

SIGNATURE ANALYSIS FOR ON-LINE MOTOR DIAGNOSTICS

Ian Culbert

Senior Member, IEEE
Qualitrol-Iris Power
3110 American Drive
Mississauga, ON
Canada

John Letal

Qualitrol-Iris Power
3110 American Drive
Mississauga, ON
Canada

Abstract - Stator current signature analysis on induction motors is a proven method for diagnosing rotor squirrel cage winding defects and air gap eccentricity problems. With this technology, specific frequency current components can be identified as an indication of cage winding defects as well as a non-uniform gap between the stator and rotor. Because this data is generally collected periodically, it is important to identify these components as early as possible. These trendable parameters can then be monitored more often to avoid in-service failure. With the application of new processing technologies, the ability to identify these critical current signature frequency components and trend the deterioration they indicate has improved. This allows for maintenance activities to be scheduled earlier and performed prior to failure avoiding costly motor component damage and unplanned downtime.

Index Terms - stator current signature analysis, rotor squirrel cage winding, broken rotor bars, air gap eccentricity, induction motor, condition based maintenance.

I. INTRODUCTION

Condition based maintenance is a strategy to detect and identify rotating machine problems prior to failure. By collecting various data from a machine, operators or maintenance personnel can determine if a machine is exhibiting certain patterns that may be an indication of degradation of certain motor components. With this knowledge, repairs can be scheduled in a manner that will maximize plant process and still avoid costly unplanned downtime for unscheduled outages and repair. Generally, if an in-service failure does occur, the repair costs will be greater due to the possibility of collateral damage than if the maintenance is scheduled appropriately [1-2].

For induction motors there are a variety of tests that can be used to assess the condition and drive maintenance efforts. One such online test, meaning data is collected during normal operation, which has been used for more than a decade is stator current signature analysis. It is a proven method for diagnosing rotor cage winding and air gap eccentricity problems by analyzing the frequency spectrum of the stator current signature. Cage winding faults including broken rotor bars (Fig. 1) are not necessarily cause for immediate concern, but there can be serious secondary effects on the machine operation. With these types of rotor problems the motor can continue to operate, but with reduced torque. The rotor slip and line currents will increase for the same load. Any sparking that results is a safety hazard in explosive environments. Long

term operation with broken rotor bars can also cause heat damage (Fig. 2) to the rotor core because the current normally carried by broken bars or shorting rings is routed through adjacent bars and the core. Large air pockets (Fig. 3) in die cast rotors and broken bars cause non-uniform bar expansion which will result in rotor unbalance and high vibration. These high vibration levels at rotational speed can cause premature bearing wear. If the broken bars lift out of the slot or with unbalanced magnetic pull, the air gap eccentricity will be affected and may cause the rotor to rub with the stator (Fig. 4) causing catastrophic winding failure. Air gap eccentricity can produce high twice line frequency vibration at destructive forces. To avoid such problems the frequencies of interest must be identified as early as possible and trended so that corrective action can be taken prior to failure.



Fig. 1 Failed brazed connection [3]



Fig. 2 Rotor core burning from broken bars



Fig. 3 Die cast rotor with air voids (courtesy of EASA)

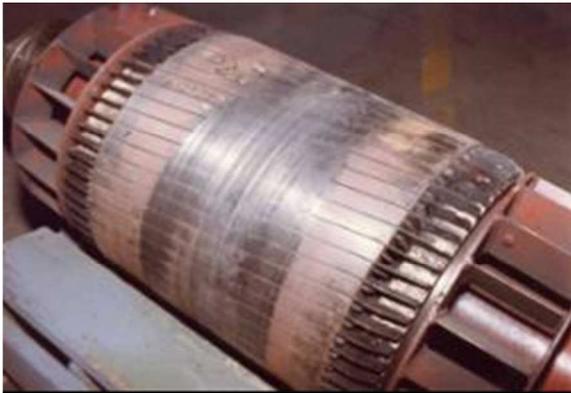


Fig. 4 (a) Rotor surface damage due to rotor rubbing stator



Fig. 4 (b) Stator core damage due to rotor rubbing stator

With the advancement of signal processing capabilities, frequencies related to these fault conditions can be identified earlier than even 5 years ago. The speed of analog to digital converters available today has vastly improved. This allows for a much higher sampling rate so that an appropriate frequency range can be used to identify the cage winding and air gap eccentricity problems described above. Higher dynamic range is available so that these frequencies can be identified and trended at the onset of a problem. By gaining insight to this condition-based knowledge even earlier than before, maintenance planners now have the ability to assess cage winding and air gap eccentricity problems earlier and schedule repair work accordingly prior to failure.

