IRMC 2012

Effect of Stator Winding Temperature on Modal Test Results

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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 effect of temperature on modal test results.

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.

Endwinding Vibration in Rotating Machines

Vibration is caused by forces that can be electrical or mechanical in origin. Generally, forces can be divided in steady state, load change and fault forces. Or, forces can be divided to 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 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 suitable end winding 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 are in the slot section, where the bars are at different levels of magnetic field. For EW 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 for 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.

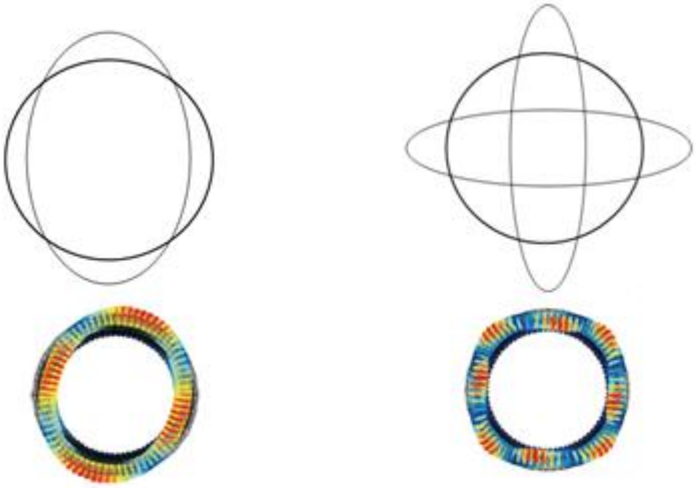


Figure 1. Force pattern for 2 pole (left) and 4 pole (right) machines

End-winding shape deformation is caused by electromagnetic forces and modal shapes of such deformations may be different for 2 and 4 pole machines. Figure 1 indicates force patterns, on top, and positions of maximal displacement (red color) on bottom [3].

A natural frequency is a frequency at which a structure will vibrate if deflected and then let go. Mass and stiffness have opposing effects on natural frequencies, with an increase in mass, the frequency will go down and with an increase in stiffness the natural frequency will go up. Therefore, the balance of mass and stiffness is the most important criteria in proper design of any endwinding structure. Any complex structure will have multiple natural frequencies. In electric rotating machines the design goal is to avoid having natural frequencies of the structure close to the rotational frequency or twice the power supply frequency, e.g., for a 2 pole synchronous generator (50/100 Hz or 60/120 Hz). Resonance is the tendency for a system to vibrate at greater amplitudes at some frequencies than at others and occurs when the natural frequencies of the structure are close the forcing frequencies. The resulting vibration levels can be very high and can cause rapid damage to the stator winding. In any machine, the vibration excitation forces from its normal operation should be well away from the natural frequencies of the structure to avoid resonant responses that can cause very high and destructive vibration levels.

To determine the natural frequencies of a structure, an impact test or bump test is the most frequently used method. A bump test is a type of vibration test that is normally run on a non-operating machine. The machine is instrumented with one or more vibration transducers, and the stator endwinding is then impacted with a massive object such as a hammer. The machine will respond to the impact with a vibration and the signals from the transducers are recorded and fed into a spectrum analyzer. The resulting spectrum will contain peaks that correspond to the natural frequencies. The further step in analysis of a bump test results is modal analysis which is an attempt to identify modes in which the endwinding can be deformed. Modal analysis, for the purposes of this testing, refers to the measuring of motion at various points of a structure when it is excited by some driving force. The pattern of motion generally takes certain shapes which are related to the natural frequencies or natural motion tendencies of the structure.

Deflection Mode Shapes of Structure

An endwinding structure can be modeled with a circular ring. Natural modes of a ring include breathing, translation, and bending. When the structure takes certain shapes at similar frequencies to a force, the resonant condition amplifies the vibration on an endwinding. For a 2 pole machine the shape for twice supply frequency deflection is oval and a for a 4 pole machine the shape is a square shown in Figure 2. The points of minimum displacement are called nodes, and are located at the intersection of the circle (end winding in stationary situation) and modal shape typical for that machine. There are 4 nodes in 2 pole and 8 nodes in 4 pole machines. Because of this (higher number of nodes) and the fact that the displacement of the oval shape is much larger than that of the square shape, , 4 pole machines are much stiffer and generally have less problems related to endwinding vibration. The other reason for higher likelihood of vibration in 2 pole machines is the length of endwinding, which is much shorter in 4 pole machines.

