Case Study: Resolving Partial Discharge Issues within a Combustion Turbine Generator

Theadora Lybarger – PSE Electrical Engineer
Chris Brown- PSE Electrical Engineering Supervisor
David Brown – PSE Plant O&M supervisor, Whitehorn Generating Station

Abstract—

A Partial Discharge (PD) Analysis on one of Puget Sound Energy's (PSE) Combustion Turbine generators revealed very high levels of PD both in pulse amplitude (Qm) and quantity of pulses (NQN). Additional inspections and testing confirmed remedial action was prudent. A Minor Generator Inspection scheduled for later that spring was expanded into a Major Inspection which included removing the generator rotor. With the machine open, the areas where PD was occurring were easily identified and accessible for repair. There was a direct correlation between data recorded on the PD Phase plots and visual evidence of corona damage to the stator winding.

Remedial action consisted of cleaning the Unit and repairing the areas of visible corona damage. Measurements taken after completion of the work confirmed that the PD levels were reduced significantly. In addition to these repairs, the overall health of the generator was improved by fixing a leaking turbine end bearing that was contaminating the inside of the Unit, replacing the aged and poorly maintained wedging system, and installing an Iris Power Rotor Flux probe for future testing and trending.

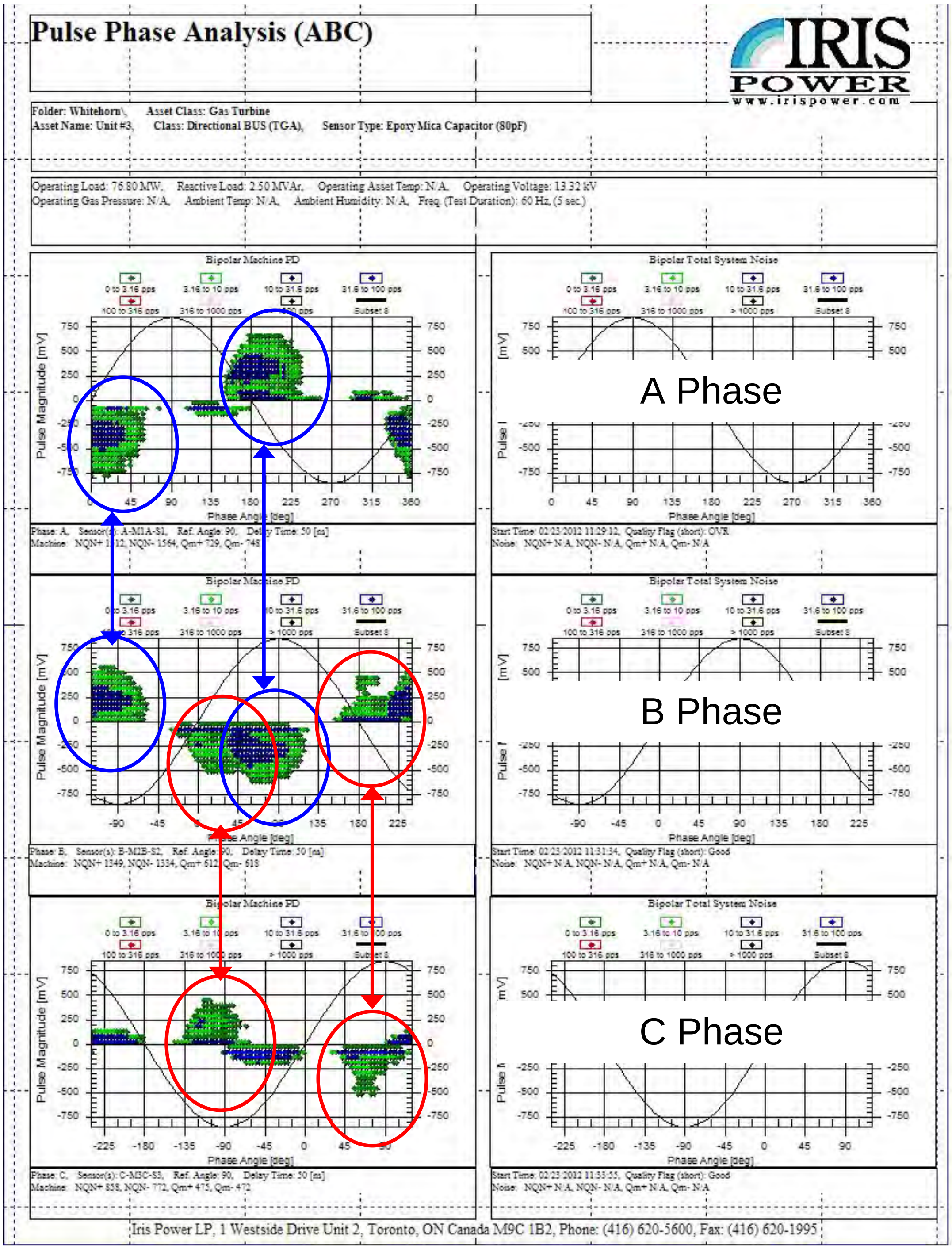
I. INTRODUCTION

Puget Sound Energy (PSE) is Washington State's oldest and largest utility, serving over a million gas and electric customers since 1873. PSE generates approximately 50% of its total customer electrical load through a mix of Thermal, Hydro and Wind generating facilities located mostly in Western Washington.

