EPRI Proposed Update to Voltage Fluctuation in SIR, Screen H

For NY Interconnection Technical Working Group
June 9, 2021

Tom Key, Cameron Riley, Devin Van Zandt and Jane Shi, EPRI
tkey@epri.com, 865-310-5724
Key Points in this Presentation

1. Screening results inform CESIR study requirements.
2. Feeder voltage impact is the most common CESIR issue.
3. Changes to screen H criteria are recommended based on;
   - Field experience and PV plant monitoring (in NY)
4. Better estimates for grid voltage and plant variability provide;
   - Sharpen grid impact evaluation for larger plants
   - Account for less cloud-related variability with larger plants
   - Enable more consistent assessments with increasing PV deployment
Rationale for reviewing flicker criteria: CESIR Failures Report from ITWG April 2021 meeting

Reference Tier 1 Failed CESIR's from Industry Members (noting flicker criteria failures, 13 April 2021)

Includes 11 CESIR sample studies, 8 that were submitted in the last 2 years plus 3 from previously.

<table>
<thead>
<tr>
<th>Utility</th>
<th>Name</th>
<th>CESIR</th>
<th>&gt;105%</th>
<th>&lt;95% agg.</th>
<th>&gt;3% agg.</th>
<th>&gt;5% agg.</th>
<th>Tap &gt;1</th>
<th>Flicker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avangrid</td>
<td>Hallock</td>
<td>16060</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
</tr>
<tr>
<td>Avangrid</td>
<td>Redacted</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
</tr>
<tr>
<td>Avangrid</td>
<td>Nastasi</td>
<td>16711</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
</tr>
<tr>
<td>Avangrid</td>
<td>Parma</td>
<td>14515</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>Avangrid</td>
<td>Lewis</td>
<td>16151</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
</tr>
<tr>
<td>NatGrid</td>
<td>Slate</td>
<td>253007</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
</tr>
<tr>
<td>NatGrid</td>
<td>Van Tassel</td>
<td>229020</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
</tr>
<tr>
<td>NatGrid</td>
<td>Bangor (x2)</td>
<td>250999</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td>Fail</td>
</tr>
<tr>
<td>NatGrid</td>
<td>Redacted</td>
<td>(not included)</td>
<td>Fail</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NatGrid</td>
<td>Redacted</td>
<td>(not included)</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NatGrid</td>
<td>Redacted</td>
<td>(not included)</td>
<td>Fail</td>
<td>Fail</td>
<td>Pass</td>
<td>Fail</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note all but one failed voltage rise, 8 of 11 failed flicker criteria. EPRI recommends revisiting flicker criteria.
Giving credit for PV plant size: from EPRI’s worst-case 10-minute plant output variability data (one-second resolution)

IEEE 1547 Flicker Allocation is $P_{st} = 0.35$

These data are from 2MW plants in NY and TN

This Short Circuit Ratio Test is NYSIR Screen F

This chart considers Grid Stiffness using the short circuit ratio, SCR, defined in SIR screen F
Example plant results for using different $\Delta V$ and $Pst$ criteria

