# DER Trip Impact Study: Methods, Results, and Conclusions

June 14, 2019

DER Ride Through Task Force

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# Executive Summary

- Motivation:
  - Multiple system events (California 2016/17/18, South Australia, Europe 2006) have highlighted the risk posed by lack of ride-through. If DER proliferates in PJM, ride-through should be mandatory.
  - Distribution system protection philosophy differs greatly from Transmission. There is a need to harmonize ride-through requirements to maintain reliability at Transmission and Distribution grids.
- Objective:
  - Parametric analysis to understand the impact of different trip settings & ride through modes on voltage recovery under varying DER deployment.
  - Inform selection of ride through modes and trip timing for implementation of IEEE 1547-2018

# Executive Summary: Preliminary Key Findings

Complex load model findings:

1. **DER <u>without</u> ride through causes impact in all scenarios.**
2. **DER <u>with</u> ride through → minimal impact in all cases.**
3. **DER with momentary cessation ride through mode also → minimal impact** when DER follow the recovery requirements of IEEE 1547-2018.
4. **A trip point of >2 seconds at V < 88% and >320 milliseconds at V < 45% may result in minimal impact** by providing low-voltage ride through times longer than voltage recovery times.
   – However, model limitations mean that Fault Induced Delayed Voltage Recovery on distribution may not be captured—voltage recovery may be longer in reality.

*Load model significantly affects voltage recovery*
--ZIP load models show adequate voltage recovery under all scenarios, however, over 4 GW of DER trip in some scenarios causing frequency concerns.

**Complex Load Model Results**

| | 3 GW DER | | 8 GW DER | | 13 GW Med Synch Gen | | 13 GW DER Lo Synch Gen | | 13 GW DER No Synch Gen | |
|---|---|---|---|---|---|---|---|---|---|---|
| NJ BES Fault: North/Central | N | C | N | C | N | C | N | C | N | C |
| Trip | Modest impact | Modest impact | Some impact | Some impact | More impact | More impact | Most impact | More impact | More impact | More impact |
| RT | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact |
| MC50 | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact |
| MC30 | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact | Minimal impact |

*Minimal impact* (green) · *Modest impact* (yellow) · *Some impact* (orange) · *More impact* (red) · *Most impact* (dark red)

# Agenda

- Study Project Overview
- Summary of Method and Assumptions
- Results and Conclusions
- Appendix: Detailed Methodology, Assumptions, & Results

# Study Project Roles

**Argonne National Lab**
- Implementation

**EPRI**
- Expert input and review

**PJM**
- Direction and oversight

*In additional to extensive review and discussion with EPRI, these EPRI references provided significant guidance:*

[1] EPRI. *The New Aggregated Distributed Energy Resources (der_a) Model for Transmission Planning Studies: 2019 Update. White Paper.* Electric Power Research Institute, Palo Alto, CA: March 2019. 3002015320. [Online] https://www.epri.com/#/pages/product/000000003002015320/

[2] EPRI. *Case Studies Analyzing the Impact of Aggregated DER Behavior on Bulk System Performance: Supplemental Project Notice.* Electric Power Research Institute, Palo Alto, CA: March 15, 2019. 3002015415. [Online] https://www.epri.com/#/pages/product/000000003002015415/

 

# Study Project Timeline

- Feb 4 start
- **Feb & Mar** Develop scenarios, model, scripts, assumptions
- **Apr – May** Run load flow and dynamic cases, analyze, and iterate
- **May – June** Analyze results and draft report
- **July** Finalize report

**We are here** (May – June)

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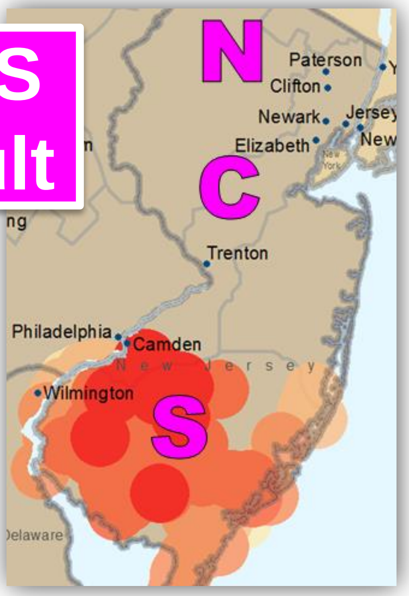
# 2031 PSS/E Dynamic Study Sequence

Summary of Method and Assumptions

**BES Fault**




**~100 ms** → **TRIP or other** → **~ 20,000 ms** →

BES Fault in 2031 → DER Trip or Ride Through → BES Fault Clearing → T+D Response → DER recovery

# Assumptions: 2031 Case

2031 case based on 2021 light load:

- Light load → less synchronous generation online to support voltage recovery.
- Distribution of load in 2021LL is consistent with today's actual NJ loading in December at noon.
- Solar DER output is modeled consistent with December at noon.
- RTO power balance per case via electrically distant generators.
- Input from PJM Transmission Ops for Synch Gen commit/dispatch.
- Resulting net exchanges NJ<>PJM not unusual today.

| | 2021 Light Load |
|---|---|
| *DER* | 2.1 GW |
| *Synch Gen* | 7.0 GW |
| *Load* | 13.8 GW |

| | 3 GW DER | 8 GW DER | 13 GW DER Med Synch Gen | 13 GW DER Lo Synch Gen | 13 GW DER No Synch Gen |
|---|---|---|---|---|---|
| *DER* | 3.0 GW | 8.2 GW | 12.6 GW | 12.6 GW | 12.6 GW |
| *Synch Gen* | 6.2 GW | 5.0 GW | 6.2 GW | 3.7 GW | 0.0 GW |
| *Load* | 13.8 GW | | | | |

# Rationale for Solar DER Deployment Scenarios



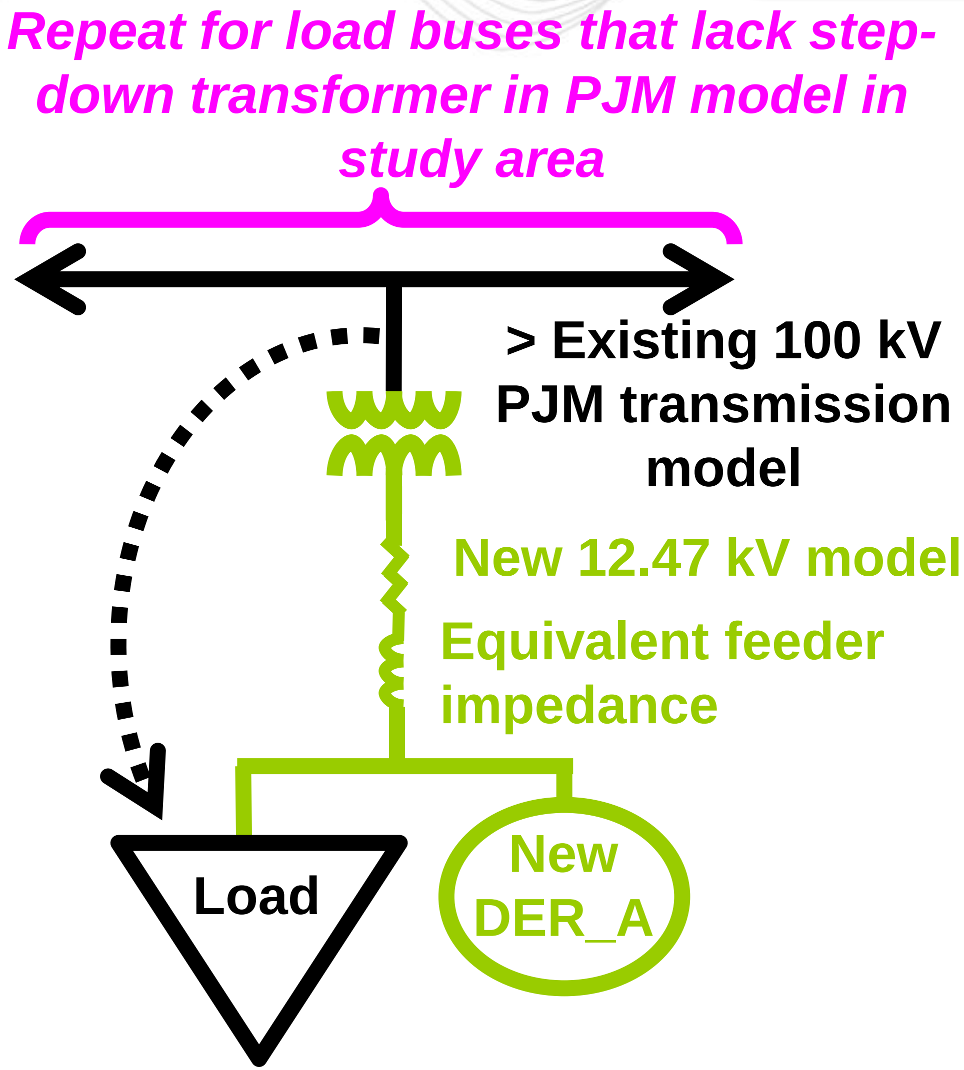
3 GW DER = PJM solar deployment forecast for NJ in 2031 → under 10% of annual NJ load from solar DER.

8 GW DER → under 20% of annual NJ load from solar DER.

13 GW DER → under 40% of annual NJ load from solar DER

# Assumptions: Model Components

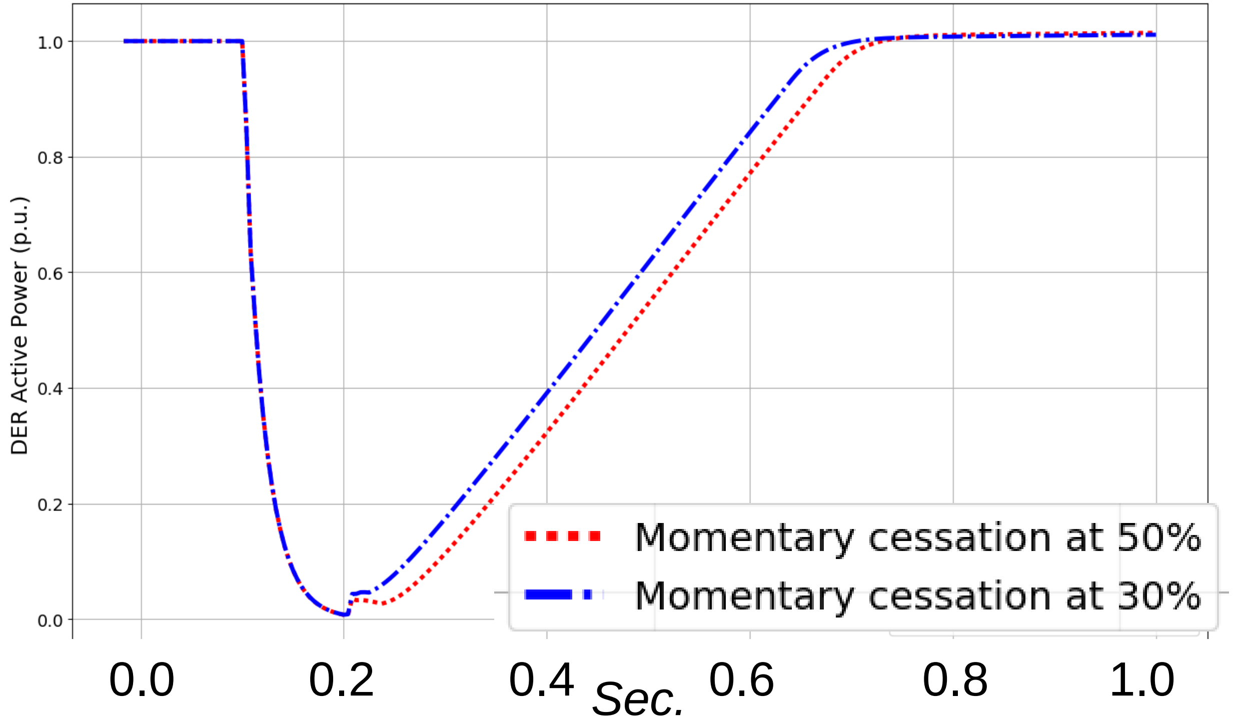
- Added a DER_A object to all load buses.
- Changed load from simpler “ZIP” to “Complex” type.
- Equivalent feeder impedance is represented in the model—
  - If load transformer exists in model (most buses), equivalent feeder impedance is already represented in existing transformer impedance.
  - If no load transformer in model, added load transformer and equivalent feeder as shown at right. 2 sensitivities cases for this feeder impedance. New feeders are 12.47 kV. EPRI feedback: behavior not expected to vary with feeder voltage.



# Assumptions: DER_A Parameters

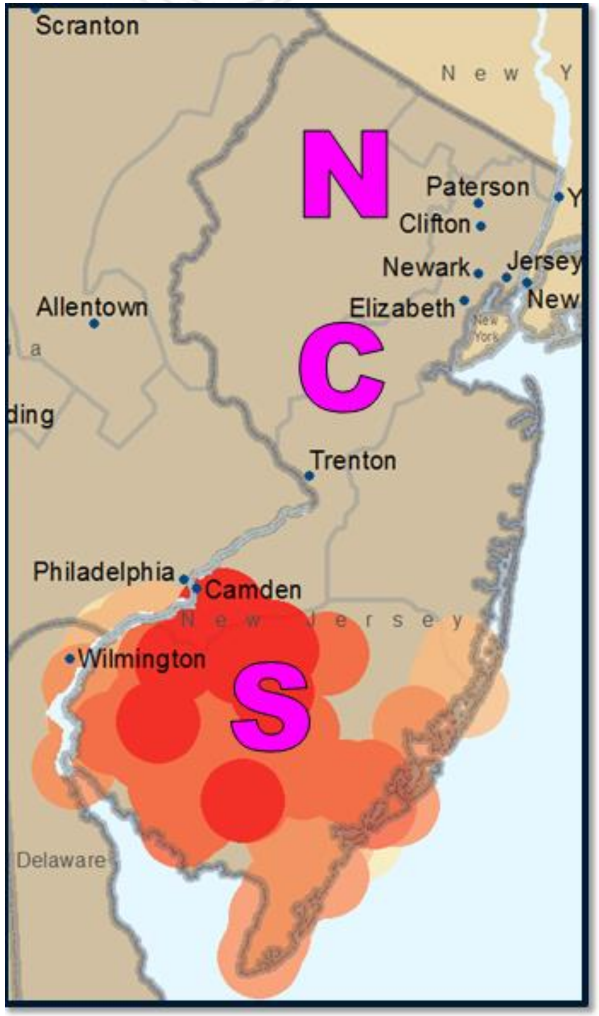
- 8 DER_A behavior scenarios:
  - Return to normal operations from Momentary Cessation was subject of careful attention relative to IEEE 1547-2018.
- DER_A scenarios tested against infinite bus to confirm real and reactive power behavior cycle-by-cycle and correspondence with IEEE 1547-2018 requirements

| **8 DER_A Dynamics Scenarios** | |
|---|---|
| *Voltage regulation OFF and:* | *Voltage regulation ON and:* |
| Trip | Trip |
| Ride Thru | Ride Thru |
| Momentary Cessation for V<30% | Momentary Cessation for V<30% |
| M.C.<50% | M.C.<50% |



