FAILURE ANALYSIS OF THREE SLOW SPEED INDUCTION MOTORS FOR RECIPROCATING LOAD APPLICATION

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Abstract - This refinery has three 5400 HP slow speed induction motors driving reciprocating compressors for a Hydrogen plant. All motors were rewound on site over a period 1998-2002 using magnetic wedges as per the original design and the motor protection was upgraded to microprocessor type relays. In summer 2003 it was noted that the motors suffered substantial loss of slot magnetic wedges and had to be scheduled for re-wedging over 2004-2005. The paper presents failure analysis, field measurements covering heat run test results, motor performance and vibration analysis before and after motor re-wedging work. The paper reviews the key factors for using magnetic versus non-magnetic wedges in these applications and techniques available to predict loss of wedges. The use of a microprocessor relay for slow speed induction motors protection is discussed particularly the thermal protection feature to address the cyclic load pattern caused by the reciprocating compressor.

Index Terms — Motor failure analysis, magnetic wedges, vibration, microprocessor protection relay, slow speed induction motor.

I. INTRODUCTION

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 rpm, 22 poles, 740 A, 4160 V, 0.78 pf, WP II enclosure, class F insulation with 80° C temperature rise. Following plant restructuring these motors were effectively placed in full service in 1988 and has been running 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 re-wound followed by C1906 in 2000 and C1904 in 2002. All rewind work was done on site to reduce plant downtime and avoid involved 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.

For this application, two out of three motors are required to be 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 non-magnetic material as well as a review of motor relay protection 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 non-magnetic wedges offer the following benefits:

- Reduce core losses and hence motor temperature rise
- Effectively reduces air gap length resulting in lower magnetizing current and hence improved power factor
- Reduce inrush current
- More efficient motor.

However, magnetic wedges are more brittle than non-magnetic 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. 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 loss of wedges without physically dismantling the motor. These motors are located in class I, division II, 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 been occurred due to the missing wedges particularly during motor starting. Also, the refinery was made aware by the motor manufacturer that magnetic wedges should always be installed using “wet” and not “dry” process. It appears that during the rewinds that were carried out in 1998-2002 dry process was used thus potentially compromising the reliability of magnetic wedges. Wet process, as strongly recommended by the manufacturer, involves applying a coating of epoxy resin in the slot before fitting the wedges and then reapplying the resin on the wedges after it they have been fitted to fill any voids and to prevent any movement of the wedges. The refinery decided to first re-wedge C1905 motor followed by C1906 and C1904 following the same sequence as they were originally rewound. A review was carried out to determine if there was any known field measuring techniques available to positively establish number of missing wedges while the motor is in operation. The results revealed that such measurements were not available. It appears that the most effective way is to conduct a regular visual inspection of the motor and look for any sign of debris particularly during starting.

Fig. 1. 5400 HP Motor overview.

Prior to taking C1905 motor out of service for detailed inspection and re-wedging, the option of using non-magnetic 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 advised that using non-magnetic wedges could result in higher stator temperature rise by about 10° C to 20° C, increased inrush current and higher losses. These motors typically run at or slightly above rated load to meet process requirements and it was feared that using non-magnetic material could impose operational limitation. It should be noted that in the last 15 years magnetic wedges are seldom used for new motors unless called for in the technical specification.

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 seconds). If there is any freedom to move, fretting will occur and the movement will slowly increase resulting in wedge failure. The problem in this case was compounded due to the following reasons:

- During motor rewinding in 1998-2002, magnetic wedges were not epoxyed, the dry and not the recommended wet process was used.
- Vacuum Pressure Impregnation (VPI) process was never used because re-winding was done on site. Also, due to the large diameter of the stator core there were no local repair facilities that can provide this service.
- Motors are typically running slightly above rated load to meet process demand.
- Motors are frequently started and this is hard on the motor in terms of thermal cycling on the stator and rotor core as well as the transient vibration seen on stator core during startup.

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

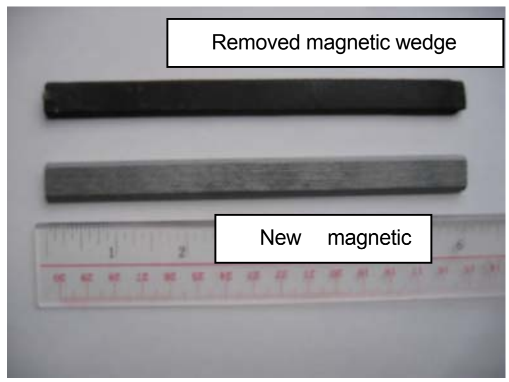

Fig. 2. Samples of new and removed magnetic wedges. Each wedge is 6” long by 9/16” wide by 0.15” deep.