Whitehorn Generating Station is a Simple Cycle plant located west of Ferndale, WA, 120 miles north of Seattle. The facility was completed in two phases. Phase one was available for commercial service in December of 1974, and retired from service in 2000. Phase two came on line in October of 1981, adding two GE Frame 7E's to the site. The two units use natural gas as a primary fuel with #2 distillate as the backup. Whitehorn provides peak load energy as well as some wind following.

II. INITIAL FINDINGS

On February 23, 2012 a Partial Discharge (PD) Analysis was performed on Whitehorn Unit 3 by personnel from PSE's Plant Technical Services (PTS), the generation engineering group. The test revealed very high levels of PD both in pulse amplitude (Qm) and quantity of pulses (NQN). Qm levels were greater than 95% of similar units when compared against the 2011 IRMC Partial Discharge Testing Progress Report. Though PSE rolled out their PD testing program at all of their Combustion Turbine facilities in 2010, including Whitehorn, this was the first analysis performed on the Unit due to limited operations. Results showed PD activity was largely confined to two distinct locations, between phases A and B, and between B and C, as can be seen in the reflected clusters of activity circled and correlated in Figure 1. The location of the pulses with respect to each 60 Hz waveform (phase) of the generator, as shown below, pointed to the endwinding as the likely source of the PD activity.



Pulse Phase Analysis (ABC)

Folder: Whitehorn\, Asset Class: Gas Turbine
Asset Name: Unit #3, Class: Directional BUS (TGA), Sensor Type: Epoxy Mica Capacitor (80pF)

Operating Load: 76.80 MW, Reactive Load: 2.50 MVAr, Operating Asset Temp: N/A, Operating Voltage: 13.32 kV
Operating Gas Pressure: N/A, Ambient Temp: N/A, Ambient Humidity: N/A, Freq. (Test Duration): 60 Hz, (5 sec.)

Phase: A, Sensor(s): A-M1A-S1, Ref. Angle: 90, Delay Time: 50 [ns]
Machine: NQN+ 1 12, NQN- 1564, Qm+ 729, Qm- 748

Start Time: 02/23/2012 11:29:12, Quality Flag (short): OVR
Noise: NQN+ N/A, NQN- N/A, Qm+ N/A, Qm- N/A

Phase: B, Sensor(s): B-M2B-S2, Ref. Angle: 90, Delay Time: 50 [ns]
Machine: NQN+ 1349, NQN- 1334, Qm+ 612, Qm- 618

Start Time: 02/23/2012 11:31:34, Quality Flag (short): Good
Noise: NQN+ N/A, NQN- N/A, Qm+ N/A, Qm- N/A

Phase: C, Sensor(s): C-M3C-S3, Ref. Angle: 90, Delay Time: 50 [ns]
Machine: NQN+ 858, NQN- 772, Qm+ 475, Qm- 472

Start Time: 02/23/2012 11:33:55, Quality Flag (short): Good
Noise: NQN+ N/A, NQN- N/A, Qm+ N/A, Qm- N/A

Iris Power LP, 1 Westside Drive Unit 2, Toronto, ON Canada M9C 1B2, Phone: (416) 620-5600, Fax: (416) 620-1995

Figure 1: ABC Plot Showing Phase to Phase PD

At this time Iris Power was consulted. They confirmed that the data indicated a condition which could lead to stator failure and should be addressed. Additionally, this type of phase-to-phase discharging was likely due to either contamination between phases resulting in electrical tracking or phase-to-phase discharging due to close proximity between endwinding coils.

The following steps were taken to confirm the initial findings and help determine what, if any, remedial actions would be required:

1. Repeat the PD test
2. Review the test and inspection data from prior inspections
3. Take a short unit outage to perform a borescope inspection on the endwindings, specifically looking for “white powder” indications typical with phase-to-phase endwinding discharge
4. Perform Polarization Index (PI) and Insulation Resistance (IR) tests to compare to previous data and the PD results for possible correlation
5. Decide if the scheduled Generator Minor Inspection should be expanded in order to include stator winding repairs

The PD test was repeated on March 8, 2012, with identical results.

PTS reviewed prior test and inspection records looking for any indication of the possible source of PD. The inspection report from a Generator Minor Inspection performed in 2008 indicated that the Unit was very dirty. The 2008 report was considered particularly important because the Unit had only run approximately 200 hours following that maintenance, so it was believed to be a good indication of the current condition. However, only the top endbells were removed and as a result, only the top endwindings were accessible for inspection and cleaning. The next logical step was to visually inspect the endwindings with a borescope to confirm information in the 2008 report and look for evidence of damage.

