STATOR ENDWINDING VIBRATION IN TWO-POLE MACHINES

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Abstract – In the past 15 years, insurance industry data indicates stator endwinding vibration has become the most important cause of failure in generators. The source of vibration is the current creating magnetic forces between coils and may be amplified due to mechanical resonance. Endwinding vibration leads to failure by insulation abrasion or copper fatigue cracking. The extent of the repair due to the ensuing damage and the loss of production have proven to be very costly. After 13 years of operation one such failure occurred to a 2-pole, 95MW generator at a plant in Indonesia with an associated loss of $40 million. This paper describes the failure mechanism, the possible reasons why endwinding vibration has become a more important issue in the past decade, and a new IEC standard 60034-32 on methods to detect the problem well before in-service failure. A case study on the affected generator will show how a repeat stator winding failure was avoided using these tools.

Index Terms — Stator Winding, Two-Pole Machines, Endwinding Vibration, Motor, Turbine Generator

I. INTRODUCTION

The stator endwindings, that is the portion of the stator winding that extends beyond the stator core at each end (Fig. 1), are one of the most critical locations in two and four-pole rotating machines. Although the stator windings produce electricity (in generators) and torque (in motors) in the portion of the stator winding within the laminated stator core, the endwindings are essential to make connections between the parts of coils in the different stator slots. The higher the speed of the machine, electromagnetic forces and spacing constraints require the endwindings to be longer, that is, extend beyond the core for a greater distance. As described below, this longer endwinding makes it more difficult to ensure that the endwindings can fulfill their function without reducing the reliability of the motor or generator.

To avoid in-service failures, the endwinding support structure must fulfill its function of connecting parts of coils in different stator slots with the following constraints:

1. Mechanically support the coils against movement resulting from the Lorentz magnetic force between adjacent coils. This force is proportional to the square of the stator current, and causes an oscillating force that is twice the power frequency (referred to as a 2f force, 120 Hz in a 60 Hz machine). The stator steady-state force is mainly in the radial and tangential directions, and is caused by the current through the stator winding. In addition, the mechanical support structure of the endwinding should also be able to survive a transient current up to 10 times the rated stator current if the motor or generator is exposed to a nearby phase to phase fault, and approximately 6 times rated current that flows in the stator winding during starting of direct-on-line start motors.
2. Mechanically support the endwinding against external vibrational forces that may be transmitted to the endwinding from the stator frame. This can include the once per revolution force from the rotor bearings, referred to as the 1x force, for example 60 Hz in a two-pole, 60 Hz machine.
3. In large motors and generators, allow for the axial expansion of the copper conductors due to the high operating temperature of the coils in the slot and endwindings.
4. Not be affected by the high magnetic fields present caused by current flowing in the coils in the endwinding. This effectively means that ferrous material (like steel) cannot be used in the endwindings support system, since they will heat up in the magnetic field, and may shift due to these magnetic forces.
5. Not be affected by the high voltages (more correctly the high electric fields) present in the endwinding, since some of the coils are connected to the phase terminals. This effectively requires that the support structure not contain metallic components that are at zero volts, since the potential difference between the metal and the surface of the stator coils will result in partial discharge (PD).

These conflicting requirements have resulted in many different solutions by different manufacturers over the years [1-3]. However most modern endwindings do not use metallic components, instead using fiberglass, epoxy, insulating blocking between adjacent coils, and fiberglass/epoxy composite surge rings or cones. All these materials are used to ensure that the coils do not vibrate in the endwinding, cause local overheating, or lead to PD and electrical tracking.

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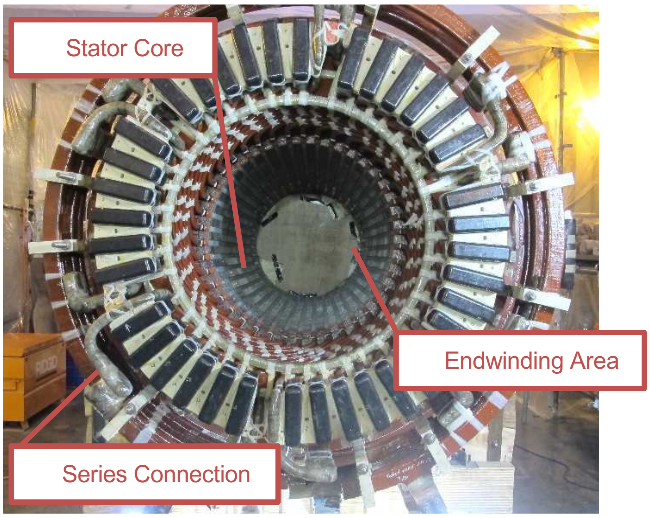

Fig. 1 Turbine Generator Stator Endwinding

Unfortunately, if the endwinding support structure is not well designed and/or well-made; or if the stator winding has aged, the coils in the endwinding may start to vibrate under the 2f or 1x forces. This vibration can cause the following issues:

