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Effective Online Monitoring of Stator Endwinding Vibration

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Abstract
In recent years, stator endwinding vibration has developed into an important failure mechanism of large motors and generators. This can be attributed partly to the efforts by manufacturers driven by end users to reduce costs. Consequently machines are being operated with insufficient stator endwinding support. This lack of support leads to excessive motion between parts resulting in dusting/greasing and ultimately cracked conductors due to high cycle copper fatigue. Additionally, load cycling machines, especially in the deregulated market and with demand fluctuations experience additional forces that can lead to endwinding vibration. In order to avoid premature failure, this excessive motion during operation should be monitored. Stator endwinding vibration has been monitored for over 20 years using fiber optic accelerometers, but it has become apparent that the results of these monitoring programs are sometimes incorrect. An effective online monitoring system should incorporate offline testing to identify optimal locations for accelerometer installation, capture a wide frequency range of data, have the ability to view the data in various measures of vibration, and correlate the vibration with operating parameters.

Keywords
Generator, stator, endwinding, end winding, vibration, impact test, bump test

Background

The primary function of a stator endwinding is to allow for the safe electrical connection between bars in series and to other parallels. These connections must be made away from the stator core to prevent insulation failure at the connection points. On higher voltage machines the required creepage distance between the core and the connections can become quite long. Additionally, higher speed machines have long endwindings for geometric reasons, e.g. 2m or longer is not uncommon [1]. The long unsupported lengths of endwinding bars, particularly on high speed machine become susceptible to excessive motion resulting in vibration.

The dynamic response of stator endwinding bars resulting in vibration can be attributed to two primary forces. The main force is the electromagnetic frequency at twice power frequency. This is generated from the magnetic fields that are produced between two parallel current carrying conductors. The electromagnetic forces between two adjacent bars are proportional to the square of the current [2]. The line frequency of the current is cycling at 50/60 Hz and the resulting force is at 100/120 Hz. Harmonics of this force can occur which are from the power system currents that excite the stator endwindings resulting in vibration at exact multiples of this fundamental frequency. Another force on a stator endwinding during normal operation is at turning speed, 50/60 Hz for 2-pole machines and 25/30 Hz for 4-pole machines.

These forces can be measured in three directions. Considering the end view of stator these are normally specified as radial, tangential (or circumferential), and axial. For the electromagnetic force the directions of most concern are radial and tangential. This is because the force is generated by two parallel current carrying conductors, i.e. the force between the top and bottom bar (radial) and between two adjacent bars (tangential) [2]. This force in the axial direction is typically negligible. The turning speed force is present in the three directions, but typically more significant in the radial and tangential directions.

To accommodate for these forces during operation each bar is often lashed to a support ring made of insulated metal. The hoop strength of the support ring prevents movement in the radial direction. Insulated blocks placed between adjacent bars prevent movement in the circumferential direction. Depending on the length of the endwinding one or more rows of blocking may be present [1].

An additional force in a stator endwinding is due to thermal expansion resulting in growth of the bars in the axial direction. Endwinding support design is a balance between stiffness to prevent movement in the radial and tangential directions from normal operating forces and flexibility to allow for growth due to thermal expansion. This need for opposite characteristics of stiffness and flexibility is a challenge when designing endwinding support systems [3].

Endwinding vibration from excessive motion in the stator endwinding structure is most likely to occur in form wound two- and four-pole machines since the endwindings are long. The windings pivot at the slot exit because they are held tight in the slot which creates a cantilever effect in the endwinding area. Proper endwinding support is required to prevent movement from this effect where the vibration forces can lead to fatigue cracking of the insulation and even the conductors at the core end or at the connections. Relative movement between bars adjacent to each other can lead to insulation abrasion and if not corrected this mechanism can result in sufficient groundwall insulation to abrade so that phase-to-ground failure occurs. Resonant conditions from inadequate endwinding structure designs will amplify the vibration generated from normal operating forces. Many system disturbances or frequent starts will create large transient forces and may accelerate the wear rate of components [1]. Age is another factor that will contribute to endwinding vibration as the insulating blocking and bracing material shrink over time loosening the endwinding support and result in excessive motion.

