Understanding the Performance of Parallel Temporary Protective Grounds

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NEETRAC
Outline

• Introduction
• NEETRAC Test Program
• Test Results
• Modeling
• De-Rating Factors
• Conclusions
Project Purpose / Scope

- Available fault currents on the order of 80 kA exist on utility systems
  - Grade 7H assemblies are rated at 68 kA
- Need ability to reliably protect linemen
- Limited information on the performance of parallel TPGs
  - How much to de-rate each TPG?
  - How many TPGs to use?
  - What spacing to use?
- NEETRAC undertook large study to try and provide information on these questions

This project does not answer all questions about parallel TPGs
Results apply to tested TPG assemblies
### ASTM F855 Symmetric & Asymmetric Fault Tests

**Table 1: Protective Ground Cable, Ferrule, Clamp and Assembly Ratings for Symmetrical Current**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield Strength, lb/in. n-m</th>
<th>Ultimate Strength, lb/in. n-m</th>
<th>Withstand Rating, Symmetrical kA, RMS, 60 Hz</th>
<th>Ultimate Rating Capacity, Symmetrical kA, RMS, 60 Hz</th>
<th>Continuous Current Rating, A, RMS, 60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>280</td>
<td>32</td>
<td>330</td>
<td>57</td>
<td>37</td>
</tr>
<tr>
<td>2</td>
<td>280</td>
<td>32</td>
<td>330</td>
<td>57</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>32</td>
<td>330</td>
<td>57</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>280</td>
<td>32</td>
<td>330</td>
<td>57</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>280</td>
<td>32</td>
<td>330</td>
<td>57</td>
<td>37</td>
</tr>
<tr>
<td>6</td>
<td>330</td>
<td>37</td>
<td>400</td>
<td>45</td>
<td>43</td>
</tr>
<tr>
<td>7</td>
<td>330</td>
<td>37</td>
<td>400</td>
<td>45</td>
<td>43</td>
</tr>
</tbody>
</table>

**Table 2: Ultimate Assembly Rating for High X/R Ratio Applications**

<table>
<thead>
<tr>
<th>High Asymmetrical Test Requirements</th>
<th>X/R = 30</th>
<th>Cycle Current Peak Values (kA)</th>
<th>Test Duration (cycles)</th>
<th>Test Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1H</td>
<td>14</td>
<td>51</td>
<td>24</td>
<td>59</td>
</tr>
<tr>
<td>2H</td>
<td>15</td>
<td>41</td>
<td>23</td>
<td>57</td>
</tr>
<tr>
<td>3H</td>
<td>16</td>
<td>42</td>
<td>22</td>
<td>55</td>
</tr>
<tr>
<td>4H</td>
<td>17</td>
<td>43</td>
<td>21</td>
<td>53</td>
</tr>
<tr>
<td>5H</td>
<td>18</td>
<td>44</td>
<td>20</td>
<td>51</td>
</tr>
<tr>
<td>6H</td>
<td>19</td>
<td>45</td>
<td>19</td>
<td>49</td>
</tr>
</tbody>
</table>

Note 1—Temperature must be held constant at 20° C.
Note 2—Assemblies should be subjected to these tests.
Note 3—For use with cables exceeding 20% asymmetry factor.
Note 4—See Table 2 for additional information.
Note 5—Alternate testing circuits are available for laboratories that cannot achieve the above requirements. See Appendix X4 for details.

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Extracted from ASTM F855-2015: Standard Specifications for Temporary Protective Grounds to be Used on De-Energized Electric Power Lines and Equipment
Standards bodies suggest minimum 10% de-rating per TPG

This project was about getting the de-rating factors

Goal: Determine the De-Rating Factors
De-Rating – What is out there?

- ASTM F855 Standard Specifications for Temporary Protective Grounds to Be Used on De-energized Electric Power Lines and Equipment
  - “The thermal withstand rating of each TPG used in the multiple assembly set should be reduced by at least 10% to account for unequal current division”
- IEEE 1246 - Guide for Temporary Protective Grounding Systems Used in Substations
  - “To account for unequal current division, reduce the thermal current rating (4.6.2) by at least 10% of each TPG used in the multiple assembly set”
  - “In grounding applications where a single personal protective ground cable does not have the necessary withstand current rating, or would require an unacceptably large conductor, identical ground cables may be connected in parallel. To account for unequal current division between parallel grounds, derating multipliers should be applied as follows.”

