Distributed Series Reactor
An overview of the conductor-impacts of the DSR

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Table of Contents

• DSR Technology
  ▪ Overview
  ▪ History
• NEETRAC Testing
• Review of NEETRAC Testing Results
DSR Technology Overview

• A multi-dimensional solution to control power flow through existing transmission lines developed by Smart Wire Grid

• Increases line impedance by injecting a pre-tuned value of magnetizing inductance of the Single-Turn Transformer

• Two modes of operation:
  1. Autonomously, based on locally programmable set points
  2. Two way communication, enabling more sophisticated operation and line monitoring
DSR Technology History

2001-2008

2009

2010

2011

2012

2013

2014

DSR Prototype

Formation of the Smart Wire Grid, Inc. (SWG)

NEETRAC Gen 1 Testing

NEETRAC Gen 2 Testing

Initial Patent Filing

Formation of the Smart Wire Focus Initiative (SWFI)

99 units installed at TVA

33 units installed at Southern Company
Testing

- NEETRAC worked with SWFI to develop tests for the DSR, including:
  - Clamp slip
  - Vibration
  - Impulse
  - Fault Current
  - Corona

- With the exception of the vibration testing, tests shown are for Gen 2 units.
Testing

NEETRAC worked with SWFI to develop tests for the DSR, including:

- Clamp slip
- Vibration
- Impulse
- Fault Current
- Corona
Clamp Slip Testing

Method
Clamp Slip Testing

Results

Sample 1

[Graph showing load vs. position for three tests, labeled Test 1, Test 2, and Test 3.]
## Clamp Slip Testing Results

<table>
<thead>
<tr>
<th>DSR Type</th>
<th>Sample ID</th>
<th>Sample</th>
<th>Test Run</th>
<th>Initial Slip Load (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>32013-002-10</td>
<td>1</td>
<td>1</td>
<td>445</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>495</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>518</td>
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<tr>
<td></td>
<td>32313-002-10</td>
<td>2</td>
<td>1</td>
<td>525</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>520</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td>3213-003-10</td>
<td>3</td>
<td>1</td>
<td>455</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>530</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>500</td>
</tr>
<tr>
<td>1500</td>
<td>3213-002-15</td>
<td>4</td>
<td>1</td>
<td>620</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>555</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>32013-002-15</td>
<td>5</td>
<td>1</td>
<td>627</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>648</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>678</td>
</tr>
<tr>
<td></td>
<td>32313-001-15</td>
<td>6</td>
<td>1</td>
<td>570</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>680</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>525</td>
</tr>
</tbody>
</table>
Clamp Slip Testing

Takeaways

– Post-test inspection of the clamps showed no deformation of the conductor or rods.
Testing

• NEETRAC worked with SWFI to develop tests for the DSR, including:
  - Clamp slip
  - Vibration
  - Impulse
  - Fault Current
  - Corona
Vibration Testing

Methods

– Tested in advance of each DSR installation using installation-specific line specifications
– So far only tested on Gen 1 DSRs
– Tests were based on:
  • IEEE Std 1368-2006: IEEE Guide for Aeolian Vibration Field Measurements of Conductors, and
Vibration Testing

• The purpose of these tests was to understand what happens to the line dynamics when one places an approximately 100 kg mass on the line.

• If line dynamics are unacceptable, develop appropriate mitigation strategy.
Vibration Testing

Results

4200 lb tension, Unit Placed 6 ft 10 in From Termination

No Damper (Config. 13)

Damper at 8 ft 6 in (Config. 14)

Damper at 9 ft (Config. 15)

Damper at 9 ft 6 in (Config. 16)
Vibration Testing

Results
Vibration Testing

Takeaways

— For TVA line, NEETRAC recommended that:
  • DSR unit should be installed 6 ft. – 4 in. ± 6 in. from the suspension clamp.
  • An AFL 1706 damper should be placed 9 ft. ± 6 in. from the DSR face.

— Results are relatively consistent across a range of DSR and damper placements so slight deviation from the recommended installation location of the DSR and/or the damper should not affect the damper’s performance.
Testing

• NEETRAC worked with SWFI to develop tests for the DSR, including:
  - Clamp slip
  - Vibration
  - Impulse
  - Fault Current
  - Corona
Impulse Testing

Method

– 1050 kV BIL selected
– Units tested to ensure functionality after impulse testing
Impulse Testing

Results

<table>
<thead>
<tr>
<th>Date</th>
<th>DSR #</th>
<th>Impulses (kV) Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/19/2013</td>
<td>32013-002-10-02-A-0</td>
<td>1133, 1146, 1116, -1153, -1105, -1160</td>
</tr>
<tr>
<td>11/19/2013</td>
<td>32013-003-10-02-A-0</td>
<td>-1072, -1187, -1179, 1055, 1054, 1055</td>
</tr>
<tr>
<td>11/19/2013</td>
<td>32013-001-10-02-A-0</td>
<td>1065, 1065, 1062, -1069, -1074, -1078</td>
</tr>
</tbody>
</table>