An articulating video borescope was secured and the Unit was taken out of service to inspect the endwindings. It proved to be a difficult task both to squeeze far enough inside the generator housing to allow the borescope to reach the endwindings, and to know the location of the optical tip with enough confidence that the entire area was adequately examined. It was evident that both the stator and rotor were caked with an oil and dirt residue. The photo below on the left was typical for the turbine end of the generator. The collector end was also very dirty, though not quite as bad.

Figure 2: Drive End with Dirt and Oil

Figure 3: Borescope Access

As expected, both ends had more dirt and oil on the lower half which was inaccessible, and thus not cleaned, during the 2008 outage. White PD residue was not observed on either end but this was believed to be due to the limited access and significant amount of dirt obscuring much of the winding. See Appendix I for additional borescope photos.

More alarming than the contaminated windings were the PI tests performed the next day. Two PI tests were performed, both at 10kVDC. The first was with the three phases connected at the neutral, testing the insulation integrity of all phases to ground. The second was with the phases separated and those not under test grounded in order to evaluate phase-to-phase insulation integrity or degree of contamination. Measured resistance values have more significance and reflect the true condition better than the PI ratio.

10kVDC PI Test*		**Left Phase (A)**	**Center Phase (B)**	**Right Phase (C)**
2008	**1 Minute Resistance**	377MΩ	442MΩ	325MΩ
	PI Ratio	2.4	5.9	2.2
2012	**1 Minute Resistance**	319MΩ		
	PI Ratio	2.03		
	1 Minute Resistance	**137MΩ**	**49MΩ**	**38MΩ**
	PI Ratio	**1.9**	**1.22**	2.37

*All values temperature corrected to 40°C. Red indicates failing results, Pass/Fail Criteria Per IEEE 43-2000

It was clear from these resistance values combined with the PD results that significant phase-to-phase electrical discharging was occurring in the endwindings.

Combining all the test and inspection data convinced PTS engineers to recommend that the upcoming Generator Minor Inspection be increased to a Major Inspection including rotor removal. With the rotor out of the machine the endwindings would be more accessible for repair and the rotor and stator could get a much-needed thorough cleaning.

III. REMEDIAL ACTION

PSE’s management approved increasing the scope of the scheduled work. It was rebid as a standard Generator Major Inspection (visual inspection, wedge tap, El CID, and electrical testing) with the addition of repairing any corona damage found. The mechanical work, which included generator disassembly and reassembly, pulling the rotor, and intensive cleaning (CO_2 blasting) of the rotor and stator, was awarded separately. By April 14th the rotor was removed.

When the generator vendor arrived on site on April 19th the mechanical vendor had already completed the CO_2 blasting, potentially removing some of the evidence of partial discharge damage. However, the PD activity was still obvious as the most significant damage was between phase connection rings on the collector end of the machine, as shown in the following photos.

