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End-winding vibration monitoring for hydro-generators

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SUMMARY

End-winding vibration issues have been an ever increasing subject of interest in the power industry, specifically in the turbo-generator side of power generation. An increasing number of major failures, due mostly to insulation breakdown, have been directly attributed to end-winding vibration. In an attempt to better understand this phenomenon, power utilities have been investing in fiber-optic technology for quite a few years now. The installation of fibre-optic accelerometers on various components has provided valuable on-line data, providing engineers an opportunity to analyse the various vibration behaviour patterns associated with end-winding structures.

Although the usefulness of this monitoring technology has been proven many times over in turbo-generators, a definite interest in the use of fibre-optic technology has been observed in hydro generation, as well as in the mining industry for application on SAG mills and gearless ball mills.

In 2001, the generator which is the focus of this paper was uprated with complete turbine replacement, re-insulation of the rotor poles and installation of a new static excitation system. No work was done to the existing stator; with the exception of cleaning, inspection and testing. No signs of anomaly were detected. The machine was uprated from 78 to 83 MW.

The generator experienced four stator winding incidents between 2006 and 2010, resulting in 17 coils being bypassed. Some of the worst incidents were caused by copper strand failure from fatigue and overheating, all in the area where the coil leads exit the stator core. A thermographic scan performed in 2009 also revealed a few other hot spots in the same area. In 2008-2009, maintenance personnel reported higher noise and vibration with this machine than with others. As a result of increased winding temperature, the unit active power was limited to 60 MW and its reactive power was limited to 0 MVAR. The generator use was also restricted to periods when hydraulic conditions made it necessary.

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In late 2009, the utility decided to install a total of 14 fibre-optic accelerometers, 8 piezo-electric accelerometers, as well as 8 optical temperature sensors on the stator to monitor the behaviour of this generator.

The case study included in this paper will show how this technology can be very effective in the monitoring, detection and identification of problems emanating from electro-magnetic stresses exerted on the end-winding structure for hydro-generators.

It will also show that with proper trending and analysis capabilities, early detection of end-winding vibration issues on hydro-generators can be achieved. This of course leads to the prevention of major and costly failure, and allows for the lifetime extension of the stator core and windings.

The intervention to improve the stiffness of a specific end-winding, covered in this paper, was deemed a success and demonstrated that such action could delay or stop a major failure mechanism. It also showed that end-winding vibration data observed doesn't always represent the highest vibration levels present on any given generator. The importance of installing the correct number of sensors, along with the proper location of said sensors, is critical in order to provide accurate and pertinent data and therefore; provide a better assessment of the end-winding structure integrity.

KEYWORDS

Hydro-generator, Stator, End-windings, End-turns, Overhangs, Absolute vibration

PLANT BACKGROUNG

The Shipshaw hydropower plant is a key component of Rio Tinto Alcan's Saguenay-Lac-Saint-Jean hydroelectric power network, in the Province of Québec, Canada. It is located at the confluent of the Shipshaw and Saguenay Rivers. Constructed in 1943 to provide electricity for the growing aluminium smelting industry during war time, the 12-Unit plant (5 from Canadian General Electric and 7 from Canadian Westinghouse) was then the largest hydroelectric power station in the world with an original installed capacity of 896 MW. Throughout time, the installed capacity was uprated to 947 MW. In 2012, a 13th Unit was added with a capacity of 225 MW, bringing the total output of the Shipshaw Powerhouse to 1,145 MW.

Aerial view of Shipshaw project.

Front gate of the powerhouse

HISTORY OF FAILURES

In 2001, Generator no. 5, which is the focus of this paper, was uprated with complete turbine replacement, re-insulation of the rotor poles and installation of a new static excitation system. The machine was uprated from 78 to 83 MW.

No work was done to the existing stator; with the exception of corn blast cleaning, detailed visual inspection, Electromagnetic Core Imperfection Detection test (El-CID) and slot wedging strength verification. No signs of anomaly were detected. The original stator core is made in 4 sections and was fitted with new epoxy-mica class F stator winding (multi-turn coils) in 1979. The stator winding consists of 8 parallel circuits per phase, each with 15 coils in series.