Figure 2. Oval (left) and Square (right) mode shapes

The oval (2 pole) and square mode (4 pole) of an endwinding are not the only modes that can be excited by forces within the rotating machine. Other modes such as cantilever modes (the whole end-winding bouncing up and down) or breathing modes (expanding and shrinking diametrically) could also become resonant if forces act on the winding in the critical directions and at the critical frequencies. However, the oval mode and square mode shape are the most critical for vibration analysis of the stator because they get naturally driven by the rotor forces if the resonant frequencies are close to the rotor forcing frequencies. For reliable operation of rotating machines, it is critical that natural frequencies for the mode shapes into which the endwinding can be deformed (see Figure 2) are far away from the driving frequencies (100 Hz or 120 Hz). To avoid resonance, it is desirable to have natural frequencies of the oval (for 2 pole) or square shape (for 4 pole) higher than twice the network frequency by 15-20 Hz. It is well known that with the increase of temperature, the stiffness of any structure will reduce and natural frequencies will decrease. 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.

Case Study

To determine the natural frequency migration and mode shape changes at different stator winding temperatures of motor endwindings a 13.8 kV, 11.9 MW, 4 pole, 48 slots TEWAC motor (Figures 3 and 4)was tested at three different temperatures. Temperatures were recorded in the cold, warm and hot conditions on the coil surface near the stator core. The non-connection end and the connection end of the motor were tested.

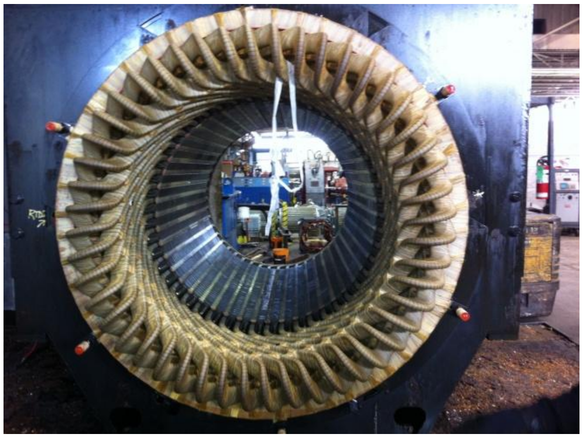


Figure 3 – Non-Connection End

Figure 4 – Connection End

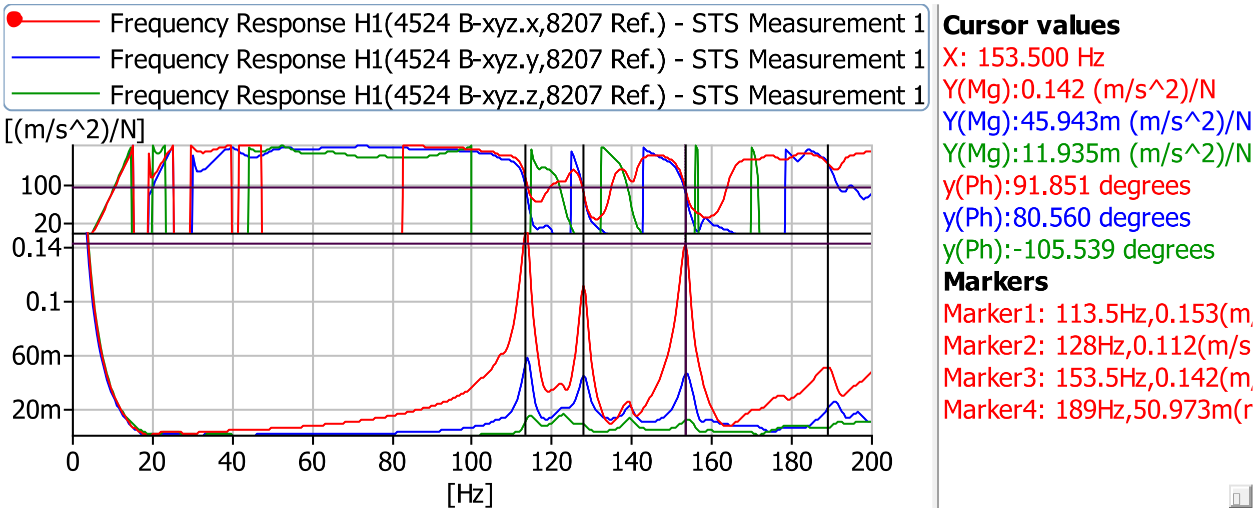
Two tests were performed on this motor, Frequency Response Test and Modal Analysis. For the Frequency Response test, the accelerometer and the impact hammer were at the same location at 4 points around the motor end winding. This test is used to determine natural frequencies which can be identified in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