<table>
<thead>
<tr>
<th>#</th>
<th>Plant Rating (MW)</th>
<th>Circuit Voltage (kV)</th>
<th>PCC to Sub (mi)</th>
<th>SCR @ PCC</th>
<th>X/R</th>
<th>Min. Load MVA</th>
<th>Plant PF</th>
<th>$\Delta V_1$</th>
<th>$\Delta V_2$</th>
<th>$\Delta V_3$</th>
<th>‘Target’ PF</th>
<th>Pst CESIR</th>
<th>Pst EPRI</th>
<th>F/dpst =1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>12.47</td>
<td>5</td>
<td>15</td>
<td>3.1</td>
<td>.58</td>
<td>1</td>
<td>2.24%</td>
<td>6.71%</td>
<td>2.04%</td>
<td>.95</td>
<td>.35</td>
<td>.037</td>
<td>1.641</td>
</tr>
<tr>
<td>2</td>
<td>2.8</td>
<td>4.8</td>
<td>1.5</td>
<td>3.2</td>
<td>1.1</td>
<td>.222</td>
<td>.95</td>
<td>17.6%</td>
<td>33.3%</td>
<td>13.6%</td>
<td>.74</td>
<td>n/a</td>
<td>.211</td>
<td>1.201</td>
</tr>
<tr>
<td>3</td>
<td>3.4</td>
<td>13.2</td>
<td>7.3</td>
<td>7.8</td>
<td>2.9</td>
<td>.97</td>
<td>.97</td>
<td>2.03%</td>
<td>13.2%</td>
<td>1.18%</td>
<td>.94</td>
<td>n/a</td>
<td>.019</td>
<td>0.928</td>
</tr>
<tr>
<td>4</td>
<td>4.8</td>
<td>13.2</td>
<td>3.5</td>
<td>8.4</td>
<td>3.4</td>
<td>2</td>
<td>1</td>
<td>4.04%</td>
<td>12%</td>
<td>3.4%</td>
<td>.96</td>
<td>.66</td>
<td>.021</td>
<td>0.522</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>12.47</td>
<td>3.3</td>
<td>6.5</td>
<td>2.9</td>
<td>.6</td>
<td>.97</td>
<td>2.58%</td>
<td>16%</td>
<td>1.34%</td>
<td>.95</td>
<td>.392</td>
<td>.012</td>
<td>0.471</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>13.2</td>
<td>2.9</td>
<td>11.9</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3.51%</td>
<td>9.72%</td>
<td>3.1%</td>
<td>.95</td>
<td>.35</td>
<td>.017</td>
<td>0.471</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>12.47</td>
<td>4</td>
<td>6.4</td>
<td>2.2</td>
<td>.17</td>
<td>.97</td>
<td>4.05%</td>
<td>16.2%</td>
<td>2.82%</td>
<td>.91</td>
<td>n/a</td>
<td>.019</td>
<td>0.471</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>13.2</td>
<td>4</td>
<td>6.6</td>
<td>1.6</td>
<td>1.9</td>
<td>.95</td>
<td>5.28%</td>
<td>16.7%</td>
<td>4.04%</td>
<td>.84</td>
<td>.544</td>
<td>.025</td>
<td>0.471</td>
</tr>
</tbody>
</table>

1 Detailed calculation, assumes no load, no regulation equipment, feeder MV voltage; 2 Estimated by IEEE 1453 simplified $\frac{AS}{S_{sc}} = \frac{AS}{V^2/Z_{sc}}$; 3 Estimated by IEEE 1453 detailed $R_{source} \times \Delta P - X_{source} \times \Delta Q / V^2$; 4 Target PF at PCC $\approx \frac{X}{R^2} \sqrt{1 + (\frac{X}{R})^2}$ minimizes $\Delta V$, increase losses. 5 Calculated by $F_{dpst=1} \times \Delta V_1$ from EPRI field measurement data and different plant sizes. Consistent with IEEE 1453 assessment methods and verified with Matlab flickermeter.
Proposed New Screen H: Voltage Impact Tests

1. **Flicker** – Can it be determined that the plant caused voltage fluctuations do not exceed the plant flicker allocation in IEEE 1547-2018? Assessment method is according to IEEE 1453 and allocation limit is $P_{st} < 0.35$ for any DER.

   The following example is specifically for a PV DER, considers moving clouds. In this case plant size must be considered in the assessment. Aggregate may be considered for other plants within 2 km of the PCC.

   $P_{st} = \frac{\text{Grid Stiffness}}{\text{PV Plant Variability}} \times \frac{\Delta S}{S_{sc}} \times \frac{F}{d_{pst=1}} = \text{Grid } \Delta V_{AVE at PCC} \% \times \text{Plant Variability}_{by size} < 0.35$

   $\text{Grid } \Delta V_{at PCC} \% = \frac{R_{SOURCE} \times \Delta P - X_{SOURCE} \times \Delta Q}{V^2}$

   - $V =$ Circuit Voltage
   - $R, X =$ Short Circuit Impedance at PCC
   - $\Delta P =$ 75% of rated plant MW
   - $\Delta Q =$ 75% of rated plant MVAR

2. **ANSI C84.1** – Can it be determined that aggregate DER does not cause voltage excursions outside Range A.

3. **Tap Changer Cycling** – Can it be determined that plant output changes of 75%, considering aggregate DER (within 2 km of the PCC), do not cause voltage changes >1.5%.