III. MOTOR RE-WEDGING

Several tests [2] were conducted for C1905 prior to motor re-wedging to examine 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 10 days were needed to cover testing, dismantling the motor on site, re-wedging work, assembling the motor, core loss test, testing after re-wedging and allowances for unforeseen condition such as the weather as this work was done in January 2004.

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 rpm. 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 minimum was 782 A. It is recommended [3] that current pulsation should not exceed 66% of full load current. In this case, current pulsation is = (1259 – 782) x 100 / 740 x 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 re-wedging the motor was started three times to record inrush current and vibration. Fig. 4A and 4B show the starting current and voltage profile. Acceleration time was measured at 5 seconds. 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:

Starting current at V rated = Measured Starting current / $(\text{reduced voltage})^{1.1} = 3219 / (0.825)^{1.1} = 3977$ A

Rated current = 740 A.

Starting current 3977 / 740 = 5.37 PU.

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 removing the rotor. Fig. 5 shows an enlarged view of the stator winding as found. Careful examination of stator winding revealed the following:

a) Almost over 50% of the magnetic wedges and packing were missing. The stator has 198 slots and each slot length requires 6 wedges. Total number of wedges is 6 x 198 = 1188.
b) Loss of wedges was sporadic but more wedges were missing in centre part of the core.
c) Air ducts were reasonably clean and no visible blockage.
d) Signs of corrosion at scattered areas in the core.
e) There was no visible sign of any coil or end winding movement in the slot in spite of many missing wedges. The end winding were secured using blocking.
f) There was no sign of any coil insulation wrapping discoloration.
g) Some sign of rotor rubbing against the stator, which probably happened when pulling the rotor out.
h) Some stator laminations were damaged.
i) There was some sign of salt particularly closer to end winding. The source of salt is probably due to the refinery proximity to sea.

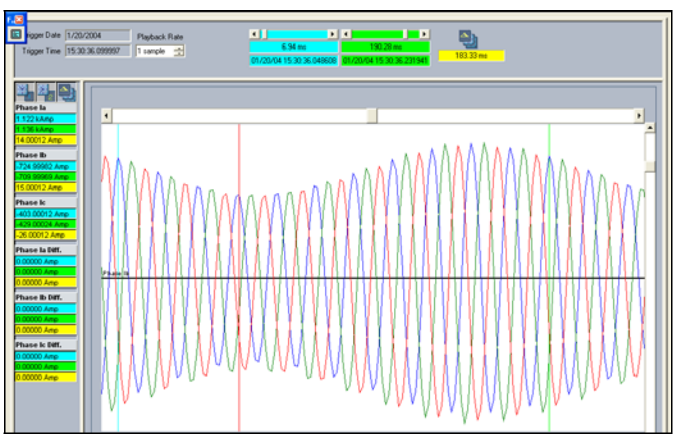

Fig. 3. Three phase motor current profile for reciprocating compressor at 100% load. Profile is cyclic and repeats itself every 11.07 cycles. Maximum amplitude is 1259 A and minimum is 782 A.

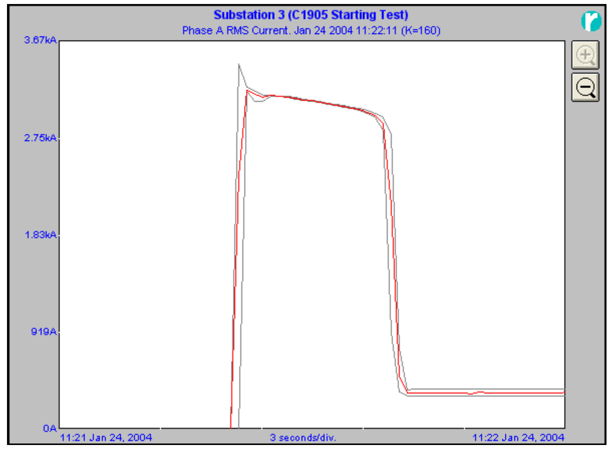

Fig. 4A. Starting current profile for 5400 HP motor prior to re-wedging and measured at 3129A and 5 seconds acceleration time.