Between 2006 and 2010, the machine experienced four stator winding incidents. In 2006, a failure following a DC Hipot test caused a situation where 4 coils needed to be by-passed. In 2008, a phase-to-phase fault, caused by copper strand failure from fatigue and overheating, all in the area where the coil leads exit the stator core, caused 6 additional coils to be by-passed. The capacity was maintained at 83 MW, but reactive power was limited to 10 MVAR. At the end of the same year, the breaking of a lower fan blade entailed the bypass of one more coil.

In 2009, another phase-to-phase fault forced the bypass of 3 additional coils; total 14 bypassed coils at the time. The cause of the incident was diagnosed as the same as the previous year. A thermographic scan revealed a few other hot spots in the same area as the ones that failed. The capacity was curtailed to 70 MW and the reactive power to 0 MVAR.

STUDYING THE PROBLEM

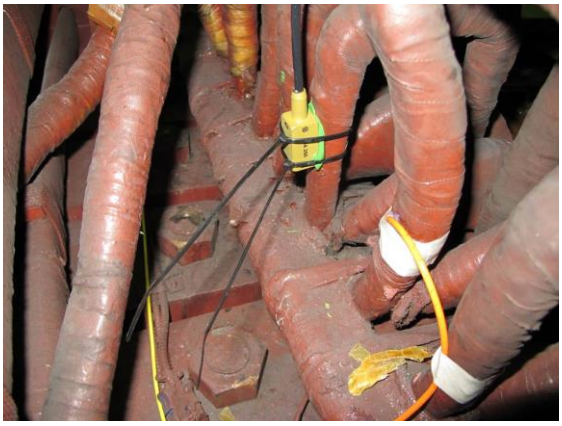
In 2008-2009, maintenance personnel reported higher noise and vibration levels with Generator no. 5 than with the other eleven generators. Engineers strongly suspected that excessive end-winding vibration could be the cause of the phase-to-phase failures in 2008 and 2009. It was suspected that the excessive vibration would cause fatigue cracking of the strands and insulation cracking at the junction where the coil leads exit the stator core.

In late 2009, it was decided to install the following array of sensors on the stator to monitor the behaviour of this generator:

- 8 optical temperature sensors at worst hot spot locations of the end-windings;
- 8 FOA™-200 bi-axial optical accelerometers on suspected end-windings (radial & tangential axes);
- 6 FOA™-100E optical accelerometers on end-windings with high PD activity (radial axis only);
- 4 piezoelectric accelerometers on the outside of the stator core at 3, 6, 9 and 12 o'clock locations (radial);
- 4 piezoelectric accelerometers on the outside of the stator frame at 3, 6, 9 and 12 o'clock locations (radial);

The following pictures show some of the optical accelerometers during the installation process. The sensors are temporarily fixed with fast curing epoxy and tie-wraps, then covered with epoxy impregnated fiberglass tape to ensure consolidated bonding.

FOA-100E optical accelerometer on an end winding



FOA-200 optical accelerometer on back side of a series-connection lead

Accelerometer on stator core (Example only)

Accelerometer on frame (Example only)

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The instrumentation was connected to the plant's existing vibration monitoring system for data analysis and trending.

OBSERVED ISSUES

In January 2010, the generator was returned to service and the instrumentation began recording data. The following graphs show 120-Hz vibration trends of the generator start-up on January 13. The generator load was gradually raised by steps, first up to 20MW at 11:30, 40MW at 13:40, 55 MW at 14:15, and 68 MW at14:40 until shutdown at 21:30. The vibratory behaviour is clearly associated to the load variation and resulting stator temperature variation.

Spectrum analysis of vibration signals revealed that most activity occurred at the electro-magnetic fundamental frequency of 120 Hz. Some coils demonstrated very high vibration activity while the Unit was warming up but the levels significantly decreased as the generator warmed up and reached stabilized temperature. Vibration levels of ~9 g and ~10 g (~310 µm, pk-pk, and ~345 µm, pk-pk, at 120 Hz) were recorded during the temperature rise, but all accelerometers stabilized below 5 g (~175 µm, pk-pk, at 120 Hz) in steady warm operation (*See Figures 1, 2 & 3*). Meanwhile, accelerometers on the stator core measured radial vibration levels of less than ~0,5 g (~20 µm pk-pk at 120 Hz).