<table>
<thead>
<tr>
<th>Ampacity of Paralleled Protective Ground Cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Rating of</td>
</tr>
<tr>
<td>Two parallel cables</td>
</tr>
<tr>
<td>Three parallel cables</td>
</tr>
</tbody>
</table>
Historical TPG Tests

- Review conducted of all TPG fault testing performed by NEETRAC and supportive members
  - 14 projects in total
  - Covers projects 1996 – 2013
  - 352 separate fault tests
  - Many different hardware and configurations tested
  - Tests performed according to ASTM F855
  - 73% of tests utilized asymmetric fault currents
Historical Data – Single and Multiple TPGs

17 Tests at 80 kA RMS

Multiple TPG Tests: 2 (27.8%), 3 (4.1%), Unknown: 5 (5.1%), 1 (63.1%)

Historical data is not able to answer de-rating question
Test Program Design & Samples
# Test Program Design

<table>
<thead>
<tr>
<th>Fixed Parameters</th>
<th>Level(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Waveform X/R</td>
<td>30 (Peak multiplier = 2.69)</td>
</tr>
<tr>
<td>Clamp Spacing</td>
<td>3.5, 6, or 12 in</td>
</tr>
<tr>
<td>Cable Length [ft]</td>
<td>20</td>
</tr>
<tr>
<td>Clamp Orientation</td>
<td>Perpendicular to bus (ASTM F855)</td>
</tr>
<tr>
<td>Mounting Hardware</td>
<td>None</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factors</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TPGs in parallel [#]</td>
<td>2 \ 3</td>
</tr>
<tr>
<td>Cable Sizes</td>
<td>2/0 (133 kcmil) \ 4/0 (212 kcmil)</td>
</tr>
<tr>
<td>Current (RMS)</td>
<td>2/0 AWG (Grade 3H) ( I_{\text{rated}} = 31 \text{ kA} ) \ 4/0 AWG (Grade 5H) ( I_{\text{rated}} = 47 \text{ kA} )</td>
</tr>
</tbody>
</table>

| Design | 4 Replicates |
Test Program Design - Complications

- Replicates were used to verify observed performance

<table>
<thead>
<tr>
<th>Replicate Tests [#]</th>
<th>Probability of all Tests Passing at Random [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

- TPGs are not inexpensive devices
  - Tests required 2 or 3 samples per test
## Final TPG Samples

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Size</td>
<td>2/0 AWG 4/0 AWG</td>
</tr>
<tr>
<td>Ferrule</td>
<td>Threaded w/shroud</td>
</tr>
<tr>
<td>Strain Relief</td>
<td>Yes Yes</td>
</tr>
<tr>
<td>Top Clamp</td>
<td>Grade 3 C-Clamp Grade 5 C-Clamp</td>
</tr>
<tr>
<td>Bottom Clamp</td>
<td>Grade 5 – Flat Face Grade 5 C-Clamp</td>
</tr>
<tr>
<td>Cable Length</td>
<td>20 ft 20 ft</td>
</tr>
<tr>
<td>Install torque</td>
<td>Manufacturer specified</td>
</tr>
</tbody>
</table>

![Images of TPG Samples]
Test Results
Tests Completed

• Group 1 tests completed at NEETRAC NJCL in September, 2016
  – Single TPG performance verified before proceeding with parallel tests
  – Setup developed to capture current split (i.e. current flowing in each individual TPG)
    o First time this was done
    o Setup likely impacted Pass/Fail results of tests due to unequal impedance paths
  – 24 tests completed (8 at 80 kA)
• Group 2 tested in June, 2017
  – 29 tests Completed (21 at 80 kA, includes single TPGs)

29 Tests at 80 kA
Group 1 Laboratory Setup

Multiple return buses
Group 2 Laboratory Setup

Single return bus
Sample Installation (Both Groups)

• All samples new and unused
• Spacing is center-to-center and equal for all TPGs in a particular test
• All clamps torqued to manufacturer recommendations using calibrated torque wrenches
• Any set screws also torqued to manufacturer recommendations
• Each TPG hung freely off the ground
Fault Tests are Challenging... (Video)