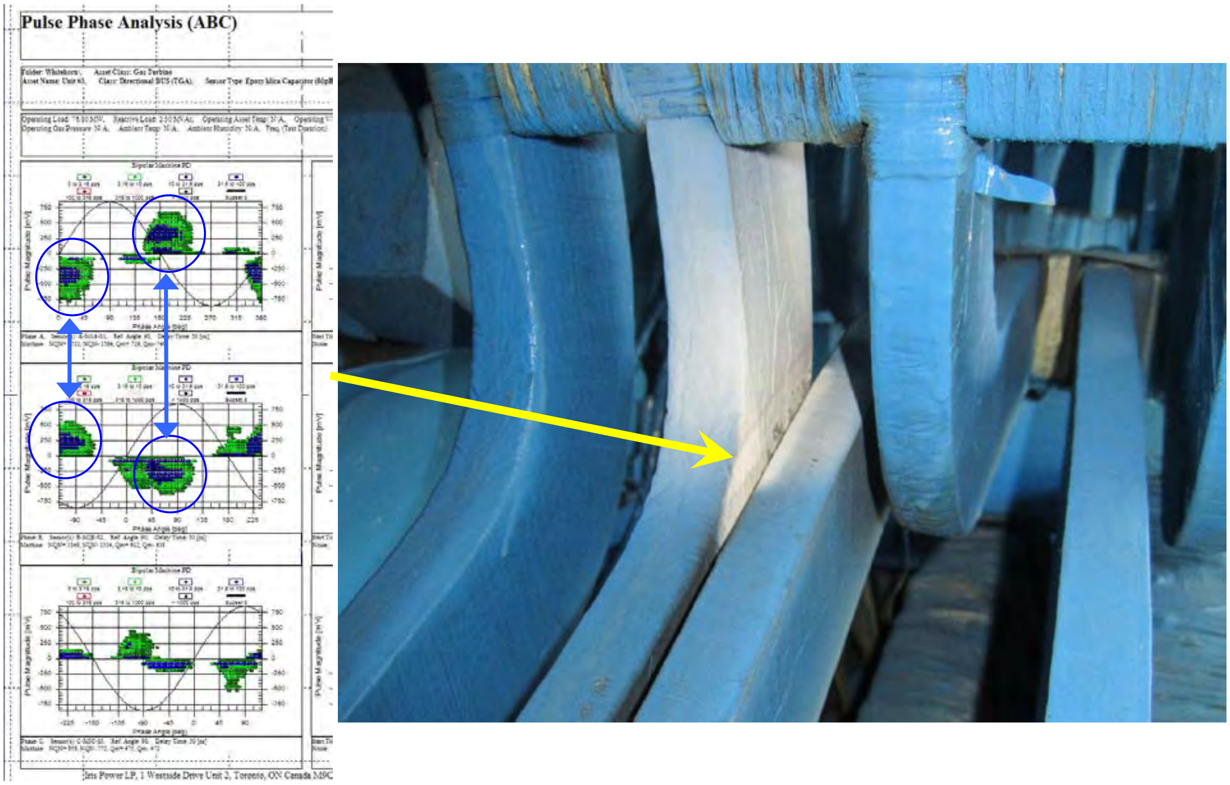


Figure 4: PD between A and B Phase, Connection Ring Bus

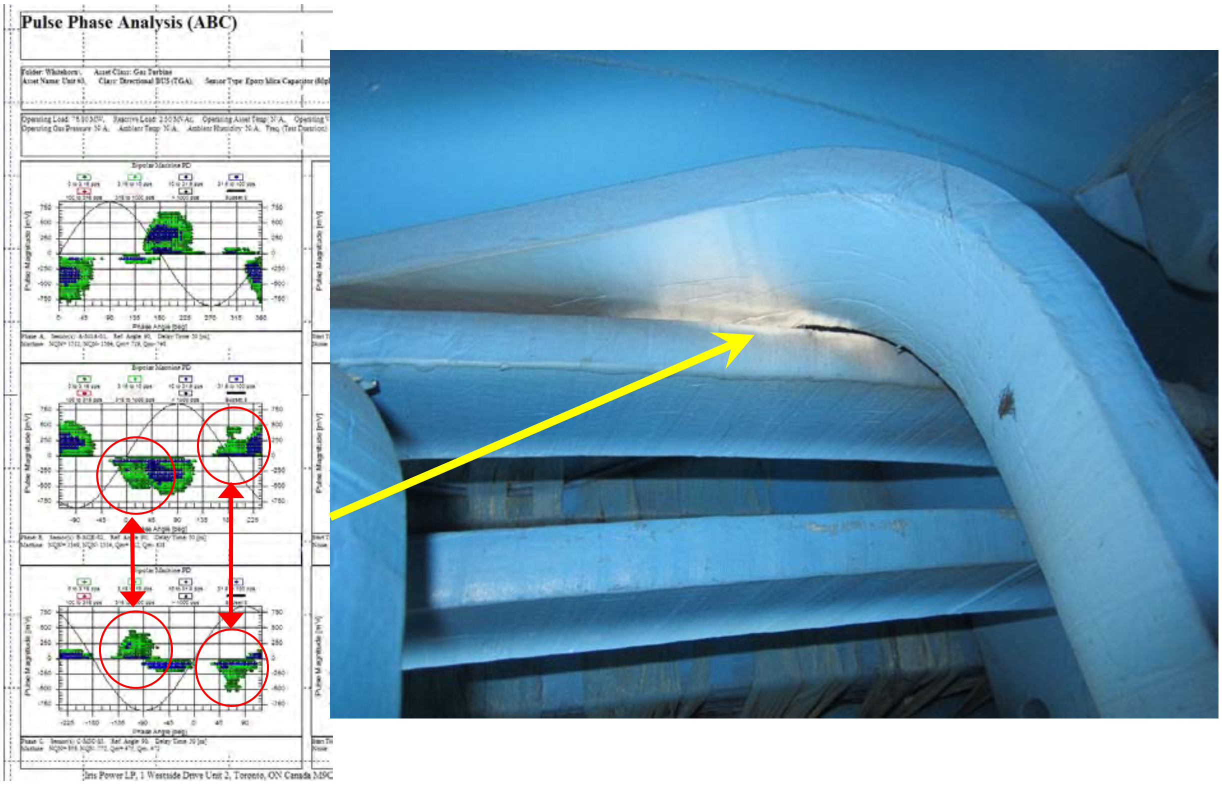


Figure 5: PD between B and C Phase, Connection Ring Bus

The PD activity in the endwindings was as significant as anticipated based on the test results. It appeared that the root cause was either an original manufacturing issue or a transient electrical event during operation which deformed the winding. In either case sections of the buses were too close together. Though it was easy to find it was not something easy to correct.

The optimal fix for any corona damage caused by insufficient spacing, especially where the bars are almost touching for an appreciable distance (Figure 6), would be to clean the area, repair any damage to the insulation and increase the distance between them. Unfortunately, the latter wasn't feasible because bending the bars to separate them could result in distortion of the winding elsewhere or cracking of the insulation. Instead, after the bars were cleaned and corona damage repaired, a non-conductive barrier was created using a high dielectric silicon RTV in the areas of closest proximity. After the RTV cured the endwindings were coated with an Anti-Corona paint to discourage future discharging between phases.