If the Unit is maintained at a load near 70 MW, while operating at nominal temperature, the end-winding vibration levels should not be an issue. However, if the generator is frequently stopped and restarted, the high vibration levels while the Unit is cool could be problematic.

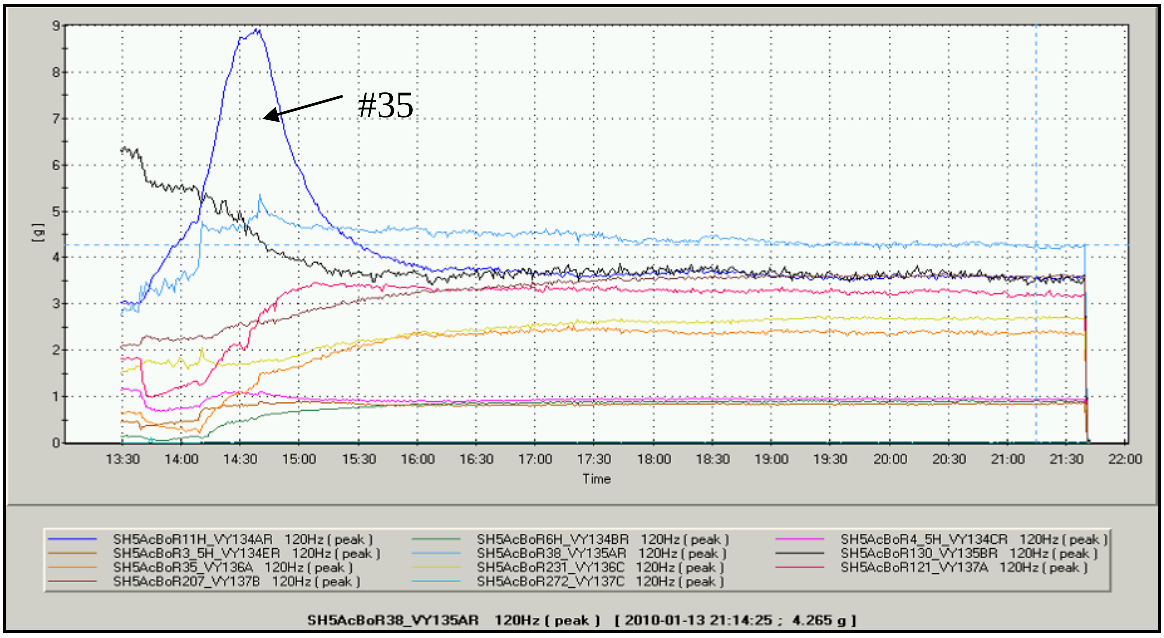

Figure 1. 12-hour trend of end-winding vibration (radial) with a peak of ~9 g (~310 µm, pk-pk, at 120 Hz) for end-winding #35 during the temperature rise. Vibration levels stabilize between ~1 g and ~4 g (~35 µm, pk-pk, to ~140 µm, pk-pk, at 120 Hz) in steady state – hot operating condition.

