# Failure Analysis of Three Slow-Speed Induction Motors for Reciprocating Load Application

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***Abstract*—The North Atlantic Refinery has three 5400-hp slow-speed induction motors driving reciprocating compressors for a Hydrogen plant. All motors were rewound on-site over the period of 1998–2002, using magnetic wedges as per the original design, and the motor protection was upgraded to microprocessor-type relays. In summer 2003, during routine maintenance, it was noted that these motors suffered substantial loss of slot magnetic wedges and had to be scheduled for rewedging over 2004–2006. This paper presents failure analysis, field measurements covering heat-run test results, and motor-performance and vibration analysis before and after motor rewedging work. This paper reviews the key factors for using magnetic versus nonmagnetic wedges in these applications and techniques available to predict loss of wedges. The use of a microprocessor relay for slow-speed induction motor protection is discussed, particularly, the thermal protection feature to address the cyclic-load pattern caused by the reciprocating compressor.**

***Index Terms*—Magnetic wedges, microprocessor protection relay, motor-failure analysis, slow-speed induction motor, vibration.**

## I. Introduction

The North Atlantic Refinery has three identical 5400-hp slow-speed induction motors used in critical process for reciprocating-compressor application to generate high-pressure hydrogen. The motors were built in Europe, in 1972, and each is rated 5400 hp (4030 kW), 325 r/min, 22 poles, 740 A, 4160 V, 0.78 pf, WP II enclosure, and class-F insulation with 80 °C temperature rise. Following plant restructuring, these motors were effectively placed in full service in 1988 and have been running ever since. The refinery undertook a project to rewind all three motors to improve reliability and increase life expectancy.

In 1998, C1905 slow-speed induction motor was rewound followed by C1906, in 2000, and C1904, in 2002. All rewind work was done on-site to reduce plant downtime and avoid potential equipment alignment problems. These motors were rewound using magnetic wedges in compliance with the original manufacturer specifications. The original motor protection was upgraded to microprocessor-type protection relay following each rewind job. In summer 2003, during routine maintenance work on C1904, debris from packing and magnetic wedge material was discovered inside the stator. This prompted the refinery to check the other two motors C1905 and C1906 and similar symptoms were found.

This application requires that two out of three motors be continuously in service, and each motor typically runs at or slightly above rated value. In addition, the overload setting of the microprocessor motor protection relay was set at 125% of full-load value to avoid nuisance tripping caused by cyclic-load pattern of the reciprocating compressor. An engineering review was conducted to evaluate using magnetic versus nonmagnetic material, as well as a review of motor protection relay with special emphasis on reducing the overload setting to 115% of full load without causing nuisance motor tripping. Vibration measurements and analysis was conducted under no-load and load conditions. In addition, heat run tests were conducted prior to and after the motor rewedging to establish its impact on motor performance, particularly in regard to the winding temperature rise and inrush current.

## II. Magnetic Wedges

Magnetic wedges [1] are used as a slot wedge in open-slot-design motors. The magnetic wedge material comprises of 75% iron powder, 7% glass mat, and 18% epoxy resin. Magnetic wedges when compared to conventional nonmagnetic wedges offer the following benefits:

1) reduce core losses, and hence, motor temperature rise;
2) effectively reduces air-gap length resulting in lower magnetizing current and, hence, improved power factor;
3) reduce inrush current;
4) more efficient motor.

However, magnetic wedges are more brittle than nonmagnetic ones due to high percentage of iron powder in the magnetic wedge. In summer 2003, a routine inspection of C1904 revealed debris of packing and magnetic wedge material inside the stator, although this motor had been completely rewedged in 2002. An investigation was undertaken to look into the premature loss of wedges and impact on the motor performance. The original motor manufacturer was consulted to review this situation as well as to determine any available measuring techniques in predicting the number of missing wedges without physically dismantling the motor for stator inspection. These motors are located in close proximity to each other, a class I, division II,

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Fig. 1. 5400-hp motor overview.

group B and D areas, and the compressor shelter is open on all four sides. Fig. 1 shows a motor overview.

