DER Trip Impact Study: Methods, Results, and Conclusions

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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 without** ride through causes impact in all scenarios.

2. **DER with** 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.
Agenda

- Study Project Overview
- Summary of Method and Assumptions
- Results and Conclusions
- Appendix: Detailed Methodology, Assumptions, & Results
In addition to extensive review and discussion with EPRI, these EPRI references provided significant guidance:


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
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2031 PSS/E Dynamic Study Sequence

BES Fault in 2031

DER Trip or Ride Through

BES Fault Clearing

T+D Response

DER recovery

~100 ms

TRIP or other

~ 20,000 ms

Summary of Method and Assumptions
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.

<table>
<thead>
<tr>
<th></th>
<th>2021 Light Load</th>
<th>3 GW DER</th>
<th>8 GW DER</th>
<th>13 GW DER Med Synch Gen</th>
<th>13 GW DER Lo Synch Gen</th>
<th>13 GW DER No Synch Gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>DER</td>
<td>2.1 GW</td>
<td>3.0 GW</td>
<td>8.2 GW</td>
<td>12.6 GW</td>
<td>12.6 GW</td>
<td>12.6 GW</td>
</tr>
<tr>
<td>Synch Gen</td>
<td>7.0 GW</td>
<td>6.2 GW</td>
<td>5.0 GW</td>
<td>6.2 GW</td>
<td>3.7 GW</td>
<td>0.0 GW</td>
</tr>
<tr>
<td>Load</td>
<td>13.8 GW</td>
<td></td>
<td></td>
<td></td>
<td>13.8 GW</td>
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</tr>
</tbody>
</table>

Summary of Method and Assumptions
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

<table>
<thead>
<tr>
<th>Voltage regulation OFF and:</th>
<th>Voltage regulation ON and:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trip</td>
<td>Trip</td>
</tr>
<tr>
<td>Ride Thru</td>
<td>Ride Thru</td>
</tr>
<tr>
<td>Momentary Cessation for V&lt;30%</td>
<td>Momentary Cessation for V&lt;30%</td>
</tr>
<tr>
<td>M.C.&lt;50%</td>
<td>M.C.&lt;50%</td>
</tr>
</tbody>
</table>

![Graph showing DER Active Power vs. Time]
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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Complex load model findings:

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

### Complex Load Model Results

<table>
<thead>
<tr>
<th></th>
<th>3 GW DER</th>
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<th>13 GW DER Lo Synch Gen</th>
<th>13 GW DER No Synch Gen</th>
</tr>
</thead>
<tbody>
<tr>
<td>NJ BES Fault: North/Central</td>
<td>N</td>
<td>C</td>
<td>N</td>
<td>C</td>
<td>N</td>
</tr>
<tr>
<td>MW DER Tripped</td>
<td>Trip</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>790</td>
<td>823</td>
<td>2,628</td>
<td>2,351</td>
<td>4,385</td>
</tr>
</tbody>
</table>

#### Impact Levels
- **Minimal impact**: PJM plans the system so no generation trips following normally-cleared transmission fault.
- **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.
- **Some impact**: PJM’s worst recent historical single-event loss of generation is <2,700 MW.
- **More impact**: Eastern Interconnection's worst recent single-event loss of generation is ~4,500 MW.
- **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

- Distribution bus voltage results for DER trip
- Transmission bus voltage results for DER trip
- Transmission bus voltage results for DER ride through
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

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<tbody>
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<td>N C</td>
<td>N C</td>
<td>N C</td>
<td>N C</td>
<td>N C</td>
<td>N C</td>
</tr>
<tr>
<td><strong>MW DER Tripped</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT</td>
<td>0 0</td>
<td>0 0</td>
<td>0 &lt;100</td>
<td>0 &lt;100</td>
<td>0 &lt;100</td>
</tr>
<tr>
<td>MC50</td>
<td>0 0</td>
<td>&lt;100 0</td>
<td>0 0</td>
<td>0 0</td>
<td>0 &lt;100 0</td>
</tr>
<tr>
<td>MC30</td>
<td>0 0</td>
<td>0 0</td>
<td>&lt;100 0</td>
<td>0 0</td>
<td>0 &lt;100 0</td>
</tr>
</tbody>
</table>

**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

TRIP: DISTRIBUTION VOLTAGE

MC50: DISTRIBUTION VOLTAGE
Finding 3. Momentary cessation $\rightarrow$ 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

MOMENTARY CESSATION < 30%

MOMENTARY CESSATION < 50%
Finding 3. Momentary cessation $\rightarrow$ 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

MOMENTARY CESSATION < 50%
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.
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

<table>
<thead>
<tr>
<th>(X and R in per unit vs. model load base)</th>
<th>R</th>
<th>X</th>
<th>X/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low impedance case</td>
<td>3%</td>
<td>15%</td>
<td>5</td>
</tr>
<tr>
<td>High impedance case</td>
<td>9%</td>
<td>18%</td>
<td>2</td>
</tr>
</tbody>
</table>
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.
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

RIDE THROUGH

Voltage (p.u.)

Time (s)

0 1 2 3 4

0.0 0.2 0.4 0.6 0.8 1.0

0 1 2 3 4

0.0 0.2 0.4 0.6 0.8 1.0
Results: Trip: Med Synch Gen vs Lo Synch Gen

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

TRIP MED SYNCH GEN

TRIP LO SYNCH GEN

www.pjm.com
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**

**MOMENTARY CESSATION < 30%**

**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

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

3 GW DER

8 GW DER

13 GW DER