Product Safety Research
October 26, 2010

Generator Failure Investigation – Inspection and Test Results

Dr. Allen C. Eberhardt, Ph.D.
Product Safety Research
Generator Failure Investigation – Inspection and Test Results

Introduction

This report supplements a report of August 17, 2010, “Generator Failure Investigation – Amortisseur Winding,” by Product Safety Research, to include test data and results of an additional inspection and investigation conducted on October 1, 2010. The additional work utilized a test protocol that was distributed and reviewed in advance of the inspection, and subsequently accepted and followed by the engineers and investigators in attendance. The inspection and test protocol is attached as an appendix to this report.

The protocol specifies additional measurements made to evaluate the electrical integrity of the generator major components, in particular the stator and rotor insulation and winding resistances, to evaluate the performance of these windings with regard not only to shorts, but for integrity of the insulation. Typical insulation requirements for generators of this type are a minimum of 5 meg-ohms. Typical measured values for these generators are to be greater than 10 Meg ohms. High values are required to provide of isolation between fields, and also to ground.

The actual work performed on October 1 has resulted in data that fulfills, and by mutual agreement to include additional measurements, extends the work outlined within the attached protocol. An Example of this is the additional fractured and arc-melted pieces of amortisseur lamination that were recovered from within the generator. These aluminum laminations were measured to confirm a plate thickness of 0.125 inches. An inspection was also made at the driven end of the generator, revealing that the opposing end lamination of the amortisseur was similarly damaged.

Background

Prior visual inspections and photographs of the generator set that were made following its highway collision on 9-19-2009, show that the outboard
Generator Failure Investigation – Inspection and Test Results

amortisseur winding (damper), and its attached aluminum end lamination, were in place and functional prior to shipment, but were found fractured after the crash and run-up. Areas of the aluminum lamination are broken, and blackened areas are burned and locally melted as a result of electrical arcing.

The additional tests and results described herein include the proposed Megger tests of the insulating properties of the field and rotor windings. Also tested in this inspection are the winding resistances, the rotor and stator concentricity, and the condition of the six diodes.

Generator Insulation Testing:

Stator

Following the guidelines of the Marathon Electric Service Procedure [1], the stator windings were isolated from all external equipment, including all electronic components, relays, and the metering and control transformer leads H1, H2, H3. The stator leads were tested in pairs for resistances between phases, phase-to-phase (P1-P2, P1-P3, P2-P3). A Megger, model MIT430-TC, was used to measure multiple DAR (Dielectric Absorption Ratio) values, recorded using 30 second and 60 second readings, being more expedient than the ten-minute PI (Polarization Index) intervals. All stator windings measured in the Gig-ohm range, well above the minimum insulation requirement of 5 Meg-ohms. Stator temperature was measured at 71°F. The results are as Shown in Table 1.

<table>
<thead>
<tr>
<th>PHASE:</th>
<th>1-2</th>
<th>1-3</th>
<th>2-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Volts:</td>
<td>1,102</td>
<td>1,102</td>
<td>1,102</td>
</tr>
<tr>
<td>Tau 1 G-Ω:</td>
<td>9.0</td>
<td>9.1</td>
<td>9.0</td>
</tr>
<tr>
<td>Tau 2 G-Ω:</td>
<td>12.5</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>DAR:</td>
<td>1.38</td>
<td>1.38</td>
<td>1.36</td>
</tr>
<tr>
<td>µ-AMP1:</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>µ-AMP2:</td>
<td>0.19</td>
<td>0.09</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 1. Stator insulation resistance test results Phase-to-Phase between each of the phases at nominal 1,000V.
Generator Failure Investigation – Inspection and Test Results

The stator phase winding insulation was also tested to ground (Phase-to-Ground) across the phase and ground buss bars. The generator ground was connected to earth at a nearby structural column. Using the Megger MIT430-TC tester with DAR (Dielectric Absorption Ratio) recorded using 30 second and 60 second readings, the results are as shown in Table 2.

<table>
<thead>
<tr>
<th>PHASE-TO-GROUND</th>
<th>Test Volts</th>
<th>551</th>
<th>1,102</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau 1 G-Ω:</td>
<td>4.35</td>
<td>4.86</td>
<td></td>
</tr>
<tr>
<td>Tau 2 G-Ω:</td>
<td>7.1</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>DAR</td>
<td>1.63</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>µ AMP1</td>
<td>0.08</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>µ AMP2</td>
<td>0.13</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Stator insulation resistance test results, Phase-to-Ground between the buss bars at a nominal 500V and 1,000V.

Generator Insulation Testing:
Rotor

As an initial check, a low-voltage resistance meter measured rotor resistance at 0.640 ohms, and rotor-to-ground as greater than one meg-ohm. Rotor leads F1 and F2 were isolated from the diodes (disconnected at the terminals).