Properly scheduled visual inspections are an important requirement to detect any evidence of excessive motion before the resulting vibration in a stator endwinding will lead to problems and machine failure. Periodic off-line tests such as impact (or bump) testing can provide an indication of how the structural characteristics of a stator endwinding change over time. Stator endwinding natural frequencies tend to decrease as the structure loosens with age and operation. As well, the structure tends to become more heavily damped resulting in the natural frequencies covering a wider range than in a new or recently repaired endwinding structure. If these changes in the endwinding natural frequencies come to influence the operating forces of a machine the vibration will be resonant resulting in excessive vibration reducing the life of stator endwinding structure significantly [2].

With this in mind and given that there is not always access to the stator windings for inspection, online monitoring of stator windings has become the best and most modern way of detecting changes to the endwinding support structure. Stator endwinding vibration has been monitored for over 20 years using fiber optic accelerometers, but it has become apparent that the results of these monitoring programs are sometimes incorrect.

Electromechanical vibration monitoring is well developed and it is possible to monitor machine health with vibration data collected on the shaft and bearing housings. This is most effective for identifying issues related to the rotor dynamics of the machine (unbalance, misalignment, bearing looseness, etc) with metallic piezoelectric accelerometers and non-contact probes measuring eddy currents proportional to shaft displacement. These same methods cannot be applied on stator endwindings in particular near the coil ends where the vibration amplitudes are the highest because metallic materials in close proximity to high currents will heat up due to losses induced by magnetic fields. Metallic accelerometers may compromise the electrical clearances of the endwinding to ground and can result in partial discharge. With the development of non-metallic fiber optic accelerometers though, it is possible to monitor endwinding coil ends.

With any vibration monitoring, good sensor mounting and permanent installation practices are required. It is important that only the component being monitored is contributing to the vibration signal and not the sensors themselves or associated cable. Any sensor movement (accelerometer bounce) may result in inaccurate or false readings.

With the continuing advancement of fiber optic technology and our increasing knowledge of stator endwinding structural and vibratory behavior other important considerations are required for effective online monitoring of stator endwinding vibration.

Case Study 1 – Temperature Effects on Stator Endwinding Natural Frequencies

As previously stated, the structural characteristics change with age resulting in a decrease to the natural frequencies and heavier damping. This effect is similar when the temperature of a stator endwinding structure increases. This is an important consideration when using offline impact testing which is generally performed at a much lower temperature than operation.

As winding temperatures increase, the stiffness of the endwinding structure decreases [2]. The standard undamped natural frequency relation is:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Where *k* is stiffness and *m* is mass.

From this equation it can be seen that a decrease in stiffness results in a decrease in the natural frequencies of the structure [2]. If a vibration component is influenced by a natural frequency, the response (or vibration amplitude) will be affected by a change in winding temperature. Because of the inverse relationship between winding temperature and natural frequency, an increase in temperature to a system that is low tuned (meaning the natural frequency is below the vibrating frequency) may decrease the vibration amplitude because the natural frequency moves further away from the vibrating frequency and influences it less, if at all. Conversely, a high tuned system may increase in vibration amplitude with an increase in winding temperature as the natural frequency moves into the vibrating frequency and influences it more. This effect can be quite dramatic at higher temperatures as the elastic quantity for epoxy mica insulation decreases significantly when the winding temperature is beyond a transition temperature of around 80°C [4]. This was demonstrated experimentally [3] in which mode shape tables were produced from impact data collected on stator endwindings in cold, warm, and hot conditions.

Table 1. Non Connection End Mode Shape Frequency. [3]

Mode	Cold (22° C)	Warm (61° C)	Hot (84-76°C)
n=1	*103.66*	*100.13*	*91.87*
n=2	*114.25*	*111.12*	*103.59*
$n=3_1$	*128.38*	*125.12*	*117.13*
$n=3_2$	*139.80*	*136.44*	*130.39*
n=4	*153.83*	*149.70*	*143.79*
n=5	*190.72*	*185.40*	*179.11*

Table 2. Connection End Mode Shape Frequency. [3]

Mode	Cold (24°C)	Warm (60-58°C)	Hot (90-82°C)
n=2	*104.36*	*101.28*	*93.32*
$n=3_1$	*122.03*	*118.26*	*110.93*
$n=3_2$	*127.01*	*124.15*	*116.25*
$n=4_1$	*162.16*	*155.96*	*148.60*
$n=4_2$	*166.78*	*161.73*	*153.44*

This experimental data indicates that even though the mode shape frequencies measured were affected by the temperature of the windings the mode shapes themselves were not. The frequencies decreased with temperature by more than 10 Hz [3]. This is important when establishing the condition of stator endwindings with offline testing. Generally, a 10% band can be used to cover for the dampening effect of natural frequencies, but a wider band may be necessary to account for temperature, as shown in this experiment.

