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On-Line Turbine Generator Endwinding Vibration Monitoring

Abstract*. According to insurance company data, the most expensive failures of air-cooled gas turbine generators have been due to stator winding copper conductor fatigue cracking, caused by high levels of endwinding vibration Excessive levels of endwinding vibration are most easily detected using fiber-optic accelerometers installed at critical locations in the endwinding. Over the past few years experience has been gained on the collection, display and interpretation of stator winding on-line endwinding vibration data.*

Streszczenie. Najbardziej kosztownymi uszkodzeniami turbin gazowych chłodzonych powietrzem jest uszkodzenie uzwojenia stojana sp0wodowane wibracjami. Wibracje te możan badać stosując światłowodowy przyśpieszeniomierz. W artykule przedstawiono wyniki takich badań. ***Monitorowanie on-line wibracji uzwojeń generatora***

Keywords: Generator, stator, endwinding, vibration, impact bump test
Słowa kluczowe: generator, wibracje, monitoring

Introduction

The stator endwinding is the winding extending beyond the stator core. Due to design requirements the endwinding from the slot exit can be quite long (sometimes greater than 2m), especially on 2-pole machines. This results in a cantilever effect when operational forces are applied to the windings. The primary forces are due to the electromagnetism effect of 2 parallel current carrying conductors at line frequency resulting in a force at twice line frequency (100/120Hz). On some machines the centrifugal forces (at once turning speed) are coupled to the stator including the endwindings (50/60Hz for 2-pole synchronous machines, 25/30Hz for 4-pole, etc). Both, the turning speed and the electromagnetic forces are predominantly in the radial direction (between the rotor and the stator and between the top and bottom bars). However there is also a signify-cant force in the tangential direction (circumferential around the endwinding basket between two adjacent bars). [1]

A stator endwinding that is vibrating excessively will result in insulation fretting or dusting between two components that should otherwise be stationary. This excessive motion can be limited by re-tightening periodically, but if this repair is not performed the copper conductor can eventually open under load. This can be a very expensive failure and take months to repair, maybe even requiring a rewind. A recent study by a global insurance company [2] of generator loss data over the last 10 years shows that while the number of losses related to endwinding vibration issues are small (<5%) the claim amount per loss is staggering (almost 50% of the total paid out for all causes). Their conclusion was that endwinding vibration has the highest total loss and average loss mitigation value for generator failures and that installing endwinding vibration monitors is the most cost effective monitoring technology for units with potential issues [2].

Fiber optic accelerometers contain no metallic parts and could be installed at locations where endwinding vibration was expected. For reliable operation, the minimum requirements for a fiber-optic sensor should be:

- Frequency: 5-1000 Hz
- Dynamic Range: 0-50 g
- Resolution: smaller than 0.007 g
- Temperature range: -50°C to +200°C

It is impractical to monitor every component of a stator endwinding and some care is required to identify the optimal locations. Once the locations for monitoring have been properly identified the offline impact test data can indicate the resulting frequency content and relative amplitudes of the online vibration data. It is widely considered that the connections are the most important locations to monitor endwinding vibration. They are generally more massive and the long unsupported lengths increase the likelihood for resonance and high vibration amplitudes. [3]

Instrumentation is required to collect the vibration data from the accelerometers and provide a tool to trend the endwinding vibration conditions. Continuously collecting on-line data enables capturing sustained increases more effectively than periodic measurements and also identifies when sudden increases in vibration data occur. As well, continuous monitoring is much more effective in correlating high vibration levels with changes in operating conditions to help determine the optimal conditions by minimizing operation at higher end winding vibration.

Data interpretation

Vibratory motion is cyclic with time and the raw signal from accelerometers is acceleration over time. This signal can be integrated once to velocity and a second time to displacement, to obtain the different measures of vibration. As well, the time domain can be transformed (a Fast Fourier Transform or FFT is the common method in vibration) to display the vibration signal in the frequency domain. Vibration viewed in the frequency domain is a much more effective method of determining the cause of vibration.

Historically, displacement (µm peak-to-peak) has been the main measure of vibration used to assess the health of stator endwindings. Displacement is a measure of the distance moved from the initial position and emphasizes low frequencies. Because the fundamental frequencies of the forces acting on a stator endwinding are low frequencies, typically 50/60 Hz (turning speed for 2-pole machines) and 100/120 Hz (due to electromagnetic forces), this is generally acceptable.

Velocity (mm/s peak) is a measure of the rate of change in displacement or the speed (and direction) of vibration and provides a smoothing effect over a wide range of frequencies. As structures loosen the response becomes non-linear and results in harmonics of the fundamental frequencies to many multiples. The smoothing effect of velocity will provide equal weighting to the fundamental frequencies (at 50/60 and 100/120 Hz) and the corresponding harmonics that may develop from looseness in the structure across a wide frequency range. This characteristic of velocity should be considered when assessing the health of the stator endwinding.

Acceleration (g peak) is a measure of the rate of change in velocity. It is the raw signal from an accelerometer. With this in mind, acceleration should not be ignored, especially at higher frequency harmonics. These may be excited by natural frequencies resulting in a resonant response that may not be present when considering the double integrated signal in displacement. The same displacement at 10 times the frequency results in 100 times the acceleration.

Case Study 1

On-line stator endwinding vibration data collected from a 300 MVA, two pole generator showed 221µm peak-to-peak at 120Hz, Figure 1.