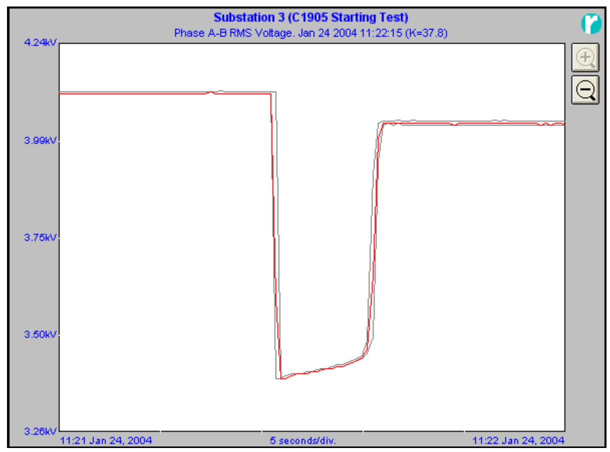

Fig. 4B. Motor terminal voltage profile during starting and it dropped from 4118 V to 3390 V or by 17.5%.

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

The C1905 motor was cleaned and all magnetic wedges removed. A core loss test was conducted using 3-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 by one, 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 hours 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 re-wedging. Prior to re-wedging the inrush current was measured at 5.37 PU and after re-wedging it was 5.22 PU, or about 4% drop.

Similar repair process and testing was followed for C1906 motor that was re-wedged in August 2004. C1904 motor is scheduled for re-wedging in August 2005.

IV. HEAT RUN TEST

Heat run test were conducted for C1906 to compare motor temperature rise before and after re-wedging and measure any improvement in motor performance. The motor underwent heat run test in August 2004 proir to re-wedging and in November 2004 after re-wedging. The motor has six stator RTDs that are wired to a microproccessor relay. The motor was started from ambient temperature and RTD temperature was recorded about every 15 minutes with the motor running steady at rated load. Table 1 shows the RTD measurements proir to rewdging. It took about 4.5 hours for stator winding temperature to stablize with average motor current at 740 A. The measured ambient temperature was 19° C. The measured temperature rise was 95 -19 = 76° C proir to re-wedging.

Heat run test was repeated for C1906 following the re-wedging. Motor temperature rise was only marginally improved and measured at 74° C. These test results do not reflect the motor manufacturer observation that substantial loss of magnetic wedges could cause 10° C to 20° C increase in operating winding temerature. Based on these test results, serious consideration should be given to using non-magnetic wedges since fitting the motor with new magnetic wedges did not result in siginificant improvement in temperaure rise.

Heat run test for C1905 proir to re-wedging was not conducted due to schedulling constrains. However, this test was conducted for C1905 after re-weding in August 2004 and temperature rise was recorded at 82° C. C1904 motor is shedulled to undergo heat run test in August 2005 following re-wedging.

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.

TABLE 1
HEAT RUN TEST MEASUREMENTS PRIOR TO MOTOR RE-WEDGING WITH MOTOR RUNNING AT RATED CURRENT

RTD Measurements (° C) for C1906 prior to re-wedging (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

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 when the thermal overload was set at 115% of rated current and the motor ran at rated value the relay tripped after about 20 minutes 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 later 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 waveform that repeats itself every compressor stroke or every one revolution. In this application, this pattern repeated itself every 183 milliseconds 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 temerature is reduced to ambient and the thermal capacity used will be zero. If the motor is running in an overload mode above the pickup value, the thermal capacity is gradually exhausted and when it reaches 100%, the relay intiates a trip. In this case, when the relay overload pickup was set at 1.15 FLA or 1.15x740= 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 reciprocating compressor. It is interesting to note during every 11 cycles, some cycles have an 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 minutes, 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" paramenter was adjusted from the factory default setting of 0 cycles 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 (Ia + Ib + Ic)/3. If this average current exceeds the over load 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 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.

Fig. 6 and 7 show vibration of the motor with approximately 50% of the magnetic wedges missing. Fig. 8 shows vibration spectrum on stator core with motor unloaded, after rewedging. The vibration spectrums are the same before and after re-wedging. It can be seen 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.

Fig. 9 and 10 show vibration of the motor after rewedging, loaded. As the motor went from no-load to full load, the severity of the high frequency vibration increased by 4 to 5 times. This high frequency vibration is not uncommon, but on a well-designed motor, the amplitude of the high frequency is very low or non-existent.