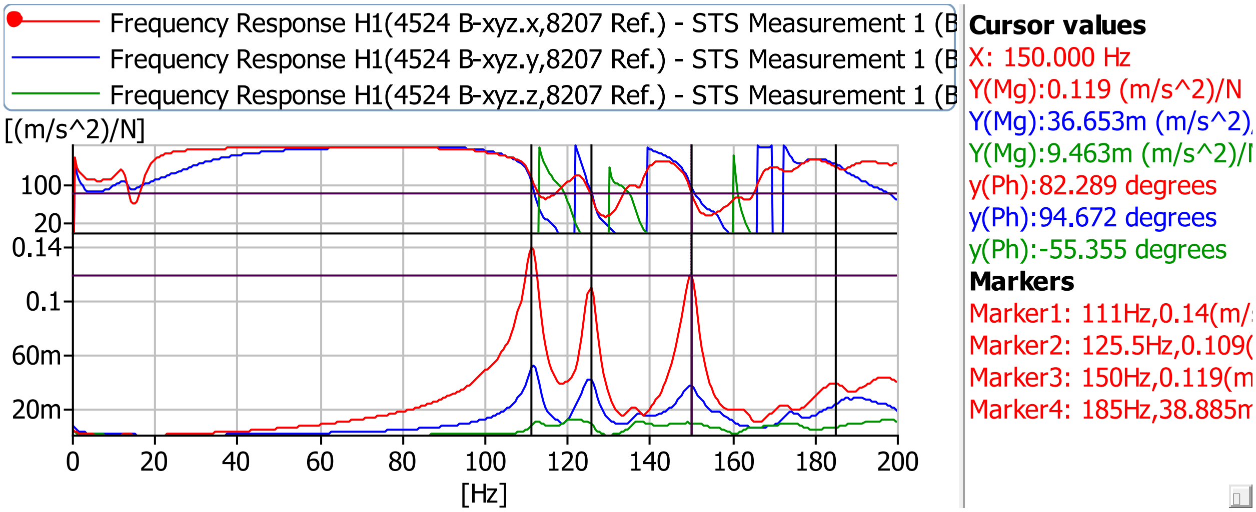
Results

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. Figures 5-7 are results from the same test point at three different temperatures. The upper part of each graph is an indication of phase and lower part is result of Fourier Transform, identifying natural frequencies of the test point. Three colors are indicators of movement in each of three axes, x, y and z.