II. FAILURE MECHANISMS IDENTIFIED WITH SIGNATURE ANALYSIS

Frequency components of motor stator current can be collected by sampling the load current on one phase. If a cage winding or air gap eccentricity problem is present, this load current will have a certain pattern. Specific fault frequency components can be identified and trended as long as there is an accurate calculation of the rotor slip frequency. Slip speed (in rpm), calculated with (1), is dependent on machine design and operational load. Per unit rotor slip “s” can be calculated by measuring rotational speed with a stroboscope or with a laser tachometer. Some instruments that collect current signature data have advanced algorithms which calculate operating slip based on load current. More load results in higher slip, and therefore, lower rotor turning speed [3].

$$s = \frac{\text{syncronous speed} - \text{turning speed}}{\text{syncronous speed}} \quad (1)$$

Where;

s per unit rotor slip

A. Cage Winding Failures

With an accurate detection or calculation of rotor slip, fault frequencies can be determined to assess the condition of induction motor rotor related conditions. Broken or cracked rotor bars, shorting rings and the connections between them in fabricated rotor windings as well as air pockets in die cast rotor windings can be identified with one such fault frequency.

A 3-phase magnetic field with the same number of poles as the stator field at the rotor slip frequencies is produced by the rotor currents. If rotor asymmetry occurs due to cage winding cracks or breaks, there will also be a resultant backward rotating field at slip frequency with respect to the forward rotating rotor. This produces a stator current with a frequency $(1-2s)f_1$ about the fundamental supply frequency. Because the rotor is constantly catching up to the stator magnetic field, the result on the rotor is an oscillation that generates a current component with a frequency of $(1+2s)f_1$ (2) about the fundamental supply frequency.

$$f_{sb} = (1 \pm 2s)f_1 \quad (2)$$

where

f_{sb} twice slip sidebands
 f_1 supply frequency

The magnitude of the currents generated at the frequencies of these sidebands increases due to [1, 3]:

- broken rotor bars
- higher motor loads
- developing additional cage winding defects.

The difference in amplitude between the fundamental supply frequency and the twice slip sideband currents gives rise to the need to identify small currents that are sometimes 200 times less than the fundamental, i.e. if the motor is drawing 100A the oscillating current at the twice slip sideband may only be 0.5A. This is the reason that a log scale (dB) is generally used for current signature analysis and also drives the requirement for a high dynamic range in signal

processing, especially since early identification of these frequencies can help schedule maintenance activities.

Broken rotor bars and other cage winding faults can be identified in a stator current signature with these classical twice slip sidebands if they are 45dB (or less) below the fundamental supply frequency [3]. The smaller this difference is, the greater the cage winding damage and in fact, if the number of rotor bars are known, it is possible to calculate how many are broken, as in Fig. 5 where 3 or 4 broken bars are identified.

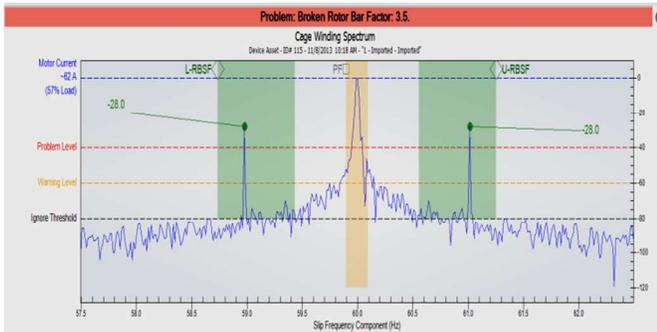


Fig. 5 Current signature cage winding spectrum

B. Air Gap Eccentricity

The air gap is the separation between the rotor and stator in a motor which conducts the magnetic flux from the stator and links it to the rotor inducing a radial force, or torque, on the rotor causing it to turn. If this gap is uniform there will be no change with rotor rotation. If the center of the rotor is displaced from the center of the stator bore, the minimum air gap will stay in the same position and the result will be static air gap eccentricity. Over time static air gap eccentricity will cause the rotor shaft to bend resulting in dynamic air gap eccentricity. When the rotor shaft is bent, the position of the minimum air gap will change. It is important to note that if a motor has air gap issues there is usually a combination of static and dynamic eccentricities. Not only does the rotor have to be machined straight to remove the dynamic eccentricity, but the bearing positions need to be adjusted to remove the static eccentricity.

The fault frequencies of interest when analyzing motor air gap are calculated with (3) which is a combination of static and dynamic forces. In particular, the stator rotor slot passing components are spaced at twice the fundamental supply frequency and the peak with the highest magnitude should be trended. Dynamic eccentricity can be identified with rotational speed sidebands around the highest magnitude rotor slot passing component [4].

$$f_{ec} = f_1 \left((R \pm n_d) \left(\frac{1-s}{p} \right) \pm n_{ws} \right) \quad (3)$$

where

- f_{ec} air gap eccentricity current frequencies
- R number of rotor bars
- n_d dynamic eccentricity index (0 or ± 1)
- p number of pole pairs
- n_{ws} odd integers (1, 3, 5 . . .)