Triple TPG 12 in spacing, 80 kA RMS
Mechanical and Thermal Failure (Video)
4/0 AWG TPG Tests

Rated Current = 47 kA
Test Currents = 63.5 & 80.0 kA
Survive – 4/0 AWG TPG

12 in Spacing, 63.5 kA RMS (Test 7-3, Trip 1)
Failure – 4/o AWG TPG

12 in Spacing, 80 kA RMS (Test 8-5, Trip 1)
Survive – 4/0 AWG TPG

6 in Spacing, 80 kA RMS (Test 8-2, Trip 2)
Survive – 4/0 AWG TPG

3.5 in Spacing, 80 kA RMS (Test 7-2, Trip 2)
## Overall Results – 4/0 AWG Tests

<table>
<thead>
<tr>
<th>Cable Size</th>
<th>TPGs [#]</th>
<th>Clamp Spacing [in]</th>
<th>Restraint [Yes/No]</th>
<th>Return Bus Config.</th>
<th>63.5 kA (1.35 ( I_{\text{rated}} ))</th>
<th>80.0 kA (1.7 ( I_{\text{rated}} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/0 AWG</td>
<td>2</td>
<td>12</td>
<td>No</td>
<td>Split</td>
<td>3/4</td>
<td>0/4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yes*</td>
<td>Single</td>
<td>Not Tested</td>
<td>0/4</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td></td>
<td>No</td>
<td>Split</td>
<td>4/4</td>
<td>0/4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yes*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td></td>
<td>No</td>
<td>Single</td>
<td>Not Tested</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Restraints were not installed deliberately. Support frame acted as restraint unintentionally.
Modeling

Expected Current Splits
Forces Involved
Simulation models are useful understanding the sensitivity & probabilistic aspects of TPG performance (i.e. Monte Carlo)
TPG Resistance Distributions

Primary sample dependent parameter:
Resistance
(all meet ASTM F2249)

Randomly generate a resistance for each TPG in Monte Carlo simulation
Monte Carlo Predicted Current Splits

Three 4/0 TPGs, 80 kA, 12 in Spacing, X/R = 30

**Peak Current**

Impacts heat generated during fault

\[ T \propto I_{n}^2 \]

Impacts force TPGs experience

\[ F \propto I_j \times I_k \]

**RMS Current**
• ASTM F855 Grade 5H TPGs are designed to withstand 47 kA for 15 cycles.

• Based on current magnitude alone, 3 TPG’s should survive 80 kA RMS fault.

• BUT…High power tests show that 3 TPGs survive at 3.5 in and not at 12 in.

Why do we need to de-rate?

Forces between TPGs are not equal (and they are large)
Forces on TPG 1

Forces on TPG 1

Force Types
1. TPG to TPG
2. Bus on TPG

\[ F_1 = \Sigma \text{Forces} = F_{12} + F_{13} + F_{1\text{Loop}} \]
Forces on TPG 2

\[ F_2 = \sum \text{Forces} = F_{23} - F_{21} + F_{2\text{Loop}} \]
Forces on TPG 3

\[ F_3 = \sum \text{Forces} = F_{3\text{Loop}} - F_{31} - F_{32} \]
Spacing Impacts Clamp Rotation
Modeling Example 1

Impact of Spacing on Current Split

1 kA difference in peak amplitude predicted for 0.1 in and 12 in spacing
Modeling Example 2

Mixed TPG Groups (Old & New)

Current distributions change significantly because of TPG 2 resistance.
De-Rating TPGs

Two cannot handle twice as much current as one...
### Overall Results

<table>
<thead>
<tr>
<th>Cable Size</th>
<th>TPGs [#]</th>
<th>Clamp Spacing [in]</th>
<th>Restraint [Yes/No]</th>
<th>Return Bus Config.</th>
<th>1.35 (I_{\text{rated}})</th>
<th>1.7 (I_{\text{rated}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/0 (I_{\text{rated}} = 31) kA</td>
<td>2</td>
<td>12</td>
<td>No</td>
<td>Single</td>
<td>Green 2/2</td>
<td>Red 0/1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>Red Not Tested</td>
<td>Green 3/3</td>
</tr>
<tr>
<td>4/0 (I_{\text{rated}} = 47) kA</td>
<td>2</td>
<td>12</td>
<td>No</td>
<td>Split</td>
<td>Red 3/4</td>
<td>Green 0/4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yes*</td>
<td>Single</td>
<td>Red Not Tested</td>
<td>Green 0/4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>Split</td>
<td>Red 4/4</td>
<td>Green 0/4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yes*</td>
<td>Single</td>
<td>Red Not Tested</td>
<td>Green 3/4**</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12</td>
<td>No</td>
<td></td>
<td>Red Not Tested</td>
<td>Green 0/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yes*</td>
<td></td>
<td>Red 0/3</td>
<td>Green 1/4</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>No</td>
<td></td>
<td>Red 4/4</td>
<td>Green 4/4</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Restraints were not installed deliberately. Support frame acted as restraint unintentionally.
** One test excluded since cable shorted to setup bus work after releasing from bus during test.
How to Calculate De-Rating Factors