It was feared that winding movement in the stator slots could have occurred as a result of the missing wedges particularly during motor starting. The motor manufacturer was consulted to assist in determining the cause of premature loss of magnetic wedges. The refinery was made aware that magnetic wedges should always be fitted using "wet" and not "dry" process. It appears that the rewind work that took place in 1998–2002 used dry process, thus compromising the reliability of magnetic wedges. Wet process involves applying a coating of epoxy resin in the slot before inserting the wedges and then reapplying the resin on the wedges after they have been fitted to fill any voids and to prevent any movement of the wedges.

A review was carried out to determine if there was any known field-measuring techniques available to positively establish the number of missing wedges without dismantling the motor to inspect the stator. The results unfortunately revealed that such measurements are not available. It appears that the most effective way is to conduct a regular visual inspection of the motor by removing the end cover as well as to look for any sign of debris or black powder exiting the exhaust ducts during motor starting. Based on these findings, the refinery decided to fully dismantle each motor and plan for rewedging if warranted using wet process. The implementation plan addressed first C1905 motor followed by C1906 and C1904.

Prior to taking C1905 motor out of service for detailed inspection and rewedging, the option of using nonmagnetic material was considered because of its superior mechanical properties including higher flexural strength. Magnetic wedges are more susceptible to damage particularly when subjected to thermal overload, repeated starts, stalls, or poor handling during installation. However, the original motor manufacturer cautioned that using nonmagnetic wedges could result in higher stator temperature rise by about 10 °C–20 °C, about 10% increase in inrush current, and higher losses. The plant-process conditions dictate that these motors operate at or about 5% above rated current. It was feared that using nonmagnetic material could cause motor overheating resulting in operational limitation. Nonmagnetic wedges are commonly used in new motors and magnetic wedges are supplied when called for in the technical specification.

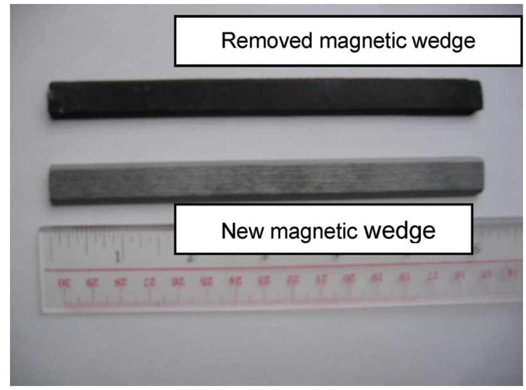



Fig. 2. Samples of new and removed magnetic wedges. Each wedge is 6-in long by 9/16-in wide by 0.15-in deep.

There are several factors that impact the reliability and longevity of magnetic wedges particularly for this refinery application. The load is of the reciprocating type and the magnetic wedges are, therefore, subjected to cyclic mechanical forces (120 times per second). If there is any freedom to move, fretting will occur and the movement will slowly increase resulting in wedge disintegrating. The problem for this refinery was compounded due to the following reasons.

1) During motor rewinding in 1998–2002, magnetic wedges were not epoxyed and a dry process was used (instead of the recommended wet).
2) Vacuum-pressure-impregnation process has not been used, because stator rewinding was done on-site. Also, due to the large diameter of the stator core, there are no local motor repair shops that can perform this work.
3) Motors are required to run slightly above rated load to meet process demand.
4) Motors are started on average every two weeks due to mechanical and process conditions. This frequent start subjects the stator and rotor core to thermal cycling as well as the transient vibration.

The technical data sheet for replacement magnetic wedge material and epoxy resin was reviewed and approved by the original motor manufacturer to be used for rewedging work. Fig. 2 shows a sample of removed and replacement magnetic wedges. Overall length of each magnetic wedge strip is 6 in. The epoxy was mixed in smaller quantities to maintain its light viscosity and then applied using a brush.

## III. Motor Rewedging

Several tests [2] were conducted for C1905 prior to motor rewedging to determine the impact of loss of magnetic wedges on its performance. Advance power-quality monitor was used to measure the load profile and inrush current. Vibration measurements were also taken. It was estimated that ten days were needed to cover testing, dismantling the motor on-site, rewedging work, assembling the motor, core-loss test, testing after rewedging, and allowances for unforeseen condition such as the weather as this work was done in January 2004, where temperature could be −10 °C.