1. The vibration can lead to relative movement between endwinding components – for example, fiber glass rope affixing the coils to the support rings and braces may abrade the coil insulation (Fig. 2). Eventually the abrasion can be severe enough to expose high voltage copper conductors within the coil. If partly conductive contamination is present, it may result in a phase to ground fault.
2. Endwinding vibration may loosen the stator wedges at the end of the stator core, which could eventually lead to the coils vibrating within the stator core, leading to slot discharge. If the coils do become loose in the slot, then this may cause the stator wedges to become loose. Also, loose coils in the slot may lead to abrasion of the PD suppression coatings, and hence high PD.
3. In the most extreme case, if the copper conductors within the coil vibrate enough, the copper conductors will fatigue crack. If all the conductors in a coil fatigue crack, the stator winding current continues to flow through the coil by forming a plasma at the severed copper, which causes extreme heating of the conductors, melting of the copper and nearby components, and often complete destruction of the stator winding (Fig. 3).

In the past, problems caused by endwinding vibration took many years, if not decades, to result in failure. However, in the past 15 years it seems that many two-pole machines, and air-cooled turbine generators in particular, have been failing in a much shorter time period. This paper reviews the possible causes of these more recent issues. The paper also describes ways owners of these machines can detect the issue at an early stage using both off-line testing and on-line monitoring. A case study is presented from a failure that occurred in two of the authors' generating station units.

II. RECENT ENDWINDING VIBRATION ISSUES

In the early 2000s, reports of catastrophic stator endwinding failures similar to that shown in Fig. 3 were being discussed at utility conferences by several operators of air-cooled turbine generators rated up to a few hundred megawatts. The endwinding failures were apparently occurring on several different brands of machines, often after only a few years of service. In addition, many cases of fretting (for example Fig. 2) were being found in modern air-cooled two-pole generators and greasing in hydrogen cooled two-pole generators. This led the Electric Power Research Institute (EPRI) to commission a report educating end users on the design of 2 and 4-pole generator endwindings, and possible failure mechanisms [4]. Various researchers also published papers on the recent increase in endwinding vibration issues [5-10]. In 2010, FM Global, a large insurance company used by generating stations, published a presentation where they indicated that in the period 2000-2010 they paid out more in claims for generator failures caused by endwinding vibration, than all other claims of generator failures combined [11]. About the same time, machine manufacturers decided that an IEC standard was needed to educate end users about the endwinding vibration issue, and ways to determine if a problem exists. This resulted in the 2016 publication of IEC 60034-32 [1].

In reviewing this information, it seems that many machine manufacturers changed the design or manufacturing of the stator endwindings sometime about the year 2000. The driver for the changes may have been a desire to simplify the design and/or manufacturing, in order to reduce costs in the fiercely competitive gas turbine generator market. Unfortunately, it seems in many cases the mechanical natural frequencies sometimes moved in such a way that resonance (or amplification) of the vibration was occurring [4-6, 8-9, 12]. That is the natural frequency of some areas of the stator endwinding were closer to the forcing frequency (usually 120 Hz in a 60 Hz machines, 100 Hz in 50 Hz machines). In other cases, the lead from a stator coil to the circuit ring bus was often not supported in as many locations as tended to occur in the past, or the method of the bonding of ropes and cords to the coils and support members were not as robust.

The publicity surrounding the premature failures motivated many manufacturers to alter their designs, and thus most machines made since 2012 or so have endwindings that are less prone to endwinding vibration. However, many 2-pole (and a few 4-pole machines) are still in operation with sub-optimal endwinding designs.

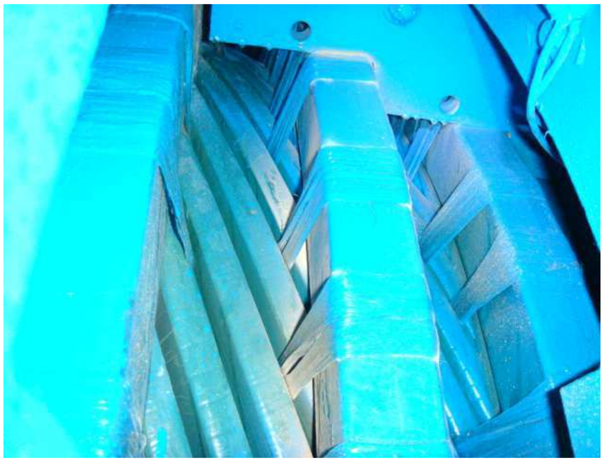

Fig. 2 Photo of insulation abrasion (white powder caused by fretting) caused by relative movement between the coil, support ring, and support brace

Fig. 3 Collateral damage to the stator winding and core caused by fatigue cracking of the copper conductors due to severe endwinding vibration

III. OFF-LINE METHODS TO ASSESS LOOSENESS OF STATOR COIL SUPPORT SYSTEM

Visual inspections of the endwinding and surrounding support structure are generally considered the main tool to detect evidence of excessive movement [12]. The dusting that results between components that are supposed to be held tightly together is an indication that they have come loose and are rubbing against each other resulting in the insulation to fret (Fig. 2).

