Requirements for Fiber Optic Sensors for Stator Endwinding Vibration Monitoring

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Abstract— **In the past few years, as manufacturers have reduced stator endwinding support to lower costs, stator endwinding vibration has emerged as an important failure mechanism of large motors and generators. Endwinding vibration, which is primarily driven by magnetic forces in normal operation and much larger forces in fault conditions, leads to high voltage insulation abrasion and copper conductor cracking from high cycle fatigue. Many catastrophic generator and motor failures have resulted. The most effective method to monitor if dangerous endwinding vibration is starting to occur is to continuously monitor the vibration levels and frequencies using fiber-optic accelerometers. Such sensors have been available for over 20 years, but it is apparent that incorrect results are sometimes obtained, leading to false indications on the condition of the stator endwinding support structure. False indications could be the result of multiple causes, and one of them is improper location of the sensors, i.e. the sensors are installed in locations of minimum vibration, making one believe there is no vibration problem. Modal testing is sometimes used to determine the optimum location of the sensors. However, since this test can only be performed at ambient temperature, not at winding operating temperature, it is possible that with a temperature increase, the optimum location positions could be changed. This paper will discuss the requirements for selection of sensors and effect of temperature on modal test results.**

Keywords-rotating machines, stator windings, on-line monitoring, endwinding vibration.

I. Introduction

Three basic types of stator windings are in common use on rotating machines [1]: random wound, form wound using multiturn coils and form wound using Roebel bars. Random wound stators are usually used in machines operating at less than 1000 V and because of this their use is normally limited to machines rated less than a few hundred kilowatts, where mechanical forces and vibration are relatively low. Form wound coils are usually used in machines operating at voltages higher than 1000 V and are made from insulated coils that have been pre-formed prior to installation in the slots. These coils can have anywhere from 2 to 12 turns, and are connected in series to create the required number of poles and turns/phase in the stator winding. With an increase in power output of large machines, form wound coils became difficult to insert in the slots and Roebel bars, developed in 1912, are now typically used for stator windings of large machines rated more than about 50 MVA. Both form wound multiturn and Roebel bar stator windings are exposed to relatively high currents and vibration due to electro-magnetic forces is possible.

Two distinct parts of a stator winding are the slot area and the endwinding area. The purpose of the endwinding area is to make electrical connections between the bars or coils and to provide a connection to the machine line and neutral terminals. These connections must be made at a safe distance from the stator core, to maintain sufficient creepage distance, and in the case of large 2 pole machines, the endwindings can be close to 2 m in length. The stator winding is mechanically well supported in the stator slots, but in the endwinding area support of the winding is a much bigger challenge. Different support methods have been developed to prevent movement of the endwinding, but a common challenge for all is to provide rigidity and flexibility, at the same time. Rigidity is required to prevent movement of the endwinding from normal operation and fault condition forces and flexibility is required to allow thermal expansion in all directions of various parts of the endwinding due to thermal cycling.

II. Endwinding Vibration in Rotating Machines

Vibration is caused by forces that can be electrical or mechanical in origin. Generally, forces can be divided into steady state, load change and fault forces. Or, forces can be divided into forces acting on the stator core, individual stator bar/coil in the slot and in the endwinding, phase group of bars and complete endwinding. Based on frequency, endwindings can vibrate in two critical ranges, line frequency, usually produced by mechanical forces and twice line frequency, produced by electromagnetic forces from current carrying phase conductors.

Mechanical vibration is the result of rotor rotation: unbalanced or misaligned rotor, damaged bearings, and electrical problems on the rotor such as shorted turns in generators and synchronous motors or broken bars in squirrel-cage induction motors [2].

Electromagnetic forces between stator bars are created by current flowing through them. In normal service these forces are relatively low and are contained by a suitable endwinding support structure. During large stress events, such as terminal short circuit or synchronization errors, the current may rise to 10 times normal rated current and the resulting endwinding forces can be up to 100 times higher than the normal operating forces. In large turbo generators the forces in normal operation can be as high as 100 lb/inch or 20,000 N/m of bar length, and may rise to more than 50 times those values in cases of severe system disturbances. Note that there are significant differences in forces between top and bottom bars in the slot section, where the bars are at different levels of magnetic field. For the endwinding, the differential is not as large and also difficult to evaluate.

Under normal operating conditions, in most designs, vibration forces are controlled and kept at levels that are not harmful to the stator winding. However, overstressing events and aging of the stator winding and its support systems can make it loose and cause a winding natural frequency to approach a forcing frequency (rotational speed or twice line frequency) and result in amplified deflection and relative motion between components of the stator winding. This process can lead to mechanical and electrical failures.