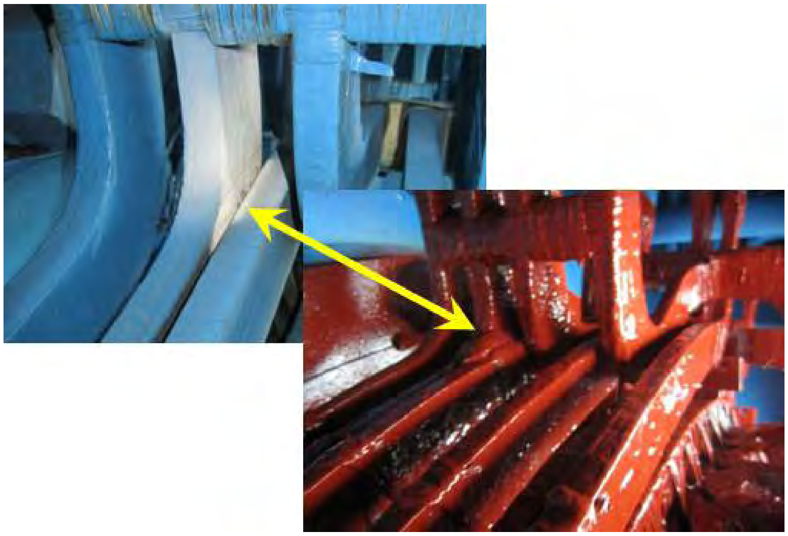


Figure 6: Before and After Repairs of Damage between A and B Phase

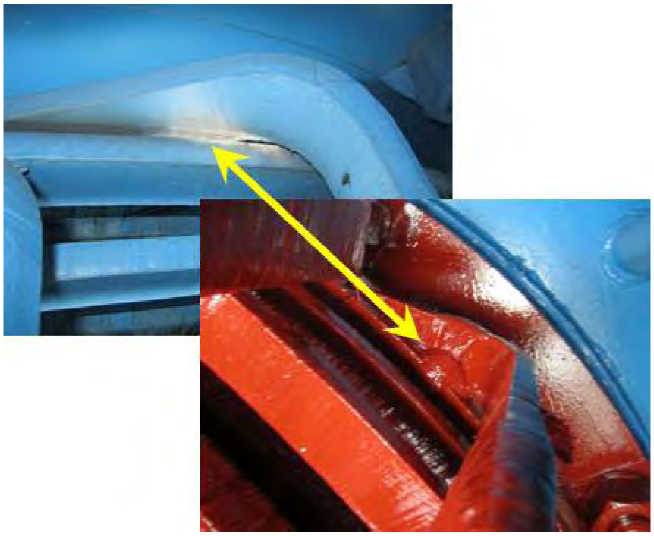


Figure 7: Before and After Repairs of Damage between B and C Phase

Smaller areas of corona damage were also discovered between some top and bottom bars at the slot exit area on the collector end as well as between adjacent phases on the turbine end as can be seen below. These locations were cleaned and repaired in a similar fashion.

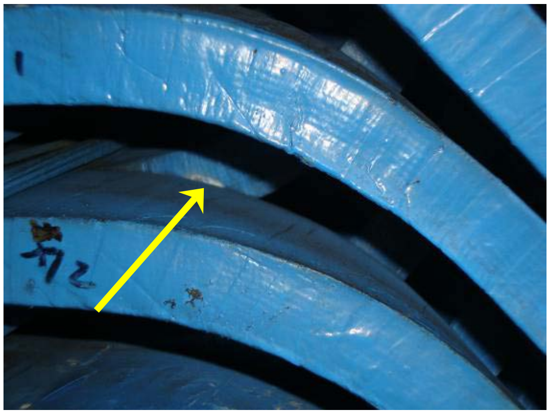


Figure 8: PD between Top and Bottom Bars

Figure 9: PD between Adjacent Phases

In addition to the areas repaired in the winding, visual inspection uncovered a few other issues typical for a machine of this age. Loose and slightly damaged bar armor, dusting between connection ring blocks and ties, and general looseness in the endwinding support hardware were indentified and repaired by the generator vendor.

IV. ADDITIONAL REPAIRS

The exceptional level of contamination discovered during the pre-outage borescope inspection indicated there was an oil leak. During disassembly special attention was paid to the endshields and oil deflectors to find the oil leak path. When the turbine end upper endshield was removed a groove intended for pumping sealant for Hydrogen cooled generator applications was discovered. Since this unit was not Hydrogen cooled the groove was left empty during initial installation. The open groove, in addition to the joint not being closed tightly, allowed oil to flow into the generator.

