Results from On-Line Turbine Generator Endwinding Vibration Monitoring

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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. This has occurred in most brands of turbine generators rated from 100 - 300 MVA, manufactured in the past decade. The root cause is believed to be from inadequate design or imperfect manufacturing that has let the endwinding to be insufficiently supported. Excessive levels of endwinding vibration are most easily detected using fiber-optic accelerometers installed at specific 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. Although it has been traditional to evaluate results in terms of either total displacement (across the measured frequency range) or the displacement at a specific frequency such as 100 or 120 Hz, it seems that it is sometimes useful to also display the data in terms of velocity. This enables the better detection of vibrations caused by power frequency harmonics or the higher frequencies that result from impacting of loose endwinding components. Enough data has also been accumulated to suggest "alert" levels for high endwinding vibration.

Keywords—stator windings; on-line monitoring; endwinding vibration; fiber-optic accelerometer

I. 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 rotor 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 significant force in the tangential direction (circumferential around the endwinding basket between two adjacent bars) [1,2].

A stator endwinding that is vibrating excessively may break bonds at some locations and will result in insulation fretting or dusting between separated components. This excessive motion can be limited by re-tightening periodically, but if this repair is not performed the copper conductor can eventually break in service. This can be a very expensive failure taking months to repair, and may even require a rewind. A recent study by a global insurance company [3] of generator loss data over the last 10 years shows that while the number of losses related to endwinding vibration issues is 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 value as well as the highest *average* loss value (total loss value per number of losses) for generator failures [3]. Installing endwinding vibration monitors is the most cost effective monitoring technology for units with potential issues [3].

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 on an air-cooled turbine generator should be [4]:

- Frequency: 5-1000 Hz
- Dynamic Range: 0-50 g
- Resolution: smaller than 0.002 g
- Temperature range: -20°C to +135°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 using the offline impact ("bump") 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 [4].

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 detecting 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 endwinding vibration.

II. 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 an effective method of determining the cause of vibration. Refer to ISO Standard 13373 for vibration condition monitoring and diagnostics of machines including general procedures and the processing, analysis, and presentation of data.

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. This is generally acceptable 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).

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. In addition, in some generators, there may be current harmonics due to the lead (for example induction furnaces). 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 - High 120Hz displacement results in dusting on 301MVA, 2-pole hydrogen-cooled steam turbine generator

On-line stator endwinding vibration data collected showed 221µm peak-to-peak at 120Hz, Fig. 1. Visual inspections were scheduled within 2 months and showed dusting (Fig. 2) near one of the phase connections being monitored in the 5:00 position.

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 (yield point) but 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.

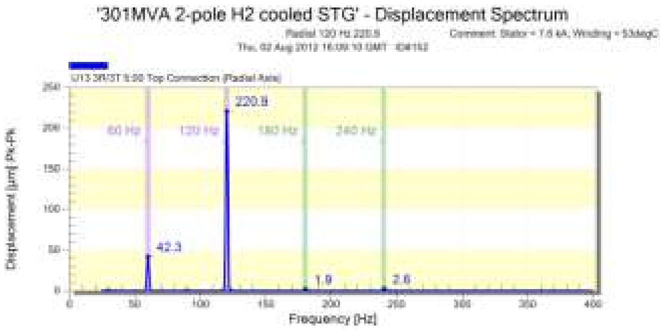

Fig. 1 Displacement spectrum of endwinding vibration accelerometer at the 5 o'clock position on the top connection

Fig. 2 Dusting on stator endwinding near the 5 o'clock position top connection

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 6g 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 – Harmonics of 120Hz on 288MVA, 2-pole air-cooled steam turbine generator

On-line acceleration data in Fig. 3 shows dominant peaks at 120Hz from the electromagnetic force with multiples at 240 and 360Hz. Harmonics are generally expected to decay linearly if not influenced by resonance as the force dissipates out of the system, as is the case for this measurement location.

The corresponding displacement spectral shape in Fig. 4 is not much different. The dominant frequency is still 120Hz with decaying harmonics, but there is more low frequency content. The overall displacement is 45µm peak-to-peak.

