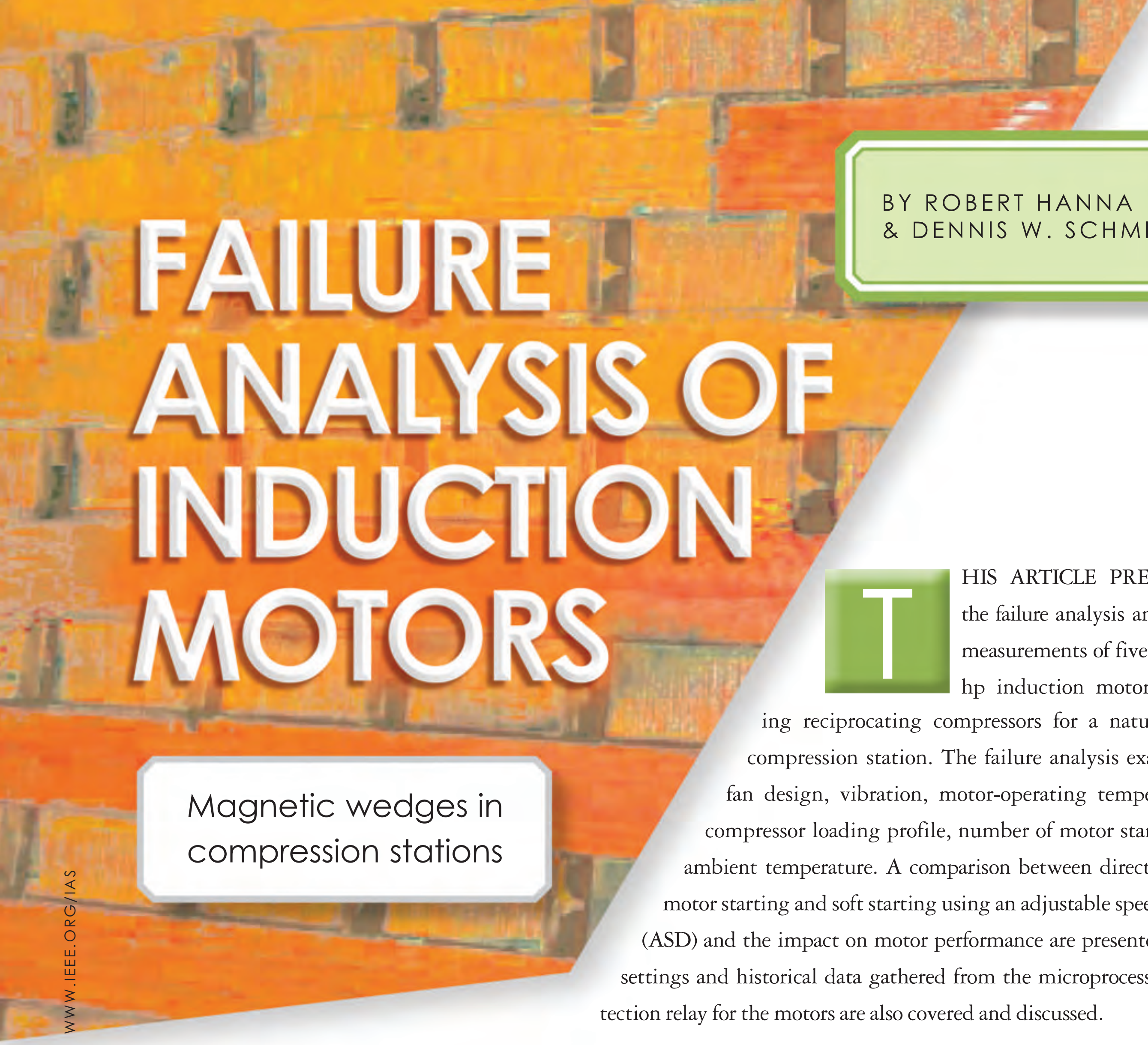

FAILURE ANALYSIS OF INDUCTION MOTORS

Magnetic wedges in compression stations

BY ROBERT HANNA
& DENNIS W. SCHMITT

THIS ARTICLE PRESENTS the failure analysis and field measurements of five 7,500-hp induction motors driving reciprocating compressors for a natural gas compression station. The failure analysis examined fan design, vibration, motor-operating temperature, compressor loading profile, number of motor starts, and ambient temperature. A comparison between direct online motor starting and soft starting using an adjustable speed drive (ASD) and the impact on motor performance are presented. The settings and historical data gathered from the microprocessor protection relay for the motors are also covered and discussed.

