Integrated Generator Rotor and Stator Winding Condition Monitoring

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Abstract – Traditionally power stations have performed maintenance on their critical machines on a time-based schedule, but this often resulted in activities occurring before they were necessary. Over the past 20 years, there has been a shift in the industry towards condition-based maintenance. This strategy requires the collection of a variety of data to detect most ageing related mechanisms that can be used to better schedule and plan maintenance. Initially, data was collected manually and infrequently, but once the benefits of condition monitoring started to be realized this has more recently shifted to continuous real time monitoring. Today, there is another shift away from application specific software to accessing a variety of data on a common platform and allowing for a more comprehensive analysis.

The most critical machines in a power plant are obviously the turbine generator sets. The generator rotor and stator windings are generally very reliable but they do age over time, thus reducing their electrical and mechanical strengths. This paper will focus on detecting turbine generator rotor and stator winding problems prior to failure using an integrated approach, and a case example including detection of partial discharge, rotor flux, and stator endwinding vibration will be discussed.

Index Terms – Generator, Condition-Based Monitoring, Partial Discharge, Rotor Shorted Turns, Endwinding Vibration

I. INTRODUCTION

Condition monitoring and condition-based maintenance have been practised for many years because the owners of capital assets recognized that resources are limited at the present economic climate. Even if the plant operation is profitable, it is still necessary to spend the reserved funds and use the labour-time wisely. With the development and advancement in technologies, a lot of information about the condition of key components can be obtained to assist plant engineers make their decisions on the required maintenance actions and also the timing. Many on-line measurements on the stator and the rotor of generators are available now, from simple winding temperature to torsional oscillation of the shaft [1]. Before this, maintenance was planned according to running hours. The approach can result in unwarranted outages because the generators are often found to be in good condition. Hence their availability and revenue are inadvertently reduced.

Generators are a piece of complex handicraft, so many things can go wrong. Inadequate design, poor workmanship, improper operation and careless maintenance, when acting in tandem with the stresses imposed by high temperature, constant vibration forces and environmental factors, can weaken the electrical and mechanical strengths of the materials and may eventually lead to premature failures. The ageing mechanisms and the state-of-the-art monitoring techniques of three common parts of the generator, the stator winding, the rotor winding and the stator endwinding, are discussed here.

The selection of on-line monitoring instrumentation will depend on the importance of the generator, usually in terms of the costs of lost production, repair and recovery. Sensors will be installed on the components of interest, and data will be collected, stored and analysed at pre-set intervals.

II. STATOR WINDING INSULATION

There are more than a dozen failure processes involving the stator winding [2, 3]. The common ones are:

- Thermal ageing
- Load cycling
- Loose windings in the slot
- Semi-conductive coating deterioration
- Interface of stress control coatings damage
- Electrical tracking due to contamination
- Insufficient clearance at endwinding area
- Improper impregnation during manufacture

Micro-voids that are formed between mica paper layers within the winding insulation or narrow gaps between two insulated conductors may produce partial discharge (PD) when there is sufficient electrical stress across a void or a gap. PD is a small electrical spark that occurs in insulation systems. The air or gas inside the gas-filled space is broken down and a localised discharge happens for a very short period of time.

On-line PD testing has been a well-established diagnostic tool and is being used on many thousands of motors and generators to detect stator winding insulation problems. However, it is essential that the measuring system is able to distinguish the winding PD from disturbances and electrical noise. Apart from the generator winding, PD can also take place in transformers, switchgear, power cables and isolated phase bus-bars with similar characteristics. Noise sources include transmission line corona, sparking at slip ring of power tools, inverters and poor electrical connections, etc. False indications of problems will be minimized if these disturbances and noise can be separated and avoided. Different sensor technologies measure partial discharge at the low-frequency (LF above 100 kHz – 3 MHz), high-frequency (HF 3 – 30 MHz), very high-frequency (VHF 30 – 300 MHz) and ultra high-frequency (UHF 300 MHz – 3 GHz) ranges. The first three are more commonly used for rotating machine application. Measurement at the VHF band is the most effective in attenuating noise from the ac power system and the surroundings, and discriminating disturbances [4].

