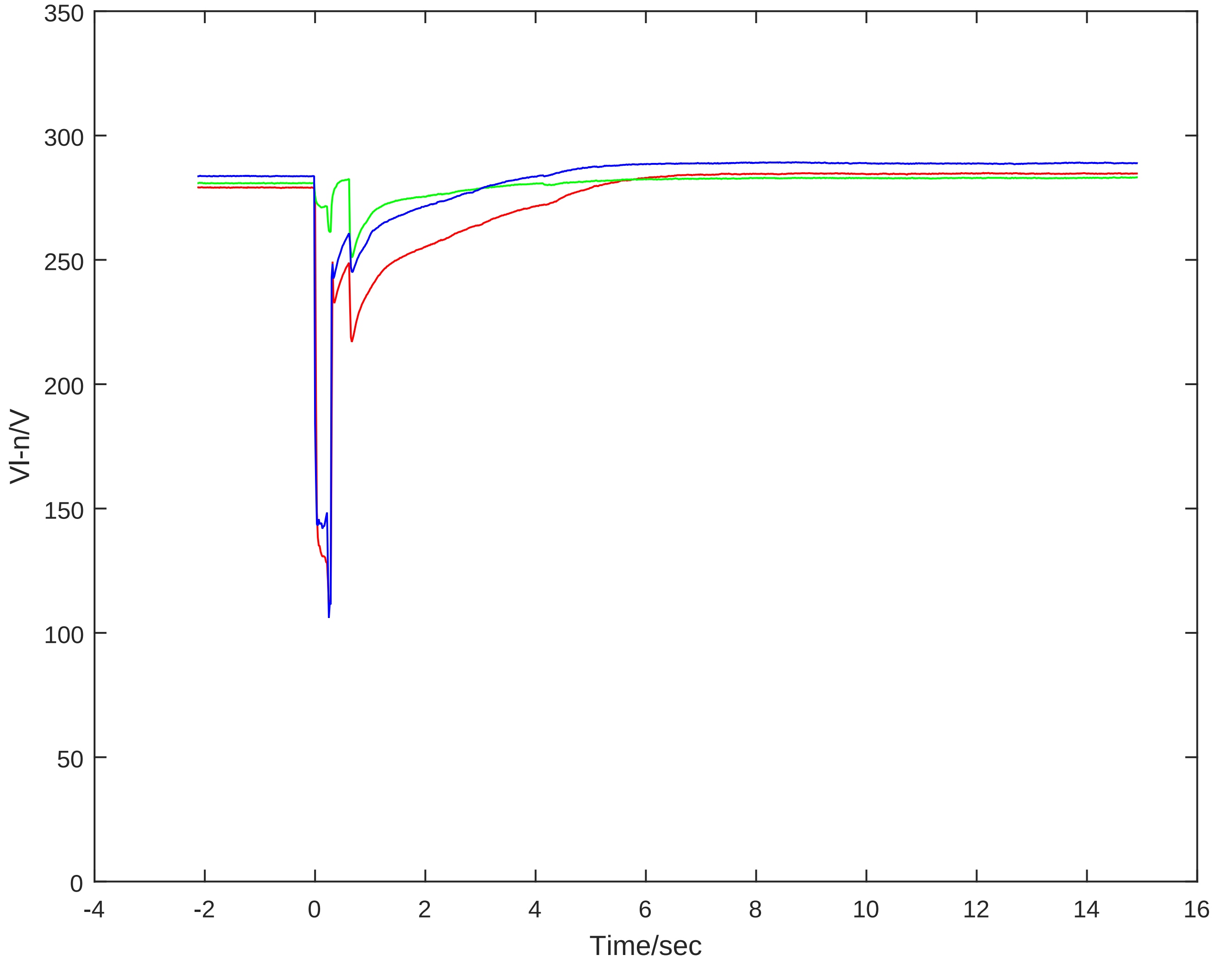

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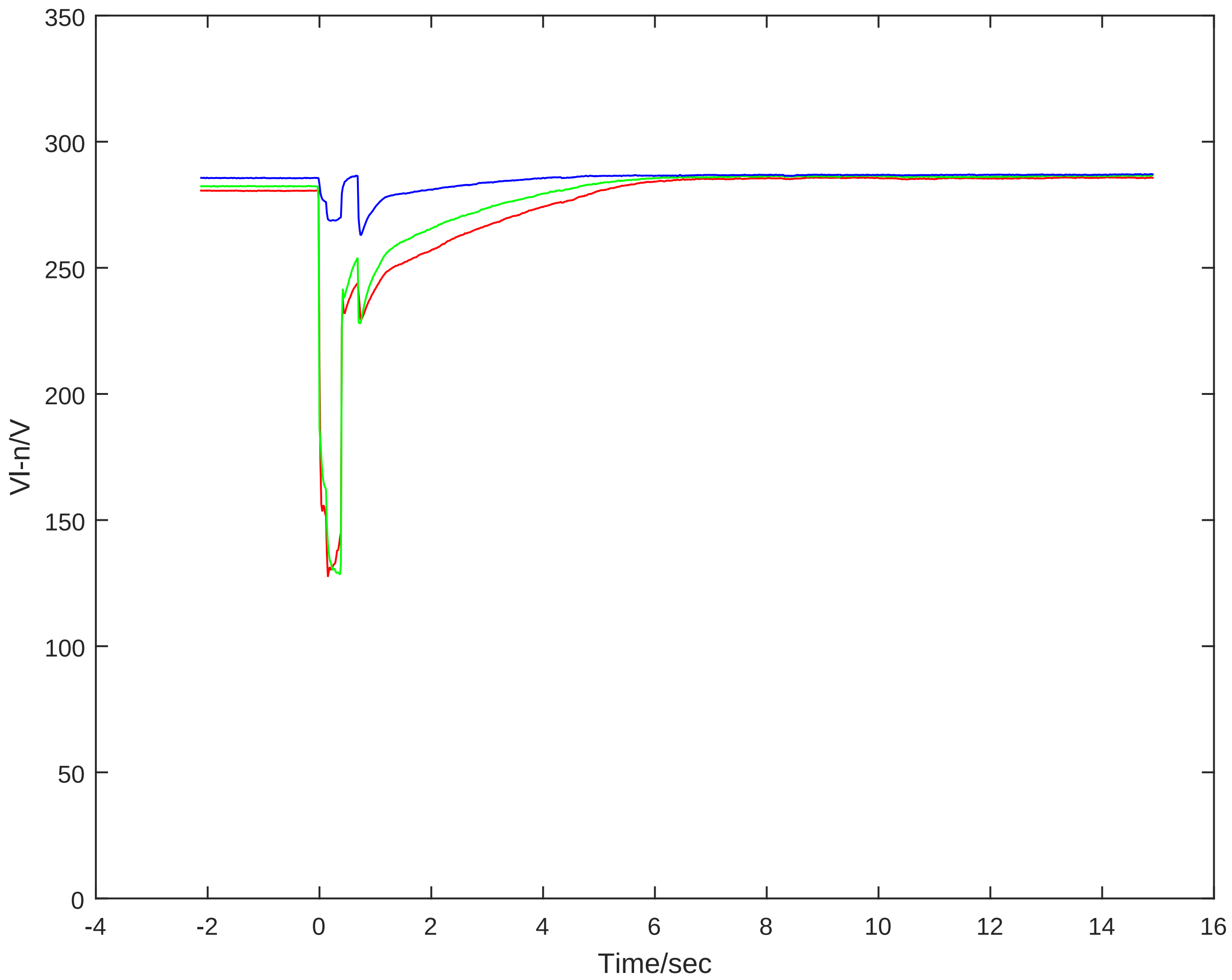

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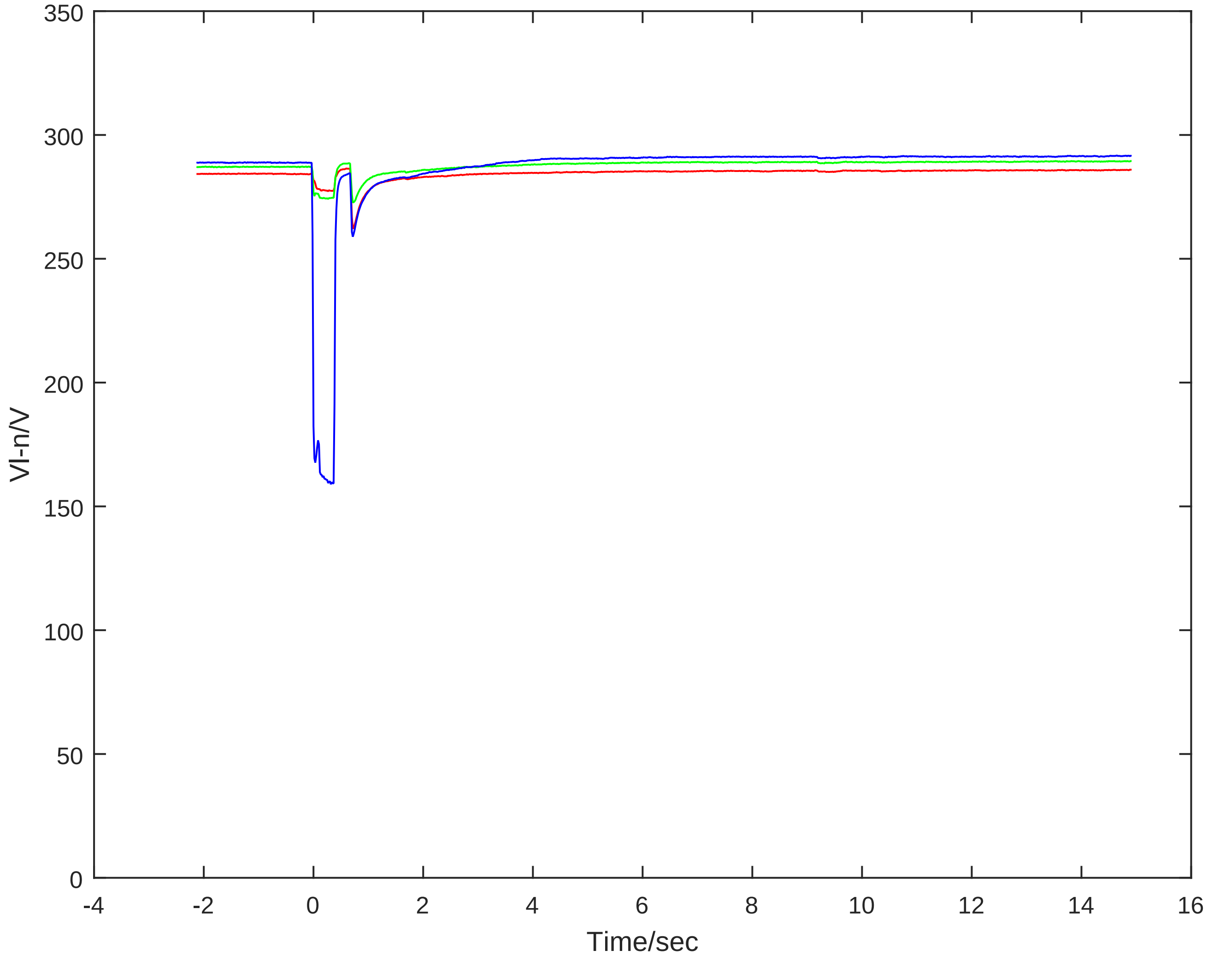

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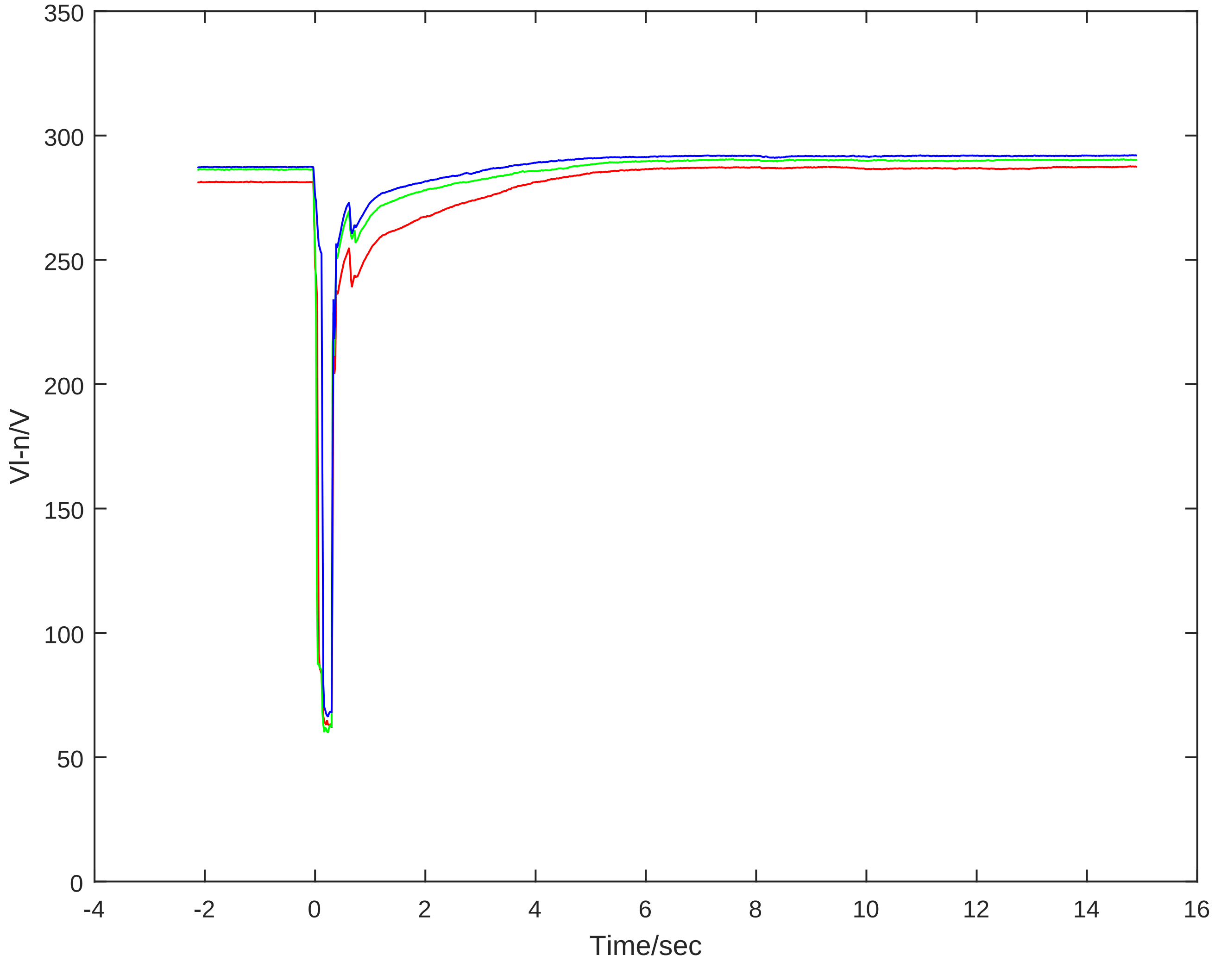

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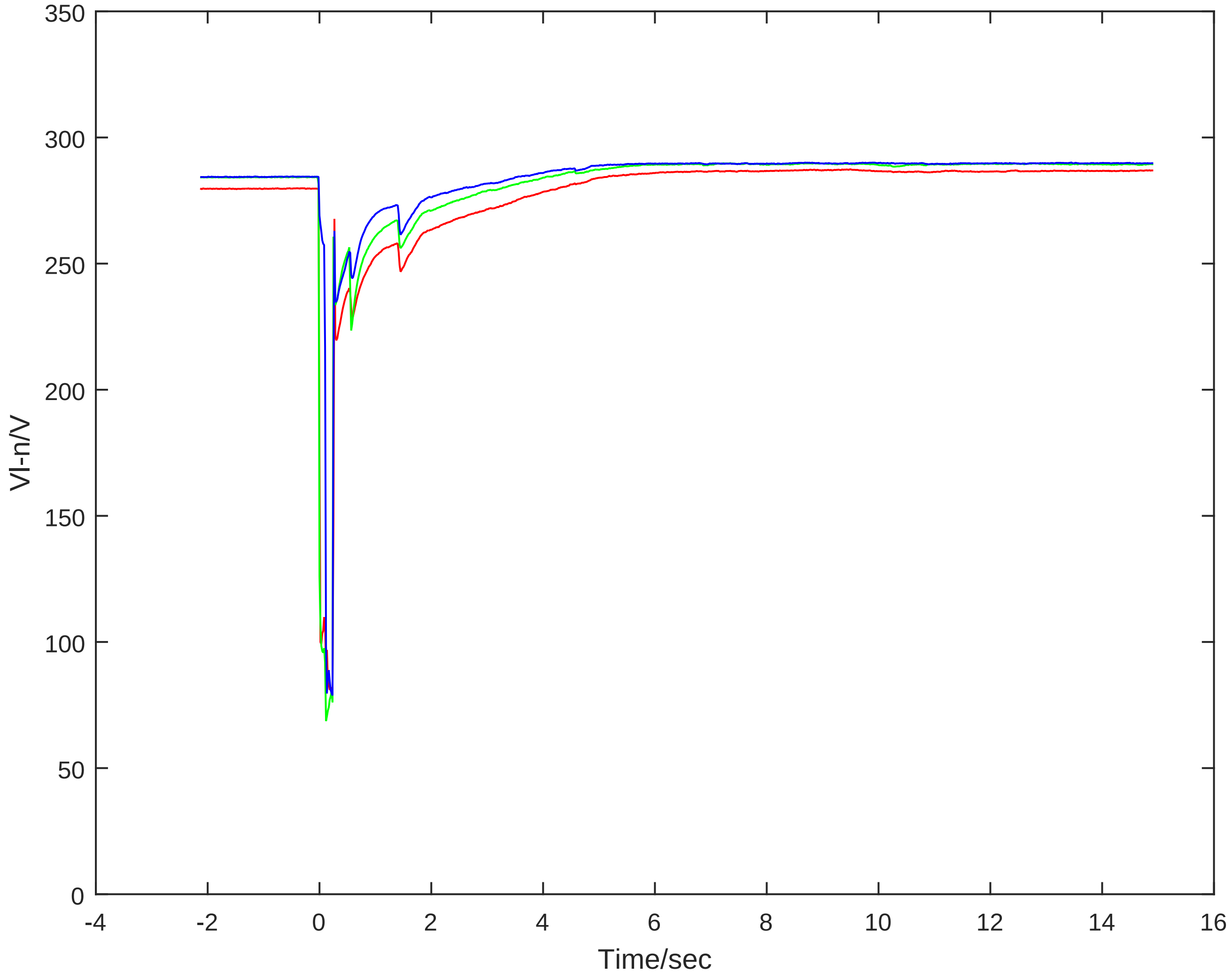

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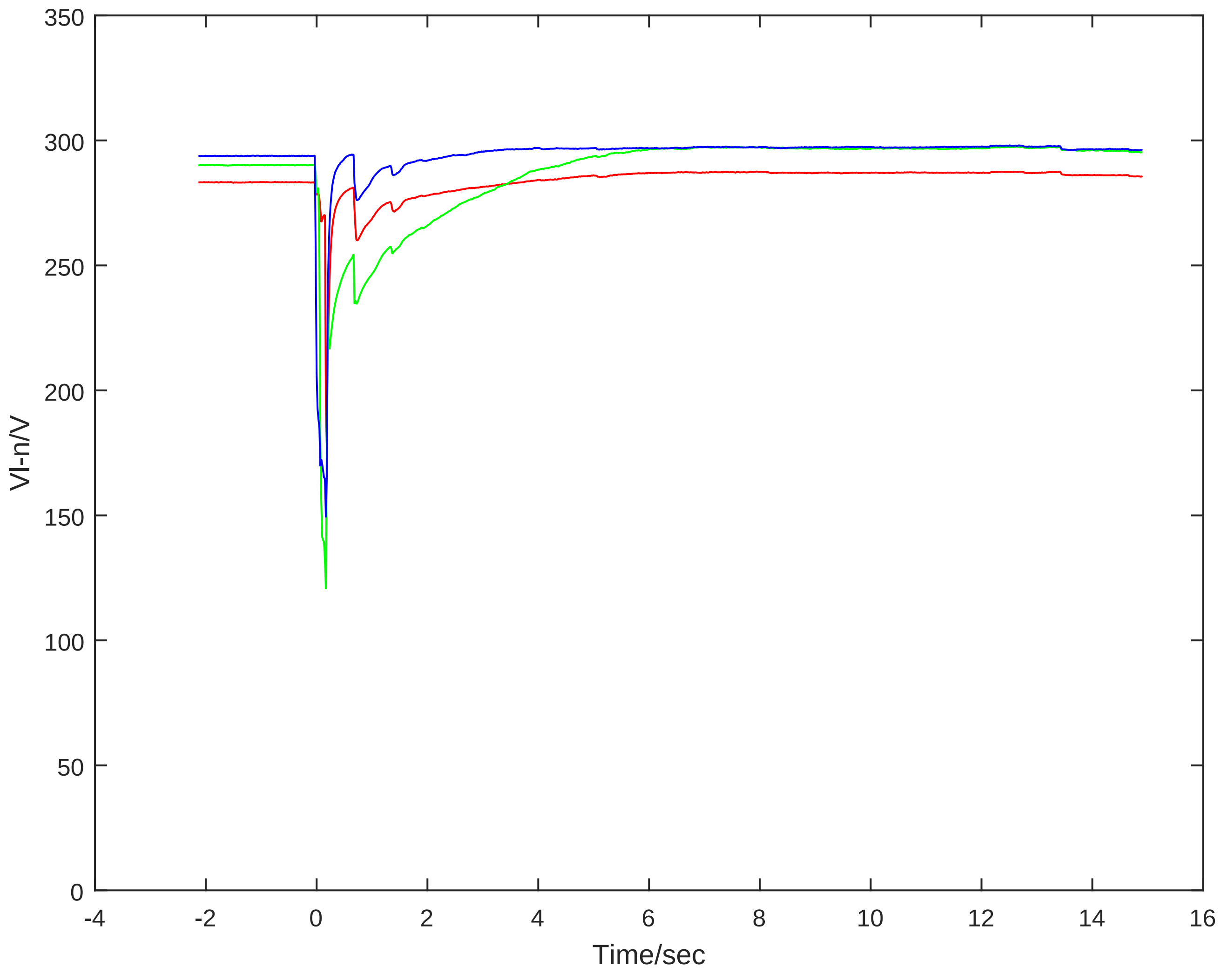

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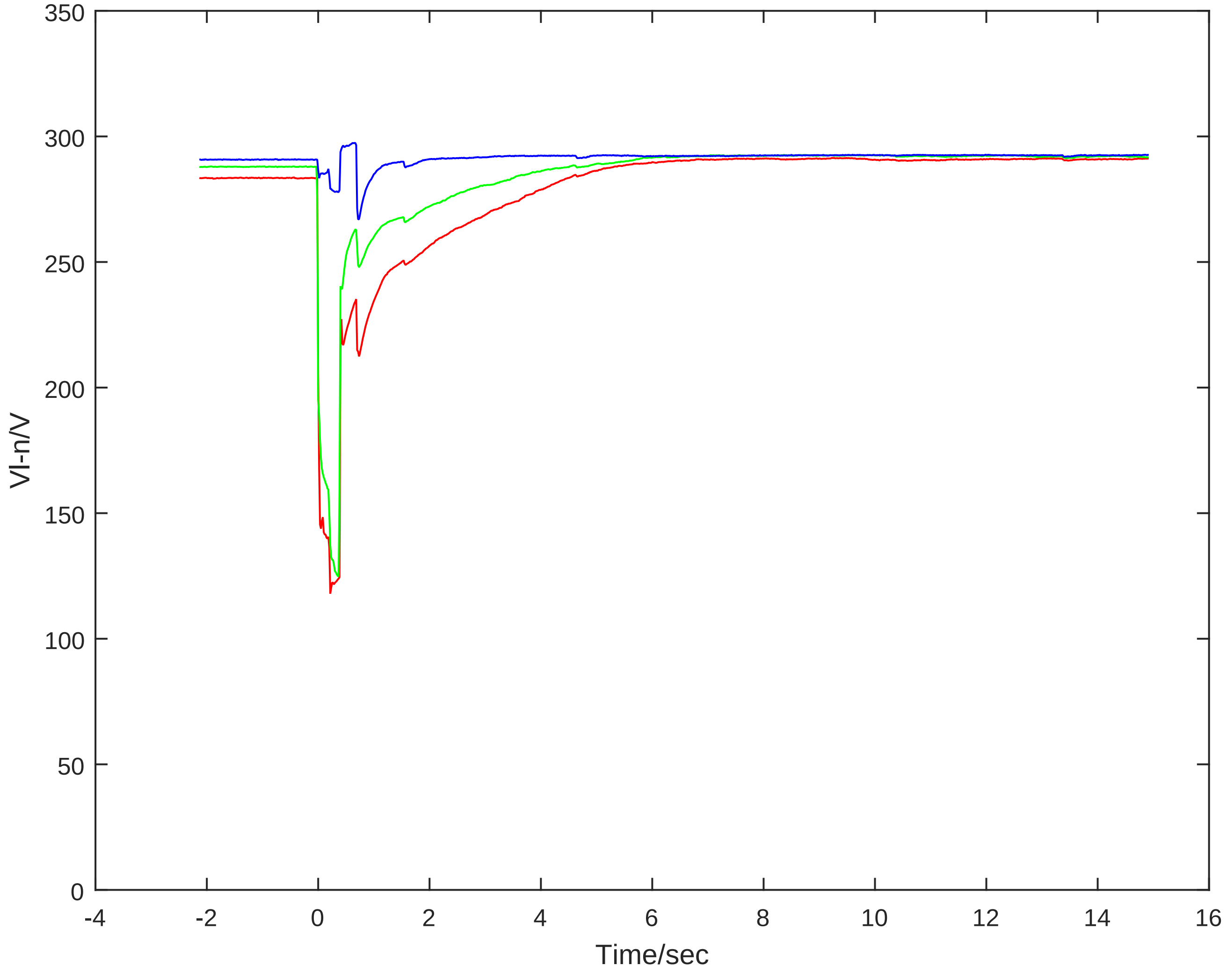

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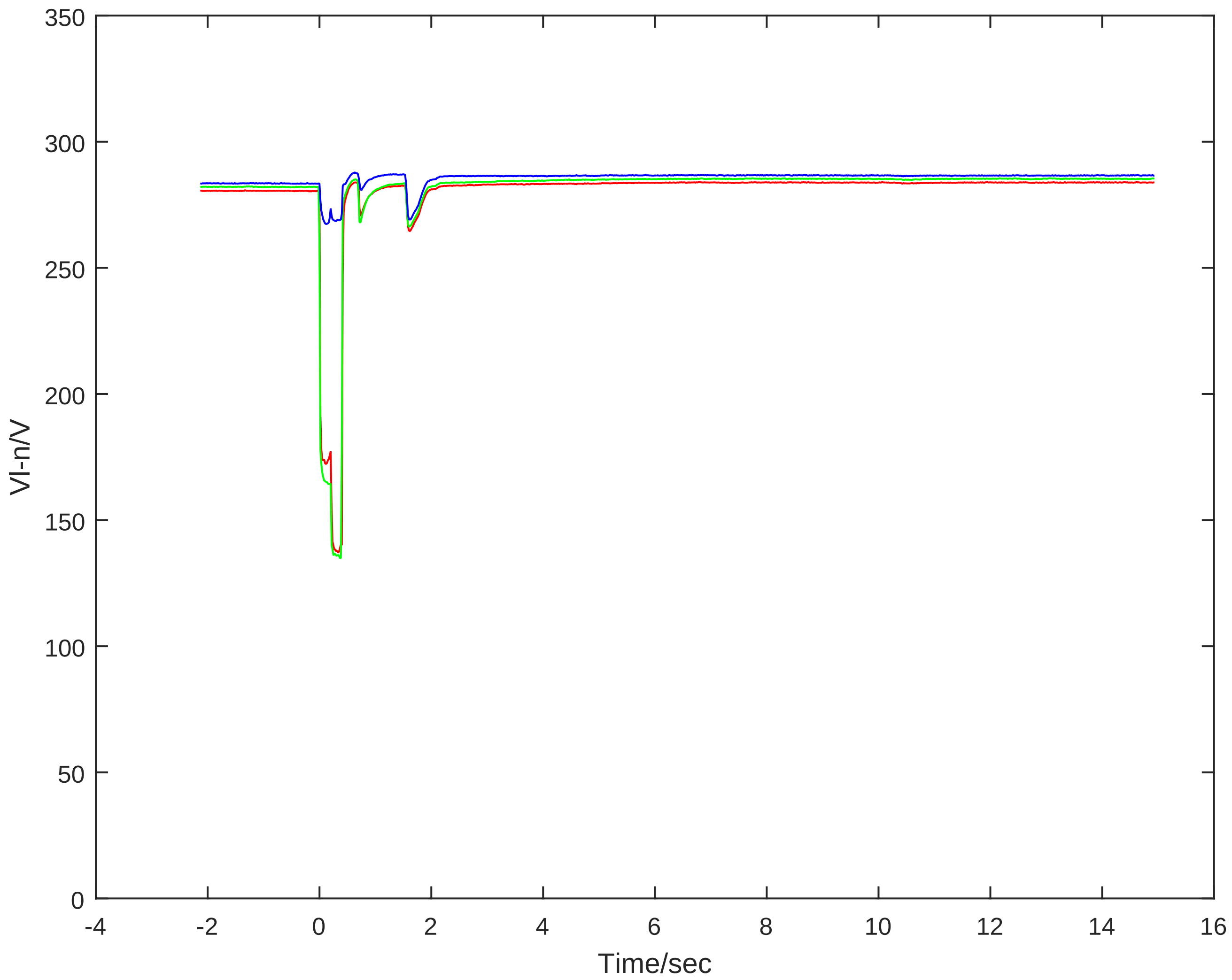

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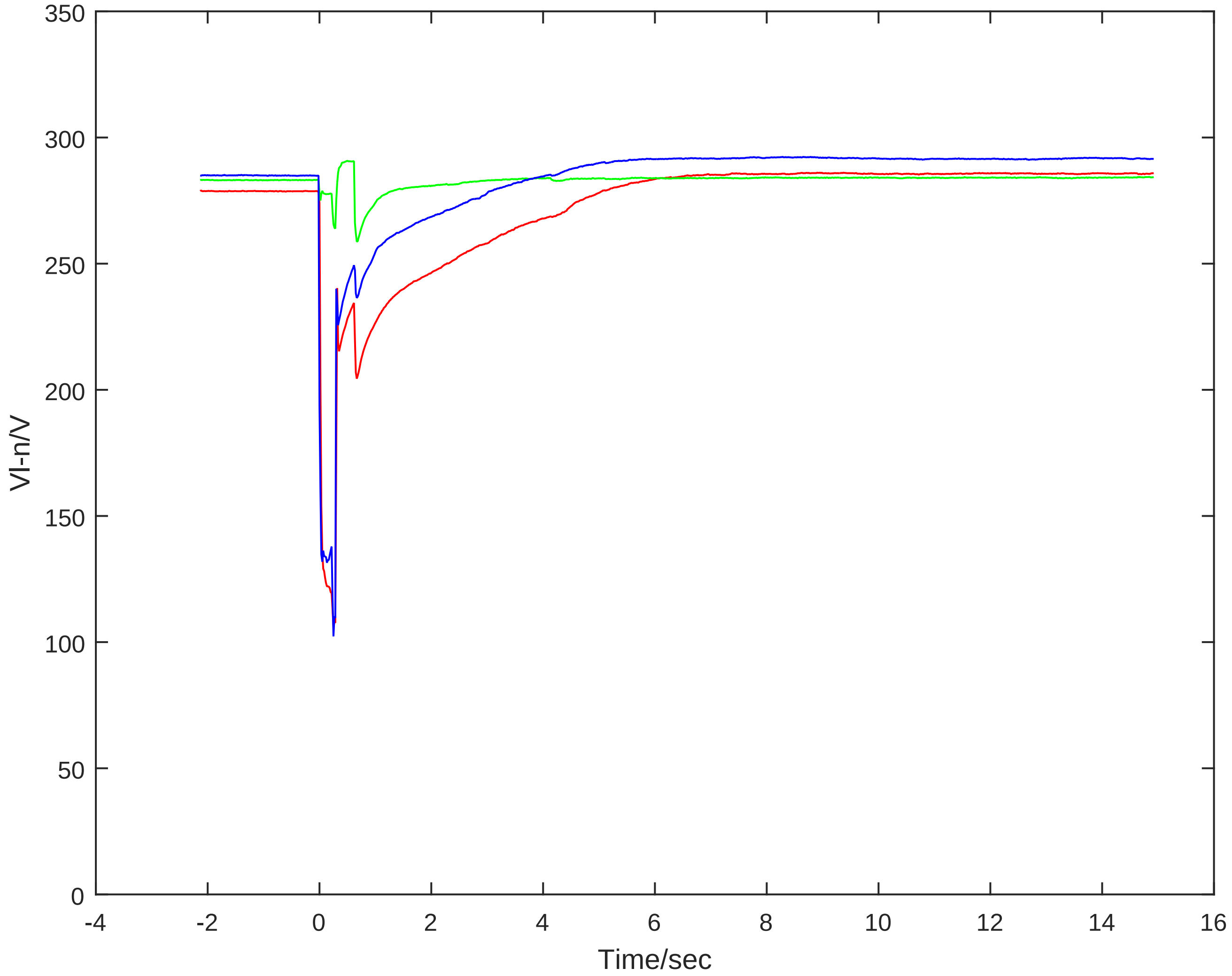

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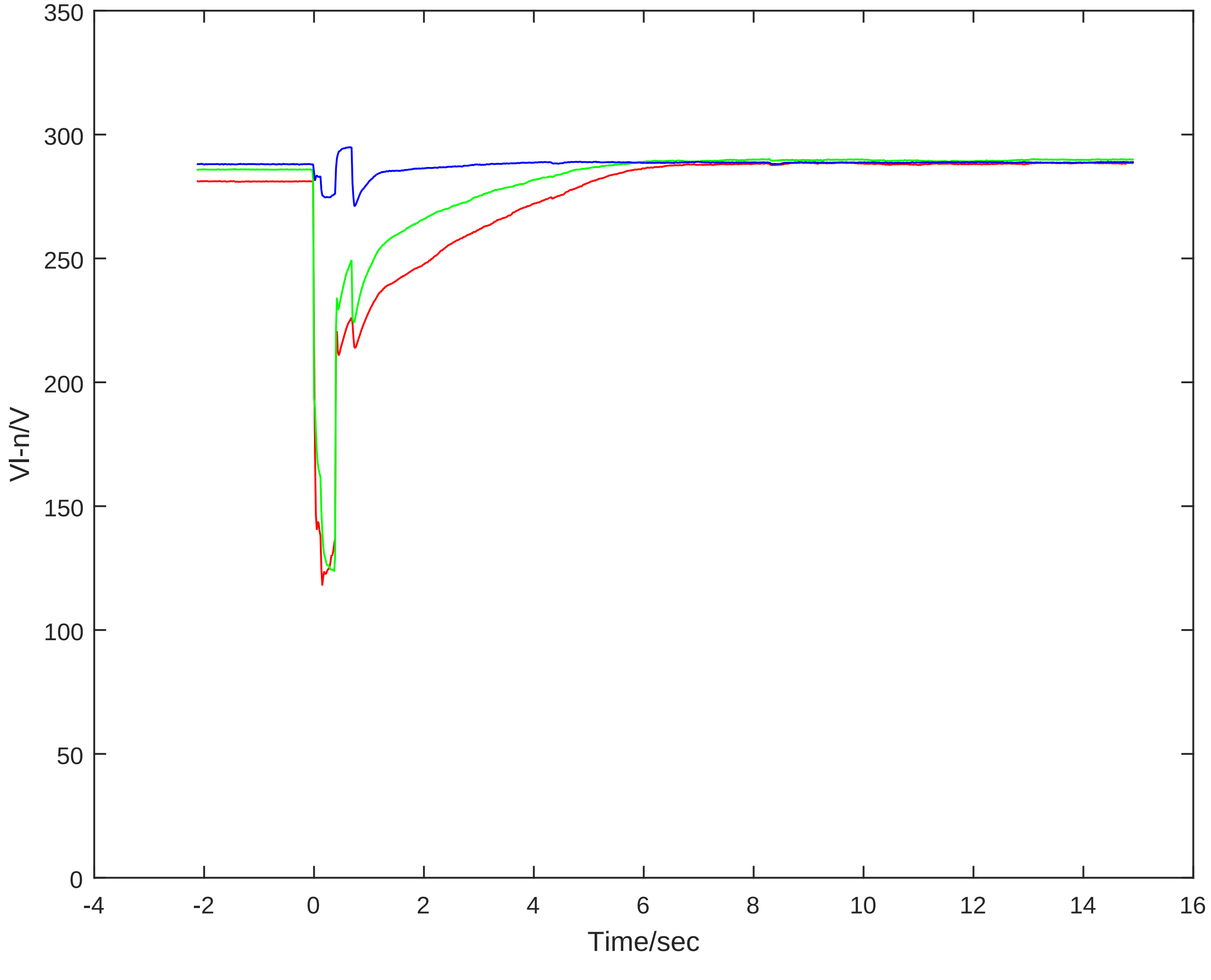