Using the Megger MIT430-TC, the insulation resistance results obtained are shown in Table 3.

<table>
<thead>
<tr>
<th>ROTOR-TO-GROUND</th>
<th>Lead</th>
<th>F1</th>
<th>F2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Volts</td>
<td>112.9</td>
<td>112.9</td>
<td></td>
</tr>
<tr>
<td>Tau 1 G-Ω:</td>
<td>9.1</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>Tau 2 G-Ω:</td>
<td>13.0</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>DAR</td>
<td>1.45</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>µ AMP1</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>µ AMP2</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Rotor insulation resistance test results for F1 and F2 to ground at nominal 100V.
Generator Failure Investigation – Inspection and Test Results

Rotor - Diode Testing

Diodes were checked using a DC VOM with a diode voltage capability. Diode resistances all checked high, and then low, when lead polarity was swapped, thus none were open or shorted. Threshold voltages were measured as shown in Table 4.

<table>
<thead>
<tr>
<th>Diode Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+) Voltage</td>
<td>0.44</td>
<td>0.43</td>
<td>0.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diode Number</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-) Voltage</td>
<td>0.43</td>
<td>0.44</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 4. Rotor diode voltage test results.

Low Resistance Measurements

Stator

A four-lead precision resistance meter (Instek GOM-801H) was used to check the field resistances of each of the six stator field windings. The measurements were made with the stator at a temperature of 71°F. Resistances were measured as shown in Table 5.

<table>
<thead>
<tr>
<th>Field ID</th>
<th>mΩ</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1-T4_1</td>
<td>37.8</td>
</tr>
<tr>
<td>T1-T4_2</td>
<td>37.8</td>
</tr>
<tr>
<td>T2-T5_1</td>
<td>37.6</td>
</tr>
<tr>
<td>T2-T5_2</td>
<td>37.6</td>
</tr>
<tr>
<td>T3-T6_1</td>
<td>38.0</td>
</tr>
<tr>
<td>T3-T6_2</td>
<td>38.0</td>
</tr>
</tbody>
</table>

Table 5. Stator winding resistances (mil-Ω) as measured at 71°F.

Low Resistance Measurements

Rotor

The same four-lead precision resistance meter (Instek GOM-801H) was used to check the field resistances of the rotor as a single measurement of the rotor winding F1-to-F2, with the leads disconnected from the diodes (windings not separated). At a temperature of 70°F the resistance was measured at 0.655 ohms, shown in Table 6.
Generator Failure Investigation – Inspection and Test Results

<table>
<thead>
<tr>
<th>Rotor ID</th>
<th>m Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1-F2</td>
<td>655.0</td>
</tr>
</tbody>
</table>

Table 6. Rotor winding resistances (mil-Ω) as measured at 70°F.

Mechanical Concentricity

As an initial mechanical check of concentricity, clearances between the exciter rotor and the exciter stator were measured at locations where access was available. The dimensions as recorded indicate clearances range from a measured minimum of 0.278 inches to a measured maximum of 0.302 inches; or an approximate mean and limit of 0.290 inches, +/- 0.012 inches. Clearance was maintained with this approximate concentricity. No marks were observed that would indicate contact between the exciter rotor and stator had occurred.

Conclusions:

1. Both the front and rear amortisseur rotor laminations and windings have failed. These 0.125-inch aluminum plates have separated from the amortisseur windings. The separation is a result of loads and forces acting on the generator during the crash sequence. The lamination fragments and pieces are evidence of both the fractures and subsequent catastrophic arc-melting at startup.

2. The stator windings remain intact, and have been tested to evaluate phase-to-phase insulation integrity. Measurements are consistent between all stator windings and phases, measuring in the range of 10 Gig-ohms, which is well above the required 5 Meg-ohm minimum for insulation. (See Table 1.)

3. Insulation testing of the stator windings between phase and ground at the buss bars, testing all windings simultaneously in parallel, measure in the range of 5 Gig-ohms, which is
Generator Failure Investigation – Inspection and Test Results

well above the required 5 Meg-ohm minimum for insulation. (See Table 2.)

4. The rotor windings remain intact, and have been tested to evaluate the phase-to-ground insulation integrity. The lead measurements at F1 and F2 are consistent, measuring in the range of 10 Gig-ohms, which is well above the required 5 Meg-ohm minimum for insulation. (See Table 3.)

5. The six rotor diodes were tested and found to be free of shorts, free of open circuits, and consistent in threshold voltages. (See Table 4.)

6. Measurements of stator resistance using a four-lead low-resistance metering device are very consistent, measuring between 37.6 and 38.0 mil-ohms across all six stator windings, and understood to be values typical to this generator. (See Table 5.)

7. The measurement of rotor resistance using a four-lead low-resistance metering device is 655.0 mil-ohms, understood to be the value typical of this type generator. (See Table 6.)