Takeaways

– Units were functional after impulse testing at 1050 kV
– Additional tests scheduled for 1550 kV BIL
Testing

- NEETRAC worked with SWFI to develop tests for the DSR, including:
  - Clamp slip
  - Vibration
  - Salt Fog
  - Impulse
  - Fault Current
  - Corona
Fault Current Testing

• Method

  – Tested in accordance with IEEE C37.100.1™-2007, IEEE Standard of Common Requirements for High Voltage Power Switchgear Rated Above 1000 V
  – 63 kA RMS 30 cycle rating selected per Table 3 of IEEE C37.32 – 2002, High Voltage Switches, Bus Supports, and Accessories Schedules of Preferred Ratings, Construction Guidelines, and Specifications
Fault Current Testing

Test Sequence

- INJECTION MODE
- BYPASS MODE
- FAULT EVENT
- ~0.5Sec
- CORE SECONDARY VOLTAGE MEASURABLE
- CORE SECONDARY CURRENT MEASURABLE
- TRANSITION TIME

Time
## Fault Current Testing

### Results

<table>
<thead>
<tr>
<th>Date</th>
<th>DSR Type</th>
<th>DSR SN</th>
<th>kA (rms)</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/20/2013</td>
<td>1000</td>
<td>32013-001-10-02A-0</td>
<td>68.9</td>
<td>Passed</td>
</tr>
<tr>
<td>11/20/2013</td>
<td>1000</td>
<td>32013-003-10-02A-0</td>
<td>69</td>
<td>Passed</td>
</tr>
<tr>
<td>11/21/2013</td>
<td>1000</td>
<td>32013-002-10-02A-0</td>
<td>68.4</td>
<td>Passed</td>
</tr>
<tr>
<td>11/21/2013</td>
<td>1500</td>
<td>32013-001-15-02A-0</td>
<td>68.8</td>
<td>Passed</td>
</tr>
<tr>
<td>11/21/2013</td>
<td>1500</td>
<td>32013-003-15-02A-0</td>
<td>68.6</td>
<td>Passed</td>
</tr>
<tr>
<td>11/21/2013</td>
<td>1500</td>
<td>32013-002-15-02A-0</td>
<td>68.8</td>
<td>Passed</td>
</tr>
</tbody>
</table>
Fault Current Testing

Voltage across DSR

Fault Current
Fault Current Testing

Voltage across DSR

Fault Current
Fault Current Testing

Takeaways

– Conductor was inspected following completion of testing. There was no visible evidence of test conductor damage.
NEETRAC worked with SWFI to develop tests for the DSR, including:

- Clamp slip
- Vibration
- Impulse
- Fault Current
- Corona
Corona/RIV Testing

• Method
  – Tested with and without protector rod.
## Corona/RIV Testing w/ Protector Rod

<table>
<thead>
<tr>
<th>Date</th>
<th>DSR #</th>
<th>Protector Rods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Inception</strong></td>
</tr>
<tr>
<td>11/19/2013</td>
<td>32013-002-10-02-A-0</td>
<td>185 kV (L to G)</td>
</tr>
<tr>
<td>11/19/2013</td>
<td>32013-003-10-02-A-0</td>
<td>187 kV (L to G)</td>
</tr>
<tr>
<td>11/19/2013</td>
<td>32013-001-10-02-A-0</td>
<td>187 kV (L to G)</td>
</tr>
</tbody>
</table>

180 kV Line to Gnd ~ 310 kV Line to Line
Corona Testing w/ Protector Rod

The RIV requirement for units installed on 230 kV lines with a 1050 kV BIL rating are less than 500 µV RIV at 156 kV.
Corona/RIV Testing w/o Protector Rod

Inception at 296 kV and extinction at 290 kV which are ~ 500 kV Line to Line
Corona Testing

• Takeaways

  – Model 1000 DSRs w/ protector rod passed RIV requirements for 230 kV line, case inception >296 kV line-ground with 11 ft. ground plane.

  – Model 1000 DSRs w/o protector rod passed RIV requirements for 345 kV line with 11 ft. ground plane (standard allows more distance to ground plane at 345 kV).

  – Re-design of protector rod may enable corona-free operation above 230 kV when using protector rod.
Conclusion

- The following tests indicate that DSR type device should have no impact on the conductor or support structures:
  - ✔ Clamp Slip
  - ✔ Impulse
  - ✔ Fault Current
  - ✔ Corona

- The following tests indicate that DSR type device, without mitigation, would have a significant impact on:
  - ✔ Vibration (Note: At TVA and Southern Company, successful mitigation strategies were developed.)