"Bump" testing can be used to identify the natural frequencies that are characteristic of the endwinding and support system structure. In the bump test, various areas in the endwinding are hit with a hammer, and the response to this impact is measured with temporarily-installed piezoelectric accelerometers. These response frequencies are proportional to stiffness. Resonance is a condition where the natural frequencies of the windings and support system coincide with the normal operating forces at turning speed (1x) and twice line frequency (2f) resulting in amplification of normal vibration levels at these frequencies and increasing the copper fatigue rate. As the endwinding looseness increases, the natural frequencies decrease. This makes the bump test a trendable off-line test if the data is collected at the same locations. Having the natural frequency information of a structure can be used to avoid resonance.

Modal analysis is a bump test procedure that provides a global evaluation of the endwinding basket to ensure any natural frequencies near twice line frequency are not of a critical shape [1, 4], for example oval for 2-pole machines (as the stator tends to deflect naturally in an oval shape due to the 2-pole rotating magnetic field) and a square shape for 4-pole machines. To capture modal data, usually the force is recorded from a calibrated hammer at a fixed location and the accelerometer is moved at equidistant positions around the endwinding basket on the same plane.

Bump testing (driving point and modal) should be carried out after a major repair or rewind to characterize the effect on the natural frequencies from the structural changes. If similar data is collected periodically it is possible to trend these frequencies, particularly if a baseline test is performed during installation of the machine. It is only possible to trend these frequencies if the data is collected with the same methods and at the same locations which requires good reporting practices since the period between tests can be several years due to limited machine access. Driving point tests where the accelerometer and hammer are at the same location can also be carried out to assist in the location of sensors to monitor the vibration online for local resonances.

When performing a bump test the effect of temperature must be considered. The natural frequencies identified at room temperature during the off-line testing will shift downward in frequency during machine operation by as much as 10 Hz or more [1, 4, 8]. It is for this reason that typical acceptance criteria for a stator endwinding bump test to avoid natural frequencies above a certain magnitude within a frequency band around 1x and 2f favoring the upper frequency band [1, 4, 12-13], e.g. 54 to 72 Hz and 108 to 144 Hz (-10% / +20% of 1x and 2f) for a 2-pole, 60 Hz machine.

If a resonance condition on the stator endwindings occur during operation, the stator wedges and the coils in the slot may loosen as well. There are several off-line methods that can be used to assess coil looseness in the slot. A manual tap will make a distinct "thud" if the wedge is hollow or loose [2-3, 12] which is a distinctly different sound than on a wedge that is tight. The qualitative analysis of listening to the sound of a tapped wedge during the test is subjective and relies on operator experience. Alternatively, a robotic calibrated hammer can be used to strike the wedge beside an accelerometer to measure the vibration response of the wedge providing repeatable and more easily comparable results. A tight wedge is used as a reference from which the remaining wedges are compared against.

IV. ON-LINE METHODS TO ASSESS LOOSENESS OF STATOR COIL SUPPORT SYSTEM

Permanently-installed accelerometers are considered the best way to understand the endwinding behavior during operation [1, 4, 12]. On-line monitoring has the benefit over off-line testing by monitoring the condition while the machine is at operating temperature and load. As well, on-line monitoring can assess the effect of a transient current on the endwinding structure without having to take the machine out of service and disassembling it for inspection, adding potentially unneeded cost in downtime and the risk of taking the machine apart. Modern stator endwinding monitoring systems use fiber optic accelerometers to avoid introducing metal into the high voltage and high magnetic fields present in the endwindings, which could potentially cause overheating or lead to partial discharge (PD) and electrical tracking.

Historically, the vibration quantity used to assess endwinding vibration is displacement, that is, the total distance of the component being monitored as it moves around its rest position. The main benefit of continuous monitoring of stator endwinding vibration levels on-line is the ability to trend the displacement over time, and whether the trend is related to machine operation (increased load results in higher forces and thus, higher vibration amplitudes). However, it is sometimes necessary to evaluate the endwinding vibration against recognized acceptance criteria. Unfortunately, progress in the development of such an absolute criterion is slow, but it is generally recognized that 250 microns (10 mil) peak-to-peak at 2f (120 Hz for a 60 Hz machine) is cause for some concern [3-4, 14]. A recent EPRI study using a modeled approach suggested much higher action levels for endwinding vibration ranging from 500 to 1200 microns peak-to-peak [10]. The hypothesized levels were separated into 4 categories based on the stiffness of the endwinding support, with higher acceptable levels on more flexible designs which is a reasonable approach. The resulting action levels though, are not consistent with the practical approach used to develop IEEE 1129 which is largely based on experience from past years with 60 Hz generators in North America [14]. Regardless of the source, it is of most concern if there is a rapid increase to the vibration levels at similar operating conditions which can be irreversible [1, 4, 10, 14]. An increase of more than 25% in the displacement under the same operating conditions is considered significant [1].

