Overhaul and repair management of a strategic generator at a chemical works in Western Australia

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Shinko 6970kW 7600kVA 6.6kV 831A 50HZ 4P 1500RPM 0.80PF Pilot excitation 60V 7.2A

Abstract

IRIS online Partial Discharge testing was performed as an integral part of condition-based maintenance of a 6.6kV Shinko Generator at a chemical plant in Western Australia.

The generator has a double shaft, connected between a steam turbine prime mover and the main production compressor for the plant. The strategic nature of the compressor is such that if the generator failed, the compressor operation would be maintained using the generator rotor as a drive shaft.

Condition monitoring assessment and trending of the PD pattern indicated an increase in the endwinding discharge. Investigation and internal inspection of the machine identified that there was significant oil ingress inside the winding chamber. Oil on the end winding surfaces was identified as the main contributor to the increasing partial discharge activity.

To minimize the production interruption a short 14-day maintenance window opportunity was identified where the generator could be removed from the turbine and compressor to effect overhaul, bearing sealing repairs and for the repairs to be qualified at a capable repair vendor off site. Detailed planning and project management was required to co-ordinate the generator removal from site, overhaul and repair and recommissioning in the time frame. Repair vendors that were identified as capable to conduct the overhaul and test the generator as a motor at full voltage were invited to quote for the works in accordance with a detailed specification. Emphasis was to effect cleaning, HV assessment and PD repairs as required, improve the bearing sealing and then to run the generator as a motor at full speed and voltage with the heat exchanger mounted. The test requirement was to permit online PD testing and to qualify the oil sealing integrity with the normal internal airflow and pressures across the bearing seals.

The vendor technical proposals were adjudicated considering the timelines supplied as project Gantt charts, compliance with the specification and the acceptance of the inspection and test audit plan for the overhaul.

The following quality assurance work was witnessed and adjudicated using the pre prepared audit plan and the inspection and test plan.

- Generator removal and transport to the repair vendor
- Review of the initial incoming generator condition assessment and opening report
- Qualification of the cleaning
- Witness insulation integrity testing
- Review and approve technical queries from the vendor
- Witness the fitting of the new bearing sealing arrangement.
- Witness balancing
- Qualify the re-build of the machine
- Inspect the set-up of the machine on the test field to run as a motor to be able to perform
- online PD testing at full voltage and to assess the lubrication and effectiveness of the oil
- sealing modifications.
- Qualify the final test results and that the objectives for the overhaul were met.

The generator was successfully recommissioned within the 14-day maintenance schedule. Online PD and oil ingress assessment is included in the operating integrity condition monitoring strategy.

Introduction

Online Partial Discharge (PD) testing is implemented at the plant as part of the condition-based maintenance strategy.

The partial discharge testing identified an increasing level of endwinding discharge activity within the generator. A visual inspection and suite of offline testing was conducted to investigate and identify the cause of the increasing PD. The presence of surface oil contamination and greasing deposits on the coils at the slot exits and between the high voltage coils on the endwinding was identified. There was excessive oil ingress from the endshield mounted bearings. A risk assessment was conducted using the inspection and test results that confirmed the anomaly should be addressed within a 3-year window. A planned 2021 outage opportunity was identified to remove the generator for off-site overhaul to effect cleaning and repair to recover the generator operating reliability.

A 14-day overhaul window required that the planning be started in 2020. A specification, audit plan and Technical Vendor Adjudication was compiled. Project meetings were scheduled initially monthly and latterly weekly to manage the progress.

Qualified vendors were assessed considering, compliance with the complete specification, in house capability to conduct the complete scope of work within the 14-day window and have the ability to qualify the repairs and running the generator as a motor at full speed and voltage.

Initial Meeting

The initial meeting was convened to discuss the failure mechanisms identified by the inspection and testing to include these specific aspects in the repair specification. Differential pressure across the bearing internal seal was identified as requiring correction and the OEM was invited to participate in resolving this anomaly.