Compressor Stations

From 2005 to 2007, five 7,500-hp, 4,160-V, 1,189-r/min induction motors were installed at compressor station A, where all had direct online starting. A sixth motor of the same rating was installed at compressor station B using a 3,000-hp ASD for the purpose of a soft-start application. This application of the ASD was necessary as a result of utility power system requirements. The two compressor stations were less than 20 mi apart. In May 2007, one of the five motors in station A suffered a cooling fan failure and was sent to a motor shop for repair. In November 2007, a second motor at the same location experienced a similar fan failure and was shipped to the same motor shop for repair. As a precautionary measure and under planned conditions, the end user decided to take the remaining 7,500-hp induction motors (with the original fan design) to the motor shop one at a time and retrofit them with a modified cooling fan design. In August 2008, when the last motor had its fan replaced, the motor repair shop noticed evidence of winding material close to the nondrive end. In each case, the rotor had to be removed in for fan replacement. Because of the winding debris, the stator was thoroughly examined. The subsequent inspection revealed that many of the magnetic wedges, fitted in the stator slots, were either partially missing or loose. In this article, we present findings for premature failure of both cooling fans and magnetic wedges for 7,500-hp induction motors with three years of service.

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Fan Failure

In 2007, two motors had serious cooling fan failures, which required the motors to be removed from service and repaired. These events called for a review of the fan design by the original motor manufacturer.

THERE WAS A CLOSE CORRELATION BETWEEN THE AMBIENT AIR TEMPERATURE AND MOTOR TEMPERATURE RISE.

Fan Failure Mechanical Analysis

In May 2007 and again in November, two separate fan failures occurred on two of the then five installed electric-driven gas compressor packages at a gas-gathering compressor station in western Colorado. These two installations have identical 7,500-hp electric motors, each driving a two-stage, six-throw natural gas compressor. The failure investigation determined that the likely sequence of events that led to the eventual fan failure were as follows:

- fan bolts became loose
- fan became loose
- vibration levels began to escalate
- bolts began to fail and some vibrated out
- vibration levels continued to escalate
- all remaining bolts failed and fan fell onto steel boss
- the unit shutted down due to very high vibration levels.

The design of the fan for this motor is a bolted joint, where a cast aluminum fan is bolted to a machined steel boss that has a shrink fit onto the steel rotor shaft. In both cases, when the fan failed, many of the bolts in the assembly were sheared, and the cast aluminum fan was damaged at the bolt holes. The failure modes for the two cooling fans were essentially identical. The aluminum fan housing had many bolt holes that were key slotted, whereas others had no damage due to the bolt backing out completely before failure (Figure 1). There was also significant evidence of fretting corrosion on the mating surface between the fan and steel boss, indicating substantial and/or frequent relative motion (Figure 2).

The 1,200 r/min units were started at full voltage with the compressor unloaded and, at the time of the failures, were shut down with the compressor fully loaded. These operational conditions led to very high acceleration during start-up (2.5 s) and approximately twice the start-up acceleration magnitude during shutdown. This combination of inertial forces caused the fan to slip during start-up and fully reverse during shutdown. It is believed that this small rotational translation is what led to the development of fretting corrosion. As the surface asperities grew in number and size, the effectiveness of the bolted joint decreased. Total rotational slip of the fan with respect to the fan boss likely increased. This relative motion combined with some inherent machine vibration and a low initial bolt torque ultimately allowed some of the bolts to become loose and vibrate out.

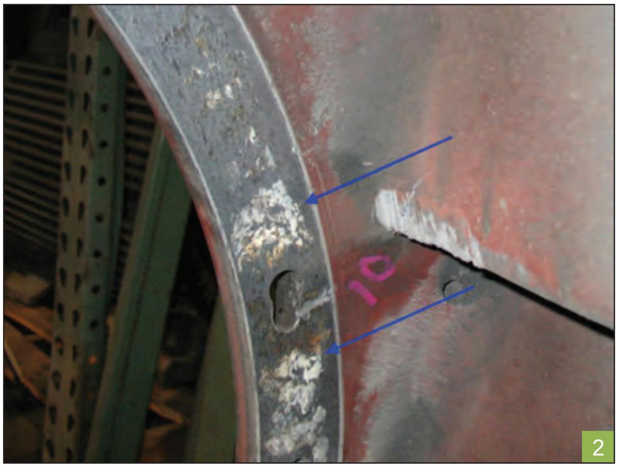
An engineering mechanics and dynamics analysis was performed for the original fan assembly design. This analysis revealed that the fan's bolted joint factor of safety (S_f), defined as the ratio of the total clamping force to the inertial force of the fan, had a potential less than one.

The motor manufacturer already had an improved fan design that was available. This improved design used 33% more bolts with 78% more cross-sectional area and included an additional steel ring as part of the improved design. This steel ring was installed on inside of the fan and created a steel-aluminum-steel bolted joint assembly. This in combination with more and larger bolts increased S_f to approximately five.