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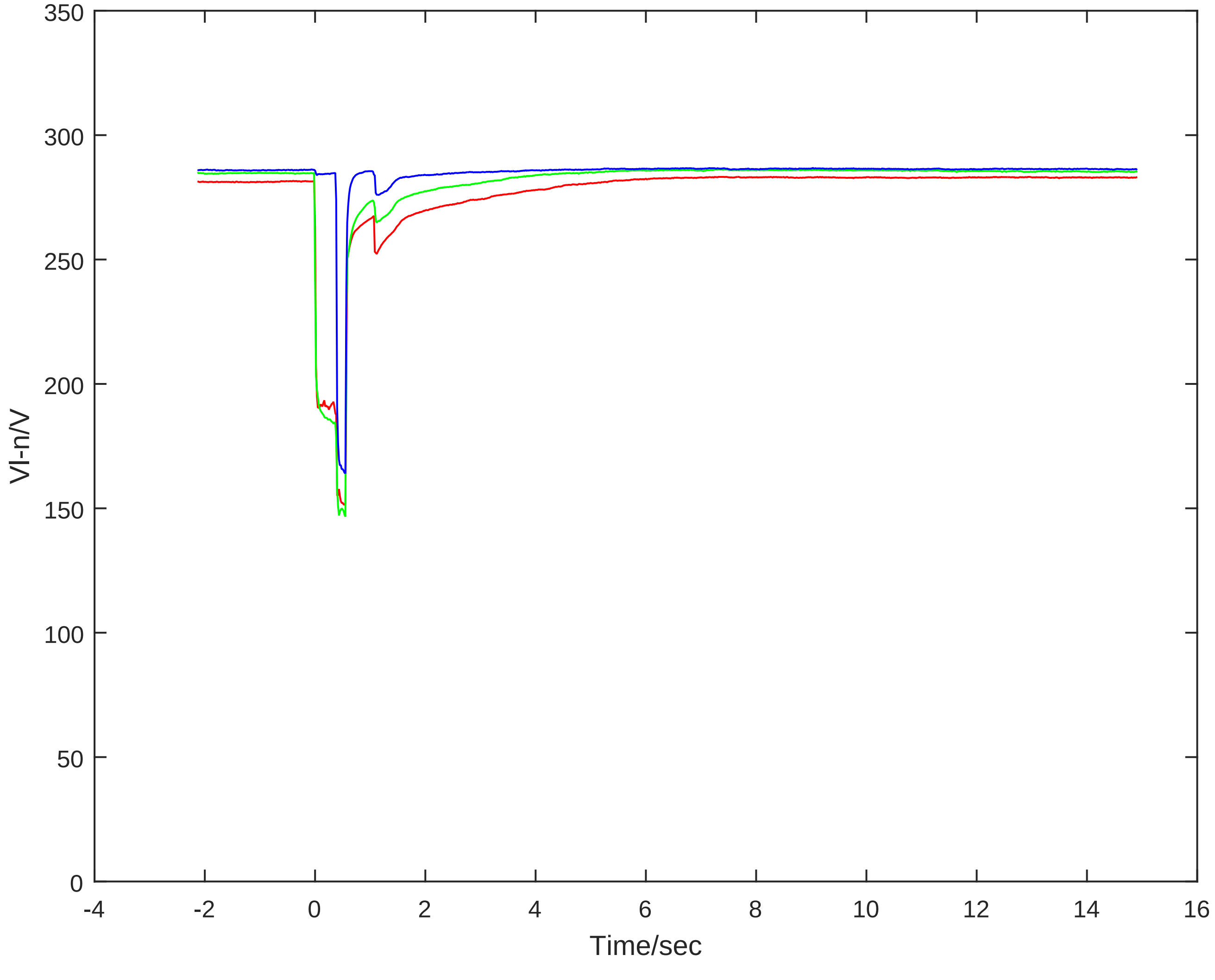

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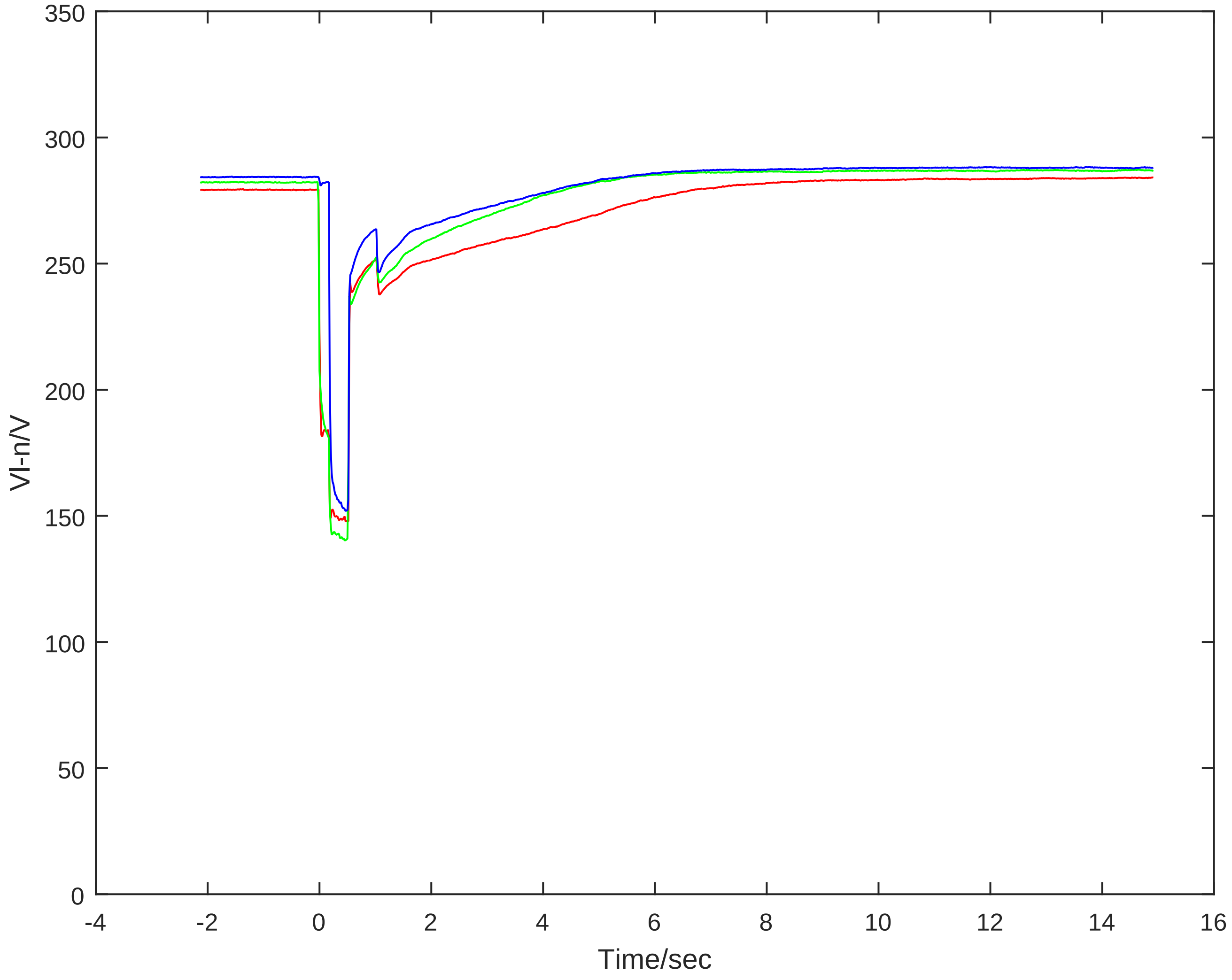
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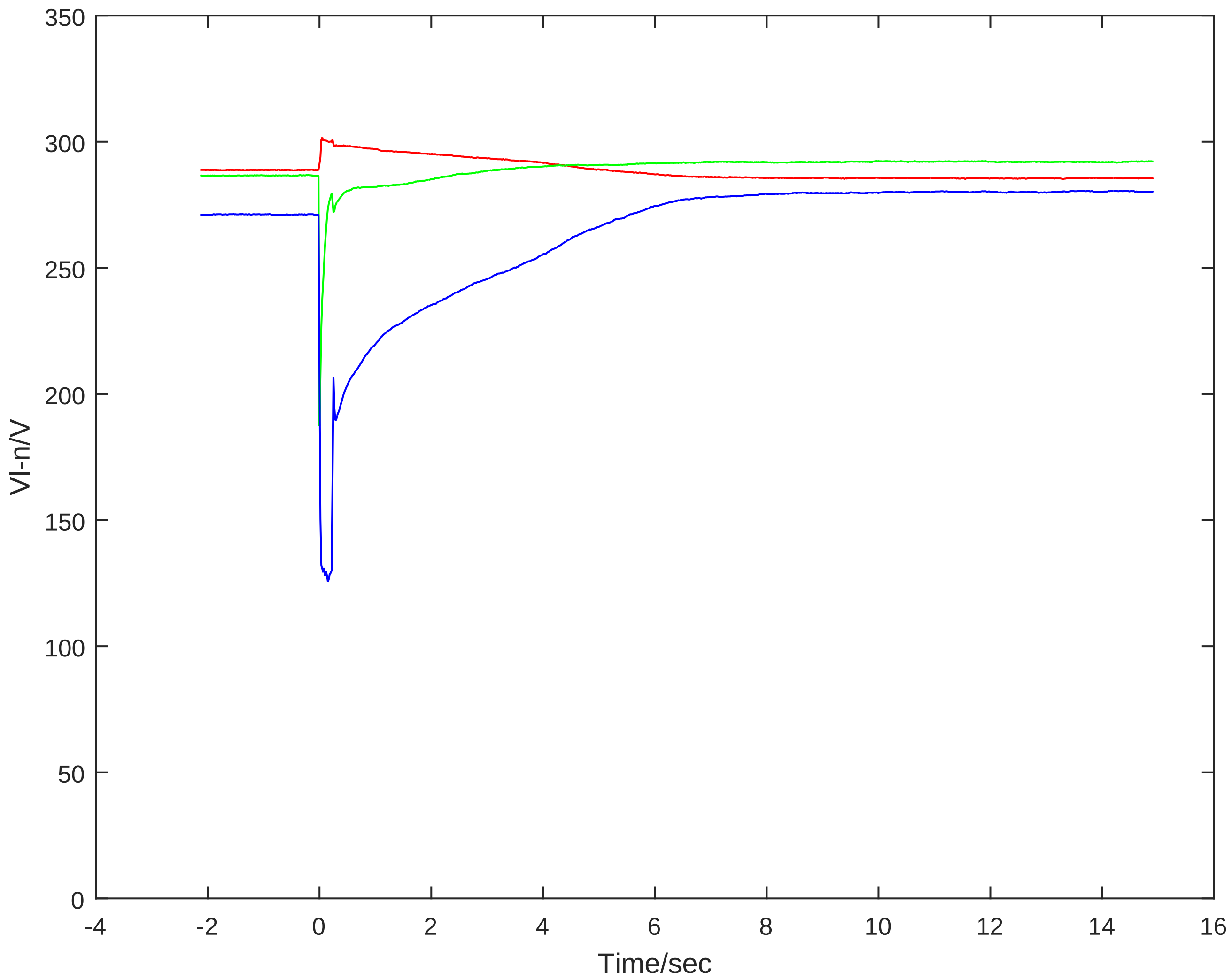

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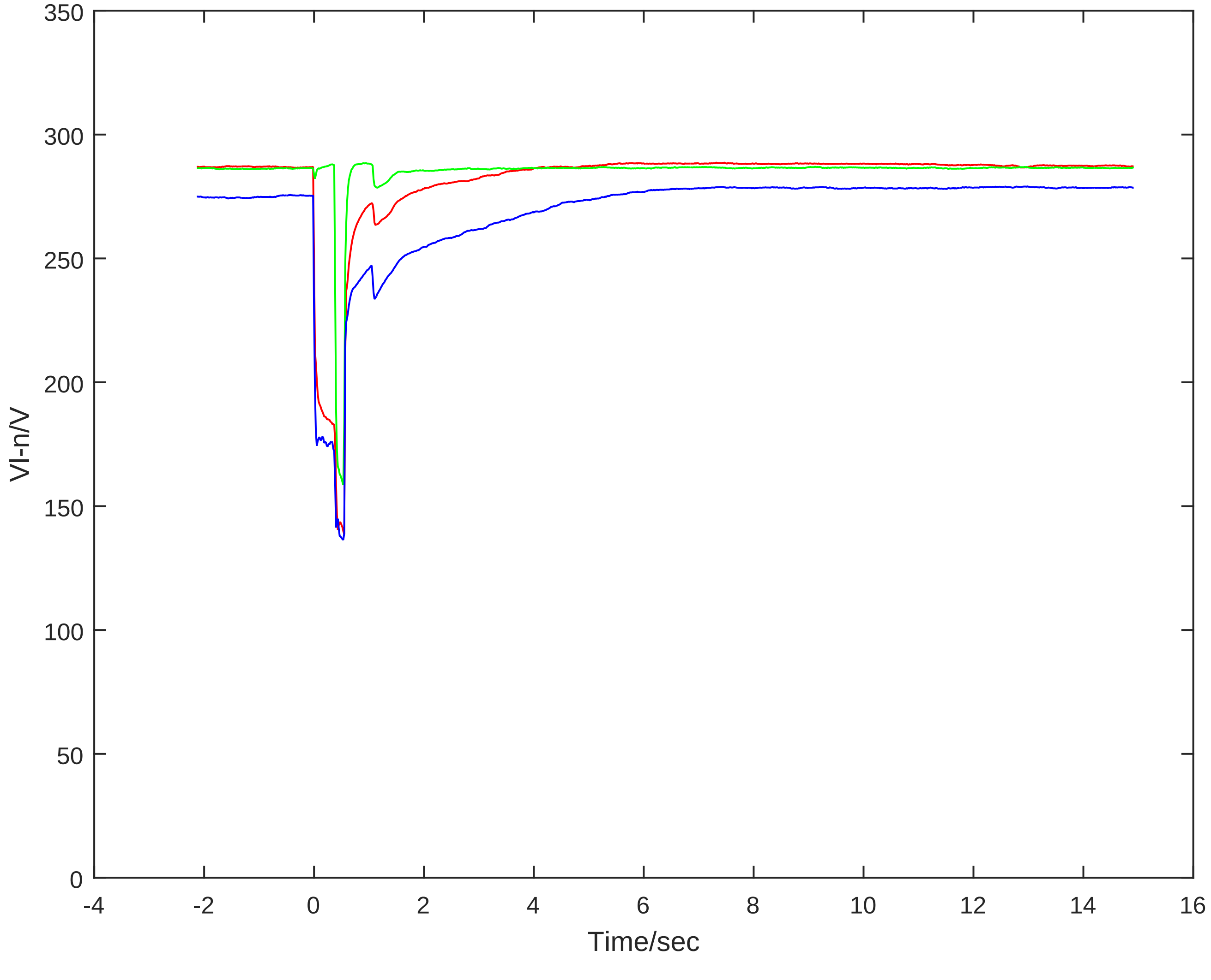

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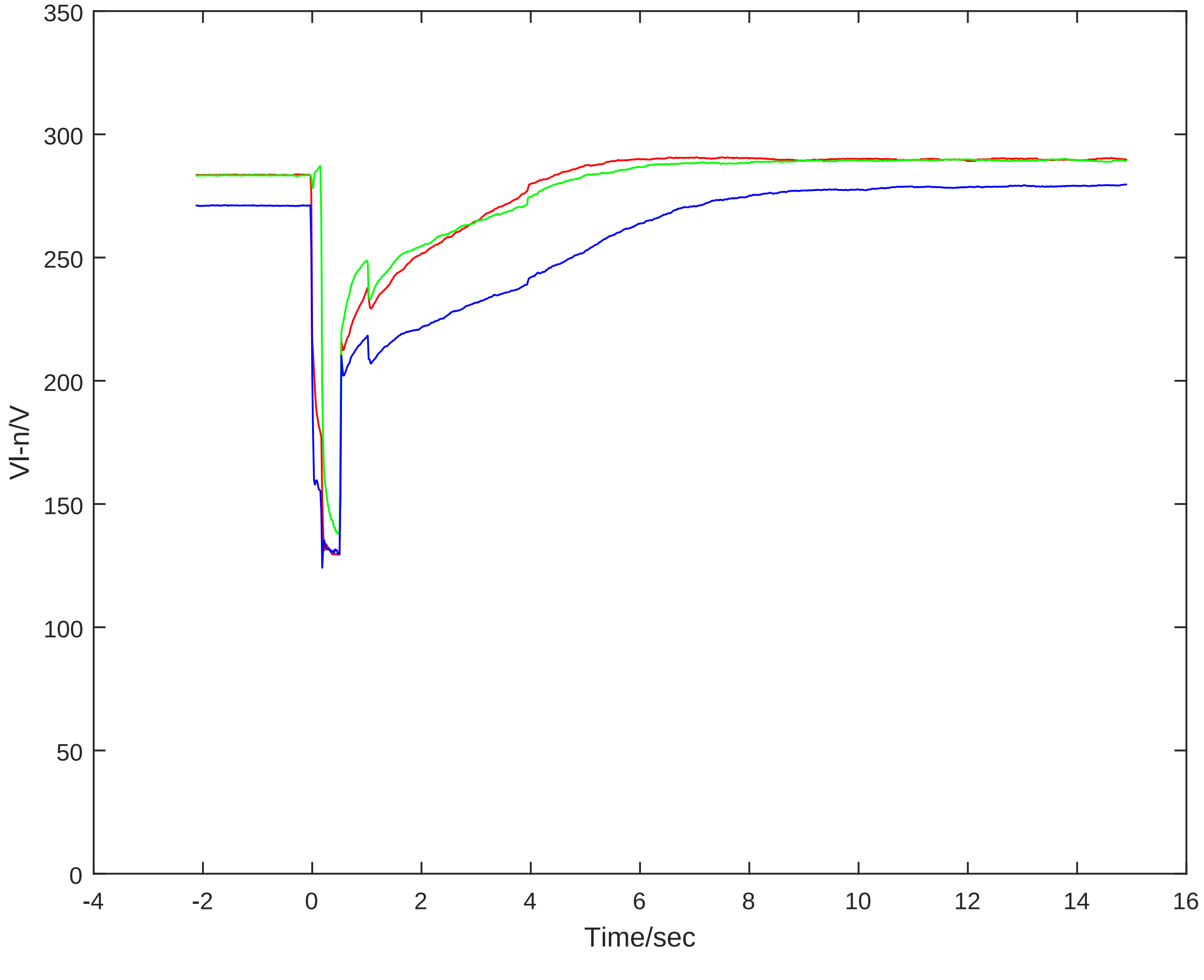
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# Composite Load Model Sensitivity Study

*"An Analysis of the Sensitivity of WECC Grid Planning Models to Assumptions Regarding the Composition of Loads"*

**NERC/DOE FIDVR Workshop**
**Alexandria, VA**

**September 30 – October 1, 2015**

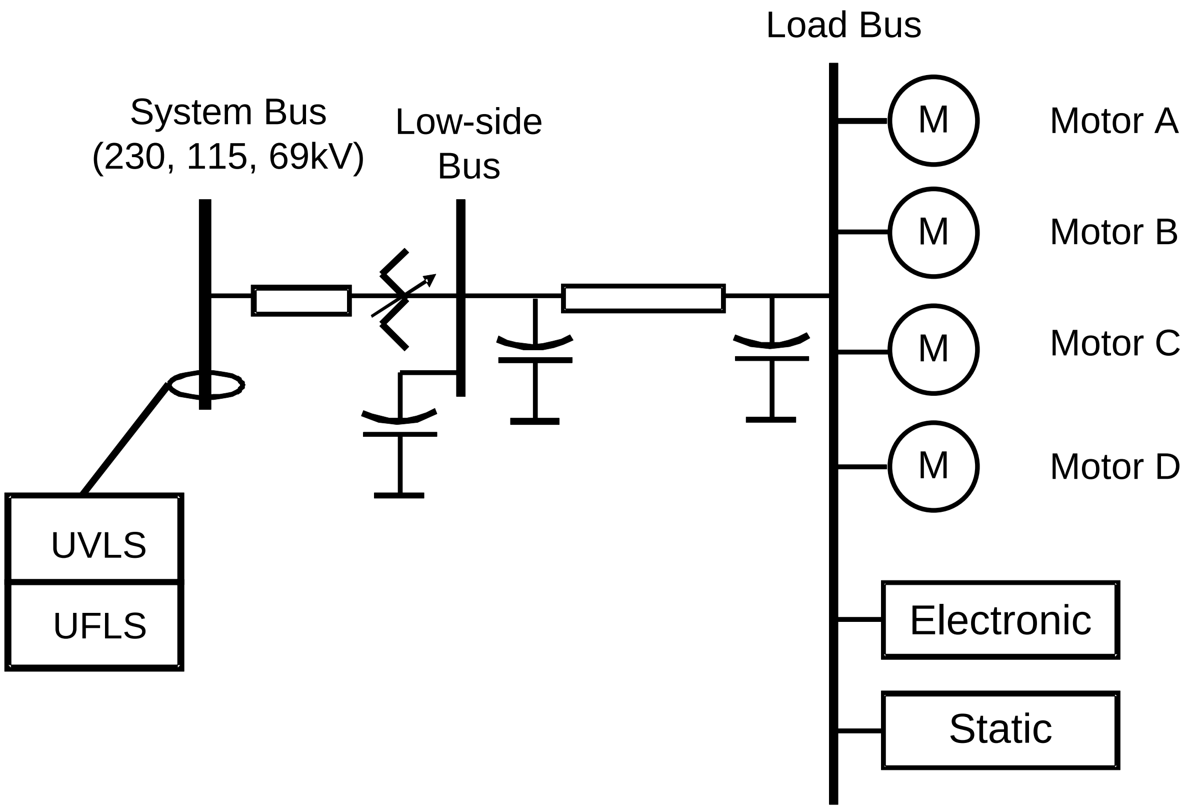
**Scott Ghiocel, Nick Tenza**

**Mitsubishi Electric Power Products, Inc. (MEPPI)**
**Power System Engineering Services Department**
**Warrendale, Pennsylvania**

# Background

- Objectives
  - Explore the sensitivity of WECC planning models to uncertainty in the composition and behavior of loads
  - Provide guidance for future planning studies and data collection
- Transmission Providers: PacifiCorp, PG&E, SCE, and SRP
- Tasks
  - Develop list of parametric simulations to be conducted
  - Investigate sensitivities of the parameter list
    - Run all contingencies for each transmission provider (TP)
    - Monitor all transmission bus voltages in each TP area
    - Monitor generation for loss of synchronism or excessive oscillation
  - Detailed analysis for specific parameters and cases
    - High-sensitivity parameters
    - Stressed base case

# Composite Load Model in WECC



# Study Work

- **Sensitivity analysis procedure:**
  - Phase 1 Base Case: No stalling
  - Phase 2 Base Case: Set Tstall = 0.033 sec
  - Vary one parameter in the Phase 2 Base Case
    - Two new cases: parameter set to minimum and maximum values
    - Total load is unchanged (same power flow case)
- **Presentation of results:**
  - Identify study thresholds and flag observations
  - Compute sensitivities with respect to Phase 2 Base Case
  - Results summarized by parameter

# Key Parameters (Motor D)

- **Vstall** – Stall voltage, p.u.
- **Tstall** – Stall time delay, sec.
- **FmA** – Motor A fraction of load P
- **FmB** – Motor B fraction of load P
- **FmC** – Motor C fraction of load P
- **FmD** – Motor D fraction of load P
- **Fel** – Electronic load fraction of P
- **Vtr1** – First under voltage trip level, p.u.
- **Ttr1** – First under voltage trip delay time, sec.
- **Fuvr** – Fraction of load with under voltage relay protection
- **Frst** – Fraction of load that can restart after stalling
- **Vrst** – Voltage at which restart can occur, p.u.
- **Trst** – Restart time delay
- **Vc1off** – Contactor voltage at which tripping starts, p.u.
- **Vc2off** – Contactor voltage at which tripping is complete, p.u.
- **Vc1on** – Contactor voltage at which reconnection starts, p.u.
- **Vc2on** – Contactor voltage at which reconnection is complete, p.u.
- **Tth** – Motor D thermal time constant, sec.
- **Th1t** – Motor D thermal protection trip start level, p.u. temperature
- **Th2t** – Motor D thermal protection trip completion level, p.u. temperature

# Key Parameters (Motors A, B, C)

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- **Motor A, B, C parameters to be studied:**
  - **Ls, Synchronous reactance, p.u.**
  - **Tpo, Transient open-circuit time constant, sec.**
  - **Ftr1, First low voltage trip fraction**
  - **Vrc1, First low voltage reconnection level, p.u. V**
  - **Trc1, First low voltage reconnection delay time, sec.**
  - **Vtr2, Second low voltage trip level, p.u.**
  - **Ttr2, Second low voltage trip delay time, sec.**
  - **H, Inertia constant, sec.**

# Parameter Value Ranges

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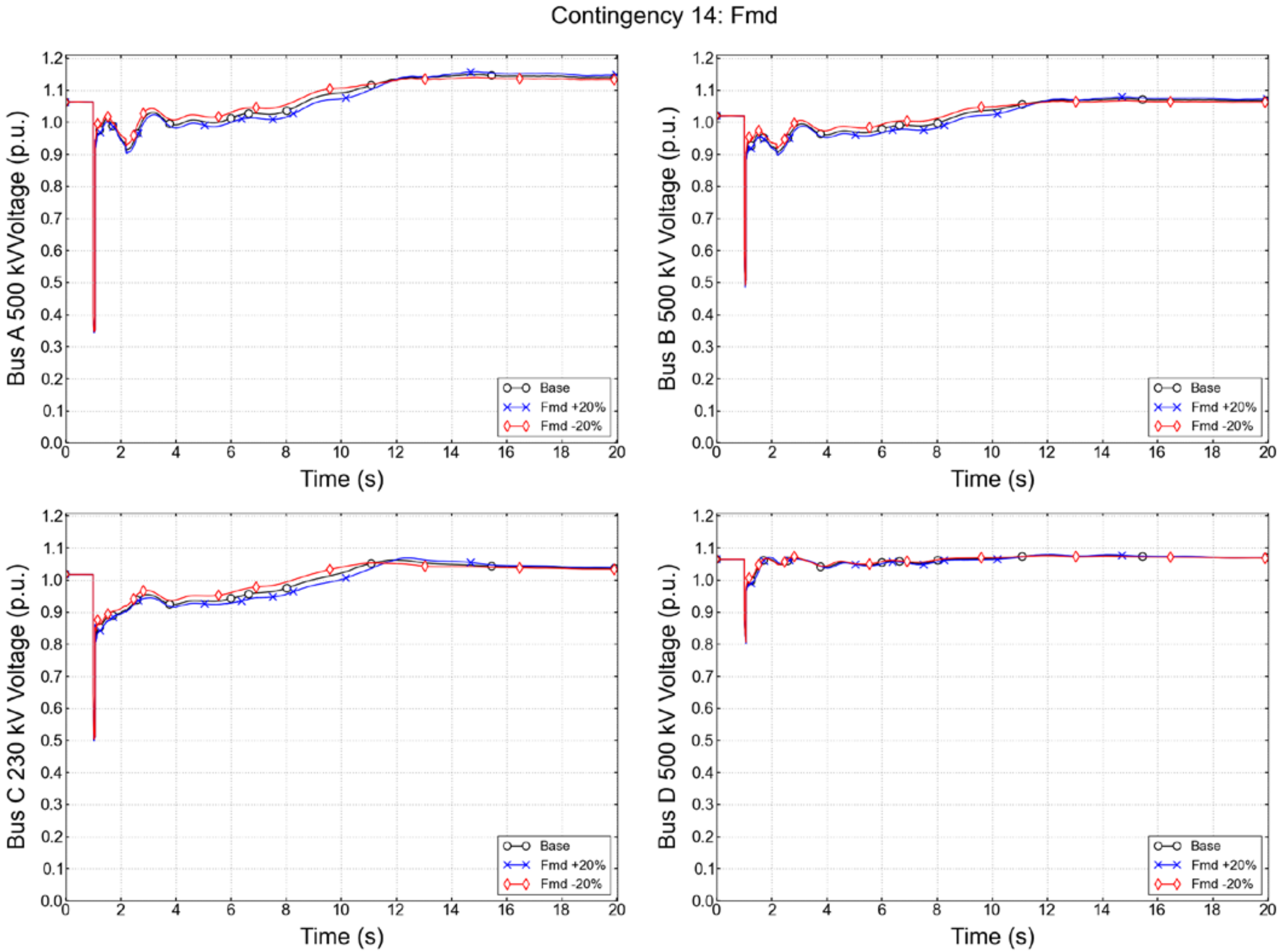
| Ref. No. | Description of Parameter | Phase 1 | Phase 2 | | |
|---|---|---|---|---|---|
| | | | Base Value as given in dyd/dyr | Minimum Value | Maximum Value |
| 1 | Vstall, Stall voltage, p.u. | 0.5 | 0.5 | 0.3 | 0.8 |
| 2 | Tstall, Stall time delay, sec. | 9999 | 0.033 | 0.01667 | 0.25 |
| 3 | Vc1off, Contactor voltage at which tripping starts, p.u. | 0.5 | 0.5 | 0.3 | 0.7 |
| 4 | Vc2off, Contactor voltage at which tripping is complete, p.u. | 0.4 | 0.4 | 0.2 | 0.6 |
| 5 | Vc1on, Contactor voltage at which reconnection is complete, p.u. | 0.6 | 0.6 | 0.4 | 0.8 |
| 6 | Vc2on, Contactor voltage at which reconnection starts, p.u. | 0.5 | 0.5 | 0.3 | 0.7 |
| 7 | Tth, Motor D thermal time constant, sec. | 15 | 15 | 5 | 25 |
| 8 | Th1t, Motor D thermal protection trip start level, p.u. temperature | 0.7 | 0.7 | 0.4 | 0.9 |
| 9 | Th2t, Motor D thermal protection trip completion level, p.u. temperature | 1.2 | 1.2 | 1 | 3 |
| 10 | FmA, Motor A fraction of load P | 0.167 | 0.167 | -20% | +20% |
| 11 | FmB, Motor B fraction of load P | 0.135 | 0.135 | -20% | +20% |
| 12 | FmC, Motor C fraction of load P | 0.061 | 0.061 | -20% | +20% |
| 13 | FmD, Motor D fraction of load P | 0.113 | 0.113 | -20% | +20% |
| 14 | Fel, Electronic load fraction of P | 0.173 | 0.173 | -20% | +20% |
| 15 | Vtr1, First under voltage trip level, p.u. | 0.6 | 0.6 | 0.4 | 0.8 |
| 16 | Ttr1, First under voltage trip delay time, sec. | 0.02 | 0.02 | 0.01667 | 0.25 |
| 17 | Fuvr, Fraction of load with under voltage relay protection | 0.1 | 0.1 | 0 | 0.5 |
| 18 | Frst, Fraction of load that can restart after stalling | 0.2 | 0.2 | 0 | 1 |
| 19 | Vrst, Voltage at which restart can occur, p.u. | 0.95 | 0.95 | 0.5 | 1 |
| 20 | Trst, Restart time delay | 0.3 | 0.3 | 0.1 | 1 |

**Notes:**

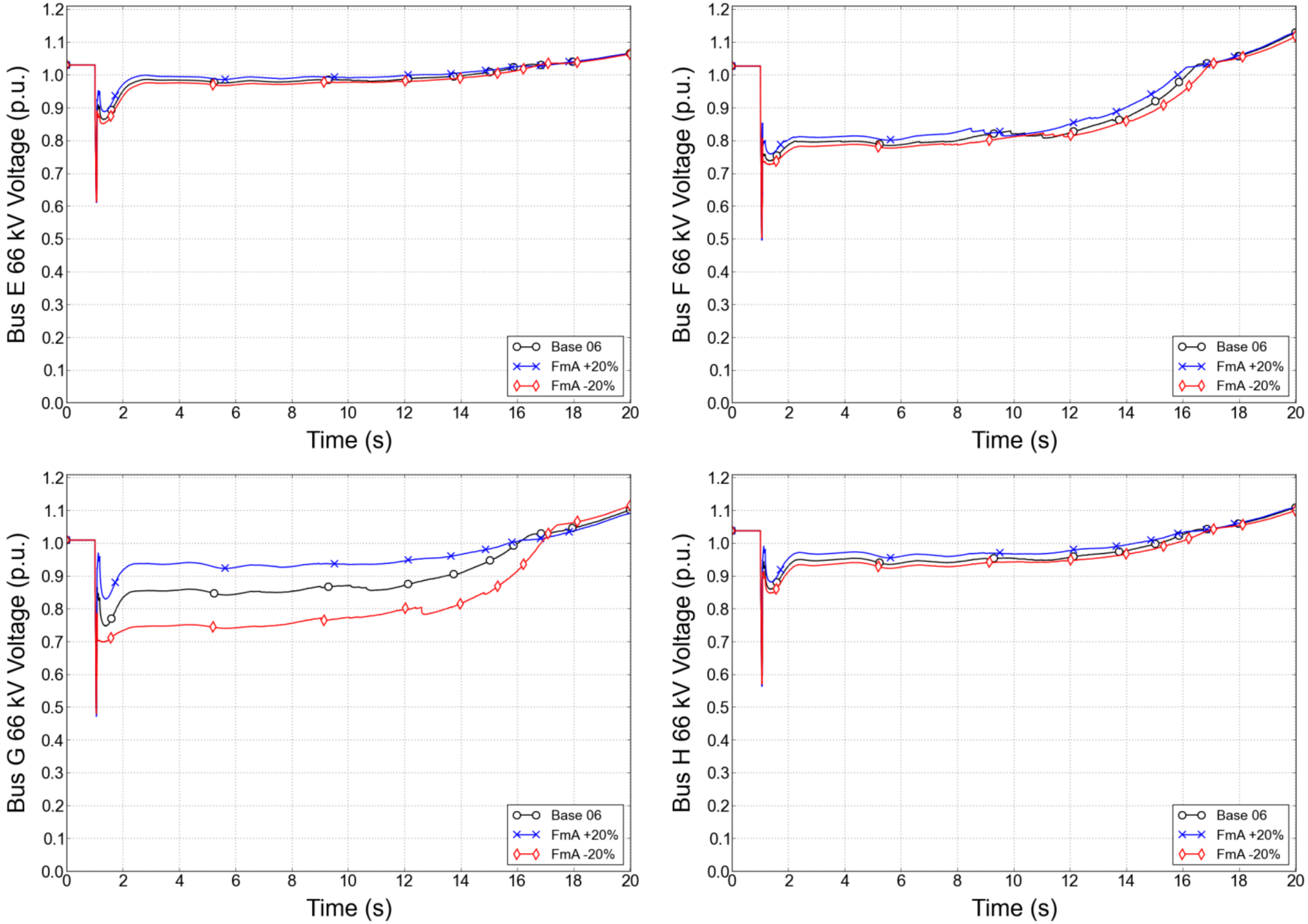
1. **Contactor settings (Vc1off, Vc2off, Vc1on, Vc2on) are changed simultaneously.**
2. **Motor fraction (FmA, FmB, FmC, FmD) base values are examples. Load fractions vary from load to load in the base case.**

# FmD (Voltages)

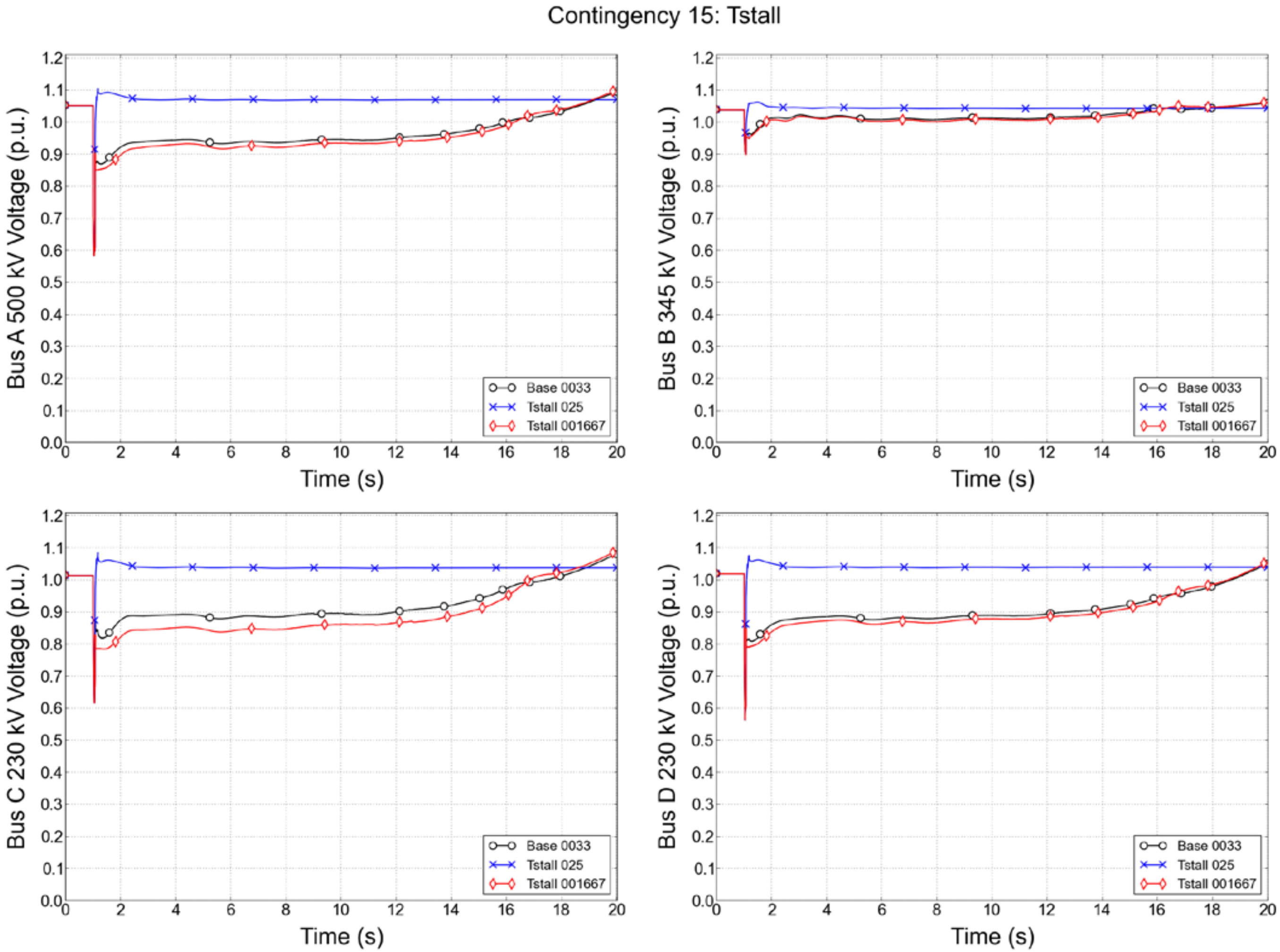


# FmA (Voltages)

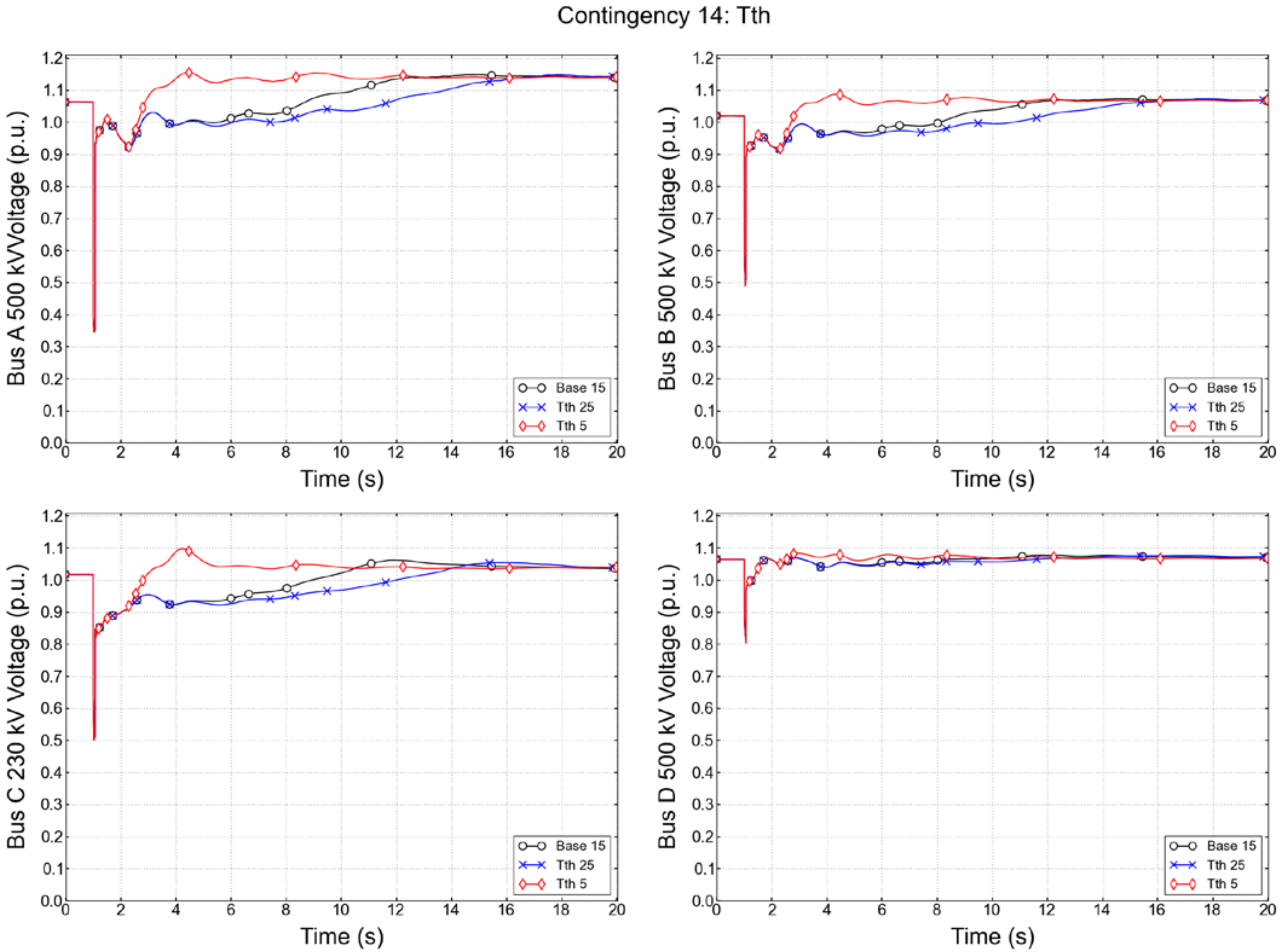
Contingency 15: FmA



# Tstall (Voltages)



# Tth (Voltages)



# Sensitivity Metrics

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- Observations based on voltage recovery, generator stability
  - Flag bus voltages and generators based on study thresholds
- Compare the number of observations to the Phase 2 Base Case (Tstall = 0.033)
- Relative number and type of observations provides a sensitivity for each parameter
  - Voltage response (fast vs. slow)
  - Generator angles (transient stability, damping ratios)
- Compute overall sensitivities by aggregating all contingencies