III. REQUIREMENTS FOR ENDWINDING VIBRATION SENSORS

Historically, it has not been possible to measure stator winding vibration using an on-line monitor. In the very early days of polyester and epoxy windings, on some machines it was possible to hear the noise of bars vibrating and this, together with visual inspection, was the indirect evidence of stator vibration. Application of traditional piezoelectric accelerometers used in rotating machine vibration monitoring was not possible due to high electrical stress present in the stator winding. In the 1980s a new type of sensor was developed using fiber-optics. This sensor did not contain any metallic parts and could be installed at locations where end-winding vibration was expected. The first version of the sensor was a single frequency device, capable of monitoring only 120 Hz vibration. Later, the frequency bandwidth of the fiber-optics sensors was expanded to include fundamental mechanical frequency, 50 or 60 Hz for 2-pole and 25 or 30 Hz for 4-pole machines. Different methods are used as operational principle but could be divided in three groups: Bragg scattering, cantilevered beam, and light modulating measurement (LMM). Today, sensors are available in single and dual axis orientation, for monitoring of radial and tangential movements. For reliable operation, the minimum requirements for a fiber-optic sensor should be:

- Sensitivity: 100 mV/g
- Frequency: 5-1000 Hz
- Dynamic Range: 0-50 g
- Resolution: smaller than 0.1 μm at 100 Hz
- Resonance Frequency: higher than 2500 Hz
- Temperature range: -20°C to +135°C

The number of sensors installed in a machine varies, and could be from 6 on one endwinding, up to 13 or more, if both endwindings and core are fitted with sensors. Although fiber-optic sensors have been in use for over 20 years, it is apparent that incorrect results are sometimes obtained, leading to false indications on the condition of the stator endwinding. The common cause of inaccurate readings is improper location of the sensors, i.e. the sensors are installed in locations of minimum vibration, making one believe there is no vibration problem. Different methods are used in the selection of sensor locations, and they could be driven by operational experience or design. In some cases, six sensors on one endwinding will be installed 60 degrees apart. If stator winding has two parallel paths per phase, 6 sensors could be located on the first line end bars of each phase. However, in both cases if modal testing was not conducted the sensors could be installed in locations of minimum vibration, making one believe there is no vibration problem. Modal testing is sometimes used to determine the optimum location of the sensors. However, since this test can only be performed at ambient temperature, not at winding operating temperature, it is possible that with a temperature increase, the optimum location positions could be changed. Also, since stiffness of the endwinding will decrease as the temperature increases, it is expected that natural frequencies in operation will be lower than during the off-line test, performed at ambient temperature. However, no published data exists on this relationship.

IV. CASE STUDY

To determine the natural frequency migration and mode shape changes at stator winding temperatures of motor endwindings, a 13.8 kV, 11.9 MW, 4-pole, 48 slot TEWAC motor (Figs 1 and 2) was tested at three different temperatures. Temperatures were recorded in the cold, warm and hot conditions on the coil surface near the stator core. Both, the non-connection end and the connection end of the motor were tested.

Two tests were performed on this motor, Frequency Response Test and Modal Analysis. For the Frequency Response test, the accelerometer and the impact hammer were at the same location at 4 points around the motor endwinding. This test is used to determine natural frequencies which can be identified in the frequency response function (FRF).

For the Modal Analysis test, the accelerometer measuring response was fixed at one point and the impact hammer was used to generate force at 24 points around the endwinding (every second coil). Curve fitting software was utilized to generate shape tables and analyze resulting mode shapes.

In addition, reciprocity was checked to validate the shapes of this deflection study. The reciprocity is established if the profile of the signature when the impact hammer at point A and the accelerometer response collected at point B is the same as when the hammer impact is at point B and the response is collected at point A.

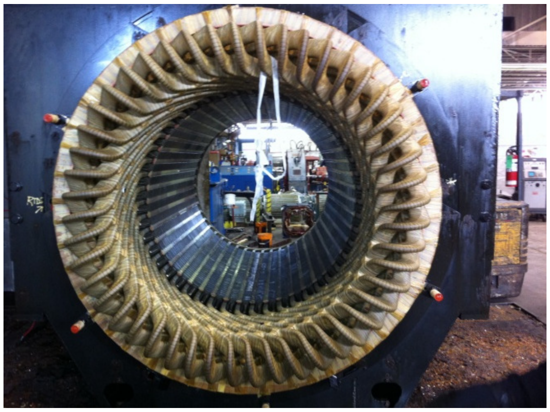

Figure 1. Non-Connection End

Figure 2. Connection End

V. RESULTS

Local natural frequencies were identified with frequency response testing at increasing temperature conditions on the non-connection end (NCE) and the connection end (CE) of the motor. The results indicate a general shift of decreasing frequency response as temperature increases. Mode shape tables were produced from the endwinding data. The mode shape can be identified by comparing the animation to the known ring mode shapes. The shape tables generated show how the endwinding dynamics change with temperature. Although only 2 mode shapes are the critical ones (n=2 and n=4) analysis of temperature effect on mode shape frequency was performed for other modes as well, see Tables 1 and 2.