In addition to the improved design, the choice of the bolt was also evaluated. The original and replacement bolts provided by the motor manufacturer were property class 4.8 (approximately SAE grade 2), which is a low-strength, mild steel bolt. For the fan upgrade process, two changes were made to the bolts. Property class 8.8 (approximately SAE grade 5) bolts were selected for use, and all of the bolt heads were drilled to fix the stainless steel safety locking wire (Figure 3). Changing the bolt property class allowed the S_f to be increased again to approximately 8.5.

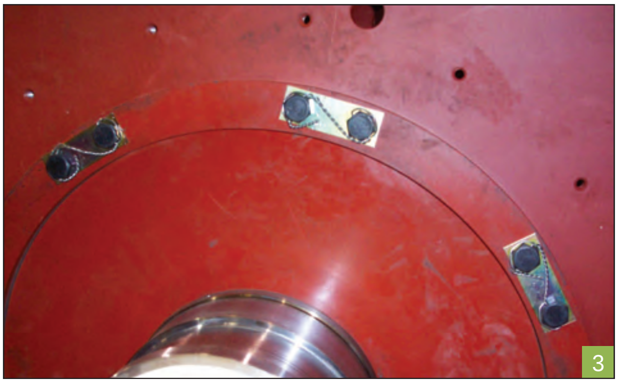
1

One damaged fan bolt hole and another with no damage.



2

Fan-mounting surface-fretting corrosion damage.



3

An example of a new fan bolt layout and a safety lock wire.

Although the hardware changes increased the safety factor for the fan assembly, operational process changes were also made. Instead of leaving the compressor fully loaded during any shutdown event, a shutdown matrix was created, and all shutdown conditions were evaluated. For all but emergency shutdown conditions, the compressor package initiates a controlled shutdown sequence whereby all the compression stages are unloaded before removing power from the motor. This process change decreases the load on the motor and increases the unpowered spin downtime for the motor and compressor by a factor of 12, eliminating the high inertial forces that contributed to original fan failures.

Motor Vibration Analysis

As part of the failure analysis process, potential energy sources that could have contributed or caused fan failures were analyzed. High or excessive vibration was identified as a possible cause for the bolts becoming loose. A series of vibration analyses were conducted in an attempt to understand the vibration characteristics of the motor as a standalone unit and also the motor/compressor package system. In addition, all pulsation and torsional vibration design study reports were reviewed.

By the time the motor vibration analyses were completed, the build out of the compressor stations was nearly complete. Hence, the eight motors at compressor station A and one motor at compressor station B were included in the vibration study.

At compressor station A, the first five motors were installed on a common skid design whereby steel adjustable chocks were used for motor support. The last three were installed on steel sole plates with shims. At compressor station B, the motor was mounted on steel adjustable chocks. Table 1 shows the motor manufacturer's vibration guidelines.

Motor fan mechanical natural frequency (MNF) vibration was investigated by the manufacturer. By way of finite element analysis (FEA), it was determined that the MNF of the fan and its assembly was 220–310 Hz, more than ten times the running speed.

TABLE 1. MOTOR MANUFACTURER'S RECOMMENDED VIBRATION LIMITS.

	Target	Alarm	Shutdown
Vibration level (in/s pk)	0.25	0.31	0.50

During the field vibration studies, 22 points on the motor housing were measured. These points included drive end and nondrive end bearing housings, frame locations, frame support (adjustable chock) locations, mounting skid/pedestal, and compressor. In general, all vibration measurements were below the motor and compressor manufacturer's vibration guidelines. Only the bearing housings (not the rotor shaft) in the axial direction indicated any elevated vibration levels. The units that had elevated vibration magnitudes were random, but when the vibration was above the target level, none were above the shutdown limit. When the vibration was above the target level, it was most often very close to three times the running speed. The bearing housings were more closely examined due to the vibration survey results.

The MNF of the bearing housings was measured with the motor in the following configurations:

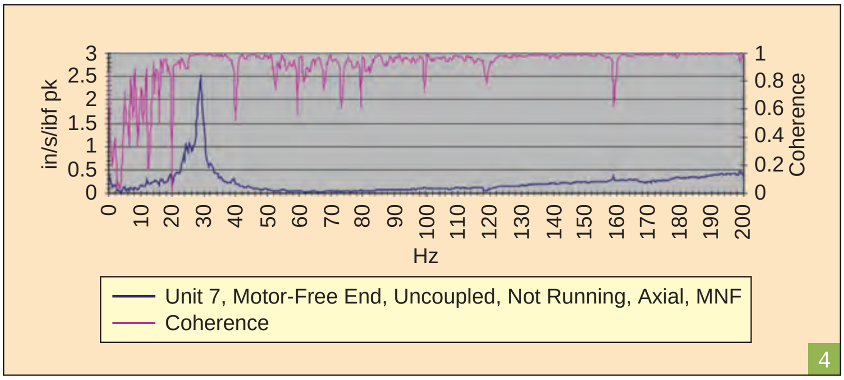
- uncoupled, not running
- coupled, not running
- uncoupled, running
- coupled, running and loaded.