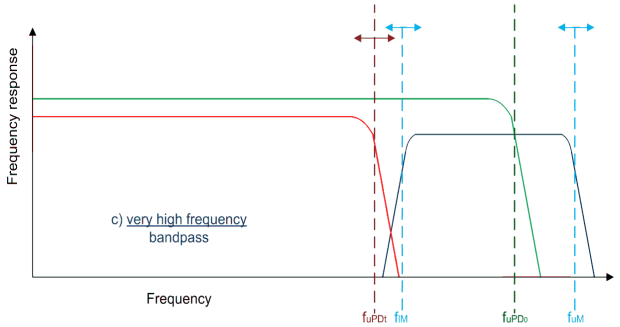

Fig. 1 Idealised Frequency Response of PD Pulse at Source, Noise and Measurement System at VHF Range [4]

Multiple ways have been developed to achieve this objective based on the fundamental principle of measurement at the VHF band:

- Filtering of signals to a frequency range that maximizes the PD signal to noise ratio be minimized.
- Gating (or blocking) of the signal when the occurrence of interferences is fixed in time and known.
- Employing two sensors per phase and implementing a "time-of-flight" algorithm to separate outside disturbances from the winding PD as determined by the relative time of signal arrival at the two sensors.
- Pulse shape analysis where research has shown that the stator winding PD pulses have a shorter rise time and different oscillation/damping waveform than noise

Moreover, PD signals travel like a wave at high frequencies, therefore the measured values of signal amplitudes are dependent on the surge impedance of the winding and not on its inductance and capacitance, which vary with different windings. This enables PD results of generators to be compared and statistics built up from those results to create gross severity levels.

A capacitive sensor of 80 pF connected in series with the typically 50 Ω input resistance inside the PD instrument provides a high pass filter with a lower cut off frequency of about 40 MHz at -3 dB. The waveform of a partial discharge pulse captured from a stator winding operating in air at atmospheric pressure is shown in Figure 2. The rise time of this sample pulse is about 3 ns, which has an equivalent (Fourier) frequency content up to 100 MHz. The capacitive PD sensor has very low impedance to the high frequency PD pulses, but it will strongly attenuate the electrical noise, most of which is below 20 MHz.

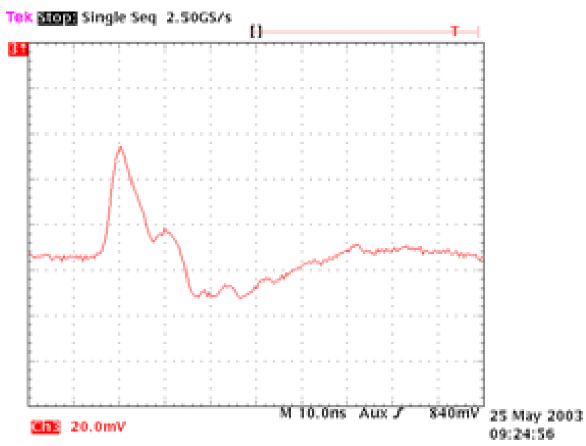

Fig 2 Oscilloscope image of a single PD pulse measured by an 80 pF capacitive PD sensor across a 50 Ω resistor. The vertical scale is 20 mV per division and the horizontal time base is 10 ns per division.

Besides noise, Figure 3 illustrates how the winding PD is picked out from external disturbances by the arrival times of sensor pairs.

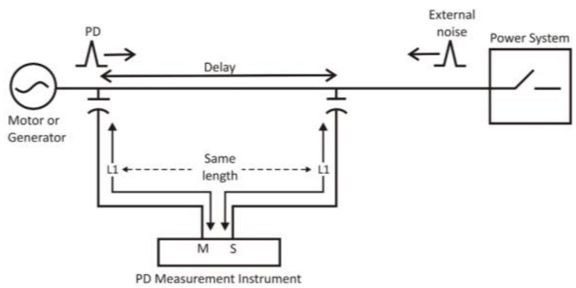

Fig. 3 Time Domain Disturbance Separation by Time of Pulse Arrival [4]

PD pulses propagate from the winding arrive at the set of sensors that is connected at the generator terminals (Machine sensor) first and then later at the second set further downstream (System sensor) are classified as "Machine PD", pulses that reach the System sensor first are classified as System Activity, while those arrive at both sensors within the Delay Time are called Between Activity. The top data plot of Figure 4 shows the stator winding PD activity and the bottom plot shows the disturbances from the power system as determined by the time-of-flight method. IEC 60034-27-2 also specifies the reliability requirements of capacitor sensors. Data is usually displayed with respect to the ac cycle.