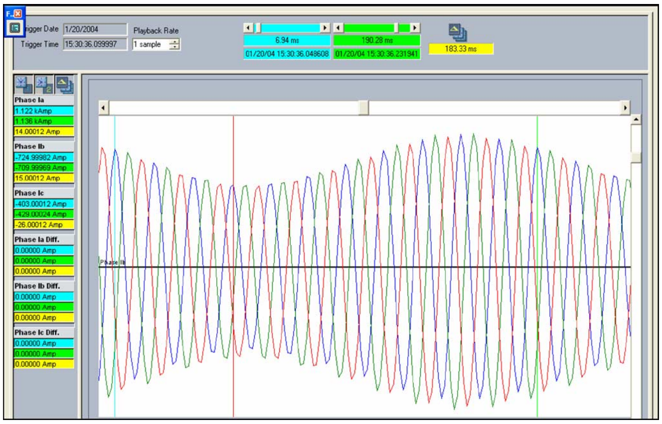


Fig. 3. Three-phase motor current profile for reciprocating compressor at 100% load. Profile is cyclic and repeats itself every 11.07 cycles. Maximum amplitude is 1259 A and minimum is 782 A.

Fig. 3 shows the motor-load profile for C1905, which is cyclic and the pattern repeats itself almost every 11 cycles. The motor has 22 poles and rated speed is 325 r/min. Number of revolution per second $= 325/60 = 5.4167$. For every one motor revolution, there are $60/5.4167 = 11.07$ cycles. Maximum measured peak current was 1259 A and the minimum was 782 A. It is recommended [4] that current pulsation should not exceed 66% of full-load current. In this case, current pulsation is $= (1259 - 782) \times 100/740 \times 1.414 = 46\%$ and this is within the acceptable limits. Similar motor-load-profile measurements were recorded for C1904 and C1906, and results were identical to that of C1905 and less than 66% of full-load current.

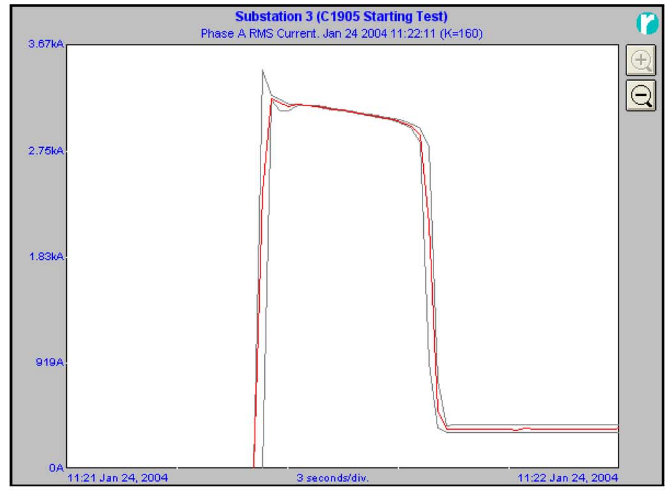
Prior to rewedging of C1905, it was started three times to record inrush current and vibration. Fig. 4(a) and (b) shows the starting current and voltage profile. Acceleration time was measured at 5 s. Starting voltage drop was 17.5% measured at 4.16-kV bus. Starting current was 3219 A. The starting current corrected to rated voltage is calculated as follows.

$$\begin{aligned} &\text{Starting current at V rated}\\ &\quad = \text{measured starting current}/(\text{reduced voltage})^{1.1}\\ &\quad = 3219/(0.825)^{1.1}\\ &\quad = 3977\ \text{A}.\\ &\text{Rated current}\\ &\quad = 740\ \text{A}.\\ &\text{Starting current } 3977/740\\ &\quad = 5.37\ \text{PU}. \end{aligned}$$

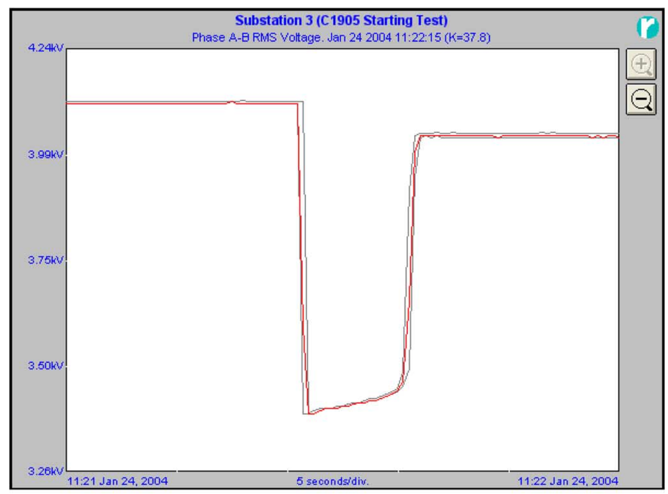
The motor nameplate shows that the starting current is 5 PU. The measured inrush current is about 7.4% higher than nameplate value.