# Assumptions: 3-Phase Faults

- Used PSS/E to screen all NJ faults for most MW of load with V < 55% during fault (e.g., red areas in figure at right for fault at 500 kV bus “S”).
- Chose among the 10 most severe faults that reflect a diversity of NJ network, load, and DER conditions:
  - 230 kV (“North NJ”)
  - 500 kV (“Central NJ”)
  - 500 kV (“South NJ”)
  - Fourth fault case: 500 kV
  - Fifth fault case: 230 kV



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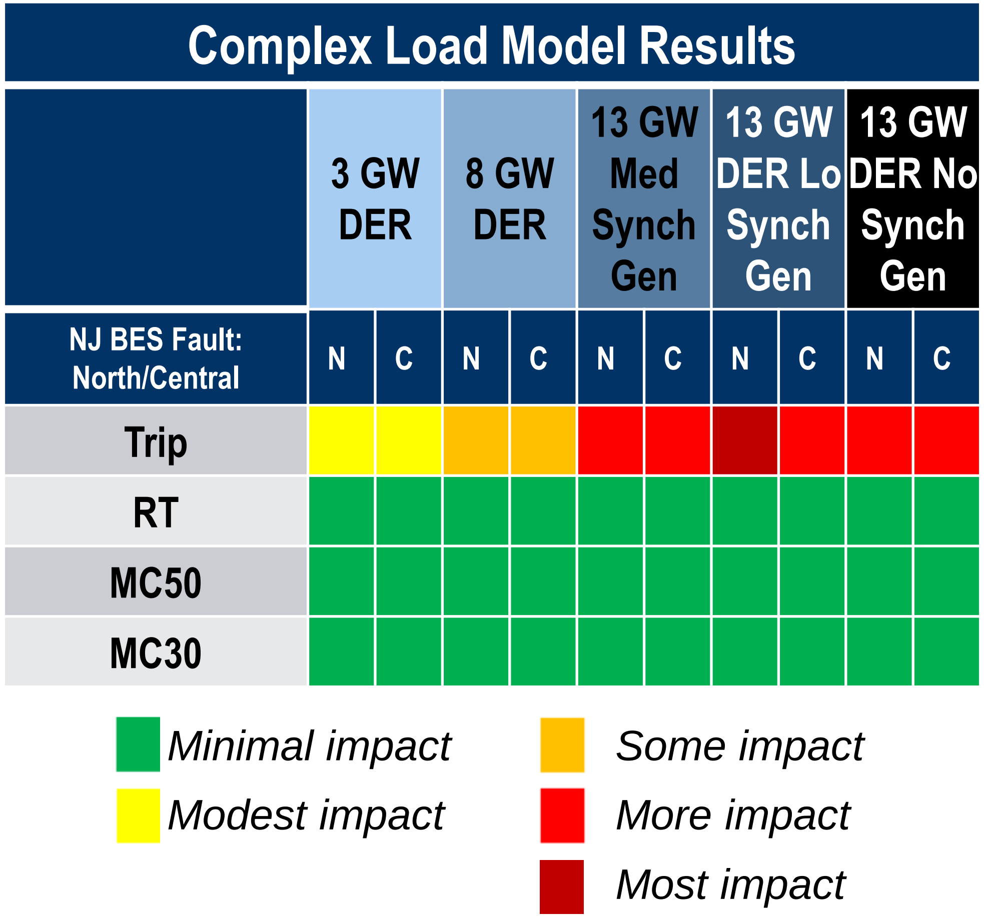
# Executive Summary: Preliminary Key Findings

Complex load model findings:

1. **DER <u>without</u> ride through causes impact in all scenarios.**
2. **DER <u>with</u> ride through → minimal impact in all cases.**
3. **DER with momentary cessation ride through mode also → minimal impact** when DER follow the recovery requirements of IEEE 1547-2018.
4. **A trip point of >2 seconds at V < 88% and >320 milliseconds at V < 45% may result in minimal impact** by providing low-voltage ride through times longer than voltage recovery times.
   – However, model limitations mean that Fault Induced Delayed Voltage Recovery on distribution may <u>not</u> be captured—voltage recovery may be longer in reality.

*Load model significantly affects voltage recovery*
--ZIP load models show adequate voltage recovery under all scenarios, however, over 4 GW of DER trip in some scenarios causing frequency concerns.



# Finding 1. DER without ride through causes impact in all scenarios

| | | Complex Load Model Results | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 GW DER | | 8 GW DER | | 13 GW Med Synch Gen | | 13 GW DER Lo Synch Gen | | 13 GW DER No Synch Gen | |
| NJ BES Fault: North/Central | | N | C | N | C | N | C | N | C | N | C |
| MW DER Tripped | Trip | 790 | 823 | 2,628 | 2,351 | 4,385 | 3,458 | 5,080 | 4,281 | 3,615 | 3,202 |

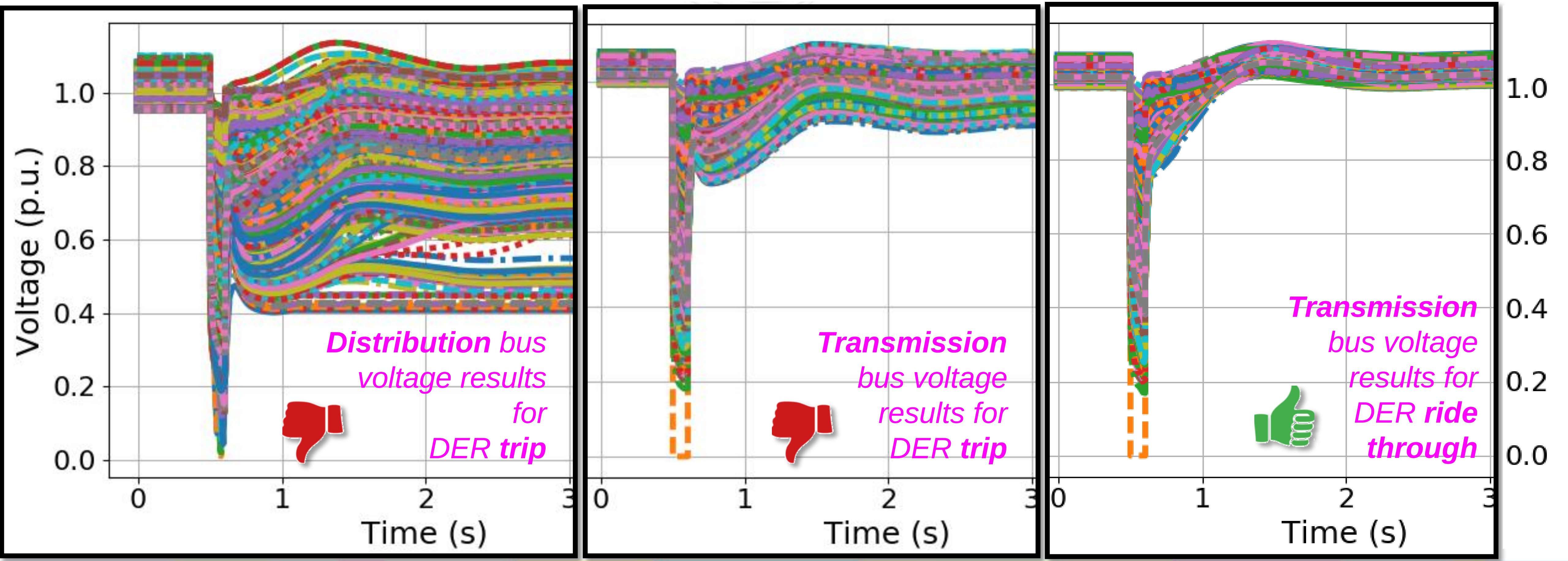
| | | |
|---|---|---|
| (green) | *Minimal impact* | PJM plans the system so no generation trips following normally-cleared transmission fault. |
| (yellow) | *Modest impact* | Any loss of generation trip caused by fault is a concern. For reference, loss of < 1,700 MW is within PJM typical operational contingency planning. |
| (orange) | *Some impact* | PJM's worst recent historical single-event loss of generation is <2,700 MW. |
| (red) | *More impact* | Eastern Interconnection's worst recent single-event loss of generation is ~4,500 MW |
| (dark red) | *Most impact* | |

# Finding 1. DER Trip Causes Poor Voltage Recovery



**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

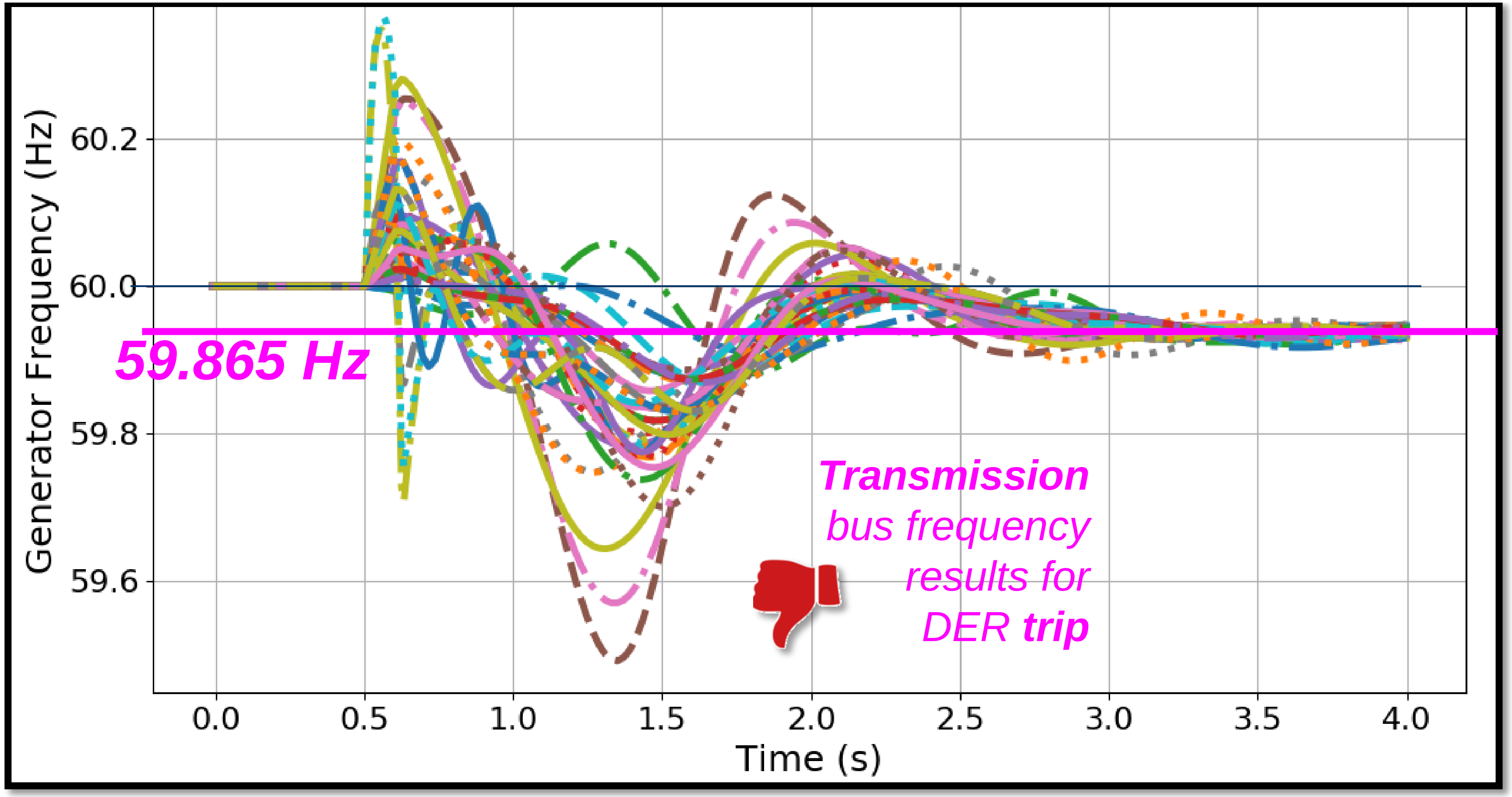
Scenario: complex load, Central NJ fault, voltage Regulation off, high feeder impedance



# Finding 1. DER Trip Causes Poor Frequency

## 13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )

Scenario: complex load, Central NJ fault, voltage Regulation off, high feeder impedance




*NERC 2013* "Eastern Frequency Response Study"—

*"On August 4, 2007, a major event included the loss of approximately 4,500 MW of generation…The lowest frequency in that event, 59.868 Hz, occurred at about 1 min after the event.*

https://www.nrel.gov/docs/fy13osti/58077.pdf

# Finding 2 and 3. DER with ride through (including momentary cessation) → minimal impact in all cases

| | | Complex Load Model Results | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 GW DER | | 8 GW DER | | 13 GW Med Synch Gen | | 13 GW DER Lo Synch Gen | | 13 GW DER No Synch Gen | |
| NJ BES Fault: North/Central | | N | C | N | C | N | C | N | C | N | C |
| MW DER Tripped | RT | 0 | 0 | 0 | 0 | 0 | <100 | 0 | <100 | 0 | <100 |
| | MC50 | 0 | 0 | <100 | 0 | 0 | 0 | 0 | 0 | <100 | 0 |
| | MC30 | 0 | 0 | 0 | 0 | <100 | 0 | 0 | 0 | <100 | 0 |