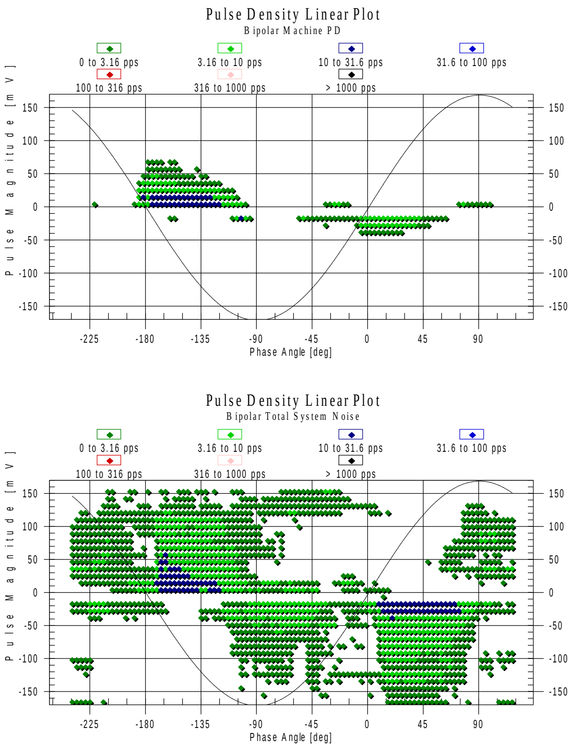

Fig. 4 Phase Resolved PD Patterns of Measurement The vertical axis is the PD magnitude in mV while the horizontal axis is the phase angle of the 60 Hz ac voltage. The colour of the dots indicates the PD pulse repetition rate.

VHF measurement makes further qualification of PD signals by pulse shape analysis possible because the high-frequency contents and the waveforms of the pulses are mostly preserved and can therefore be measured and qualified.

III. ROTOR WINDING SHORTED TURNS

The rotor winding suffers from its own stresses. A short circuit between turns in a coil is a chronic problem that is not protected by relays. Damage to the turn insulation and bridging between turns by conductive materials can be caused by these deterioration processes:

- Thermal ageing
- Load cycling
- Copper dusting
- Contamination

Electrical unbalance of the rotor will lead eventually to bearing wear, vibration and shaft bowing, at which stage the remedy will become expensive. Air gap magnetic flux measurement has been used for over 40 years as an on-line method to find turn insulation shorts in round rotors of turbine generators [5]. A flux probe is a small coil mounted on a stator wedge or core tooth, and protrudes into the air gap. It produces a voltage output that is induced by the radial leakage flux surrounding each slot in the rotor as each slot passes by the probe. Comparison of the flux waveforms of opposite poles can identify the amount of shorted turns and their slot locations. A reduced flux at any slot indicates fewer turns of the coil.