Following these tests, the motor was released for dismantling and for removal of the rotor. Fig. 5 shows an enlarged view of the stator winding as found. Careful inspection of C1905 stator winding revealed the following.

1) About 50% of the magnetic wedges and packing were missing. The stator has 198 slots and each slot length requires six wedges. Total number of wedges is $6 \times 198 = 1188$.




(a)




(b)

Fig. 4. (a) Starting current profile for 5400-hp motor prior to rewedging and measured at 3129 A and 5-s acceleration time. (b) Motor terminal voltage profile during starting and it dropped from 4118 to 3390 V or by 17.5%.

Fig. 5. Enlarged area for C1905 motor showing several partially or completely missing magnetic wedges from stator slots.

2) Loss of wedges was sporadic but noted that more wedges were missing in the center part of the core.

3) Air ducts were reasonably clean and no visible blockage.

4) There were some signs of corrosion at scattered areas in the core.
5) There was no visible sign of any coil- or end-winding movement in the slot in spite of too many missing wedges. This is because the end winding were secured using blocking.
6) There was no sign of any coil-insulation-wrapping discoloration.
7) There was some sign of rotor rubbing against the stator, which probably happened during the rotor removal.
8) Some stator laminations were damaged.
9) There was some sign of salt, particularly closer to end winding. The source of salt is probably due to the refinery proximity to sea.

The C1905 motor was cleaned and all magnetic wedges removed. A core-loss test was conducted using three-phase 600-V portable generator to supply the required voltage and current. There were very few hot-spot areas noted and were corrected by separating the lamination using a mallet. A coat of epoxy resin was first applied with a brush in the slot before fitting the wedges. Magnetic wedges were driven into position one piece at a time, and then, a second coat of epoxy resin was applied to fill in any voids and to prevent movement of wedges. The process of fitting the new magnetic wedges took about 48 h with two service technicians working, one at each end. The motor was assembled and underwent more testing that included measuring inrush current and vibration. The results showed that there was hardly any change in magnitude of inrush current before and after rewedging. Prior to rewedging the inrush current was measured at 5.37 PU and after rewedging it was 5.22 PU, or about 4% drop. C1905 was placed in service in the end of January 2004.

In August 2004, C1906 was dismantled to determine the condition of magnetic wedges. The inspection revealed that C1906 was as bad as C1905 with more than 50% of magnetic wedges missing. Based on this, heat-run and starting tests were conducted for C1906 prior to and after fitting magnetic wedges to determine impact-on-motor performance.

In October 2005, the end cover for C1905 was removed to carry out limited visual inspection of the magnetic wedge condition that were fitted in January 2004. The magnetic wedges were found intact indicating that the wet process used to fit the wedges has improved their longevity. Based on these preliminary encouraging results, the refinery decided to continue using magnetic wedges rather than nonmagnetic wedges for rewedging C1904.

In March 2006, the third and last motor, C1904, was dismantled and again found that about 50% of magnetic wedges were missing. C1904 was rewedged using magnetic wedges and wet process.

The refinery is planning to carry out a comprehensive visual inspection of the magnetic wedges by dismantling the motors in five years time to coincide with the plant major turnaround.

## IV. Heat Run Test

C1906 underwent heat run test in August 2004, prior to rewedging, and in November 2004, after rewedging. The motor has six stator RTDs that are wired to a microprocessor relay. The motor was started from ambient temperature, and RTD temperature was recorded about every 15 min with the motor running steady at rated load. Table I shows the RTD measurements prior to rewedging. It took about 4.5 h for stator-winding temperature to stabilize with the average motor current at 740 A. The measured ambient temperature was 19 °C. The measured temperature rise prior to rewedging was $95 - 19 = 76$ °C.