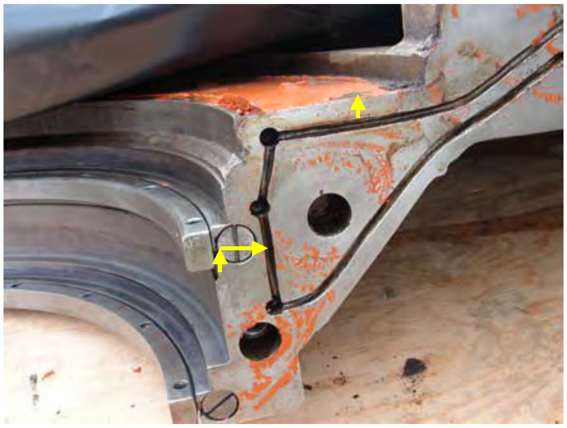


Figure 10: Upper Endshield Horizontal Flange - Arrow Shows Oil Path to Generator from Bearing Seal Cavity

The OEM factory endshield installation procedure was obtained and followed during reassembly which should eliminate future oil leakage and limit the amount of contamination observed at the next outage.

Another finding was that the stator had a compromised “camelback” wedging system. Camelback wedges use triangular and rectangular wedges that overlap and are compressed from the ends. Over time this press-fit loosens. They can be tightened and it is intended that the wedges are serviced every five years. Unfortunately, on this Unit there was no evidence that the wedges had ever been retightened in over 30 years of operation. As a result, they were loose and there was obvious, visual evidence of migration at various locations.

There were two options for repairing the loose wedges. The obvious solution would be to tighten the system, however, that could result in broken wedges that would need to be replaced and still have to be maintained every five years. The alternative was to replace them with a wedging system that didn’t require regular maintenance and would stay tight longer. The same camelback system was found in both units at PSE’s Frederickson Generating Station within the last two years. Frederickson has similar units to the Whitehorn Generators and, though neither was as loose as this one, both were rewedged. These rewedges, combined with the Unit’s maintenance history, led PTS to recommend replacement.

The stator was rewedged with a different design that included a ripple spring in the top layer of filler material. The spring is compressed between 95% and 80% upon installation and will maintain pressure on the wedge even as the system loosens over time. Five rings of test wedges were installed making it easy to test the compression of the ripple spring, and thus the tightness of the system, during future outages.

Finally, with the rotor removed there was an opportunity to install an Iris Flux Probe. Rotor flux analysis and trending is another predictive maintenance activity that PTS is deploying across PSE’s CT fleet, either by utilizing existing probes or installing Iris probes on units that don’t already have them. To date over 50% of PSE’s units have flux probes installed.

IV. RESULTS

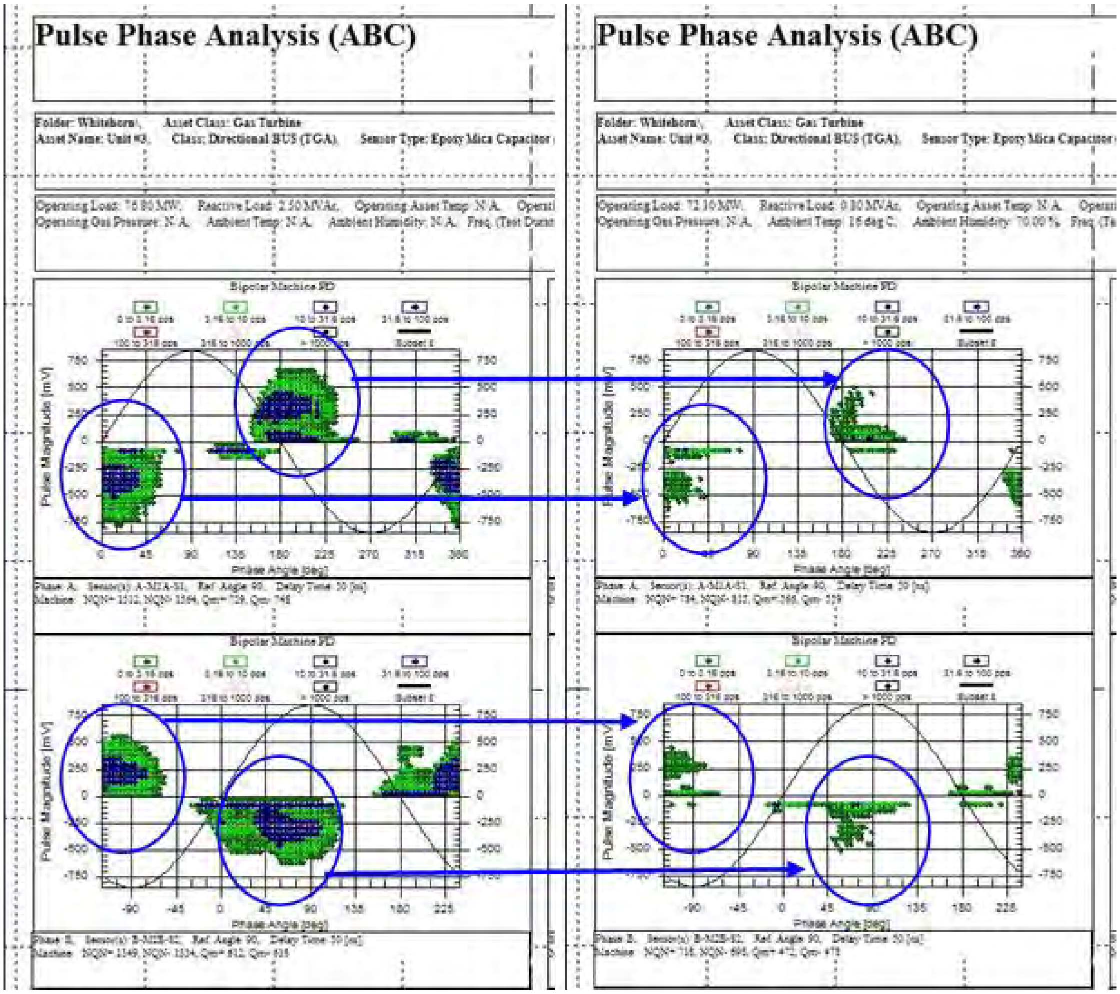
Unit 3 was returned to Service on May 17th. New test data shows improvement in PI and IR results as well as significant decrease in phase-to-phase PD activity in the previously identified areas (Phase A to B, and Phase B to C).