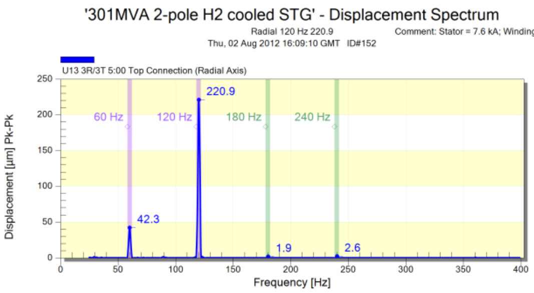

Fig. 1 Displacement spectrum of endwinding vibration accelerometer at 5:00 top connection

Visual inspections were scheduled within 2 months and showed dusting, Figure 2 near one of the phase connections being monitored in the 5:00 position.

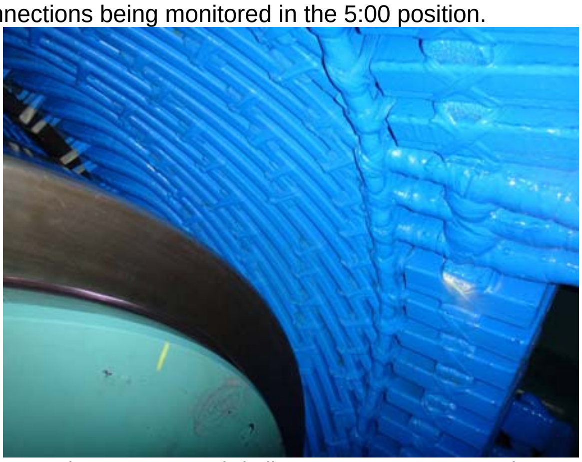

Fig. 2 Dusting on stator endwinding near 5:00 top connection

Although dusting may not be cause for immediate concern it is an indication of the stator bars relative motion at their supports and insulation abrasion. Copper does not have a distinct fatigue limit and may eventually fail from small stress amplitudes due to high cycle fatigue. The generator failure can occur from phase to phase faults or broken conductors. The vibration signature indicated the onset of excessive movement and was confirmed visually. The excessive movement should be limited to prevent failure and the vibration should be monitored continuously to indicate any change to the endwinding support system.

This case study indicates that 200µm peak-to-peak at 120Hz is a reasonable displacement alert limit. Equivalent vibration measures at 120Hz are approximately 80 mm/s peak and 6 g peak for velocity and acceleration respectively, but this does not account for potentially higher vibration levels due to harmonic content that are suppressed with displacement.

Case Study 2

Stator endwinding vibration amplitudes are not only affected by structural characteristics, but they are also by the machine operating conditions. Generally, a change in vibration can be attributed to different operating conditions or degradation in the condition of the stator endwinding support structure due to relative movement. Trending the vibration over time can assist in determining the cause of vibration.

The electromagnetic forces between two adjacent bars are proportional to the square of the current. These forces attribute to the stator endwinding vibration if the endwinding is loose; an increase in stator current will result in an increase in stator endwinding vibration levels. This can be seen in Figure 3, where for a reasonably constant winding temperature and increasing current the vibration response increases.

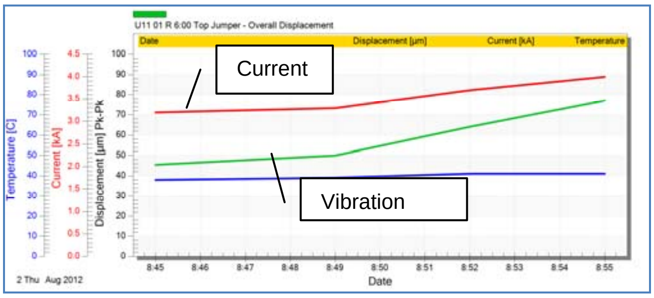

Fig. 3. Increasing Vibration with Current Trend

A stator endwinding structure will have multiple natural frequencies that will be equally affected by temperature [4] and they may or may not influence the vibration response and a change may increase, decrease, or have no effect on stator endwinding vibration levels. Figure 4 shows for a reasonably stable stator current an increasing winding temperature appears to influence the vibration response in a manner that as the temperature increases, the natural frequency decreases, changing the vibration response. The effect is not dramatic (~20 µm pk-pk) because the winding temperature is below the elastic transition temperature (80°C) for epoxy mica insulation [3].

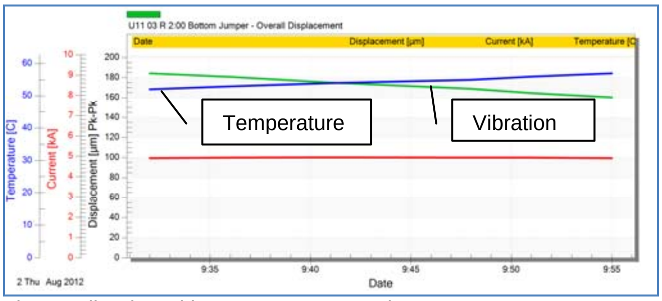

Fig. 4. Vibration with Temperature Trend

When evaluating the condition of a stator endwinding an increase in vibration trend is most concerning if the stator current and winding temperatures are stable. Operating parameters must be considered when analyzing stator endwinding vibration data.

Conclusions

Partly due to the efforts of manufacturers driven by end users to reduce costs and additionally, on load cycling machines with demand fluctuations has resulted in stator endwinding vibration developing into an important failure mechanism. Consequently machines are being operated with insufficient stator endwinding support leading to excessive motion between parts and ultimately cracked conductors due to high cycle copper fatigue. In order to avoid premature failure, this excessive motion during operation should be monitored. Displacement amplitudes of 200µm peak-to-peak at 120Hz seems to be a reasonable alert limit. Acceleration and velocity are important measures as well, particularly for assessing harmonics that can often be attributed to looseness. As shown by the case studies in this paper, an effective online monitoring system requires:

1. Sensors to be installed at locations most likely to vibrate
2. Sensors and monitor to cover a wide frequency range
3. Monitor to have the ability to view the data in various measures of vibration
4. Vibration trends to be correlated with operating parameters

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