TABLE I
HEAT RUN TEST MEASUREMENTS PRIOR TO MOTOR REWEDGING WITH MOTOR RUNNING AT RATED CURRENT

| RTD Measurements (° C) for C1906 prior to rewedging (Readings taken every 15 minutes) | | | | | |
|---|---|---|---|---|---|
| RTD1 | RTD2 | RTD3 | RTD4 | RTD5 | RTD6 |
| 34 | 35 | 36 | 35 | 33 | 35 |
| 41 | 43 | 43 | 42 | 41 | 42 |
| 55 | 57 | 58 | 56 | 57 | 57 |
| 59 | 62 | 63 | 60 | 62 | 62 |
| 63 | 66 | 67 | 63 | 65 | 66 |
| 70 | 73 | 73 | 69 | 73 | 73 |
| 76 | 78 | 78 | 74 | 78 | 78 |
| 78 | 80 | 80 | 76 | 80 | 80 |
| 82 | 85 | 85 | 80 | 85 | 85 |
| 84 | 86 | 86 | 81 | 86 | 87 |
| 85 | 89 | 88 | 83 | 88 | 89 |
| 86 | 90 | 89 | 84 | 90 | 90 |
| 88 | 91 | 90 | 85 | 91 | 91 |
| 89 | 92 | 91 | 85 | 92 | 92 |
| 89 | 93 | 92 | 86 | 92 | 93 |
| 90 | 93 | 92 | 86 | 93 | 93 |
| 90 | 93 | 92 | 86 | 93 | 93 |
| 90 | 93 | 92 | 87 | 93 | 93 |
| 91 | 93 | 93 | 87 | 93 | 94 |
| 92 | 94 | 93 | 87 | 94 | 94 |
| 93 | 95 | 93 | 88 | 94 | 95 |

The heat run test was repeated for C1906 following the rewedging. Motor temperature rise was marginally improved and measured at 74 °C. These findings do not reflect the motor manufacturer observation that substantial loss of magnetic wedges could cause 10 °C to 20 °C increase in operating winding temperature. Based on these results, in the future, the refinery should consider using nonmagnetic wedges if magnetic wedges fail prematurely again, since fitting the motor with new magnetic wedges resulted in insignificant improvement in stator temperature rise.

C1905 did not undergo heat run test prior to rewedging due to scheduling constraint. However, in August 2004, heat run test was conducted for C1905 after rewedging. The test lasted for 4 h, and the stator temperature rise was recorded at 82 °C. Heat run test was not conducted for C1904 motor either before or after rewedging.

The motor over temperature protection is set to alarm at 110 °C, high alarm at 130 °C, and trip at 150 °C. Voting feature is activated so that two RTDs should be at or above 150 °C for the relay to initiate a motor trip.

## V. Motor Protection

The motors utilize microprocessor relays for protection. This relay has several features to provide adequate motor protection during starting and running. It was noted that when the thermal overload was set at 115% of rated current and the motor ran at rated value, the relay tripped on overload after about 20 min in service. The overload setting had to be increased to 125% of rated value to avoid nuisance tripping caused by exhausting the thermal capacity. The refinery engineering had to decide between either selecting 125% overload setting and, thus, compromising motor protection or setting at 115% and imposing limitation on plant throughput by running the motor at or below 90% rating. On temporary basis, the refinery elected the latter option of running the compressors at 90% capacity. A review of motor protection was initiated to allow the motor to run at 100% compressor load with the overload pick up set at 115% and without exhausting the thermal capacity.

The microprocessor relay applied for this application uses 16 samples per cycle to calculate the phase current. In most industrial applications, the current waveform is uniform, namely the positive and negative half cycles are the same and repetitive. This is typical for centrifugal-type load such as pumps and fans. For reciprocating compressors, the required load torque is variable resulting in pulsating-current pattern that repeats itself every compressor stroke or every one revolution. In this application, this pattern repeated itself every 183 ms or every 11 cycles.

