CONFIDENTIAL

Docket No. 2020001-EI
Cross-Examination
Hearing Exhibit

Exhibit No.: 4C

Proffered by: Public Counsel

Title: Siemens Stator Ground Fault Report

Witness(s): FPL - Coffey

SIEMENS

ROOT CAUSE ANALYSIS – STATOR GROUND FAULT – ST. LUCIE NUCLEAR PLANT UNIT 1 GENERATOR

Michael Garmon
Generator Service Engineering
PG PR R&D GN GNS TIAM
Orlando, FL.

August 23, 2019

CONFIDENTIAL

August 26, 2019

ROOT CAUSE ANALYSIS – STATOR GROUND FAULT – ST. LUCIE NUCLEAR PLANT UNIT 1 GENERATOR

Abstract

On April 25, 2019, at 0918, the Unit 1 generator at the St. Lucie Nuclear Plant reportedly tripped off-line by fault protection relay 64G, indicating a generator stator ground fault.

A Fault Tree Analysis approach was used to attempt to identify the most probable root cause. This report summarizes the findings and results of the root cause analysis investigation.

The stator ground fault at St. Lucie Unit 1 was the result of an insulation fault at bottom bar 17. The fault was located at the top surface of bottom bar 17, underneath banding that was found intact. A definitive root cause of the fault mechanism could not be determined. At the conclusion of the root cause analysis, the following hypothesized potential initiation mechanisms were neither concluded to be causes or ruled out as potential causes:

- Magnetic particles
- Ground wall insulation abrasion due to foreign object
- Impact damage of the main ground wall insulation

A secondary propagation mechanism is considered a likely contributor. There were no signs of potential contributors such as OCP erosion, which is associated with partial discharge, or relative motion, which is associated with mechanical vibration.

The information, analyses, conclusions, recommendations and descriptions in this report: (i) are provided for information only, (ii) should not be considered as all-inclusive or covering all contingencies, and (iii) ARE FURNISHED WITHOUT ANY WARRANTY WHATSOEVER, WHETHER EXPRESS OR IMPLIED, OF FITNESS FOR PURPOSE, MERCHANTABILITY, FROM COURSE OF DEALING OR USAGE OF TRADE, AS TO ADEQUACY, ACCURACY, COMPLETENESS OR USEFULNESS, OR OTHERWISE. Unless otherwise specifically stated in this report, the observations, analyses, conclusions and recommendations in this report are based solely upon engineering evaluation and assessment of information and certain observations or inspections made by Siemens of the product(s) referenced. Any operational or other plant information or data used or referred to herein was not independently verified by Siemens. Observations and assumptions made in this report may not reflect actual conditions.

TABLE OF CONTENTS

1. INTRODUCTION

The St. Lucie Nuclear Plant is a twin reactor nuclear power plant with two steam turbine generators. The Unit 1 turbine generator was commissioned in December of 1976. On April 25, 2019, at 0918, the Unit 1 generator at the St. Lucie Nuclear Plant reportedly tripped off-line by fault protection relay 64G, indicating a generator stator ground fault.

The investigation included review of the available operating records, design, manufacturing, installation, erection, and commissioning information. An on-site investigation was performed to assess the condition of the unit and locate the faulted bar. This investigation included electrical, mechanical and specialty testing, and it identified bottom bar 17 as the grounded bar. This report is based solely on the available records and information reviewed, and, where specifically identified in this report only, observations made by Siemens personnel.

The faulted bar and several reference bars from the unit were sent to the Charlotte materials laboratory, where further testing and evaluation was performed. The investigation was performed with witness point participation by customer representatives. A section of bottom bar 17 including the assessed fault location was sent to Orlando for a CT (computerized tomography) non-destructive examination.

A Fault Tree Analysis was performed in collaboration with customer representatives to hypothesize potential root causes and eliminate each, leaving only the most probable root cause. A Support/Refute Matrix was constructed to support the Fault Tree Analysis.

This report includes a brief description of the unit, the description of initial findings, and discussion of the tests, investigations, and root cause analysis that followed.

2. MACHINE DESCRIPTION

The St. Lucie Nuclear Plant is a twin reactor nuclear power plant with two steam turbine generators. The generators attached to each of the steam turbines are hydrogen inner-cooled generators. The plant is located near Port St. Lucie, Florida, United States of America. See Figure 1.

Figure 1. Photograph of St. Lucie Nuclear Plant

2.1. St. Lucie 1 – Generator Nameplate Data

The generator has the following nameplate rating data:

KVA	1,200,000	Power Factor	0.9
Stator Voltage	22,000	Stator Amperes	31,492
Hz	60	RPM	1,800
Phases	3	Rated Gas Pressure	75 psig
Exciter Voltage	616	Rotor Amperes	7,924
Max. Cold Gas:	46°C	Max. Inlet Water Temp.	99°F
Serial Number	1S-76P135	Made in	USA
Stator Thermal Class	B	Rotor Thermal Class	B

2.2. General Construction of a Hydrogen Inner-Cooled Generator

The steam-turbine-driven generator at the St. Lucie Nuclear plant is a hydrogen inner-cooled model rated at 1200 MVA with a .90 Power Factor at 46 degrees C cold gas. Reference the longitudinal section of Figure 2.