Vibration collected from an accelerometer requires double integration of the signal to get displacement. Integrating the signal twice with respect to time puts an emphasis on amplitudes at lower frequencies. Thus, if the focus of vibration assessment is less than a few hundred Hz, as is the case for monitoring stator endwinding 1x and 2f fundamental frequencies, displacement is suitable. However, mechanical looseness can present itself in a vibration spectrum with a series of harmonics (multiples of some fundamental frequency) [1] often amplified by one or more resonances so it can sometimes be advantageous to view the data as acceleration, or integrated just once to velocity. Velocity has a smoothing effect over a wider range of frequencies to more readily identify harmonics possibly associated with mechanical looseness. The excitation force is still 1x or 2f and the looseness allows the component to vibrate more freely than if there was a tight bond due to a reduction of stiffness in the support structure. It is this condition that can result in rattling and the production of harmonics in the frequency spectrum. For comparison, below are displacement and velocity spectra at the onset (Figs. 4-5) and leading up to (Figs. 6-7) endwinding support structure looseness identified during a visual inspection (Fig. 8) [9]. Not only is the dominant frequency at 2f (120 Hz for 60 Hz machine) which is considered typical endwinding vibration, but the harmonics present are indicative of mechanical looseness. When comparing the relative amplitudes at 240 and 360 Hz to the fundamental 120 Hz they are more easily identified when viewing the velocity.