The thermal model for this relay is set to simulate temperature buildup in the motor to adequately protect it against overheating. If the motor is not running for several hours, the winding temperature is reduced to ambient and the thermal capacity used will be zero. If the motor is running in an overload mode above the pickup values, the thermal capacity is gradually exhausted and when it reaches 100%, the relay initiates a trip. In this case, when the relay-overload pickup was set at 1.15 FLA or $1.15 \times 740 = 851$ A (rms) and the measured current per cycle exceeded the overload pickup value of 851 A, it was calculated as thermal capacity used. If the overload condition persisted, it would cause the thermal-capacity used to reach 100% and the relay would initiate a trip. The load pattern, as shown in Fig. 3, is cyclical, because the motor is driving a reciprocating compressor. It is interesting to note that during every 11 cycles, some cycles have amplitude that exceeds 115% overload settings and others are lower. When the amplitude of a cycle exceeds the pickup settings, it contributes to the thermal memory usage (equivalent of thermal build in motor) and when it is less than the pickup value, the thermal capacity is replenished (equivalent of motor cooling). The motor tends to heat up faster than it takes to cool down. Hence, over extended period of time, in this case, about 20 min, the thermal capacity was exhausted causing a motor trip. To address the impact of cyclic load of the reciprocating compressor on the thermal capacity usage, "the load filter" parameter was adjusted from the factory default setting of 0 cycle to 11 cycles. This means that the current value is now averaged over 11 cycles to smooth out the impact of current pulsation and, more adequately, simulate the impact on thermal capacity usage. The current for phases A, B, and C is still calculated every cycle but is averaged over 11 cycles. The average motor current is calculated as $(\mathrm{Ia} + \mathrm{Ib} + \mathrm{Ic})/3$. If this average current exceeds the overload-pickup value, it would contribute to thermal capacity usage. By adjusting the "load filter" parameter for this relay to 11 cycles, it was possible to reduce the overload-pickup setting from 125% to 115% and run the compressor at 100% without resulting in any thermal trip.

## VI. Vibration Analysis

Reciprocating compressors (even with a flywheel) create an oscillating load. Hence, the driving motor sees this oscillating load and, in turn, exhibits oscillating vibrations. This oscillating vibration is detrimental to the equipment as it can lead to fatigue failures. In addition to running-speed vibrations, the three compressor motors exhibited unique vibrations at slot-pass frequencies.

Analyzing the vibration spectrums during motor startup, at no load and full load operation, revealed that there is a high-frequency vibration originating from the stator core, which is commonly known as slot-tooth-pass frequency/harmonics. The reciprocating compressor, to which the motor is coupled, creates a fluctuating load, which causes the speed of the motor (angular velocity) to vary. This variation in motor current, speed, and magnetic field causes the fluctuating and varying vibration in the stator teeth between 60 000 and 70 000 cpm (cycles per minute). In addition, the fundamental 60-Hz frequency in the stator causes the magnetic wedges to vibrate at the fundamental frequency. These fluctuating vibrations will cause the magnetic wedges to breakdown prematurely because of the high iron content of the wedge and its poor mechanical properties. In addition, the salt in the atmosphere caused corrosion of the stator laminations and magnetic wedges compounding the problem.

Figs. 6 and 7 show vibration of the motor with approximately 50% of the magnetic wedges missing. Fig. 8 shows the vibration spectrum on stator core with motor unloaded after rewedging. The vibration spectrums are the same before and after rewedging. It is shown that the amplitude of the high-frequency vibrations exceeds the amplitude of the low-frequency vibrations. This is not common and is an indication of high flux densities in the stator core.

Figs. 9 and 10 show vibration of the motor loaded after rewedging. As the motor went from no-load to full load, the severity of the high-frequency vibration increased by four to five times. This high-frequency vibration is not uncommon, but on a well-designed motor, the amplitude of the high frequency is very low or nonexistent.

The wet process of securing the wedges into the slot will slow down the destructive nature of the vibration process, on a temporary basis. The epoxy holding the wedges in place might eventually break down and wedges will come loose. Due to this fact, the use of magnetic wedges has seen limited applications.