   $PV_{f} = 3.77 \times e^{-0.416 \times \text{MW}}$

   - A 10-kW resolution look up table is posted on ITWG for June 9, 2021
   - This equation can also be used to estimate variability by plant footprint:
PV Plant Variability Factor (F/dpst=1) by size (from EPRI 1-second plant data, full year and worst-case 10-minutes)

<table>
<thead>
<tr>
<th>Plant rating (MW)</th>
<th>F/dpst=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.641</td>
</tr>
<tr>
<td>2.75</td>
<td>1.201</td>
</tr>
<tr>
<td>3.37</td>
<td>0.928</td>
</tr>
<tr>
<td>4.75</td>
<td>0.522</td>
</tr>
<tr>
<td>5</td>
<td>0.471</td>
</tr>
<tr>
<td>5</td>
<td>0.471</td>
</tr>
<tr>
<td>5</td>
<td>0.471</td>
</tr>
<tr>
<td>5</td>
<td>0.471</td>
</tr>
</tbody>
</table>

Notes on use and available of EPRI PV plant variability factor data:

1. Limits apply only for PV flicker and may be applied directly to describe worst-case 10-minutes.
2. A safety factor may be used to address other unforeseen voltage/plant interactions.
3. Data for high resolution look up is posted on the ITWG site (1000 points at 10kW intervals from 10kW to 10MW from curve fit)

\[ PVF = 3.77 \times e^{-0.416 \times MW} \]
Concept of Planning Levels and Safety Factor

• EPRI plant variability data does not include any safety margin except, the high-power variability hours per year are limited (typical NY climate we expect ~10-20 hours/year within 50% of worst-case 10 minute).

• For example, planning levels are typically, more conservative than specific case studies, see flicker planning levels in 1453;

• Screening criterion sometimes includes a safety margin. For example, it is reasonable to consider unforeseen equipment interactions, fluctuating loads or high ambient voltage variability.

<table>
<thead>
<tr>
<th>Recommended Planning Levels, L_{Pst}, L_{Plt} [from IEEE 1453-2015]</th>
<th>Flicker planning levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MV</td>
</tr>
<tr>
<td>L_{Pst}</td>
<td>0.9</td>
</tr>
<tr>
<td>L_{Plt}</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Main Take-Aways from this Research

1. For larger DER, voltage rise is an issue, flicker generally is not
2. Larger plants, at low X/R locations, challenge pf correction
3. Plant size should be considered in PV variability assessments
4. Changes from moving clouds do not add up beyond a km
5. Recommended next steps;
   - Update screen H using the IEEE 1453 approach.
   - For PV, consider plant size and use detailed estimate for ΔV
   - For battery and other DER applications use detailed estimate for ΔV
Common Solar uses cases for Batteries (symbiotic relationships)

1. Peak shaving
2. Time shifting
3. Valley filling
4. Smoothing
5. Firming and shaping
6. Load following

Note: Flicker reduction is not a recommended use case for batteries.
Together...Shaping the Future of Electricity
Supporting Materials for Voltage Screening Discussion
Reminder of the current SIR Screens

SIR Preliminary Screens

A. Is the PCC on a Networked Secondary System?
B. Is Certified Equipment Used?
C. Is the Electric Power System (EPS) Rating Exceeded?
D. Is the Line and Grounding Configuration Compatible with the Interconnection Type?
E. Simplified Penetration Test (15%)
F. Is Feeder Capacity Adequate for Individual and Aggregate DER? (25%)

SIR Supplemental Review (CESIR reference)

G. Supplemental Penetration Test
H. Voltage Flicker Test
I. Operating Limits, Protection Adequacy and Coordination Evaluation
Original Screen H: Voltage Flicker Test

Can it be determined that the voltage fluctuation is within acceptable limits as defined by IEEE 1453

1. Voltage flicker emission generated by each fluctuating installation (Pst) should be limited to its emission limit (E_{pst}).

\[ P_{st} = \left( \frac{Grid}{Stiffness} \right) \times \frac{PV \text{ Plant Variability}}{Varibility} \approx \left( \frac{\Delta S}{Ssc} \right) \times \frac{F}{d_{pst=1}} = Grid \Delta V_{PCC} \% \times \text{Plant Variability by size} \]