• For 2 TPG cases:
  Base Current = 2 $I_{\text{rated}}$ (De-Rating Factor = 0)
  Example Applied Current = 1.70 $I_{\text{rated}}$
  Difference = $(2 - 1.70) \times I_{\text{rated}}$
  = 0.30 $I_{\text{rated}}$
  De-Rating Factor per TPG = 0.30 / 2 = 0.15 (15%)

• For 3 TPG cases:
  Base Current = 3 $I_{\text{rated}}$ (De-Rating Factor = 0)
  Example Applied Current = 1.70 $I_{\text{rated}}$
  Difference = $(3 - 1.70) \times I_{\text{rated}}$
  = 1.3 $I_{\text{rated}}$
  De-Rating Factor per TPG = 1.30 / 3 = 0.43 (43%)
## Tested De-Rating Factors

<table>
<thead>
<tr>
<th>TPG Cable Size [AWG]</th>
<th>RMS Test Current [kA]</th>
<th>Test Current [x I_{\text{rated}}]</th>
<th>TPGs [#]</th>
<th>De-Rating Factor [% per TPG]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2/0</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/0</td>
<td>31.0</td>
<td>1.0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>41.9</td>
<td>1.35</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>52.7</td>
<td>1.70</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>43</td>
</tr>
<tr>
<td><strong>4/0</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/0</td>
<td>47.0</td>
<td>1.00</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>63.5</td>
<td>1.35</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>80.0</td>
<td>1.70</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>43</td>
</tr>
</tbody>
</table>
De-Rating Factors for Test Program (New TPGs)

<table>
<thead>
<tr>
<th>TPG Size</th>
<th>TPGs [#]</th>
<th>O.C. Spacing [in]</th>
<th>De-Rating Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 75% Survival Rate [% per TPG]</td>
</tr>
<tr>
<td>2/0 AWG</td>
<td>2</td>
<td>12.0</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12.0</td>
<td>43</td>
</tr>
</tbody>
</table>

ASTM allows pass rate on QA test of 75% or higher

Unrestrained Only
# De-Rating Factors for Test Program (New TPGs)

<table>
<thead>
<tr>
<th>TPG Size</th>
<th>TPGs [#]</th>
<th>O.C. Spacing [in]</th>
<th>De-Rating Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>≥ 75% Survival Rate [% per TPG]</td>
</tr>
<tr>
<td>2/0 AWG</td>
<td>2</td>
<td>12.0</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12.0</td>
<td>43</td>
</tr>
<tr>
<td>4/0 AWG</td>
<td>2</td>
<td>12.0</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.5</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>&gt; 43</td>
<td>&gt;&gt; 43</td>
</tr>
<tr>
<td></td>
<td>12.0</td>
<td>55</td>
<td>55</td>
</tr>
</tbody>
</table>

Unrestrained Only
Conclusions

- Performance of parallel TPGs during faults are impacted by:
  - Relative positions / spacing
  - Degree of difference in current paths (additional/unequal impedance)
  - Absolute current magnitude (not relative magnitude)
    - 80 kA for 4/0 AWG is more difficult than 53 kA for 2/0 AWG
  - Restraining the cables to a structure
- Interaction of TPGs with fault current as well as themselves is complicated to predict but may be modeled to some extent
  - Indicates that large changes in currents can result for small changes in setup
Conclusions