Case Study 2 – Stator Endwinding Harmonic Vibration and Impact Testing

Resonance occurs when a driving frequency becomes equal to an undamped natural frequency. Two observations are required to identify resonance. As a driving frequency approaches an undamped natural frequency, 1) the magnitude approaches a maximum and 2) a phase shift crosses through 90° [5]. To identify natural frequencies these observations can be determined with impact testing.

Offline impact testing can not only be used to assess the condition of a stator endwinding, i.e. how close natural frequencies are to forcing frequencies, but it can also be used to identify the locations that are most likely to vibrate. 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.

Figure 1 shows offline impact test data on a connection that identified a natural frequency around 320 Hz. The two characteristics can be identified near this frequency; high magnitude, 0.015 g/N in the lower plot and phase shift crosses through 90° in the upper plot. From Case Study 1 these natural frequencies are expected to shift down at operating temperatures. This 60 Hz machine has primary forces at 60 and 120 Hz. Any power frequency harmonics result in harmonics of 120 Hz. The natural frequency identified is not expected to influence these forces and harmonics significantly.

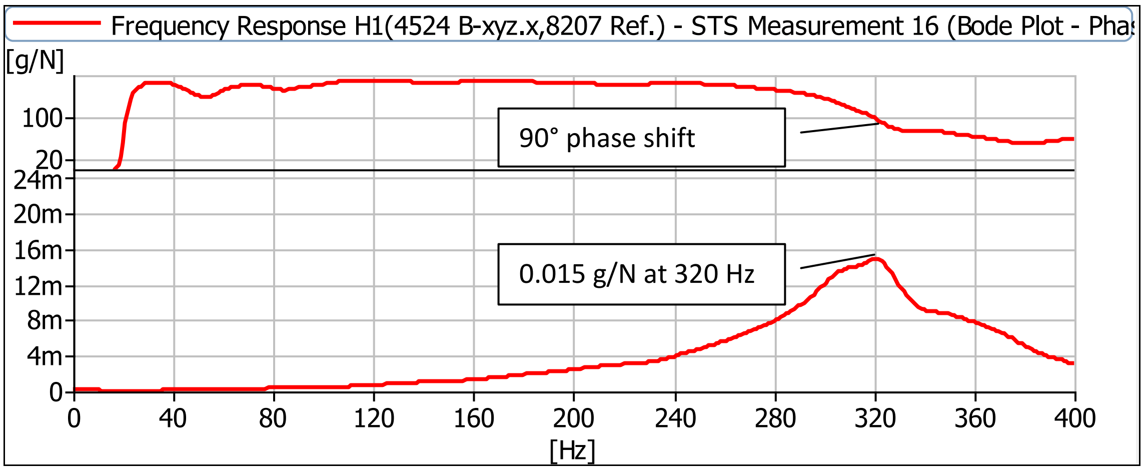

Figure 1. Offline Impact Data Connection.

The resulting online acceleration data in Figure 2 showed dominant peaks at 120 Hz from electro-magnetic force with multiples at 240 and 360 Hz. Harmonics are generally expected to decay linearly if not influence by resonance as the force dissipates out of the system, as is the case.