## VII. Conclusion

Magnetic wedges are more susceptible to failure when compared to nonmagnetic wedges. At present, magnetic wedges

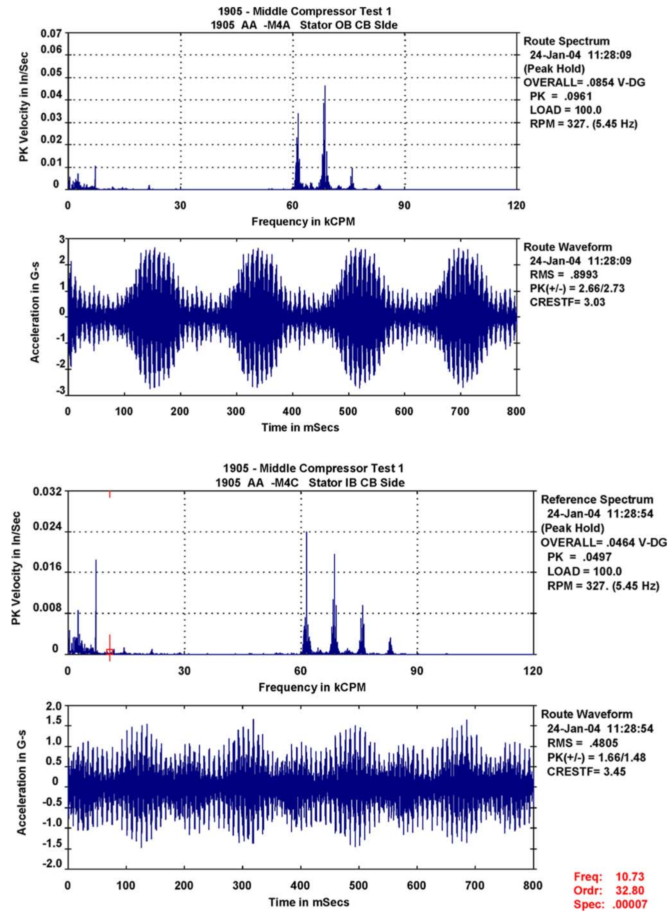



Fig. 6. Vibration spectrum of the stator core taken at 9 and 12 o'clock positions, before rewedging with about 50% of the magnetic wedges missing. The reciprocating load is reflected in the time waveform signature.

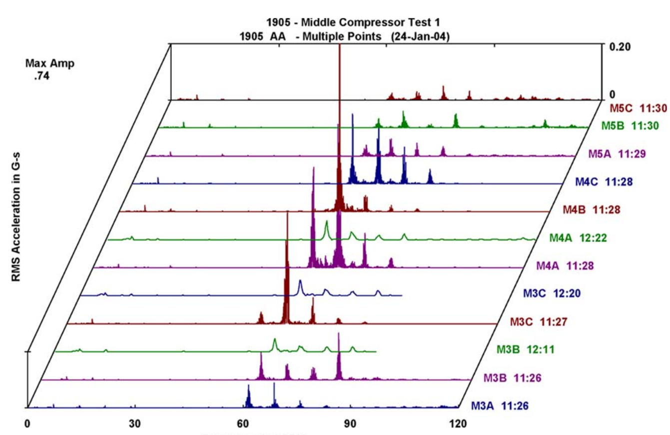



Fig. 7. Cascade plot of the vibration spectrum prior to rewedging. The cycling nature of the compressor is directly reflected in the vibration spectrums over time.

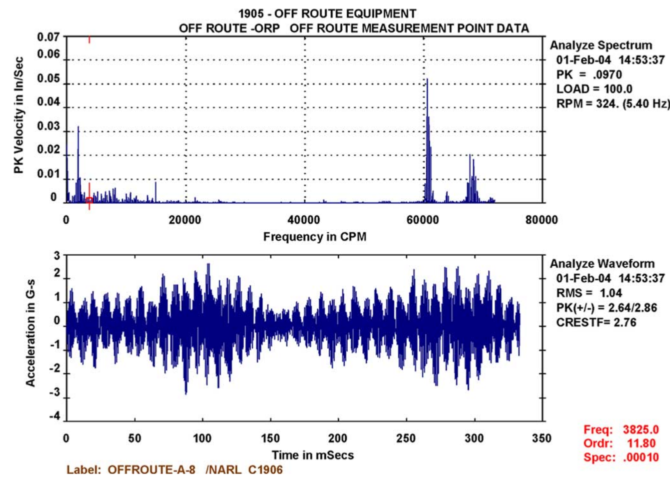



Fig. 8. Vibration spectrum on stator core, unloaded, after rewedging.