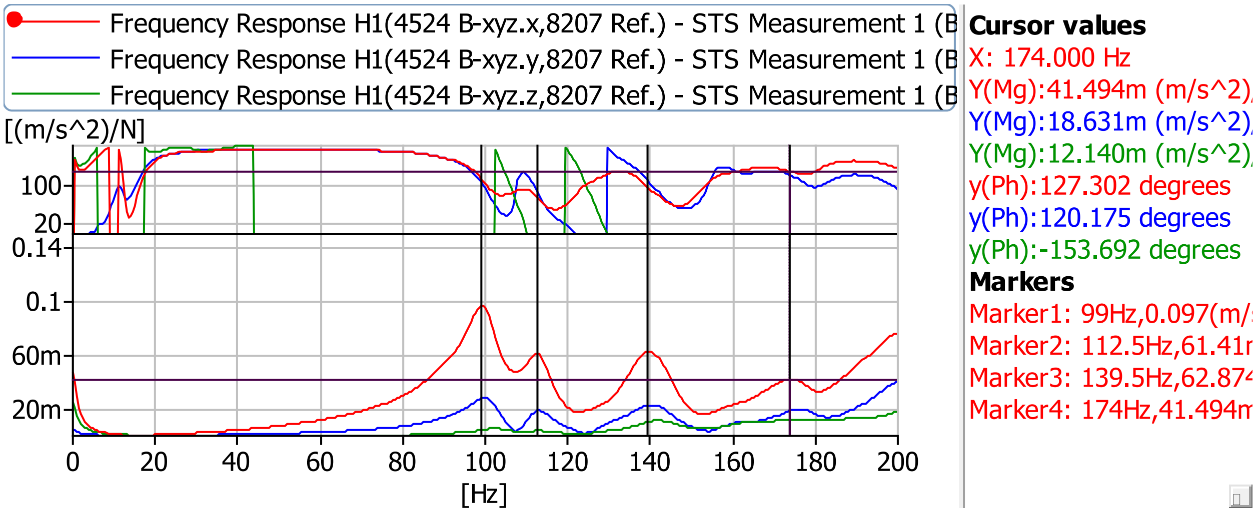
Cursor values
X: 153.500 Hz
Y(Mg):0.142 (m/s^2)/N
Y(Mg):45.943m (m/s^2)/N
Y(Mg):11.935m (m/s^2)/N
y(Ph):91.851 degrees
y(Ph):80.560 degrees
y(Ph):-105.539 degrees
Markers
Marker1: 113.5Hz,0.153(m
Marker2: 128Hz,0.112(m/s
Marker3: 153.5Hz,0.142(m
Marker4: 189Hz,50.973m(r

Figure 5 - NCE Point 1 FRF Cold at 22°C



Cursor values
X: 150.000 Hz
Y(Mg):0.119 (m/s^2)/N
Y(Mg):36.653m (m/s^2)
Y(Mg):9.463m (m/s^2)/
y(Ph):82.289 degrees
y(Ph):94.672 degrees
y(Ph):-55.355 degrees
Markers
Marker1: 111Hz,0.14(m/
Marker2: 125.5Hz,0.109(
Marker3: 150Hz,0.119(m
Marker4: 185Hz,38.885m

Figure 6 - NCE Point 1 FRF Cold at 58°C



Cursor values
X: 174.000 Hz
Y(Mg):41.494m (m/s^2)
Y(Mg):18.631m (m/s^2)
Y(Mg):12.140m (m/s^2)
y(Ph):127.302 degrees
y(Ph):120.175 degrees
y(Ph):-153.692 degrees
Markers
Marker1: 99Hz,0.097(m/
Marker2: 112.5Hz,61.41r
Marker3: 139.5Hz,62.87
Marker4: 174Hz,41.494m

Figure 7 - NCE Point 1 FRF Hot at 90°C

Mode shape tables were produced from the end winding 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.

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	*139.80*	*136.44*	*130.39*
n=4	*153.83*	*149.70*	*143.79*
n=5	*190.72*	*185.40*	*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*	*148.60*
n=4	*166.78*	*161.73*	*153.44*

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 figure below.