• For the samples and configurations used in this project:
  – De-rating factors for unrestrained TPGs mounted directly to buswork are **clearly higher than the 10%** commonly discussed in industry standards
    o De-rating factor is greater than 30%
    o Other grounding methods may need to be considered
• De-rating factors for other TPG assemblies or mounting techniques may be different.
Suggestions for F18 Committee to Consider

• De-rating factors
  – Current standards suggest 10% minimum but the minimum part is generally ignored by utilities
  – Should provide reasonable de-rating factors based on actual performance of TPG assemblies

• Spacing
  – Clearly, clamps should be installed as close together as possible
  – 1 ft may be too much

• Guidance for Design / Qualification Tests
  – How many samples?
  – Current F855 specifies considers 2/2 OR 3/4 pass rate acceptable for QA tests. Is a 75% passing rate high enough?
Still Many Unanswered Questions

- Effect of different mounting orientation
  - Degree of performance improvement (i.e. decrease in de-rating factor)
- Unequal spacing for 3-TPG setups
- Other clamp styles (duckbill, all-angle, etc.)
- Multi-cable clamps
- Restraint
  - Tying all cables together at different locations
  - Securing to structures
- Mechanically stronger clamp & ferrule combinations
- Mixtures of new and slightly used TPGs (increase of inequality in current split)
Thank you for your attention

Questions?
TPG Samples - Resistances

![Graph showing cable sizes and estimated resistances](image)

- **ASTM F2249 2/0 Maximum (not to exceed)**: 1956 µΩ
- **ASTM F2249 4/0 Maximum (not to exceed)**: 1349 µΩ

Estimated Resistances:
- **TPG Samples - Resistances**: 1208.04 µΩ

Cable Size [AWG]
Single TPG Tests

Single TPG performance verified at H rating
How does a TPG fail during a fault test?

**Two primary failure mechanisms:**

- **Mechanical** – High electromechanical forces exerted on clamps as cables move during the fault
  - What happens?
    - Clamp or ferrule break
    - Clamp loosens and detaches from structure
  - When?
    - During first few cycles of fault application
- **Thermal** – Melting of clamp, ferrule, or cable that occurs because of Ohmic heat generation
  - What happens? - Clamp or ferrule melts
  - When? - During last few cycles of fault application
2/0 AWG TPG Tests

Rated Current = 31 kA RMS
Test Currents = 41.9 & 52.7 kA RMS
Survive – 2/0 AWG TPG

12 in spacing, 41.9 kA RMS (Test 5-3, Trip 2)
Survive – 2/0 AWG TPG

12 in spacing, 52.7 kA RMS (Test 6-8, Trip 2)
## Overall Results – 2/0 AWG Tests

<table>
<thead>
<tr>
<th>Cable Size</th>
<th>TPGs [#]</th>
<th>Clamp Spacing [in]</th>
<th>Restraint [Yes/No]</th>
<th>Return Bus Config.</th>
<th>41.9 kA (1.35 (I_{\text{rated}}))</th>
<th>52.7 kA (1.7 (I_{\text{rated}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/0 AWG</td>
<td>2</td>
<td>12</td>
<td>No</td>
<td>Single</td>
<td>2/2</td>
<td>0/1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>Not Tested</td>
<td>3/3</td>
<td></td>
</tr>
</tbody>
</table>
Simulated Fault Current Waveform

47 kA RMS Fault, X/R = 30

Total Fault Current

Individual TPG currents (small phase differences)
• Current predictions do not match measured values nor are they as expected
Challenges of Measuring Current Split

- Added impedance also identified by examining the movement of the TPG cables.
- Cables should meet near TPG 2 during a 3-TPG test.
- Current split in Trip 1 indicates additional impedance imbalance
Measurement of Current Split

Path lengths different
Added self and mutual inductances

TPG 1
TPG 2
TPG 3
Tweak the Model with Series Impedance

**Actual Waveform**

**Simulation Waveform**

Inductance Added:
- L1 = 6μH
- L2 = 3.5μH
- L3 = 4.5μH

Resistance Added:
- R1 = 601μΩ
- R2 = 383μΩ
- R3 = 470μΩ

ADD TO THE MODEL
Current Split Model - Verification

(includes Measurement Bus Work)

- Desired model can be made by removing required additional series impedance
- Measured = Tests completed at NJCL
- Predicted = Monte Carlo simulation
Predicted Currents – Single Bus Return

80 kA RMS, 12 in spacing, X/R = 30