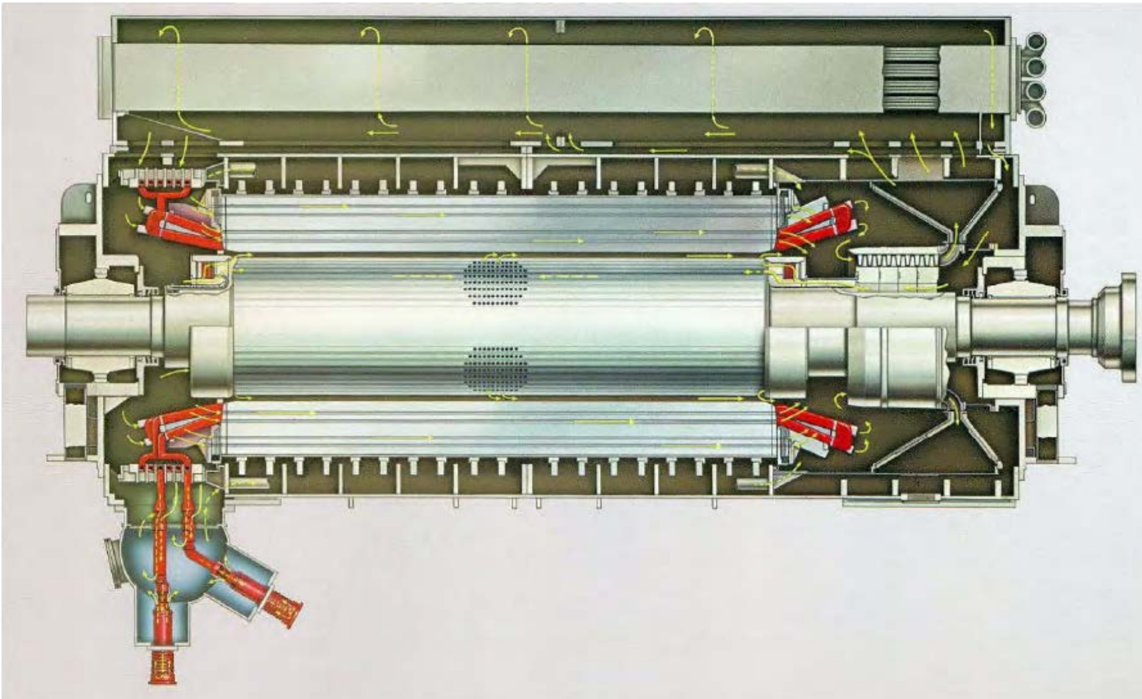

Figure 2. Cross-Section: Large 4-Pole Generator with Gas-Cooled Stator Winding

The general construction includes a frame which supports the core through a spring-mounted system that isolates the foundation from normal electrical vibration associated with operation. The frame also supports bearing-bracket-mounted bearings for the rotor.

St. Lucie Unit 1 uses a brushless excitation system which is separately cooled using air.

The generator stator core was built using resin-bonded donuts of magnetic steel. These donuts are clamped together through rings of grounded key-bars and building bolts behind the core and with insulated through-bolts through the core. End fingers and pressing plates are used at the ends of the machine as part of the clamping method.

The stator bars are wound into the magnetic core. The end-windings are supported with a Rigi-Flex ™ style end-winding bracing system.

2.3. General Fleet Data

Based on the information reviewed in the Siemens database for this fleet, twenty similar design generators were in operation at the time of the event, and only one of these units experienced a fault inside the generator frame prior to the reported event at St. Lucie Unit 1. The root cause analysis for this previous fault concluded that the fault was a result of a portion of the stator core overheating, which deteriorated the adjacent bar ground wall insulation.

2.4. Operational Observations

St. Lucie Nuclear Unit 1 is one of two steam-turbine-driven units in the plant. The unit was reportedly commissioned in May of 1976. The original name plate rating was 1,000MVA.

In 2012, St. Lucie Unit 1 was uprated to its current name plate rating of 1,200MVA. During this uprate, new stator core and stator winding assemblies were installed.

On April 25, 2019, at 0918, the Unit 1 generator at the St. Lucie Nuclear Plant reportedly tripped off-line by fault protection relay 64G, indicating a generator stator ground fault.

At the time of the trip, the site was reportedly conducting a NERC capability grid test. The unit was operating at approximately full real power and 50% reactive power capability when the ground fault trip was reported. This increased the output voltage by approximately 2.7% over the nameplate voltage, which is within the specified capability limit.

2.5. Relay and Oscillography

Figure 3 and Table 1 show the three phase voltages as measured at the generator terminals from phase to ground. The relay that reportedly tripped, 64G, is a voltage signal from an open delta PT circuit. Relay 59N, Neutral Overvoltage, did not trip.