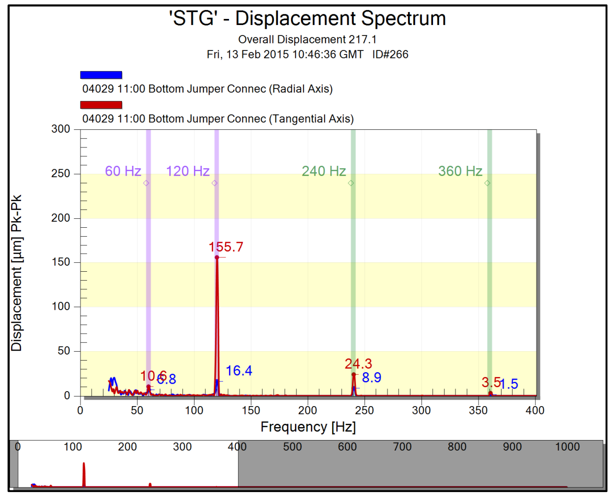

Fig. 4 Displacement spectra at the onset of looseness

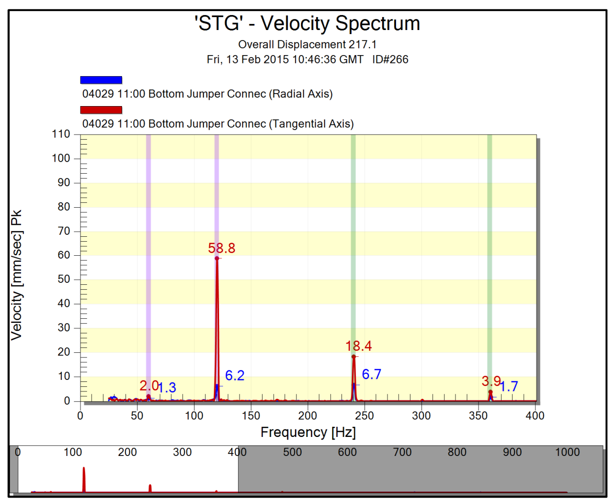

Fig. 5 Velocity spectra at the onset of looseness

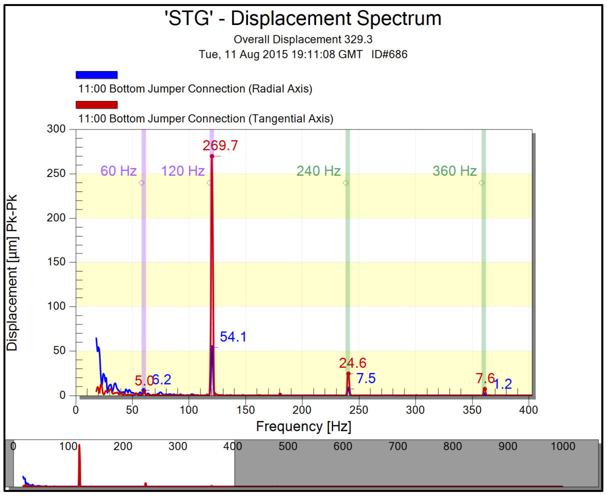

Fig. 6 Displacement spectra just prior to visual inspection confirming looseness

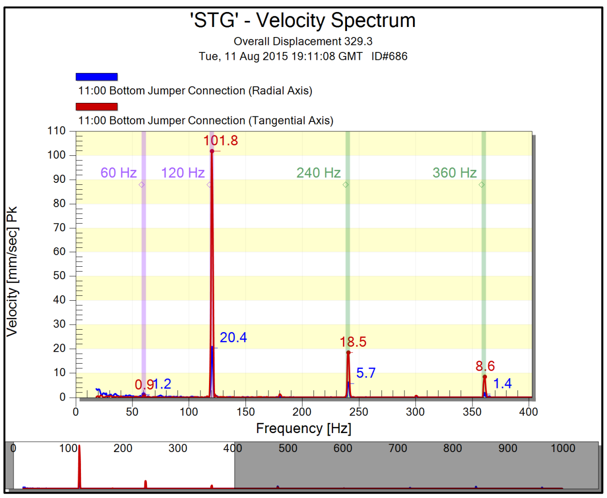

Fig. 7 Velocity spectra just prior to visual inspection confirming looseness

Fig. 8 Visual inspection showing looseness between the support block, circumferential support ring and connection between the winding and circuit ring [9]

Operating Deflection Shape analysis can also be used for global vibration and comparisons with modal analysis. If the relative locations of the accelerometers are known and if the signals are collected at the same time with a multichannel instrument, the relative amplitudes and phase timing of the vibratory signals can be compared and even animated to represent the global behavior of the endwinding. This can help relate the operational movement on-line with the mode shape from the bump test data recorded off-line to assess the potential for exciting a global resonance of the endwinding basket. A global resonance is an indication of an impending fault which often requires thorough investigation and structural modifications to reduce the amplification. On the other hand, a local resonance can often be controlled by periodically tightening the structural components and continuing to trend. In most cases a permanent fix is difficult, if even possible when an endwinding vibration issue is present, so on-line monitoring can be utilized to effectively plan and schedule maintenance outages.

In extreme situations where the stator wedge and/or coil in the slot have loosened, fiber optic accelerometers can be used to directly monitor the vibration at the slot exit. In general, the maximum movement in the slot is near the exit. This is based on the physical evidence of the location of the surface abrasion during winding inspections and it is for this reason that attention is paid to the end wedges after stator winding faults as they are generally the loosest. Alternatively, capacitive sensors can be used to measure the relative vibration between the wedge and the stator coil, but this approach requires the modification of the wedges to properly install the sensors. As well, the results of the capacitance change can be misleading if the wedges become loose and the coils remains tight. Generally, loose wedges can be tolerated, but loose coils require tightening to avoid damage to the surface coating.

V. CASE STUDY – 2-POLE, 95 MW, GENERATOR

In 2013, after 13 years of operation Unit 2 (Fig. 1) tripped when the generator relay phase differential current was activated due to a Phase B – Phase C to ground fault. This resulted in generator damage and loss of production of more than 40 million USD. An incident investigation concluded that the probable cause was vibration occurring on the generator endwinding abraded the insulation leading to cracking of the coil insulation just outside of the stator slot (Fig. 3). As is known from similar failures elsewhere, in severe cases, this vibration may cause the copper conductors to fatigue crack. Once all the copper conductors in a coil had cracked, a high arcing current occurred between the severed ends. The plasma melted the insulation in adjacent coils, leading to the phase to phase fault. The recommendation of the investigation was to install a generator stator endwinding vibration monitoring system.

Bump testing was used to determine the most responsive areas where the potential for vibration was greatest to locate where the accelerometers should be installed. The maximum accelerance responses ($(m/s^2)/N$) were recorded in the critical frequency band of 90 to 120 Hz for this 50 Hz machine (Fig. 9).

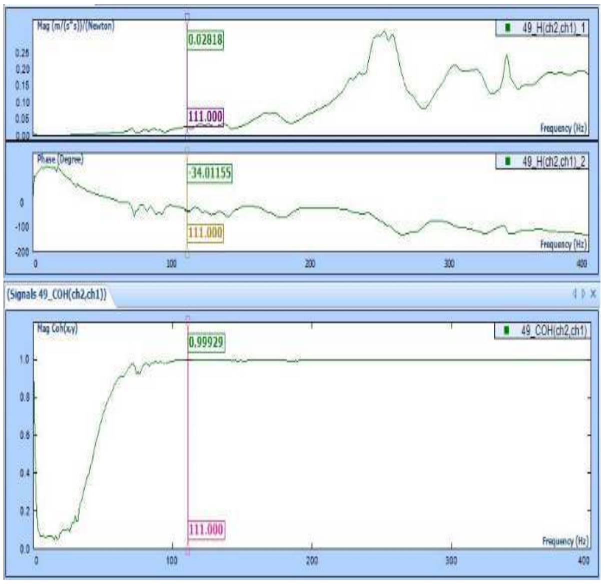

Fig. 9 Typical frequency response function showing 0.028 m/s^2/N (0.013 g/lb-F) at 111 Hz (top plot) with phase (middle plot) and coherence (bottom plot)