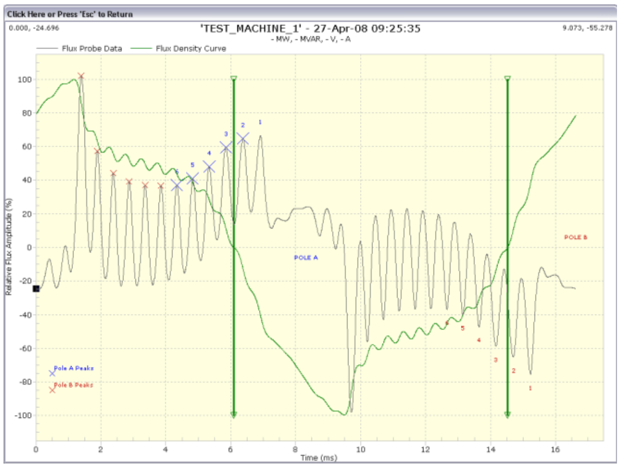

Fig.6 Raw Flux Waveform

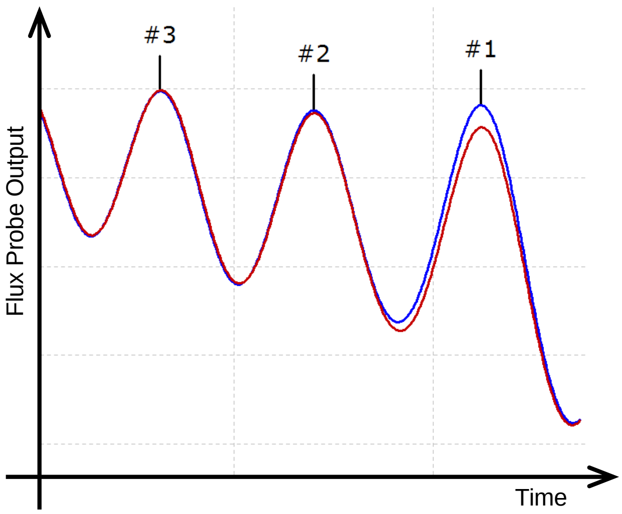

Fig.7 Analysed Flux Data and Peaks show reduced flux at coil number 1

Historically, it was necessary to collect the flux data repeatedly at many load points for a thorough analysis and for higher sensitivity reading for each slot. The radial leakage flux measured from a slot/coil is the least distorted when the main flux density is zero at that slot. The position of the zero crossing is a function of the load. Figure 8 shows that flux lines are modified at two load conditions. Hence it is necessary for the data collector to spend long hours, often at odd times, to gather data during generator start up or shut down. The testing would be tedious and time consuming.

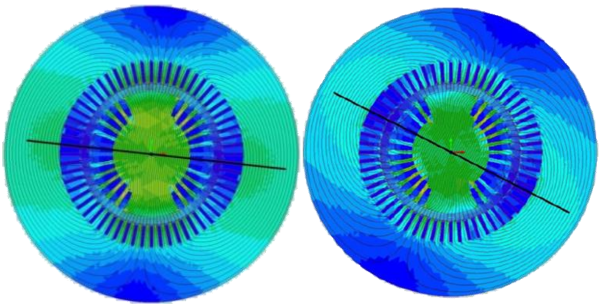

Fig. 8 Magnetic Flux Lines and Shift in Location of Flux Density Zero Crossing at Low Load (Left Diagram) and High Load (Right Diagram) [6]

Acknowledging this inconvenience after many years of user experience, recent improvements to the technology and hardware have demonstrated that reliable initial detection of rotor winding shorted turns can be obtained with a reduced need to vary the load on the generator [6]. Additional algorithms besides basic evaluation of peaks difference are devised to adjudicate more features of the waveforms and provide dependable assessment.

IV. STATOR ENDWINDING VIBRATION

The endwinding basket is subject to high vibrational forces in the radial and tangential directions at twice the power frequency due to electric currents running in parallel in adjacent stator bars during normal operation. These forces can be multiplied 100 times in the event of power system transients. The presence of high electromagnetic forces and high voltage prohibit the choice of strong metallic structures to support the stator bars outside the core and restrain their excessive movement. Stator endwinding vibration issues are more frequent on large generators with especially long winding overhangs that are not sufficiently supported. If any part of the endwinding has natural frequencies close to the forcing frequency, the displacement response will be the maximum and the result can be disastrous. Hence there is a need to monitor the vibration if a problem is suspected, issues on a similar model of generator are known or after repair/reinforcement of the endwinding.

Off-line impact testing has been used for a long time to check the natural frequencies and help determine if a resonant condition may exist. Otherwise the endwinding is visually inspected for symptoms of vibration such as dusting, greasing and movement. The inspection looks for evidence after some damage has already been sustained but cannot track the worsening of the situation. It is also an off-line examination when no mechanical forces are present. Both of the impact test and inspection require partial dismantling of the generator.

Monitoring the vibration displacement by means of accelerometers attached to the endwinding, connections provides a direct indication when the endwinding support structure starts to loosen. Since the number of locations that will be monitored is limited to the quantity of sensors, off-line impact testing should be carried out to determine the components that are likely to vibrate the most during operation [6]. Considering that the accelerometers are placed where high voltage and strong magnetic fields exist, the choice of accelerometer type is important. The regular piezoelectric sensor is not suitable. It may compromise the electrical clearance of the endwinding to ground and can result in partial discharge.