When uncoupled, the motor MNF was consistently very close to 30 Hz. When the motor was coupled, running or not, the MNF was consistently between 64 and 68 Hz (Figures 4 and 5). The running speed tripled and was close to 60 Hz. Based on the nature of vibration amplification, as it approaches the first harmonic, there is a strong likelihood that the high axial bearing housing vibration is being amplified by the MNF of the bearing housing and support structure itself. Mechanical modifications to the bearing housing have been investigated; however, none have been implemented to date.

Motor Failure

Compressor station A received its incoming power at 230-kV single overhead line and B at 69 kV. At compressor station A, the power was stepped down to 4,160 V via two oil-type transformers, each rated 20/26.6/28 MVA. Two 7,500-hp motors are connected to one side of the bus and the remaining three motors to the other side with the tiebreaker in the normally open position. Five induction motors were installed at compressor station A for a period of three years from 2005 to 2007. In November 2008, an expansion project was in process to install additional three motors to meet process requirements. Each motor is rated at 7,500 hp, 4,160 V, 872 A, 1,189 r/min, 1.15 SF, class F insulation, and direct online start. All motors underwent vacuum pressure impregnation processing. At compressor station B, the ASD is used to soft start a similar motor and automatically transfers it to 60-Hz bypass mode.

In August 2008, during scheduled repair work to upgrade the cooling fan for the fourth 7,500-hp motor from compressor station A, it was accidentally discovered that about 50% of the magnetic wedges were either partially missing or loose (Figure 6). The stator has 90 slots, and each slot has three magnetic wedges. The slot length is 38 1/2 in. The use of magnetic wedges in the stator winding widely depends on the manufacturer's preference and their design practices. In this case, the motor manufacturer generally uses magnetic wedges for induction motors rated 7,500 hp and 1,200 r/min, and this practice has been followed for almost 20 years. It should be noted that information regarding the type of wedges used in stator slots is not normally published, shared, or provided by any motor manufacturer at the bidding stage, unless it is specifically requested or called for in the engineering specification. This information is considered a detail design and privy to the manufacturer's practices.



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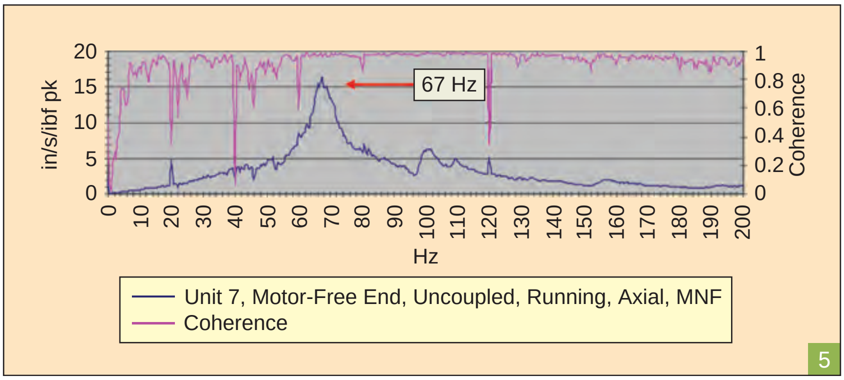
An MNF of uncoupled motor, not running.



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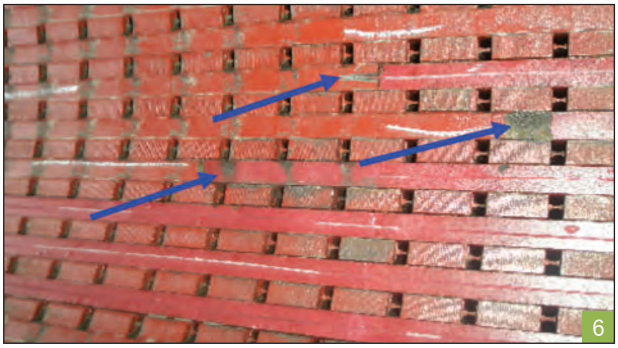
An MNF of uncoupled motor running.

Magnetic wedges, when compared with nonmagnetic wedges, have both pros and cons [1], [2]. The key advantages of using magnetic wedges are

- lower stator temperature rise and reduced core losses
- slightly higher motor efficiency
- reduced inrush current
- reduced noise level.