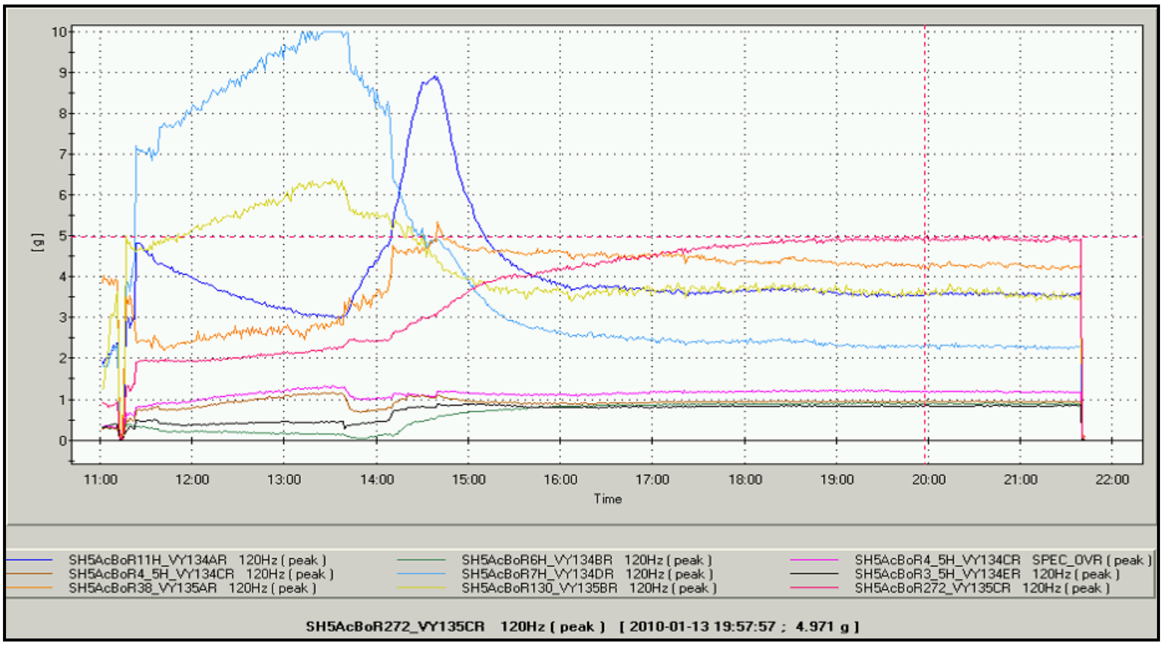

Figure 2. Same trend of radial vibration for the series-connection leads. One coil peaks at ~10 g (~345 µm, pk-pk, at 120 Hz) during the temperature rise, then vibration levels for all coils stabilize below 5 g (170 µm, pk-pk, at 120 Hz).