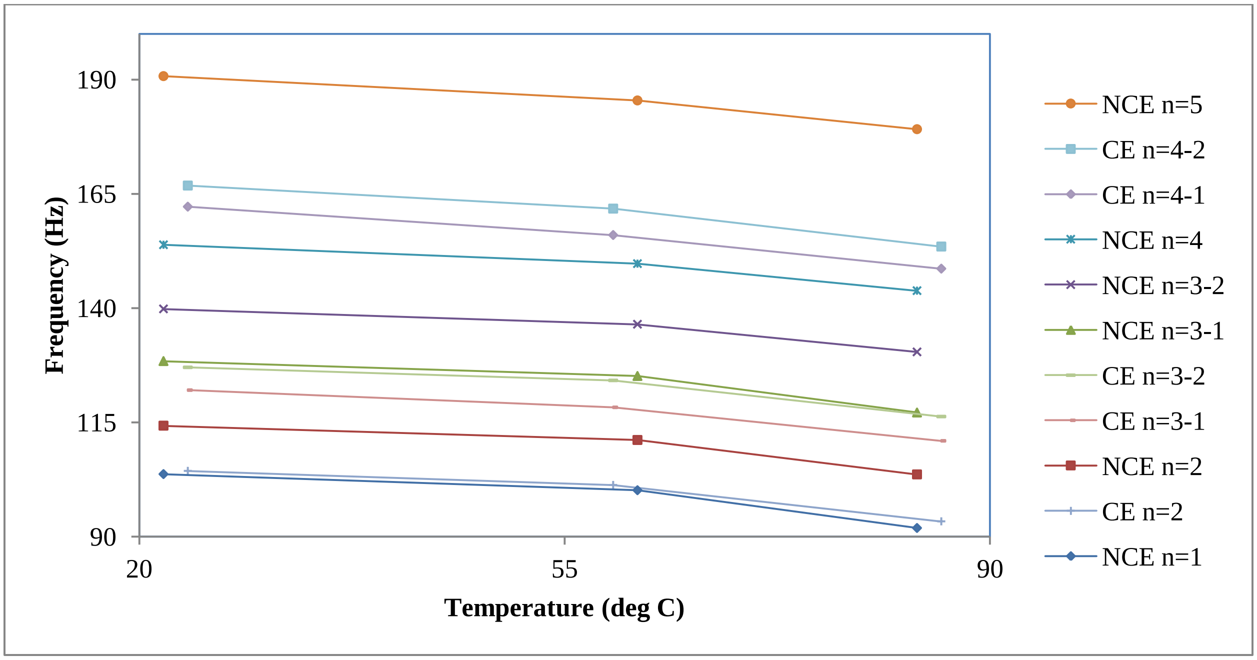


Figure 8 – Temperature vs. Mode Shape Frequency Plot

A correlation factor was calculated between these mode shapes as an indicator of how closely they match each other. A high factor, close to 1 is a good match. Lower correlation factors on the CE are a representation of the additional local natural frequencies previously discussed.

Tables 3 and 4 – NCE and CE Mode Shape Correlation Factors

	NCE Warm Correlation Factor	
Mode	**to Cold**	**to Hot**
n=1	*0.961*	*0.901*
n=2	*0.968*	*0.955*
n=3_1	*0.984*	*0.951*
n=3_2	*0.957*	*0.878*
n=4	*0.950*	*0.897*
n=5	*0.924*	*0.858*

	CE Warm Correlation Factor	
Mode	**to Cold**	**to Hot**
n=2	*0.942*	*0.911*
n=3_1	*0.719*	*0.416*
n=3_2	*0.717*	*0.612*
n=4_1	*0.693*	*0.637*
n=4_2	*0.866*	*0.816*

This indicates that even though the mode shape frequencies measured were affected by the temperature of the end winding the mode shapes were not. This 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.