IR and PI testing following the repair showed a substantial increase in the insulation resistance for each phase as well as the PI ratio. It is believed the improvement is due to both the repairs as well as removing the contamination from the stator.

After Repair 10kVDC PI Test*	Left Phase (A)	Center Phase (B)	Right Phase (C)
1 Minute Resistance	3300MΩ	3600MΩ	3600MΩ
PI Ratio	6.0	5.0	4.2

*All values temperature corrected to 40°C. Red indicates failing results, Pass/Fail Criteria Per IEEE 43-2000

The Phase A to B PD levels were reduced by 25-30% in Qm and more than 50% in NQN (see blue circled sections in Figure 11.) Although the damaged area was repaired it is not surprising the winding still shows discharge coupling between these two phases because the two ring bus sections (A and B) are still in close proximity (¼" to ⅛" of separation) and parallel to each other for several inches. As mentioned before it was not possible to physically move the ring bus sections apart without causing other damage, therefore, the section where the buses were the closest (the white powder in Figure 4) was reinsulated. Because the adjacency remains beyond the reinsulated section, moderate PD activity is still present from this location. This should not be an issue; however, it should be tracked during future PD testing. Figure 6 shows the repair.



Pulse Phase Analysis (ABC)

Folder: Whitehorn\, Asset Class: Gas Turbine
Asset Name: Unit #3, Class: Directional BUS (TGA), Sensor Type: Epoxy Mica Capacitor

Operating Load: 76.80 MW, Reactive Load: 2.50 MVAr, Operating Asset Temp: N/A, Operati
Operating Gas Pressure: N/A, Ambient Temp: N/A, Ambient Humidity: N/A, Freq. (Test Durat

Phase: A, Sensor(s): A-M2A-S1, Ref. Angle 90, Delay Time 30 [ns]
Machine: NQN+ 1512, NQN- 1364, Qm+ 729, Qm- 748

Phase: B, Sensor(s): B-M2B-S2, Ref. Angle 90, Delay Time 30 [ns]
Machine: NQN+ 1349, NQN- 1334, Qm+ 812, Qm- 815

Pulse Phase Analysis (ABC)

Folder: Whitehorn\, Asset Class: Gas Turbine
Asset Name: Unit #3, Class: Directional BUS (TGA), Sensor Type: Epoxy Mica Capacitor

Operating Load: 72.10 MW, Reactive Load: 0.80 MVAr, Operating Asset Temp: N/A, Operati
Operating Gas Pressure: N/A, Ambient Temp: 16 deg C, Ambient Humidity: 70.00 %, Freq. (Te

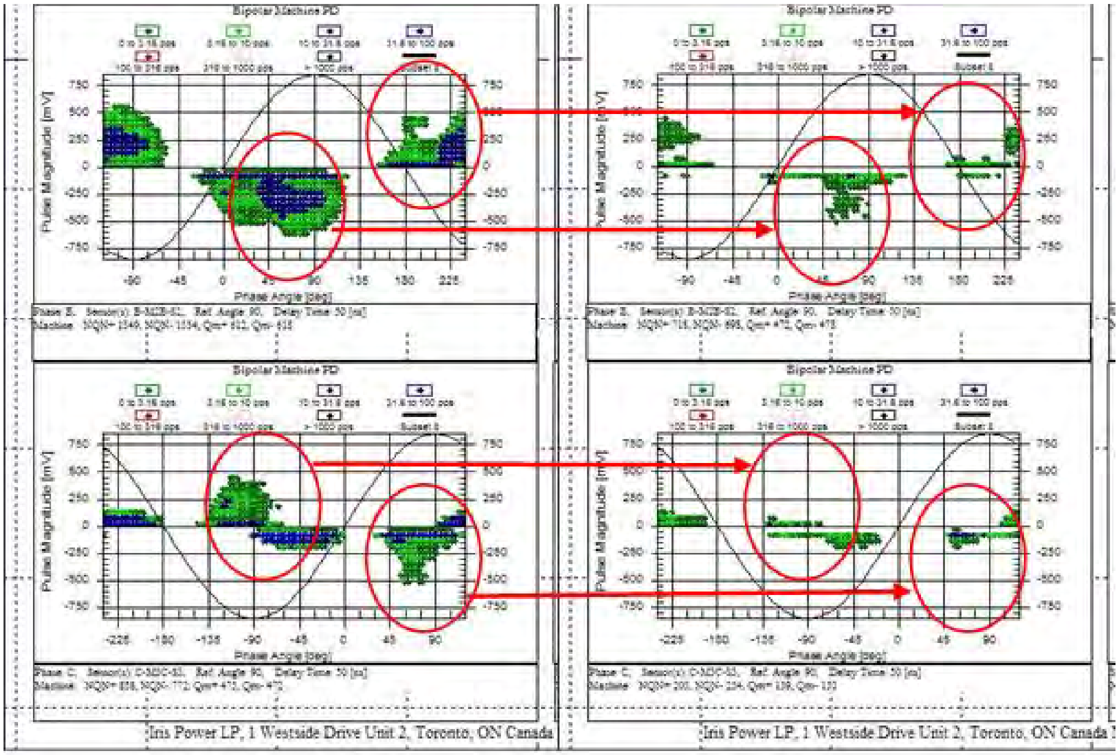
Phase: A, Sensor(s): A-M2A-S1, Ref. Angle 90, Delay Time 30 [ns]
Machine: NQN+ 734, NQN- 813, Qm+ 368, Qm- 379