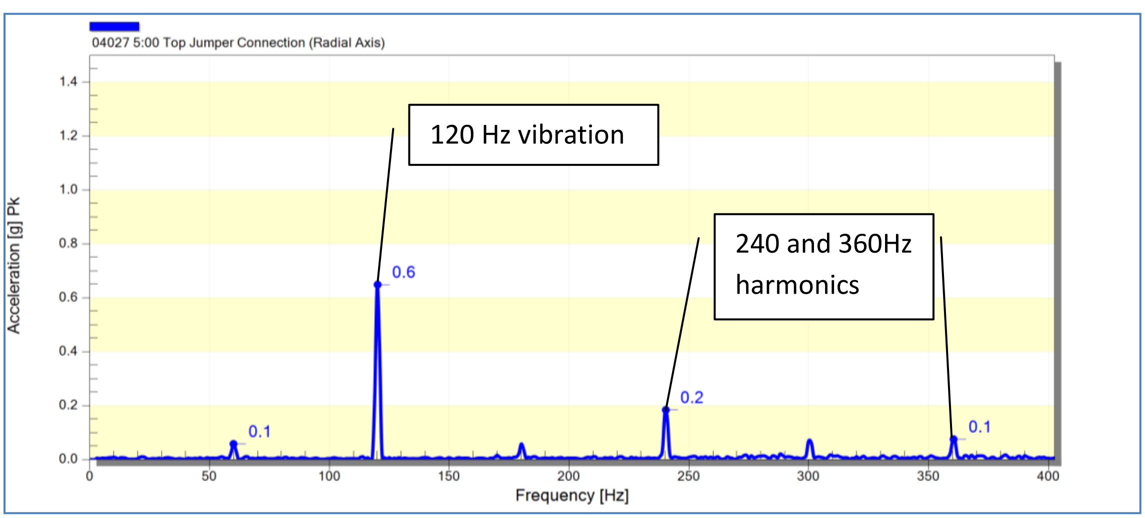

Figure 2. Online Vibration Response Connection.

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.

Figure 3 shows offline impact test data collected on a winding bar on the same machine as above. The test identified natural frequencies near 211 and 392 Hz. Again, the two characteristics can be identified near 211 Hz frequency; high magnitude, 0.011 g/N in the lower plot and phase shift crosses through 90° in the upper plot. The natural frequency near 392 Hz has high magnitude, 0.020 g/N in the lower plot and phase shift crosses through 90° in the upper plot.

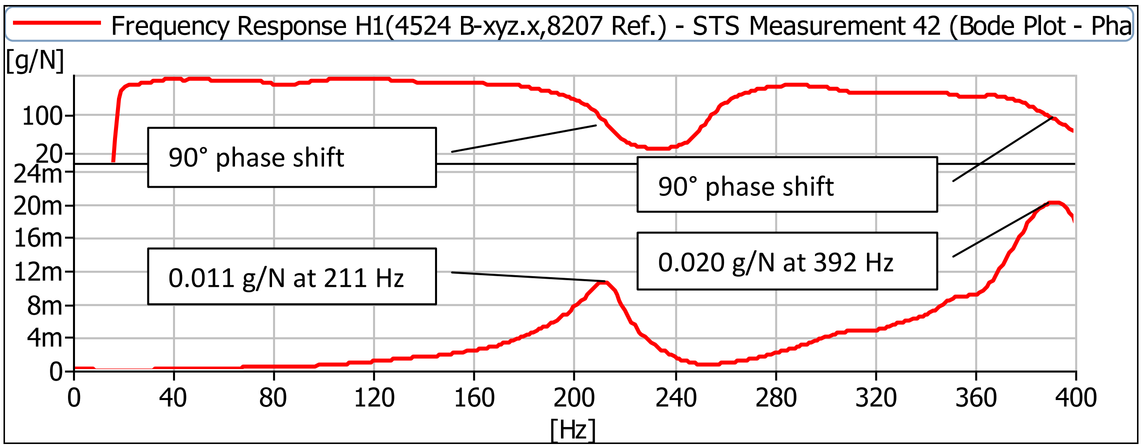

Figure 3. Offline Impact Data Winding.

The resulting online acceleration data in Figure 4 showed dominant peaks at 120 Hz from electro-magnetic force with multiples at 240 and 360 Hz. Because these harmonics are influenced by a natural frequency they do not decay linearly as seen on the connections. The high amplitude at 360 Hz is due to a resonant response. The system at this winding location is approximately eight times more responsive at 360 Hz than at 240 Hz and the online vibration data behavior showed this correlation.