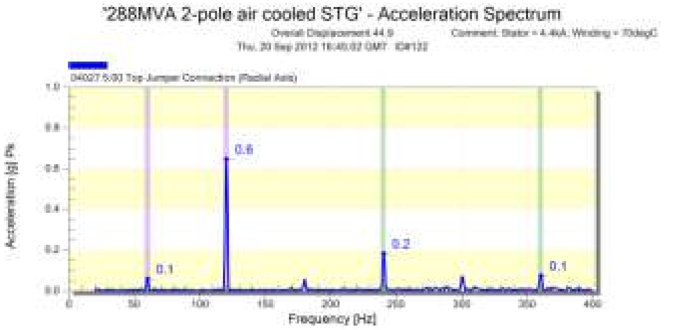

Fig. 3 Acceleration spectrum at the 5 o'clock position on the top jumper connection

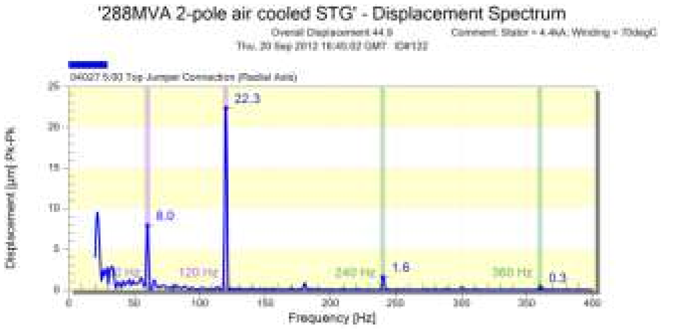

Fig. 4 Displacement spectrum at 5 o'clock position on the top jumper connection

Data from the same machine collected at the same time in Fig. 5 shows dominant peaks at 120 Hz from electromagnetic force with multiples at 240 and 360Hz. Because the harmonics at this location are influenced by a natural frequency, they do not decay linearly.

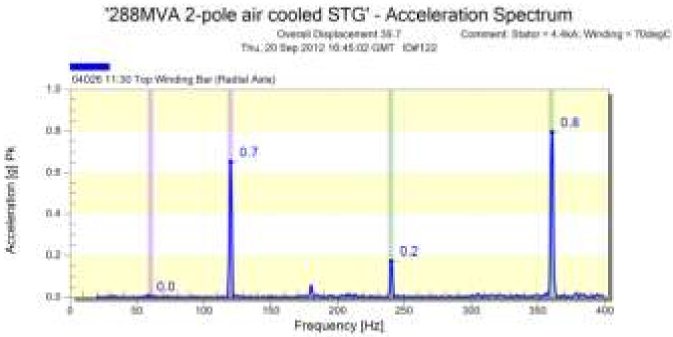

Fig. 5 Acceleration spectrum between the 11 and 12 o'clock position on the top winding bar

The corresponding displacement spectrum in Fig. 6 shows a dominant frequency at 120Hz with almost no activity at 360Hz. The overall displacement is 40µm peak-to-peak, less than that on the jumper connection in the 5:00 position.

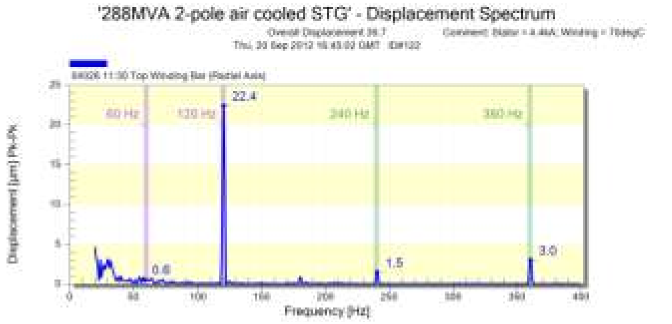

Fig. 6 Displacement spectrum between the 11 and 12 o'clock position on the top winding bar

This case demonstrates the importance of using different measures of vibration to assess the health of a stator winding because if only the overall displacement were considered, the connection would garner the most attention because displacement emphasizes lower frequencies (less than a couple hundred hertz). It is not until this data is viewed as acceleration that the vibration at 360Hz can be identified and the significant differences in response from the two locations can be observed. Problems like mechanical looseness usually generate a series of frequencies (harmonics) due to non-linear response and often excite one or more natural frequencies.

III. Conclusion

Stator endwinding vibration is becoming a problem of increasing concern in 2-pole turbine generators – since catastrophic failures have occurred in relatively new machines. Using fiber-optic accelerometers permanently monitoring on the endwinding, it has become apparent that 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. Another benefit of considering acceleration and/or velocity is that low frequency instabilities, common in displacement spectra, can be smoothed out.

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