# Study Criteria (Thresholds)

- Transient voltage dips will be monitored and recorded for dips that exceed:
  - 25% at load buses and 30% at non-load buses
  - 20% for more than 20 cycles at load buses
- Frequency oscillations will be monitored and recorded for dips below 59.6 Hz for 6 cycles or more at load buses
- Post-transient voltage deviations exceeding 5% at any bus
- Voltage recovery to 70% in 1 second, 80% in 3 seconds, 90% in 5 seconds
- Power, angle, or voltage magnitude oscillations will be monitored and recorded for 5% damping from the first swing peak to the 3rd swing peak
- Voltage overshoot will be monitored
  - Voltage greater than 1.1 p.u, or greater than 1.05 p.u. for 5 seconds or longer.
- Any non-consequential load loss (total load loss to be calculated)
- Any generator that loses synchronism
- Damping ratio sensitivities (stressed cases)

# Sensitivity Results – Utility A (1)

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Changes for the Better

| Ref. No. | Variable | Setting | Voltage < 70% in 1 second | | Voltage < 80% in 3 seconds | | Voltage < 90% in 5 seconds | | Voltage overshoot over 1.1 p.u. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) |
| 1 | Phase 2 | - | 78 | - | 1011 | - | 4506 | - | 3194 | - |
| 2 | Fel | -20% | 22 | -72% | 946 | -6% | 4450 | -1% | 2503 | -22% |
| 3 | | +20% | 164 | 110% | 1035 | 2% | 4715 | 5% | 3634 | 14% |
| 4 | FmA | -20% | 19 | -76% | 1255 | 24% | 5150 | 14% | 2153 | -33% |
| 5 | | +20% | 211 | 171% | 882 | -13% | 4151 | -8% | 4582 | 43% |
| 6 | FmB | -20% | 20 | -74% | 1043 | 3% | 4631 | 3% | 2523 | -21% |
| 7 | | +20% | 151 | 94% | 1049 | 4% | 4392 | -3% | 3480 | 9% |
| 8 | FmC | -20% | 22 | -72% | 1076 | 6% | 4552 | 1% | 2811 | -12% |
| 9 | | +20% | 101 | 29% | 1005 | -1% | 4558 | 1% | 3466 | 9% |
| 10 | FmD | -20% | 19 | -76% | 415 | -59% | 2928 | -35% | 2015 | -37% |
| 11 | | +20% | 219 | 181% | 1623 | 61% | 5504 | 22% | 3829 | 20% |
| 12 | Frst | 0 | 78 | 0% | 1011 | 0% | 4518 | 0% | 3302 | 3% |
| 13 | (0.2) | 1 | 78 | 0% | 1011 | 0% | 4518 | 0% | 2930 | -8% |
| 14 | Fuvr | 0 | 78 | 0% | 1472 | 46% | 5637 | 25% | 2571 | -20% |
| 15 | (0.1) | 0.5 | 78 | 0% | 27 | -97% | 66 | -99% | 6428 | 101% |
| 16 | Th1t | 0.4 | 78 | 0% | 1011 | 0% | 4432 | -2% | 3199 | 0% |
| 17 | (0.7) | 0.9 | 78 | 0% | 1011 | 0% | 4506 | 0% | 3142 | -2% |
| 18 | Th2t | 1 | 78 | 0% | 1011 | 0% | 4505 | 0% | 5196 | 63% |
| 19 | (1.2) | 3 | 78 | 0% | 1011 | 0% | 4506 | 0% | 1406 | -56% |

**Notes:**

1. **Phase 2 base case values are shown in parentheses under each parameter.**

# Sensitivity Results – Utility A (2)

MITSUBISHI ELECTRIC
Changes for the Better

| Ref. No. | Variable | Setting | Voltage < 70% in 1 second | | Voltage < 80% in 3 seconds | | Voltage < 90% in 5 seconds | | Voltage overshoot over 1.1 p.u. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) |
| 20 | Trst | 0.1 | 78 | 0% | 1011 | 0% | 4518 | 0% | 3176 | -1% |
| 21 | (0.3) | 1 | 78 | 0% | 1011 | 0% | 4518 | 0% | 3265 | 2% |
| 22 | Tstall | 0.25 | 78 | 0% | 27 | -97% | 62 | -99% | 8600 | 169% |
| 23 | (0.033) | 0.01667 | 210 | 169% | 5404 | 435% | 13919 | 209% | 8121 | 154% |
| 24 | Tth | 5 | 78 | 0% | 1011 | 0% | 4148 | -8% | 5948 | 86% |
| 25 | (15) | 25 | 78 | 0% | 1011 | 0% | 4506 | 0% | 2668 | -16% |
| 26 | Ttr1 | 0.25 | 78 | 0% | 1452 | 44% | 5578 | 24% | 2674 | -16% |
| 27 | (0.02) | 0.01667 | 78 | 0% | 1020 | 1% | 4501 | 0% | 3292 | 3% |
| 28 | Vc1off | 0.7 | 18 | -77% | 133 | -87% | 3392 | -25% | 3599 | 13% |
| 29 | (0.5) | 0.3 | 148 | 90% | 2693 | 166% | 7498 | 66% | 3815 | 19% |
| 30 | Vrst | 1 | 78 | 0% | 1011 | 0% | 4518 | 0% | 3276 | 3% |
| 31 | (0.95) | 0.5 | 78 | 0% | 340 | -66% | 3477 | -23% | 3049 | -5% |
| 32 | Vstall | 0.3 | 78 | 0% | 27 | -97% | 171 | -96% | 7688 | 141% |
| 33 | (0.5) | 0.8 | 4822 | 6082% | 32667 | 3131% | 49106 | 990% | 25291 | 692% |
| 34 | Vtr1 | 0.4 | 78 | 0% | 1385 | 37% | 5622 | 25% | 2588 | -19% |
| 35 | (0.6) | 0.8 | 20 | -74% | 999 | -1% | 4763 | 6% | 3179 | 0% |

**Notes:**

1. **Phase 2 base case values are shown in parentheses under each parameter.**
2. **Contactor settings (Vc1off, Vc2off, Vc1on, Vc2on) are changed simultaneously. (Ref. No. 28 and 29)**

# Sensitivity Results – Utility B (1)

MITSUBISHI ELECTRIC
Changes for the Better

| Ref. No. | Variable | Setting | Voltage < 70% in 1 second | | Voltage < 80% in 3 seconds | | Voltage < 90% in 5 seconds | | Voltage overshoot over 1.1 p.u. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) |
| 1 | Phase 2 | - | 10770 | - | 17866 | - | 23250 | - | 6717 | - |
| 2 | Fel | -20% | 10327 | -4% | 16271 | -9% | 21092 | -9% | 6160 | -8% |
| 3 | | +20% | 10938 | 2% | 19003 | 6% | 24204 | 4% | 7974 | 19% |
| 4 | FmA | -20% | 11351 | 5% | 16923 | -5% | 21160 | -9% | 4150 | -38% |
| 5 | | +20% | 9818 | -9% | 18353 | 3% | 24147 | 4% | 9589 | 43% |
| 6 | FmB | -20% | 9493 | -12% | 14016 | -22% | 17921 | -23% | 5018 | -25% |
| 7 | | +20% | 11067 | 3% | 19909 | 11% | 25915 | 11% | 8243 | 23% |
| 8 | FmC | -20% | 10485 | -3% | 16572 | -7% | 21099 | -9% | 5838 | -13% |
| 9 | | +20% | 10845 | 1% | 18707 | 5% | 23906 | 3% | 7813 | 16% |
| 10 | FmD | -20% | 8219 | -24% | 12982 | -27% | 17528 | -25% | 14550 | 117% |
| 11 | | +20% | 11259 | 5% | 17608 | -1% | 23858 | 3% | 1741 | -74% |
| 12 | Frst | 0 | 10770 | 0% | 17910 | 0% | 23220 | 0% | 6478 | -4% |
| 13 | (0.2) | 1 | 10770 | 0% | 17870 | 0% | 23182 | 0% | 7928 | 18% |
| 14 | Fuvr | 0 | 12235 | 14% | 22019 | 23% | 26668 | 15% | 2533 | -62% |
| 15 | (0.1) | 0.5 | 2899 | -73% | 3916 | -78% | 7354 | -68% | 15373 | 129% |
| 16 | Th1t | 0.4 | 10770 | 0% | 17884 | 0% | 23243 | 0% | 21466 | 220% |
| 17 | (0.7) | 0.9 | 10770 | 0% | 17851 | 0% | 23183 | 0% | 1062 | -84% |
| 18 | Th2t | 1 | 10770 | 0% | 17880 | 0% | 23254 | 0% | 31083 | 363% |
| 19 | (1.2) | 3 | 10770 | 0% | 17862 | 0% | 23252 | 0% | 185 | -97% |

**Notes:**

1. **Phase 2 base case values are shown in parentheses under each parameter.**

# Sensitivity Results – Utility B (2)

MITSUBISHI ELECTRIC
Changes for the Better

| Ref. No. | Variable | Setting | Voltage < 70% in 1 second | | Voltage < 80% in 3 seconds | | Voltage < 90% in 5 seconds | | Voltage overshoot over 1.1 p.u. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) |
| 20 | Trst (0.3) | 0.1 | 10770 | 0% | 17851 | 0% | 23234 | 0% | 6961 | 4% |
| 21 | | 1 | 10550 | -2% | 17634 | -1% | 23148 | 0% | 6818 | 2% |
| 22 | Tstall (0.033) | 0.25 | 3439 | -68% | 24 | -100% | 30 | -100% | 9206 | 37% |
| 23 | | 0.01667 | 14448 | 34% | 25039 | 40% | 30774 | 32% | 12215 | 82% |
| 24 | Tth (15) | 5 | 10769 | 0% | 17852 | 0% | 23181 | 0% | 29807 | 344% |
| 25 | | 25 | 10770 | 0% | 17829 | 0% | 23246 | 0% | 185 | -97% |
| 26 | Ttr1 (0.02) | 0.25 | 12235 | 14% | 21227 | 19% | 26173 | 13% | 9984 | 49% |
| 27 | | 0.01667 | 10896 | 1% | 18238 | 2% | 23555 | 1% | 7056 | 5% |
| 28 | Vc1off (0.5) | 0.7 | 2791 | -74% | 3248 | -82% | 9387 | -60% | 13917 | 107% |
| 29 | | 0.3 | 17262 | 60% | 29810 | 67% | 33771 | 45% | 1764 | -74% |
| 30 | Vrst (0.95) | 1 | 10770 | 0% | 17870 | 0% | 23253 | 0% | 6565 | -2% |
| 31 | | 0.5 | 10770 | 0% | 17939 | 0% | 23667 | 2% | 14915 | 122% |
| 32 | Vstall (0.5) | 0.3 | 5474 | -49% | 2532 | -86% | 3466 | -85% | 2915 | -57% |
| 33 | | 0.8 | 19832 | 84% | 33328 | 87% | 39705 | 71% | 38333 | 471% |
| 34 | Vtr1 (0.6) | 0.4 | 12042 | 12% | 21813 | 22% | 26404 | 14% | 3602 | -46% |
| 35 | | 0.8 | 10636 | -1% | 14462 | -19% | 19165 | -18% | 4893 | -27% |

**Notes:**

1. **Phase 2 base case values are shown in parentheses under each parameter.**
2. **Contactor settings (Vc1off, Vc2off, Vc1on, Vc2on) are changed simultaneously. (Ref. No. 28 and 29)**

# Sensitivity Results – Utility C (1)

| Ref. No. | Variable | Setting | Voltage < 70% in 1 second | | Voltage < 80% in 3 seconds | | Voltage < 90% in 5 seconds | | Voltage overshoot over 1.1 p.u. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) |
| 1 | Phase 2 | - | 2127 | - | 2025 | - | 3092 | - | 2680 | - |
| 2 | Fel | -20% | 2097 | -1% | 2087 | 3% | 3050 | -1% | 2370 | -12% |
| 3 | | +20% | 2132 | 0% | 2170 | 7% | 3289 | 6% | 2875 | 7% |
| 4 | FmA | -20% | 2322 | 9% | 2256 | 11% | 3554 | 15% | 2657 | -1% |
| 5 | | +20% | 1925 | -9% | 1959 | -3% | 3021 | -2% | 2946 | 10% |
| 6 | FmB | -20% | 2066 | -3% | 1990 | -2% | 2993 | -3% | 2373 | -11% |
| 7 | | +20% | 2150 | 1% | 2246 | 11% | 3362 | 9% | 2934 | 9% |
| 8 | FmC | -20% | 2106 | -1% | 2016 | 0% | 3059 | -1% | 2493 | -7% |
| 9 | | +20% | 2096 | -1% | 2100 | 4% | 3232 | 5% | 2793 | 4% |
| 10 | FmD | -20% | 1960 | -8% | 1524 | -25% | 2616 | -15% | 1846 | -31% |
| 11 | | +20% | 2137 | 0% | 2297 | 13% | 3311 | 7% | 2485 | -7% |
| 12 | Frst | 0 | 2127 | 0% | 2020 | 0% | 3104 | 0% | 2733 | 2% |
| 13 | (0.2) | 1 | 2127 | 0% | 2019 | 0% | 3088 | 0% | 2670 | 0% |
| 14 | Fuvr | 0 | 2433 | 14% | 2738 | 35% | 4075 | 32% | 2655 | -1% |
| 15 | (0.1) | 0.5 | 1332 | -37% | 359 | -82% | 920 | -70% | 4248 | 59% |
| 16 | Th1t | 0.4 | 2128 | 0% | 2018 | 0% | 3058 | -1% | 2778 | 4% |
| 17 | (0.7) | 0.9 | 2128 | 0% | 2019 | 0% | 3094 | 0% | 1825 | -32% |
| 18 | Th2t | 1 | 2127 | 0% | 2019 | 0% | 3096 | 0% | 5426 | 102% |
| 19 | (1.2) | 3 | 2128 | 0% | 2019 | 0% | 3094 | 0% | 174 | -94% |

**Notes:**

**1. Phase 2 base case values are shown in parentheses under each parameter.**

# Sensitivity Results – Utility C (2)

MITSUBISHI ELECTRIC
Changes for the Better

| Ref. No. | Variable | Setting | Voltage < 70% in 1 second | | Voltage < 80% in 3 seconds | | Voltage < 90% in 5 seconds | | Voltage overshoot over 1.1 p.u. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) | # of Buses | Delta (% change) |
| 20 | Trst | 0.1 | 2127 | 0% | 2019 | 0% | 3096 | 0% | 2624 | -2% |
| 21 | (0.3) | 1 | 2127 | 0% | 2019 | 0% | 3096 | 0% | 2736 | 2% |
| 22 | Tstall | 0.25 | 1264 | -41% | 106 | -95% | 59 | -98% | 5079 | 90% |
| 23 | (0.033) | 0.01667 | 2882 | 35% | 3104 | 53% | 5100 | 65% | 4877 | 82% |
| 24 | Tth | 5 | 2127 | 0% | 2010 | -1% | 2905 | -6% | 5361 | 100% |
| 25 | (15) | 25 | 2127 | 0% | 2019 | 0% | 3097 | 0% | 204 | -92% |
| 26 | Ttr1 | 0.25 | 2432 | 14% | 2676 | 32% | 3985 | 29% | 3308 | 23% |
| 27 | (0.02) | 0.01667 | 2158 | 1% | 2065 | 2% | 3097 | 0% | 2679 | 0% |
| 28 | Vc1off | 0.7 | 1101 | -48% | 559 | -72% | 1291 | -58% | 2992 | 12% |
| 29 | (0.5) | 0.3 | 3165 | 49% | 3663 | 81% | 5533 | 79% | 3580 | 34% |
| 30 | Vrst | 1 | 2127 | 0% | 2019 | 0% | 3096 | 0% | 2722 | 2% |
| 31 | (0.95) | 0.5 | 2125 | 0% | 1898 | -6% | 3042 | -2% | 2156 | -20% |
| 32 | Vstall | 0.3 | 1748 | -18% | 264 | -87% | 418 | -86% | 3578 | 34% |
| 33 | (0.5) | 0.8 | 4271 | 101% | 6946 | 243% | 10086 | 226% | 8070 | 201% |
| 34 | Vtr1 | 0.4 | 2415 | 14% | 2726 | 35% | 4126 | 33% | 2804 | 5% |
| 35 | (0.6) | 0.8 | 2369 | 11% | 2140 | 6% | 3500 | 13% | 3152 | 18% |

**Notes:**

1. **Phase 2 base case values are shown in parentheses under each parameter.**
2. **Contactor settings (Vc1off, Vc2off, Vc1on, Vc2on) are changed simultaneously. (Ref. No. 28 and 29)**

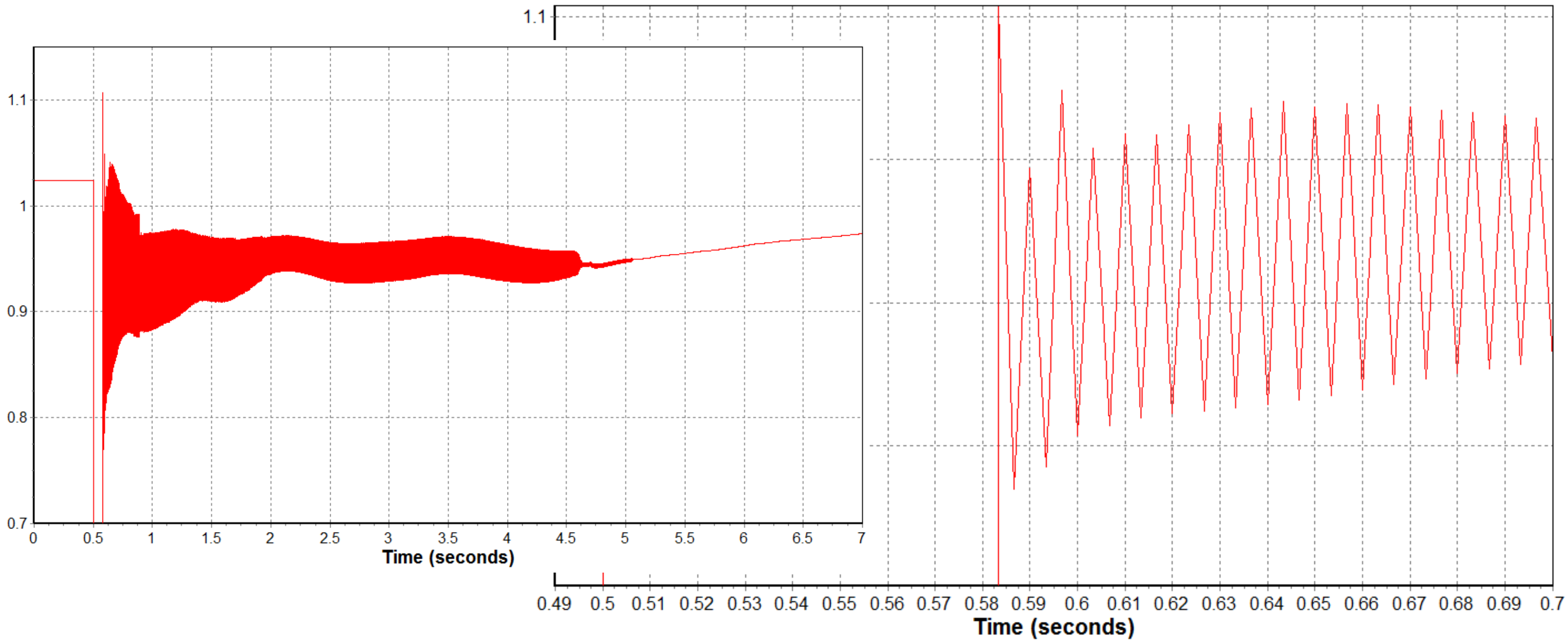
# Overall Summary

MITSUBISHI ELECTRIC
Changes for the Better

- **Observed similar results for all sets of data (SRP, SCE, PG&E, PacifiCorp)**
- **Important parameters across all four utilities studied:**
  - **Tstall and Vstall**
  - **Vc1on/Vc2on and Vc1off/Vc2off (Motor D contactor)**
  - **FmD**
  - **Tth**
  - **Th1t**
  - **Th2t**
  - **Fuvr**
  - **Vrst**

# Other Observations

- **Switching behavior can cause "hunting"**
  - **Example: Motor D contactors:**



# Next Steps



- Discuss results with each Transmission Provider
  - Summary of results and sensitivity tables
  - Detailed results for each contingency can be provided
  - Select contingencies for more detailed analysis
    - Criteria for selecting contingencies to be documented
- Next stage of the study
  - Examine stressed case provided
  - Perform more in-depth sensitivity study on Motor D parameters
  - Sensitivity analysis on additional model parameters
  - Study results to be presented at November WECC LMTF meeting in Salt Lake City, UT

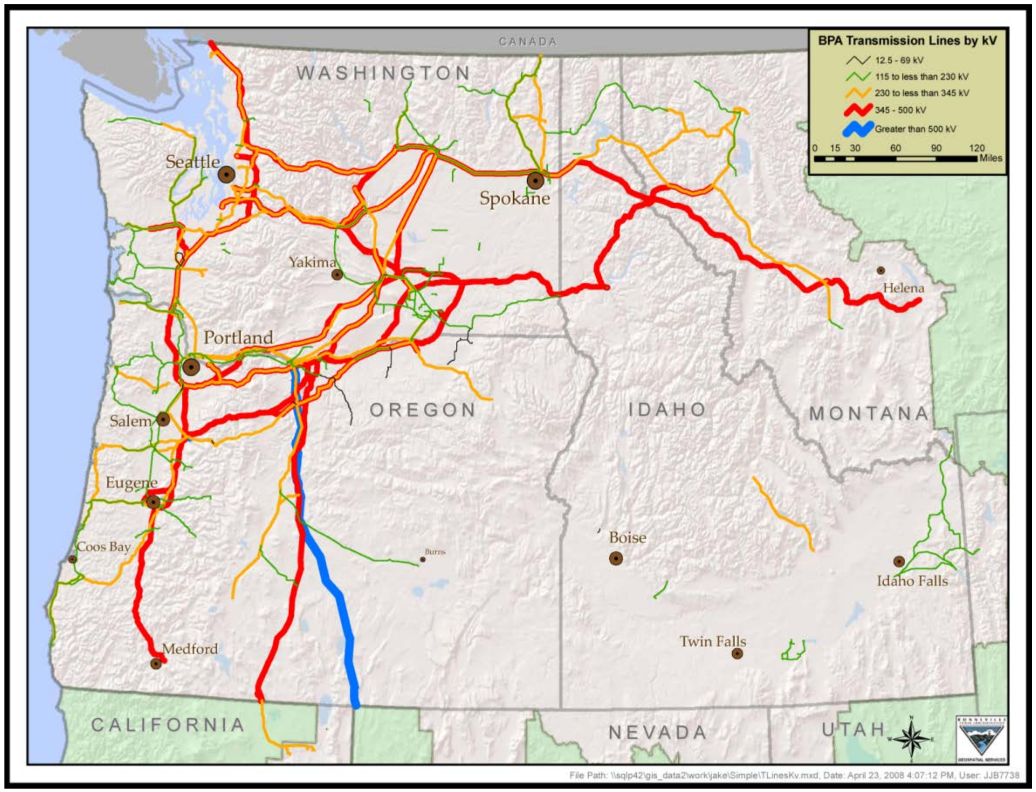
# BPA Studies Using Composite Load Model – Portland Metro Area

2015 NERC-DOE FIDVR Conference

Presented by

Dmitry Kosterev, BPA

# BPA Overview




- Bonneville Power Administration (BPA) is a federal Power Marketing Agency in Pacific Northwest
- BPA markets power from 31 Federal dams and the Columbia Generating Station Nuclear Plant
- BPA operates more than 15,000 miles of transmission, including 4,735 miles of 500-kV lines

- BPA operates several large paths in the Western Interconnection – California Oregon AC Intertie (4,800 MW), Pacific HVDC Intertie (3,100 MW), Northern Intertie (3,100 MW), and Montana Intertie (2,200 MW)

# Portland Area Study

The study has multiple objectives:

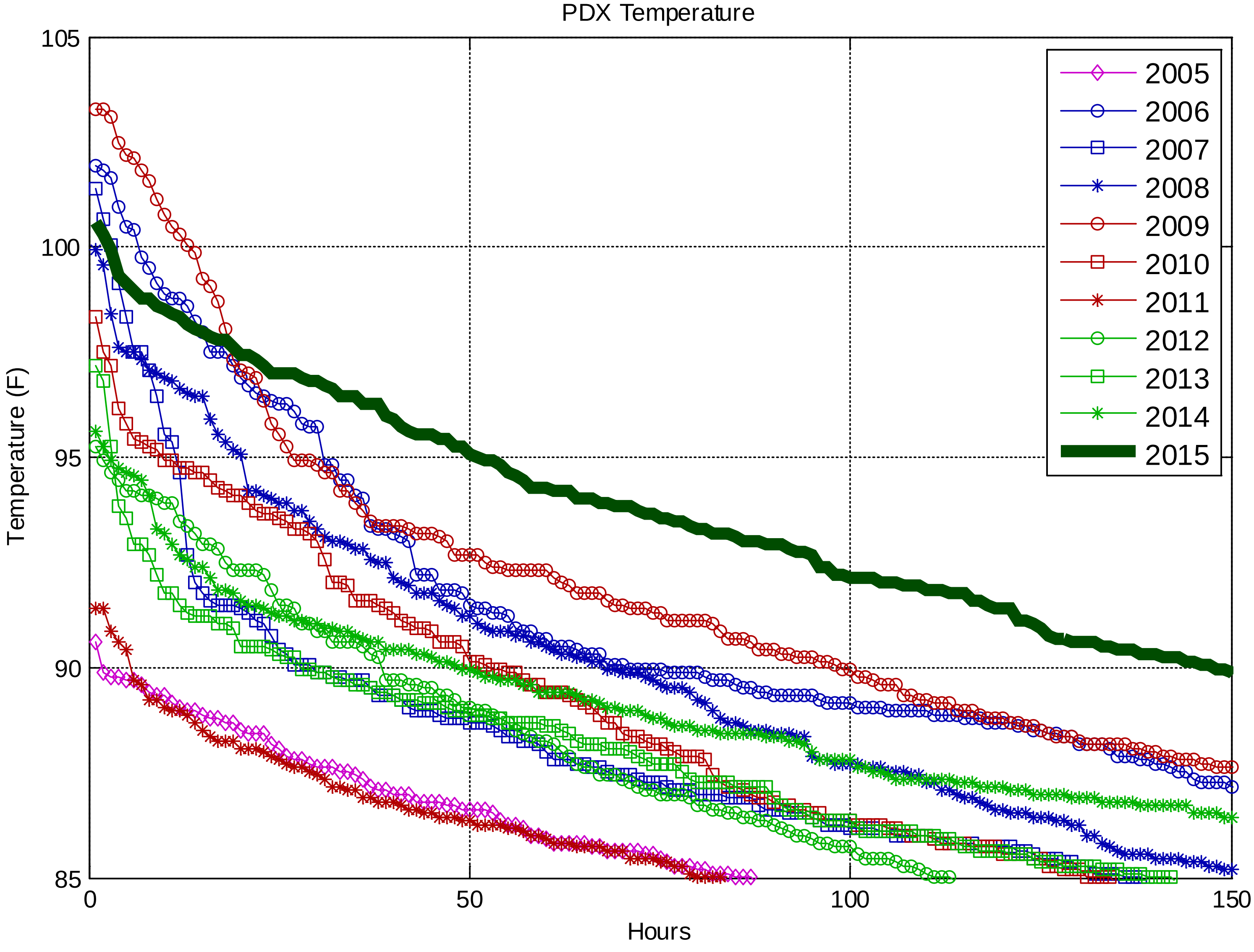
- Modeling
  - One of the first large scale studies using phase 2 load models (air-conditioner stalling is enabled)

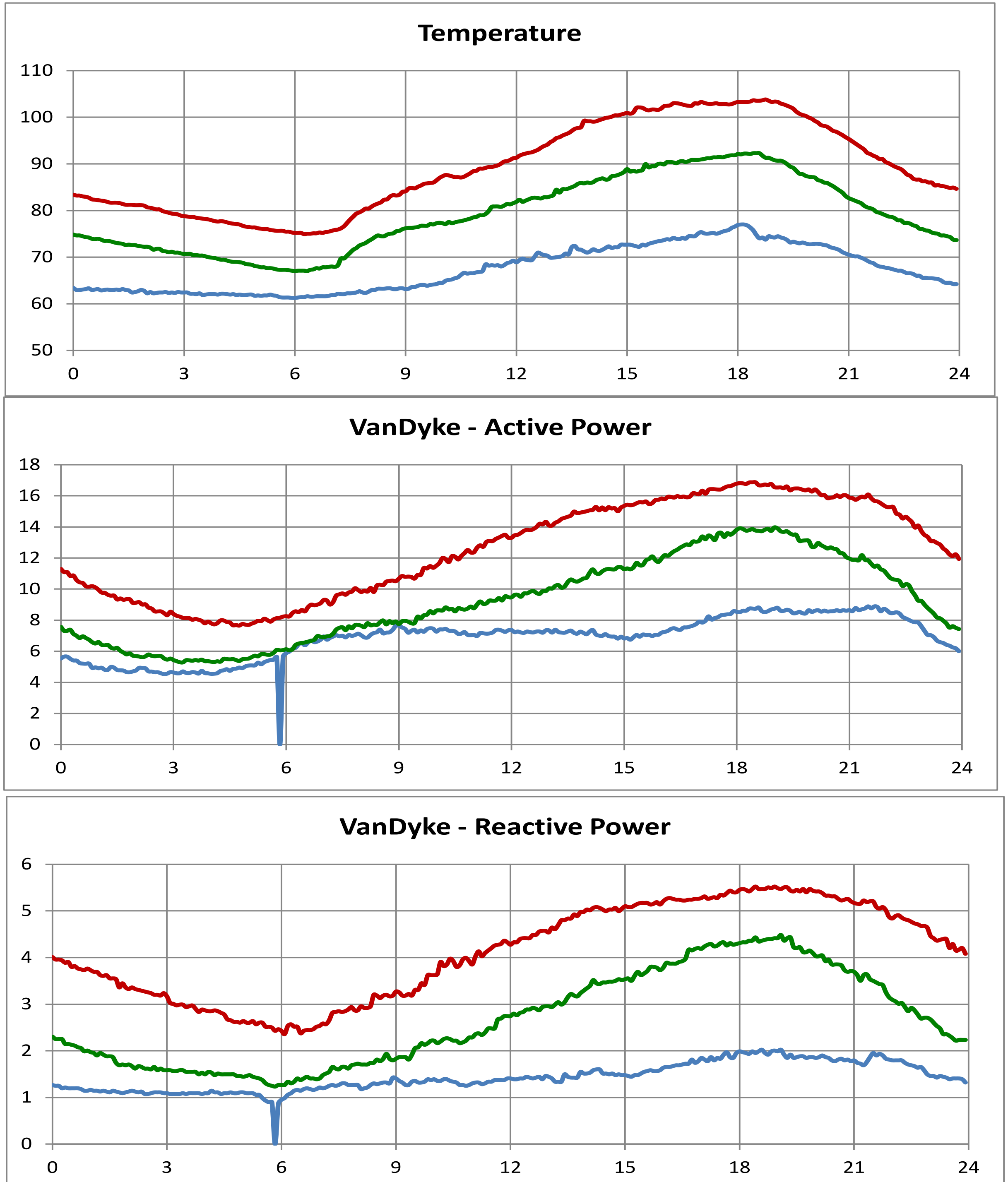
- Reliability Assessment
  - What types of faults and under what conditions can cause load-induced voltage instability or delayed voltage recovery in Portland Metro area?
  - Should a wide-spread load-induced voltage instability or delayed voltage recovery occur in Portland Metro area, what are the risks of it cascading in other parts of the system?
  - What solutions can be used to mitigate FIDVR phenomenon and limit its propagation?