An effort was made to distribute the accelerometers sufficiently to maximize coverage for monitoring the generator stator endwinding vibration. Dual axis sensors were installed to measure in the radial and tangential directions at 6 locations on the connection end of the generator. Various components were selected to generalize the vibration behavior of the stator endwinding including 2 sensors on line end connections from the windings to the circuit rings, 1 on a jumper connection, 1 on a winding near the series connection end cap (Fig. 10), and 2 on the circuit rings. Additionally, 1 single axis sensor was installed on the stator core as a reference. The instrumentation used to continuously monitor the endwinding vibration data online was commissioned to store the raw vibration signals once per day on all the sensors for the data set that had the maximum overall displacement levels.

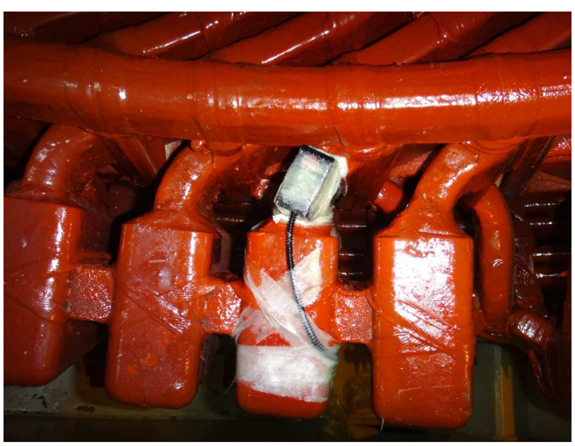

Fig. 10 Example of an installed sensor on a winding near the end cap which insulates the connection between two coils

Vibration levels greater than 250 microns (10 mils) peak-to-peak (broadband) on the connection end led to a shut down in October 2016 (Fig. 11). The predominant frequency was subsynchronous (below turning speed). This peak was present on all the sensors at varying amplitudes, including the core. It is likely that the source is external to the endwindings (Fig. 12). Viewing the data as velocity shows some higher frequency response that is not related the 2f (Fig. 13), which is totally suppressed when viewing the displacement spectra. It is likely that the 333 Hz vibration amplitude is being amplified by a natural frequency. The vibration amplitude from the electromagnetic force at 100 Hz was acceptable at less than 75 microns (3 mil) peak-to-peak (Figs. 12 and 14).

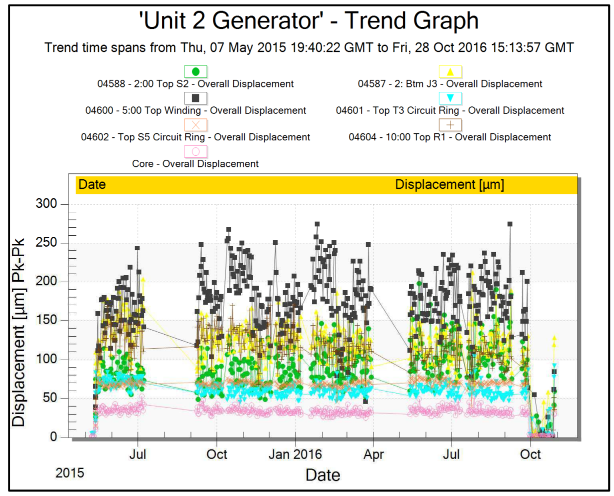

Fig. 11 Overall broadband (25 to 1000 Hz) displacement trend before and after October 2016 repair