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 will eventually break down and wedges will come loose. Due to this fact, the use of magnetic wedges has seen limited applications.

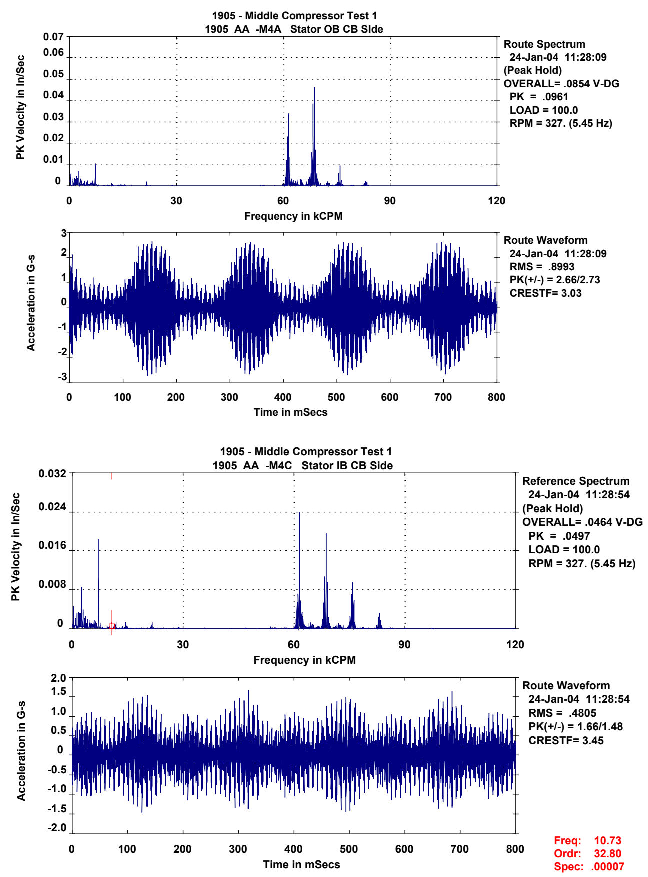

Fig. 6. Vibration spectrum of the stator core taken at 9 and 12 O'clock positions, before rewedging with about 50% of the magnetic wedges missing. The reciprocating load is reflected in the time waveform signature.

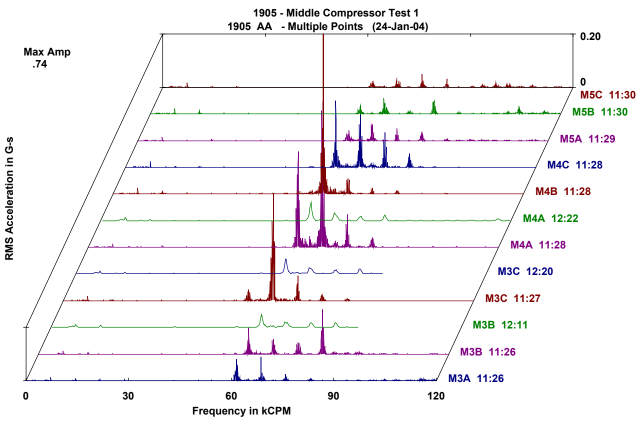

Fig. 7. Cascade plot of the vibration spectrum prior to rewedging. The cycling nature of the compressor is directly reflected in the vibration spectrums over time.

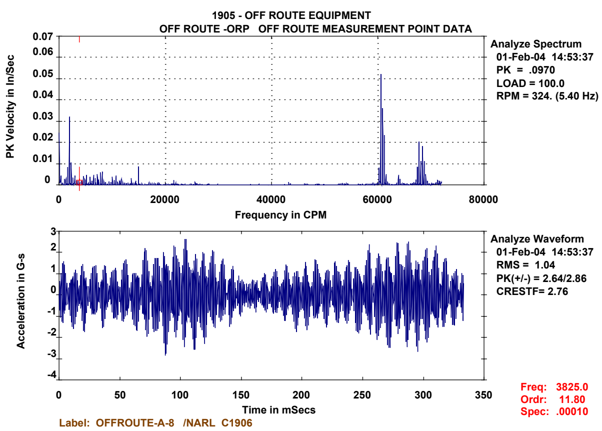

Fig. 8. Vibration spectrum on stator core, unloaded, after rewedging.