- Regulatory Support (NERC TPL-001-4 Standards R5)

# It does get hot in Portland

# … but not very often

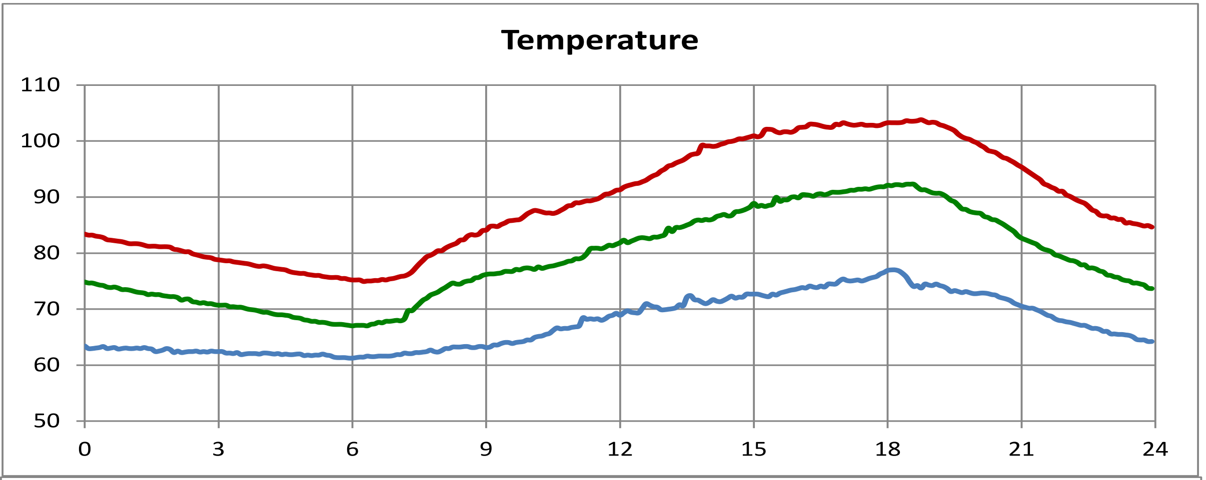


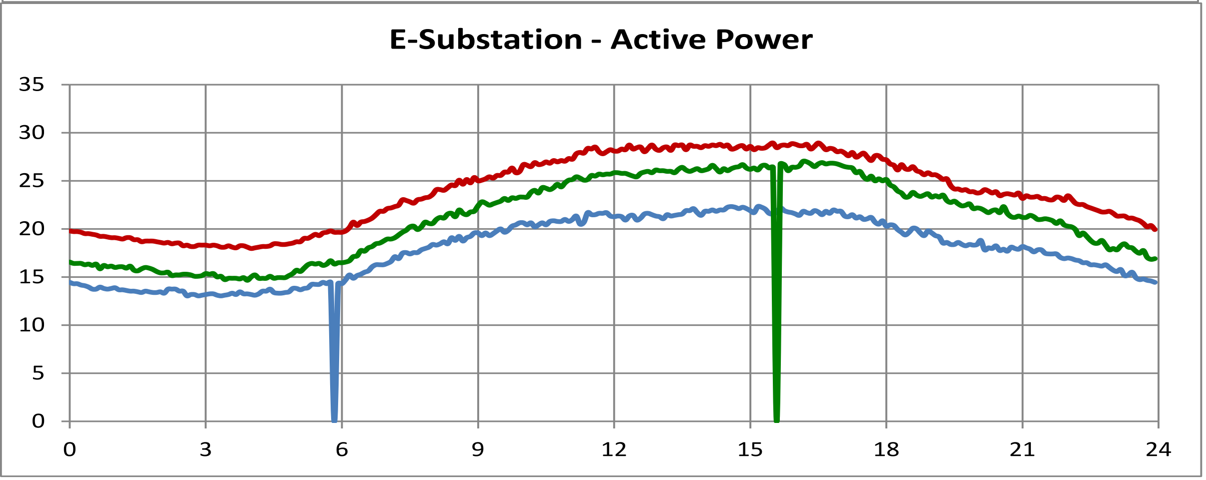


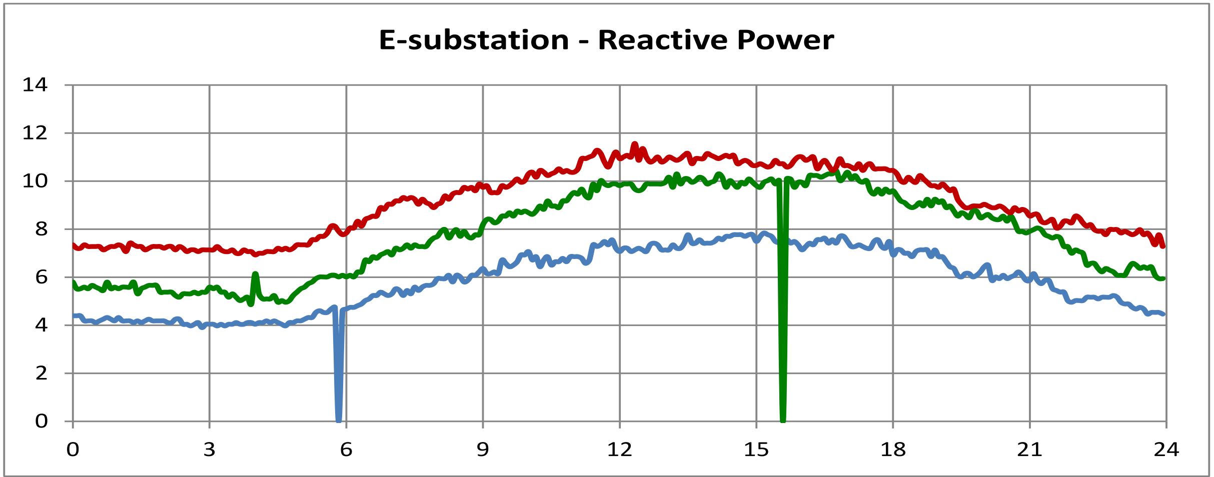

# Sub-urban residential neighborhood (newer construction)

Air-conditioning load accounts for 40 to60% of total summer load

# Downtown commercial

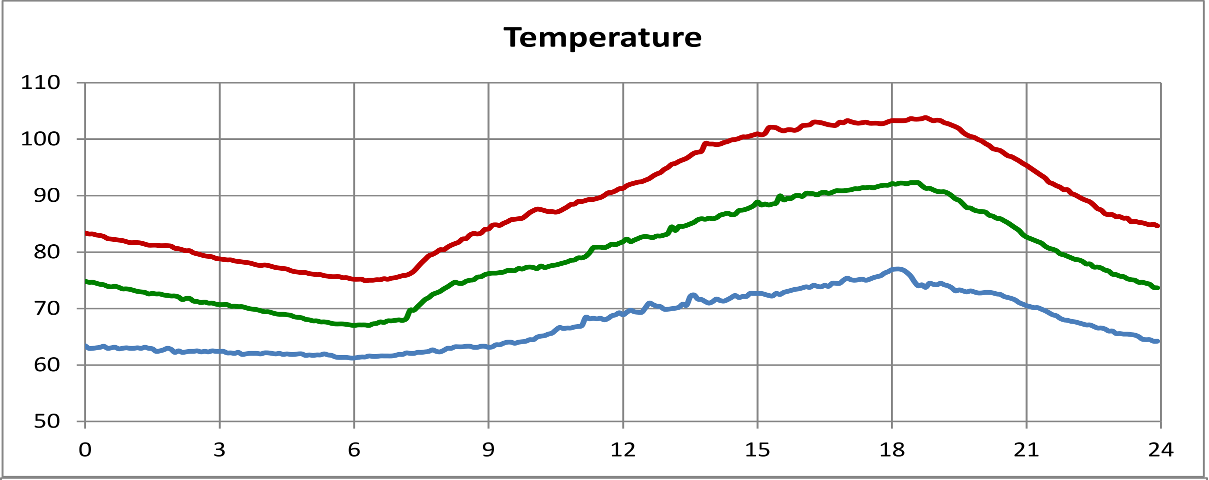


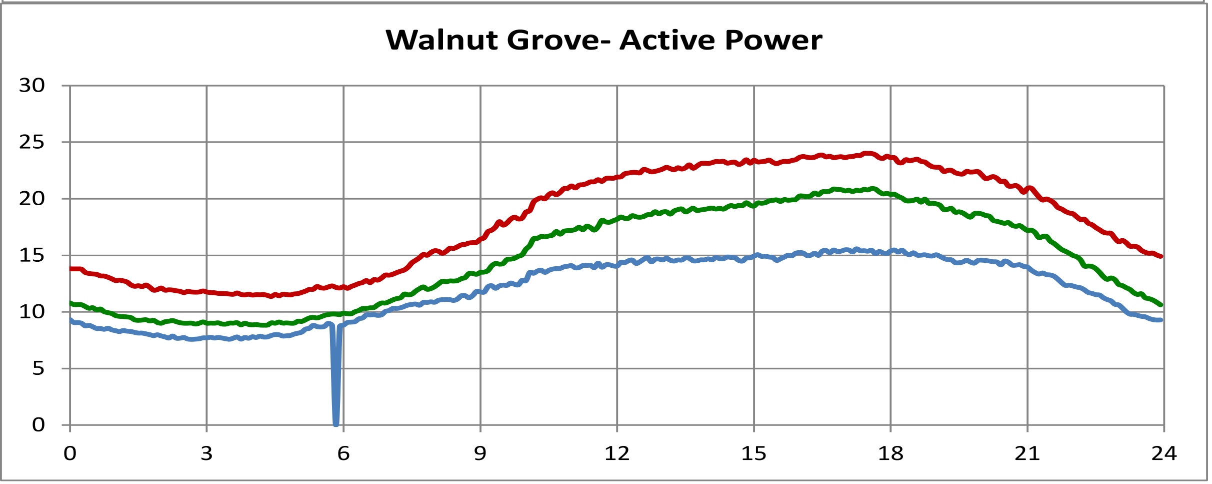



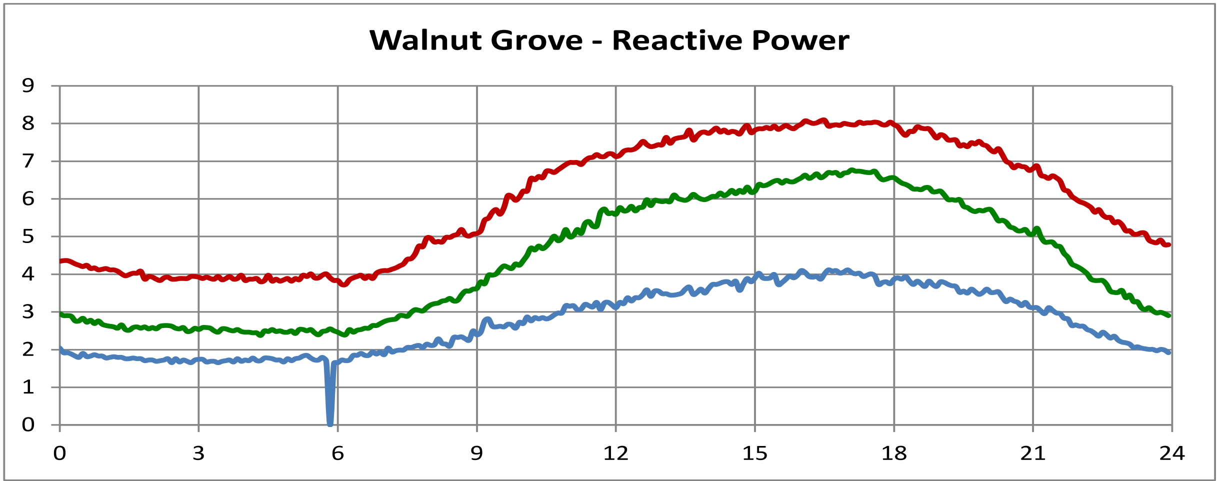




Commercial loads show less temperature sensitivity

# Mixed Loads


Temperature
110
100
90
80
70
60
50
0
3
6
9
12
15
18
21
24


Walnut Grove- Active Power
30
25
20
15
10
5
0
0
3
6
9
12
15
18
21
24


Walnut Grove - Reactive Power
9
8
7
6
5
4
3
2
1
0
0
3
6
9
12
15
18
21
24

# Portland Area Study

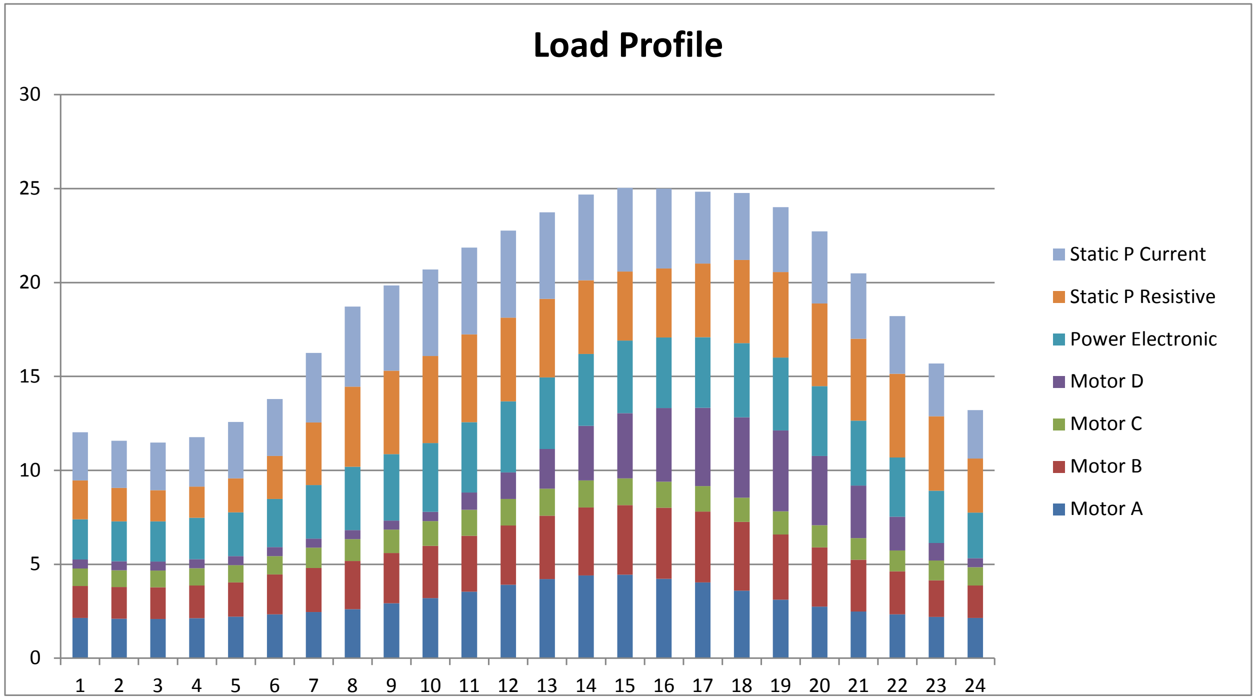
High-volume of transient simulations is performed:

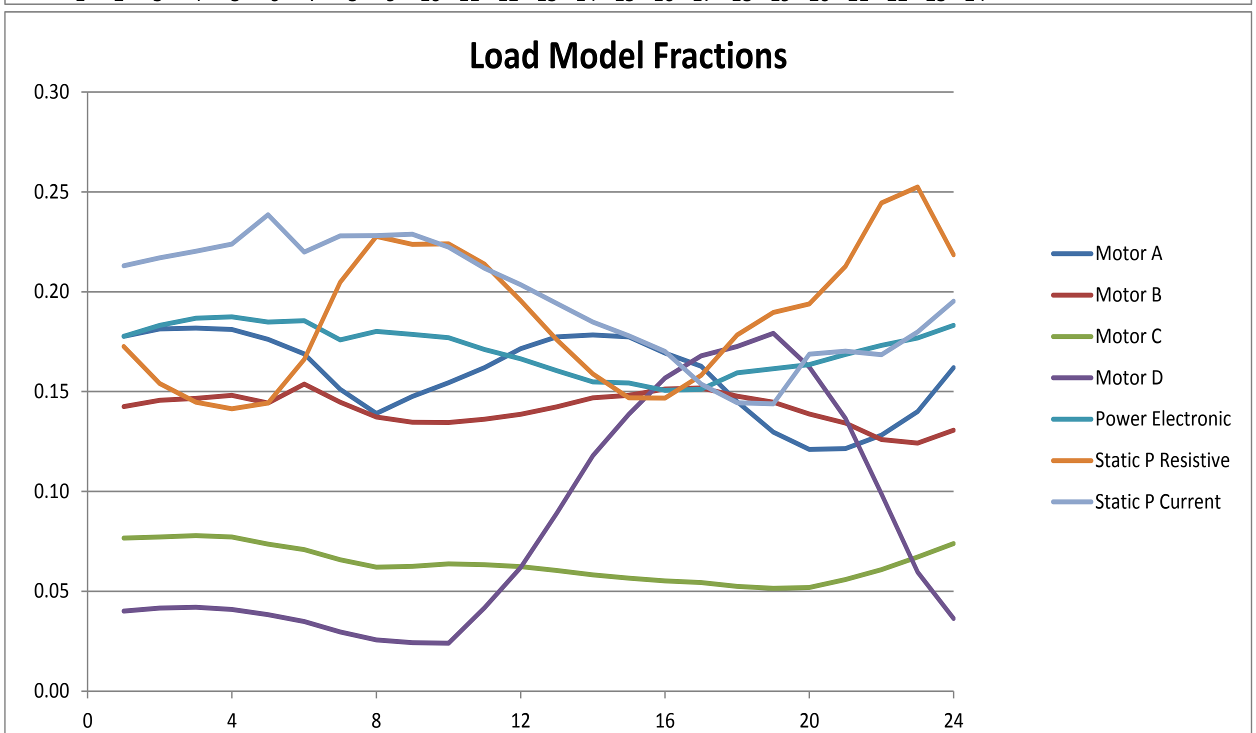
- Base Case scenarios = 3
- Hours (14:00 to 18:00) = 5
- Contingencies = 132
- Temperature sensitivities = 2
- Total Runs = 3,960

In addition to composite load model, we modeled shunt capacitors and reactor relays (Ryan Quint), and line distance relays

We also run scenarios of generation tripping during a contingency

# WECC Load Composition Model



# Modeling Assumptions (for HE 17:00)

**Normal Summer**

| Load | MA | MB | MC | MD | Electronic | Static - R | Static - I |
|---|---|---|---|---|---|---|---|
| Mixed | **0.16** | 0.15 | 0.05 | **0.17** | 0.15 | 0.16 | 0.15 |
| Residential | **0.08** | 0.13 | 0.03 | **0.31** | 0.13 | 0.23 | 0.09 |
| Commercial | **0.21** | 0.14 | 0.03 | **0.12** | 0.19 | 0.12 | 0.19 |

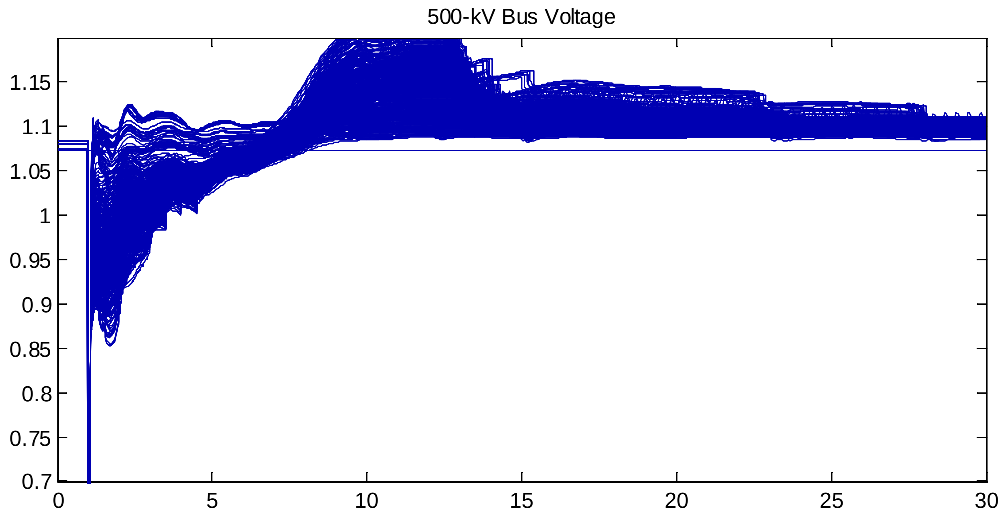
AC stalls if voltage drop below 54% for 3 cycles

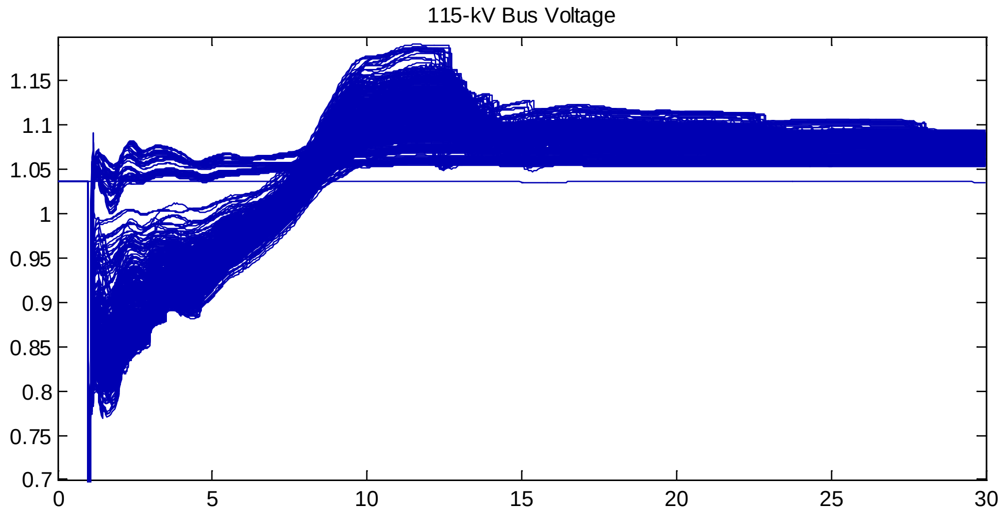
**Hot Summer (95+ F)**

| Load | MA | MB | MC | MD | Electronic | Static - R | Static - I |
|---|---|---|---|---|---|---|---|
| Mixed | **0.17** | 0.15 | 0.05 | **0.24** | 0.13 | 0.13 | 0.13 |
| Residential | **0.06** | 0.15 | 0.02 | **0.42** | 0.10 | 0.20 | 0.05 |
| Commercial | **0.25** | 0.15 | 0.04 | **0.13** | 0.14 | 0.09 | 0.20 |

AC stalls if voltage drop below 60% for 3 cycles

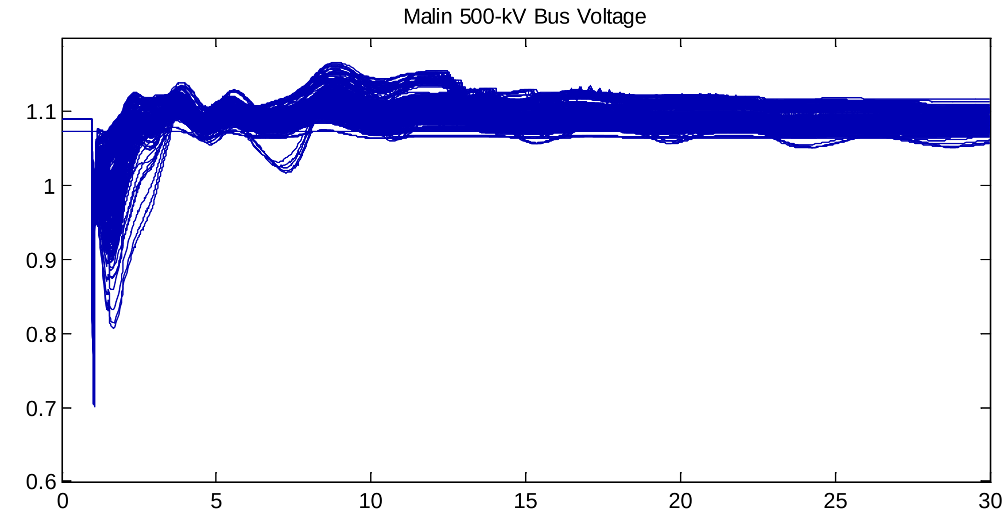
# Portland Area Voltages



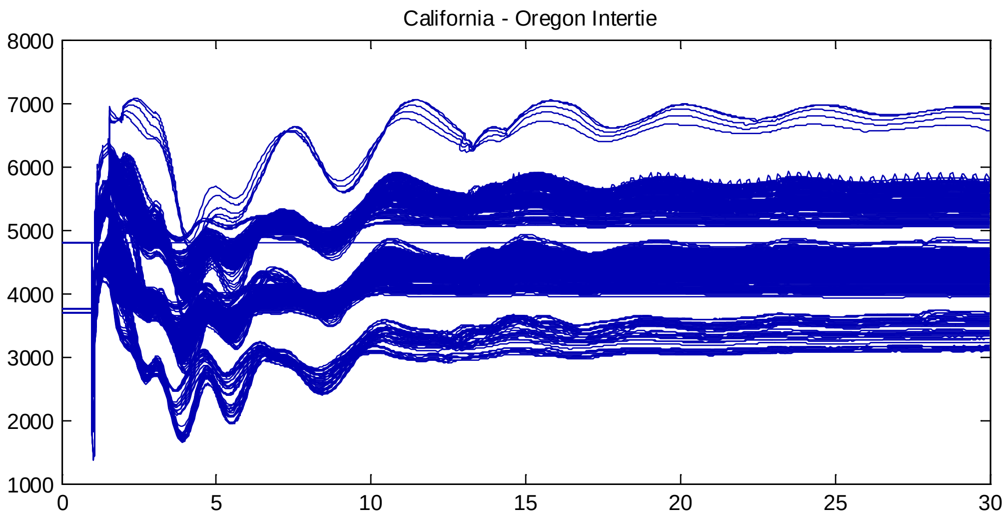




3-phase faults
500-kV and 230-kV
normal clearing

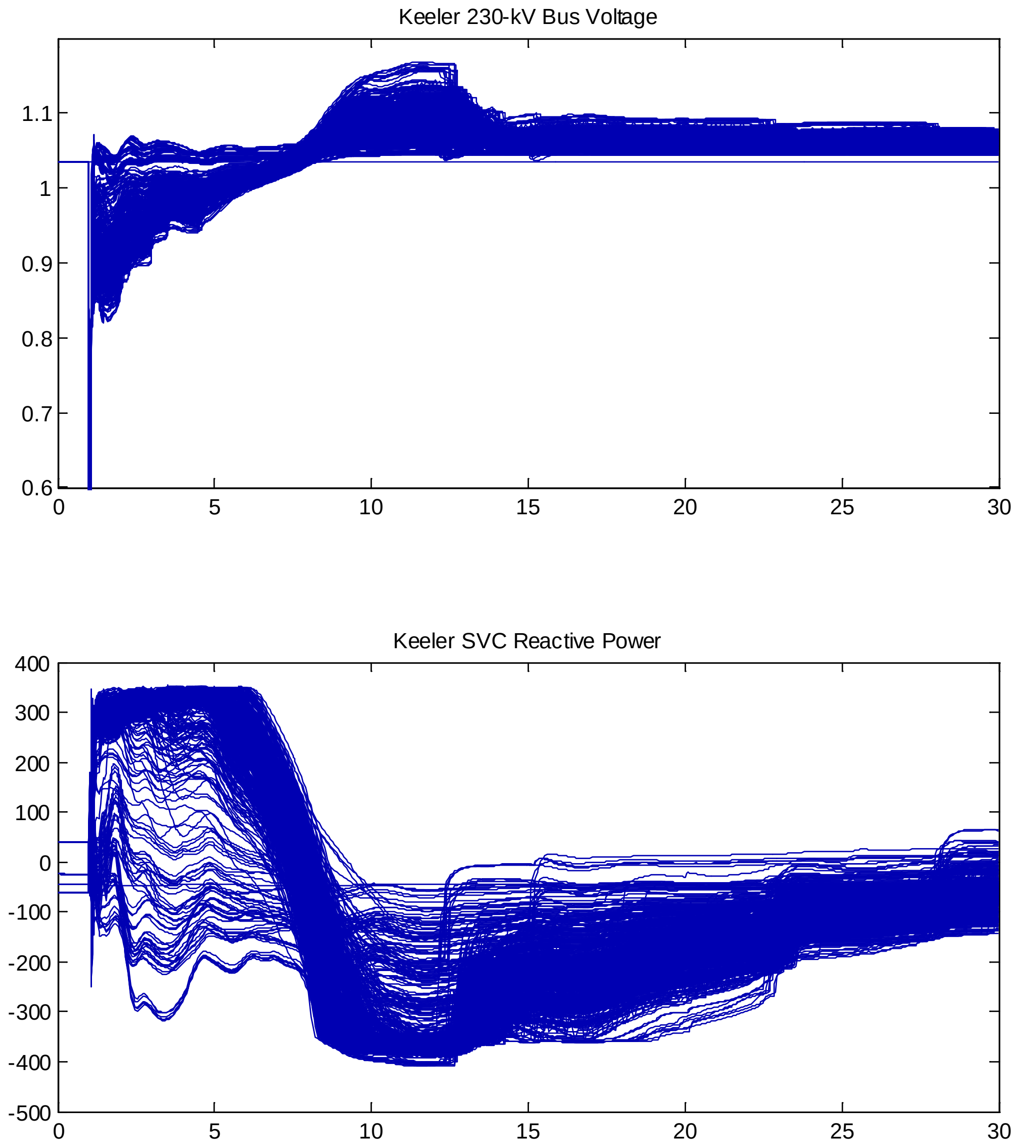
# California – Oregon Intertie




3-phase faults
500-kV and 230-kV
normal clearing

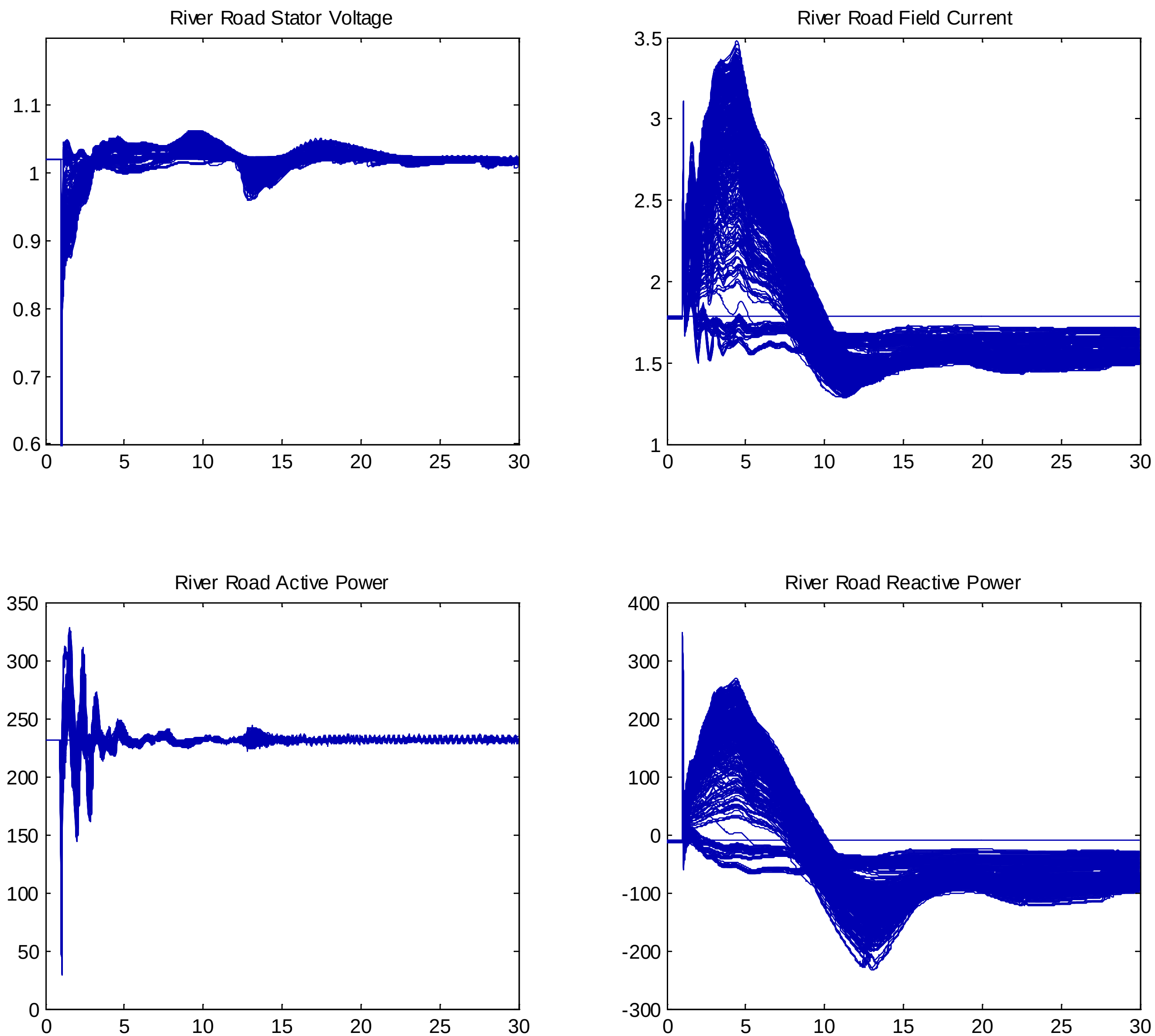


# Portland Area SVC



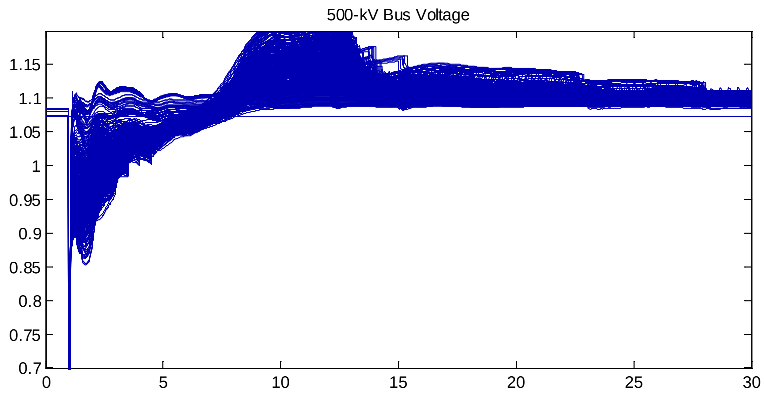

3-phase faults
500-kV and 230-kV
normal clearing

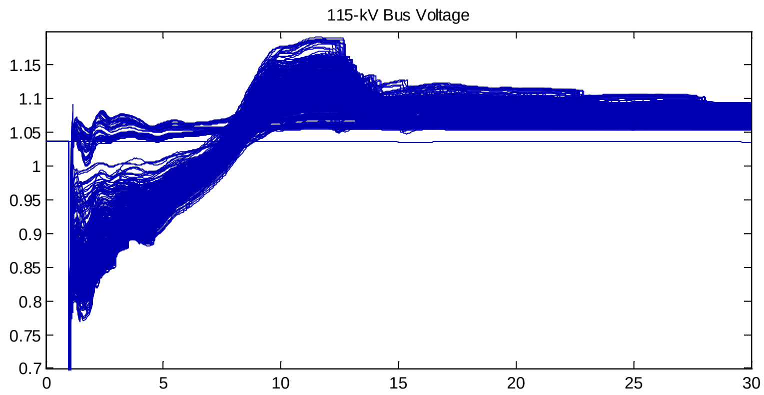
# Portland Area Generation



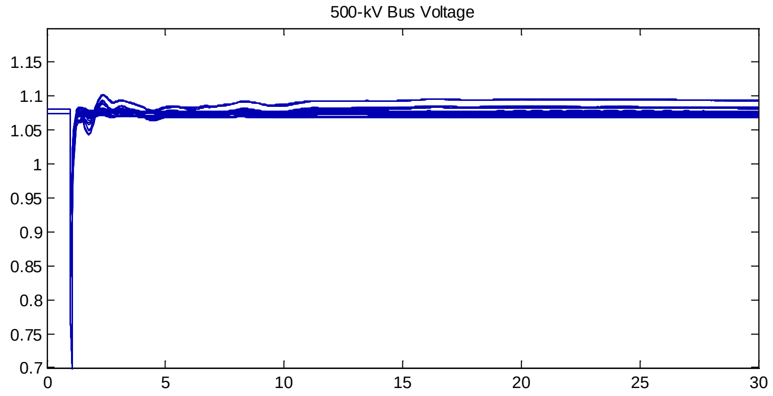
# Fault Type Matters

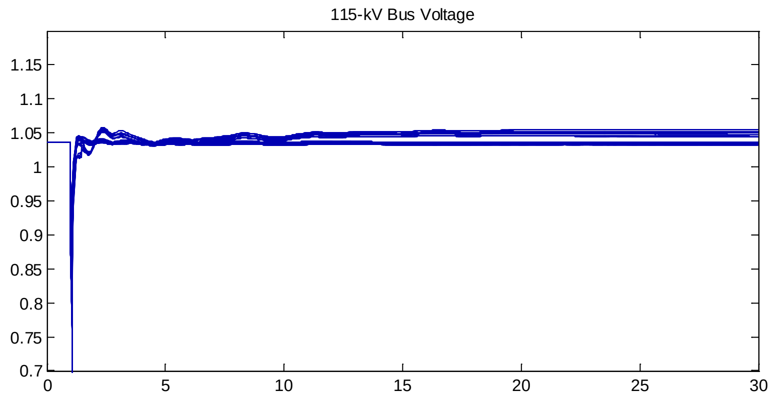
## 3-phase fault, normal clearing




## 1-phase fault, normal clearing

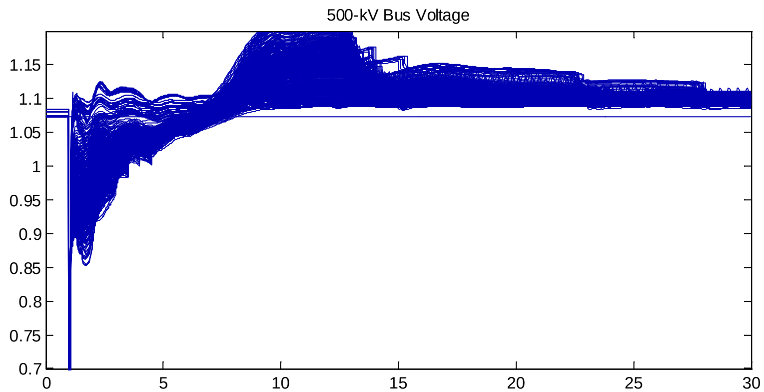


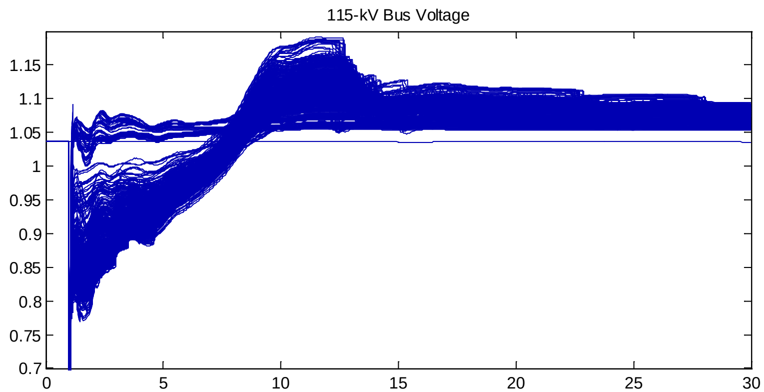




Portland area voltages

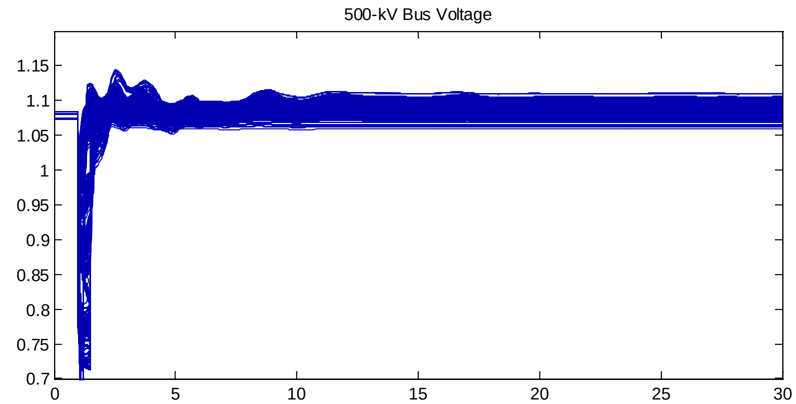
# Fault Type Matters

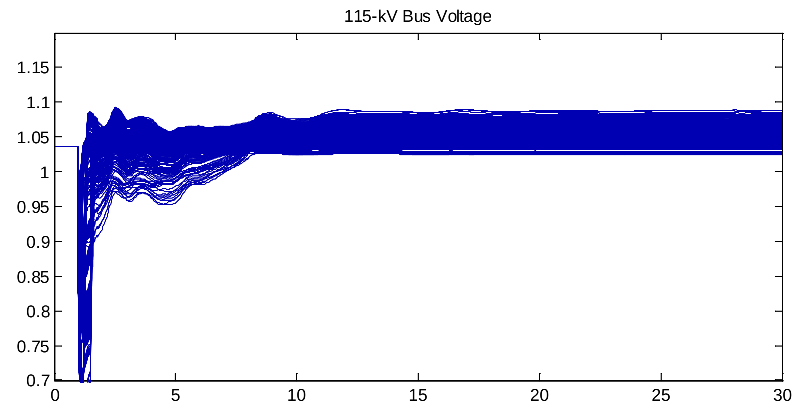
## 3-phase fault, normal clearing




## 1-phase fault, delayed clearing




Portland area voltages

# Observations

Modeling:

- Phase 2 Composite Load Modeled performed well numerically in 4,000 runs, results look credible
- Further review of high voltages is required
  - Whether transformer saturation needs to be modeled (Carson Taylor)
  - Whether restart of air-conditioners needs to be modeled (Richard Bravo)
- Generators step-up transformers must be modeled, cannot have generators connected at 115-kV level
- Shunt reactor and capacitor relays need to be modeled
- Generator OEL and UEL need to be modeled

# Observations

System Performance:

- 3-phase faults are likely to cause FIDVR in Portland area under hot temperatures
- 1-phase faults are not likely to result in FIDVR
- Should a FIDVR event occur, it does not cascade outside Portland area
- High voltages are possible after FIDVR due to loss of load
- High voltages are aggravated by shunt capacitor switching, many of the switching occur during voltage recovery

# Next Steps – Portland Area Studies

- Monitoring
  - BPA has good PMU coverage of 500-kV grid and main 230-kV substations in the area
  - Continue expansion of synchronzied measurements down to sub-transmission and distribution levels (work with LSEs)
- Model Improvements
  - Re-run the studies after the revised AC model is implemented – results are expected to get better
  - Continue risk-based scenario planning to ensure robustness with respect to unexpected generator control actions and trips during FIDVR

# Thank You

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# National Grid Experience with PSS/E Composite Load Model