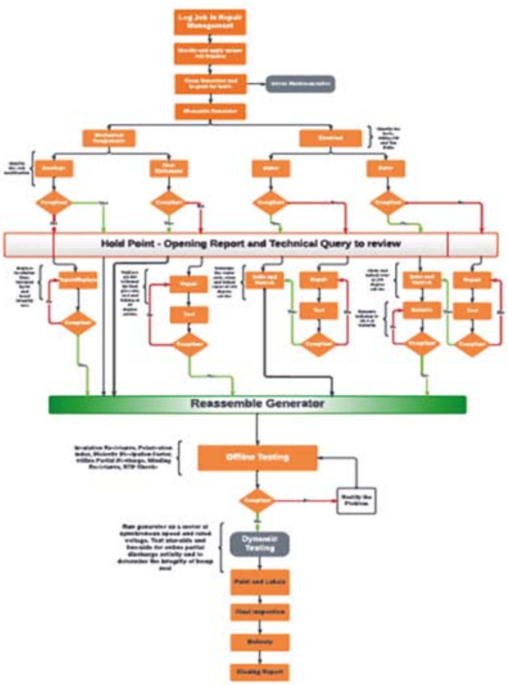
An inspection and test plan was prepared to correlate with the specification and audit plan to use for quality assurance during the project. Drawings of the bearing arrangement detail were included in the specification and emphasised as one of the main repair requirements.

The objectives of the initial meeting were to:

- Set up a project management system to track the overhaul by measuring progress against the project Gantt chart, capture correspondence, progress update reports, images, and test reports. The system also includes the facility for technical queries to be raised by the vendor for expert analysis as required.
- Review the online partial discharge activity and trends to adjudicate that the generator operating risk was being managed towards the scheduled outage.
- Review of the overhaul specification and the main repair aspects.
- Review the vendor assessment from the site meeting criteria checklist.
- Adjudicate the repair vendor quotations and capability assessments.
- Introduce the successful repair vendor team to be involved in 14-days overhaul.
- Discussion on Gantt chart, specific repair items, bearing sealing and the required full speed full voltage test.

Specification

The specification was prepared to detail the requirements for the overhaul and included a compliance checklist for the repair vendor to acknowledge with his submission to conduct the repair work.
The chart below shows the workflow addressed in the specification.



Audit Plan

This document was compiled as a checklist for each of the specification clauses to be signed off as completed by the repair vendor, audited and checked by the inspector and accepted by the customers representative.

Prior to Decommissioning

Online partial discharge tests and vibration analysis were conducted prior to decommissioning the generator,1 week before the shutdown.
These results were recorded to provide a benchmark to compare with the results after the overhaul and repair to objectively show the recovery realised.

Electrical and Mechanical Survey

An Electrical and Mechanical survey was conducted to quantify the condition of stator winding and rotor winding before the overhaul to identify the components for repair or replacement based on the pre-existing issues identified in the specification.

Electrical

- Insulation Resistance
- Polarisation Index
- Winding Resistance
- RTD continuities
- Visual Inspection
- Corona shield to Earth resistance

Mechanical

- Shaft Cleaning and Check
- Bearings and Clearances
- Shaft Earthing
- Heat Exchanger
- Wedge tightness survey

The results were included in an opening report compiled by the repair vendor that included any other repair requirements identified on strip down of the machine with repair recommendation for review by the repair manager.

Repair and Assembly

The repair work was based on the specification and the opening report. A detailed clean was effected to remove the oil and grease from the stator and rotor windings. Stator slot wedge integrity was assessed, and local repairs effected, the bearing sealing arrangement at the inboard labyrinths was closely inspected and considered with respect to fitting the machine seal modification from the OEM.

Static and Dynamic Testing

A suite of testing was conducted to qualify the overhaul of the generator and to compare the results with the pre-overhaul condition recorded during the strip and assess. The test results were witnessed by the client's machine expert and confirmed compliant to the repair specification requirements and the relevant standards.

Static Testing

- Airgap and spigot measurement
- Limits of axial float
- Bearing Clearances
- Baffle Clearances
- Axial alignment
- Pressure test on Heat Exchanger
- Flux shield fasteners and clearances
- Offline electrical testing

Dynamic Testing

- Rotor Dynamic Balancing
- No-load test as a motor
- Bearing temperature including set up of a flood lubrication system
- Direction of rotation
- Overall Vibration and vibration spectrum Shaft Voltage
- Mark Magnetic centre
- Run down time

Liaison with OEM

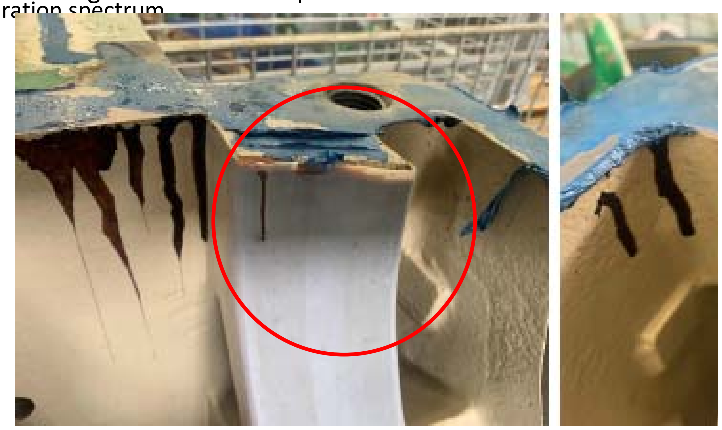
SINFONIA (earlier known as SHINKO, OEM) was involved to provide the bearing machine seal installation instruction and drawing, to rectify the oil ingress into the bearing.