Fig. 9 Accelerometer Installed on Endwinding

Fiber optic accelerometers are used nowadays as they are immune to the electrical and magnetic fields present in the high voltage stator endwinding area [7]. With the modern fiber optic technology, more data at a broader frequency range can be collected. Not only endwinding displacement, velocity and acceleration data is assessed as well.

V. PLATFORM INTEGRATION

Deterioration of generator components is usually a slow process where the time between condition detection and failure may take many years. In principle, periodic measurements can be sufficient for detecting problems. However, a continuous, automated and fully integrated monitoring system has many more advantages:

- Site Operations and Maintenance staff are under increasing work load. Integrated monitoring systems allow automated measurements to be made, sparing time and expense of having to send personnel to the plant, which is particularly useful for remote plants or harsh climate.
- The monitored conditions are often affected by operating conditions, such as winding temperature, generator load, voltage and current, etc. An automated monitoring system eliminates this unpredictability by regularly updating the generator operating parameters and storing the readings with the saved measurements. Then the trend and any variation can be correlated with the operating state of the generator for better informed confirmation of deterioration or merely fluctuation due to other factors.
- Collecting data at various operating conditions is useful in the data interpretation process. For example, for the benefit of stator partial discharge measurements, winding looseness can be confirmed by comparing full-load and half-load PD magnitudes. At a higher load, the electromagnetic forces on the winding is increased and proportional to the load, so PD is increased with more winding vibration in the slots. Such an integrated automated monitor gives maintenance engineers comprehensive data and a complete picture of the generator condition when analysing the data collected in this manner.
- A single database, unified database structure and one protocol simplify the efforts and resources in coping with the diversity of user interface, data formats and communications properties of multiple independent systems.
- Expert systems or intelligent software can be used to correlate data from various sensors into one platform. An integrated condition monitoring system can augment the capabilities of more complex data types such as PD, rotor flux and endwinding vibration by processing data into simplified information. An integrated platform will corroborate fault diagnosis from multiple monitors to provide a cooperative approach to condition-based monitoring.

An integrated platform to collect data from a variety of sensors can be used for trending and assessing the stator and rotor conditions. Each generator to be monitored requires one data acquisition unit (DAU) to be mounted outside of the machine and near to the sensors. Coaxial cables and fibre optic cables connect the sensors to the data acquisition unit. It will raise an alert if a particular measured quantity exceeds a predefined value for the current machine operating conditions. Ethernet communications is used to connect the DAU to the plant local area network for configuration and data downloading. In this way, personnel at distant offices can conveniently define or change trigger conditions and alert levels, as well as download test results for display and analysis. The software is also a single platform for generator definition, sensor configuration, data downloading and data analysis. A common database archives data from all technologies along with relevant operating data. Engineers can look at long-term and short-term trends, compare data and perform detailed analysis to assess the generator health. A typical block diagram of the system layout is shown in Figure 10.