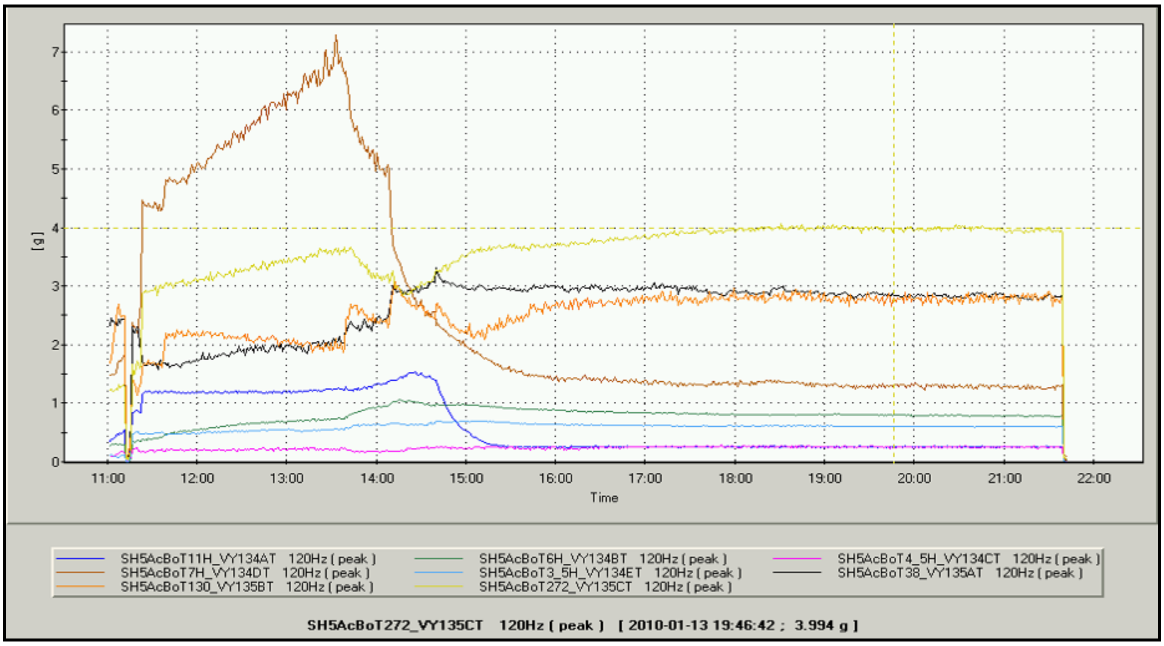

Figure 3. Same trend of tangential vibration for the series-connection leads. Vibration levels peak at ~7,4 g (~255 µm, pk-pk, at 120 Hz) on one coil during the temperature rise, then stabilized below 4 g (140 µm, pk-pk, at 120 Hz).

It is common knowledge that three (3) possible vibratory behavior can occur at the end-windings according to temperature and/or armature variations (increase in this case). Firstly, end-winding vibration levels decrease as the thermal expansion stiffens the stator bars in their slots, causing a decrease. Secondly, the end-winding vibration increases as the thermal expansion changes the resonance properties of the stator bars, decreasing the resonance frequency close to the electro-magnetic frequency of the Unit (100 Hz or 120 Hz), hence the vibration level increases. In addition, the increasing armature current increases the electro-magnetic stresses hence the elevated vibration levels. Thirdly, the end-winding vibration levels vary very little in reaction to the thermal and electro-magnetic forces, indicating that the end-winding structure performs admirably, limiting the results to acceptable levels. The data shown here indicates that the initial increase in armature current, along with the increase in temperature, produced elevated end-winding vibration levels for a few locations, which reached their maximum amplitude at or near 70 MW. A significant decrease was then observed until the Unit was shut down. However, for most locations, the levels increased gradually to eventually stabilize at acceptable levels. Therefore; we can safely say that reactions to the forces differed somewhat from some location compared to others, although the results were not contrary to known behavior for stator end-windings.