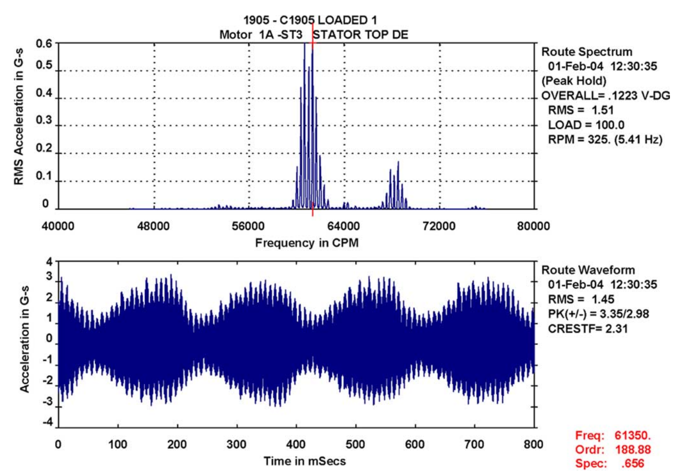



Fig. 9. Vibration spectrum on stator core, loaded, after rewedging. Vibration cycling is still very predominating.

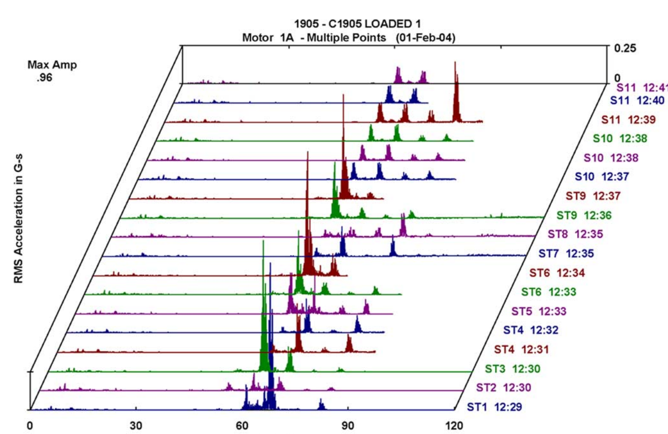



Fig. 10. Cascade of vibration spectrum on the stator core, when the motor is loaded. No change in vibration exhibited on the stator core even after rewedge.

are not commonly used in new motors unless called for in the engineering specification. Magnetic wedges, when used, offer improvement in efficiency (lower losses), power factor, thermal performance, and lower inrush current. The motor manufacturer recommended that the "wet process" be used when rewedging to secure the magnetic wedges in the stator slot. For this application, all three motors were completely dismantled and new magnetic wedges were fitted using wet process in the period 2004–2006. In October 2005, the end cover for C1905 motor, that was rewedged in January 2004, was removed to conduct limited inspection of the condition of the magnetic wedges. The magnetic wedges were found intact indicating that using wet-process method when fitting magnetic wedges does improve their longevity.

There are many factors that should be considered to try and improve the reliability and longevity of magnetic wedges. These are the following.

1) Number of motor starts should be kept to minimum as these subjects the magnetic wedges to excessive magnetic and thermal stress.
2) Motors should not run above rated-design value for extended period of time. The original design for this application called for a compressor load of 4900 hp and a motor rating of 5400 hp. Presently, when the compressor is required to run at 100% load, the equivalent motor load is about 5% above rating.
3) The reciprocating compressor load profile exerts greater electromagnetic forces on the magnetic wedges because of pulsating current and mostly running at rated load. This causes gradual deterioration in performance of magnetic wedges and eventual failure.

The results of heat run tests revealed less than 2 °C difference in motor temperature rise before and after rewedging, although 50% of the wedges were found missing. These test results do not reflect the motor manufacturer's observation that switching from magnetic to nonmagnetic wedges could result in estimated 10 °C−20 °C increase in operating winding temperature. The absence of 50% of magnetic wedges effectively resembles a motor having nonmagnetic wedges.

The current profile for a reciprocating-compressor application is cyclic and the pattern repeats itself every one motor revolution. The microprocessor motor protection relay should be compatible for use with reciprocating compressor to avoid nuisance thermal overload tripping caused by pulsating current.

## ACKNOWLEDGMENT

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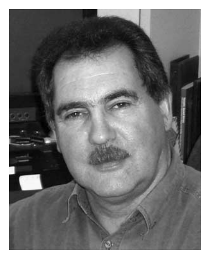

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