- \( d \sim \left( \frac{\Delta S}{Ssc} \right) \) is the relative voltage change caused by the project
- \( \Delta S \) is the power variation from the project
- \( Ssc \) is the available short-circuit capacity of area EPS at the PCC
- \( F \) is the shape factor related to the shape of expected voltage fluctuation (can be considered equal to 0.2 if detailed information is not available)
- \( d_{pst=1} \) is the relative voltage change that yield \( P_{st} \) value of unity assuming rectangular voltage fluctuation (2.56\% assuming 1 dip per minute)

Notes:

1. The .2 (not from IEEE) was adopted in the absence of more specific DER Plant information.
2. The 2.56\% and .35 are from IEEE
3. PV plant monitoring indicates that plant size has a substantial effect in smoothing output variability.
4. Need to consider plant size when evaluating flicker

2. Can it be determined within the Supplemental Review that aggregate DER does not cause voltage excursion outside of ANSI C84.1 Range A?
3. Can it be determined that an aggregate DER voltage fluctuation of 75\% does not result in a voltage change of greater than half the bandwidth of any voltage regulating device on the associated feeder.

A Pst greater than 0.35 as calculated in Step 1 or no to the determination in Steps 2 and 3 constitutes failure of this screen.
Original Screen H: Voltage Flicker Test  (from NYDPS SIR dated 10/3/2018)

Can it be determined that the voltage fluctuation is within acceptable limits as defined by IEEE 1453

1. Voltage flicker emission generated by each fluctuating installation (Pst) should be limited to its emission limit (Epst).

\[ P_{st} = \frac{\text{Grid Stiffness}}{\text{PV Plant Variability}} \approx \frac{\Delta S}{S_{sc}} \times \frac{F}{d_{pst=1}} \approx \frac{\Delta V}{V} \times 0.2 \times 2.56 = \Delta V \% \times 7.8 \leq 0.35 \]

- \( d \approx \left( \frac{\Delta S}{S_{sc}} \right) \) is the relative voltage change caused by the project
- \( \Delta S \) is the power variation from the project
- \( S_{sc} \) is the available short-circuit capacity of area EPS at the PCC
- \( F \) is the shape factor related to the shape of expected voltage fluctuation (\( F \) can be considered equal to 0.2 if detailed information is not available)
- \( d_{pst=1} \) is the relative voltage change that yield \( P_{st} \) value of unity assuming rectangular voltage fluctuation (2.56% assuming 1 dip per minute)

2. Can it be determined within the Supplemental Review that aggregate DER does not cause voltage excursion outside of ANSI C84.1 Range A?

3. Can it be determined that an aggregate DER voltage fluctuation of 75% does not result in a voltage change of greater than half the bandwidth of any voltage regulating device on the associated feeder.

A Pst greater than 0.35 as calculated in Step 1 or no to the determination in Steps 2 and 3 constitutes failure of this screen.

Note, .2 is suggested unless more specific DER Plant information is available, PV plant size matters.
Screen H: Voltage Flicker Test

Can it be determined that the voltage fluctuation is within acceptable limits as defined by IEEE 1453.

Voltage flicker emission generated by each fluctuating installation (Pst) should be calculated using the following formula:

\[
\Delta V = \left( \frac{d}{dp_{st}} \right) \times F \leq 0.35 \quad \text{and} \quad d = \left( \frac{R_l \times \Delta P + X_l \times \Delta Q}{V^2} \right)
\]

When: \(\frac{X_l}{R_l} \leq 5\)

OR

\[
\Delta V = \left( \frac{d}{dp_{st}} \right) \times F \leq 0.35 \quad \text{and} \quad d = \left( \frac{\Delta V}{V} \right) \approx \frac{\Delta S}{S}
\]

When: \(\frac{X_l}{R_l} \geq 5\)

Explanation of Variables & Acronyms:
- \(d\) is the relative voltage change caused by the DER at the PCC.
- \(d_{st} = 1\) (curve value) is the relative voltage change that yields a Pst value of unity when voltage fluctuations are rectangular.
- \(P_{st}\) is the short-term flicker emission limit for the customer installation (typically based on 10-minute time frame).
- \(X_l\) is the line reactance in ohms.
- \(R_l\) is the line resistance in ohms.
- \(I_{sc}\) is the maximum available 3-phase fault current at the PCC in amperes.
- \(S_{sc}\) is the maximum available fault apparent power at the PCC.
- \(\Delta S\) is the change in apparent power in volt amperes.
- \(\Delta P\) is the change in real power in watts of the DG.
- \(\Delta Q\) is the change in reactive power in vars of the DG.
- \(V\) is the nominal line to line voltage.
- \(\Delta V\) is the change in voltage at the PCC.
- \(F\) is the shape factor related to the shape of the expected voltage fluctuation.