NERC FIDVR Workshop - Panel Session – October 1, 2015

Dean Latulipe, National Grid

# Overview

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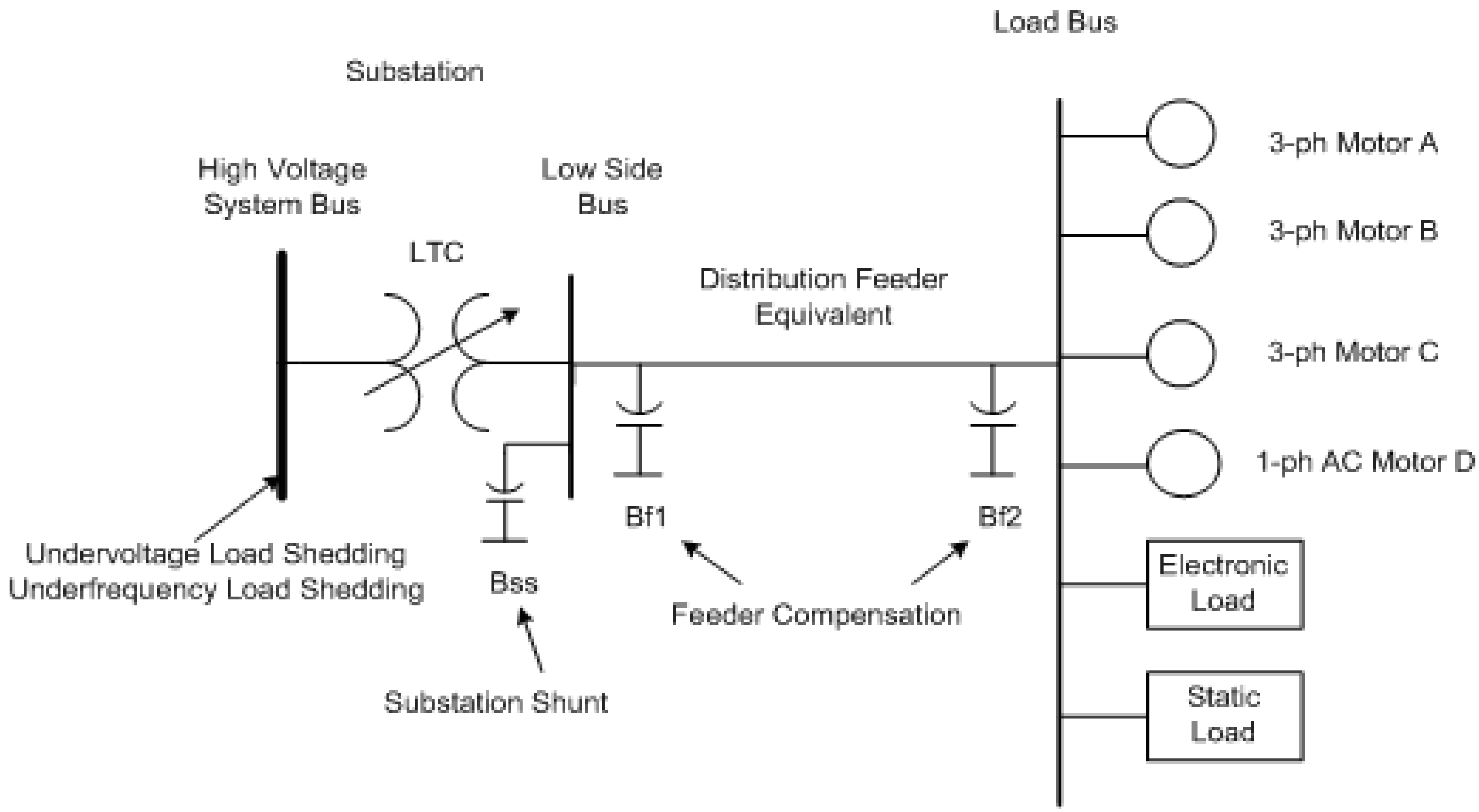
- National Grid has Service Territories in New England and New York
- The Composite Load Model (CMLD) Dynamic Load model was tested on the New England system.
- PSS/E Rev 32.2.4 was used conduct simulations

# CMLD Model



Load Bus
Substation
High Voltage
System Bus
Low Side
Bus
LTC
Distribution Feeder
Equivalent
3-ph Motor A
3-ph Motor B
3-ph Motor C
1-ph AC Motor D
Electronic
Load
Static
Load
Bf1
Bf2
Bss
Undervoltage Load Shedding
Underfrequency Load Shedding
Feeder Compensation
Substation Shunt

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# Baseline CMLD Parameters - Load Breakdown

- Load Survey conducted for New England in 2013
- Summer Peak Load Breakdown:

| New England Region | Electronics | Motor A | Motor B | Motor C | Motor D | Constant Current | Constant Impedance |
|---|---|---|---|---|---|---|---|
| Connecticut | 18% | 14% | 12% | 6% | 25% | 12% | 13% |
| Massachusetts – East | 16% | 18% | 12% | 7% | 23% | 12% | 13% |
| Massachusetts - West/Central | 14% | 15% | 13% | 8% | 25% | 10% | 14% |
| Maine | 16% | 15% | 12% | 9% | 19% | 12% | 17% |
| New Hampshire | 16% | 16% | 12% | 8% | 18% | 13% | 17% |
| Rhode Island | 14% | 15% | 13% | 7% | 26% | 11% | 14% |
| Vermont | 15% | 17% | 11% | 10% | 19% | 12% | 16% |
| New England | **16%** | **16%** | **12%** | **7%** | **23%** | **12%** | **14%** |

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# Baseline CMLD Parameters – Motor A

Motor A: Commercial 3-phase Air Conditioners (Motor A < 250 HP)

- Vtr1 - U/V Trip1 Voltage: 0.70 pu
- Ttr1 - U/V Trip1 Time: 0.033 sec (2 cycles)
- Ftr1 - U/V Trip1 fraction: 0.20
- Vrc1 - U/V Trip1 reclose Voltage: 1.0 pu
- Trc1 - U/V Trip1 reclose Time: 999 sec (no restart)
- Vtr2 - U/V Trip2 Voltage: 0.50 pu
- Ttr2 - U/V Trip2 Time: 0.033 sec (2 cycles)
- Ftr2 - U/V Trip2 fraction: 0.70
- Vrc2 - U/V reclose Voltage: 0.70 pu
- Trc2 - U/V reclose Time: 0.033 sec

# Baseline CMLD Parameters – Motor B

Motor B: Commercial 3-phase Pumps

| | |
|---|---|
| Vtr1 - U/V Trip1 Voltage: | 0.50 pu |
| Ttr1 - U/V Trip1 Time: | 0.033 sec (2 cycles) |
| Ftr1 - U/V Trip1 fraction: | 0.50 |
| Vrc1 - U/V Trip1 reclose Voltage: | 0.70 pu |
| Trc1 - U/V Trip1 reclose Time: | 0.033 sec |
| Vtr2 - U/V Trip2 Voltage: | 0.50 pu |
| Ttr2 - U/V Trip2 Time: | 0.033 sec (2 cycles) |
| Ftr2 - U/V Trip2 fraction: | 0.50 |
| Vrc2 - U/V reclose Voltage: | 0.95 pu |
| Trc2 - U/V reclose Time: | 999 sec (no reclose) |

# Baseline CMLD Parameters – Motor C

Motor C: Commercial 3-phase Fans

| | |
|---|---|
| Vtr1 - U/V Trip1 Voltage: | 0.70 pu |
| Ttr1 - U/V Trip1 Time: | 0.033 sec (2 cycles) |
| Ftr1 - U/V Trip1 fraction: | 0.20 |
| Vrc1 - U/V Trip1 reclose Voltage: | 1.0 pu |
| Trc1 - U/V Trip1 reclose Time: | 999 sec (no restart) |
| Vtr2 - U/V Trip2 Voltage: | 0.50 pu |
| Ttr2 - U/V Trip2 Time: | 0.033 sec (2 cycles) |
| Ftr2 - U/V Trip2 fraction: | 0.70 |
| Vrc2 - U/V reclose Voltage: | 0.70 pu |
| Trc2 - U/V reclose Time: | 0.033 sec |

# Baseline CMLD Parameters – Motor D

Motor D:  Single Phase Air Conditioners

- Stall Voltage: 40%
- Under-voltage contactor dropout:
  - VC1off:  50% drop out at 0.45 pu voltage,
  - VC2off:  50% drop out at 0.35 pu voltage.
- Contactor Reclose:
  - VC1on: 50% close back in at 0.70 pu voltage
  - VC2on:   50% close back in at 0.65 pu voltage.
  - Stall time:  2 cycle (0.033 sec) after stall voltage is encountered.
  - Fraction of Motors that restart: 20%
- Restart Voltage: 0.90 pu (assumed)
- Restart Time: 0.033 sec

# Baseline CMLD Parameters – Motor D (continued)

Motor D:  Single Phase Air Conditioners

- Thermal Relay – Compressor motor heating time constant:   15 sec
- Thermal Relay – Temp. at which compressor motors begin tripping:     0.7 pu
- Thermal Relay – Temp. at which all motors are tripped:  1.9 pu
- Under-voltage relay - Fraction of motors with U/V relays: 0%
- Under-voltage relay - First U/V pickup level: N/A
- Under-voltage relay - Second U/V pickup level: N/A
- Under-voltage relay - First definite time for U/V trip: N/A
- Under-voltage relay - Second definite time for U/V trip: N/A

# Sensitivity to Motor D

# Vstall and Undervoltage Dropout Voltages

# Sensitivity Testing: Motor D (1-phase Air Conditioner)

- Varied stall voltage (Vstall):
  - Baseline: Vstall = 0.40 pu
  - Sensitivity 1: Vstall = 0.35 pu
  - Sensitivity 2: Vstall = 0.30 pu

- Varied contactor dropout voltages (VC1off and VC2off):
  - Baseline: VC1off = 0.45 pu, VC2off = 0.35 pu
  - Sensitivity 1: VC1off = 0.40 pu, VC2off = 0.30 pu
  - Sensitivity 2: VC1off = 0.35 pu, VC2off = 0.25 pu

# Test Fault

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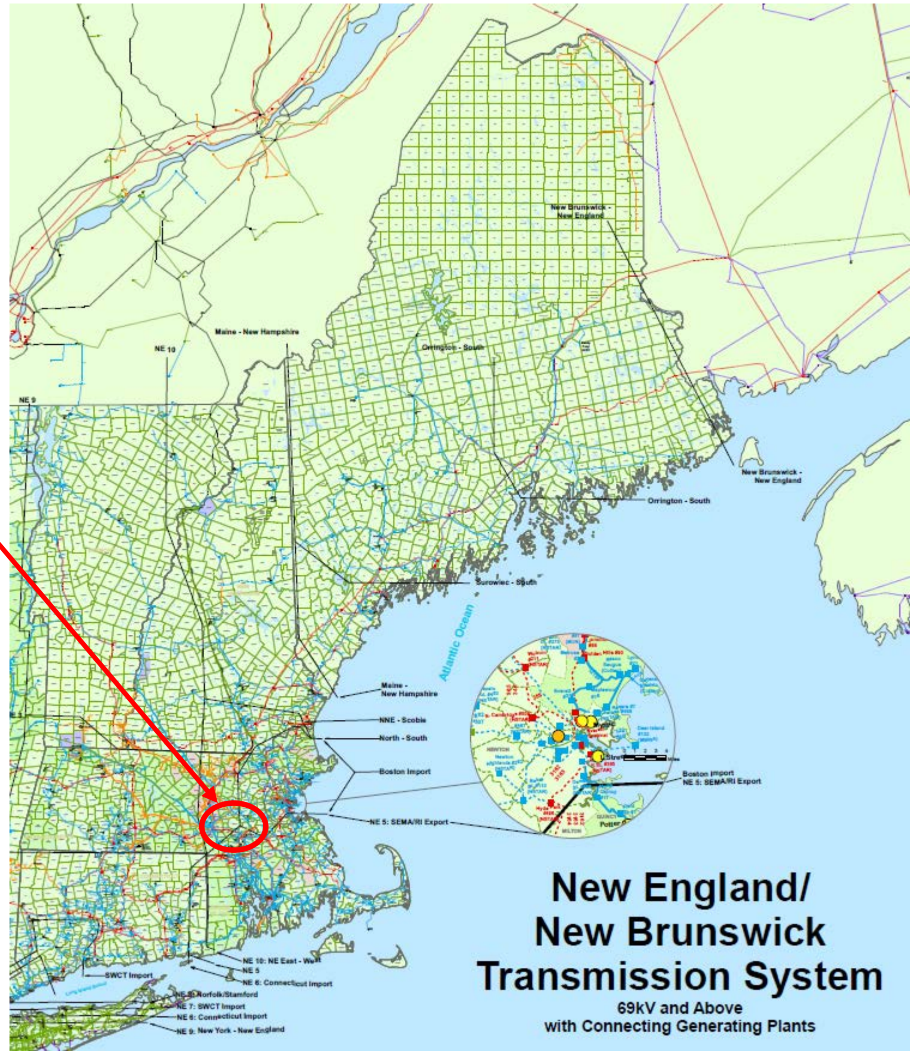
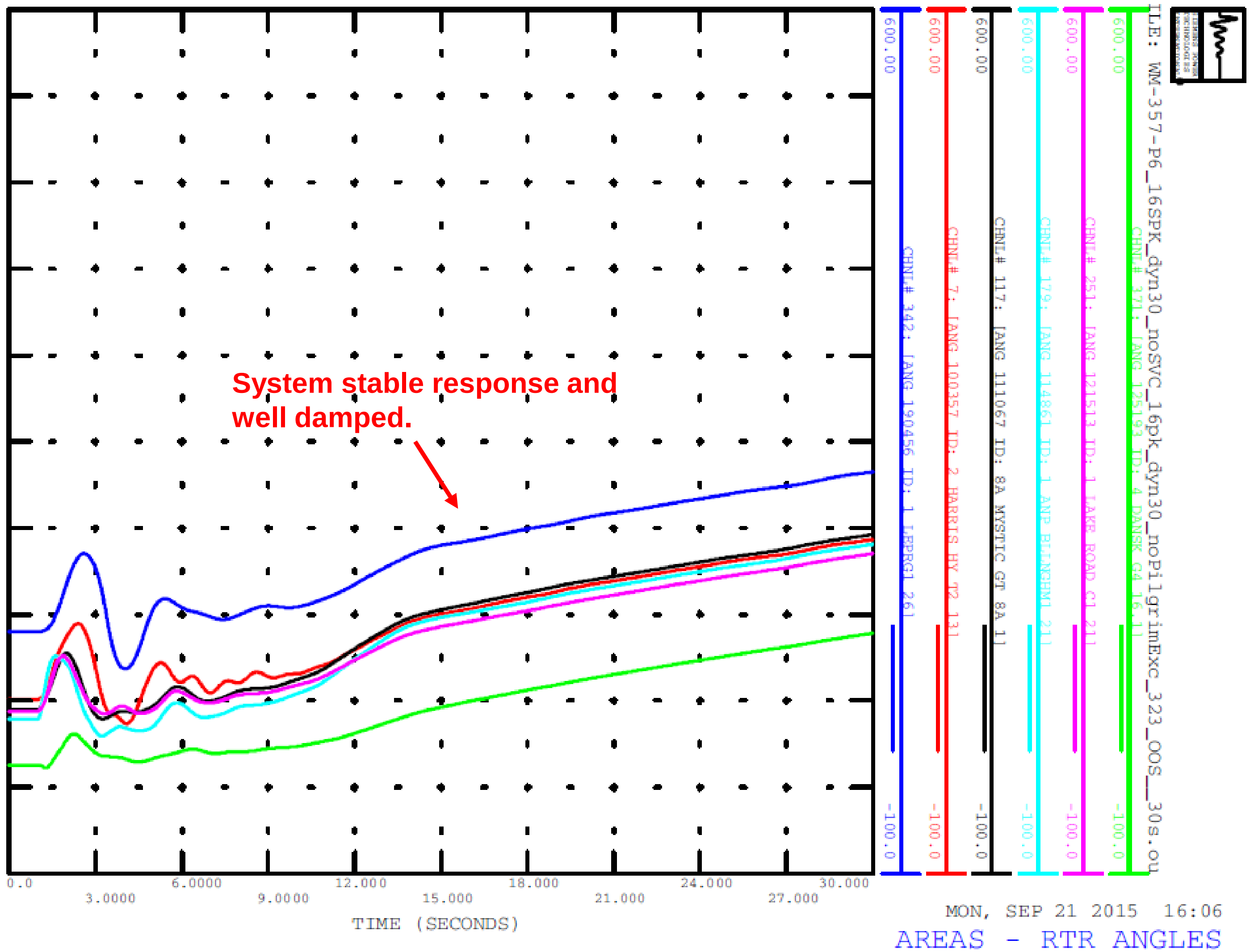
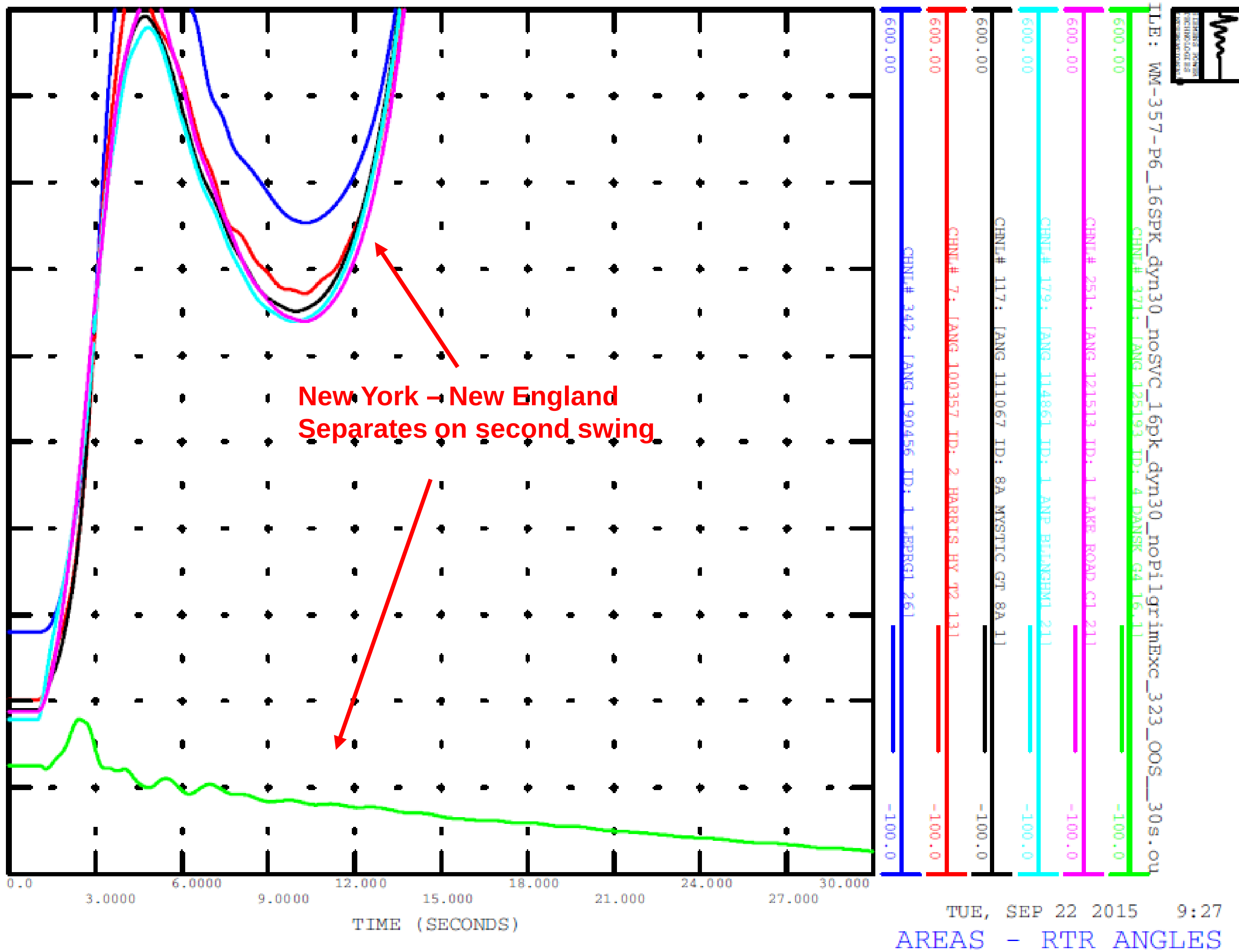
**Normally Cleared 3ph Fault on 345 kV Line (4.5 cycles) in Southern New England**



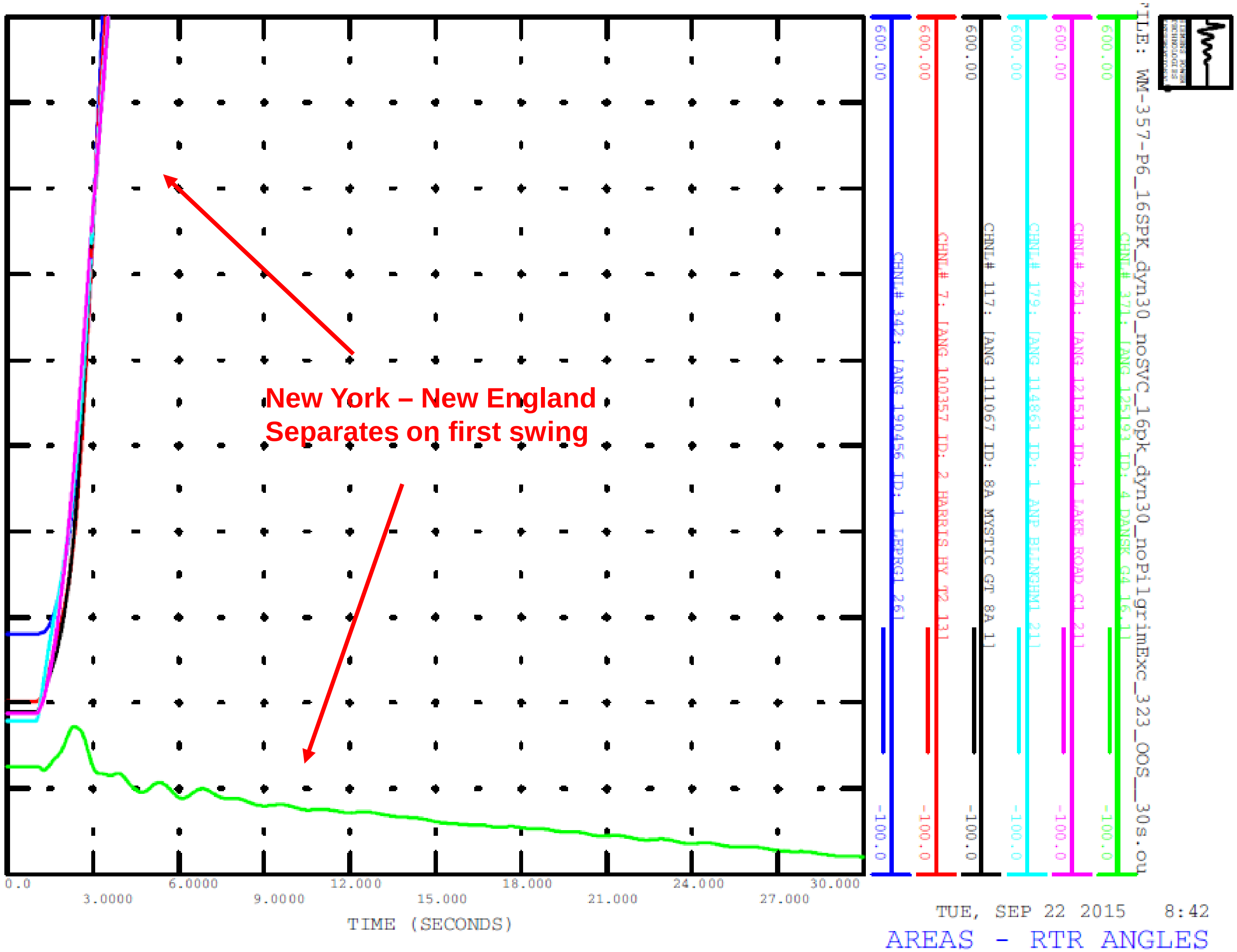
# Results using Baseline assumptions for Motor D: Vstall = 40%, VC1off = 0.45 pu, VC2off = 0.35 pu



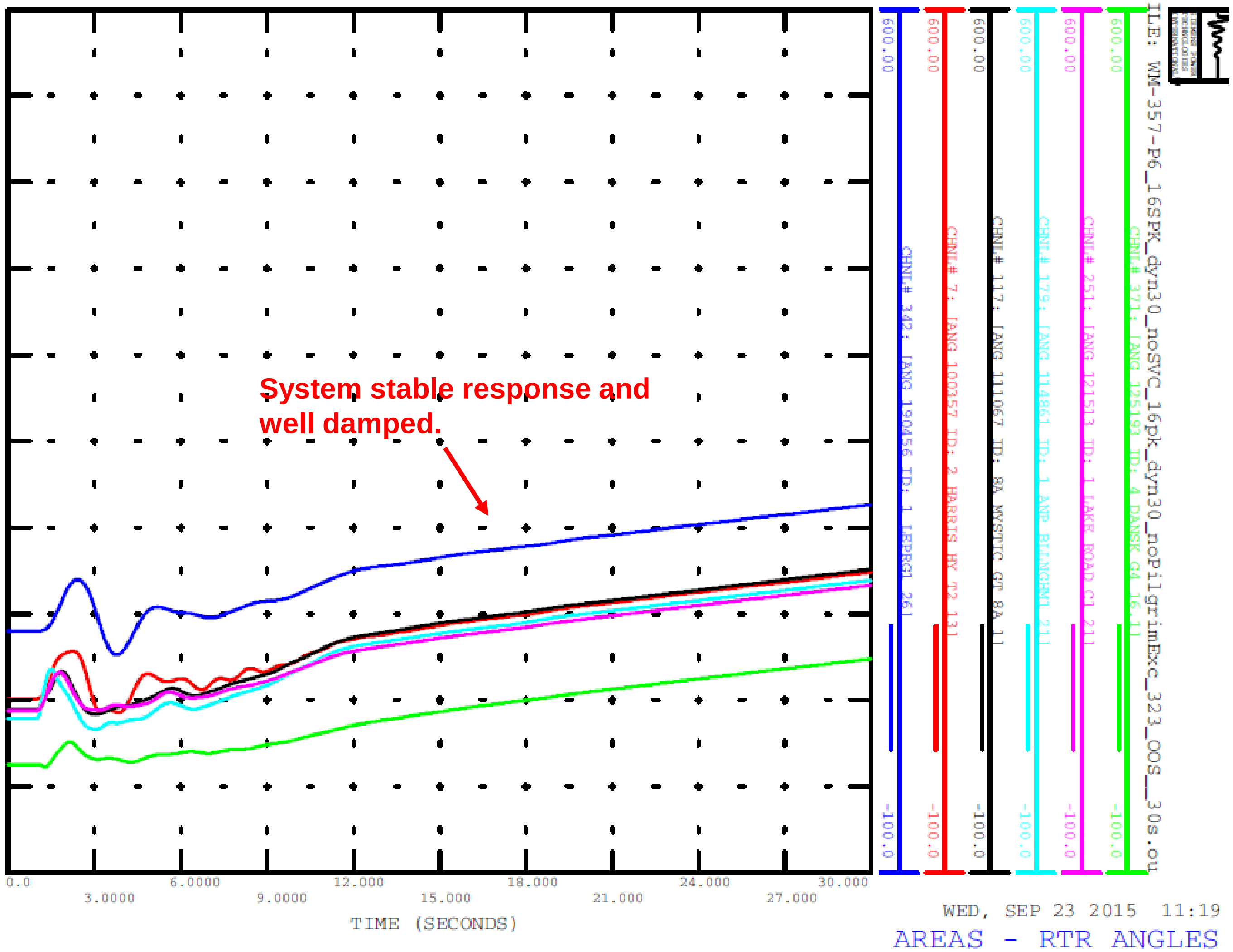
# Results for lowering VC1off and VC2off for Motor D:
# Vstall = 40%, VC1off = 0.40 pu, VC2off = 0.30 pu



# Results for lowering VC1off and VC2off for Motor D: Vstall = 40%, VC1off = 0.35 pu, VC2off = 0.25 pu



# Results using Baseline assumptions for Motor D: Vstall = 35%, VC1off = 0.45 pu, VC2off = 0.35 pu



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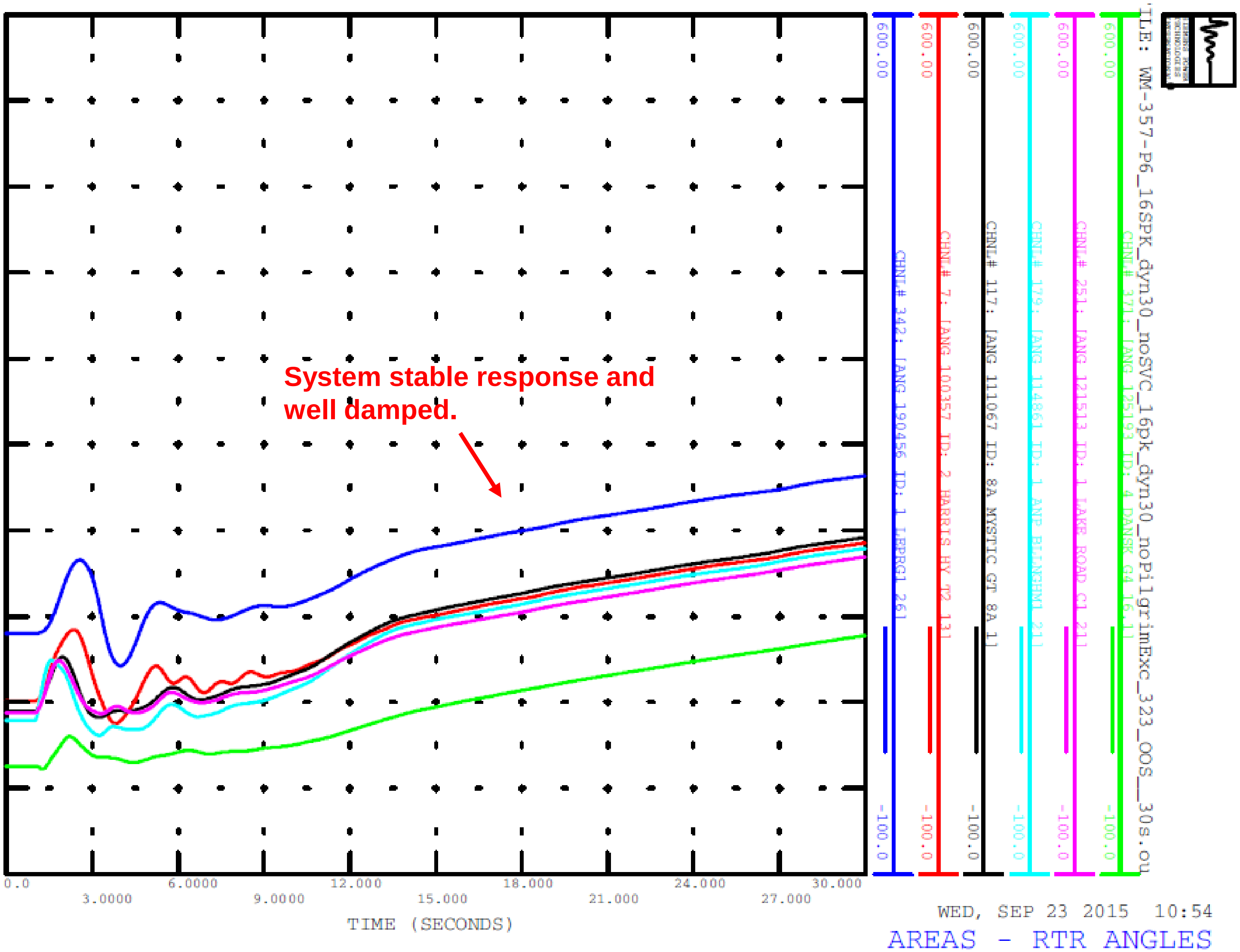
# Results using Baseline assumptions for Motor D: Vstall = 35%, VC1off = 0.40 pu, VC2off = 0.30 pu



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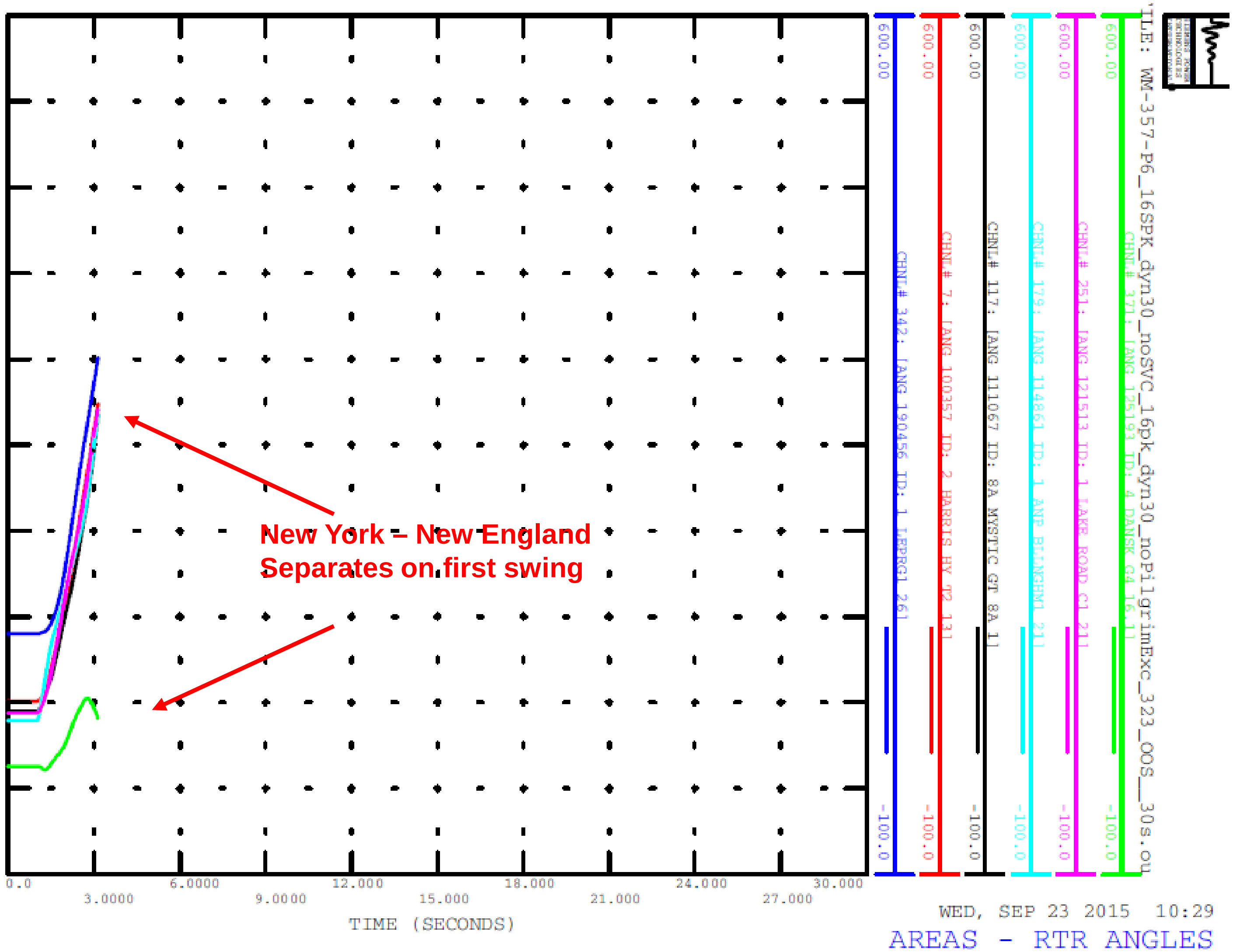
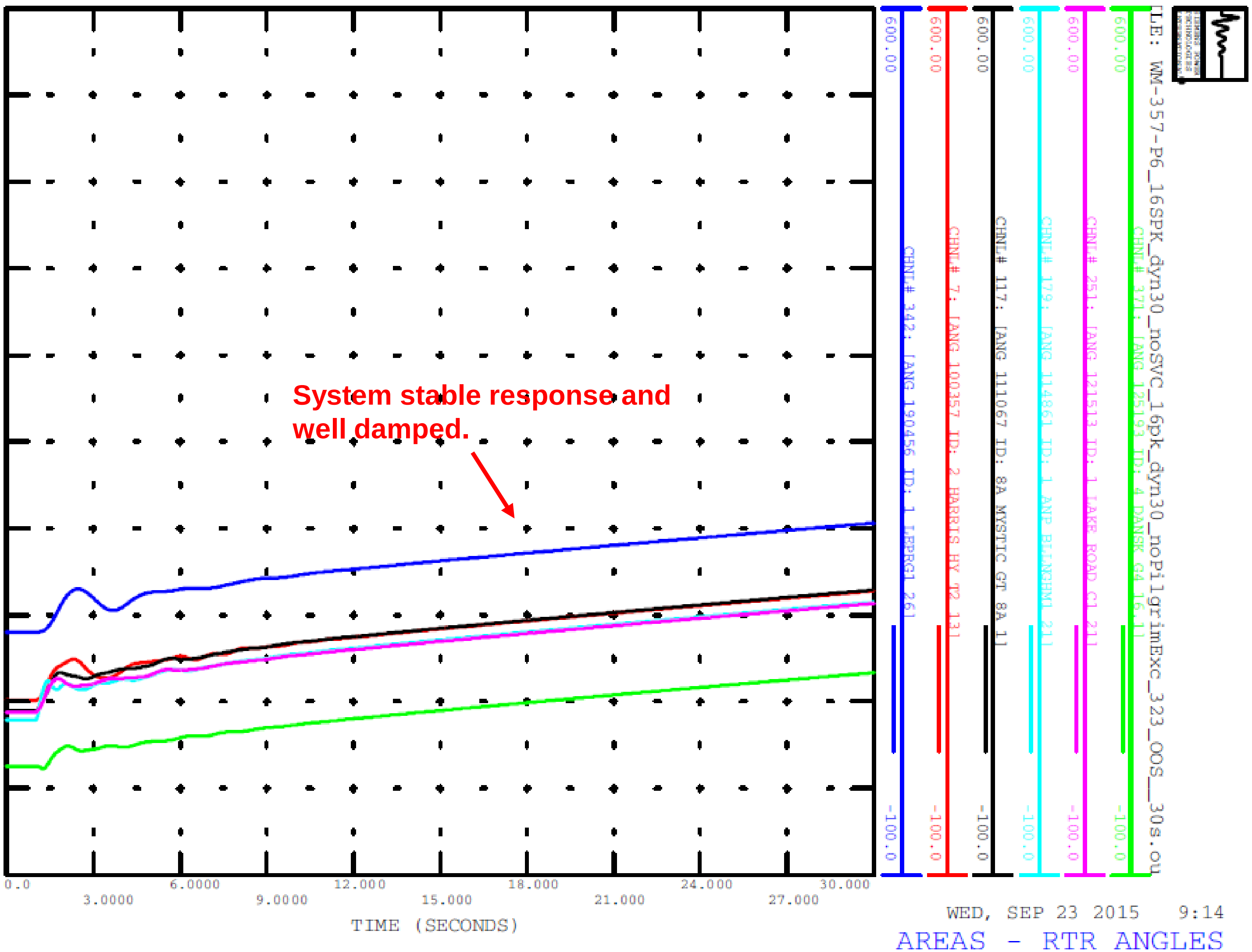
# Results using Baseline assumptions for Motor D: Vstall = 35%, VC1off = 0.35 pu, VC2off  = 0.25 pu