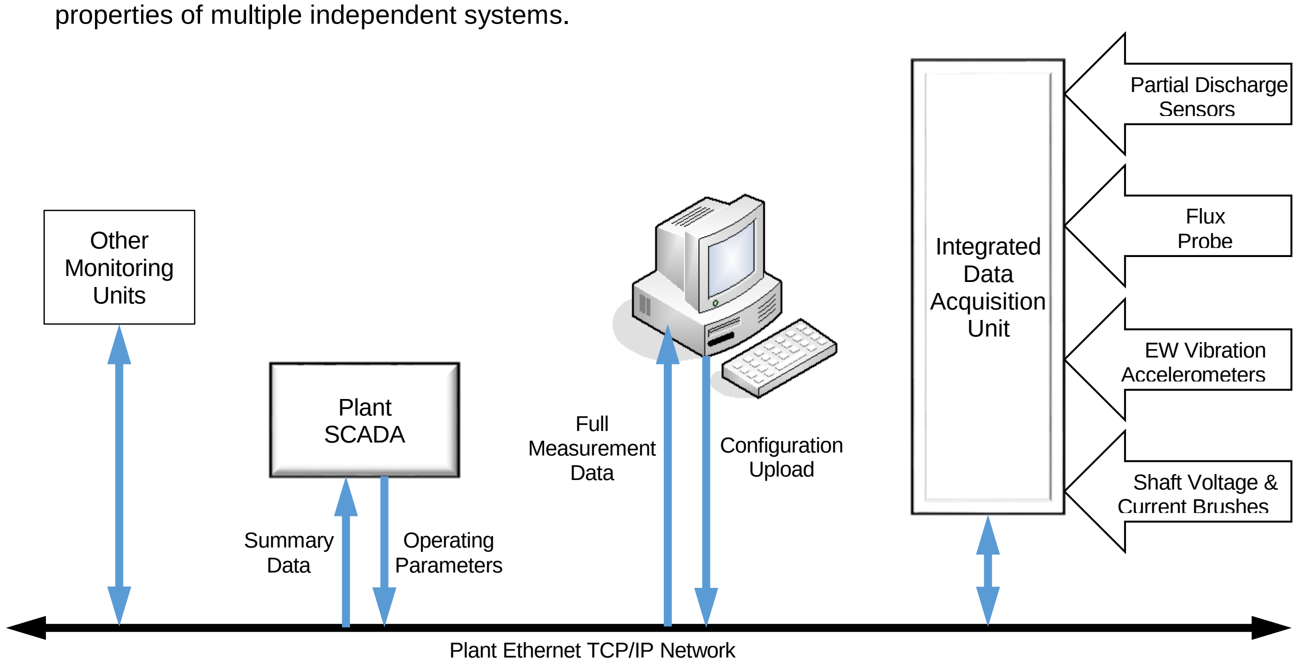

Fig. 10 System Schematic Diagram

Using such a platform, it is often possible to predict the "expected" values for sensors based on mathematical models of machine parameters. These predicted values can then be compared to the actual measured values and the deviations analysed to detect failure modes. For instance, the predictions of stator endwinding vibration can be made based on the stator current and winding temperature of the generator. If the temperature is constant, Ampere's force law can be used to calculate the force between two current-carrying conductors, which is directly related to vibration. This relationship with collected data is shown in Figure 11.

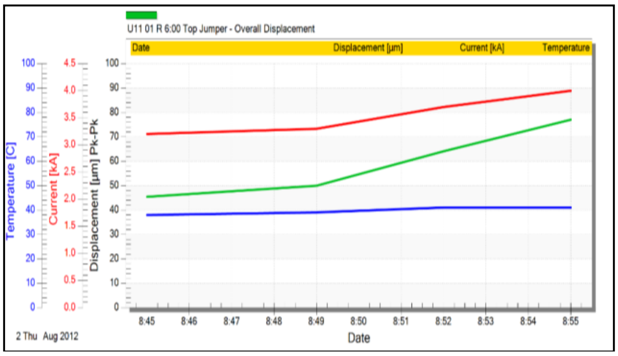

Fig. 11 Endwinding vibration, stator current and winding temperature over time

Once calibrated with baseline data, any change in current (or force) can be used to estimate the expected endwinding vibration and any deviation from which can be attributed to a change in the endwinding structural support structure. For many sensors, the alert levels may be significantly different depending on the operating mode of the machine.

The assessment of the generator stator insulation system is enhanced by having access to an extensive PD statistical database. The collective experience and results that are summarized in statistical tables [8] can be used to automatically configure alert levels, thereby ensuring an objective reference for the interpretation of insulation condition. Smart triggers can be utilised to save data at various generator load and winding temperature conditions, and also according to PD activity behaviour.

With a shaft synchronisation (keyphasor) provided, rotor flux waveforms recorded can be grouped and stored under different load points. The organization of measurements will add value and convenience in analysing the results.

Endwinding vibration data is continuously acquired from the accelerometers and alerts are set on high overall displacements. With complementary input of generator load, displacement values can be normalised to remove the influence of load on the data. Additional analysis capabilities enable the displays of displacement, velocity and acceleration at the selected frequency points of interest.