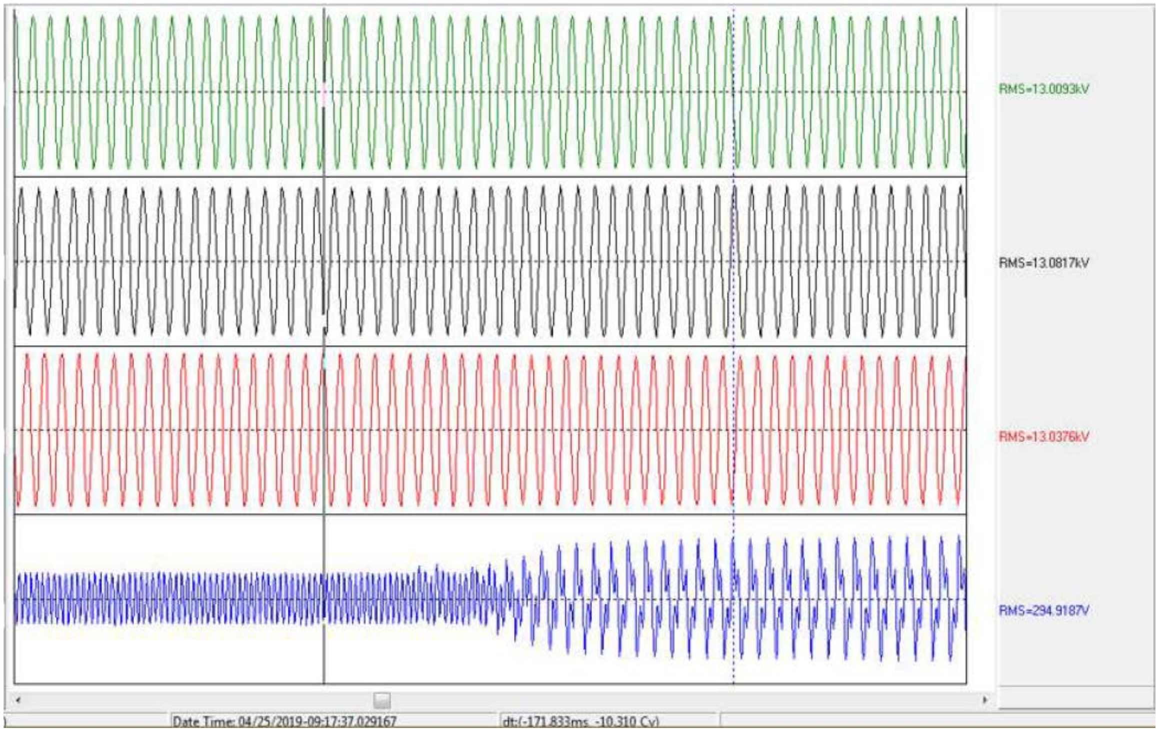

Figure 3. Reported Phase Voltages at the Time of Fault

Table 1. Reported Phase Voltages Prior to and Following the Fault

Phase	Voltage Prior to Fault	Increase over Nominal Voltage (12.7017kV)	Voltage After Fault	Voltage Change
A	13.0093kV	2.42%	12.9065kV	-0.1028kV
B	13.0810kV	2.99%	13.4914kV	0.4104kV
C	13.0376kV	2.64%	12.7334kV	-0.3042kV
Neutral	294.9187V	-	525.7836V	230.8649V

3. FINDINGS

After the trip, the unit was brought to standstill.

3.1. Stator Ground Investigation

The generator bushings were electrically isolated, and the winding phases were tested individually. The testing results indicated that the ground was in the C phase. Resistance with a low voltage ohmmeter was determined to be 1800-1900 ohms. Attempts to megger the C phase were unsuccessful, as the megger would not hold 500 volts.

To find the individual grounded bar, a transposition test set was set up to circulate 100A current in the winding, and the voltage from each end of the set to ground was measured with a precision voltmeter. Since this is a two-parallel machine, the low resistance was determined to be in either bottom bar 17 or bottom bar 38. These two bars are at the null point in the circuit.

Next, the current was circulated between the two bars near the null point with the parallels connected. This allowed the null point to move while the ground would remain at a null point. This test showed bottom bar 17 as the faulted bar.

The St. Lucie Unit 1 stator winding configuration has an internal corona protection (ICP) system with a copper strip that runs along a semi-conductive tape that is applied to the stator bar before the ground wall insulation. This copper strip is connected to the copper strands near the turbine end (TE) side of the bar. See Figure 4 for an example bar insulation illustration.

The copper strip was electrically isolated from the copper strands, and it was determined that the fault through the stator winding insulation was from the outer corona protection (OCP) to the ICP. The copper strand bundle was concluded as not part of the fault.

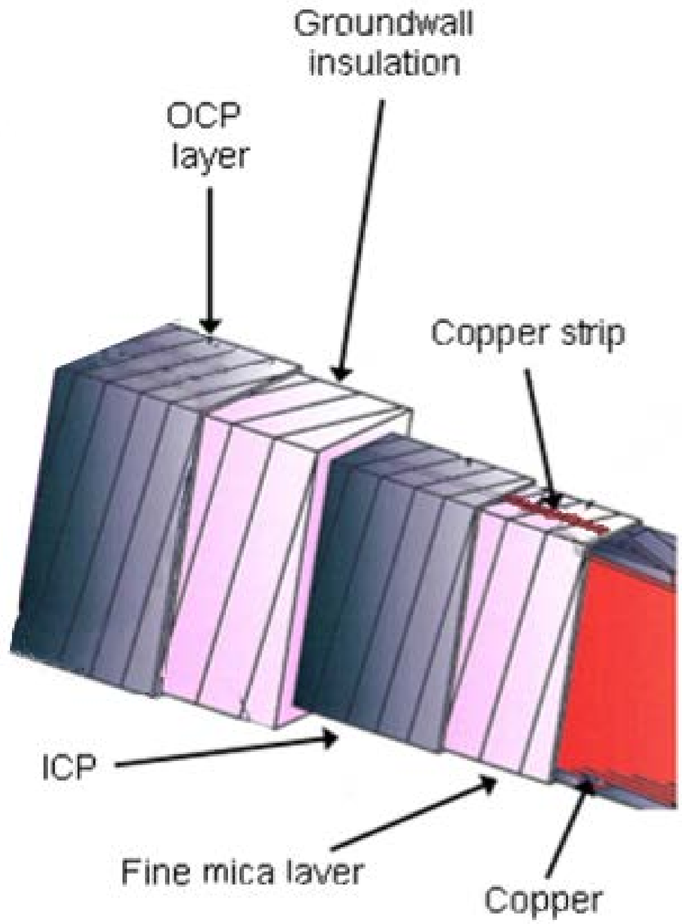

Figure 4. Stator Bar Insulation Example Illustration

3.2. Visual Inspection

While performing the electrical testing described above to identify the ground location, a visual inspection was performed. Because the rotor was still installed, access was limited to a crawl-through of the lead box and generator end regions. The stator windings and core ends were inspected via borescope.