The assembly of the machine seal and shaft seal was completed per the OEM instructions. The instructions included aligning both halves of the labyrinth seal and including a hemp packing material on the inside groove of the machine seal and the torque values for the fasteners, pressure equalizing hoses were fitted across the labyrinth seal between the machine side seal chamber and bearing sump. New RENK centre flange-mounted bearings were fitted to replace the original bearings.

Repair assessment

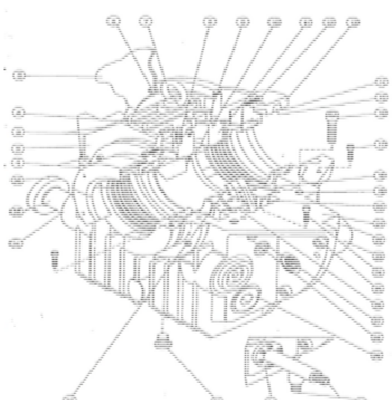
Bearings

During the assessment, the insulated liner on DE bearing was found to be damaged, no electrical anomaly was recorded during Insulation Resistance testing. To maintain the reliability of the bearing, DE housing the bearing insulation was replaced.



Oil staining on the bearing seal on both sides of the shaft was evident

Item 15 from bearing diagram below shows the hemp packing used to provide sealing between the stator chamber and the bearing inner labyrinth seal which is identified as required by the OEM.



Stator Winding

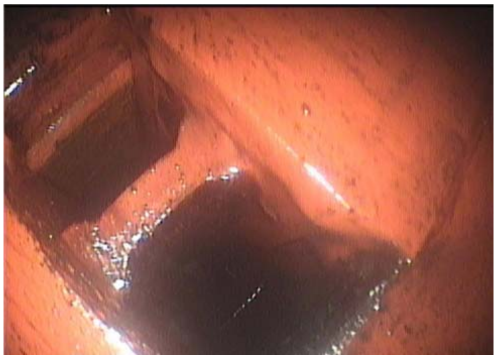
During the visual inspection, the main stator winding was found with moderate dirt contamination and oil mist over the endwinding. The grease residue was noted in between phase group end coils.

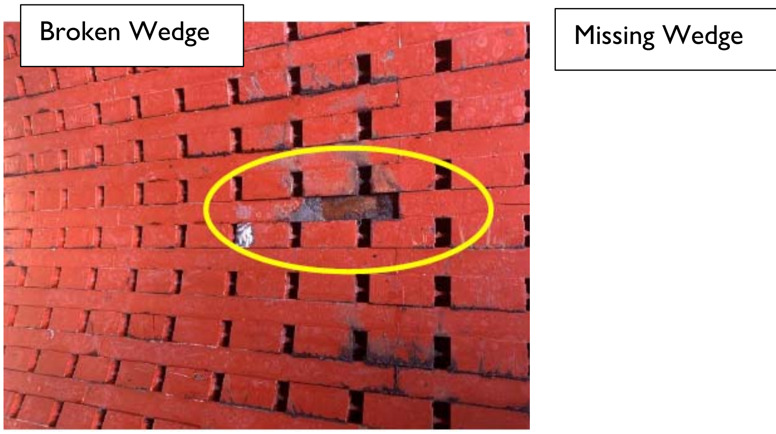
Grease was built-up on stress-grading area at the slot exit. Discolouration was noted at stress-grading junction on stator coils, few centimetres away from slot exits with, indications of corona discharge to stator tooth. The same discolouration was also found on the stator coils at the slot exits onto the core tooth supports at both ends of the stator core.

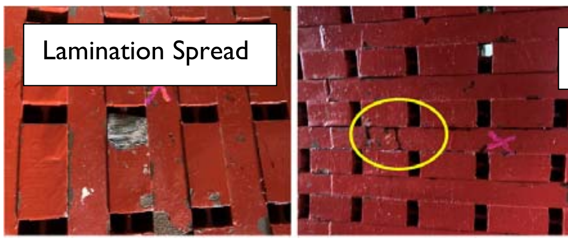
Oil Strains on the stator core and inside the slots were found dripping from the back iron and on the keybars. A pool of oil ingress was evident at the bottom surface of stator chamber.
Greasing was identified at the slot exits in the areas where loose stator wedges were identified.