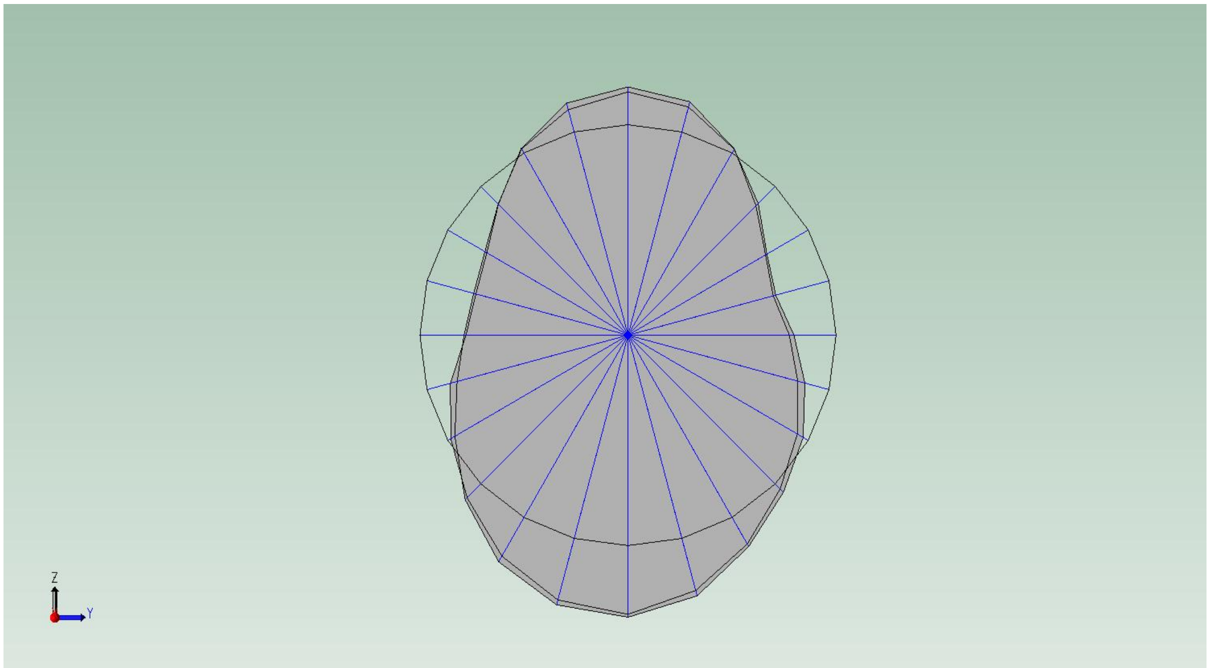


Figure 9 – NCE n=2 Mode Shape Position 1 Cold and Hot results

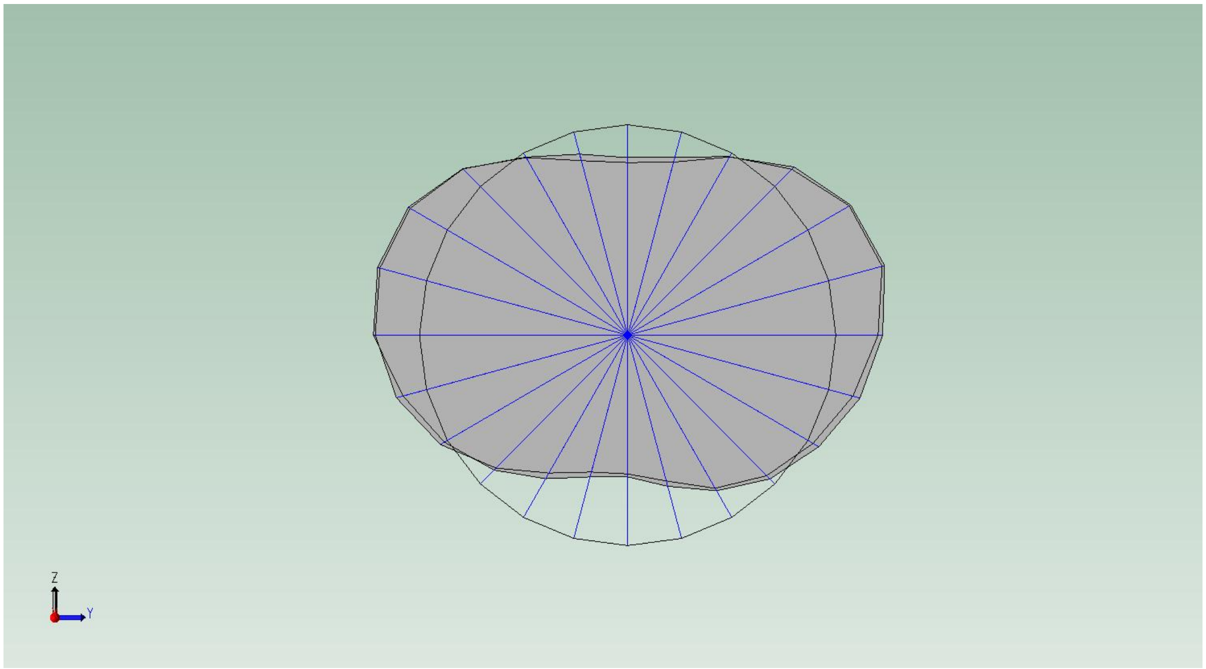


Figure 10 – NCE n=2 Mode Shape Position 2 Cold and Hot results

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. This phenomenon can be seen on all the mode shapes identified on both ends of the motor.

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

The experimental results were done with the help of Motion Electric in Mississauga, Canada.

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