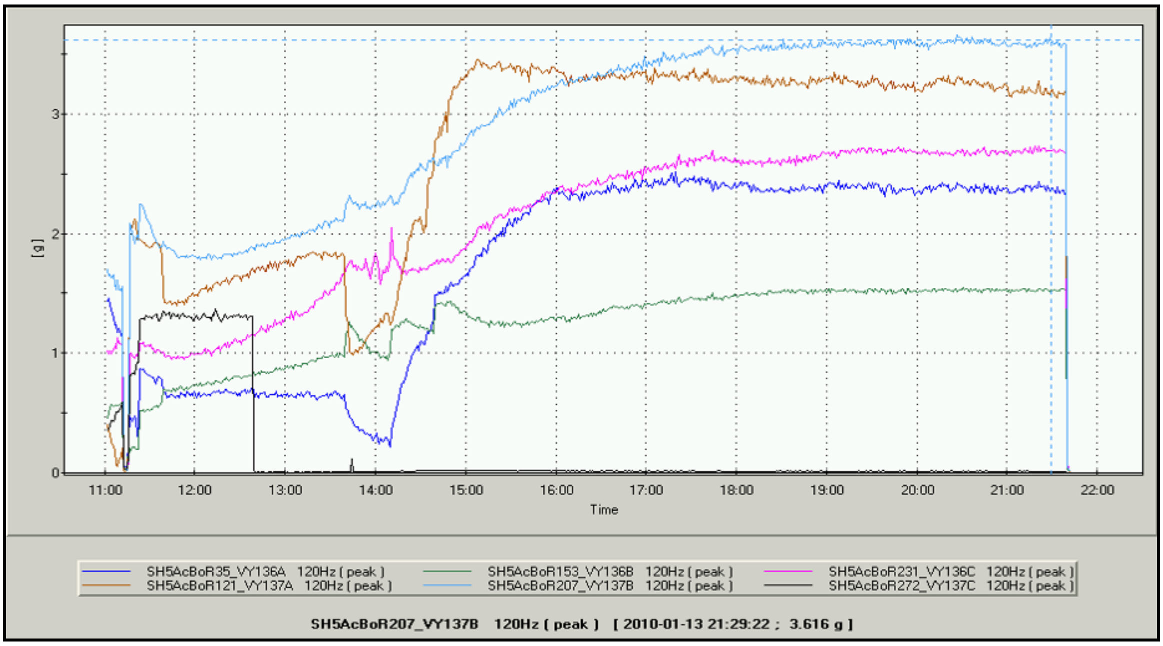

Figure 4. Trend of radial end-winding vibration of the coils with high PD activity. Vibration levels remain below 3.6 g (125 µm, pk-pk, at 120 Hz).

The Unit operated normally for some period but near the end of 2010, the generator sustained another phase-to-phase winding failure, due to dielectric breakdown from insulation fretting and surface tracking (partial discharge) because of insulation contact between adjacent coils of different phases. This incident caused that an additional 3 coils be bypassed. The generator capacity was further limited to 60 MW and 0 MVAR, in addition to generator use restrained to periods when hydraulic conditions made it necessary.

Besides testing after repairs, the Unit did not operate until early May 2011.

Around the same time of the incident, at the end of 2010, it was decided to instrument Generator no. 11 from the same OEM, which did not display the same problems, for comparison purposes:

- 6 FOA™-100E optical accelerometers on 3 end-windings and 3 phase leads (radial);
- 4 piezoelectric accelerometers on the outside of the stator core at 3, 6, 9 and 12 o'clock locations (radial);
- 4 piezoelectric accelerometers on the outside of the stator frame at 3, 6, 9 and 12 o'clock locations (radial);

Results on Generator no.11 showed that end-winding vibration levels were 4 times less than Generator no. 5, as well as half the vibration levels of the stator core and stator frame radial vibration.

INTERVENTION

Upon restart of generator no. 5, in May of 2011, the radial vibration levels of end-winding #35 trended upwards, from ~4 g in early May to ~7.5 g at the end of July (~140 µm, pk-pk, to ~260 µm, pk-pk, at 120 Hz) (*See Figure 5 below*). This result clearly indicated some looseness of the end-windings, specifically at end-winding #35. After interpretation of these results, it was decided to attempt restoring the stiffness of this end-winding using wet ties (Dacron® felt and fibreglass tape impregnated with epoxy) and bracing blocks.