## Results using Baseline assumptions for Motor D: Vstall = 30%, VC1off = 0.40 pu, VC2off = 0.30 pu



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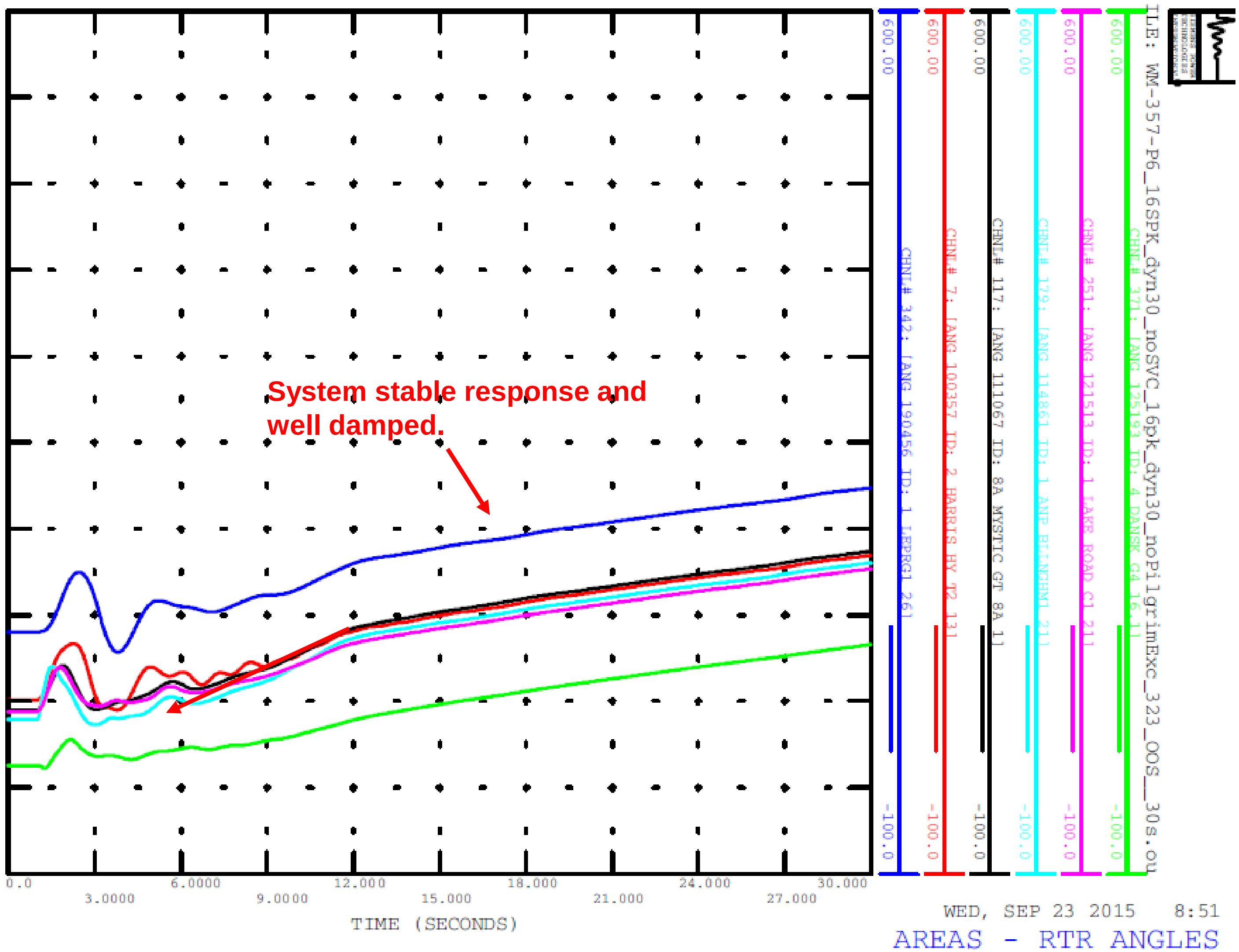
# Results using Baseline assumptions for Motor D: Vstall = 30%, VC1off = 0.35 pu, VC2off = 0.25 pu



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# Sensitivity to Motor A, B, & C

# Under-voltage Contactor Dropout Voltages

# Sensitivity Testing: Motor A, B, C U/V Trip Parameters

| Baseline assumptions (Kosterev) | Motor A | Motor B | Motor C |
|---|---|---|---|
| Vtr1 - U/V Trip1 V (pu) | 0.70 pu | 0.50 pu | 0.70 pu |
| Ftr1 - U/V Trip1 fraction | 0.20 | 0.50 | 0.20 |
| Vrc1 - U/V Trip1 reclose V (pu) | no reclose | 0.70 pu | no reclose |
| Vtr2 - U/V Trip2 V (pu) | 0.50 pu | 0.50 pu | 0.50 pu |
| Ftr2 - U/V Trip2 fraction | 0.70 | 0.50 | 0.70 |
| Vrc2 - U/V Reclose V (pu) | 0.70 pu | no reclose | 0.70 pu |

| Sensitivity parameters | Motor A | Motor B | Motor C |
|---|---|---|---|
| Vtr1 - U/V Trip1 V (pu) | 0.70 pu | 0.70 pu | 0.70 pu |
| Ftr1 - U/V Trip1 fraction | 0.50 | 0.50 | 0.50 |
| Vrc1 - U/V Trip1 reclose V (pu) | no reclose | no reclose | no reclose |
| Vtr2 - U/V Trip2 V (pu) | 0.50 pu | 0.50 pu | 0.50 pu |
| Ftr2 - U/V Trip2 fraction | 0.50 | 0.50 | 0.50 |
| Vrc2 - U/V Reclose V (pu) | 0.95 pu | 0.95 pu | 0.95 pu |

# Load loss using Baseline Assumptions

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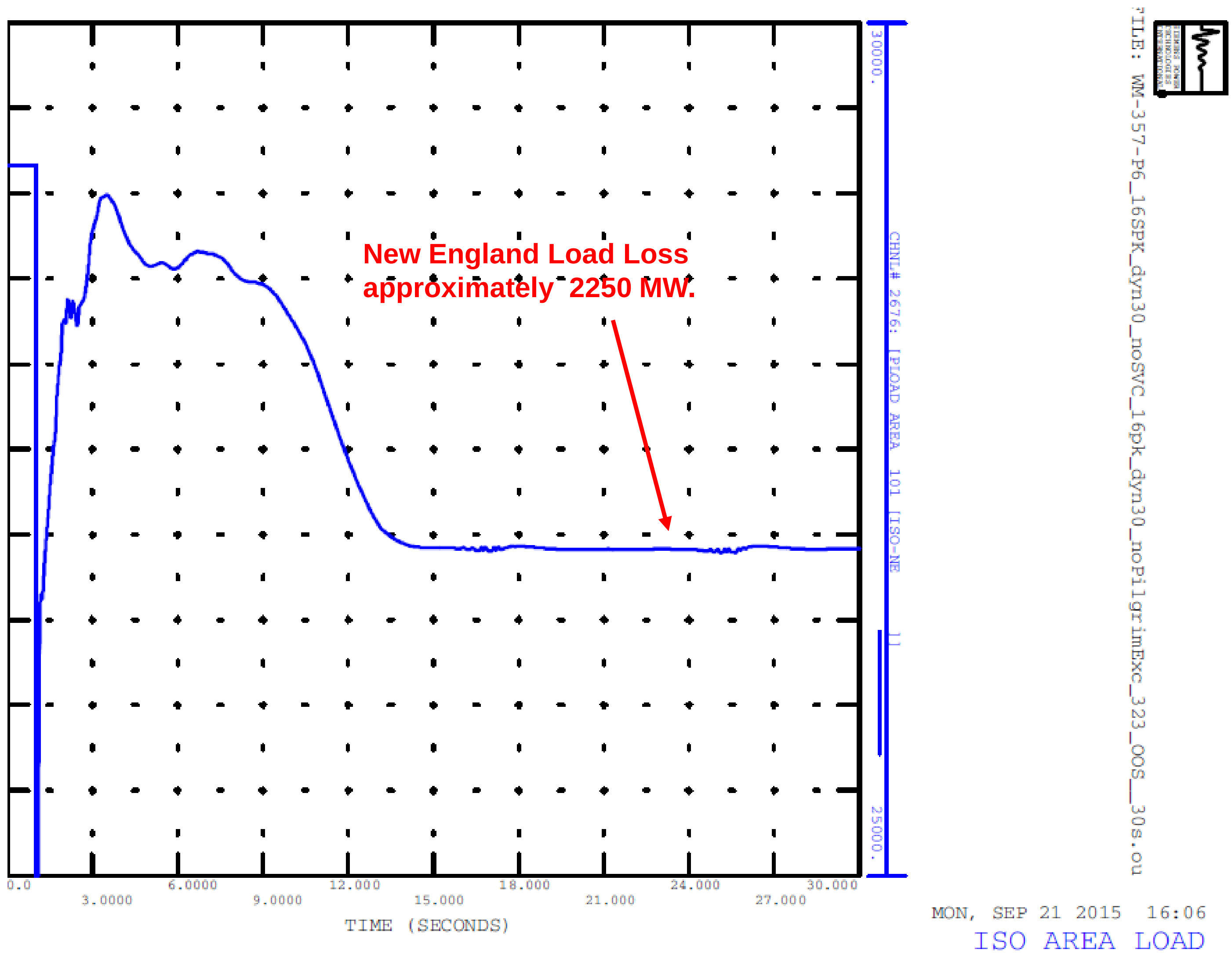

# Load loss using with Motor A, B, C U/V Tripping Sensitivity Parameters

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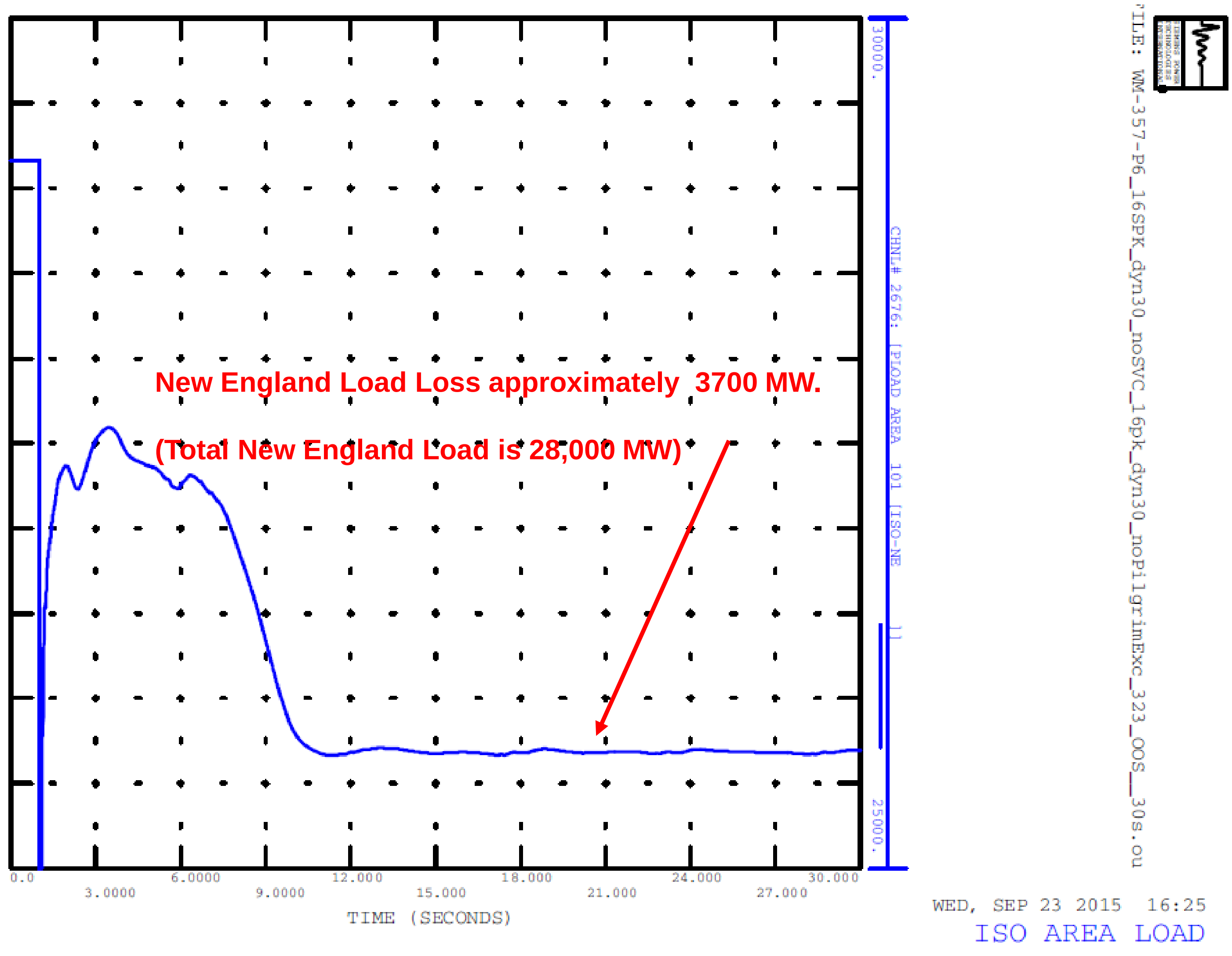

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# Numerical Problems

# With CMPL Model in PSSE

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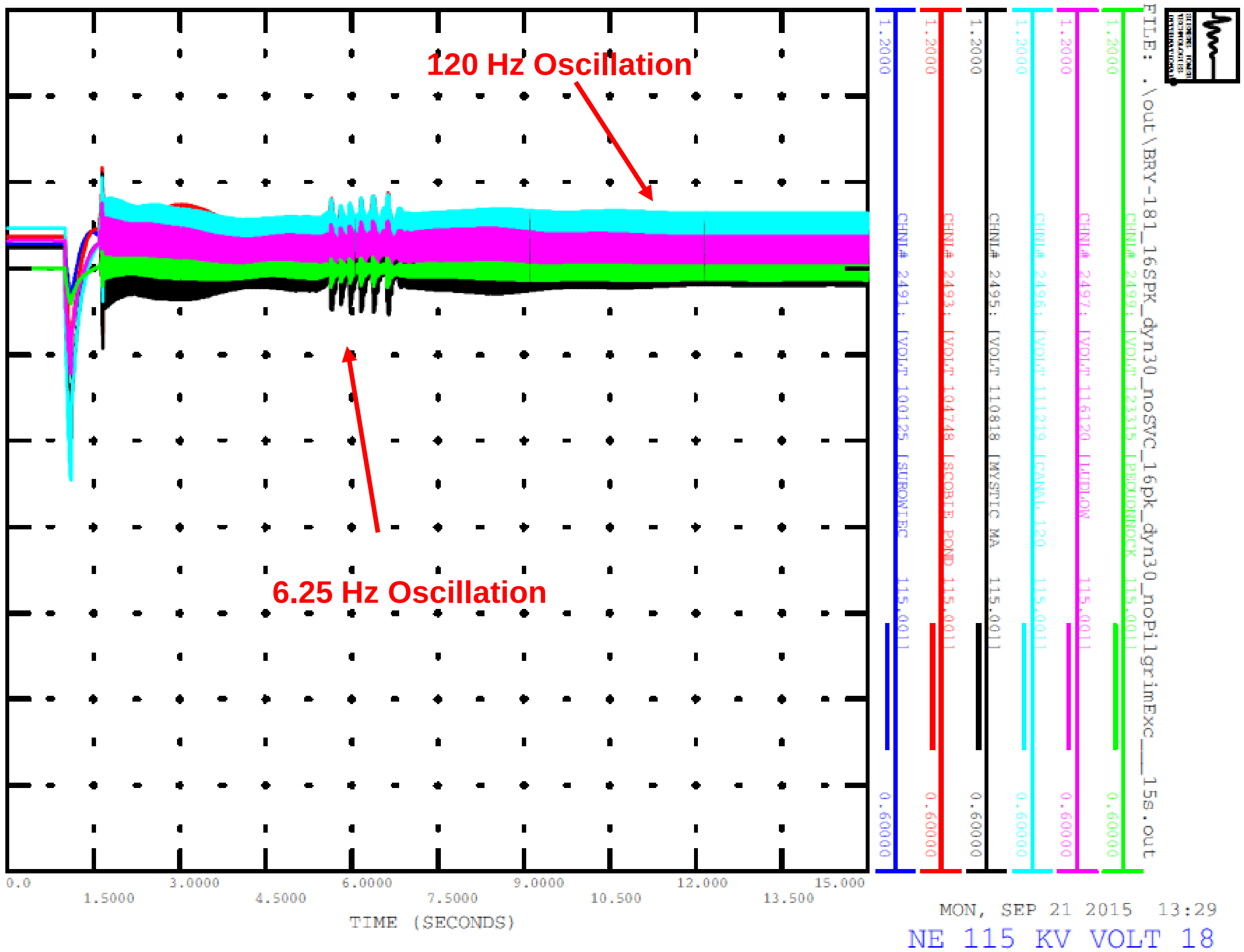
# 120 Hz oscillations found to certain 3ph fault



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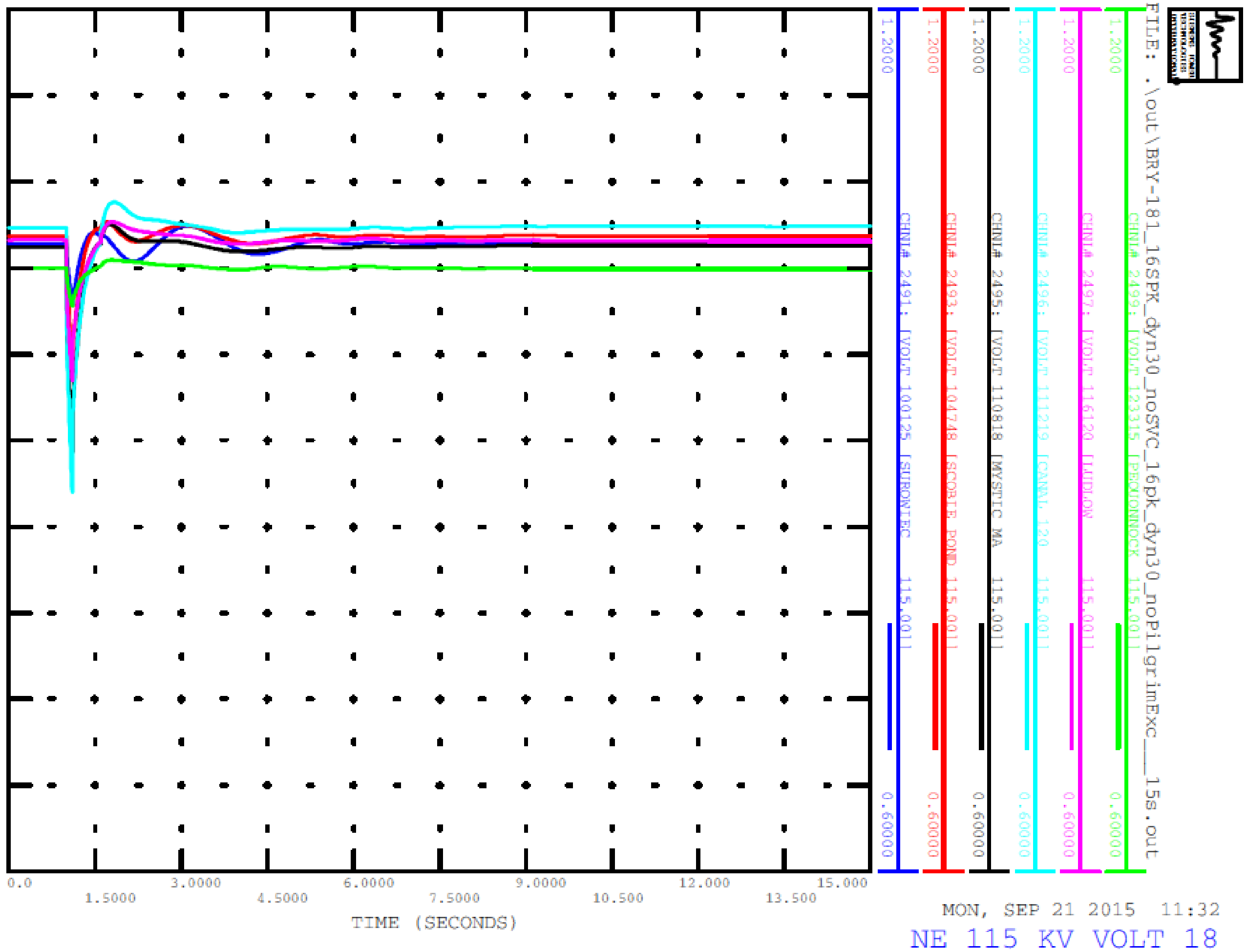
# Changed Motor A parameter LPPA from 0.104 pu to 0.12 pu

## Original Motor A Parameters:

| | |
|---|---|
| LFmA - Loading factor | 0.75 |
| RaA - Stator resistance | 0.04 pu |
| LsA - Synchronous reactance | 1.80 pu |
| LpA - Transient reactance | 0.12 pu |
| LppA - Sub-transient reactance | changed 0.104 pu to 0.120 pu |
| TpoA - Transient open circuit time constant | 0.095 sec |
| TppoA - Sub-transient open circuit time constant | 0.0021 sec |
| HA - Inertia constant | 0.05 |
| etrqA - Torque speed exponent | 0.00 |

# Results after increasing LppA of Motor A to 0.12 pu



## Changed Network Solution Iterations to 200

Original Network Solution Iterations: 60

Increased Network Solution Iterations to 200

Left Motor LppA - Sub-transient reactance at original value of 0.104 pu

# Results after increasing Network Solution Iterations to 200 (Motor A LppA= 0.104 pu)

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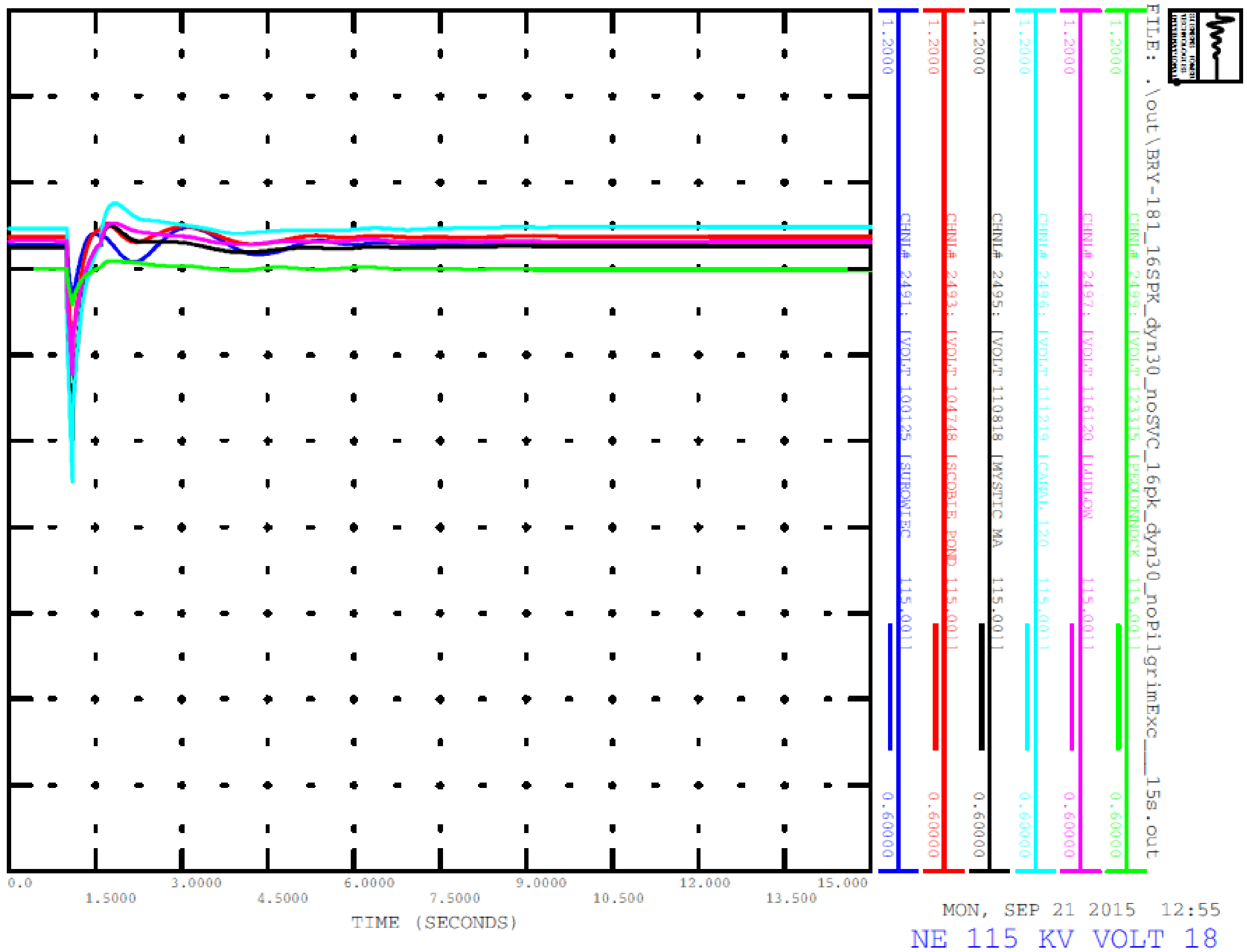

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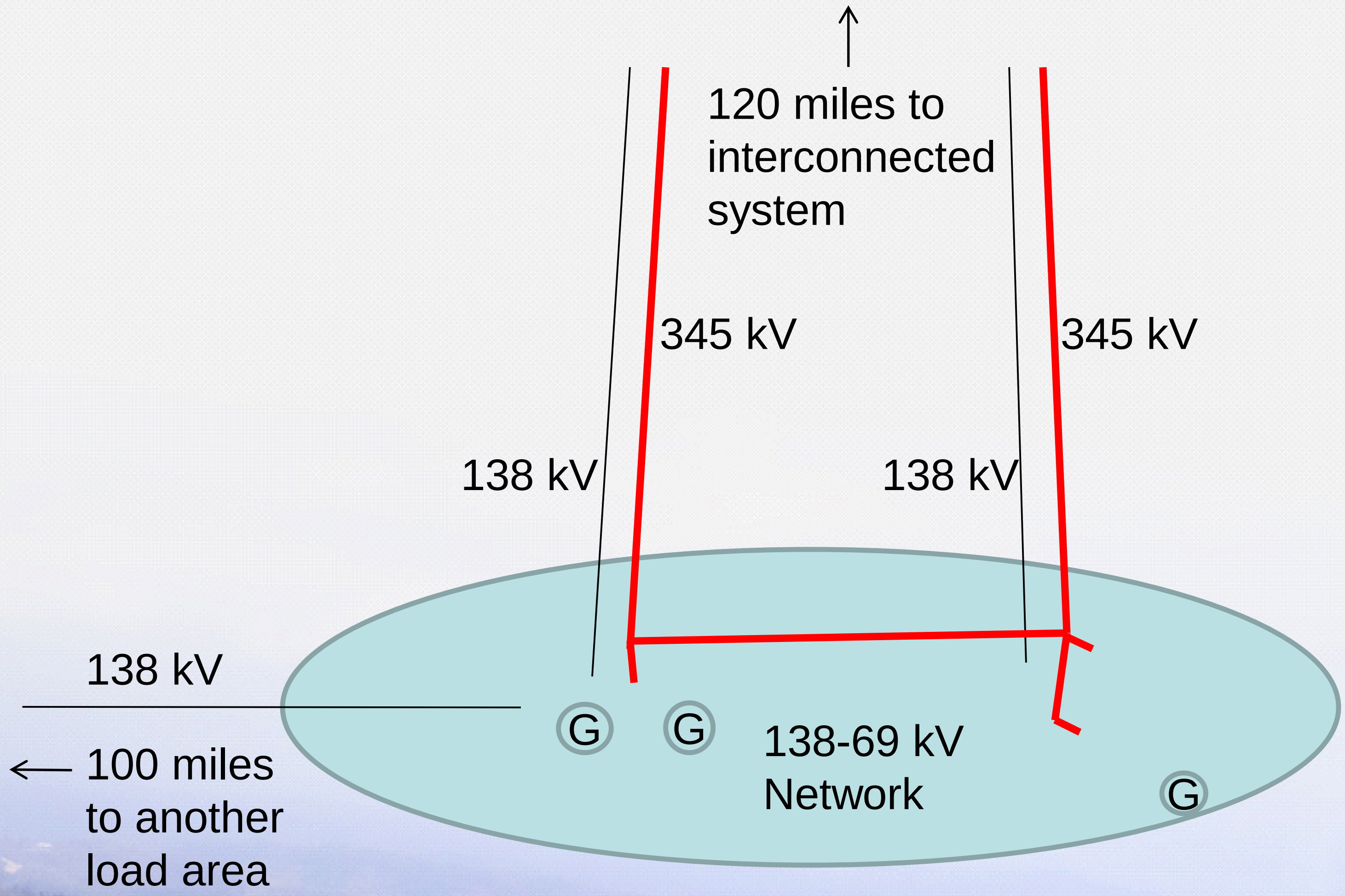
# Questions?

# Experience with CMLD in a Practical SOL Application

## DOE-NERC
## FIDVR & Dynamic Load Modeling Conference
## Alexandria, VA
## October 1, 2015

**Robert J. O'Keefe**
**American Electric Power**

# Load Area Overview



# Single-Phase A/C Component Sensitivity

**5% increase in D-component shows following effects on area import limits:**

**<u>Non-fault initiated generating plant trip</u>**

**150 mw decrease in limit based on avoiding voltage collapse**

**<u>345 kV transmission line fault and trip</u>**

**200 mw decrease in limit based on avoiding UVLS operations**

**500 mw decrease in limit based on avoiding transient instability**

# CMLD Issues

1. **Question about effect of D-component Tstall value as voltage decreases below Vstall**

2. **Question about tripping of stalled A, B, and C components as their speed reaches zero**

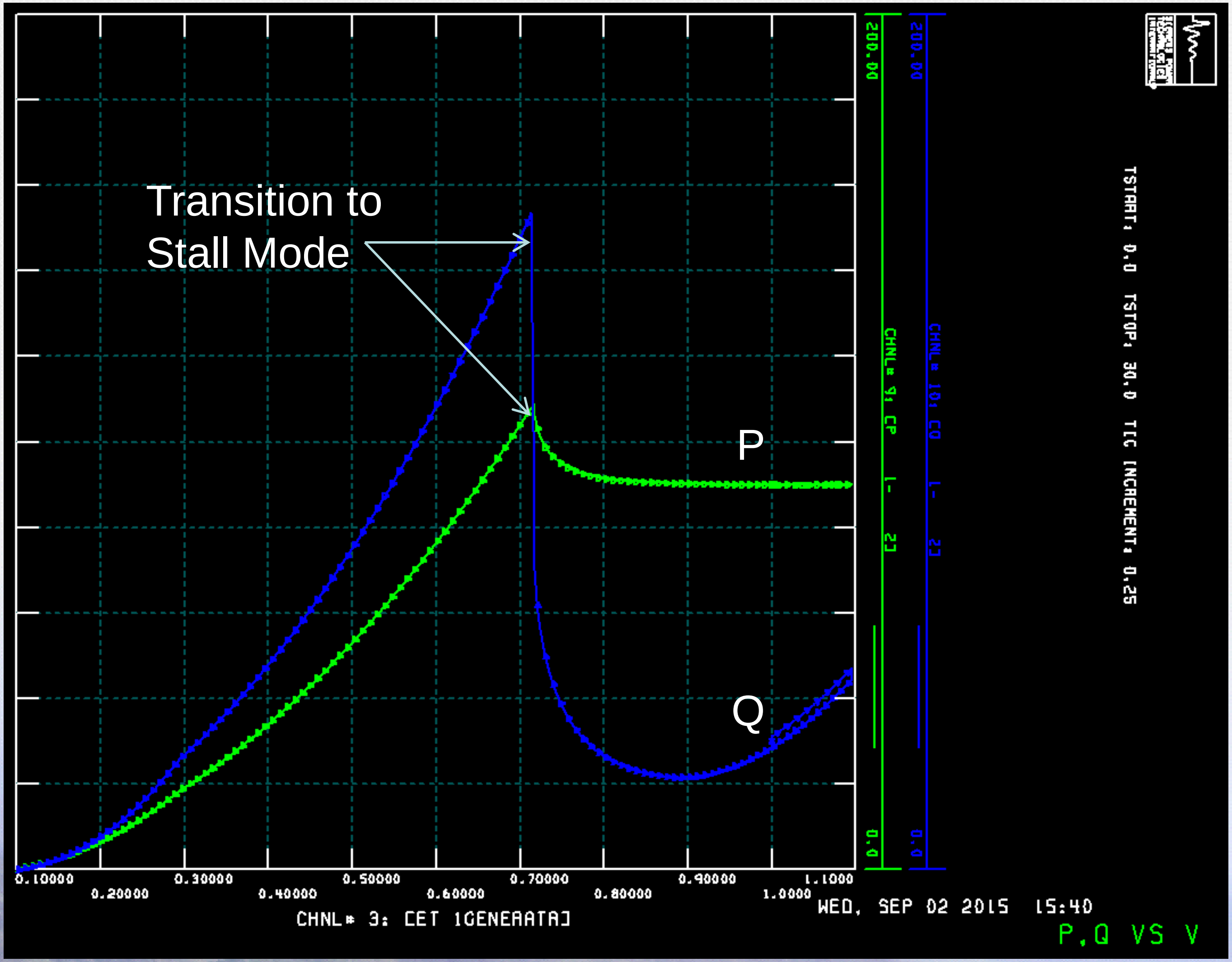
3. **Question on representation of D-component stalling and associated FIDVR effect**

**These issues encountered in attempt to calculate stability import limits for load area**

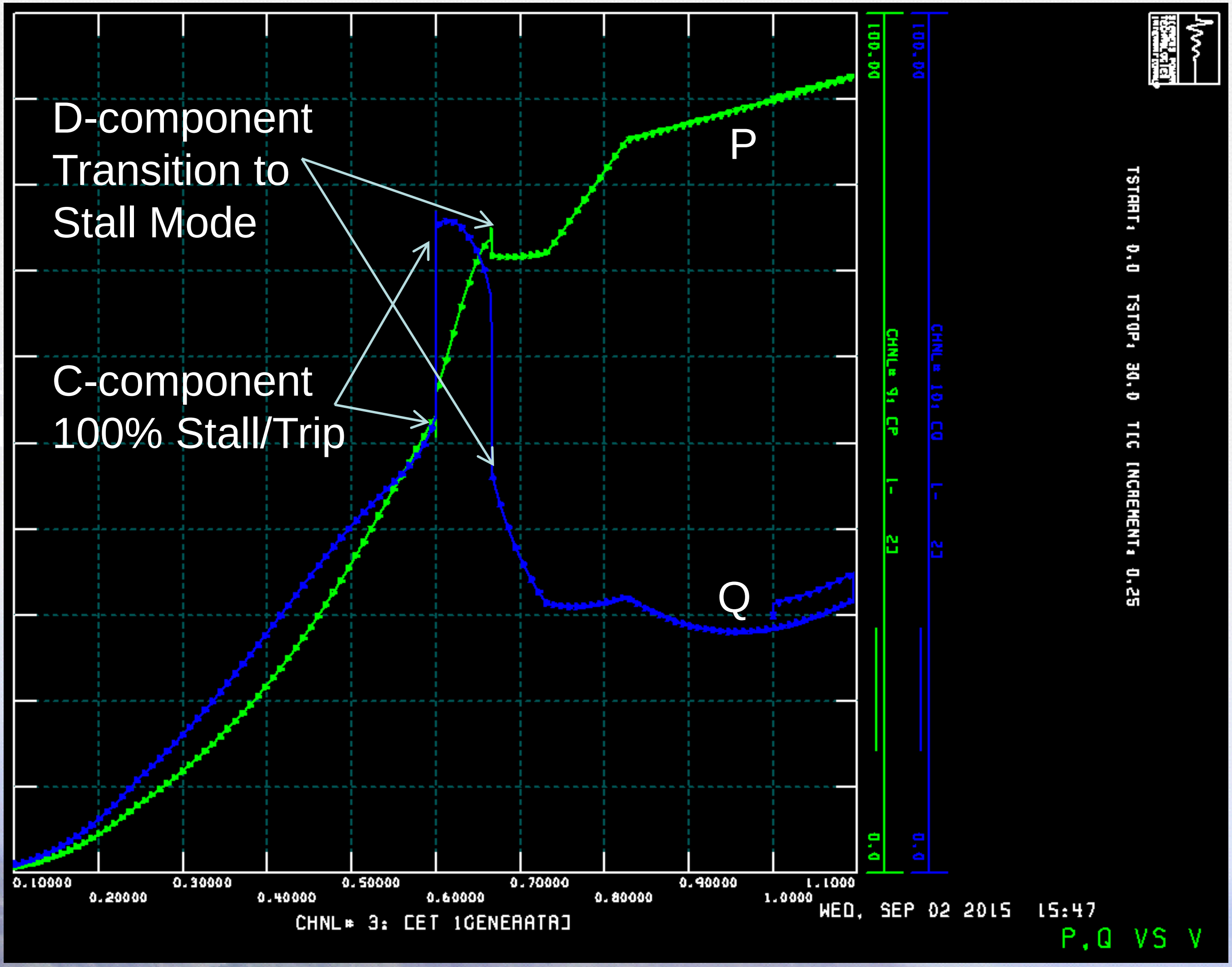
# 2-Bus Test Case

- **Set controllable voltage source on bus 1; CMLD on bus 2**
- **Ramp voltage source down / up or apply fault**
- **View CMLD P&Q vs V or T**