Stator Core

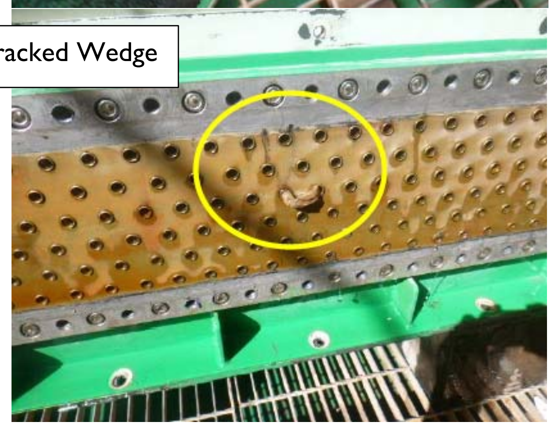
Dirt and grease contamination was found on the surface of stator wedges and within the stator core radial ventilation ducts. 3 slots were identified loosely wedged and some stator wedges were found to be missing.







Lamination Spread



Cracked Wedge

Heat Exchanger

The heat exchanger was pressure tested and slight leakage was identified from the compressed gasket and drain values. During the testing, some tubes were found partially blocked with plastic bags and foreign material.

Repairs and modification carried out

The following repair and modification were conducted.

Component	Result	Assessment	Repair
Stator frame	Pass	Minor corrosion	Sand blasting followed by painting
Stator Feet	Pass	Minor corrosion	Sand blasting followed by painting
Stator windings	Pass	Full of oil contaminants Coil middle packers extended past semi-coating effectively shorting the grading region	Clean and baked at 130°C. Took 2 cleaning and baking cycles to remove all the oil contamination between the windings and slots to suppress the partial discharge activity
Leads and lugs	Pass	No anomaly noted	No repair required
Wedges	Fail	1 complete wedge was found missing. 2 wedges were broken.	3 slots partially re-wedged using free issue magnetic wedges and Repair vendor supplied packers.
Stator core	Pass	Greasing was evident around the slot wedges and 1 small area of lamination separation	Cleaned during the overhaul, re-wedged and packed secure
Main terminal box	Pass	No anomaly noted	Required painting
Gasket	Fail	Gasket between the stator chamber and heat exchanger was found brittle. Gasket at heat exchanger seal found compressed.	All gaskets were replaced.
RTDs	Pass	Cables were routed through the endwinding region and not possible to re-route during this overhaul.	No action taken. Kept away from the HV winding as best as could be achieved
Heaters	Pass	Contaminated with oil	Dismantled, cleaned, re-installed and tested.
Exciter	Pass	Contaminated with oil	Clean and baked at 130°C. Took 2 cycles of cleaning baking to remove all the oil contamination.
Exciter terminal	Fail	Exciter terminal block was found cracked.	Replaced during this overhaul.
Fan	Pass	Contaminated with oil	Cleaned
Coupling	Pass	No anomaly noted	No repair required
Rotor	Pass	Contaminated with oil	Cleaned and baked at 130°C. Dynamic balancing to G1.0 (500RPM)
Rotor coil	Pass	Contaminated with oil	Cleaned and baked.
Shaft	Pass	Oil staining on the seal Maximum 0.02mm TIR recorded	Cleaned.
Shaft Brush	Fail	Contaminated with oil	Cleaned and reused

			New Perspex covers fitted.
DE Bearing	Fail	Insulation liner damaged	Insulation liner replaced and tested for IR and bond integrity
DE/NDE Fitting	Fail	Gasket and seals were found damaged	New free issued Renk type10 Labyrinth seals installed
DE/NDE Seals	Fail	No Hemp packing was fitted	Original Machine seal fitted with new Hemp packing
Heat Exchanger	Fail	Pressure test found non-complaint with slight leakage from the gasket and drain valves. Tubes were found blocked with plastic/foreign material. Head gasket was found compressed at some spots. Head cover was corroded and scaled.	Final pressure test Passed Unit cleaned and baked @ 80°C Installed free issue head gaskets head covers cleaned, de-scaled, primed and painted internally 2x drain valves Replaced

Tests during repair

A suite of electrical tests was conducted to qualify the repair work.