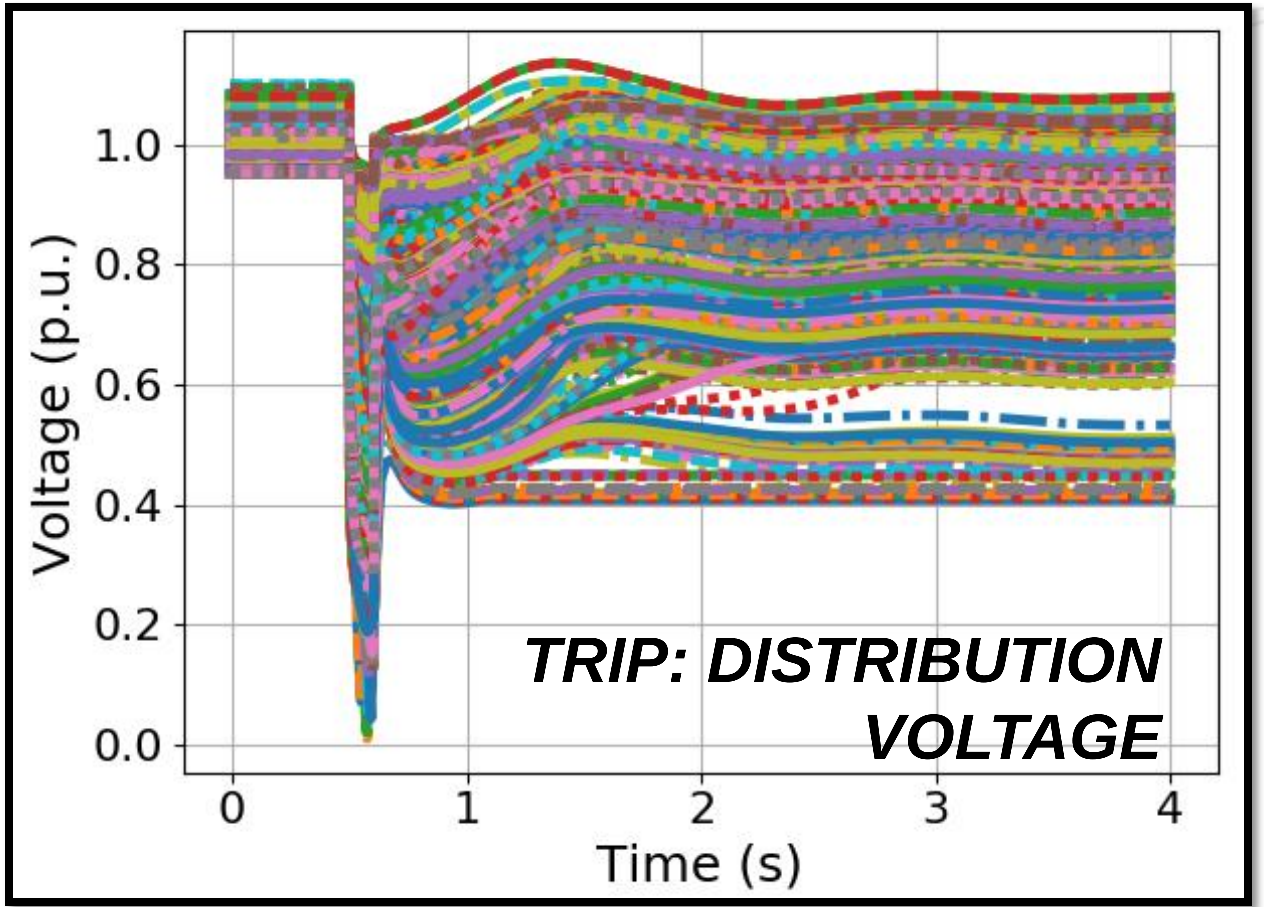
| | | |
|---|---|---|
| (green) | *Minimal impact* | PJM plans the system such that no generation trips following a normally-cleared transmission contingency. |

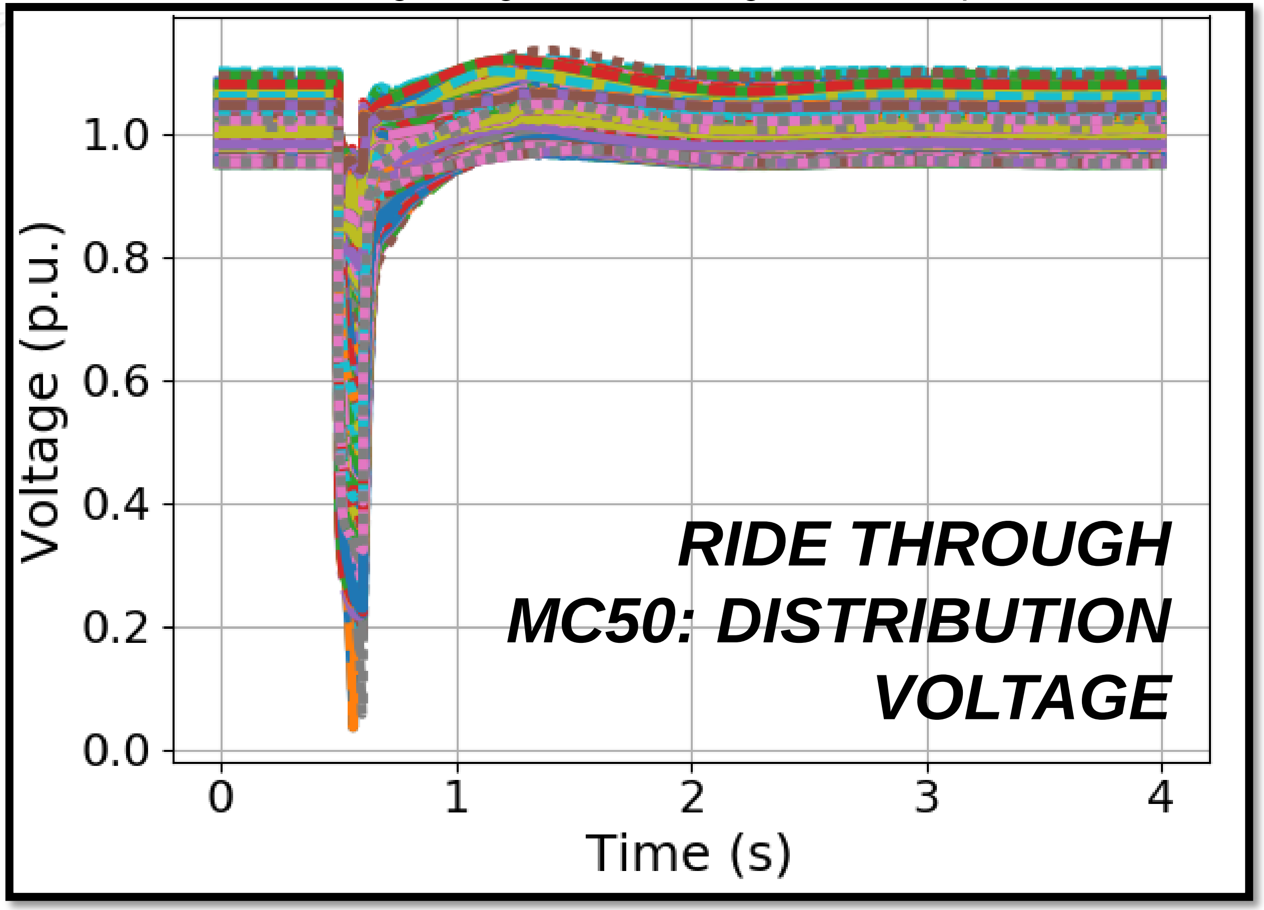
# Finding 2 and 3. Distribution Voltage Recovery--Trip vs. Momentary Cessation for V<50%



**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance



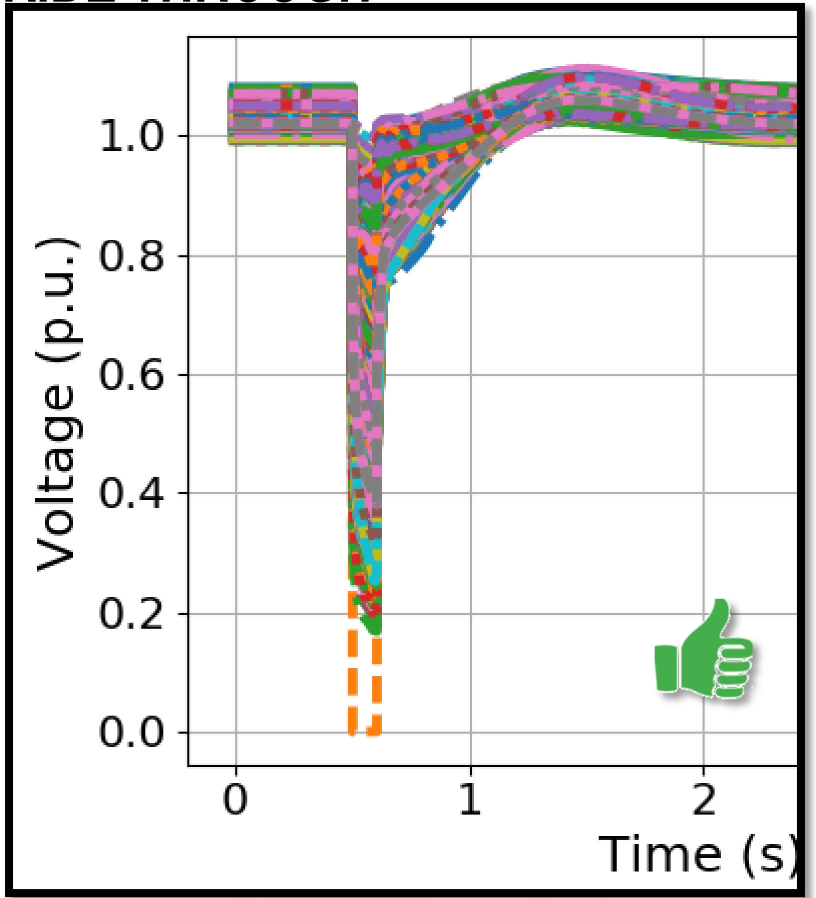
# Finding 3. Momentary cessation → minimal impact

Results and Conclusions

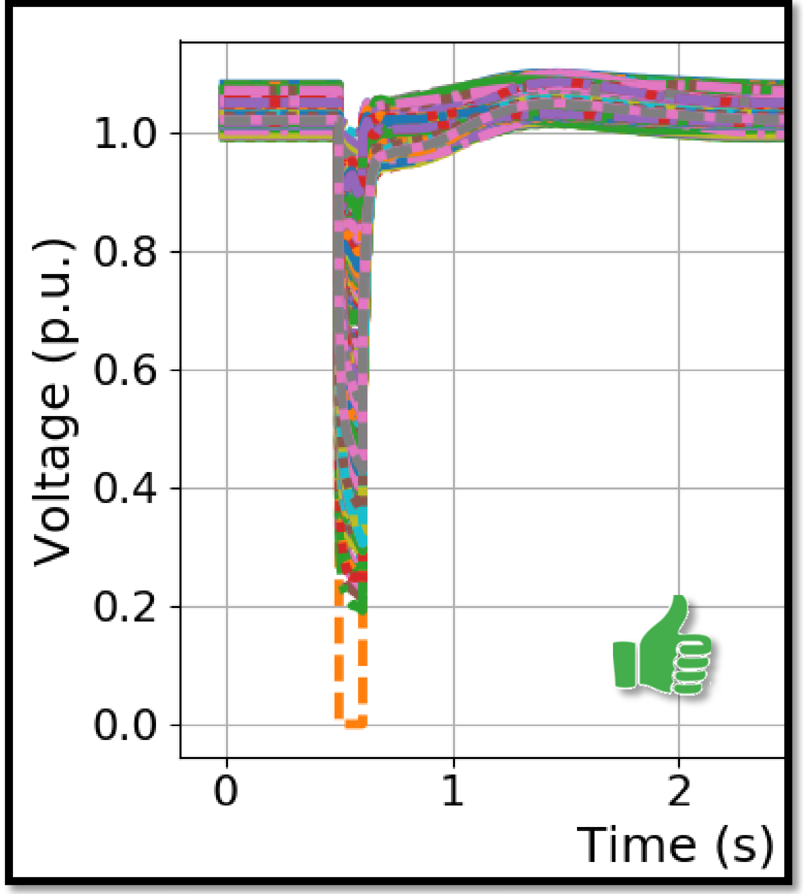
**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance, **transmission busses**

***RIDE THROUGH***




***MOMENTARY CESSATION < 30%***

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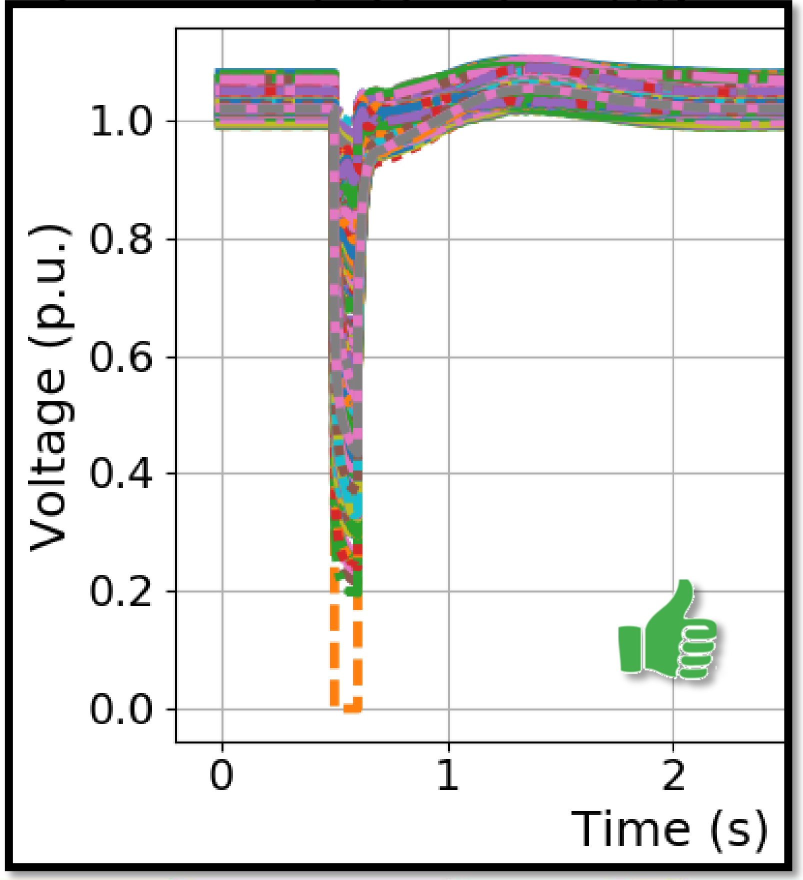
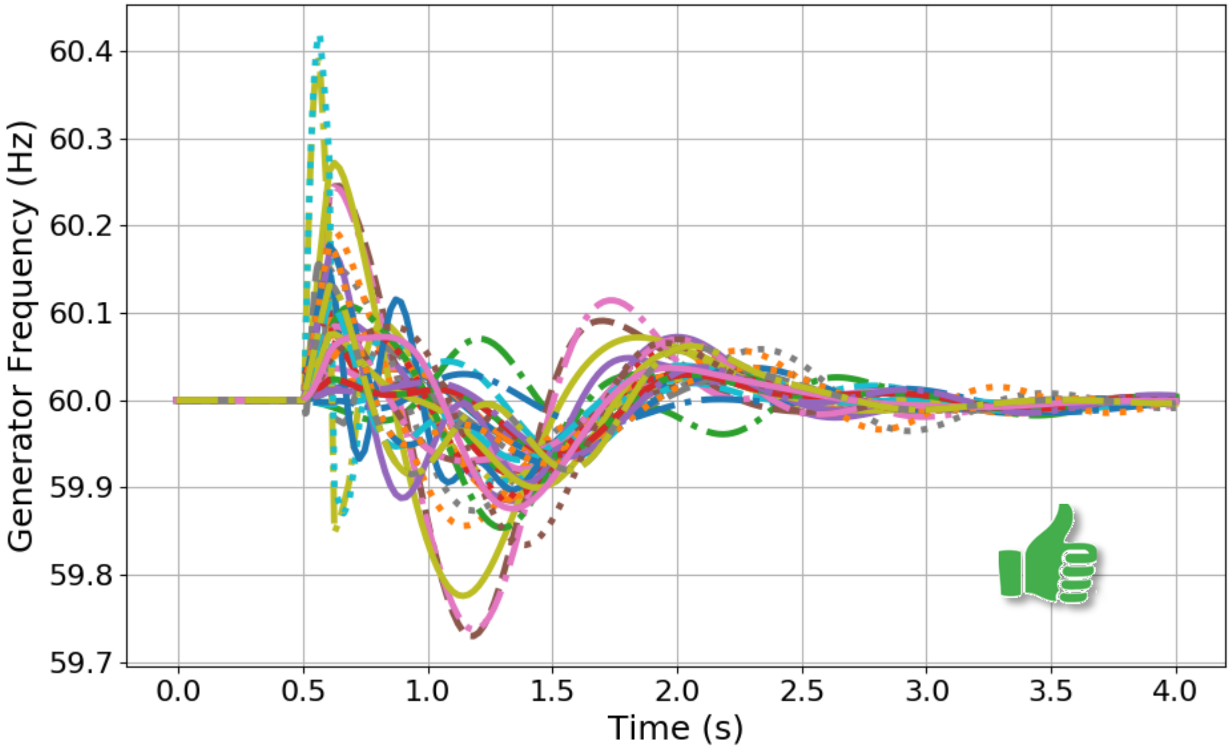