The lead box crawl-through did not show any signs of a stator ground. Borescope pictures of the stator bars in the area of the core end plates and finger plates showed a discolored area on the turbine end of bottom bar 17, shown in Figure 5. The discoloration was observed on the straight part of the bar as it exits the stator core slot, near the core finger plate. There were no other significant findings during the crawl through inspection.

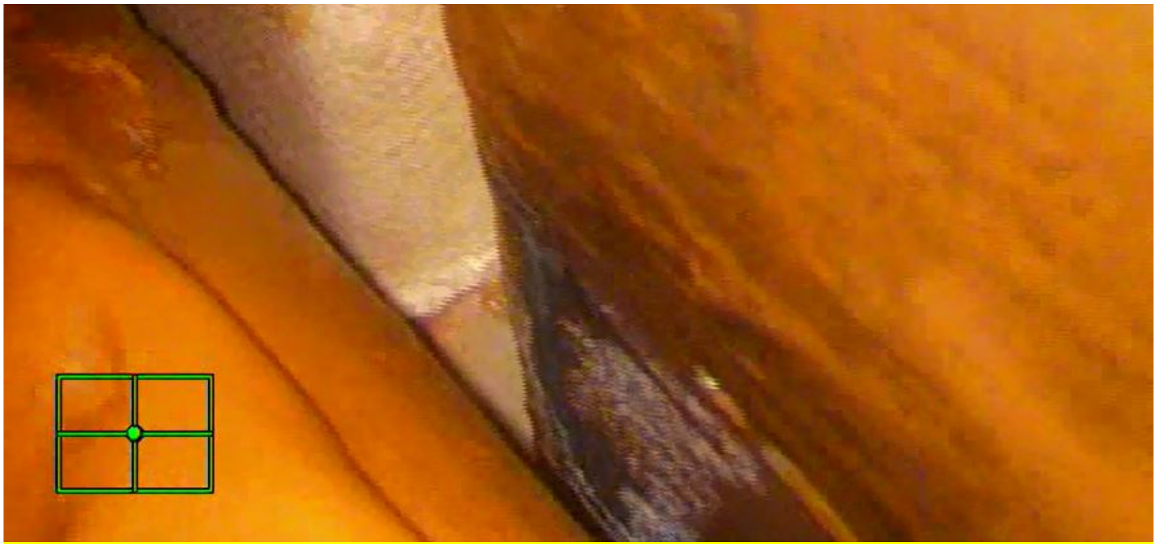

Figure 5. Discoloration on Bottom Bar 17

3.3. Disassembly

Though the results of the investigation described above narrowed down the location ground fault to the copper strip on Bottom Bar 17, the exact location could not be conclusively determined, and an in-situ repair was not feasible. Accordingly, the customer elected to pull the rotor for further evaluation. After the rotor was removed from the stator bore, the tightness of the stator slot wedges was evaluated by measuring the pre-stressed driving strip (PSDS) deflection in the slot. The results are shown below for Slot 17.

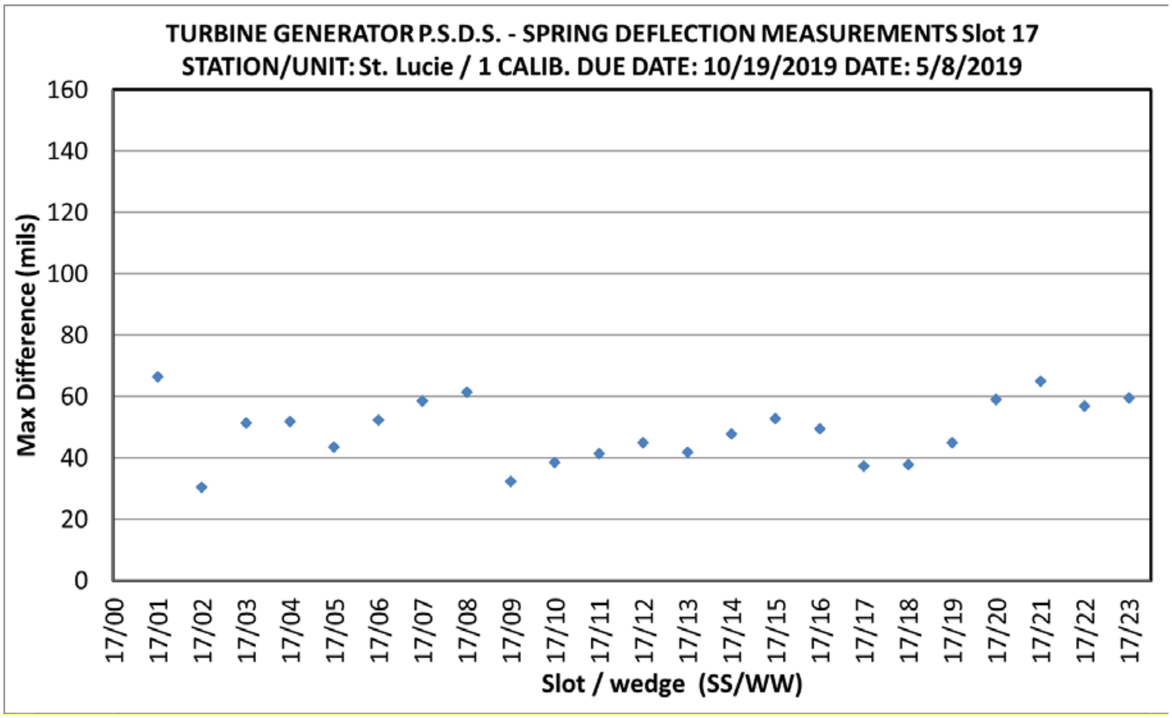

Figure 6. PSDS Deflection Measurements – Slot 17

The average deflection measurement for slot 17 is .049in. This indicates that the spring relaxed from installation, where the average was reported to be .032in, but this is within Siemens' experience for a generator after a period of operation.