Modbus over Ethernet protocol links all parties of this plant information system together. It provides an interface with third-party applications and add the ability to receive machine operating condition data such as active power, reactive power, stator voltage, winding temperature and hydrogen pressure from the plant digital control system. Summary numbers of measured quantities and the status data of the monitor are transferred to the plant system for central trend display and validation of data quality. This two-way data transfer capability provides context to the PD, flux and endwinding vibration measurements and improves the value of the trending data.

Working groups at the international (IEC) and the national (such as IEEE) levels are necessary to realise true integration.

VI. CASE STUDY

An independent electricity utility company in North America operates a combined cycle generating station and applied condition-based monitoring with combined instrumentation of the stator winding insulation, rotor winding shorted turns, endwinding vibration and shaft voltage on the three generators at the plant. The implementation was proved to be successful and loose blocking in the 21 kV 260 MW 2-pole air-cooled gas turbine generator was discovered by the endwinding vibration monitoring module.

In June 2012, off-line impact test data revealed no critical natural frequencies near 120 Hz (Figure 12). Endwinding vibration accelerometers installed for periodic on-line monitoring as part of the condition-based monitoring program.

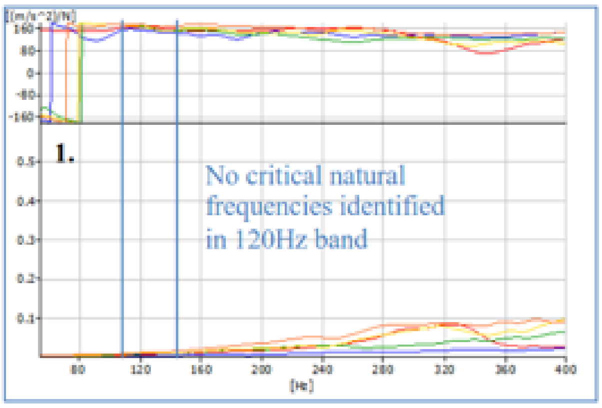

Fig. 12 Impact Test Results in June 2012

In August 2014, the on-line endwinding vibration measurements indicated a step change (Figure 13). The displacement exceeded the typical alert level of 250 µm or 10 mils peak-to-peak based on the guidelines recommended by IEEE 1129 [1, 9].

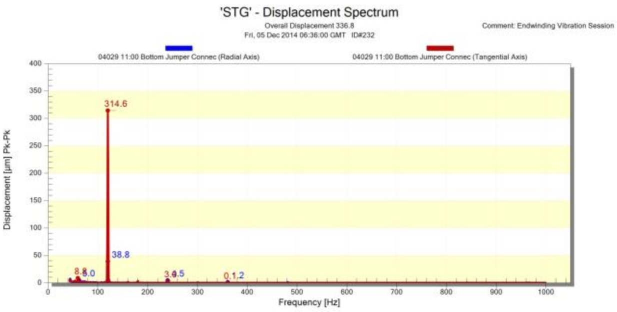

Fig. 13 Displacement Spectrum of Bottom Jumper Near 11 o'clock Position of Stator

Surprised by the finding and worried about the possibility of the onset of loosening, the endwinding vibration module was added to the existing monitor and half-yearly periodic testing replaced. The vibration data was frequently watched and reviewed until the next scheduled outage in March 2015 (Figure 14).

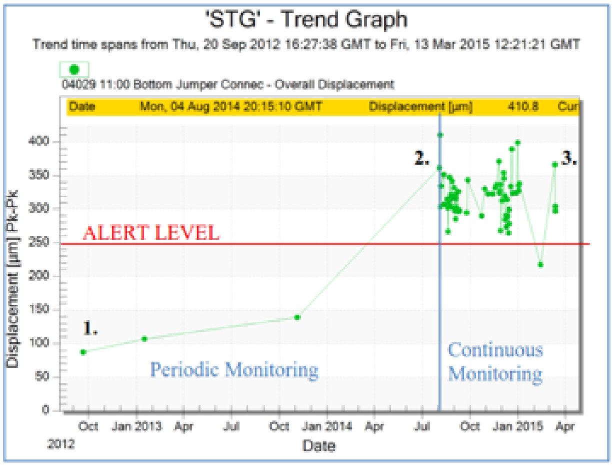

Fig. 14 Trend of On-line Vibration Displacement

Fig. 15 Dusting and Looseness at One Support Block

A visual inspection found loose support blocks and dusting at multiple locations (Figure 15). Another off-line impact test was carried out to determine whether the structural properties of the endwinding had changed. It showed that the accelerance was as high as 0.5 m/s²/N or 0.2 g/lb-f at critical natural frequencies near 120 Hz (Figure 16). Monitoring had continued until permanent repairs could be made.