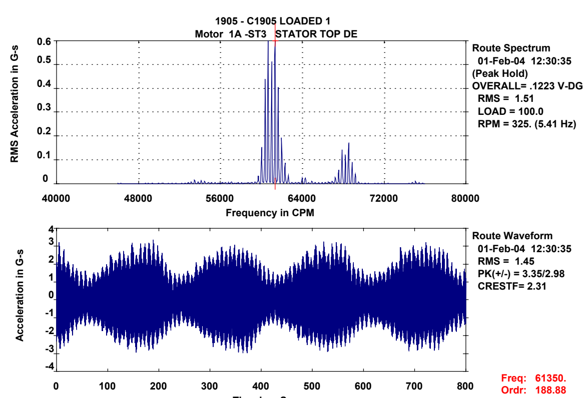

Fig. 9. Vibration spectrum on stator core, loaded, after rewedging. Vibration cycling is still very predominating.

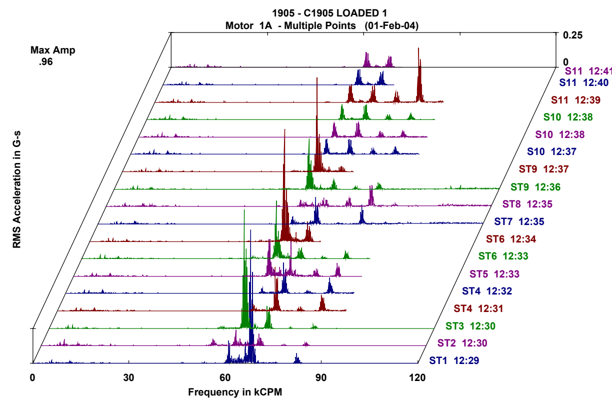

Fig. 10. Cascade of vibration spectrum on the stator core, when the motor is loaded. No change in vibration exhibited on the stator core even after re-wedge.

VII. CONCLUSIONS

Magnetic wedges are more susceptible to failure when compared to non-magnetic wedges. At present, magnetic wedges 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 re-wedging to secure the magnetic wedges in the stator slot. For this application, wet process was implemented in 2004 and it is too early to establish the impact on the performance of magentic wedges.

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

- Number of motor starts should be kept to minimum as this subjects the magnetic wedges to excessive magnetic and thermal stress.
- 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.
- The reciprocating compressor load profile exerts greater electro magnetic 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 re-wedging, although 50% of wedges were found missing. These test results do not reflect the motor manufacturer observation that switching from magnetic to non-magnetic 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 non-magnetic 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.

VIII. ACKNOWLEDGEMENTS

Special thanks to the refinery staff for all their help in facilitating conducting field measurements.

IX. REFERENCES

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[2] IEEE Recommended Practice for the Repair and Rewinding of Motors for the Petroleum and Chemical Industry. IEEE Std 1068-1996.

[3] ANSI/NEMA MG 1-2003 "Motors and Generators", part 20.30, page 419.

X. VITA

Robert A. Hanna received the B. Shc. degree from the University of Basra, Iraq in 1971, M. Sc. Degree (with Distinction) from Queen Mary College, University of London, England in 1973 and Ph. D. degree from Imperial College of Science and Technology, University of London, England in 1977, all in electrical engineering. Following a short teaching career, in 1981 he joined Petro Canada (formerly Gulf Canada) as a central engineering specialist providing technical support to the refineries in implementing capital projects and equipment selection. In 1995, he founded RPM Engineering Ltd., a certified consulting company in Ontario, Canada specializing in Adjustable Speed Drive applications, power quality studies, emergency shutdown equipment and equipment failure investigations.

Dr. Hanna is registered professional engineer in the provinces of Ontario, Alberta, British Columbia, Fellow of the Institute of Electrical and Electronics Engineers (FIEEE) and Fellow member of the Institution of Electrical Engineers (FIEE), England. He is Director-Elect of IEEE Region 7 and President-Elect of IEEE Canada.

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Peter Klinowski is a Senoir Engineer with Shur West Engineering Inc., specializing in rotating electrical equipment. Registered as a professional engineer in the province of Ontario and a graduate of McMaster University and Niagara College in mechanical engineering, along with a degree in econmics. After graduation he began his career with Westinghouse Canada Motor Diision, designing AC induction motors. Eventually moving to Westinghouse Service Division, central engineering department, providing technical support on AC, DC and synchronous motor and generators across Canada and globally.