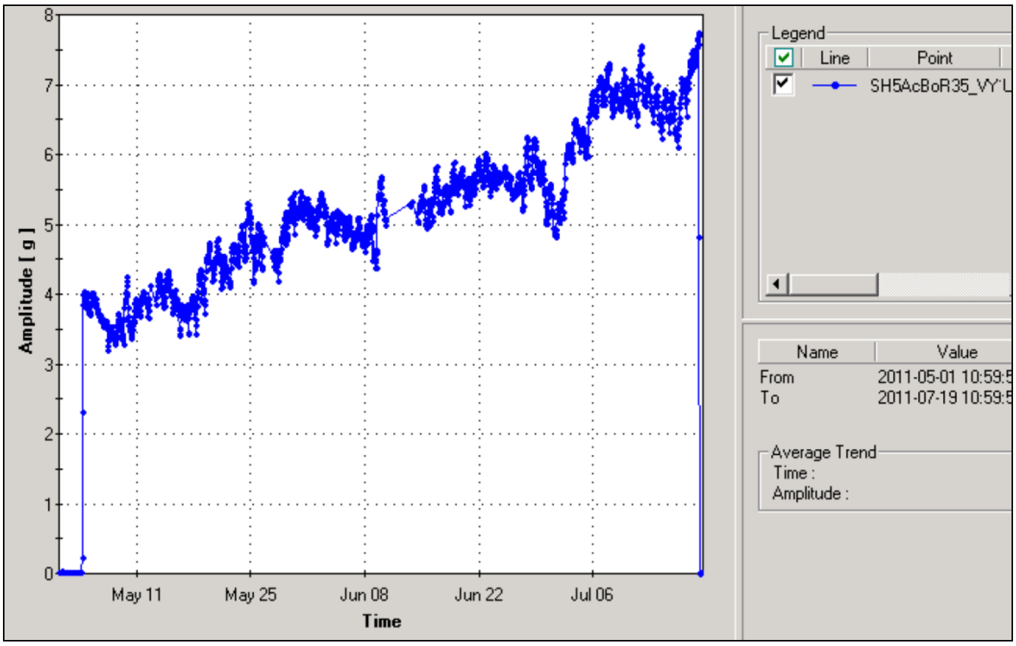

Figure 5. Upward trend of end-winding #35 radial vibration levels from ~4 g in early May to ~7.5 g on July 19th (~140 µm, pk-pk, to ~260 µm, pk-pk, at 120 Hz).

Felt and fibreglass tape behind coil #35.

Another view of the same coil

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RESULTS

When the Unit was returned to service in early August 2011, a significant reduction of radial vibration levels was immediately observed. The vibration levels decreased from ~7.5 g down to ~3 g for end-winding #35 (~260 µm, pk-pk, to ~105 µm, pk-pk, at 120 Hz) (*See Figure 6 below*).

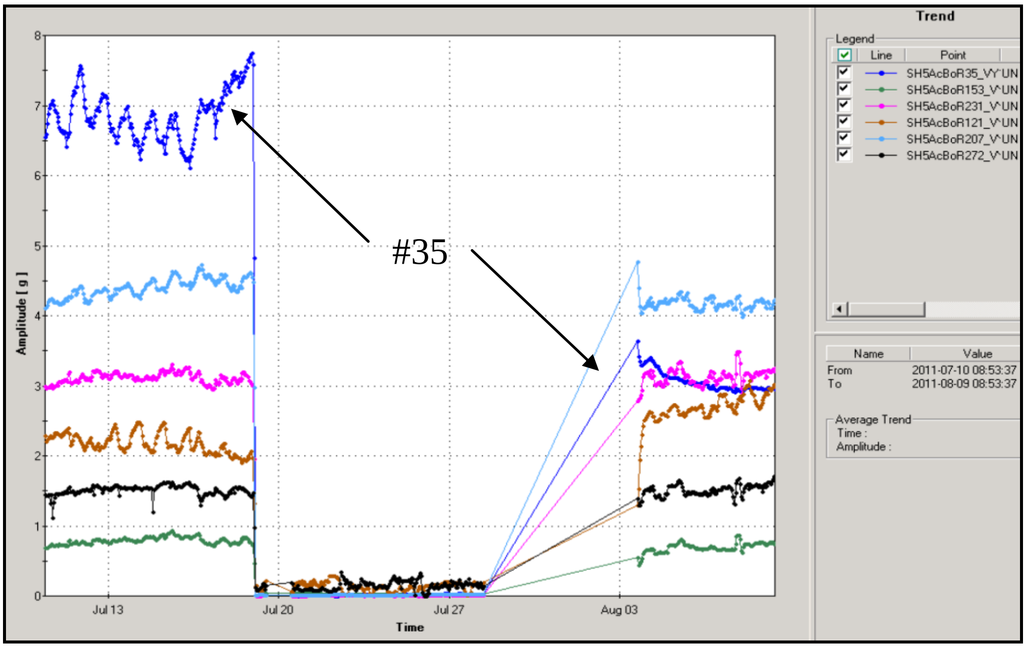

Figure 6. Trend of radial vibration levels of end-windings before and after the intervention shows a reduction of ~4.5 g (~155 µm, pk-pk, at 120 Hz) on end-winding #35.