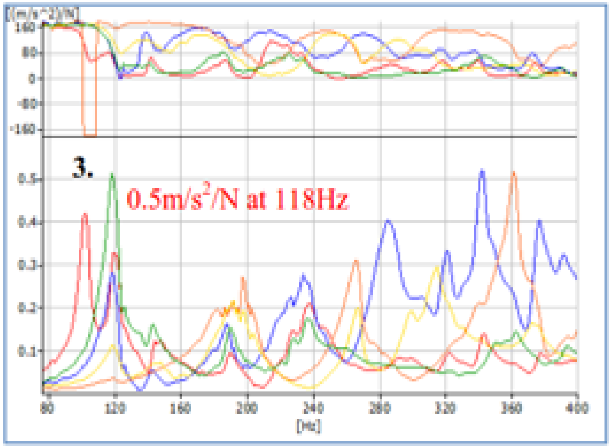

Fig. 16 Results of Repeat Impact Test in March 2015

VII. REFERENCES

[1] IEEE 1129-2014 Guide for Online Monitoring of Large Synchronous Generators (10 MVA and Above

[2] G.C. Stone, I Culbert, E. Boulter, H. Dharani, *Electrical Insulation for Rotating Machines*, Wiley-IEEE Press, 2014.

[3] G. Klempner, I. Kerszenbaum, *Handbook of Large Turbo-Generator Operation and Maintenance*, 2nd Edition, Wiley-IEEE Press, 2008

[4] IEC TS 60034-27-2: 2012, On-line partial discharge measurements on the stator winding insulation of rotating machines

[5] D. R. Albright, *Interturn Short-circuit Detector for Turbine-Generator Rotor Windings*, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-90 No. 2, March/April 1971

[6] M. Sasic, B. Lloyd, A. Elez, *Finite Element Analysis of Turbine Generator Rotor Winding Shorted Turns,* IEEE Transactions on Energy Conversion Vol. 27, No. 4, December 2012

[7] M. Sasic, H. Jiang, G.C. Stone, *Requirements for Fiber Optic Sensors for Stator Endwinding Vibration Monitoring*, in Proc. IEEE-CMD, September 2012, pp 118-121

[8] V. Warren, *Partial Discharge Testing – A Progress Report*, Proc. Iris Rotating Machine Conference, Scottsdale, Arizona, U.S.A., June 2016

[9] H.O. Ponce, et al. *Generator Stator Endwinding Vibration Tutorial Guide,* EPRI Report 1021774, June 2011

VIII. VITA

Connor Chan has been employed with Iris Power LP, Canada, since 2001 and is currently Rotating Machines Engineer. Prior to this position, he was Field Service Manager. Connor Chan graduated in Electrical Engineering from the University of Hong Kong. He is a member of the Institution of Engineering & Technology (formerly the Institution of Electrical Engineers), the Institution of Engineers Australia, and the Institute of Electrical and Electronics Engineers, and is a Chartered Engineer.

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Greg Stone has BASc, MASc and PhD degrees in electrical engineering from the University of Waterloo in Canada. From 1975 to 1990, he was Dielectrics Engineer with Ontario Hydro, a large Canadian power generation company. Since 1990, Dr. Stone has been employed at Iris Power LP in Toronto, Canada, a motor and generator condition monitoring company he helped to establish. He is a past president of the IEEE Dielectrics and Electrical Insulation Society, and continues to be active on many IEEE and IEC standards working groups. He has published three books and over 200 papers concerned with insulation of rotating machines. He has received awards from the IEEE, CIGRE and IEC for his technical contributions to rotating machine assessment. Greg Stone is a Fellow of the IEEE, a Fellow of the Engineering Institute of Canada and is a registered Professional Engineer in Ontario, Canada.

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