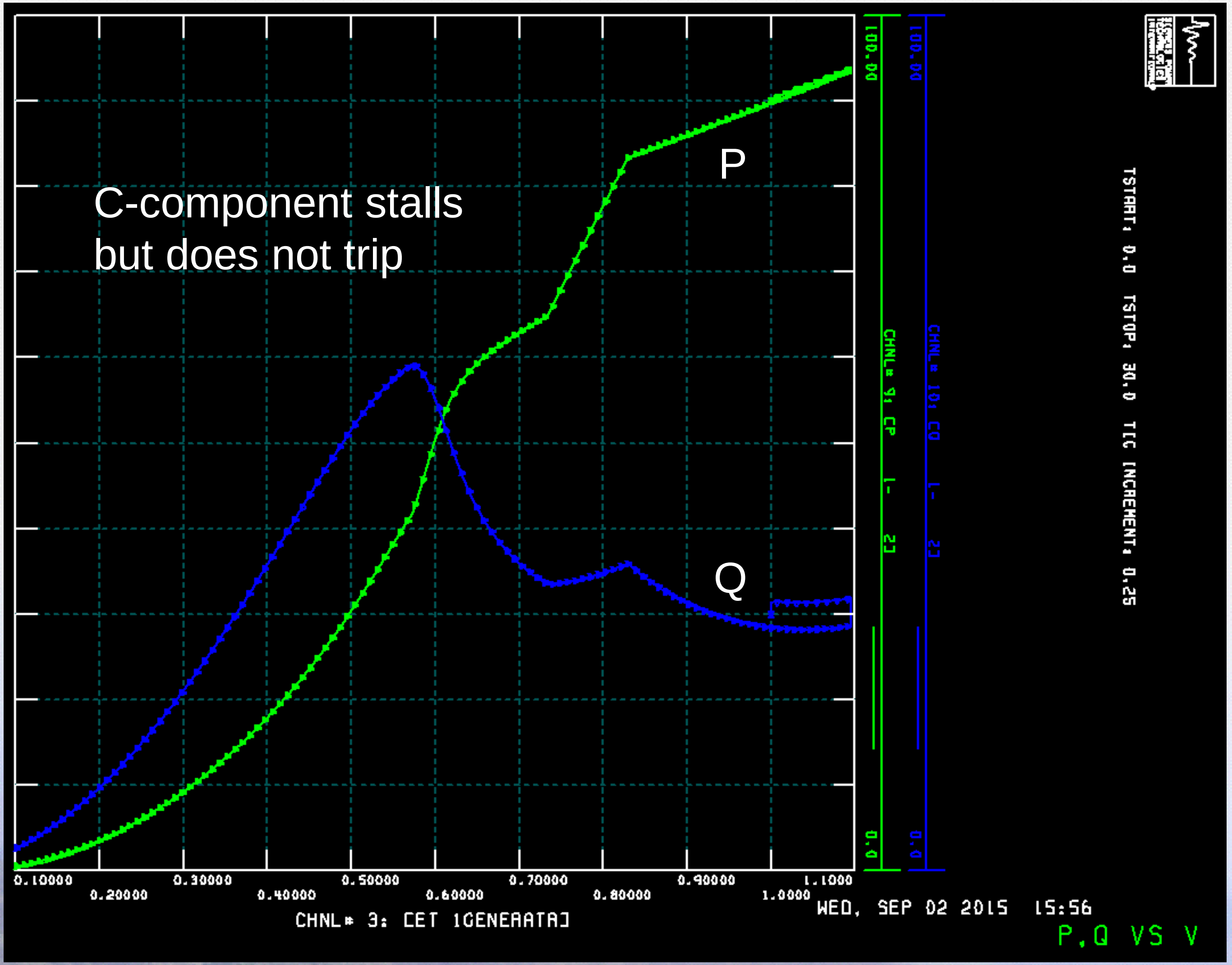
# EPRI CMLD Data, D-Component = 100%
# Steady-State P,Q vs V Characteristics



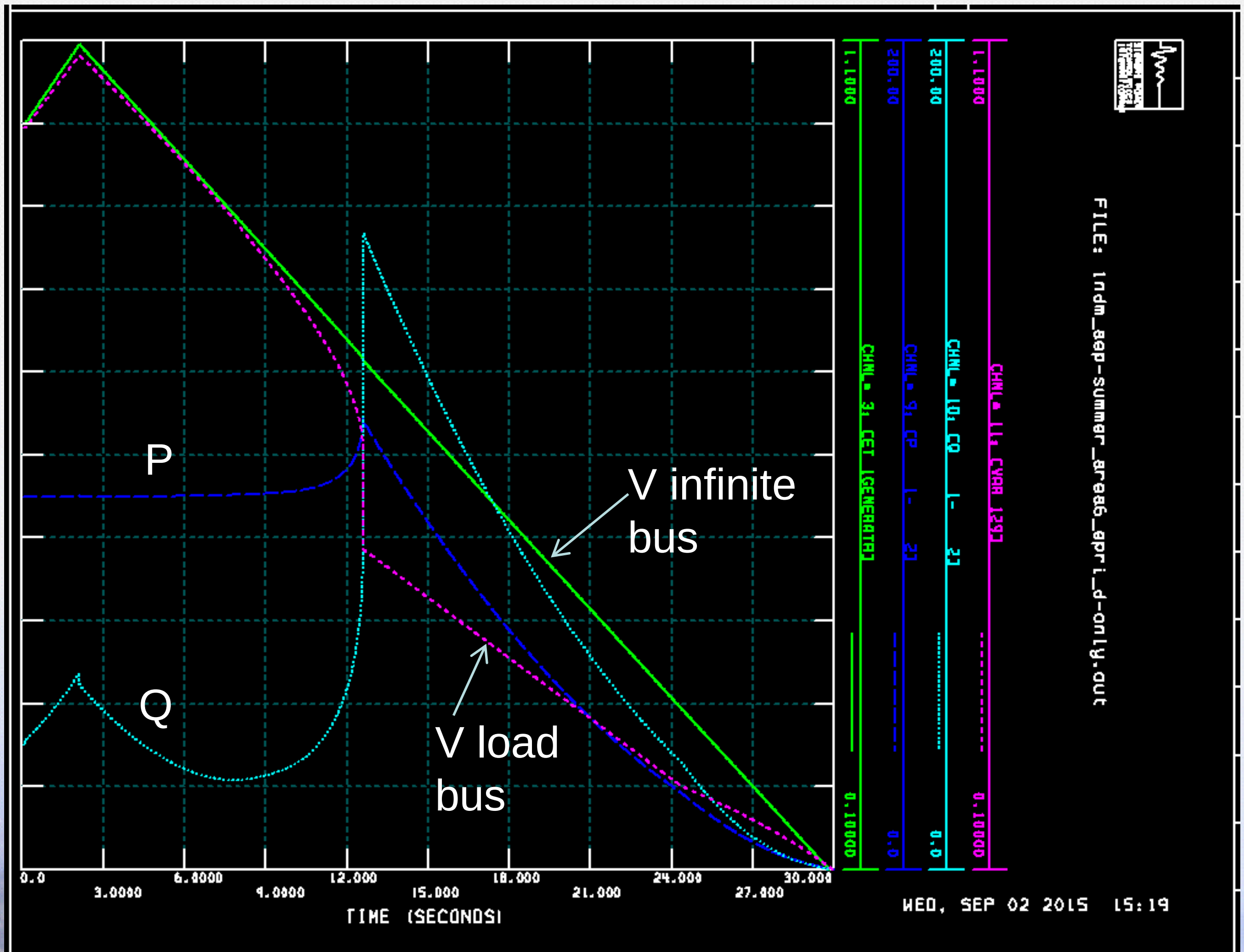
# EPRI CMLD Data
# Steady-State P,Q vs V Characteristics



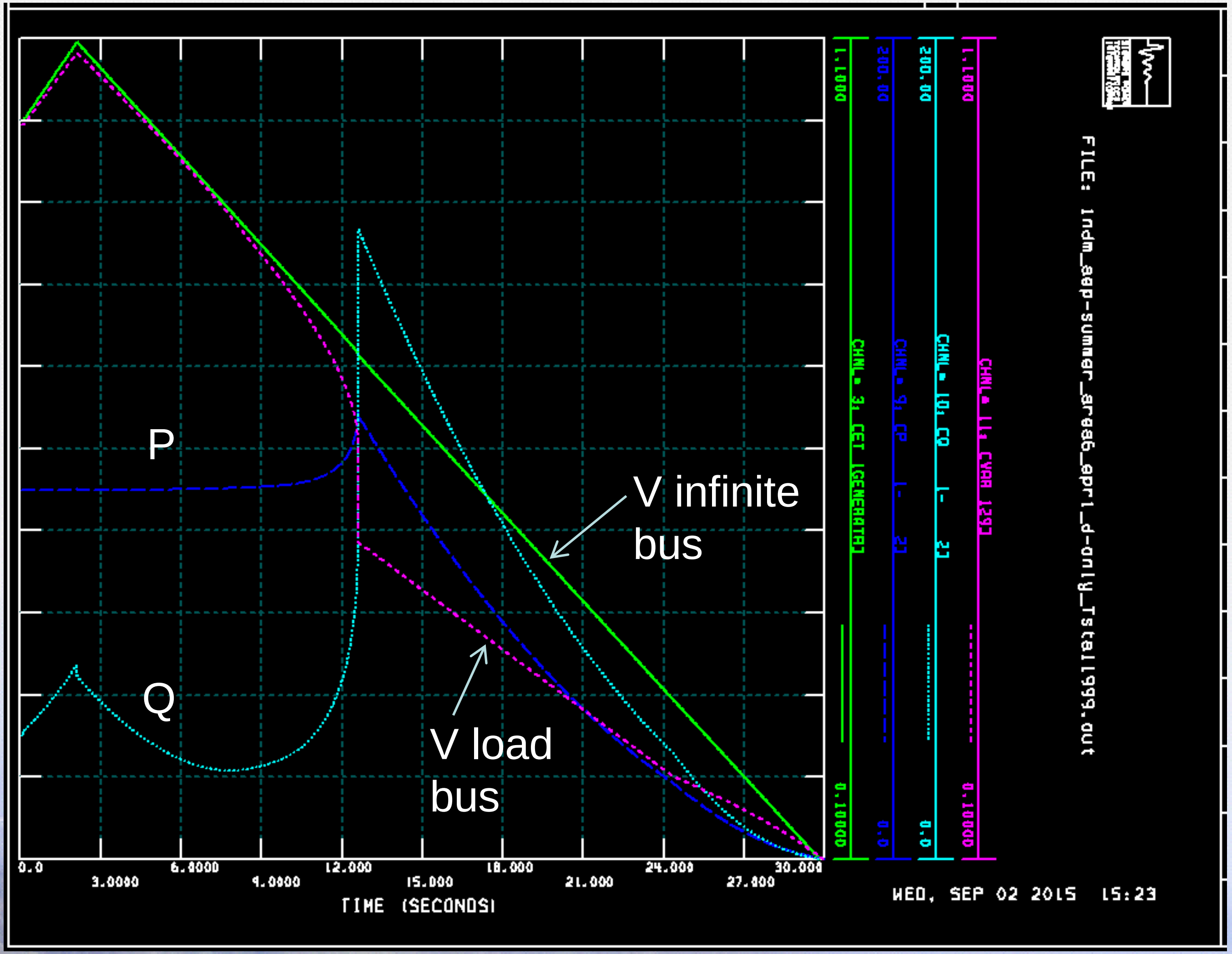
# EPRI CMLD Data, D-Component = 0%
# Steady-State P,Q vs V Characteristics



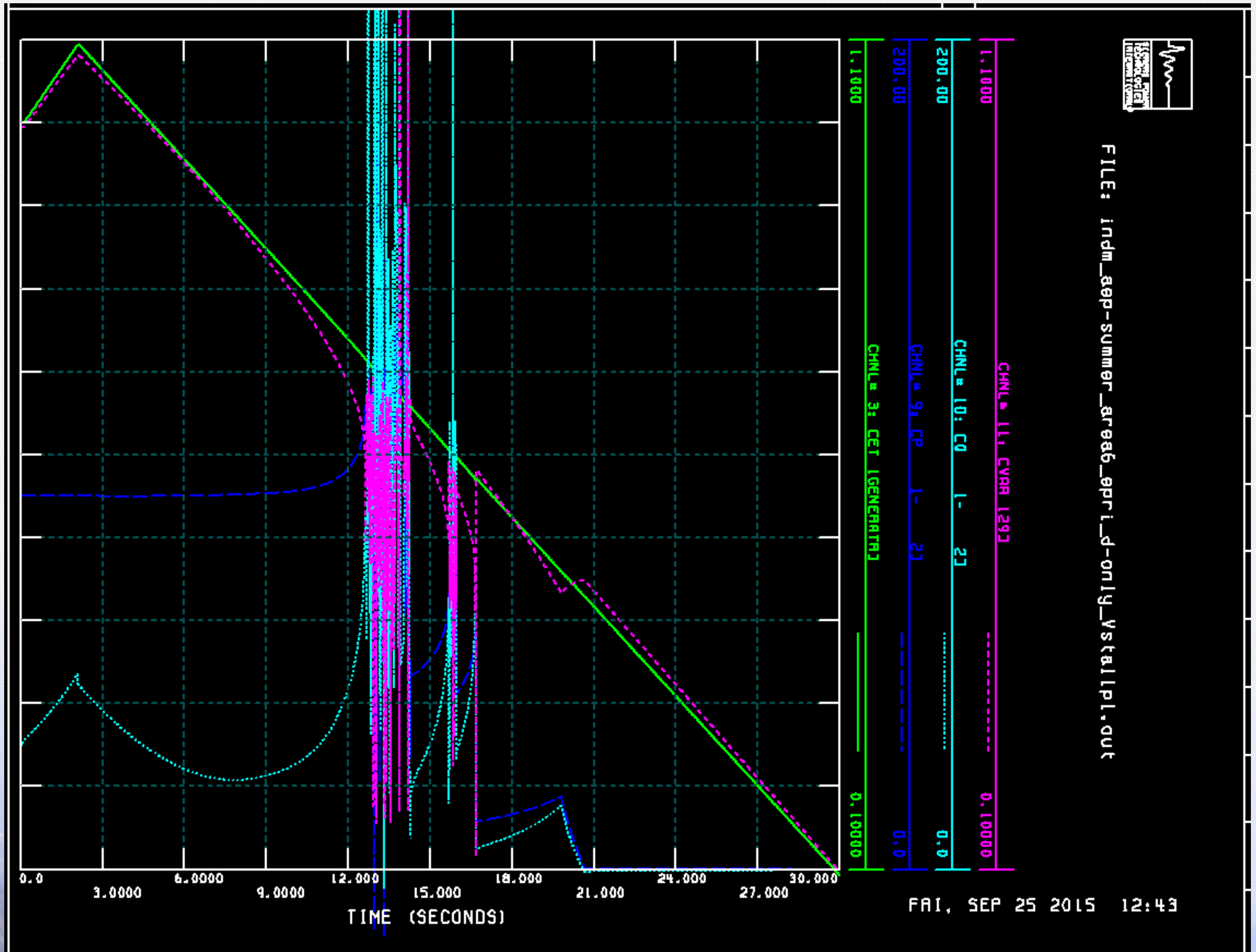
# EPRI CMLD Data, D-Component = 100%
# Tstall = .033



# EPRI CMLD Data, D-Component = 100%
# Tstall = 999



# EPRI CMLD Data, D-Component = 100%
# Vstall = 0.10



# PSS/E Implementation Questions

**What is supposed to be D-component state below Vstall and before Tstall timer times out?**

- **Is this an artificial question arising from the performance (static-empirical) model?**

**What is supposed to happen to A, B, and C components should their speed reach zero?**

- **Trip or stay energized?**

# Single-Phase A/C Stalling
# Non-Modeled Factors

- **Point-on-wave variability considering three 120-degree displaced phases**
- **Distance from fault / dependency on rate of voltage drop**

**Does it make sense to attenuate**

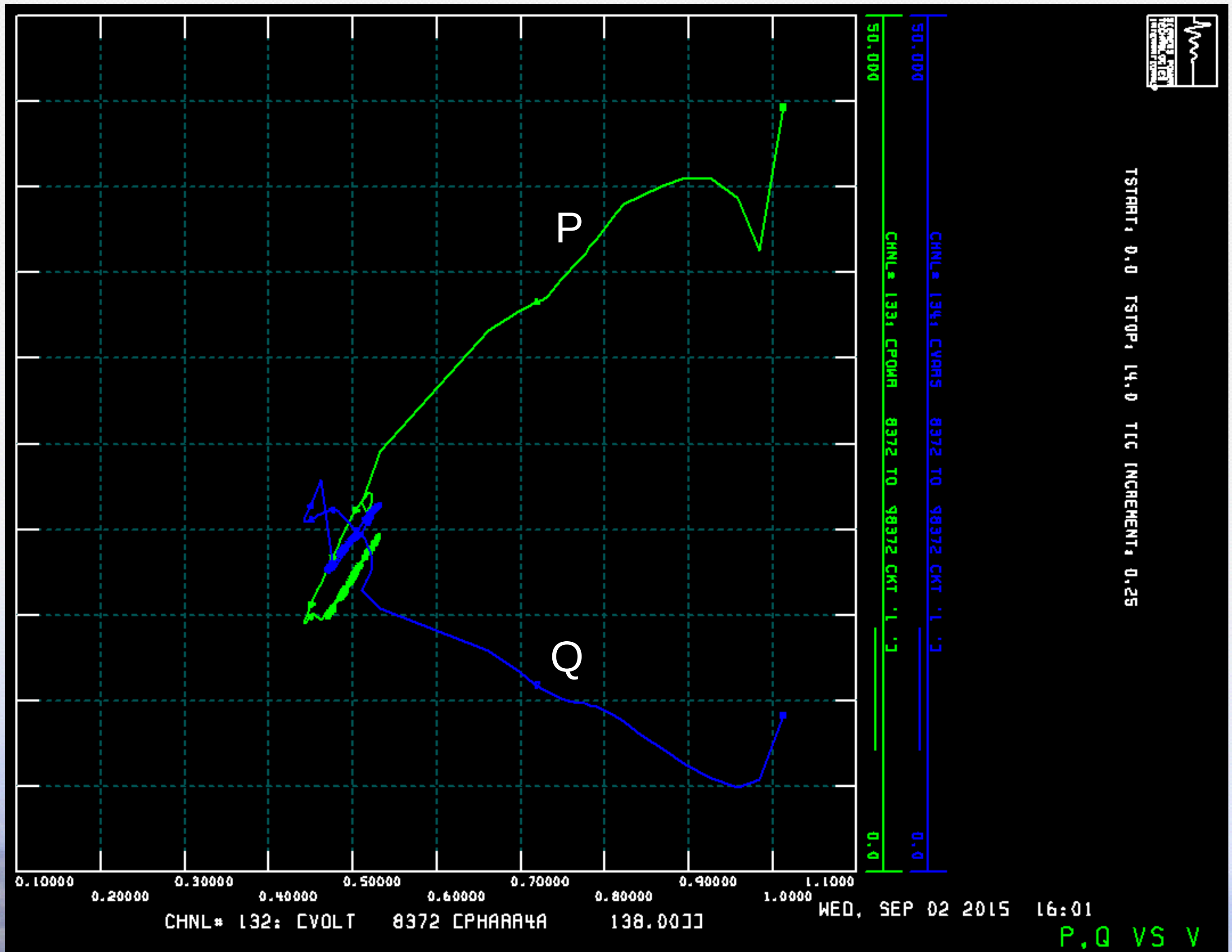
**D-component stall effect somehow?**

**Interim Remedies Rejected:**

-**Disable stall mode by increasing Tstall or decreasing Vstall**

-**Increase Rstall and Xstall, and perhaps Vstall**

# EPRI CMLD Data
# P,Q vs V Trajectories of a Load Bus from Simulation of Generator trip & Sudden Voltage Collapse



# Other CMLD Advice

**Network non-convergence associated with CMLD model may cause simulations to drift**

**Have found it necessary to decrease the acceleration factors to 0.25 or less to avoid non-convergence in most cases**

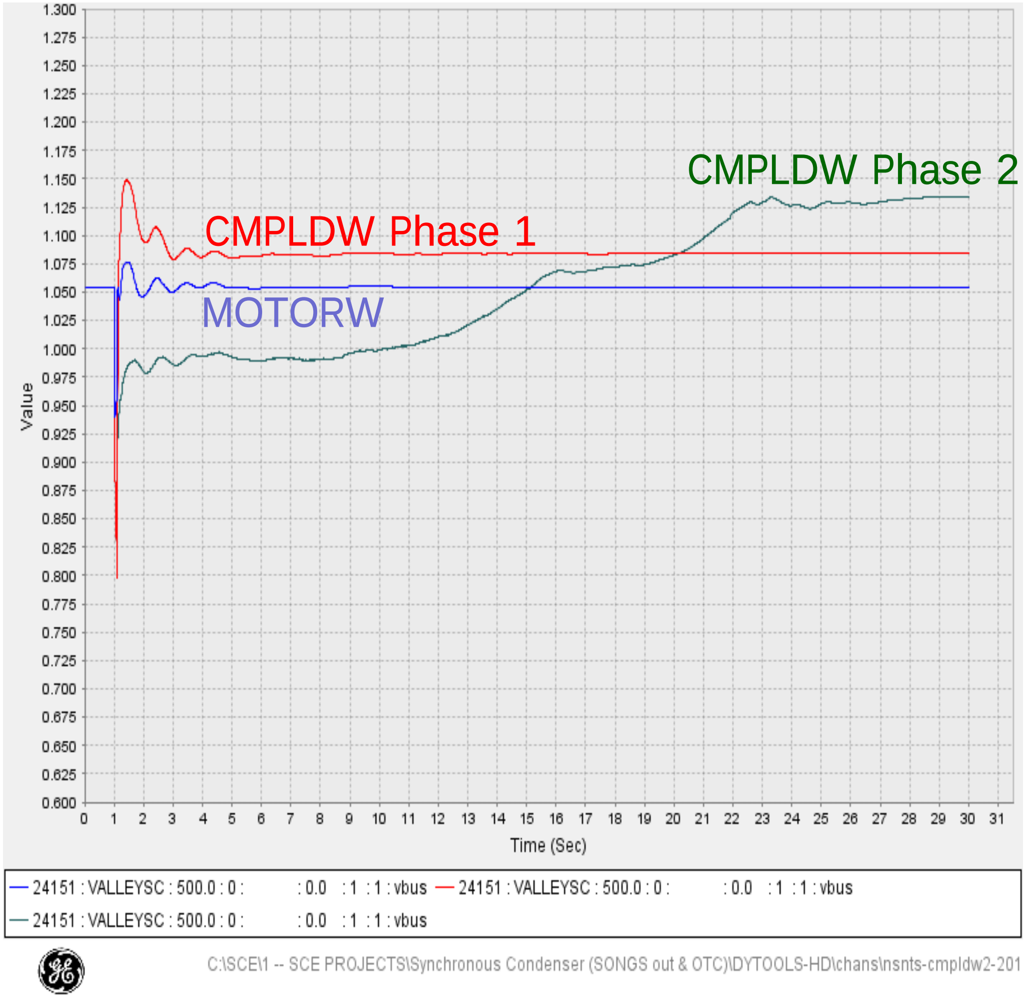
# NERC-DOE FIDVR Workshop
# SCE FIDVR Study Experience

**Oct 1, 2015**

Jun Wen
Southern California Edison
jun.wen@sce.com

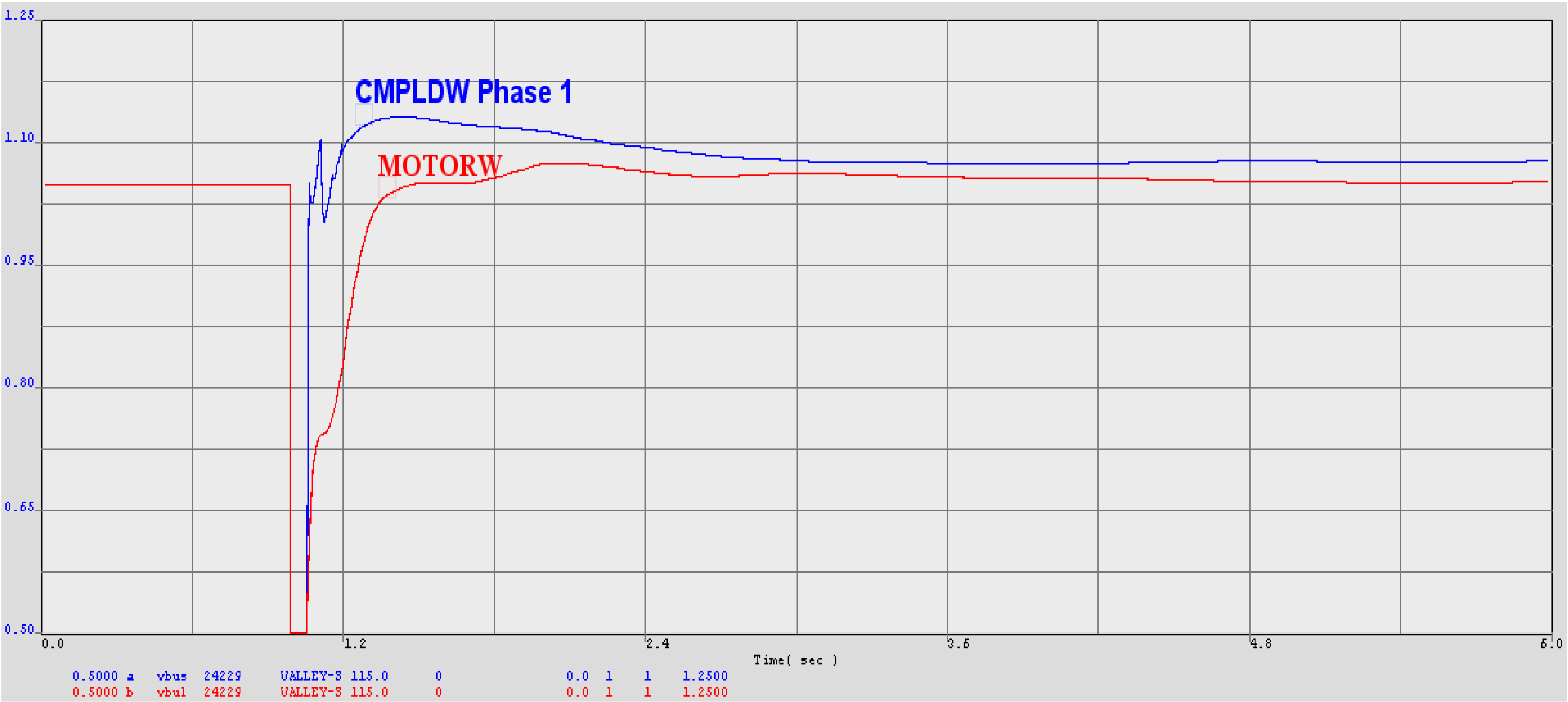
# WECC Load Model Implementation

- MOTORW + ZIP (past)
- CMPLDW Phase 1 (now)
  - Tstall = 9999
  - Approved for implementation starting with 2014 WECC study program base cases.
- CMPLDW Phase 2 (future)
  - Tstall = 0.03
  - Improvements in progress



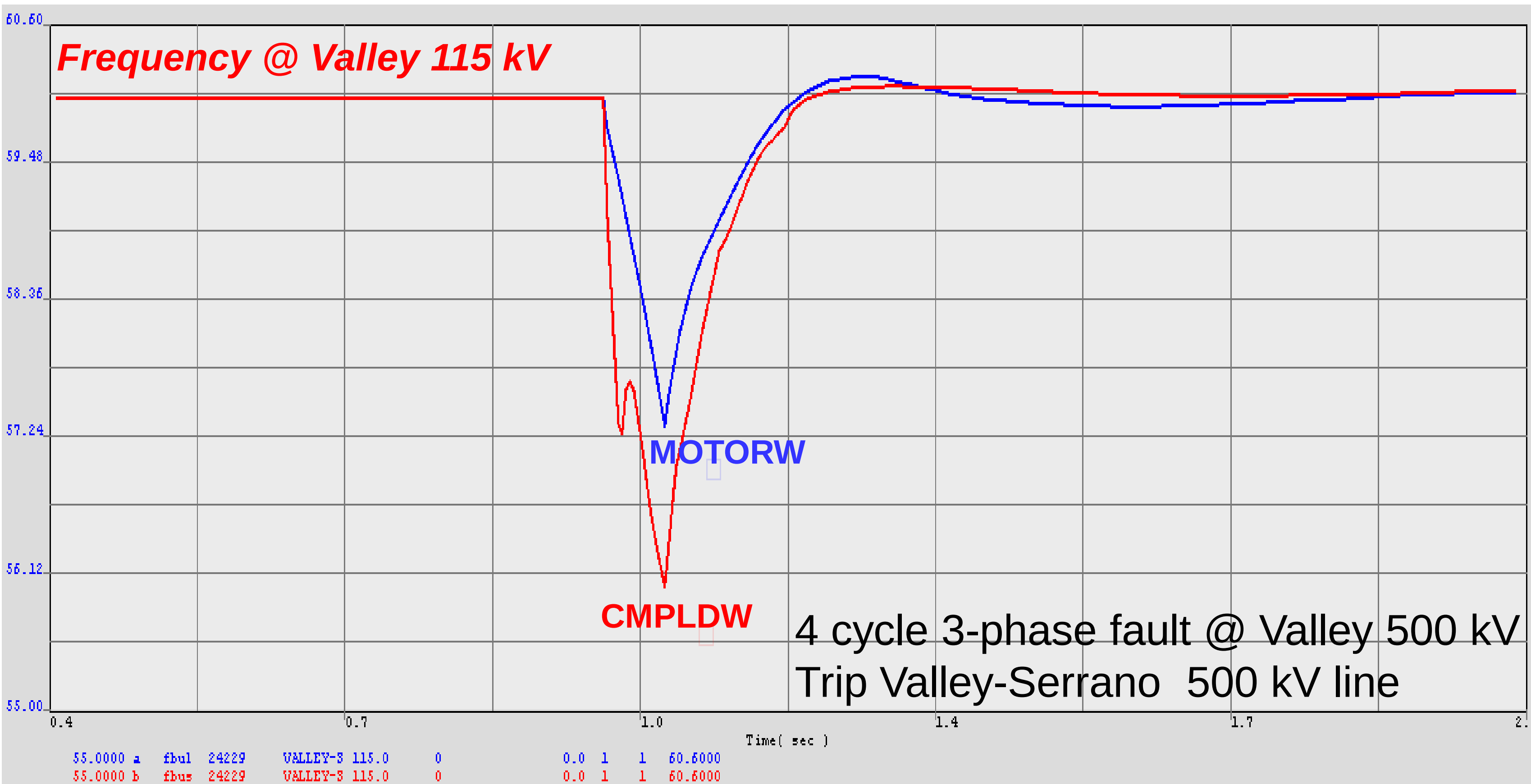
# Phase 1 System Impact Study

- Higher voltage overshoot is generally seen after fault clearing with CMPLDW P1 due to motor tripping
- Higher post-transient voltage is generally seen using CMPLDW P1 due to motor tripping



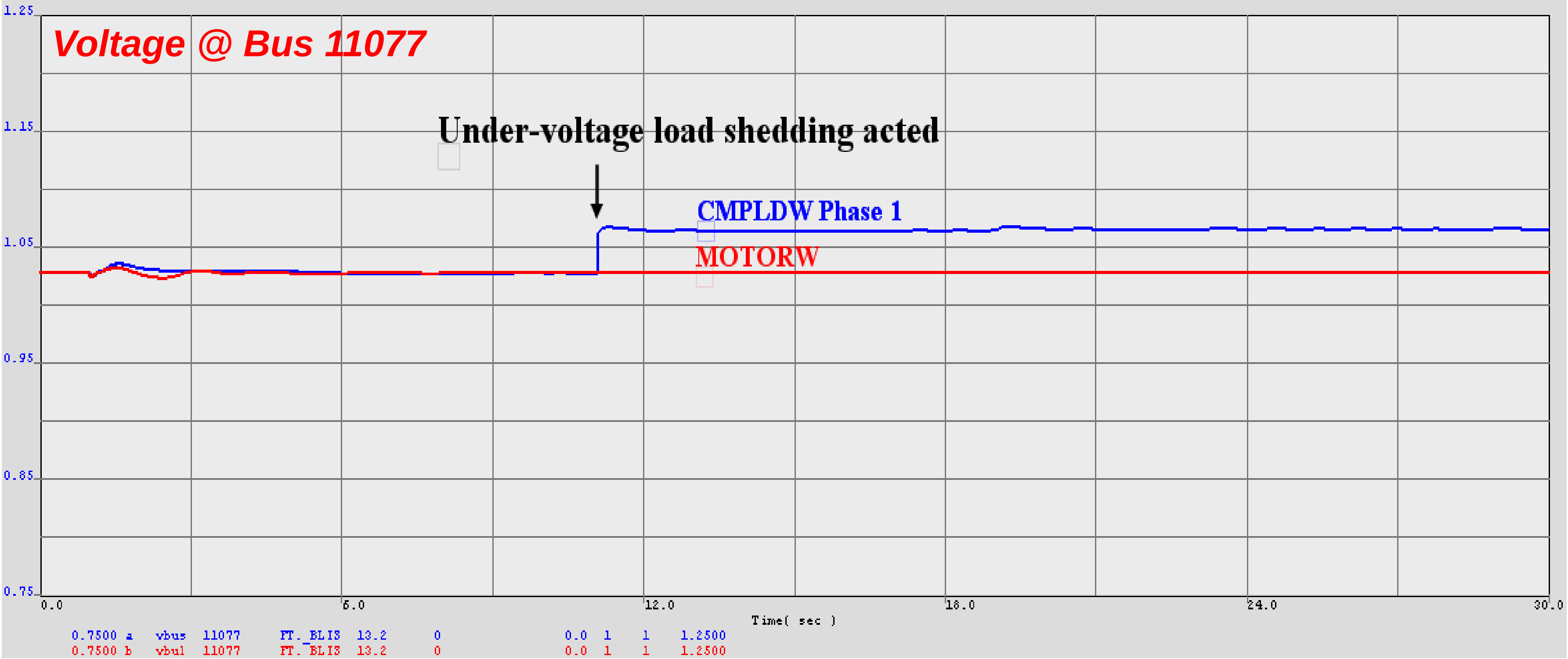
# Phase 1 System Impact Study

- Additional under-frequency load tripping is seen using CMPLDW P1 under some contingencies



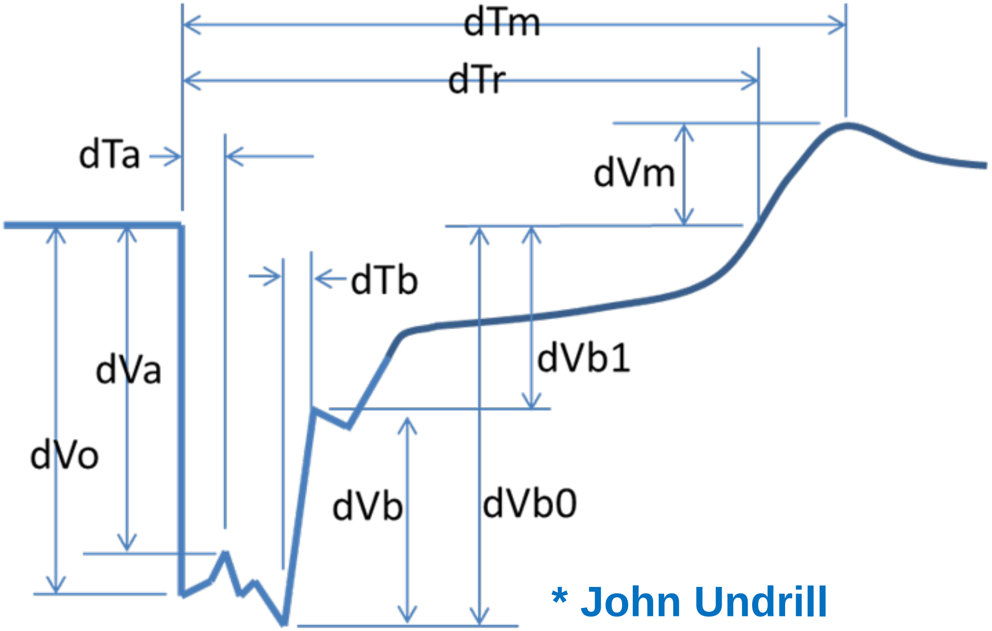
# Phase 1 System Impact Study

- Additional under-voltage load tripping is seen using CMPLDW P1
  - 4 cycle 3-phase fault @ Valley 500 kV and trip Valley-Serrano 500 kV line, additional under-voltage load tripping is seen in Area 11
  - This is due to load shedding relay monitoring the lower voltage bus (911077), already fixed in later revision.



# Phase 2 System Impact Study

Heavy summer case, selected N-1 contingencies with normal fault clearing at key 500 kV buses were studied.

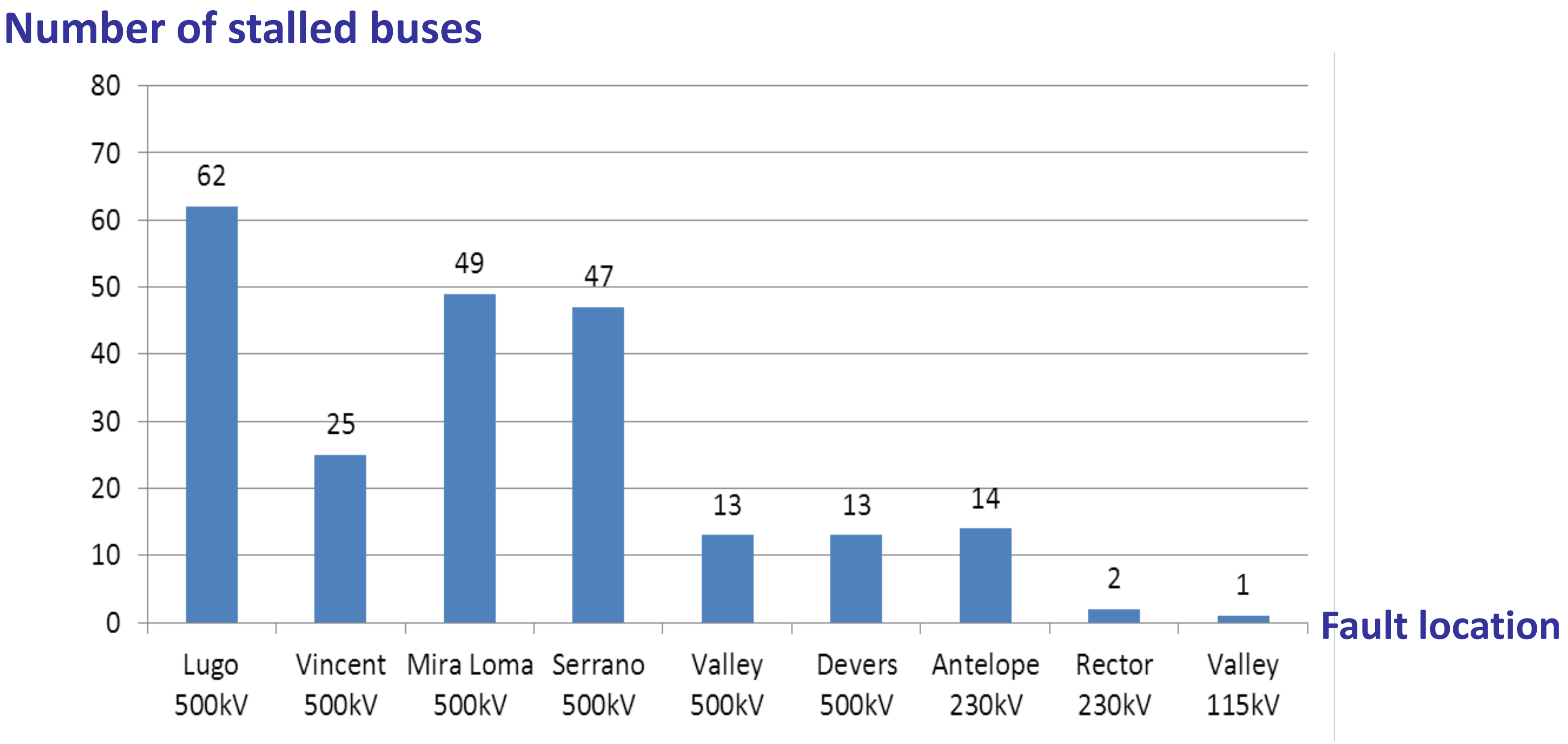



* John Undrill

| Variable | Variable description |
|---|---|
| dVo ( % ) | First sample voltage dip |
| dVa ( % ) | Persistence voltage dip |
| dTa (cycl) | Persistence time |
| dVb0 ( % ) | Lowest value of dVb in % |
| dVb1 ( % ) | Highest value of dVb in % |
| dVb (kV) | dVb in KV |
| dTb (cycl) | Time from lowest to highest value of dVb |
| dVm ( % ) | Peak voltage overshooting |
| dTr (sec) | Time to reach initial volt level |
| dTm (sec) | Time to reach maximum voltage |

- dVo: average 28.8%, 30% and more is seen in sub-transmission
- dVm: average 14%, maximum 21.7%
- dTr: average 21 second, maximum 25 sec

# Phase 2 System Impact Study




**Note: Total 80 load buses in SCE's service territory are modeled with composite load models**

# Phase 2 Sensitivity Study

- Sensitivity study on the 3 phase commercial motor protection settings has been performed.