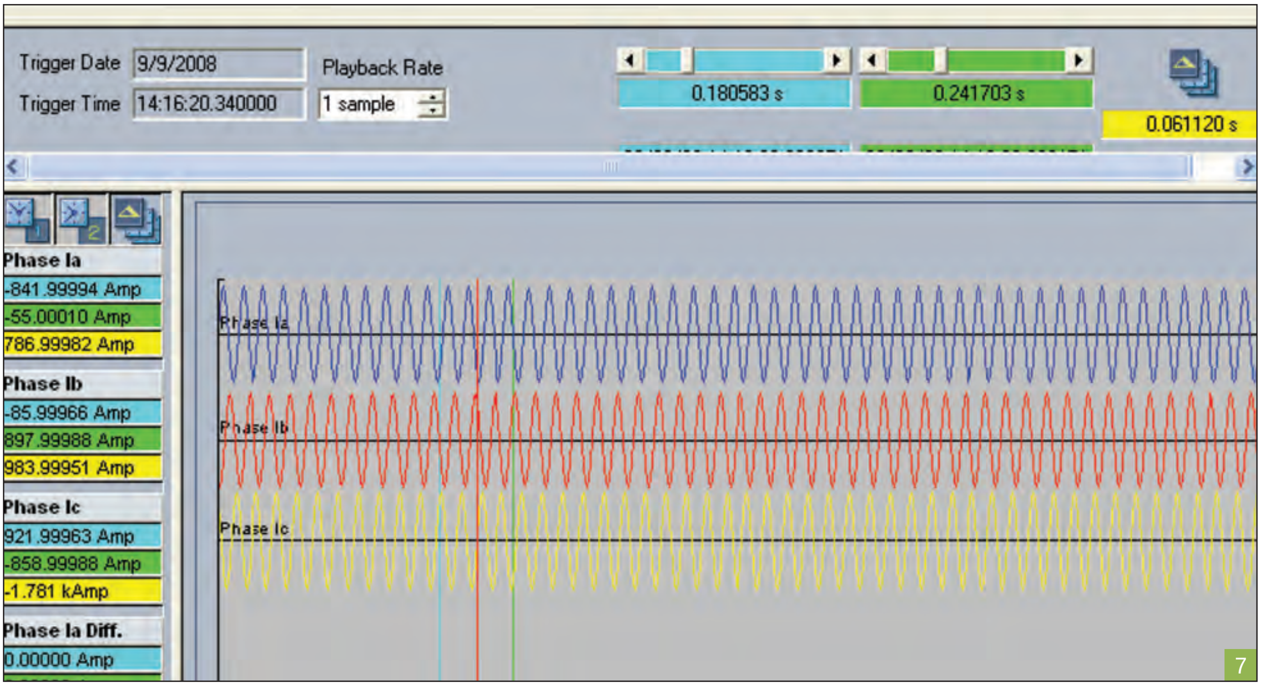
A typical magnetic wedge, material comprises 75% iron powder, 7% glass mat, and 18% epoxy resin. Magnetic wedges are more susceptible to failure when compared with nonmagnetic wedges because they are more brittle due to the high percentage of iron powder. In addition, for reciprocating-type loads, the magnetic wedges by their nature are subject to cyclic mechanical forces (120 times per second) so that if there is any freedom to move in the stator slot, fretting can occur, and the movement will slowly increase until wedge failure occurs. Upon failure, magnetic wedges normally disintegrate into very small pieces and get crushed in the small air gap (2.8 mm) between the stator and rotor. Typically, upon failure, magnetic wedges leave a distinct color mark on the rotor surface. The reliability and longevity of magnetic wedges are greatly impacted by the following factors:

- The number of full-voltage motor starts should be minimized as it causes excessive magnetic and thermal stresses on the magnetic wedges. In this case, the data retrieved from motor protection microprocessor relay show that the number of motor starts is high, and the motor is started, on average, once every three days.
- Motor vibration should be kept within design limits. High vibration could result in weakening of magnetic wedges and possible failure.
- Motors should normally run at or below 80 °C (176 °F) temperature rise. In this case, the motors were running at an elevated temperature rise, although the actual measured motor loading is at approximately 80% of rating. This situation is compounded because of poor air ventilation in the compressor building for station A and elevated ambient temperature during summer months. On the other hand, forced ventilation fans were installed at compressor building B.
- The surrounding area of compressor building A is fairly dusty, and all the motors have weather protected type II (WPII) enclosures without a provision to add air filters.
- It is common that a reciprocating compressor load profile exerts greater electromagnetic forces on the magnetic wedges due to the pulsating currents and the motor being run at a rated load. This was not a factor in this case because the stator current profile (Figure 7) is uniform (nonpulsating) and the motor was running at 80% load. MG1-2003 standard [3] calls for the current variation in induction motors driving a reciprocating-type load not to exceed 66% of full load value. In this case, the variation between minimum and maximum current measurements was insignificant, less than 2%, well within MG1 requirements.