# Finding 3. Momentary cessation → minimal impact

**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance, **transmission busses**

***RIDE THROUGH***

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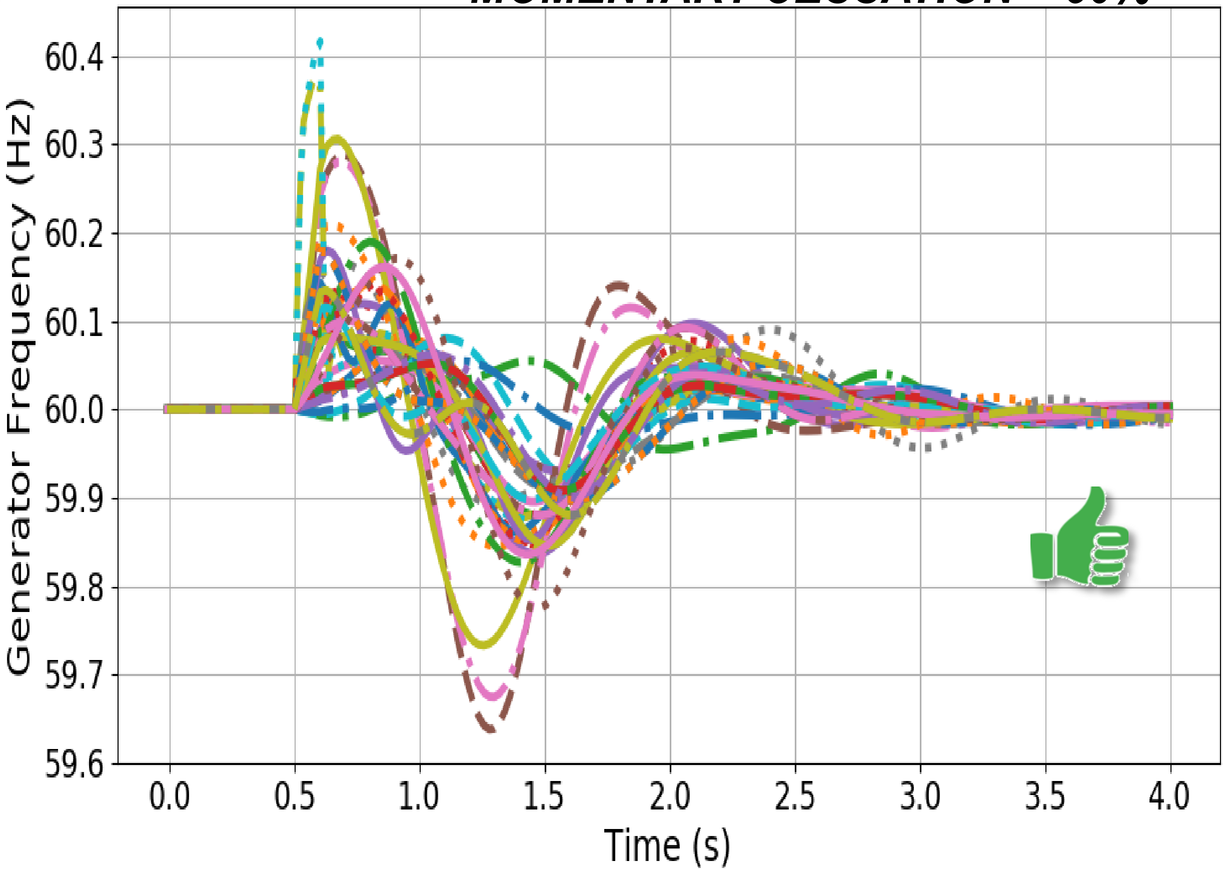
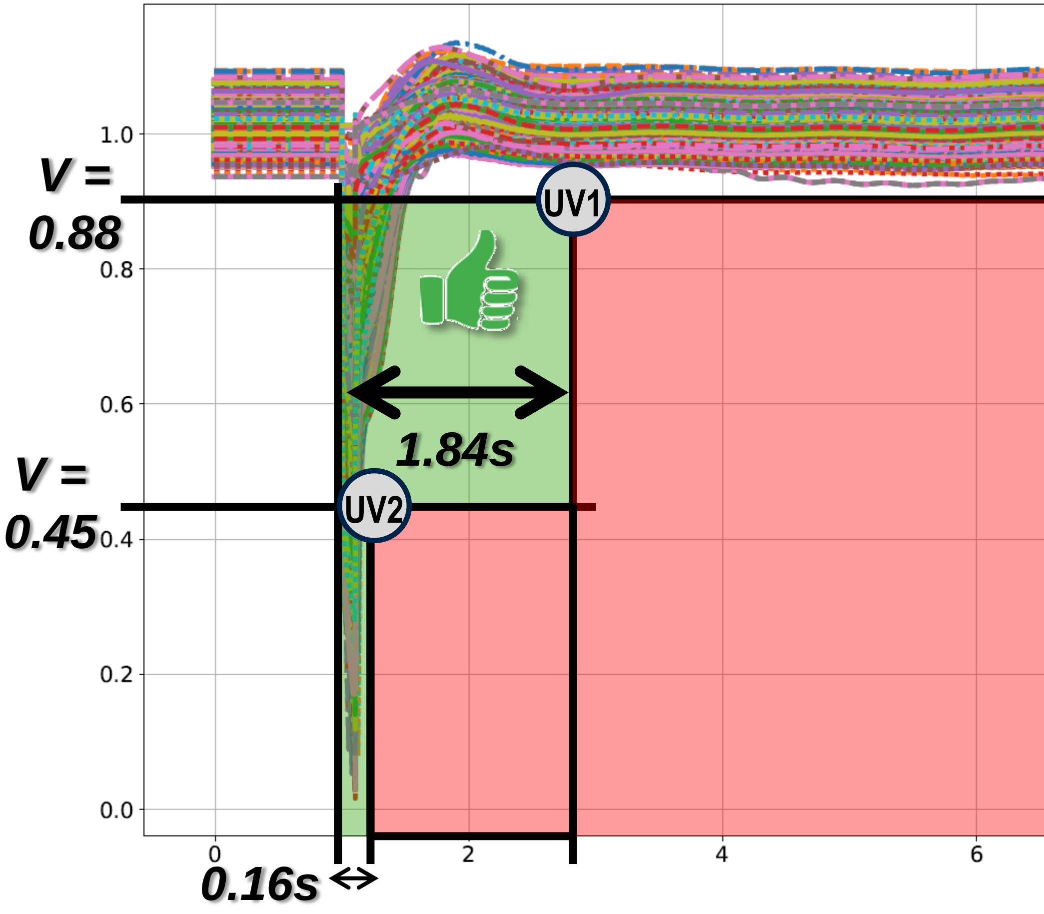


# Finding 4. Trip >2 seconds at V < 88% & >320 milliseconds at V < 45% may be adequate

**For each ride through and momentary cessation case, voltage at each DER bus (except 1 or 2 buses in worst case scenarios) recovered faster than:**

- **Voltage recovery to > 88% in < 1.84 seconds (UV1)**
- **Voltage recovery to > 45% in < 160 milliseconds (UV2)**

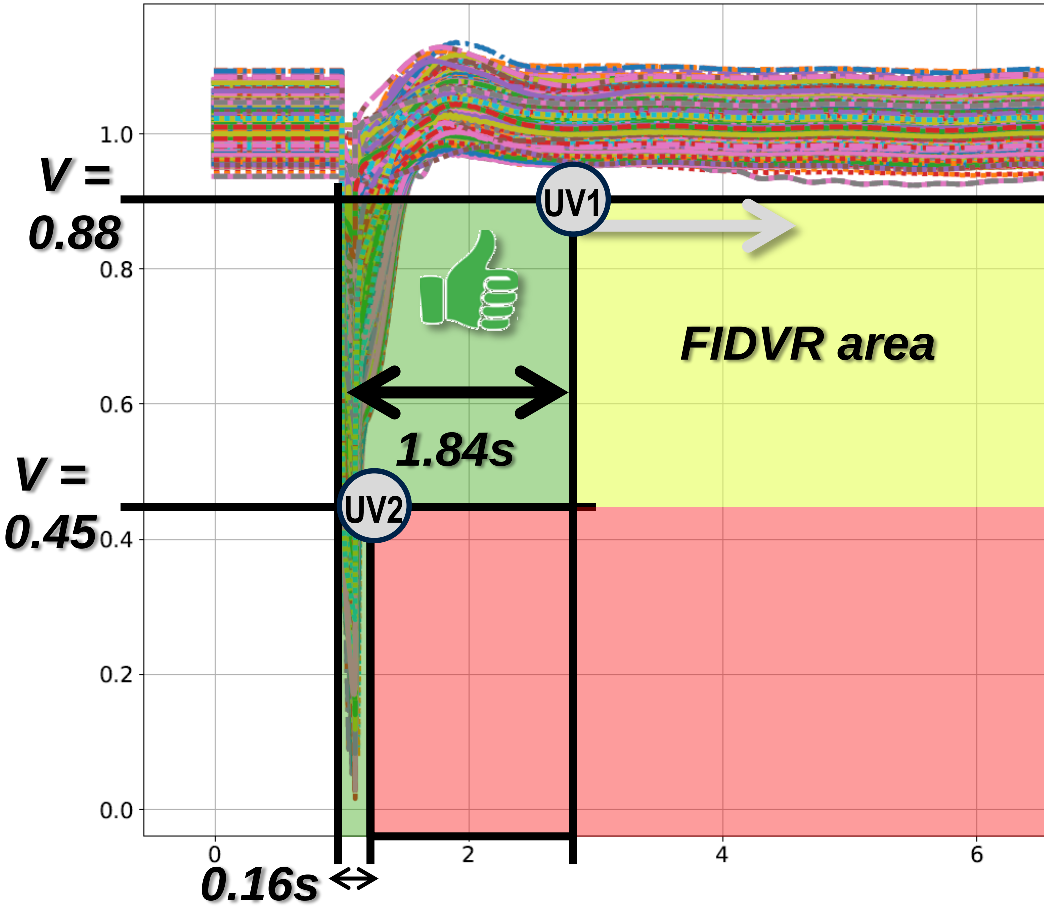



- IEEE 1547-2018 allows a 160 millisecond "grace period" exemption from ride through requirement prior to trip time.
- Therefore, a 2-second trip time implies a **1.84 ride through requirement** (assuming the ride through requirement is otherwise > 1.84 seconds).
- Likewise, a 320 millisecond trip time implies a **160 ride through requirement**.

# Finding 4. Trip >2 seconds at V < 88% & >320 milliseconds at V < 45% is minimal impact

**For each ride through and momentary cessation case, voltage at each DER bus (except 1 or 2 buses in worst case scenarios) recovered faster than:**

- **Voltage recovery to > 88% in < 1.84 seconds (UV1)**
- **Voltage recovery to > 45% in < 160 milliseconds (UV2)**




Caveat: the Complex Load Model used in this study is known to have limited ability to simulate "Fault Induced Delayed Voltage Recovery" caused by loads on distribution.

- PJM is not aware of any detailed studies of distribution-level FIDVR in the Mid-Atlantic or Midwest.
- Actual recovery to V> 88% may be slower than simulated.
- Therefore, UV1 trip times longer than 2 seconds and UV1 voltage thresholds below 88% (where practicable) are generally preferred.
- In areas where distribution-level FIDVR is known, UV1 trip times should be longer than 2 seconds.

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# Assumptions: Solar DER Deployment by Bus

**2018 solar DER by bus**

- Mapped existing DER to PJM bus using available data

→

**Scale to 2021 PJM solar deployment forecast**

- 2.12 GW based on expected output for case.

→

**Replace 2021 net load with 2021 gross load**

- 2021 Light Load: 11.64 GW of NJ load
- Gross load masked by 2.12 GW DER.
- Therefore gross load in 2021 = 13.8 GW

→

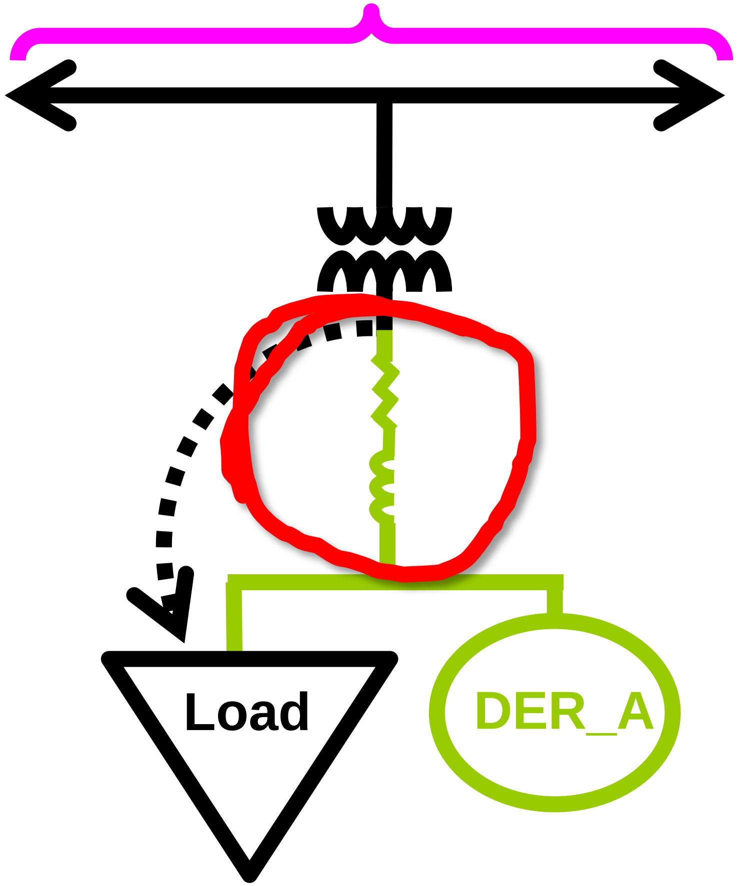
**Scale up DER to match 2031 case (3/8/13 GW)**

- DER at bus not to exceed light load + peak load.
- Buses with no DER are allocated the median for the case.