Insulation Resistance and Polarisation Index Test

The test was conducted on stator winding at 2500V DC as stated in IEEE43 to meet the minimum requirement to identify any insulation damaged caused by the cleaning Insulation Resistance test was conducted before high voltage AC test was performed Dielectric Dissipation Factor (Tan Delta) or Offline Partial Discharge testing.

	Test Voltage (V)	Insulation Resistance (MΩ)	Polarisation Index	Result
U – V, W & Earth	2500	16750	6.13	Pass
V – U, W & Earth	2500	16350	5.57	Pass
W – U, V & Earth	2500	17780	5.53	Pass

Rotor winding and exciter windings were IR tested after overhaul at 500V DC to provide a minimum value of 2MΩ and 5MΩ respectively.

	Test Voltage (V)	Insulation Resistance (MΩ)	Polarisation Index	Result
Rotor – Earth	500	5000	1.79	Pass
Exciter Field – Earth	500	12600	-	Pass
Exciter Rotor – Earth	500	6430	-	Pass

Other components space heaters, bearings and rotor earth fault ring were tested for the insulation resistance prior to assembly at 500V was.

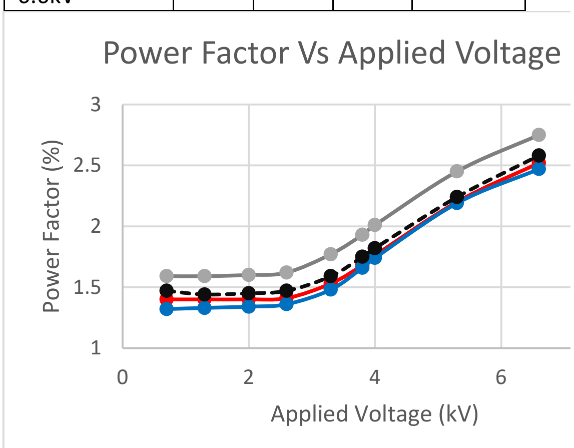
	Test Voltage (V)	Insulation Resistance (MΩ)	Result
Space Heater Set 1	500	21000	Pass
Space Heater Set 2	500	5000	Pass
Bearing to Housing	500	1000	Pass
Rotor Earth Fault Ring	500	630000	Pass

Dielectric Dissipation Factor Test

The stator winding was tested up to rated voltage using a grounded Specimen Test (GST) mode and at 2kV at Ungrounded Specimen Test (UST) mode as per IEEE286-2000. The UST mode was conducted to determine the condition of inter-phase capacitance and the stress grading integrity on the coils.

The power factor and tip up were the main parameters adjudicated. During the testing, the voltage was applied at the interval of 10% line voltage and the measurements leakage current, power loss (watts), Power Factor (%) and capacitance were recorded.

DDF Test Analysis	Phase U	Phase V	Phase W	UVW - Combined
Power Factor at 1.3kV	1.40	1.59	1.33	1.44
Tip-up % from 1.3kV to 4.0kV	0.36	0.42	0.41	0.38
Change in Capacitance from 0.7kV to 6.6kV	2.1	2.2	2.2	2.2

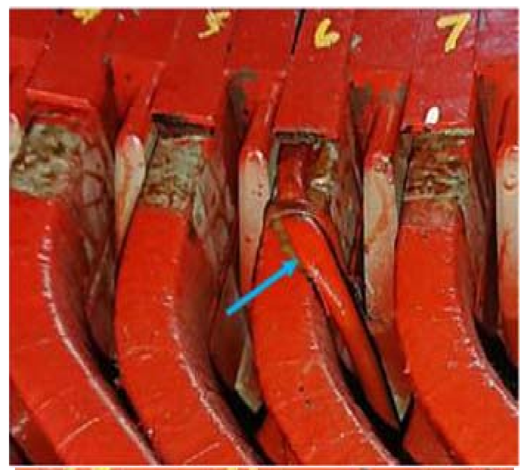


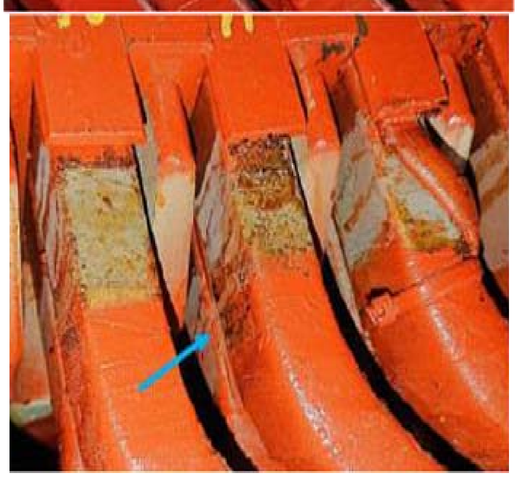
Offline Partial Discharge Test

The stator winding was tested up to 100% phase to ground voltage, 3.8kV at IEC standard frequency band filter setting for an offline PD test. The test voltage was applied at neutral end and the PD activity was measured on the line end of the winding. The voltage was increased to rated phase to ground voltage and ramped down in the same steps.