6

Stator winding at the motor repair shop. White chalk marks identify partially damaged or loose magnetic wedges.


Trigger Date 9/9/2008

Trigger Time 14:16:20.340000

Playback Rate 1 sample

0.180583 s

0.241703 s

0.061120 s

Phase Ia

-841.99994 Amp

-55.00010 Amp

786.99982 Amp

Phase Ib

-85.99966 Amp

897.99988 Amp

983.99951 Amp

Phase Ic

921.99963 Amp

-858.99988 Amp

-1.781 kAmp

Phase Ia Diff.

0.00000 Amp

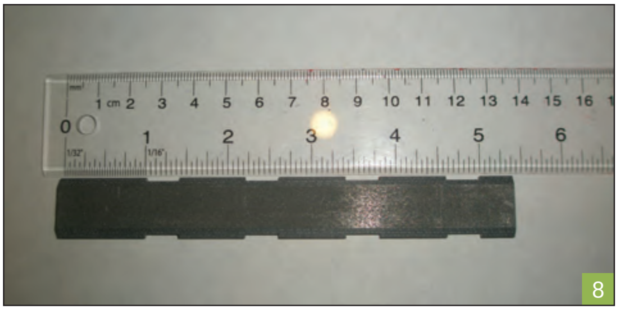
7

Sample of stator current waveforms for phases A–C. FLA is 872 Arms.

There is no known field-measuring technique available to positively predict loss of magnetic wedges of the stator winding without removing the rotor and visually inspecting the stator. The spectrum analysis method has been used [4] to compare the pattern of each phase motor current and has provided some advanced results of loss of magnetic wedges. However, for this site, during a scheduled station shutdown, a special borescope was inserted in the motor air gap (2.8 mm) to look for any marks (wear bands) on the rotor surface to establish loss of magnetic wedges. This inspection method proved to be reasonably effective to assess the condition of magnetic wedges. To date, none of the borescope inspections have found any new wear (rub) marks on the rotors, indicating that there are no additional magnetic wedge failures without removing the rotor.

The motor manufacturer cautioned that, if the motor is repaired using nonmagnetic wedges, the stator temperature rise would be approximately 125% higher than when magnetic wedges were used. This could potentially cause operational limitations and hence is unable to run the motor at the current loading conditions.

The repair work was carried out using magnetic wedges with the following dimensions: 5 3/8 in long × 3/4 in wide × 1/8 in deep (Figure 8). The replacement magnetic wedges were half the length of the original wedges to facilitate easier insertion at the repair shop. Here, the total number of wedges that were installed was 270. The motor manufacturer approved the product technical specification for the two epoxies used by the motor repair shop for installing the new magnetic wedges. The first epoxy was applied at room temperature in the stator slots before inserting the magnetic wedges. The second product was applied over the magnetic wedges after the stator is removed from the oven. The motor was subjected to a core loss test before and after rewedging, and the results were acceptable.



8

Sample of new magnetic wedge replacement.

During the course of the magnetic wedge failure investigation, the motor manufacturer provided a copy of a factory heat run test that was conducted for one of the 7,500-hp motors in September 2005. The factory test results showed that the stator winding temperature rise was recorded at 53.1 °C, which is considerably less than the design value of 80 °C. Accordingly, the motor temperature rise when running at 1.15 service factor is expected to be $(1.15)^2 \times 53.1 = 70.2$ °C. If the same motor was rewound using nonmagnetic wedges, the motor temperature rise, according to the manufacturer, is expected to increase by 25%, or $1.25 \times 53.1 = 66.4$ °C. Likewise at 1.15 service factor, it would be $(1.15)^2 \times 66.4 = 87.8$ °C.