The customer elected to rewind the generator stator. While stripping the existing bars, five bars, including the faulted bar, were identified for materials analysis. Besides the faulted bar, the selected bars were either:

- Considered to have been operating at similar voltages as the faulted bar
- Adjacent to the faulted bar, or
- Considered to be at or near highest operating voltage

The intent was not to analyze all five bars chosen, but to have enough bars available for analyses in case any were determined unsuitable after removal. The bars were shipped to the insulation lab in Charlotte, NC, for testing. Additional winding assembly components sent for testing included:

- Slot wedges
- Center, side, and top fillers
- PSDS ripple springs
- Slot coupler
- Cone pad section

3.4. Materials Lab Investigation

The Materials Lab investigation included electrical and mechanical evaluation of the removed bars in the Charlotte laboratory. The faulted bar and reference bars were dissected for measurement and visual inspection.

Detailed analysis was performed on the faulted bar, which identified electrical tracking along the outer corona protection (OCP) at the area of discoloration originally observed at site. Following the tracking in the outboard direction, the fault location was assessed as underneath a spacer block and its associated banding. The banding above the fault was found intact.

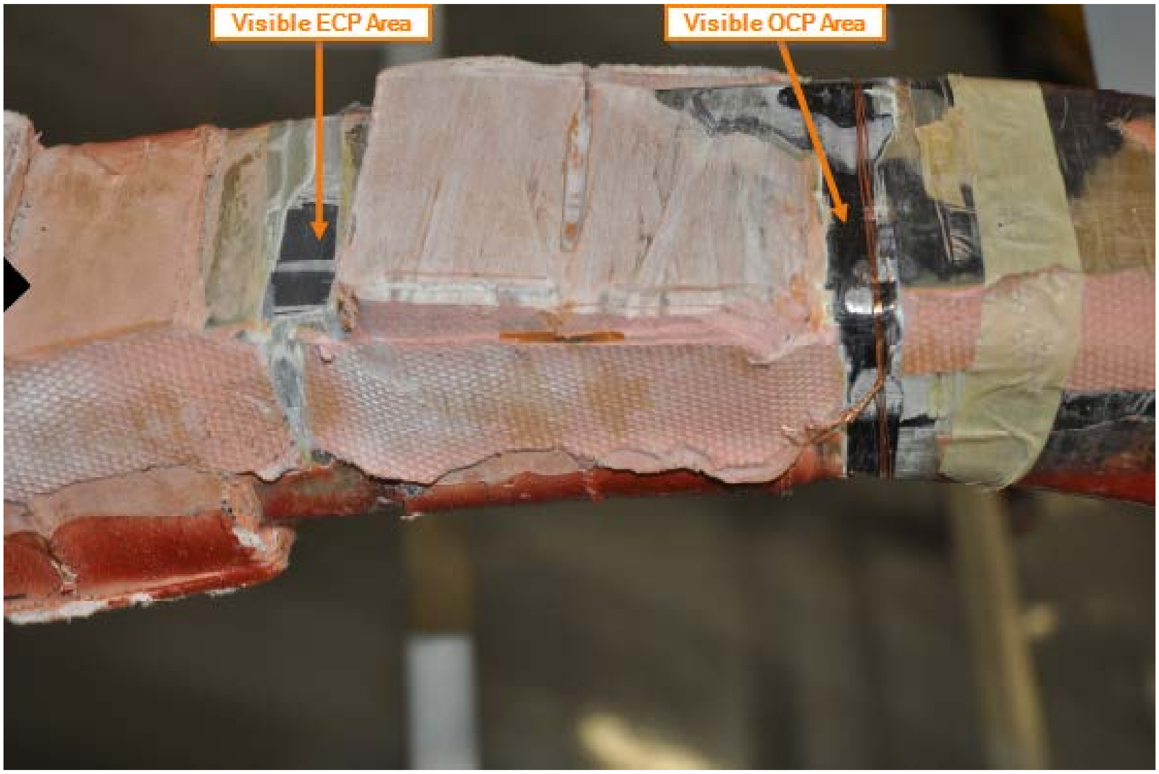

Figure 7. Spacer Block and Banding Above Assessed Fault Location

Figure 8. Spacer Banding Partially Removed, Showing the Assessed Fault Location

Figure 9. Assessed Fault Location, Microscope View

The fault had the appearance of a linear, V-shaped indication. This was confirmed by a CT scan of a section of the faulted bar.

Figure 10. CT Image of the Assessed Fault Location

Evaluation of the insulation on a non-faulted bottom bar indicated that the insulation had acceptable mechanical, thermal and chemical properties.

The Materials Testing report summarizes inspections and testing performed on the St. Lucie Unit 1 stator winding insulation and slot contents.

4. FAULT TREE ANALYSIS

A fault tree considering potential hypothetical causes of a stator ground fault was used to guide the analysis. Seven secondary level elements were hypothesized, including thermal damage, insulation cracking, electrical damage, and material issues. By investigating the tertiary and lower level elements below each secondary element, the hypothetical potential causes were assigned as a probable root cause, contributor, or not a contributor. The fault tree is shown in detail in Appendix A.