Non-classic PD activity, gap type discharge at the grading interface was identified during the offline PD testing.

An ultrasonic audibled discharge test was performed to validate the local surface PD activity around the endwinding region at 3.8kV. Headphones were used to locate the audible PD. Minor to moderate level of PD activity was confirmed at the slot exit at both connection end (CE) and non-connection end (NCE) of the stator winding. A moderate to high level of PD was recorded where the RTD cable were brought out of the slots across the stress grading region on the coils. Displaced centre packers between top and bottom coil sides were identified as compromising the stress grading on the non-connection end of the winding.





Stator Corona Probe (TVA Probe) Test

The stator windings were energised to 3.8kV (100% phase to ground voltage). Each slot was scanned with the PPM-97 Corona Probe. Most of the slots were qualified as having low readings at 5-10mA. The average reading was

11mA with 4 slots had areas measured up to 45mA. The maximum reading recorded was 90mA at slot 43.

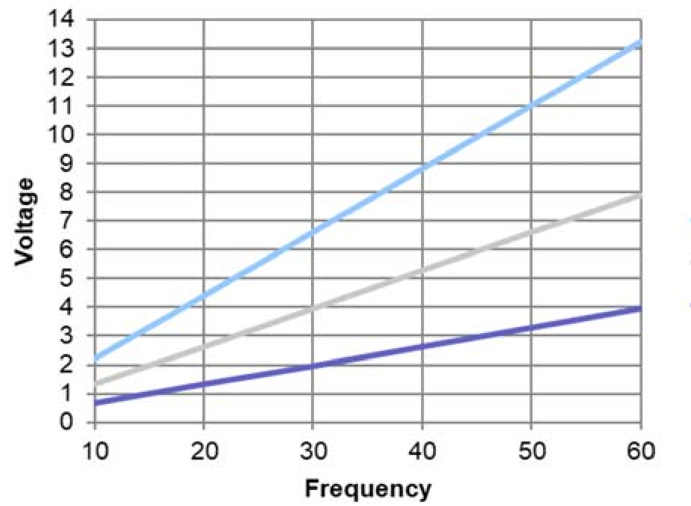
The local areas of higher discharge were inspected and considered with respect to the operating voltage of the coil in that location. The test voltage was varied to identify the discharge inception level.

Consideration was given to reversing the orientation of the line and star leads to reverse the winding stress. It was decided that this would be verified during the full voltage run test using the bus couplers on-line.

Run test as motor

A no-load test run as a motor was performed after the generator overhaul. The purpose of this test was to run the machine at full speed and voltage with the correct oil flow and pressure across the bearing seals to verify the effectiveness of the bearing seal repairs.