# Load Flow Assumptions: Feeder

- Two feeder equivalent impedance sensitivities for those buses that did not already have a substation load step down transformer:
  - Input from NJ utilities, existing PJM complex load model for NJ, IEEE standard models, EPRI

| *(X and R in per unit vs. model load base)* | R | X | X/R |
|---|---|---|---|
| Low impedance case | 3% | 15% | 5 |
| High impedance case | 9% | 18% | 2 |



# PSS/E Static Load Flow: Additional Details

- PSS/E 33.12 required for DER_A model. Recompiled existing custom gen models from PJM's model in PSS/E 33.10 using Intel Visual Fortran.
- Script builds static cases by starting with 2021LL case, adding some DER, re-solving, and iterating until final scenario is reached.
- Likewise, script dials down or up Synch Gens incrementally, solves, and iterates.
- Total of 10 static cases. All found stable initial load flow solutions.
- All PJM transmission lines at boundary of NJ utilities, and 500 kV lines in vicinity, maintained within thermal, reactive, and N-1 limits
- Most remaining transmission lines in the vicinity within thermal and reactive limits as well.
  - Any violations examined and deemed inconsequential using engineering judgement.

# Feeder & Gen/DER → 10 Load Flow Cases

| | 3 GW DER | 8 GW DER | 13 GW DER Med Synch Gen | 13 GW DER Lo Synch Gen | 13 GW DER No Synch Gen |
|---|---|---|---|---|---|
| Lo Feeder Z | *Load Flow* | *Load Flow* | *Load Flow* | *Load Flow* | *Load Flow* |
| Hi Feeder Z | *Load Flow* | *Load Flow* | *Load Flow* | *Load Flow* | *Load Flow* |

Results were minimally sensitive to feeder impedance assumptions—results are generally shown from high impedance case (R = 9%, X = 18%).

# Assumptions: Load Model

- ZIP model scenarios used default from the 2021LL model.
- Complex load model scenarios:
  - Parameters originally from existing complex load parameterization on file at PJM, validated using load type share ratios from peak load forecast.
  - For some areas, PJM reduced small motor component vs. value on file at PJM.
  - Per internal PJM guidance, loads < 5 MVA were left as ZIP, as well as loads with poor power factor.
  - In certain cases, several complex load objects were manually switched to ZIP.

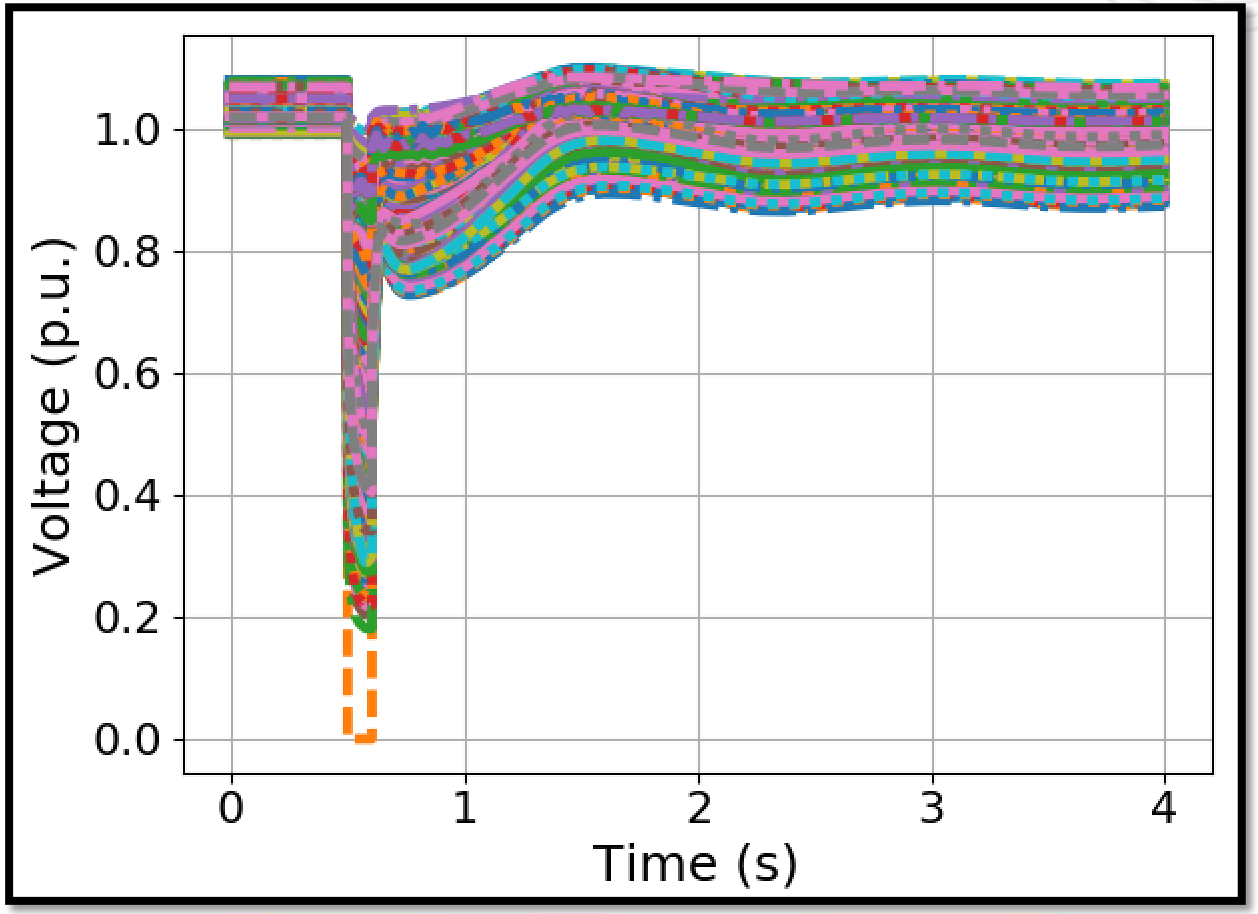
 

# Results: Trip vs. Ride Through

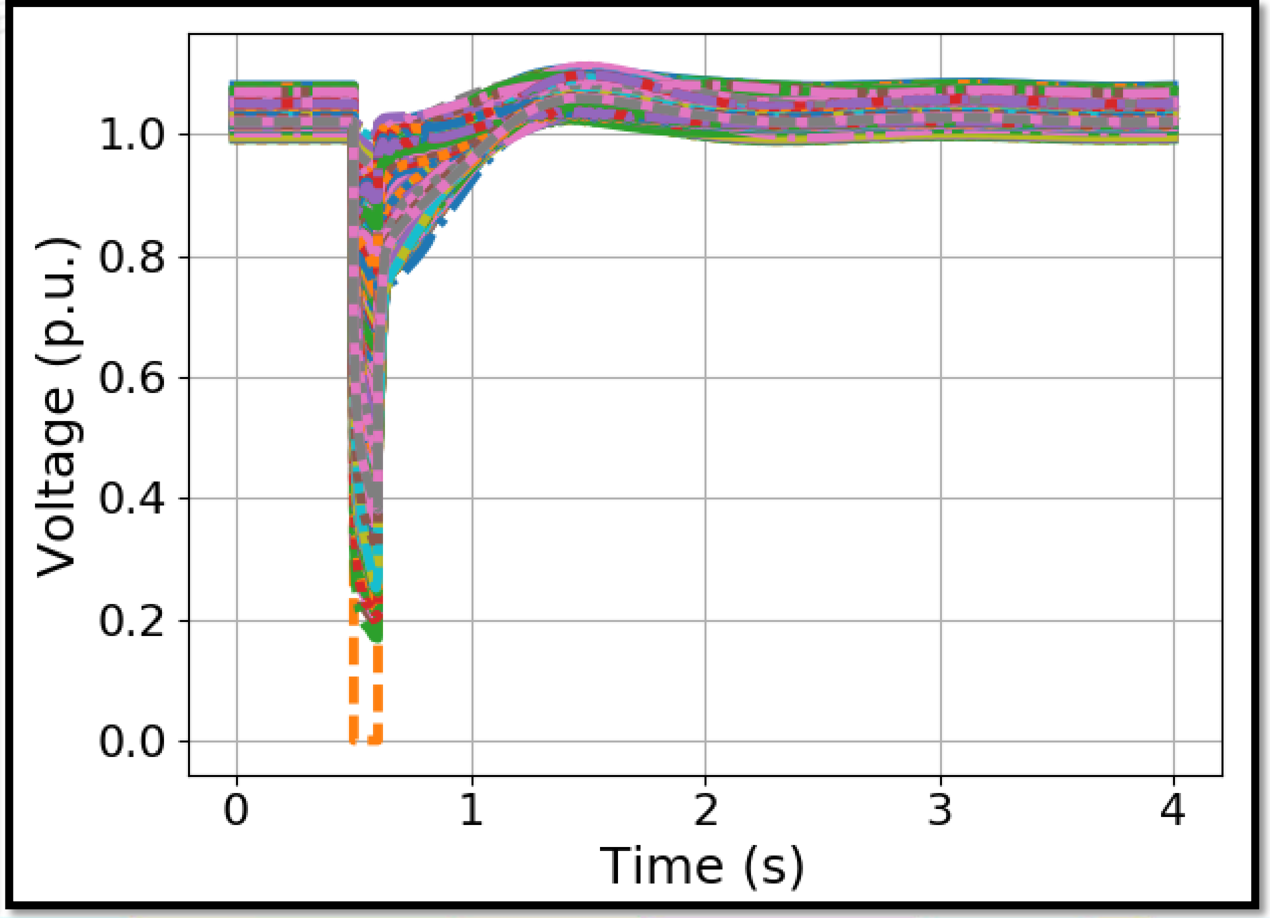
**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance, transmission bus voltages

***TRIP***




***RIDE THROUGH***

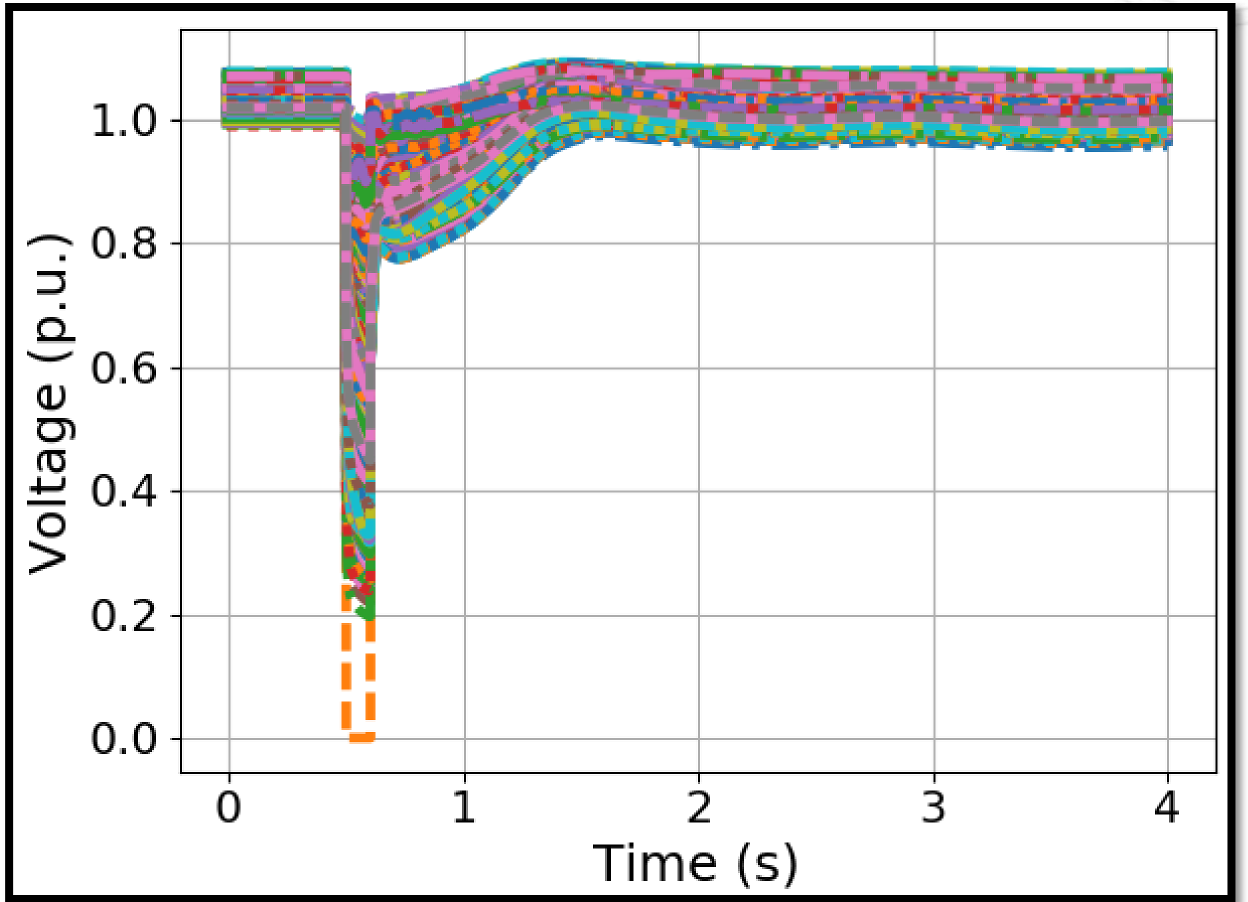


# Results: Trip vs. Ride Through

## 8 GW DER Case (5 GW Synch Gen )

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance, transmission bus voltages