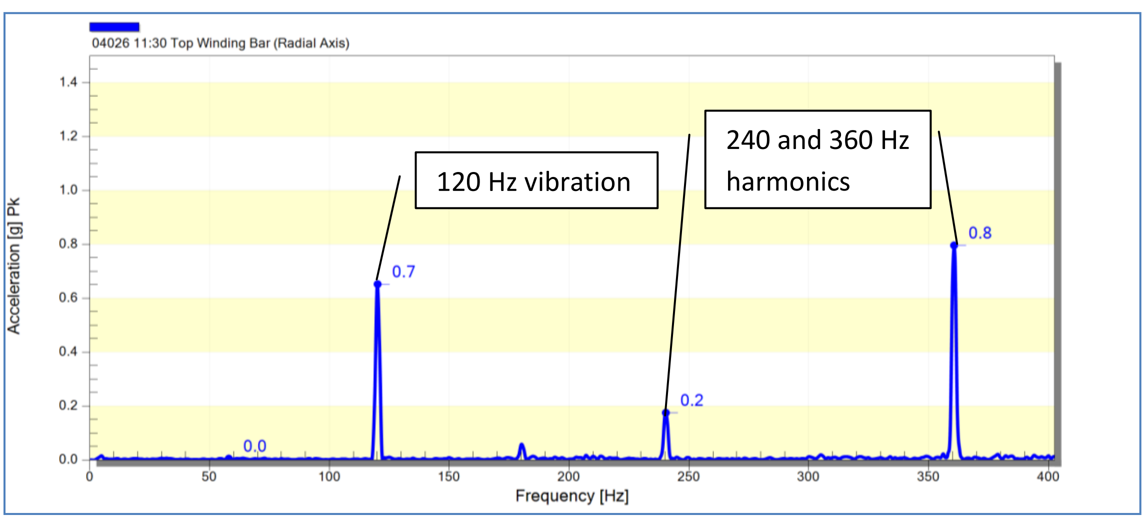

Figure 4. Online Vibration Response Winding.

The driving frequency (electromagnetic force) at 120 Hz is similar at both locations. This is readily apparent by comparing response amplitudes, 0.6 g pk on the connection and 0.7 g pk on the winding, and considering there is minor sensitivity from the impact test data at both locations. The vibration amplitude at 360 Hz is significantly greater on the winding compared to the connection due to a local natural frequency identified on the winding that is influencing this response.

This demonstrates the importance of impact testing to determine the optimal locations. High sensitivity measured with offline testing in critical frequency bands should be considered for online vibration monitoring as these are the locations that are most likely to vibrate. The data presented shows that even though the connections are generally considered the critical components for monitoring vibration, and this is generally true, the windings are a more suitable location for this particular machine because the response characteristics identified with impact testing.

As well, 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 was considered the connection would garner the most attention because displacement emphasizes lower frequencies (less than a couple hundred hertz). Historically, displacement (mil pk-pk or µm pk-pk) has been the main measure of vibration used to assess the health of stator endwindings. 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.

Now that fiber optic accelerometers can collect data at a range of frequencies (using micro laser technology measuring internal membrane vibration from 5 to 1000 Hz) instead of single frequency measurement (cantilever style tuned to a single frequency) additional measures of vibration become more useful and should be utilized for a more complete understanding of how a stator endwinding vibrates.

Velocity (in/s pk or mm/s pk) 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. This effect will provide equal weighting to the fundamental frequencies (at 50/60 and 100/120 Hz) and the corresponding harmonics. The combination of distance and frequency gives rise to velocity being a measure of fatigue. This is especially important as vibration relates to copper fatigue. Copper fatigue rates are influenced by amplitude and frequency. Faults like mechanical looseness usually generate a series of frequencies (harmonics) due to non-linear response and often excite 1 or more resonances.

Acceleration (g pk or rms) is a measure of the rate of change in velocity. It is the raw signal from an accelerometer and is directly proportional to force. With this in mind, acceleration should not be ignored, especially at higher frequency harmonics. This indicates that monitoring endwinding vibration to at least 400 Hz, ideally 1000 Hz is required.

Case Study 3 – Stator Endwinding Vibration and Machine Operating Conditions

The level of acceptable vibration for stator endwindings has not been standardized, thus the main result from continuously monitoring endwinding vibration is the trend over time. Not only are stator endwinding vibration amplitudes affected by structural characteristics, but they are also influenced by the machine operating conditions. Generally, a change in vibration can be attributed to different operating conditions or degradation in the health 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 5, where for a reasonably constant winding temperature and increasing current the vibration response increases at all 4 test locations.