Due to a number of local resonances on the connection end, additional frequencies were present in the FR plots and the resulting mode shapes have increased complexity. Regardless, the results show that even though the NCE is a better structural ring compared to the CE, the frequency migration for the natural frequencies identified are similar at increasing temperatures. This effect is displayed in the Fig 3.

Tables 1 and 2 – NCE and CE Mode Shape Tables

	Non Connection End Mode Shape Frequency (Hz)		
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	*128.38*	*125.12*	*117.13*
n=3	*139.8*	*136.44*	*130.39*
n=4	*153.83*	*149.7*	*143.79*
n=5	*190.72*	*185.4*	*179.11*

	Connection End Mode Shape Frequency (Hz)		
Mode	**Cold (24°C)**	**Warm (60-58°C)**	**Hot (90-82°C)**
n=2	*104.36*	*101.28*	*93.32*
n=3	*122.03*	*118.26*	*110.93*
n=3	*127.01*	*124.15*	*116.25*
n=4	*162.16*	*155.96*	*148.6*
n=4	*166.78*	*161.73*	*153.44*

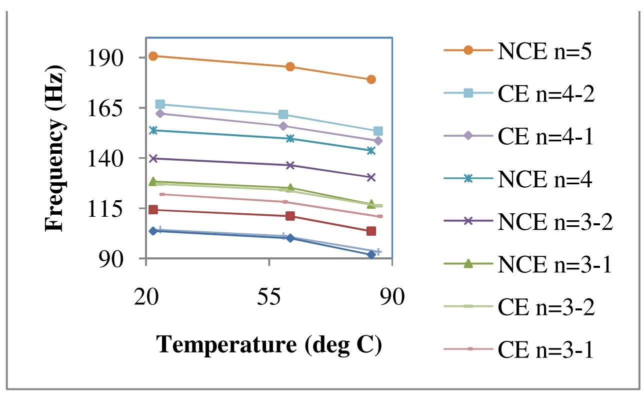

Figure 3. Temperature vs. Mode Shape Frequency Plot

Correlation between cold and hot modal shapes can visually be confirmed with the plots below showing the n=2 mode of the non-connection end in the cold condition superimposed on the hot condition.

The locations of the node points and corresponding anti-nodes where the maximum vibration amplitudes occur on a circular ring were not affected by temperature as indicated in Figs 4 and 5. This phenomenon can be seen on all the mode shapes identified on both ends of the motor.

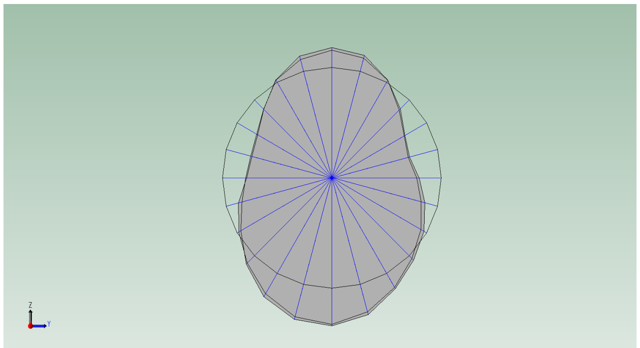

Figure 4. NCE n=2 Mode Shape Position 1 Cold and Hot results

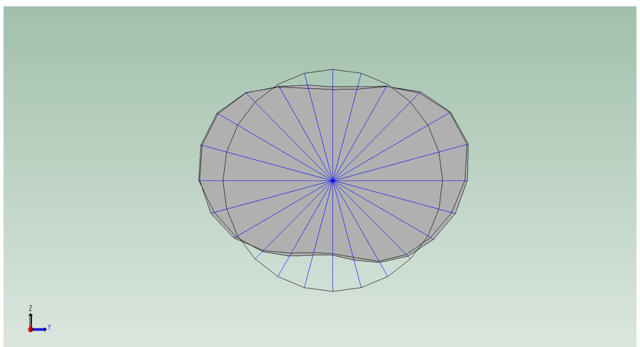

Figure 5. NCE n=2 Mode Shape Position 2 Cold and Hot results

VI. CONCLUSIONS

Based on tests performed on a 13.8KV, 4-pole stator, the natural frequencies of the endwinding mode shapes decreased as temperature increased. In general, these frequencies decreased by 9-12 Hz as temperature increased from 22°C to 85°C. However, the characteristics of the mode shapes including anti-node locations remain stable across the range of temperatures. This information is important to establish proper location for installation of endwinding vibration sensors since the maximum deflection locations identified with modal analysis at ambient temperature did not change at stator winding operating temperature.

ACKNOWLEDGEMENT

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