Motor Protection

A microprocessor-based protection relay was used for all 7,500 hp at compressor stations A and B. The digital relay is equipped with several features to provide comprehensive motor protection during starting and running conditions. The relay has the capability to display actual field measurements, historical data, current waveforms, and past events. This information was important to assist in determining the premature failure of the magnetic wedges and overall motor performance. A laptop was used to communicate with all the relays and retrieve all pertinent data, including actual motor loading, stator and bearing resistance temperature detector (RTD) temperatures, maximum stator and bearing RTD temperatures, total number of motor starts, total number of hours in service, starting current, and acceleration time. The data for the five relays at station A were almost identical and are summarized as follows:

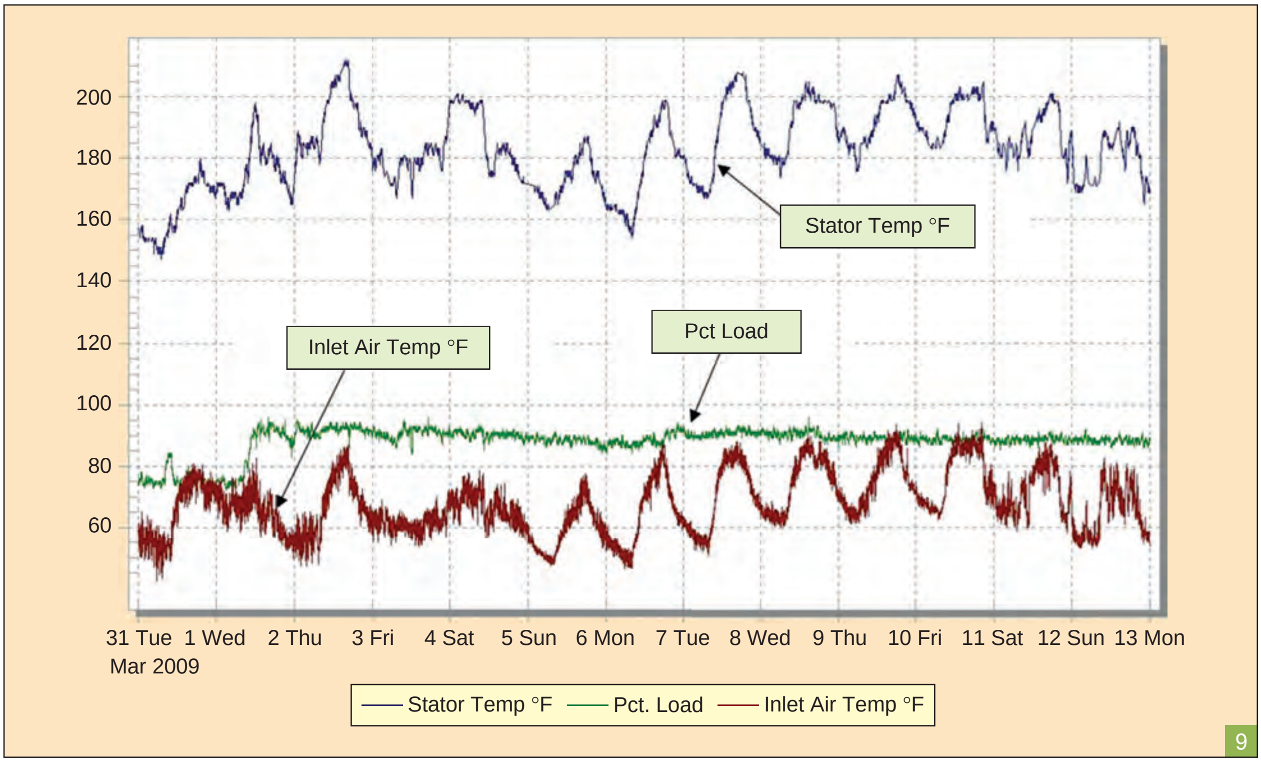
- The average loading was 81% rated value.
- The motor stator RTD was set to alarm at 125 °C, high alarm at 130 °C, and trip at 150 °C.
- The bearings were set to alarm at 80 °C, high alarm at 85 °C, and trip at 90 °C.
- The highest stator RTD temperature was recorded at 146 °C, and, for the bearings, it was 79 °C. This indicates that the motor stator winding had experienced a high stator temperature close to the tripping point, despite the average motor load being 81%. It is unlikely that these motors would be able to run at service factor rating because the stator temperature would exceed the trip settings of 150 °C, especially, during the summer months.
- The average motor acceleration time was 2.5 s and the motor starting current was 5.15 per unit.
- The average power factor was 90%.
- On average, the motor was started every three days and in some cases more frequently.
- Most of the captured events were either motor starts or stator RTD high temperature.

Historical data shows that the number of motor starts were high, and the motor was exhibiting many overtemperature stator RTD alarms although it was running only at an 81% average load. Typical reasons for a motor to run hot are as follows:

- overload condition
- excessive number of starts
- high ambient temperature around the motor
- dirty air filters.