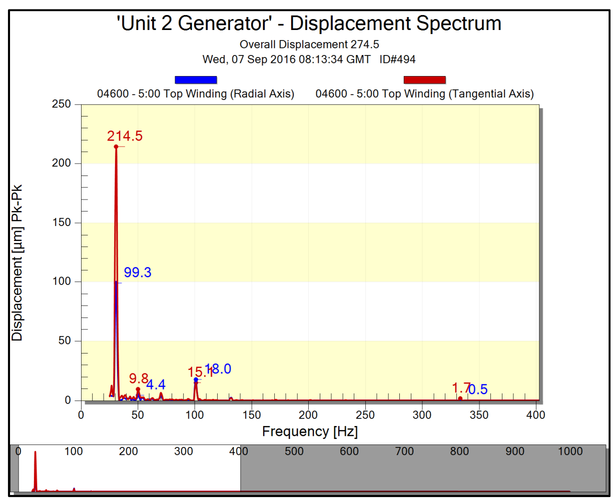

Fig. 12 Displacement spectra before repair

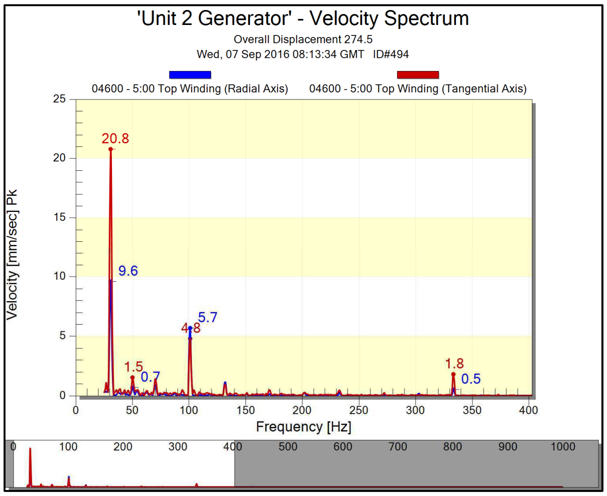

Fig. 13 Velocity spectra before repair

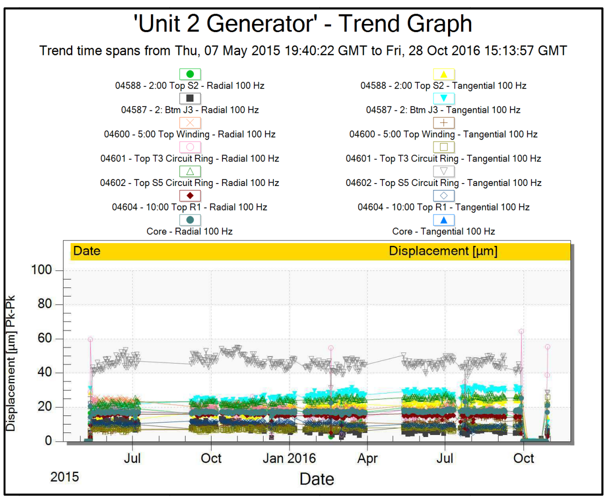

Fig. 14 – 100 Hz displacement trend before and after repair

During the outage, a manual tap test of the stator slot wedges showed that many were loose and needed to be replaced. A bump test on the endwindings was also performed and there seemed to be some correlation between 5 of the loose wedges with end turns that had high response in the bump test on the turbine end. The loose wedges numbered 1, 19, 22, 25, 28 correspond with T1, T25, T22, T19, and T16 location that experienced high bump test levels (Fig. 15).

The criteria used for the bump test was an acceleration response of greater than 0.055 $m/s^2/N$ (0.025 g/lb-F) within 5 Hz of 50 and 100 Hz and greater than 0.110 $m/s^2/N$ (0.050 g/lb-F) within 10 Hz was considered failed. The results from the bump test also led to the decision to install additional sensors on the turbine end of the generator stator endwinding. The stator slot wedges which were loose were also replaced.

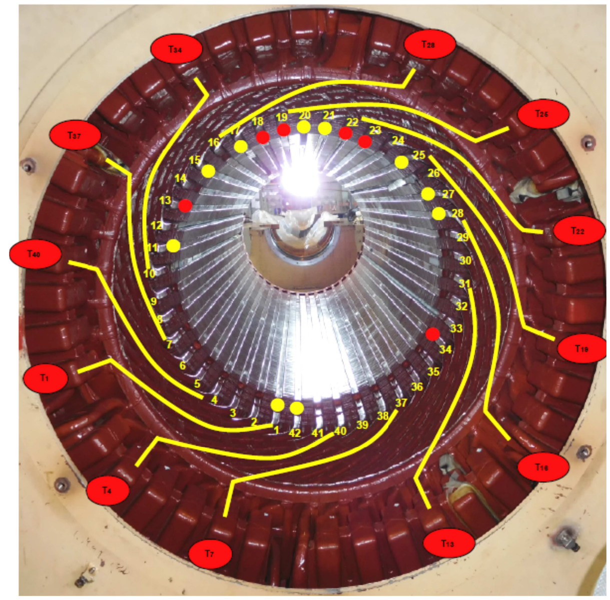

Fig. 15 Unit 2 Generator with wedges and bump test locations identified

Wedge replacement on the connection end appears to have affected the endwinding vibration response. After the outage, the unfiltered vibration levels were reduced to 200 microns (8 mils) peak-to-peak for the remainder of the year (Figs. 11 and 16). Tightening the coils in the slot seems to have limited the endwinding vibration response from the subsynchronous external source. The 100 Hz vibration remained unchanged.