One significant finding that guided the fault tree analysis was the shape of the ground fault. Visual and CT inspections showed a linear, V-shaped indication (see Figure 9 and Figure 10). Considering this finding and the insulation testing, which showed properties within typical ranges, the root cause team concluded that the most likely cause was an external event, i.e. not related to bar design or insulation material properties.

Another significant finding is that the unit passed a high potential test at 76,500VDC prior to starting operation following the 2012 rewind. The calculated voltage at bottom bar 17 at the assessed time of the fault was 3,738VAC.

Considering the bar passed a high potential test that was both

- Significantly above the operating voltage at the assessed time of the fault, and
- Performed after all stator winding banding was installed

the root cause team therefore concluded that a propagation mechanism grew the fault through the ground wall during operation after the high potential test.

At the conclusion of the fault tree analysis, three potential causes/contributors were neither concluded to be nor ruled out as a hypothetical cause/contributor:

1. *Metallic Particles*: Loose metallic particles, sometimes referred to as “termites,” can cause a bar fault due to magnetic forces pulling them towards the stator winding copper. Over a period of operation, the particles may tunnel through the winding insulation, resulting in an electrical path to ground. Any loose particles under banding should be captured by the resin used to fix the banding in place, but the condition of the resin at the time of the fault could not be determined by the materials laboratory. EDS analysis of debris from areas above and near the

fault found small amounts of iron (max size approximately 500µm), but it could not be ruled out that this was introduced in the lab during the bar dissection process (see materials report for details).

2. *Foreign Object in the Stator*: This hypothesis is that a non-magnetic particle or object may have been present in the windings and wore through the ground wall via relative motion, which can be from expected stator winding vibration.

3. *Impact Damage*: An impact event could cause a puncture through the ground wall insulation. Because the unit passed a high potential test after winding installation, any impact damage that occurred prior to banding the bar would have needed to propagate during operation. However, there were no signs of propagation mechanisms:
    a. There was no OCP erosion, which would be expected if the fault propagated due to partial discharge.
    b. There was no dusting or greasing, which would be expected if the fault propagated due to bar movement.

5. SUMMARY

The stator ground fault at St. Lucie Unit 1 was the result of an insulation fault at bottom bar 17. The fault was located at the top surface of bottom bar 17, underneath banding that was found intact. A definitive root cause of the fault mechanism could not be determined. At the conclusion of the root cause analysis, the following hypothesized potential initiation mechanisms were neither concluded to be causes or ruled out as potential causes:

- Magnetic particles
- Ground wall insulation abrasion due to foreign object
- Impact damage of the main ground wall insulation

A secondary propagation mechanism is considered to have been necessary for the fault to occur but could likewise not be determined. There were no signs of potential contributors such as OCP erosion, which is associated with partial discharge, or relative motion, which is associated with mechanical vibration.