Phase: B, Sensor(s): B-M2B-S2, Ref. Angle 90, Delay Time 30 [ns]
Machine: NQN+ 718, NQN- 694, Qm+ 472, Qm- 475

Before **After**

Figure 11: Before and After ABC Phase Plot Showing Decreased A to B Phase PD Levels

The Phase B to C PD levels were almost completely eliminated with the repair. These levels decreased more than 75% in both Qm and NQN. The remaining levels are typical background values; see red circled sections on the right side of Figure 12. This makes sense as this phase coupling was a specific point where the two ring buses (B and C) came in close proximity. Refer to Figure 7 for before and after photos of this repair.



Before **After**

Figure 12: Before and After ABC Phase Plot Showing Decreased B to C Phase PD Levels

V. CONCLUSIONS

Partial Discharge testing and analysis helped Puget Sound Energy engineers detect, identify and repair phase-to-phase PD that would have eventually led to failure. The direct correlation between PD phase data and visible corona damage proves the ability of this test method to clearly detect phase-to-phase discharges in stator endwindings and connection ring assemblies.

In addition, the results triggered testing and inspections that led to repairs that would not have been uncovered otherwise. After the outage not only had the winding damage been repaired, but the endwindings tightened, the stator cleaned, a leaky bearing fixed and the stator wedges replaced with a system requiring less maintenance. Also, a Rotor Flux Probe was installed for future testing and trending capabilities.

Appendix I: Borescope Photos from Endwindings

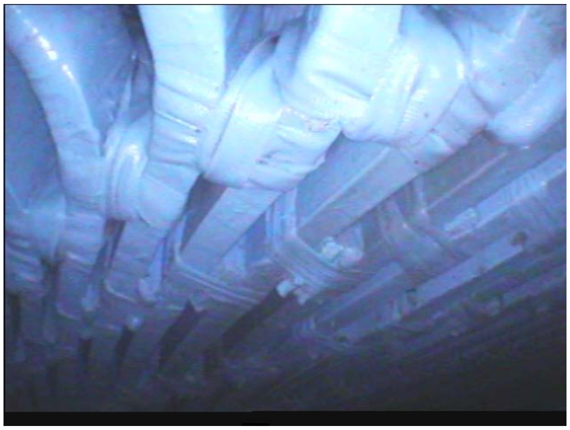


Figure 13: Non Drive End - Clean Top Endwinding

Figure 16: Drive End - Lower Endwinding with Dirt and Oil

Figure 14: Drive End - Lower Endwinding with Dirt and Oil

Figure 17: Drive End - Air Gap with Dirt and Oil

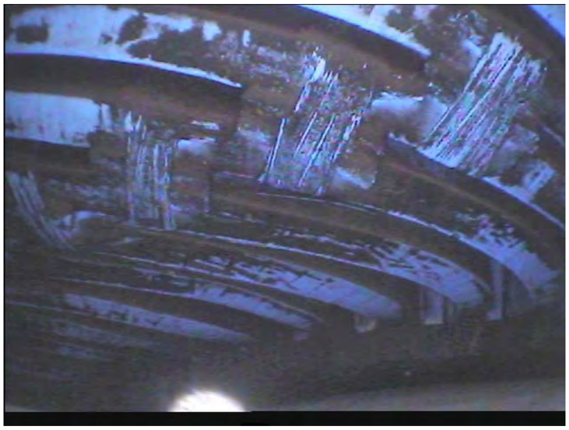


Figure 15: Drive End - Lower Endwinding with Dirt and Oil

Figure 18: Non Drive End - Lower Endwinding with Dirt and Oil