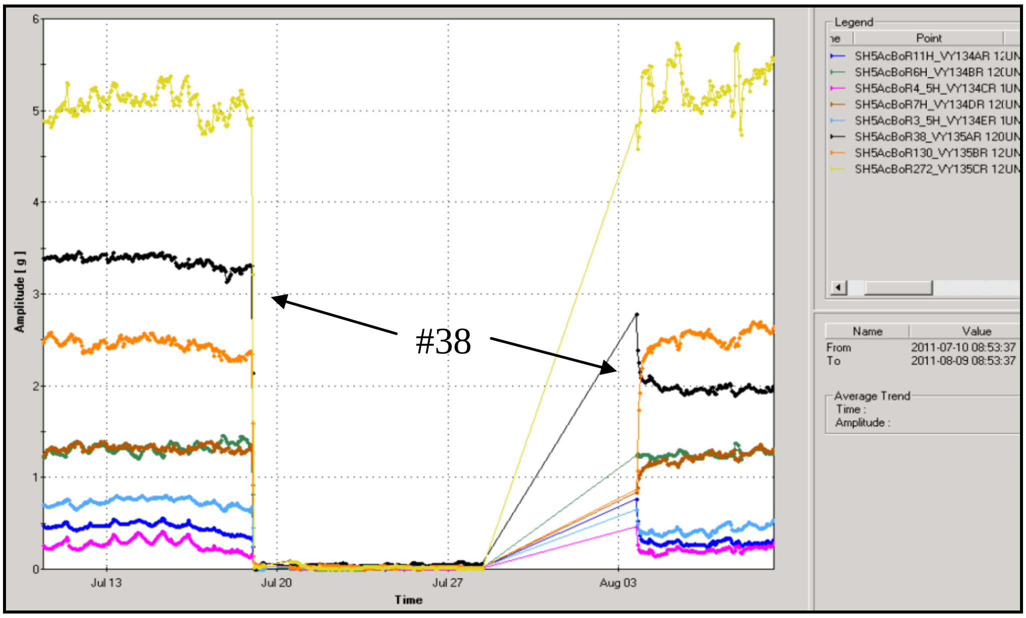

Figure 7. Trend of radial vibration levels of end-windings lead connections for the same period shows improvement of adjacent end-winding vibration levels at end-winding #38 as well.

A positive impact was also observed on adjacent end-winding #38 (lead series-connection); where a noticeable reduction of ~3.4 g down to ~2 g (~115 µm, pk-pk, to ~70 µm, pk-pk, at 120 Hz) was measured in the radial axis and ~3 g to ~1.6 g (~105 µm, pk-pk, to ~55 µm, pk-pk, at 120 Hz) in the tangential axis (*See Figure 7 on the previous page*). All the while, the stator core and stator frame radial vibration levels remained between ~0.25 g and ~0.5 g (~10 µm, pk-pk, and 20 µm, pk-pk, at 120 Hz).

FURTHER INTERVENTION

The intervention to improve the stiffness of end-winding #35 was deemed to be a success and demonstrated that such action could delay or stop the failure mechanism. It also showed that adjacent end-windings benefitted from the increased stiffness. This aspect clearly indicates that when monitoring end-winding vibration, one must be careful as the vibration levels recorded and interpreted at any given location may not be the highest vibration present in the Unit. This also means that with proper trending and early detection of end-winding vibration on hydro-generators, a major and costly failure can be avoided while the lifetime of the stator core and windings can be prolonged.

Comparison of Generator no. 5 measurements with similar measurements from Generator no. 11 confirmed the severity of the G5 stator winding structural degradation. This information served as basis to justify the complete stator core and stator winding replacement scheduled for 2015. Until such a time as these components are replaced, Generator no. 5 is still in restricted operation.

As part of the stator refurbishment, it is planned to conduct a thorough stator “autopsy” so as to gather as much information on the actual condition of the stator core and winding as possible, for use with the remaining five generators from the same OEM.

CONCLUSION

While turbo-generators have historically been more prone to end-winding vibration issues, as expected because of the disposition of long end-windings external to the stator core, other types of large electric rotating machines have experienced such severe problems. Machines such as hydro-generators have also experienced particular end-winding vibration problems. The use of fiber-optic technology has provided Utilities with valuable information for many years and continues to do so in order to help management understand and better assess the risks involved with long-term operation of their assets. The application covered in this paper is only one of many cases where major problems were detected on large electric rotating machines, properly identified and managed to mitigate the damage, enhance availability and reduce outage and repair/replacement costs.

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