6. APPENDIX A: FAULT TREE HYPOTHETICALS

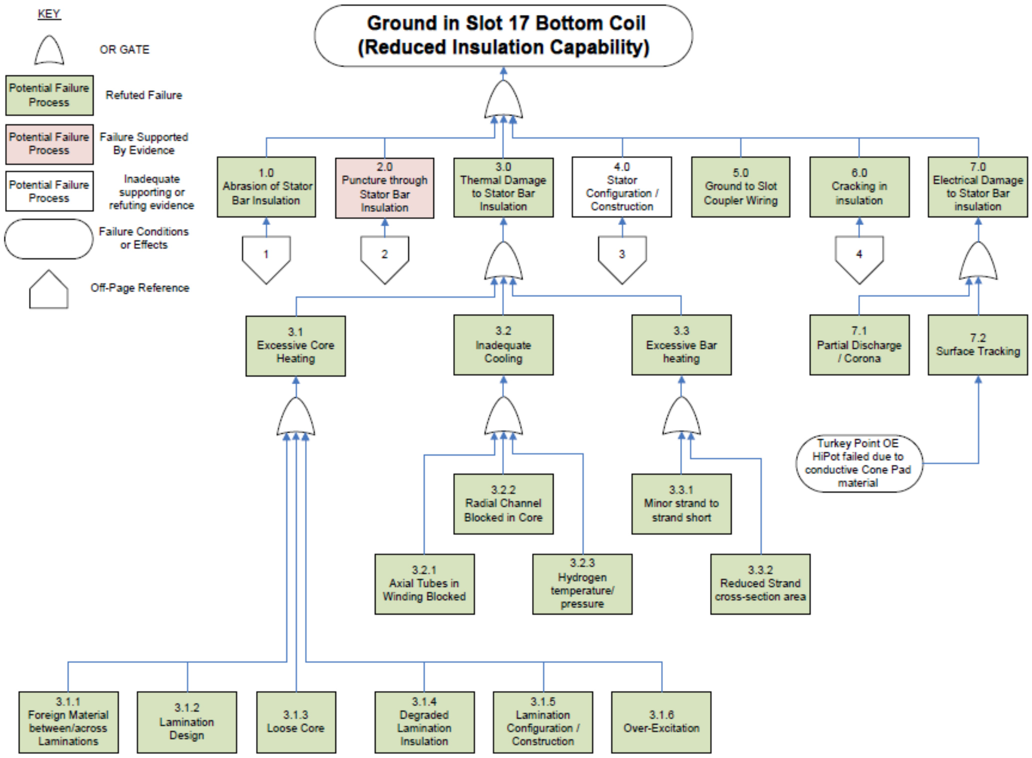

Figure 11. Fault Tree

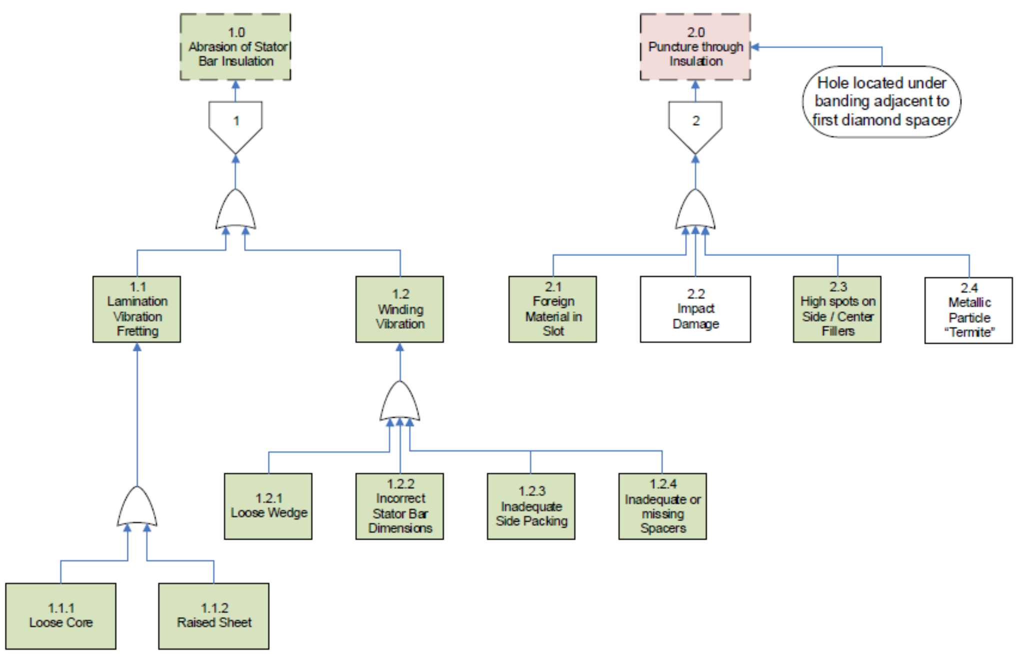

Figure 12. Fault Tree Hypotheticals, Continued

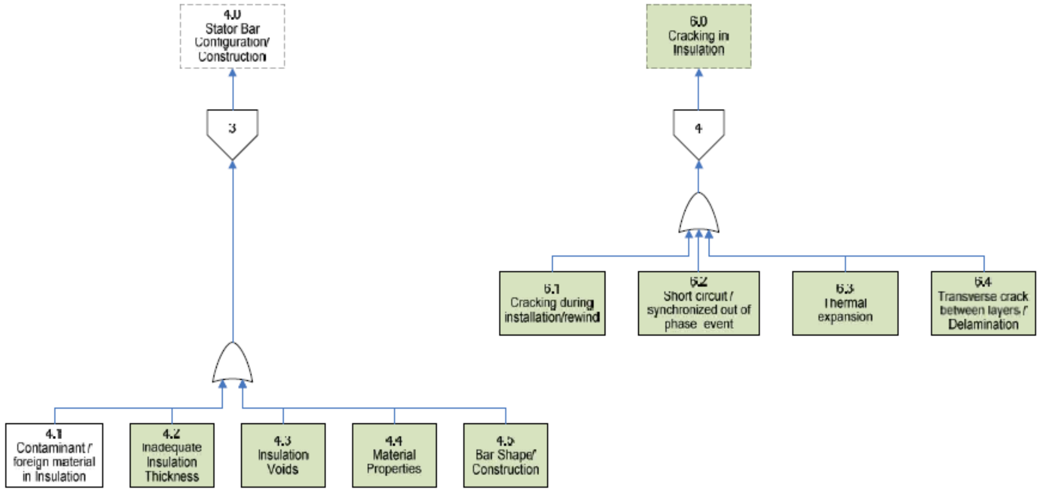

Figure 13. Fault Tree Hypotheticals, Continued

1. Abrasion of Stator Bar Insulation

    1.1. Lamination Vibration Fretting

        1.1.1. Loose Core

- **Conclusion:** Not a potential cause or contributor
- **Observations:**
    - Deformed laminations were noted in the step iron.

Figure 14. Deformed Laminations

- **Refuting Findings:**
    - Any deformed laminations found were attributed to winding removal activities.
    - Visual inspection before and after removal of slot 17 stator bars showed no evidence of greasing or dusting in the area of the slot.
    - The fault location was identified outside of the slot during materials testing.
    - SMCAS after fault did not show any systemic indications
    - The core tightness check prior to installing the new winding showed the through bolts and building bolts were sufficiently tensioned.

1.1.2. Raised Sheet

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
    - Visual inspection after removal of slot 17 stator bars showed no evidence of insulation damage in the area of the slot.
    - Visual inspection of the slot showed the laminations were properly aligned in the slot.
    - The fault location was identified outside of the slot during materials testing.

1.2. Winding Vibration

1.2.1. Loose Wedge

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
    - Wedge tightness checks before stator bar removal were acceptable.
    - PSDS measurement in the Insulation Lab showed that the spring force was sufficient to overcome bar forces in the slot (see materials report for details).
    - The fault location was identified outside of the slot during materials testing.

1.2.2. Incorrect Stator Bar Dimensions

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
    - Cross-sections of both the faulted bar and reference non-faulted bars passed all dimensional checks (see materials report for details).

1.2.3. Inadequate Side Packing

- **Conclusion:** Not a potential cause or contributor
- **Observations Findings:** None
- **Refuting Findings:**
    - Visual inspection after removal of slot 17 stator bars showed no evidence of insulation damage in the area of the slot.
    - Examination of the slot contents in the insulation lab showed dimensional requirements were met (see materials report for details).
    - The fault location was identified outside of the slot during materials testing.