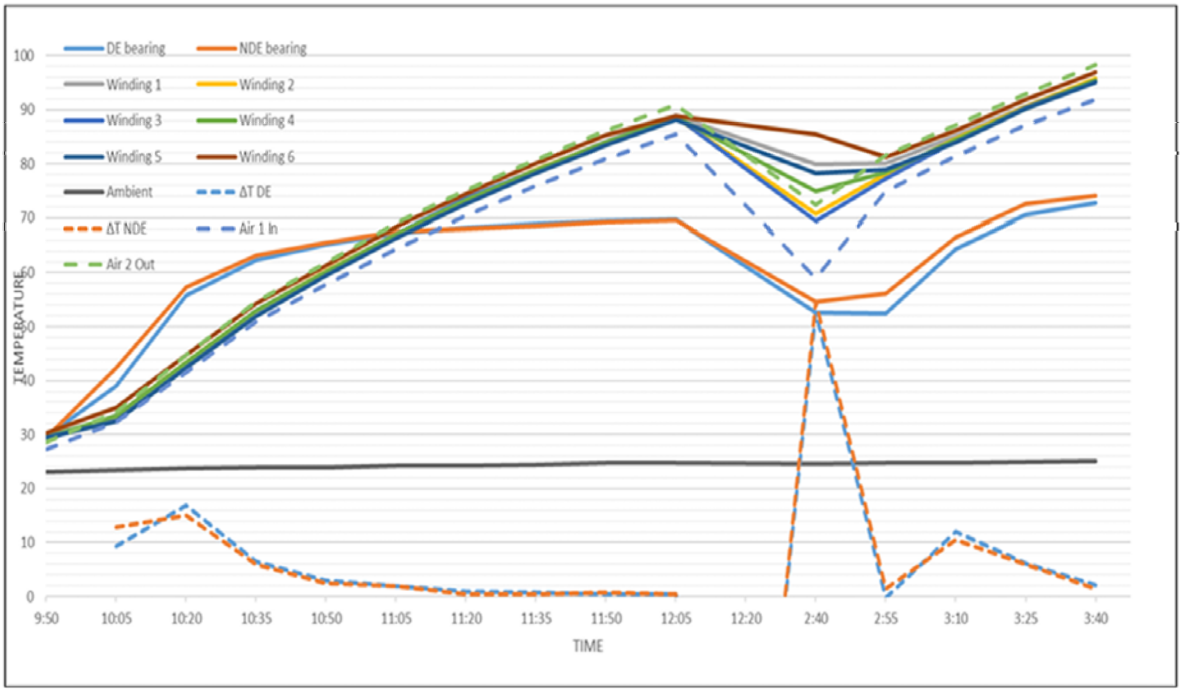
The generator was soft started with the test supply initially set at 10Hz. A crane with a soft sling around the shaft was used to lift the bearing and initiate rotation. Excitation was applied to follow the provided V-F curve as the machine was accelerated to full speed. 1500rpm and 6600V.



The test run was performed for 2hours and the following operating parameters were recorded:

- Test Voltage
- Supply Current
- Absorbed power
- Reactive Power
- Excitation level
- Powr factor
- Winding Temperatures
- Ambient Temperatures
- Bearing Temperatures
- Motor Running Vibration Levels

Run test results as a motor showing absorbed power, Volts, Amps, vibration, internal air bearing and winding temperatures



Oil seal evaluation

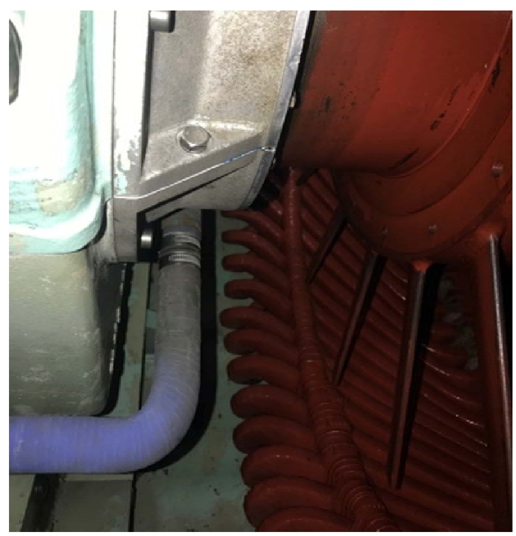
The lube oil system's pump pressure and supply values were set up at 20L per minute (10L per minute for each bearing) and 100kPa. The oil return was gravity fed and maintained to keep the minimum oil levels in each bearing housing pump. The oil grade was VG 46.

The following aspects were inspected during the enhanced oil seal evaluation:

- Pressure was measured at three different locations on each side of the generator: Within the bearing housing, inside the machine seal and inside the stator housing. The pressure differentials were calculated to assess the integrity of the solution.
- Two test runs were performed, followed my internal visual inspection to identify any oil migration.
- During the first inspection on DE side, no oil residue was found at the bottom of generator housing. However, there was slight oil misting identified on the endwinding support, shaft surface and rotor pole. On the NDE side, a waxy residue was found at the bottom of generator housing and was removed for analysis.
- After the second run, the endshield covers were removed to inspect for oil migration. Similar observations were noted. The accumulation of waxy residue at the bottom of generator housing (underneath the machine seal) was relative lower than what was found after 1st test run.

  Dynamic testing was performed with the heat exchanger mounted and without water circulation to provide the correct airflow within the generator housing, the winding temperatures at the end of the test were ~88.9°C and 96.9°C.
- Shaft induced voltage was measured at 123mV.
- Run down on the first test run was recorded as 20 minutes 2 seconds.

A fluke 922 Air Flow Meter was used to record the air pressure in the bearing housing, machine seal and stator chamber at both ends of the machine. The purpose of this test was to prove the effectiveness of the hemp sealing at the bearing housing to the stator winding chamber.