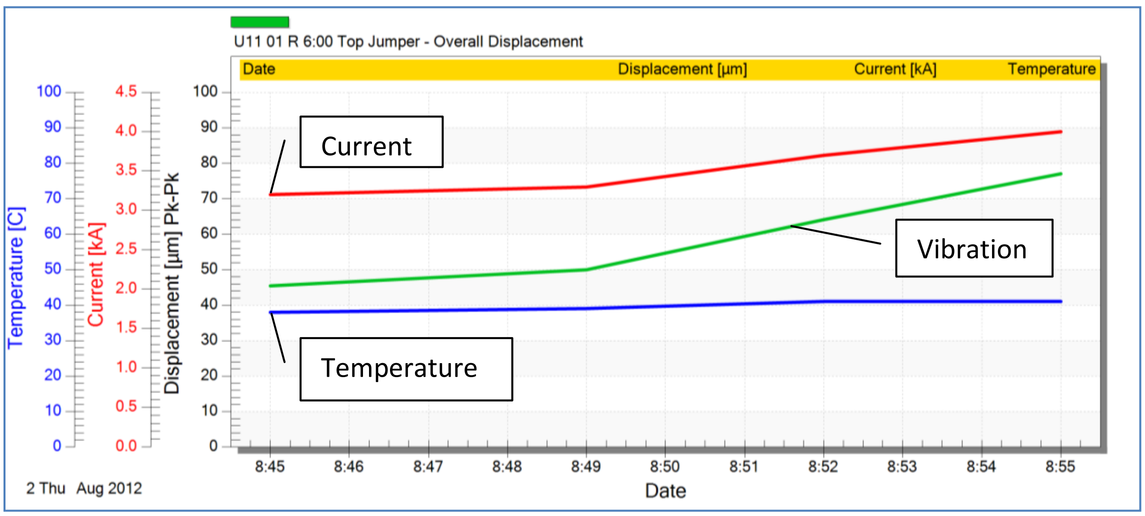

Figure 5. Increasing Current Trend with Vibration.

From Case Study 1, it should be considered that a stator endwinding structure will have multiple natural frequencies that will be equally affected by temperature [3] and they may or may not influence the vibration response. As such, a change in winding temperature may increase, decrease, or have no effect on stator endwinding vibration levels. Figure 6 shows for a reasonably stable stator current and increasing winding temperature appears to influence the vibration response in a manner that would indicate the location is low tuned at that position. 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 [4].

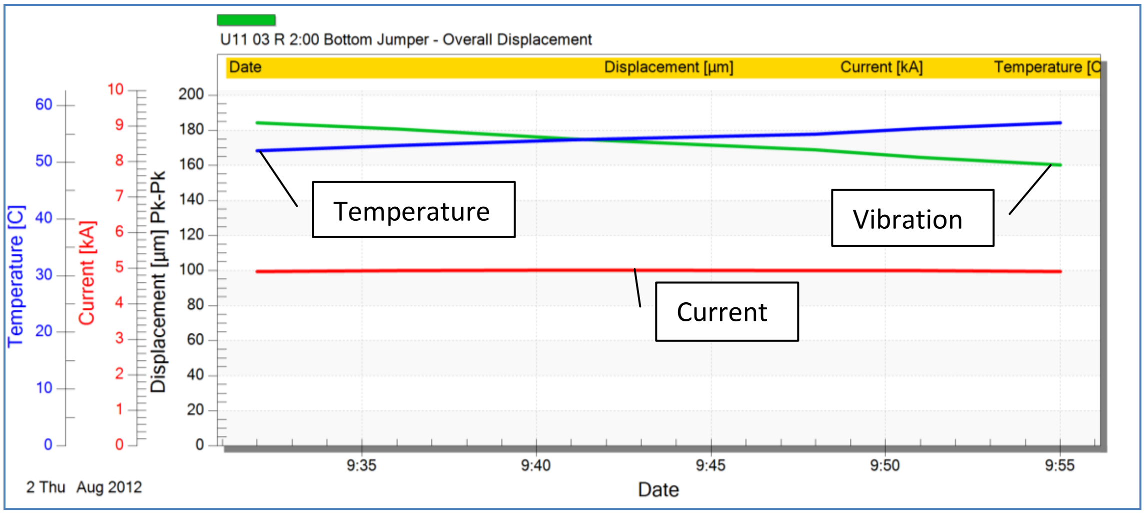

Figure 6. Increasing Temperature Trend with Vibration.

This online vibration data can be related back to the experimental results in Case Study 1 reinforcing that winding temperature changes the structural characteristics of the stator endwinding structure and the resulting natural frequencies shifts may affect the vibration amplitudes.

When evaluating the health 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

Stator endwinding vibration has developed into an important failure mechanism attributed partly to the efforts by manufacturers driven by end users to reduce costs and additionally, on load cycling machines with demand fluctuations. 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. 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

Once excessive vibration in the stator endwinding area has been detected the following remedies should be considered [1]:

1. Complete endwinding support replacement
2. Reinstall blocking and lashing material
3. Installation of additional blocking and bracing

The above should be done in conjunction with impact testing to ensure any changes made to the support system does not have a negative effect on the resulting vibration amplitudes during operation. Continuing to monitor the online stator endwinding vibration will indicate if the results of any structural changes are positive and when additional remedies are required from aging of the support structure and/or excessive forces from high current faults.

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