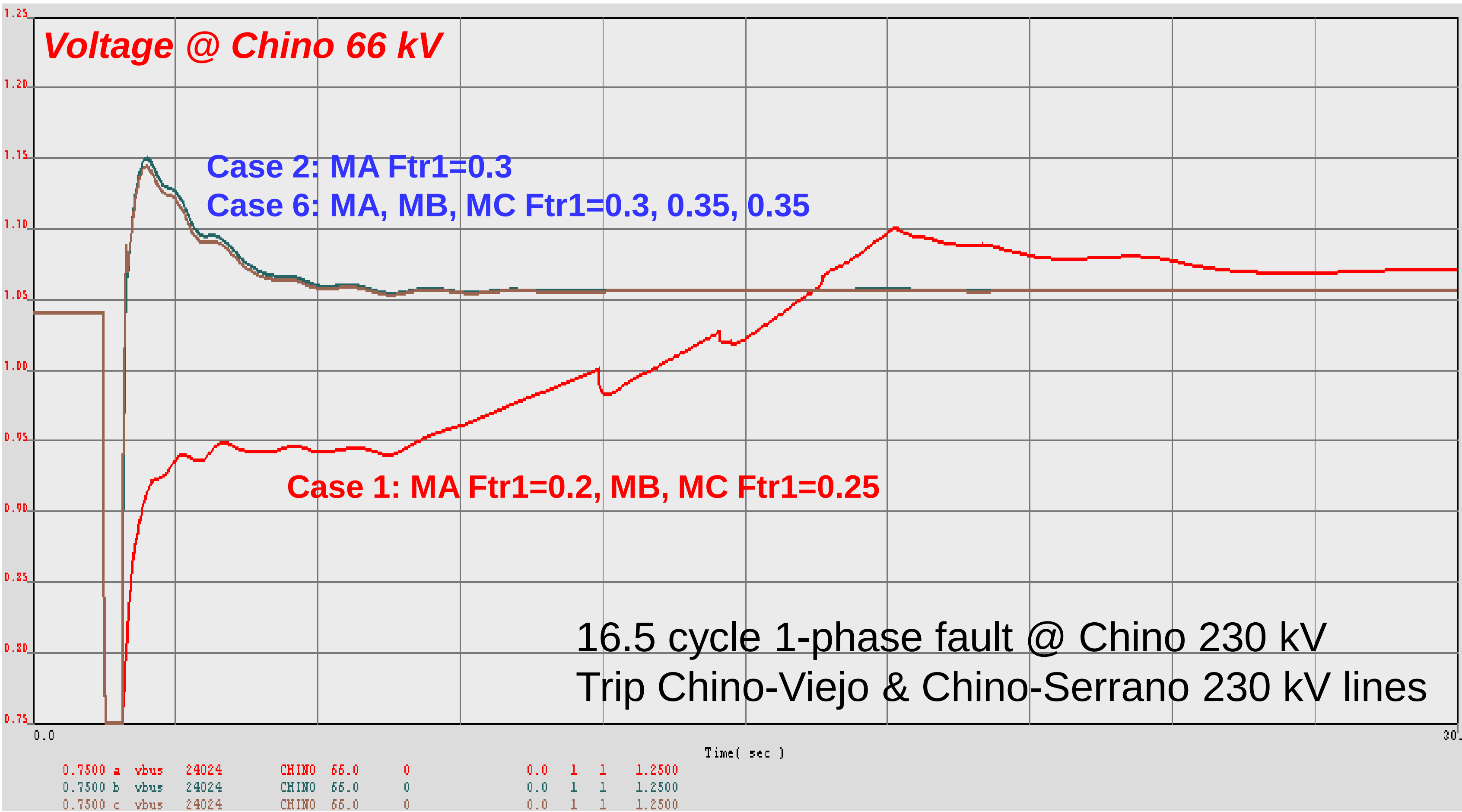
- Studied contingencies include: selected N-1 and N-2 with normal and delayed fault clearing at selected 500 kV, 230 kV, 115 kV buses

| | Vtr1 | | Ttr1 | | Ftr1 | | Vrc1 | Trc1 | | Vtr2 | | Ttr2 | | Ftr2 | | Vrc2 | Trc2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MA | 0.6 | 0.7 | 0.02 | 0.033 | 0.2 | 0.3 | 1 | 9999 | 9999 | 0.5 | 0.5 | 0.02 | 0.033 | 0.6 | 0.7 | 0.65 | 0.1 | 0.2 |
| MB | 0.6 | 0.7 | 0.02 | 0.033 | 0.25 | 0.35 | 0.9 | 0.05 | 9999 | 0.5 | 0.6 | 0.02 | 0.033 | 0.5 | 0.6 | 0.85 | 0.05 | 0.2 |
| MC | 0.6 | 0.7 | 0.02 | 0.033 | 0.25 | 0.35 | 0.9 | 0.05 | 9999 | 0.5 | 0.6 | 0.02 | 0.033 | 0.5 | 0.6 | 0.85 | 0.05 | 0.2 |

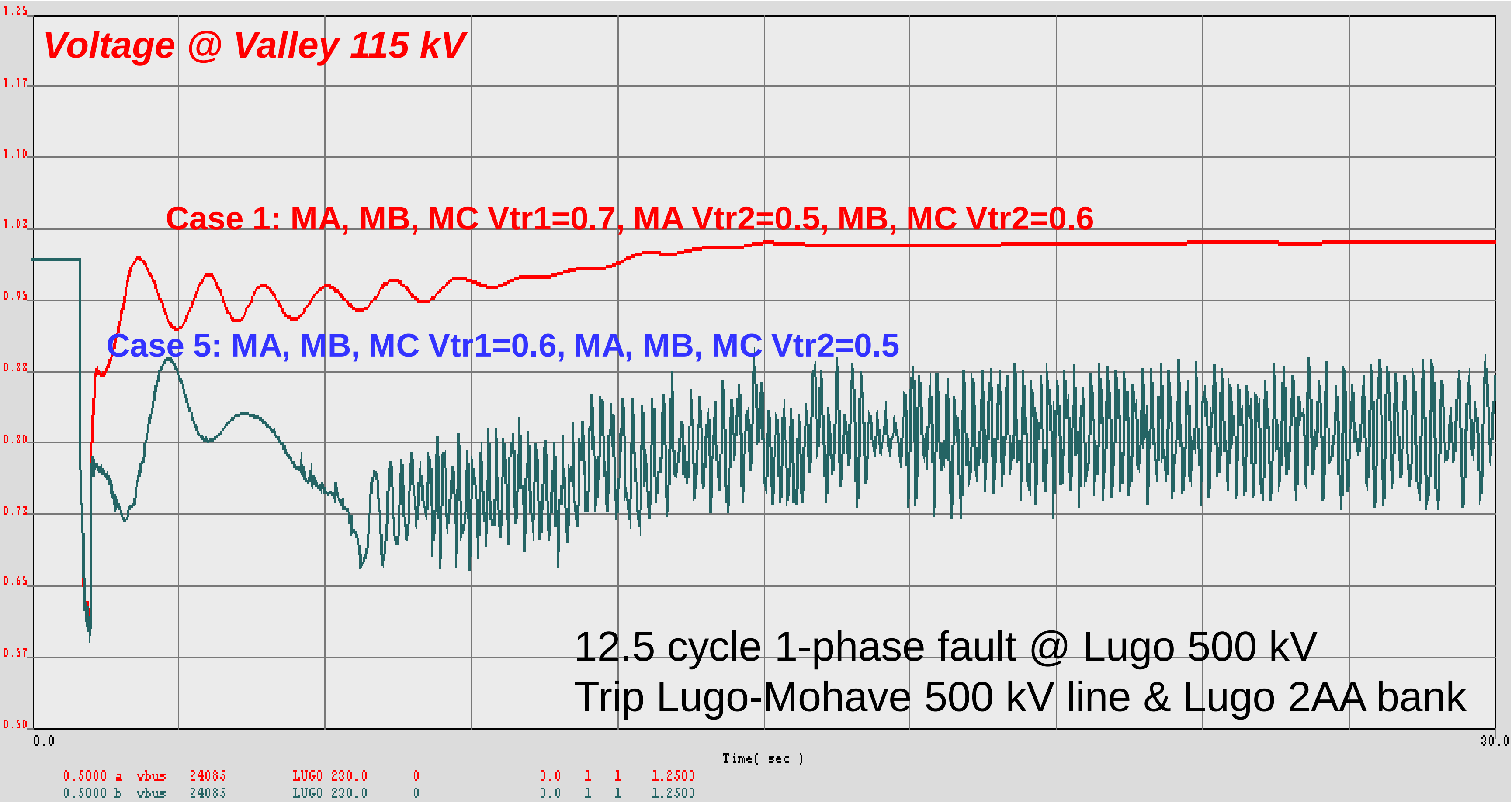
* Note: black – default, red - sensitivity

- Overall, little difference was observed.

# Phase 2 Sensitivity Study
## - Fraction of motor tripping (Ftr1)



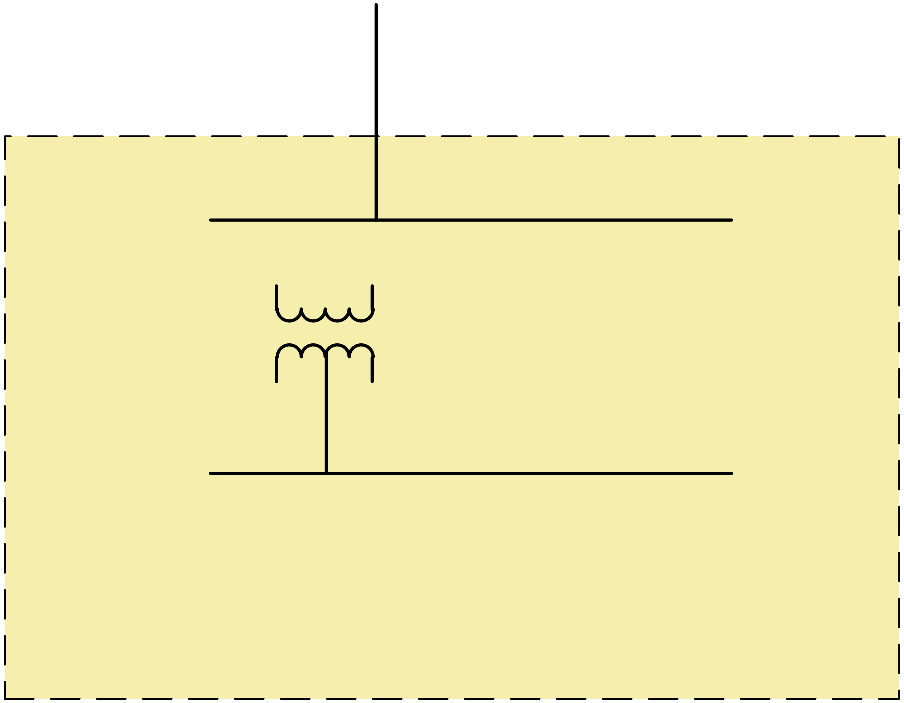
# Phase 2 Sensitivity Study
## - Voltage trip level (Vtr1, Vtr2)



# Model Validation Study

## July 24 2004 FIDVR Event

5:02 PM July 24, 2004, 115 kV bus connection equipment at Valley Substation failed resulting in a phase to ground fault. The fault cleared in four cycles isolating the number three 500/115 kV transformer bank.



# Valley 115 Composite Load Model

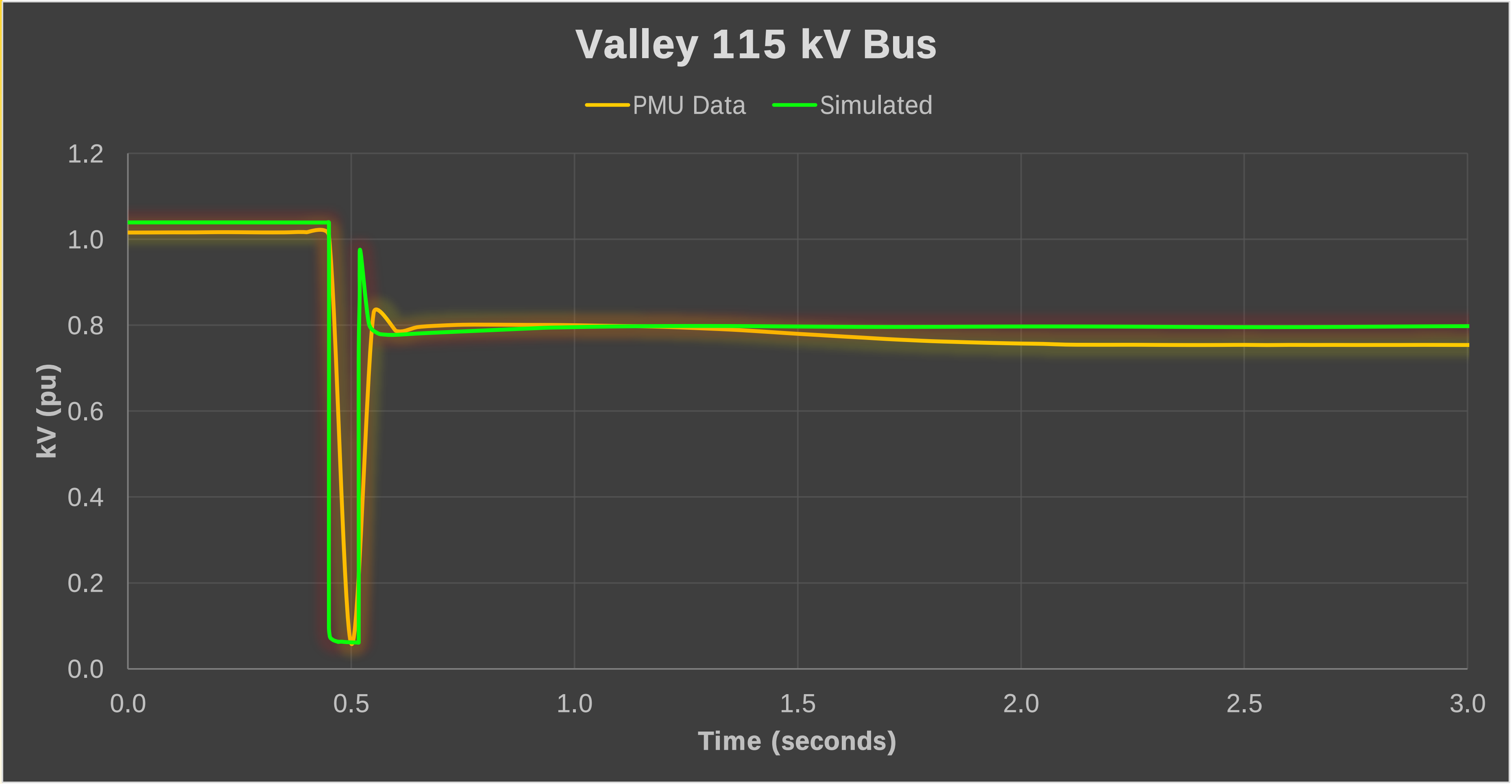
Default data set from LCM tool was used, no data tuning.

| LONG ID | Condition | Hour (PST) |
|---|---|---|
| SCI_RES | 1 = Normal Summer | 17:00 |

Fma = 0.0822, Fmb = 0.1548, Fmc = 0.0311, Fmd = 0.3909
Fel = 0.1109, Fzip = 0.2301

cmpldw 24160 "VALLEYSC " 115.00 "1 " : #9 mva=-1.2000 "bss" 0.0000 "rfdr" 0.0400 "xfdr" 0.0400 "fb" 0.75000
"xxf" 0.0800 "tfixhs" 1.0000 "tfixls" 1.0000 "ltc" 0.0000 "tmin" 0.9000 "tmax" 1.1000 "step" 0.006250 "vmin" 1.0000
"vmax" 1.0200 "tdel“ 30.0000 "ttap" 5.0000 "rcmp" 0.0000 "xcmp" 0.0000 "fma" 0.0822 "fmb" 0.1548 "fmc" 0.0311 "fmd" 0.3909
"fel" 0.1109 "pfel" 1.0000 "vd1" 0.7000 "vd2" 0.5000 "frcel" 0.8000 "pfs" -0.997762 "p1e" 2.0000 "p1c" 0.554056 "p2e" 1.0000
"p2c" 0.445944 "pfrq" 0.0000 "q1e" 2.0000 "q1c" -0.500000 "q2e" 1.0000 "q2c" 1.500000 "qfrq" -1.0000 "mtypa" 3.0
"mtypb" 3.0 "mtypc" 3.0 "mtypd" 1.0 "lfma" 0.7500 "Rs" 0.0400 "Ls" 1.8000 "Lp" 0.1200 "Lpp" 0.1040 "Tpo" 0.0950
"Tppo" 0.0021 "H" 0.1000 "etrq" 0.0000 "vtr1" 0.7000 "ttr1" 0.0200 "ftr1" 0.2000 "vrc1" 1.0000 "trc1" 99999.0000 "vtr2" 0.5000
"ttr2" 0.0200 "ftr2" 0.7000 "vrc2" 0.7000 "trc2“ 0.1000 "LFmb" 0.7500 "Rs" 0.0300 "Ls" 1.8000 "Lp" 0.1900 "Lpp" 0.1400
"Tpo" 0.2000 "Tppo" 0.0026 "H" 0.5000 "etrq" 2.0000
"vtr1" 0.6000 "ttr1" 0.0200 "ftr1" 0.2000 "vrc1" 0.7500 "trc1" 0.0500 "vtr2" 0.5000 "ttr2" 0.0200 "ftr2" 0.3000 "vrc2" 0.6500
"trc2" 0.0500 "LFmc" 0.7500 "Rs" 0.0300 "Ls" 1.8000 "Lp" 0.1900 "Lpp" 0.1400 "Tpo" 0.2000 "Tppo" 0.0026 "H" 0.1000
"etrq" 2.0000 "vtr1" 0.6500 "ttr1" 0.0200 "ftr1" 0.2000 "vrc1" 1.0000 "trc1" 9999.0000 "vtr2" 0.5000 "ttr2" 0.0200 "ftr2" 0.3000
"vrc2" 0.6500 "trc2" 0.1000 "LFmd" 1.0000 "CompPF" 0.9800 "Vstall" 0.5600 "Rstall" 0.1000 "Xstall" 0.1000 "Tstall" 0.0300
"Frst" 0.2000 "Vrst" 0.9500 "Trst" 0.3000 "fuvr" 0.1000 "vtr1" 0.6000 "ttr1" 0.0200 "vtr2" 1.0000 "ttr2" 9999.0000 "Vc1off" 0.5000
"Vc2off" 0.4000 "Vc1on" 0.6000 "Vc2on" 0.5000 "Tth" 15.0000 "Th1t" 0.7000 "Th2t" 1.9000 "Tv" 0.0250

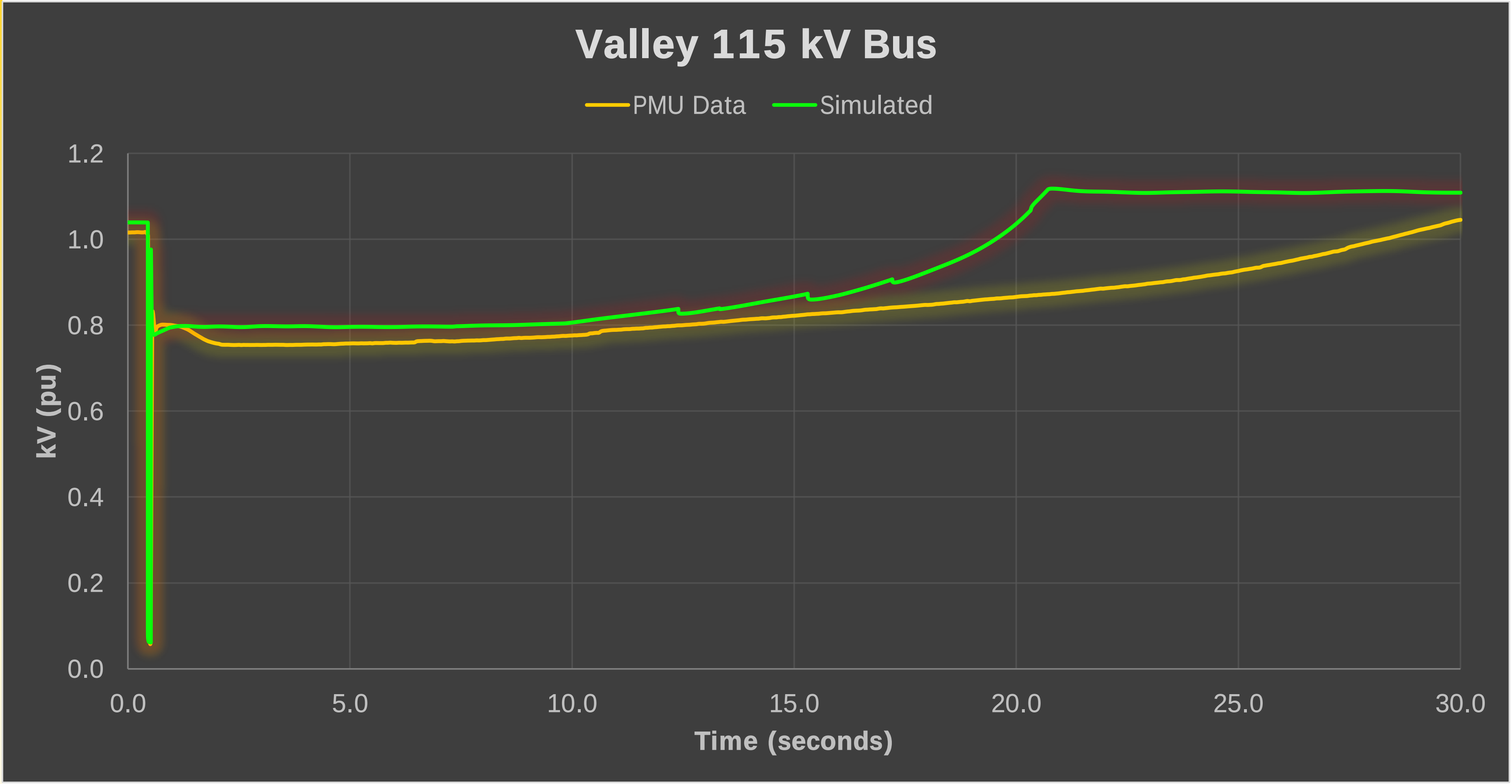
# Measured versus simulated (3 seconds)




Total MW of Valley 115 kV load shed experienced : 400 MW

Total MW of Valley 115 kV load shed by cmpldw model: 386 MW

# Measured versus simulated (30 seconds)



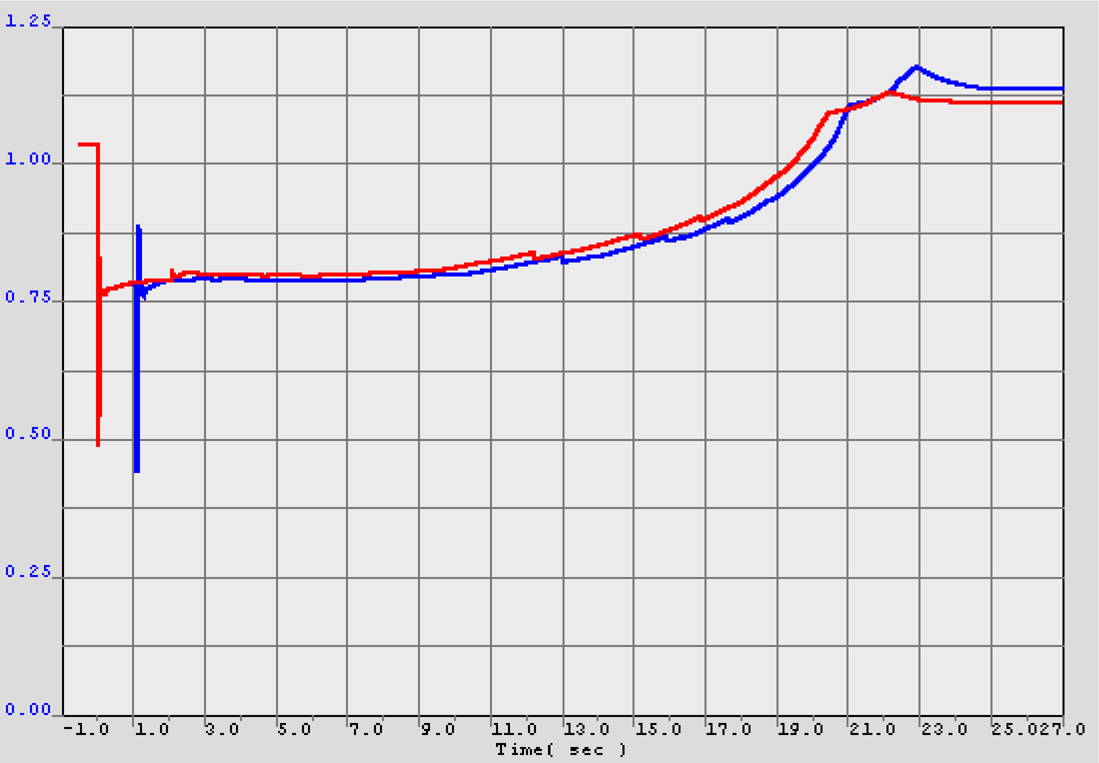

With default data set, the simulation showed a close match to PMU measurement (initial voltage recovery, post voltage recovery, and load loss). The simulation shows faster recovery than measurement (Tth can be modified to fit the curve).

# Simulated Load Loss at Valley Substation

| --P-- | Type | -MdName- | --BUS-- | --NAME-- | --KV-- | -SPREAD-- |
|---|---|---|---|---|---|---|
| 24160 | fuva | cmpldw | 24160 | VALLEYSC | 115 | 0.9 |
| 24160 | fuvb | cmpldw | 24160 | VALLEYSC | 115 | 0.5 |
| 24160 | fuvc | cmpldw | 24160 | VALLEYSC | 115 | 0.5 |
| 24160 | fuvd | cmpldw | 24160 | VALLEYSC | 115 | 0.1 |
| 24160 | fthA | cmpldw | 24160 | VALLEYSC | 115 | 1 |
| 24160 | fthB | cmpldw | 24160 | VALLEYSC | 115 | 0.926 |

# High Speed Reclosing Study

*TPL-001-4 Requirement R4.3.1.1*: "Successful high speed (less than one second) reclosing and unsuccessful high speed reclosing into a Fault where high speed reclosing is utilized."




Single-phase to ground fault at time 0;

Red – successful reclosing at time 2 second

Blue – unsuccessful reclosing at time 1 second

# THANK YOU

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# Load Modeling & FIDVR

FIDVR & Dynamic Load Modeling Workshop
September 30 – October 1, 2015

Robert W. Cummings
NERC Director of Reliability Initiatives and System Analysis

RELIABILITY | ACCOUNTABILITY

# Introduction

- **End-Use Load is Evolving –** Electronically coupled loads, distributed generation, etc.
- **Continually Changing –** End-use load continually changes
  - Day, time, season, geography, weather, economics, etc.
- **Difficult to Model –** Even with load composition known, difficult to relate to load model parameters – *Rules of Association*
- **Minimal Data –** Distribution data hard to collect; often minimal collaboration between transmission and distribution entities
- **Best Practices –** Sharing best practices and experiences is critical
- **Benchmarking –** Historical events can be benchmarked against today's models
- **Prediction –** Does not make them useful for predicting future events

# What's in Your House?

- Inverters are everywhere
- Variable frequency motor drives
- CFL & LED lighting
- Plug-in electric vehicles
- Motors

# Distributed Generation

- Solar energy penetration is growing rapidly; likely to continue into future
  - Declining cost of materials
  - More economical

- May not be "BES", but this has an impact on reliability and performance
- This is likely not in your planning model; it needs to be!
- ***Collaboration key to develop best practices***

# Battery Storage

- Battery storage systems are also increasingly becoming popular
  - Declining cost of materials
  - More economical
- "If I can cheaply put rooftop panels on my house, store my energy, and use it through the night, why wouldn't I?"
- Grid will likely still play a critical role
- What are its electrical characteristics?
- How is this being modeled?
- ***Collaboration key to develop best practices***

# Nature of the Issue

- End-use load (response) changing rapidly – need collaboration between utility industry, manufacturing community, and end-use standards; ensure devices are grid friendly
  - Energy Efficient Loads are often not “Grid Friendly”
- Voltage sensitive loads often trip
  - Normally cleared faults – 1-ϕ motor stalling can occur for normally cleared 3-phase faults, Sensitivity to point on wave voltages, voltage rate of change, voltage magnitude and duration, etc.
  - Slowly-cleared faults – power quality requirements
- Behind the meter generation (distributed resources) becoming increasing popular – solar, micro-turbines, etc.
  - Some of those resources have voltage and frequency ride-through sensitivities
  - How should these be modeled??

# Nature of the Issue

Loss of voltage-sensitive loads are NOT classified as Consequential Load Loss (NERC Glossary*)

**Consequential Load Loss**

All Load that is no longer served by the Transmission system as a result of Transmission Facilities being removed from service by a Protection System operation designed to isolate the fault.

**Non-Consequential Load Loss**

Non-Interruptible Load loss that does <u>not</u> include: (1) Consequential Load Loss, (2) the response of voltage sensitive Load, or (3) Load that is disconnected from the System by end-user equipment.

- Models not perfect – need improvements to address complexities
- Transient voltage response study criteria is vague

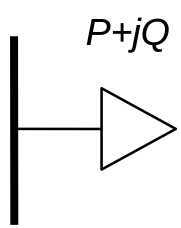
**http://www.nerc.com/files/glossary_of_terms.pdf*

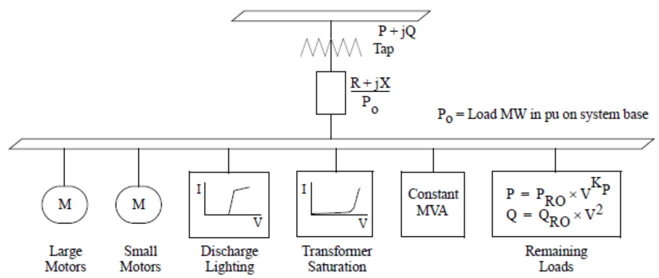
# Voltage Sensitivities Highlighted

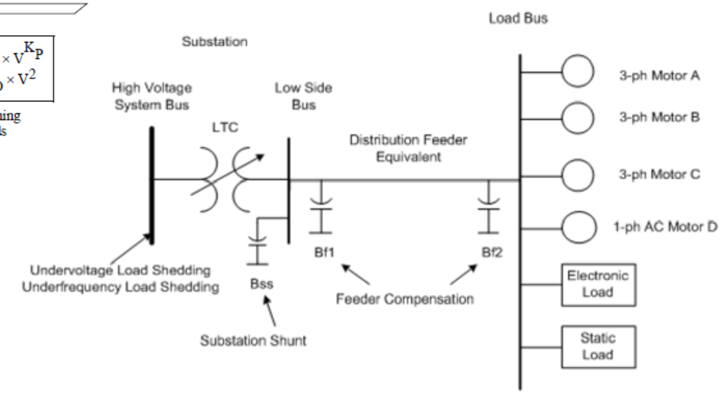
- Toronto, Ontario – 2007
  - 230 kV cap bank failure – slow clearing 3-Ø fault
  - 1,700 MW of voltage-sensitive load lost in the Greater Toronto Area
- Salt Lake Valley – 2009
  - low voltage spike initiated ~920 MW non-consequential load lost
  - 138 kV SLG fault of 4 cycles, evolving into a three-phase fault for 6 more cycles; 10 cycles total fault duration
  - Load – several server farms – voltage-sensitive loads transfer to backup power sources
- Washington, DC Area – 2015
  - Protracted 230 kV fault created prolonged low-voltage
  - ~445 MW load lost
    - Some voltage sensitive load transferred to backup supplies
    - Some tripped by end-user connection protection action

# TPL-001-4 - Transition in Load Models

- TPL-001-4 requires use of "a Load model which represents the expected dynamic behavior of Loads … considering the behavior of induction motor Loads."




***FROM…***

$$\boldsymbol{P}=\boldsymbol{P}_0[p_1\boldsymbol{V}^2+p_2\boldsymbol{V}+p_3]$$
$$\boldsymbol{Q}=\boldsymbol{Q}_0[q_1\boldsymbol{V}^2+q_2\boldsymbol{V}+q_3]$$

***TO…***

- *3-phase Motors – Fans, Pumps, Compressors*
- *1-phase Induction Motors*
- *Power Electronic Load*
- *Static (Polynomial) Load*
- *Distribution Equivalent*

# Transient Voltage Recovery

- TPL-001-4 requires PCs and TPs have a *transient voltage response criteria* in place
  - Clarification is needed – Is this transient voltage dip criteria or a transient voltage recovery criteria?
- How does transient voltage response criteria directly relate to reliability?
  - *Used as a metric for ensuring reliability*
  - *Future work to focus on developing a criteria that directly relates to continuity of the bulk power system for large voltage excursions.*
  - *Need improved models (on load and generation side) to accomplish this*

# Goals for Reliability

- **High Probability, Low Risk –** Faults such as SLG, simple generator trips, etc., should be evaluated against a criteria in which continuity of serving load is priority
  - Load bus transient voltage response criteria
- **Low Probability, High Risk –** Faults such as 3-phase or stuck breaker should have a criteria in which continuity of the bulk power system is priority
  - PRC-024 ride through requirements
- **Resolution of Consequential vs. Non-Consequential Load Loss –** Clarify how to classify voltage-sensitive and frequency-sensitive loads in reliability analysis

# Moving Forward – Next Steps

- Share best practices for dynamic load modeling and FIDVR events
- Share best practices for non-traditional resource modeling
- Collaborate with software vendors to further develop and improve available dynamic models in software
- Continue engaging manufacturing community to raise awareness of grid needs – promote grid-friendly devices
- Engage in IEEE equipment standards – awareness of aggregate impact of multiple small devices
- Collect as much load data as possible (classification, end use , feeder information, etc.)
- Develop a process for creating load models – ***zonal or regional load models are NOT sufficient***
- Sensitivity, sensitivity, and more sensitivity studies

# Questions and Answers

# U.S. DOE-NERC Workshop on Fault-Induced Delayed Voltage Recovery (FIDVR) & Dynamic Load Modeling

# Summary

Joe Eto, Lawrence Berkeley National Lab

October 1, 2015

Alexandria, VA

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# Take Aways pt 1

**Current State of Load Modeling**

- Explicit representation of the dynamic behavior of load is now essential for planning studies of the performance of the transmission system
- The CMPLDW represents the current state-of-the-art in dynamic load modeling

**Fundamentals, Testing & Modelings of Air-Conditioners**

- The physics of stalled residential central AC units have long been understood and can now be modeled accurately
- A solid understanding of the propensity of populations of central AC units to stall (or not stall) in response to faults is now also close at hand

# Take Aways pt 2

**Manufacturing Perspective, Future Trends & Technologies**

- We are moving toward a future in which the majority of end-use loads will no longer be directly coupled to the grid – instead they will be coupled through power electronic interfaces
- On-going communication and information exchange with end-use (load, storage, generation) manufacturing communities is essential – and *they are waiting to hear from us*

**Load Model Data**

- The CMPLDW was developed to model explicitly a range of dynamic load behaviors and account for the effects of the distribution systems that connect loads to transmission
- WECC's experience developing and using CMPLDW has led to rapidly maturing, systematic modeling practices, including reliance on DOE-developed tools – Yet, more needs to be done to facilitate (ease) the use of CMPLDW in conducting planning studies

# *Take Aways pt 3*

**Field Measurements**

- Field measurements of AC stalling have been instrumental in directing needed improvements in modeling studies aimed at reproducing FIDVR
- This experience has taught us that there is no substitute for field measurements in improving our understanding, in the future, of the aggregate behavior of a changing population of end-use loads

**Experiences conducting studies using CMPLDW**

- Phased adoption has allowed utilities to gain experience and build confidence in using CMPLDW
- Systematic sensitivity studies help to identify specific inputs to the CMPLDW that deserve focused attention
- Vendor engagement needed

# *Take Aways pt 4*

**Reliability Focus**

- FIDVR originating from within distribution is no longer the most significant load-related issue for the operational security of the bulk power system
- CMPLDW is evolving and use of it should be considered a “best practice”
- The transient voltage dip criteria is being reconsidered
- Traditional generation and load technologies, by design, had either performance margins or grid-friendlier behaviors, respectively, that reduced concerns regarding what could not be studied adequately with conventional simulation tools
- These margins and behaviors are disappearing as both fleets (generation and loads) change and hence our exposure to the limitations of what can be studied with current simulation tools is increased

# Take Aways pt 5

**Reliability Focus** (continued)

- Looking forward we need to revisit the purposes served and manner by which future planning studies are conducted, starting with the reliability objectives they seek to support
- The value of modeling is insight not numerical outputs
- We must acknowledge explicitly that there is a trade-off between planning criteria that emphasize continuity of service to customers in the face of high probability disturbances and planning criteria that emphasize the sustained security of the bulk power system (including re-establishment of supply) in the face of low probability but severe events.

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# Contacts for Follow-Up


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