1.2.4. Inadequate or Missing Spacers

- **Conclusion:** Not a potential cause or contributor
- **Details/Background Information:** See Section 1.2.3 above

2. Puncture Through Insulation

2.1. Foreign Material in Slot

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:** See Section 1.2.3

2.2. Impact Damage

- **Conclusion:** Could not be determined or ruled out as a potential cause or contributor
- **Observations:**
    - The shape of the fault was a deep linear indication, which could indicate a puncture.
- **Refuting Findings:**

- The fault was located underneath banding that was found intact. Any impact damage would likely have occurred before the banding was installed during the 2012 rewind. However, the unit passed a high potential test after the rewind was complete.
- There were no signs of additional propagation mechanisms, e.g. partial discharge or cracking due to stator winding vibration.

2.3. High Spots on Side/Center Fillers

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:** See Fault Tree Section 1.2.3

2.4. Metallic Particle (“Termite”)

- **Conclusion:** Could not be determined or ruled out as a potential cause or contributor
- **Observations:**
  - The fault location is a linear, v-shaped indication, which could be the path of a thin metallic particle.
  - A sample of debris collected from an area near the fault was analyzed for material composition and small quantities of copper and iron were found (typically less than 100µm in length).
- **Refuting Findings:**
  - The fault region was located underneath banding that was found intact. There is no apparent path for a particle into the insulation from outside the banding. Additionally, a particle already on the bar surface before the banding was installed should be fixed in place by the banding resin.

3. Thermal Damage to Stator Bar Insulation

3.1. Excessive Core Heating

3.1.1. Foreign Material Between/Across Laminations

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
  - Visual inspection of the core after removing all stator bars showed no findings.

  - SMCAS test of the core before rewind reported no issues did not show significant indications at slot 17.
  - The fault location was identified outside of the slot during materials testing.

3.1.2. Lamination Design

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:** See Fault Tree Section 3.1.1

3.1.3. Loose Core

- **Conclusion:** Not a potential cause or contributor

3.1.4. Degraded Lamination Insulation

- **Conclusion:** Not a potential cause or contributor

3.1.5. Lamination Configuration / Construction

- **Conclusion:** Not a potential cause or contributor

3.1.6. Over-Excitation

- **Conclusion:** Not a potential cause or contributor
- **Observations:**
  - The fault reportedly occurred during a NERC grid capability test. During the test, the output voltage was approximately 2.7% over the name plate voltage.
- **Refuting Findings:**
  - The overvoltage was within the +/-5% capability per design
  - The faulted bar was not a high voltage bar. Calculated voltage at bottom bar 17 was 3,738VAC at reported time of fault.

3.2. Cooling

Note: the following sections are dispositioned together, as the potential fault mechanisms and the refuting findings are considered similar.

3.2.1. Axial Tubes in Winding Blocked

3.2.2. Radial Channel Blocked in Core

3.2.3. Hydrogen Temperature/Pressure Incorrect

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
  - Operational data showed no signs of overheating
  - Insulation and copper inspections in the lab revealed no thermal damage
  - Visual inspection of cooling tubes showed no blockages

3.3. Excessive Bar Heating

Note: the following sections are dispositioned together, as the potential fault mechanisms and the refuting findings are considered similar.

3.3.1. Minor Strand to Strand Short

3.3.2. Reduced Strand Cross-Section Area

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
  - Copper strands passed all dimensional checks
  - The fault was located at the copper strip; the strands were not part of the fault.

4. Stator Configuration/Construction

4.1. Contaminant/Foreign Material in Insulation

- **Conclusion:** Potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
  - Copper strands passed all dimensional checks

4.2. Insulation Thickness

- **Conclusion:** Not a potential cause or contributor

4.3. Insulation Voids

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None

- **Refuting Findings:**
  - The faulted bar passed a tap test for insulation voids in the lab.
  - No signs of partial discharge were observed in the area of the fault.

4.4. Material Properties

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
  - Insulation samples on both faulted bar and reference non-faulted bars passed all qualification testing (see materials report for details).

4.5. Bar Shape/Construction

- **Conclusion:** Not a potential cause or contributor

5. Ground to Slot Coupler Wiring

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
  - Electrical testing showed no issue with slot coupler (see materials report for details).
  - The fault location was identified in an area away from the coupler wire during materials testing.

6. Cracking in Insulation

Note: the following sections are dispositioned together, as the potential fault mechanisms and the refuting findings are considered similar.

6.1. Cracking During Installation/Rewind

6.2. Short Circuit/Synchronized Out of Phase Event

6.3. Thermal Expansion

6.4. Transverse Crack Between Layers/Delamination

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None

- **Refuting Findings:**
    - Operating data does not indicate any short circuit or out of phase synchronization events.
    - Operating data does not indicate bar overheating.
    - No insulation cracking was observed in the area of the fault.

7. Electrical Damage to Stator Bar Insulation

7.1. Partial Discharge / Corona

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
    - The faulted bar was not a high voltage bar. Calculated voltage at bottom bar 17 was 3,738VAC at reported time of fault.
    - Visual inspection indicated no findings of OCP erosion, which is expected when partial discharge occurs.

7.2. Surface Tracking

- **Conclusion:** Not a potential cause or contributor
- **Observations:** None
- **Refuting Findings:**
    - Visual inspection shows no indication of tracking.
    - Fault located near the OCP, which is a conductive layer.
    - Cone pad material had acceptable insulation resistance.