Online Partial Discharge Testing

Online Partial Discharge testing on the line side of the winding was conducted and compared with the previous PD test performed in October 2021. The highest PD activity was found to be decreased and improved by the maintenance. The generator was energised for 2nd run from star side connection to evaluate if lead reversal was an option to reverse the voltage stress on the winding. The PD activity was found relatively higher on star-side due to RTD anomalies identified in the assessment. No change was made.

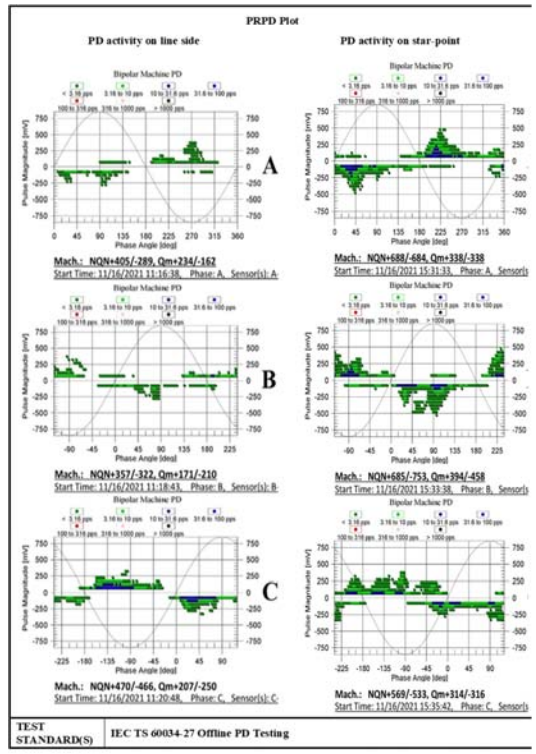
IRIS couplers installed on line side

During the online partial discharge testing, all the phases exhibited moderate level of partial discharge activity. The classic partial discharge activity had no polarity predominance indicative of voids and discharge within the main wall insulation. Non-classic pulse distributions were indicative of endwinding discharge and cross-coupling among the phases. The endwinding and surface discharge had effectively been recovered.

IRIS couplers installed on star-point

During the online partial discharge testing, all the phases exhibited a moderate to high level of partial discharge activity. The classic partial discharge activity had no polarity predominance indicative of voids and discharge within the main wall insulation. Non-classic pulse distributions were indicative of PD activity on endwinding at the RTDs and cross-coupling among the phases.

The partial discharge activity after the overhaul was improved and was qualified lowest on the original line side orientation. The stator winding was re-configured with this orientation.



Final Assembly and return to site

After final assembly and painting, the generator was returned to site,

Conclusion

The generator overhaul was successfully achieved and managed during the 14-day outage time. The repairs effected recovered the operating PD levels on the windings to an improved level and the bearing sealing modification was effective in limiting the oil ingress into the winding chamber.

Online PD monitoring and annual visual inspections form part of the reliability centred maintenance strategy for this generator. The series mechanical connection of this machine between a steam turbine and critical compressor requires that operating integrity has high priority.

The project management systems employed, specifications, vendor qualification, audit plan, inspection and test strategy and quality assurance served to achieve on time delivery for the recovery of this critical machine.

REFERENCES

1. Machinemonitor Repairmonitor project management system
2. OEM manual for the Fuji Generator
3. Specification for the overhaul, repair and testing of the Shinko 6970kW 7600kVA 6.6kV 831A 50HZ 4P 1500RPM 0.80PF Generator

Author curriculum vitae

Vikas Bhandari holds the bachelor's degree in Electrical Power Engineering with First-Class Honours from Curtin University, Australia. He works as Electrical Asset Management Engineer in Machinemonitor, focused on high voltage testing, inspection and overhaul of electrical rotating machines. He performs consulting services on Root Cause Analysis and investigation projects under Ron Scollay, *Principal Engineer Machinemonitor* and practices the principles of Reliability Centred Maintenance.
Vikas has recently completed a Professional Competency of Power Protection System and trained by IRIS on Prediction Maintenance Tool for stator windings in rotating machines. He has acquired Level I certification in thermography and Level 2 certification on Vibration Analysis.
Currently, Vikas is preparing for his Chartered Engineer credentials.

Ron Scollay **FIE (Aust) CPEng NER APEC Engineer Int PE Aus FSAIEE** is a Specialist Electrical Engineer with 35 years' experience in the field of electrical machines and auxiliary equipment. His experience covers general design, re-design, construction, testing and investigating application problems and failures of motors, generators and auxiliary equipment. Ron is currently Principal Engineer at machinemonitor.
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