These factors were investigated and, in this case, the overload factor was disregarded because the motor was running at 81% rating. The ambient temperature was measured throughout compressor building A in the proximity of five compressors using an infrared temperature instrument. The measurement showed a considerable difference between the outside and inside ambient temperatures, and this difference was greater in the afternoon. On the other hand, at compressor building B, the inside and outside ambient temperatures were close because the building is equipped with forced ventilation using several fans. The ventilation scheme that exists in compressor building B was very effective in cooling the building. There was a close correlation between the ambient air temperature and motor temperature rise. The higher the ambient temperature adjacent to the motor, the higher was the motor stator temperature rise. Figure 9 shows data

THE USE OF MAGNETIC VERSUS NONMAGNETIC WEDGES IN STATOR SLOTS DEPENDS ON THE MANUFACTURER'S EXPERIENCE AND PREFERENCE.



9

Correlation between stator and inlet temperature.

retrieved from the distributed control system during March 2009 for a two-week period.

It was discovered that none of the 7,500-hp motors had an air filter or even had a provision to install them. The motors have a standard WPII enclosure.

Field Measurements

For a period of two weeks during September 2008, two portable online power-quality monitors were installed at compressor station A to monitor the voltage and current profile and motor starting characteristics for two 7,500-hp motors. The starting current was measured at 4,563 A or 4,563/872 = 5.23 per unit. The starting voltage drop was measured at 15.5% and starting time at almost 3 s. The measured voltage drop was marginally high and might have caused nuisance tripping of 480-V small ASDs. The magnitude of the motor starting voltage drop would be worse under abnormal conditions with a single main transformer in service and tiebreaker closed. The steady-state voltage fluctuation at 4.16 kV bus was within ±1%, and this is acceptable. The same online measurements were repeated for compressor station B. At this location, the 7,500-hp motor was started using an ASD, and the acceleration time was set at 40 s. The motor was automatically transferred to bypass power. The motor starting hardly caused any voltage drop because the motor was started in a soft mode.

THE EIGHT MOTORS AT COMPRESSOR STATION A AND ONE MOTOR AT COMPRESSOR STATION B WERE INCLUDED IN THE VIBRATION STUDY.

Conclusions

Fan Failure

As part of the fan-replacement process, all fans have been upgraded to the manufacturer's improved design, and all motors (at both compressor stations) have had property class 8.8 bolts installed with safety-lock-wired heads. To date, there have been no additional fan failures.

Field vibration measurements have been collected, and efforts are being made to ensure that values are within the motor design limits. A review of the motor vibration data has indicated that mounting the motor on adjustable chocks or on sole plates has had no attributable effect on the vibration amplitudes. It is recognized that high vibrations could accelerate the damage and ultimate loss of magnetic wedges.

Elevated axial vibrations at the bearing housings are caused by the amplification effect of the approaching MNF of the bearing housing structure. No modifications to the motor-bearing housings have been pursued.

As a result of mechanical analysis, the shutdown procedures for all the compressors at both stations have been modified to unload all stages of compression (except for emergencies) before removal of power to the motor. This process change increased the spin downtime by a factor of, at least, ten times.

Magnetic Wedges Failure

Several factors are attributed to the premature failure of magnetic wedges for the 7,500-hp motor at compressor station A with less than three years of service. These are elevated motor temperatures, excessive motor starts, and high vibration. All five motors at compressor station A exhibited high RTD stator temperatures measured at 144 °C, despite running at approximately 80% rated load. Primary causes for high stator temperatures were inadequate compressor building ventilation, dusty surrounding with no motor air filters, and excessive motor starts.

Many measures were undertaken to address the factors impacting the longevity of magnetic wedges. In June 2009, the ventilation scheme for compressor building A was improved similar to that in compressor building B. The motor enclosures were modified to install air filters with differential pressure gauges. Serious consideration was given to install two ASDs at compressor station A, similar in concept to that at compressor station B, to soft start the existing five 7,500 hp.

Information regarding the type of wedges used in stator slots is not normally published, shared, or provided by any motor manufacturer at the bidding stage, unless it is specifically requested or called for in the engineering specification. The use of magnetic versus nonmagnetic wedges in stator slots depends on the manufacturer's experience and preference. In this particular case, the motor manufacturer has been using magnetic wedges for more than 20 years.

There is no known conclusive field-measuring technique available to predict the loss of magnetic wedges without dismantling the motor to inspect the stator. A technique using a special borescope inserted in the 2.8-mm air gap was tested to check for discoloration (wear band) on the rotor surface as a result of magnetic wedges failure. This inspection method appears to be a reasonably effective method to establish advance warning of magnetic wedge failures.

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Robert Hanna (r.hanna@ieee.org) is with RPM Engineering Ltd. in Mississauga, Ontario, Canada. Dennis W. Schmitt is with Encana Corporation in Calgary, Alberta, Canada. Hanna is a Fellow of the IEEE. This article first appeared as "Failure Analysis of 7,500 hp Induction Motors Driving Reciprocating Compressors with Three Years Service" at the 2010 Petroleum and Chemical Industry Conference.