***TRIP***

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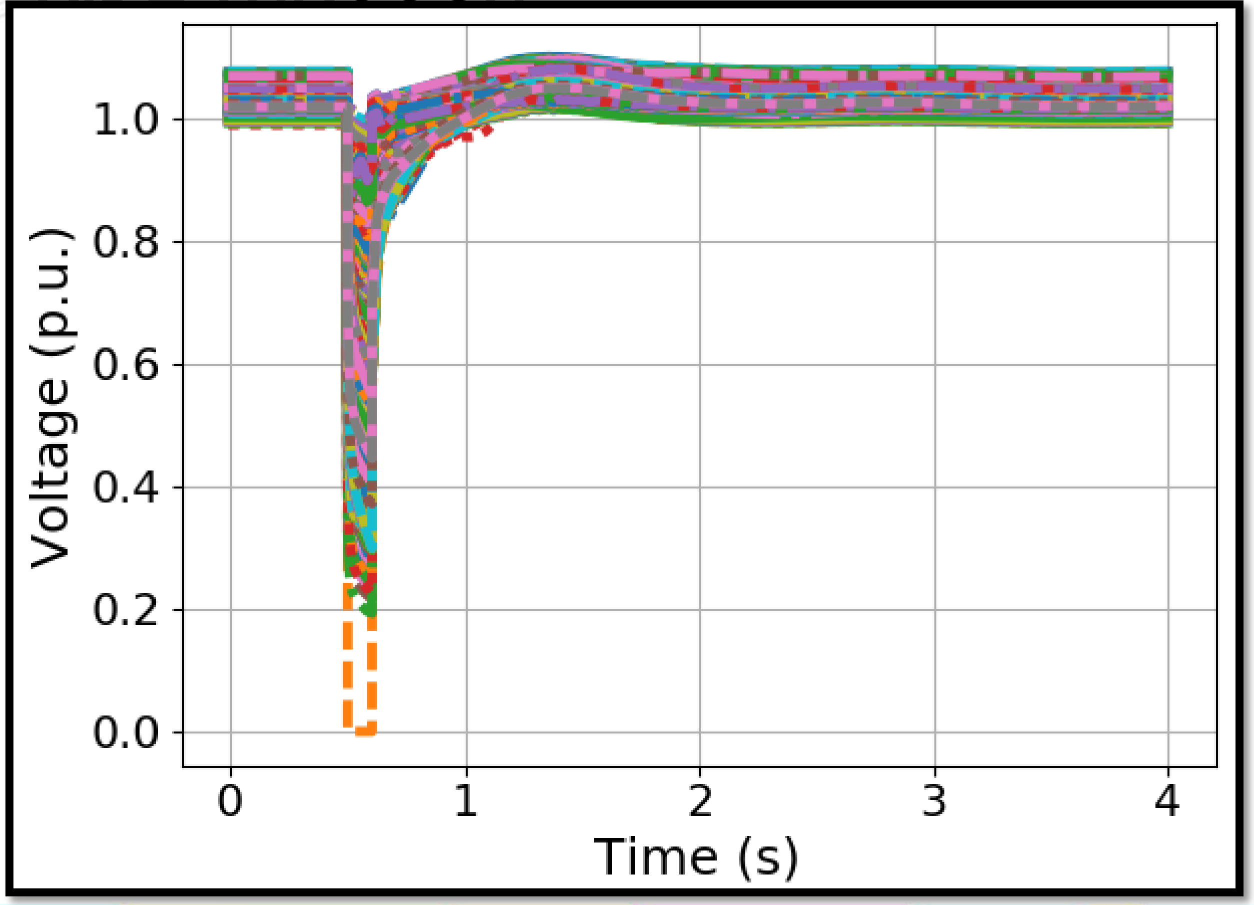
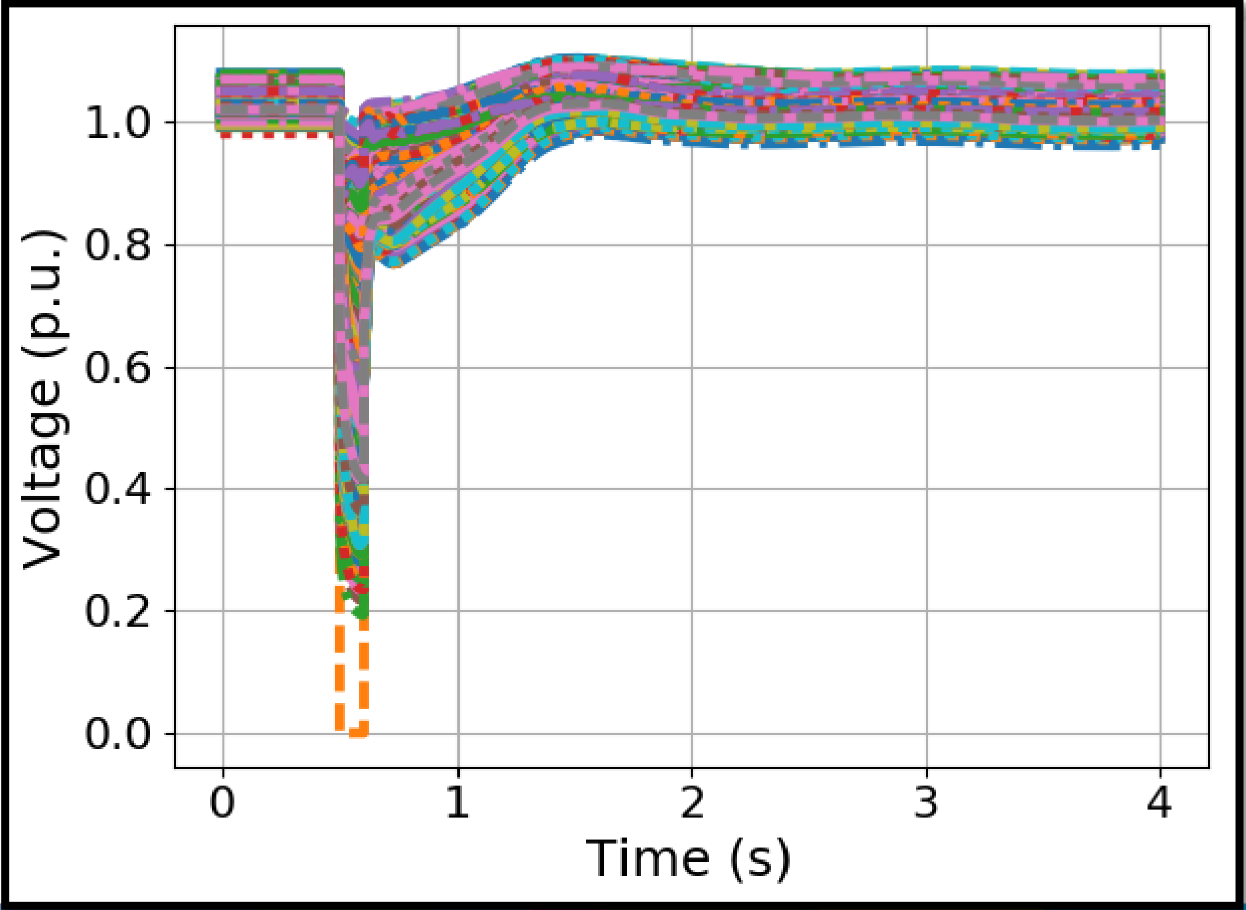


# Results: Trip: Med Synch Gen vs Lo Synch Gen

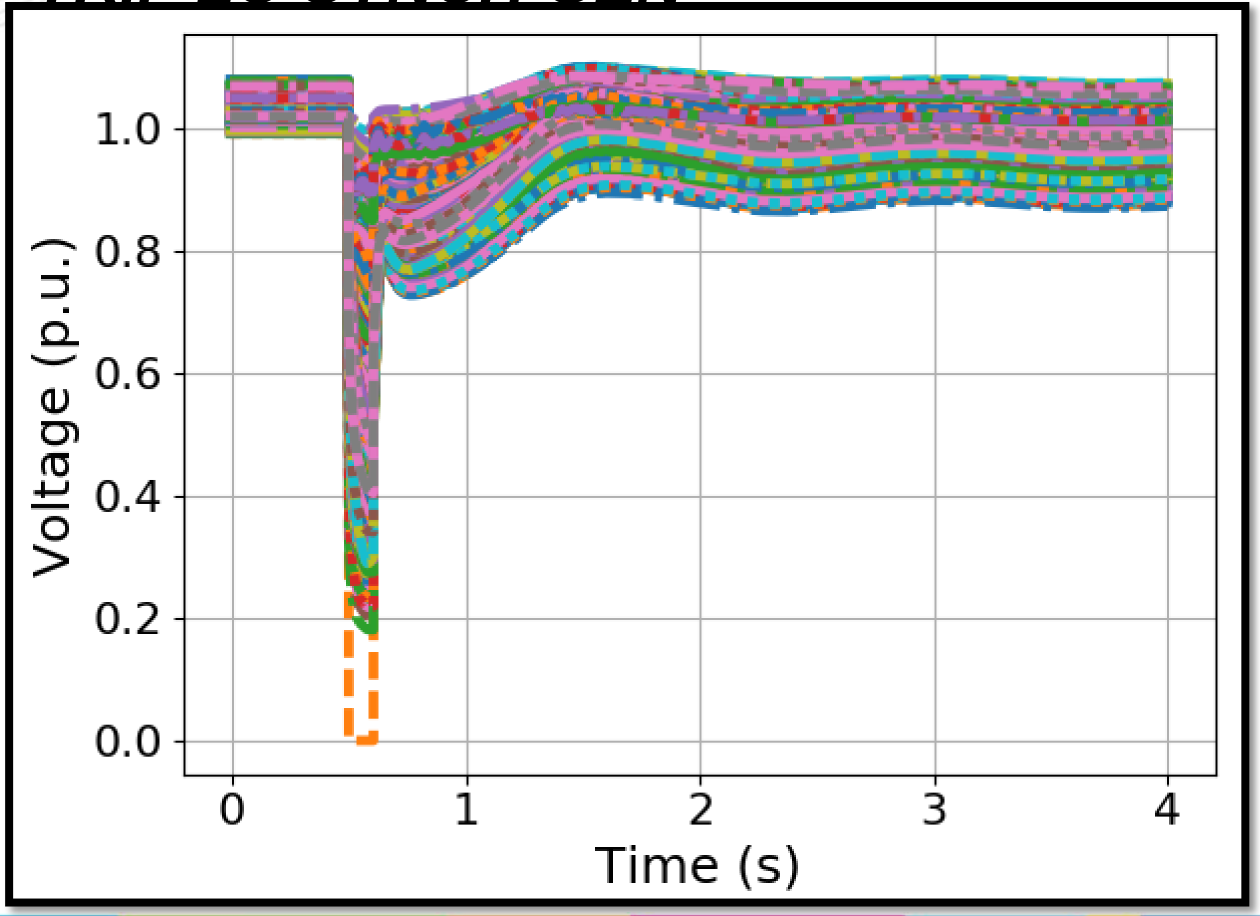
| 13 GW DER-Med Synch Gen Case (6 GW Synch Gen ) | 13 GW DER-Lo Synch Gen Case (4 GW Synch Gen ) |
| --- | --- |

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance, transmission bus voltages