8. Other than the fractures causing separation between the amortisseur windings where they are joined with the two aluminum end laminations, no physical or electrical anomalies are found within the generator.

Respectfully submitted,

Allen C. Eberhardt, Ph.D.
Product Safety Research

[Signature]
Generator Failure Investigation – Inspection and Test Results

References
1. Marathon Electric–Service Procedure Generator Insulation Testing, Marathon Electric, 100 E. Randolph Street • PO Box 8003, Wausau, WI 54402.


Attachments
1. Protocol - Generator Disassembly, Inspection, and Resistance Testing, Product Safety Research, 3200 Glen Royal Road, Suite 102, Raleigh, NC 27617.
Protocol
Generator Disassembly, Inspection, and Resistance Testing

I. STATOR TESTS

A. Main Stator Windings – Insulation Resistance – to Ground (Meg-Ohms)
   1) Remove the conduit box upper-cover and louvered lower-cover
   2) Connect a ground cable at the generator ground buss
   3) Check to assure that electronic components are disconnected (regulators, diodes)
   4) Disconnect the small leads H1, H2, and H3 at the transformer
   5) Check that all stator leads are isolated from ground
   6) Record the temperatures of rotor and stator windings
   7) Connect the positive megger lead to the stator neutral buss (all stator windings)
   8) Connect the negative megger lead to the generator ground buss
   9) Test potential - set the megger test voltage to 500 volts (DC)
  10) Record resistance readings R1 and R2 at intervals of T1=30 seconds and T2=60 seconds, respectively
  11) Calculate the Dielectric Absorption Ratio (DAR) = R2/R1
  12) If DAR < 1.0, or R2 < 5.0 Meg-ohms, re-test using T1=1 min and T2=10 min, and calculate the Polarization Index (PI) = R2/R1

Note:
- Insulation resistance is acceptable if 5.0 Meg-ohms or greater.
- Insulation DAR or PI is acceptable if 1.0 or greater.
Generator Failure Investigation – Inspection and Test Results

- If the insulation resistance is below 5.0 Meg ohms, and/or the DAR is less than 1.0, the main stator windings may be tested individually, using the same procedure as above after separating each from the buss.

B. Main Stator Windings – Insulation Resistance – Winding-to-Winding (Meg-Ohms)

1) Disconnect all six stator leads from the phase buss and from the neutral buss
2) Connect positive and negative megger leads across every pair combination
3) Record resistance readings R1 and R2 at intervals of $T_1=30$ seconds and $T_2=60$ seconds, respectively for each pair
4) Calculate the Dielectric Absorption Ratio (DAR) $= \frac{R_2}{R_1}$ for each pair

C. Main Stator Windings – Winding Resistance Testing (mil-Ohms)

1) With the stator windings disconnected from the buss bars, measure the resistance across each of the stator windings.
2) Compare resistance values obtained for each of the windings.
3) Realizing that rotor position will influence impedance measurements, as an option, using an AC impedance meter, measure the impedance across each of the stator windings (ohms).

Note:
- The stator is spattered with aluminum, as the amortisseur laminations have separated and some amortisseur windings have melted.
II. ROTOR TESTS

A. Main Rotor Core and Windings – Insulation Resistance Testing (Meg-Ohms)
   1) Note markings and disconnect the main rotor leads (F1 lead and F2 lead) from the rectifier assembly.
   2) Connect the F1 and F2 leads together with the positive megger lead.
   3) Connect the negative megger lead to the exciter mounting bolt, or other good ground on the rotor assembly.
   4) Test potential - set the megger to 500 volts and apply the test voltage.
   5) Record resistance readings R1 and R2 at intervals of T1=30 seconds and T2=60 seconds, respectively
   6) Calculate the Dielectric Absorption Ratio (DAR) = R2/R1
   7) If DAR < 1.0, or R2 < 5.0 Meg-ohms, re-test using T1=1 min and T2=10 min, and calculate the Polarization Index (PI) = R2/R1

Note:
   • Insulation resistance is acceptable if 5.0 Meg-ohms or greater.
   • Insulation DAR is acceptable if 1.0 or greater.

B. Main Rotor Core and Windings – Winding Resistance Testing (mil-Ohms)
   1) With the windings disconnected from the diodes, measure the resistance through the rotor windings.
   2) Attempt to identify connection points of the rotor windings between each of the four pole segments.
   3) If the windings can be isolated into four segments, measure the resistance through each of the rotor segments.
   4) Compare resistance values obtained for each of the winding segments.
Generator Failure Investigation – Inspection and Test Results

5) Realizing that rotor position will influence impedance measurements, as an option, using an AC impedance meter, measure the impedance across each of the four rotor winding segments (ohms).

6) Test for shorted turns by comparing readings of the four segments for agreement to within a few percent.

Note:
- Impedance is affected by rotor position within the stator.

References:
2. Marathon Electric - Service Procedure - Generator Insulation Testing