1. Can it be determined within the Supplemental Review that aggregate DER does not cause voltage excursion outside of ANSI C84.1 Range A?
2. Can it be determined that an aggregate DER voltage fluctuation of 75% does not result in a voltage change of greater than half the bandwidth of any voltage regulating device on the associated feeder.

Note this 2019 CESIR update lost the formula \(d/d_{st}=1\) and left out the conservative definition of plant variability (.2/2.56%).
### 7 example feeders showing load and x/r relative to head (right) and tail (left)

<table>
<thead>
<tr>
<th>Feeder Number</th>
<th>Rated kV</th>
<th>X value at head end</th>
<th>R value at X/R=1</th>
<th>Range of X/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>631</td>
<td>0.95</td>
<td>2.08</td>
<td>12.3 -.7</td>
</tr>
<tr>
<td>2</td>
<td>2885</td>
<td>0.74</td>
<td>4.24</td>
<td>11.1 -.6</td>
</tr>
<tr>
<td>3</td>
<td>420</td>
<td>0.43</td>
<td>2.29</td>
<td>15.7 -.9</td>
</tr>
<tr>
<td>4</td>
<td>281</td>
<td>1.15</td>
<td>3.26</td>
<td>19.4 -.2</td>
</tr>
<tr>
<td>5</td>
<td>2921</td>
<td>1.11</td>
<td>3.22</td>
<td>9.9 -.55</td>
</tr>
<tr>
<td>6</td>
<td>683</td>
<td>0.97</td>
<td>6.8</td>
<td>13.2 -.65</td>
</tr>
<tr>
<td>7</td>
<td>888</td>
<td>0.22</td>
<td>0.93</td>
<td>20.5 - 1</td>
</tr>
</tbody>
</table>

**Notes on the graphic color scheme with respect to reactive power compensation on the sample feeders;**

1. Beige area indicates less ΔV resulting with compensation
2. Green indicates effective range for reactive compensation
3. Red indicates increasing losses if reactive compensation is used

**Feeder 683 Characteristics**

- Capacity ~ 20 MVA
- Three-Phase Nodes – 550
- DER\textsubscript{MW} if stiffness at 25 = 6.4 -.4 MW
Four Methods for Estimating ΔV - EPRI recommends IEEE 1453 detailed ...see comparison of results in the following slides

- **Actual** feeder parameters and a detailed calculation of ΔV using:

  \[ d = \frac{\Delta V}{V} = \sqrt{\left(1 + \frac{\Delta P}{V^2} R_L - \frac{\Delta Q}{V^2} X_L\right)^2 + \left(\frac{\Delta P}{V^2} X_L + \frac{\Delta Q}{V^2} R_L\right)^2} - 1 \]

- **IEEE 1453 Simplified (using SCR)** - A simplified formula from IEEE 1453 (for load power change)

  \[ d = \frac{\Delta V}{V} \sim \frac{\Delta S}{S_{SC}} = \frac{\Delta S}{V^2/Z_{SC}} \]

- **IEEE 1453 Detailed** - A more detailed formula from IEEE 1453 (for lower x/r ratios) when used for generator the ΔQ needs to be "-" sign convention.

  \[ d = \frac{\Delta V}{V} \sim \frac{R_{SOURCE} \times \Delta P - X_{SOURCE} \times \Delta Q}{V^2} \]

- **Only R** - Use the simplified formula from IEEE 1453 but neglect \( X_{source} \).

  \[ d = \frac{\Delta V}{V} \sim \frac{\Delta S}{S_{SC}} = \frac{\Delta S}{V^2/RSC} \]
Comparing $\Delta V$ estimate on feeder #683 - In terms of $X/R$

At unity power factor, IEEE 1453 detailed method ("IEEE 1453") and estimation using only $R$ ("Only R") are equivalent.

PF = 1.0

PF = 0.975