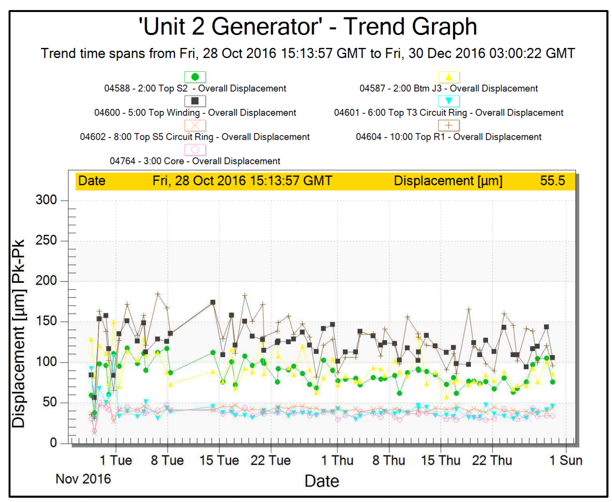

Fig. 16 – Overall broadband (25 to 1000 Hz) displacement trend after repair

Partial discharge levels were recorded prior to the outage in August 2016. The Qm values were 59 mV maximum (Fig. 18). For air-cooled stators equipped with 80 pF sensors on the terminals these amplitudes are within the 25% of about 20,000 statistically independent test results from about 6,000 machines and is generally considered low [15]. Even though the wedges were loose the coils were not vibrating sufficiently to degrade the semi-conductive surface coating.

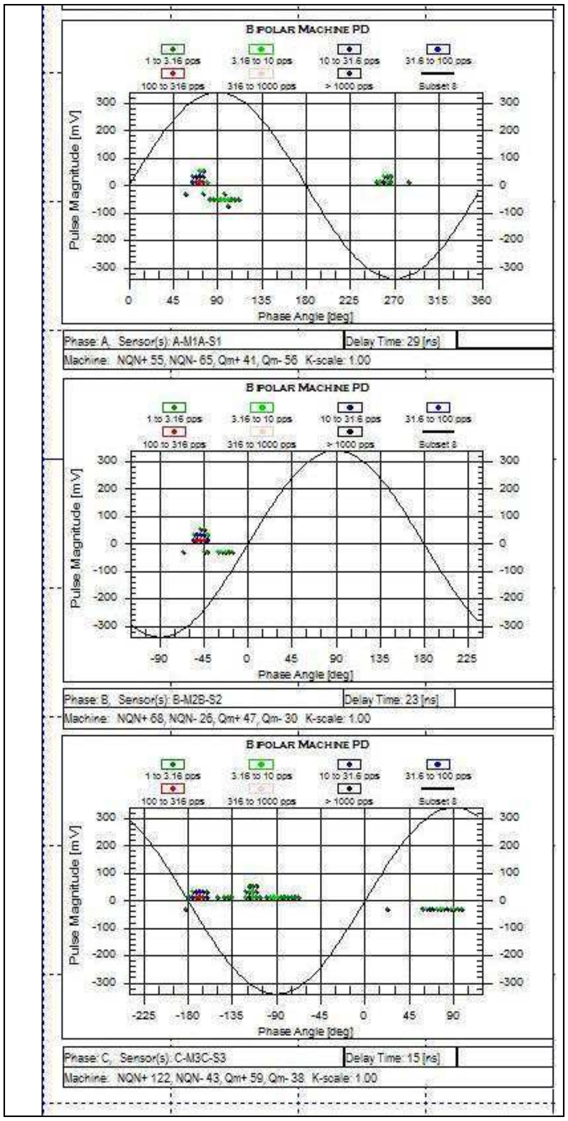

Fig. 17 - Machine PD at 20-340mV Sensitivity Range

VI. CONCLUSIONS

Problems in two and four-pole motors and generators can be avoided with careful specifications prior to the purchase or rewind of these machines. This seems to have had an impact on the condition of the stator coils between the slot exit of the core and the end turns since machines more recently manufactured appear to have less issues with endwinding vibration. Those machines requiring a bump test with appropriate exclusion zones have less potential for resonance resulting in lower vibration amplitudes during operation.

For those machines with high endwinding vibration amplitudes, the increased rate of copper fatigue can lead to stator winding failure. The degrading looseness conditions can extend from the end turn and support system to the coils inside the slot including the wedge tightness. Periodic testing off-line can assess this looseness and help to determine the potential for resonance during operation. If there are local resonance issues or when a generator is being fitted for online monitoring driving point testing is sufficient. Conversely, if there are concerns about global resonance related to design or if there has been a significant structural change to the endwinding and support system then additional modal analyses should be performed.

The best way to assess degrading looseness conditions for machines with endwinding vibration issues is to monitor the response to operational forces on-line. Rapid deterioration to the support system can be identified with increasing vibration trends at similar operating conditions to assist in the planning of maintenance activities. Any change to the structural support system should be validated with a bump test to limit the potential for resonance and the repairs can be deemed successful with a reduction in vibration amplitudes on-line.

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VIII. VITAE

John Letal is a Rotating Machines Engineer at Iris Power responsible for supporting rotating machine mechanical monitoring initiatives including stator endwinding vibration. Prior to Iris, he spent 7 years with Siemens TurboCare as a Field Service Engineer troubleshooting large rotating equipment using such tools as vibration analysis, force response measurements, and modal analysis. He was also involved in the implementation and execution of vibration analysis programs. John holds a BSc in Manufacturing Engineering from the University of Calgary, a MEng degree in Mechanical and Industrial Engineering from the University of Toronto, and is registered as a Professional Engineer in Alberta, Canada.

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