***TRIP MED SYNCH GEN***




***TRIP LO SYNCH GEN***

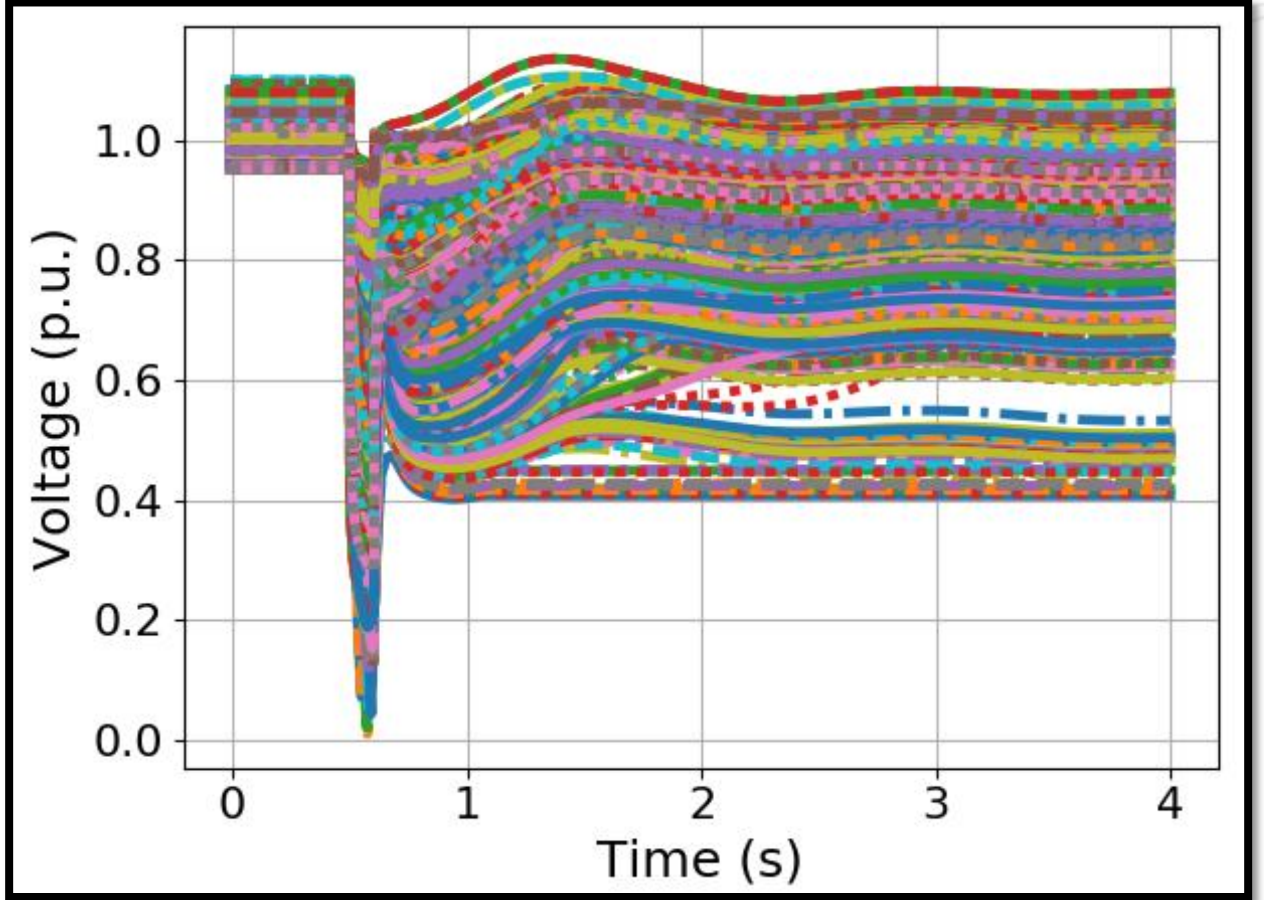


# Results: Trip: T vs. D Bus Voltage Recovery

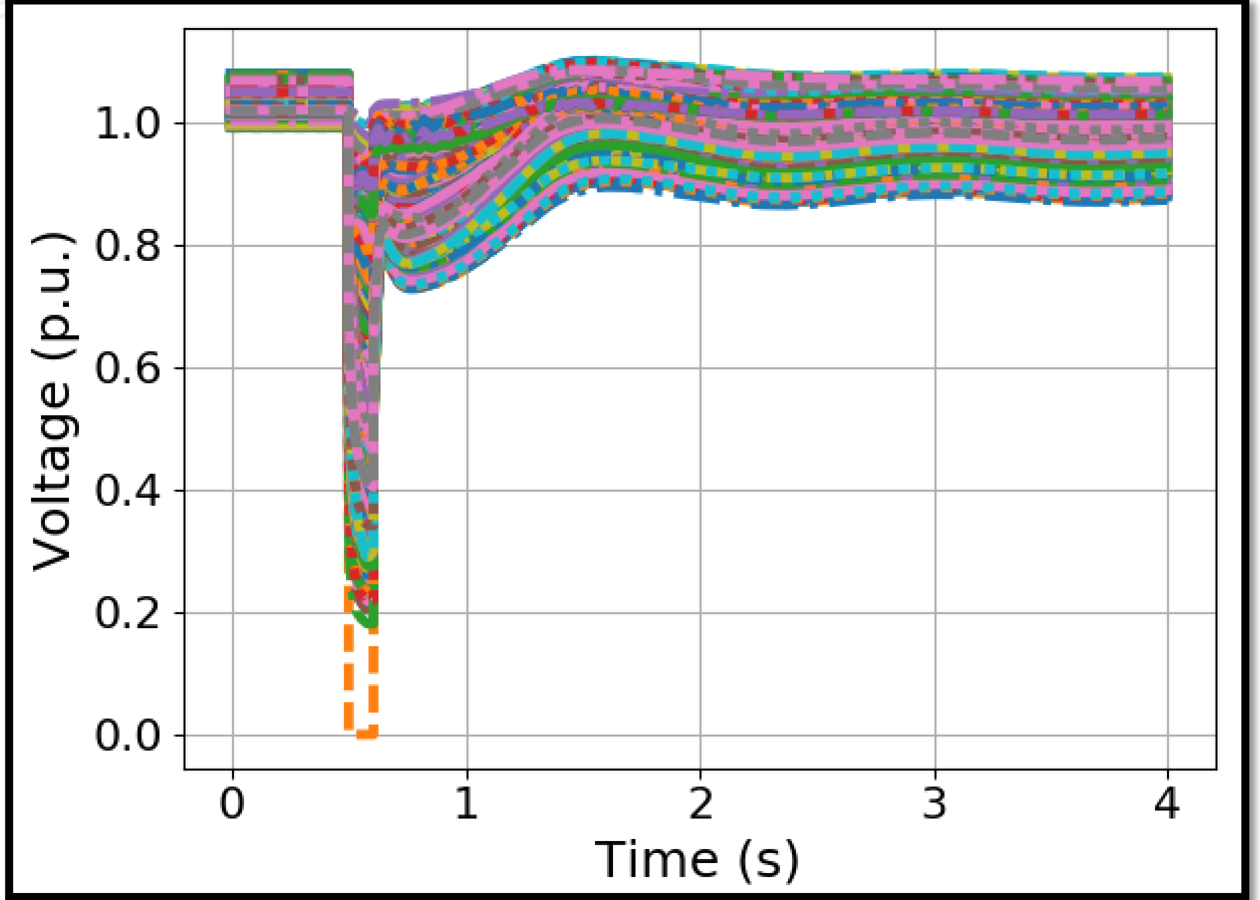
**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance

***TRIP LO SYNCH GEN: DISTRIBUTION***




***TRIP LO SYNCH GEN: TRANSMISSION***

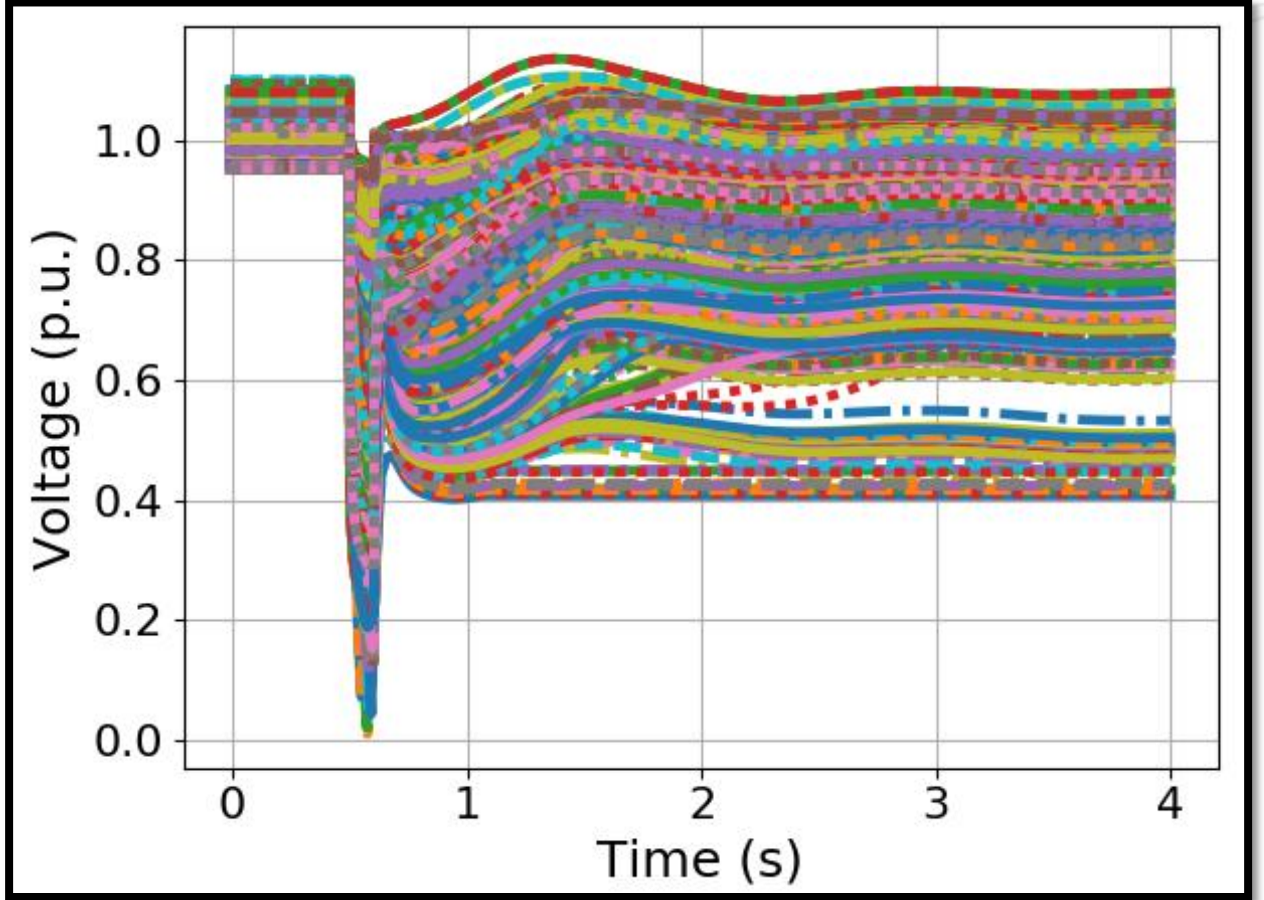


# Results: Distribution Voltage in Trip vs. Ride Through

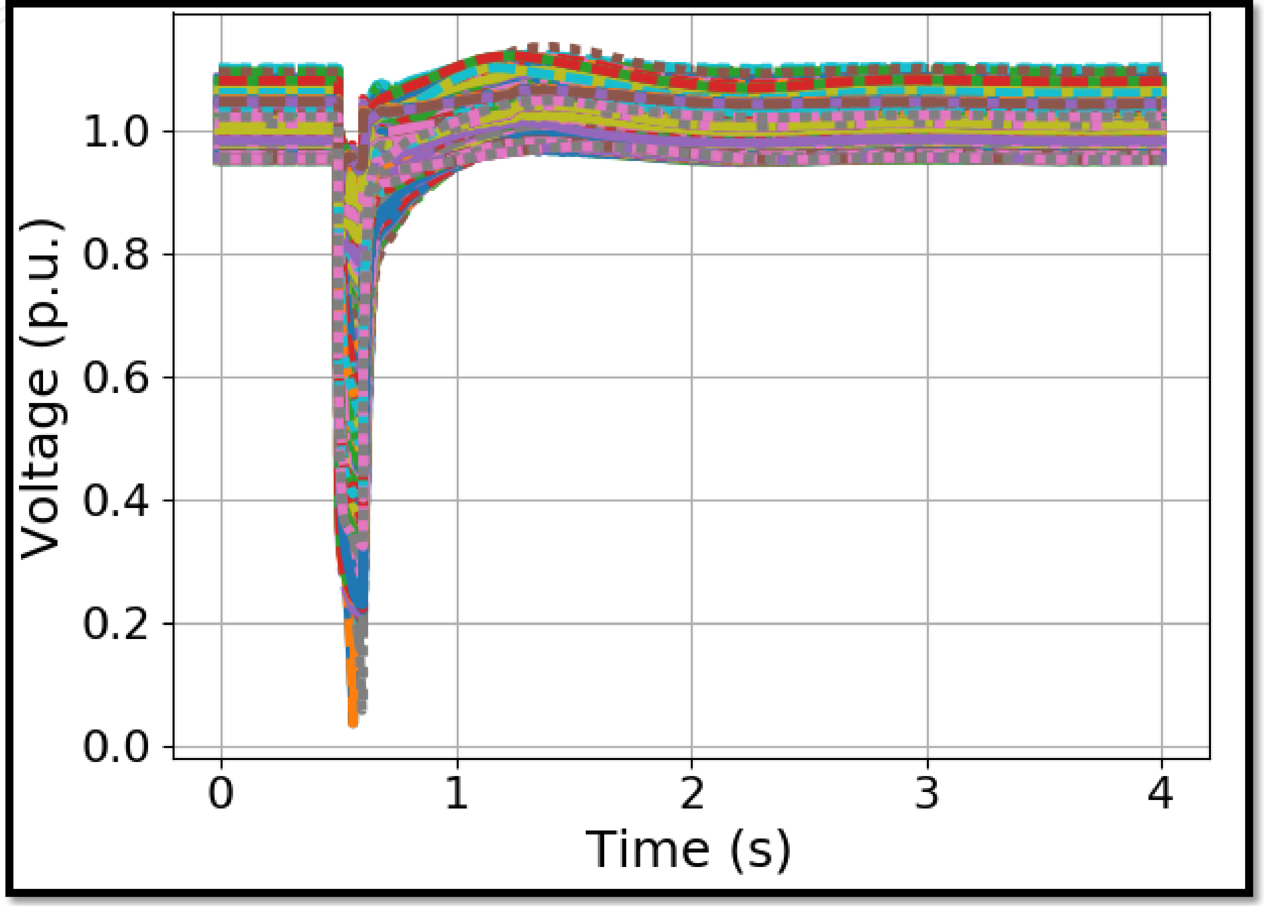
**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance

***TRIP: DISTRIBUTION***




***RIDE THROUGH MC50: DISTRIBUTION***

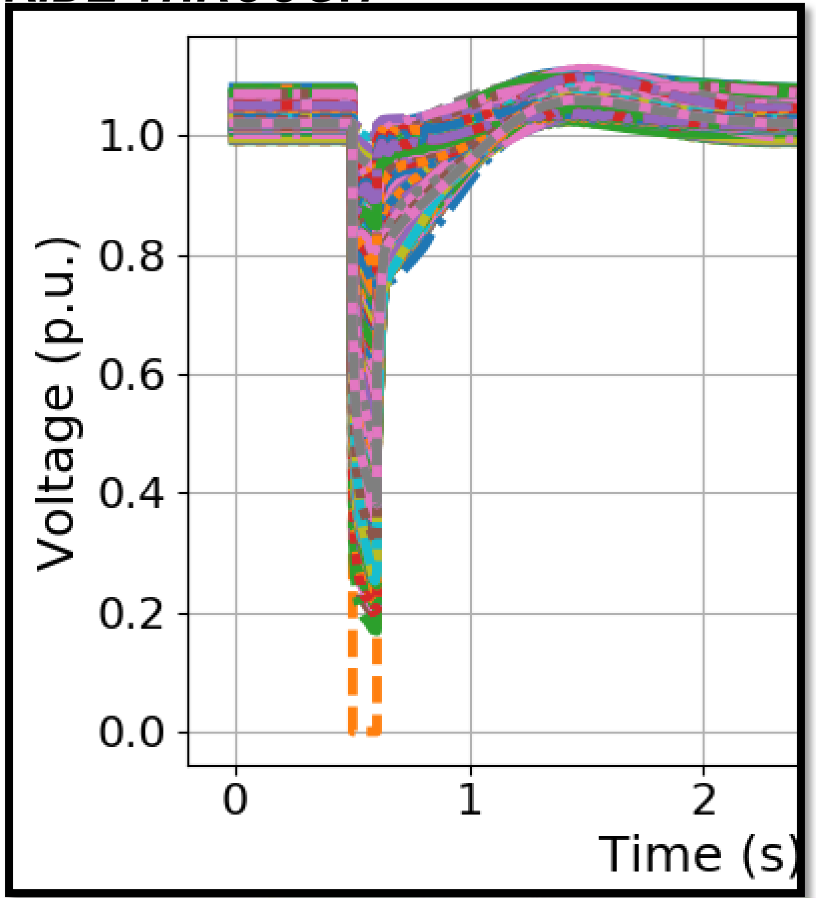


# Results: Ride Through vs. Momentary Cessation

**13 GW DER-Lo Synch Gen Case (4 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance, **transmission busses**

***RIDE THROUGH***

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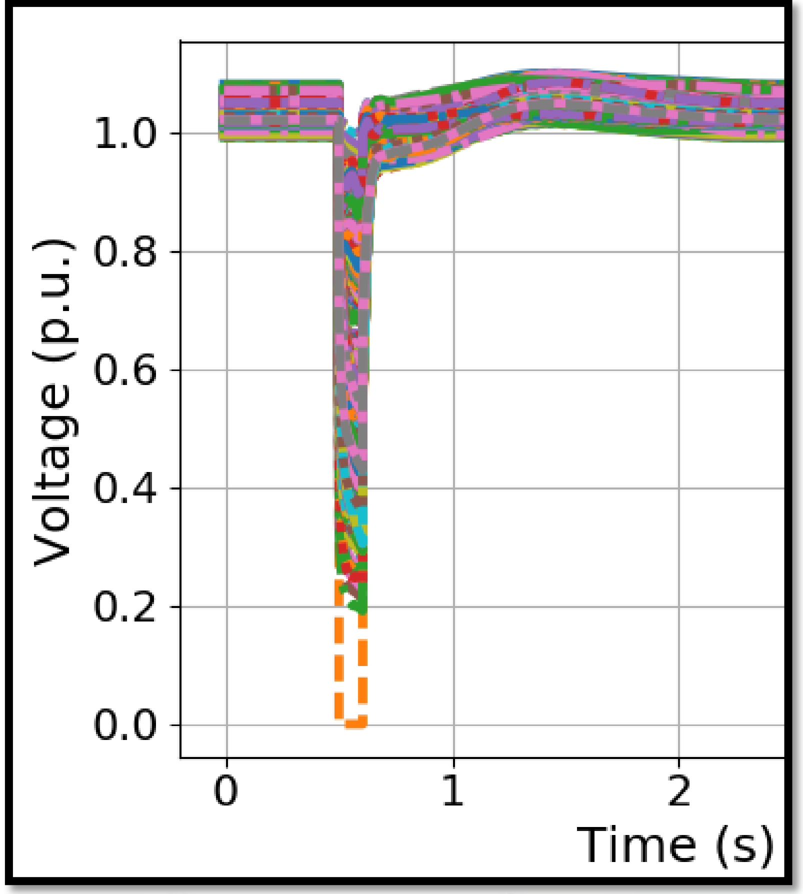
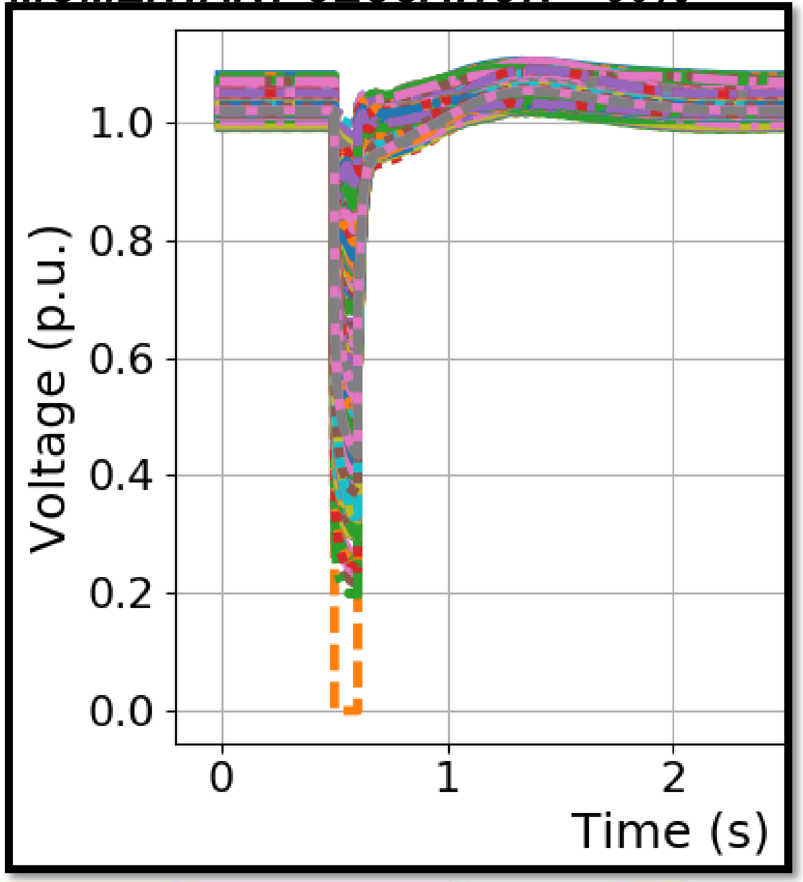



***MOMENTARY CESSATION < 50%***

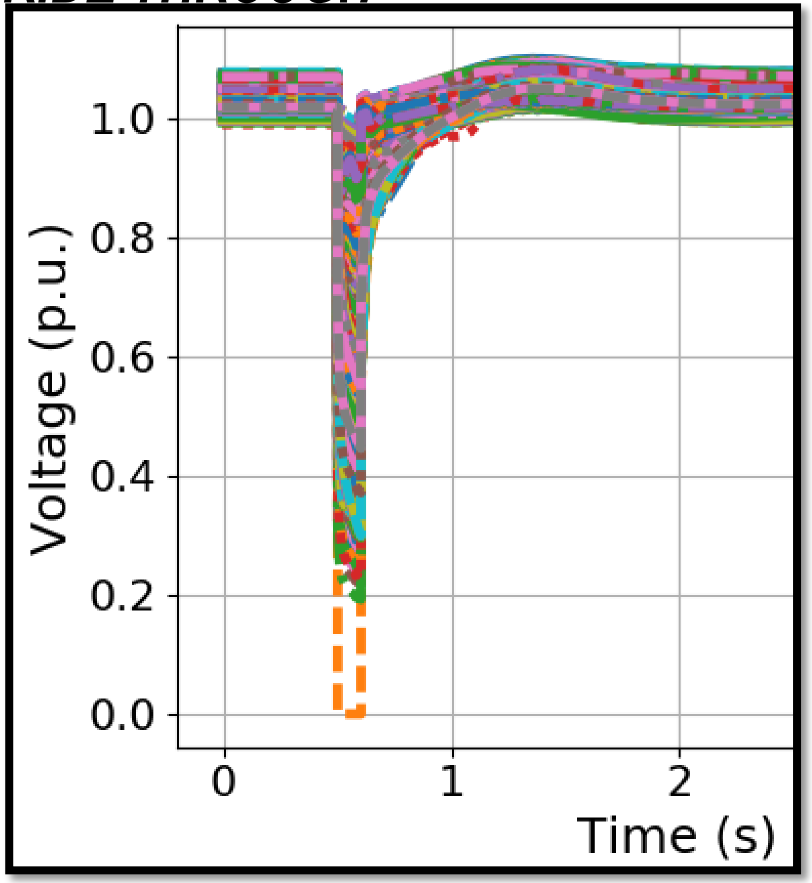


# Results: Ride Through vs. Momentary Cessation

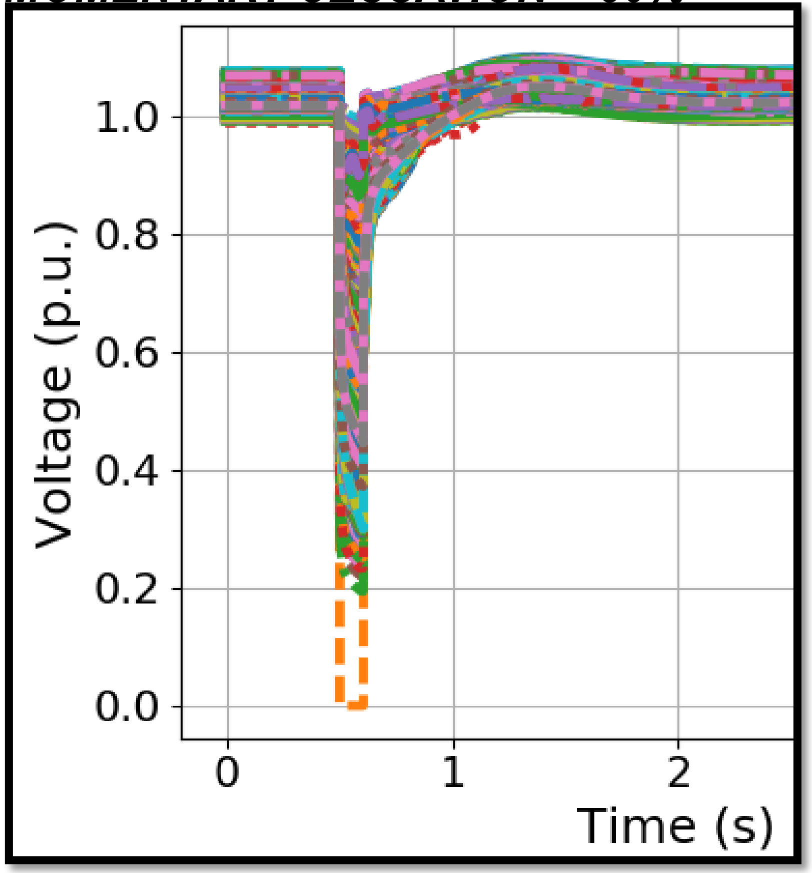
**8 GW DER Case (5 GW Synch Gen )**

Complex Load, Central NJ fault, Voltage Regulation off, high feeder impedance, **transmission busses**

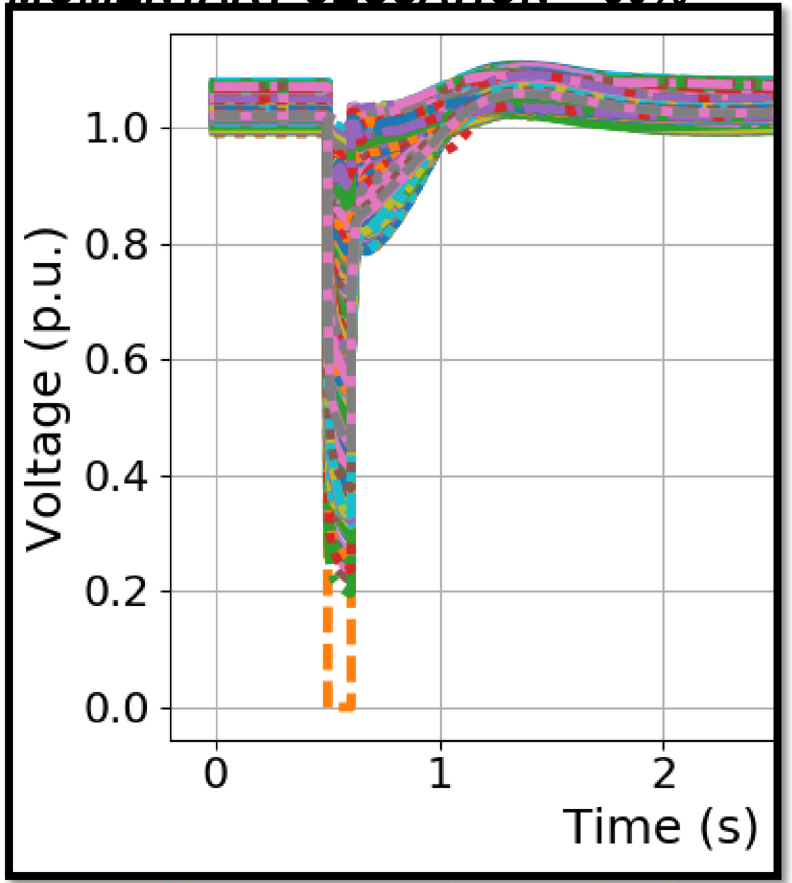
***RIDE THROUGH***




***MOMENTARY CESSATION < 30%***




***MOMENTARY CESSATION < 50%***

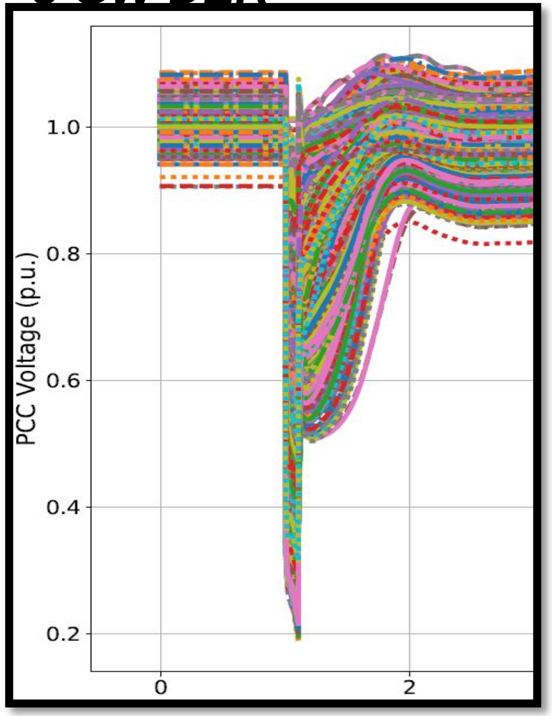


# Results: 3 GW vs. 8 GW vs. 13 GW DER

| 3 GW DER (6 GW Synch Gen ) | 8 GW DER (5 GW Synch Gen ) | 13 GW DER (6 GW Synch Gen) |
|---|---|---|

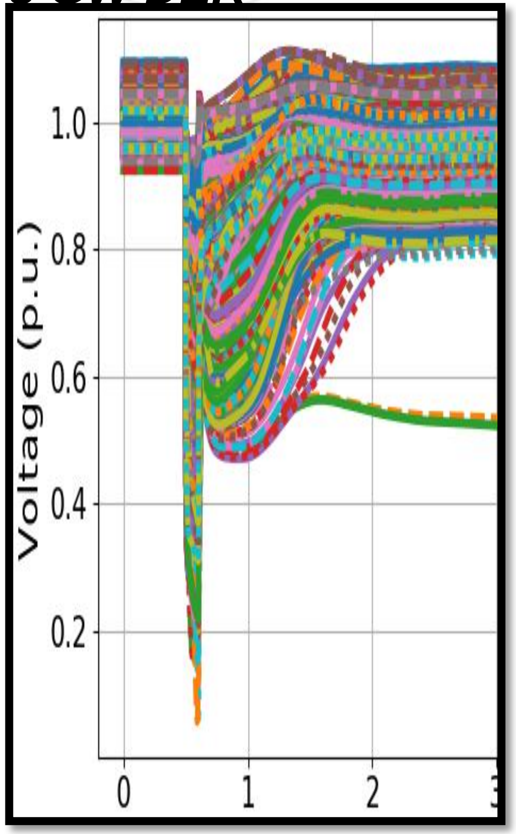
Complex Load, Trip, Central NJ fault, Voltage Regulation off, high feeder impedance, **transmission and distribution bus voltages**

***3 GW DER***



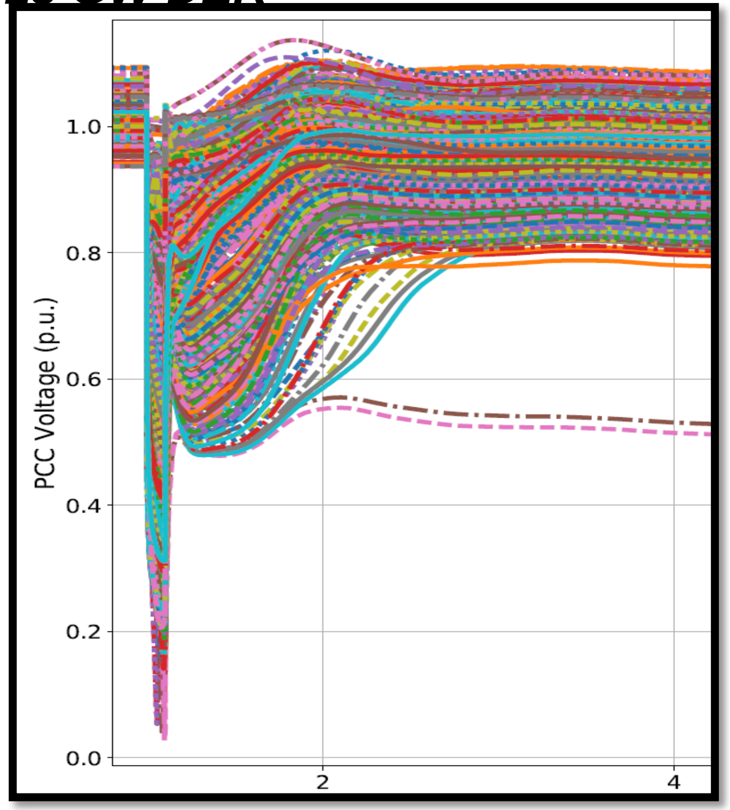

*time (s)*

***8 GW DER***




*time (s)*

***13 GW DER***




*time (s)*