Rotor slot passing components indicate static eccentricity when the dynamic eccentricity index is 0. If there is dynamic eccentricity as well, the dynamic eccentricity index will be ± 1 generating sidebands around each air gap eccentricity frequency and the rotation speed frequency (4). The spectrum when the dynamic eccentricity index is 0 will show the rotor slot passing components spaced at twice fundamental supply frequency, first part of (4). If dynamic eccentricity exists, which is nearly always the case, the slot passing frequencies will have sidebands at rotational speed frequency, second part of (4). Some monitors can even determine the rotor slip from motor nameplate information and measured load current. The static and dynamic air gap eccentricity components can also be determined and identified with pattern recognition algorithms for analysis eliminating the need for experts who have a firm grasp of the mathematics introduced above.

$$f_{ec} = f_1 \left[R \left(\frac{1-s}{p} \right) \pm n_{ws} \right] \pm f_1 \left[\frac{1-s}{p} \right] \quad (4)$$

The criterion for air gap eccentricity severity is based on the average difference between the highest magnitude rotor slot passing frequency component and the rotational speed frequency components. In general if this average difference is 15 to 25 dB then a problem related to air gap eccentricity exists and must be investigated. This is illustrated by the following example of an air gap eccentricity analysis performed on a 2700 hp (2014 kW), 4.0 kV, 60 Hz, 6-pole Flue Gas Compressor Motor in a combined cycle power plant. The air gap eccentricity current versus frequency spectrum around the highest rotor slot passing frequency from this motor is shown in Fig. 6. From this, it can be seen that the highest magnitude rotor slot passing frequency is -69 dB and the average rotational speed sidebands is -83.25 dB (average of -79 and -87.5). The resulting difference is 14.25 dB which is unacceptable.

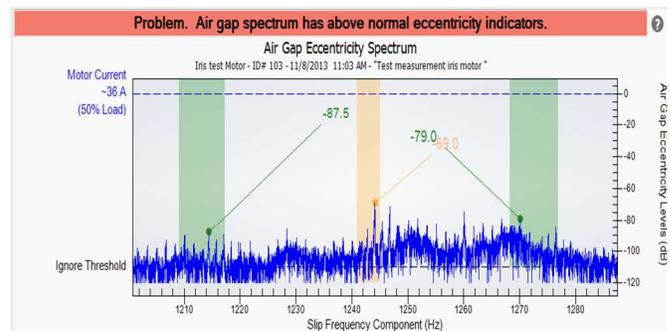


Fig. 6 Current signature air gap eccentricity spectrum

Since such excessive air gap eccentricity will produce much higher than normal 2 x power supply frequency (120 Hz) bearing housing radial vibration levels the most recent motor vibration levels were analyzed. As can be seen from Fig. 7 this analysis did in fact show a 120 Hz vibration magnitude of 4.537 mm/s rms which was assessed to confirm the current signature analysis indicating poor air gap eccentricity.

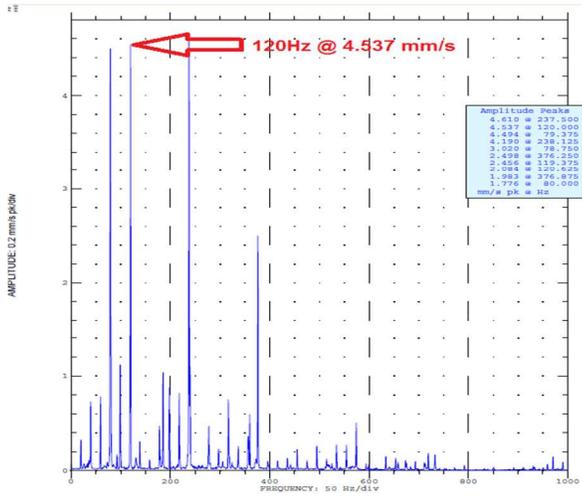


Fig. 7 Motor Bearing Radial Vibration Spectrum

C. Trending

Once cage winding and air gap eccentricity fault frequencies have been identified, they should be trended at approximately the same load so that an increase can correctly be attributed to degradation in the condition of the motor. In the case of cage winding faults, a broken bar factor is a good indicator to assess the machine and schedule an outage appropriately. If the number of bars is not known, which is often the case, a severity indicator should be based on the dB difference between the fault frequencies and fundamental supply frequency. Similarly, the average difference between the highest magnitude rotor slot passing frequency component and the rotational speed frequency components should be trended for air gap eccentricity issues. Generally measurements should be taken at least once every six months based on the criticality of the motor to the process. If these trendable parameters start to show warning or problem levels, then the frequency of measurements should be increased to even at least once a month until repair work can be carried out, as is shown in Fig. 8.

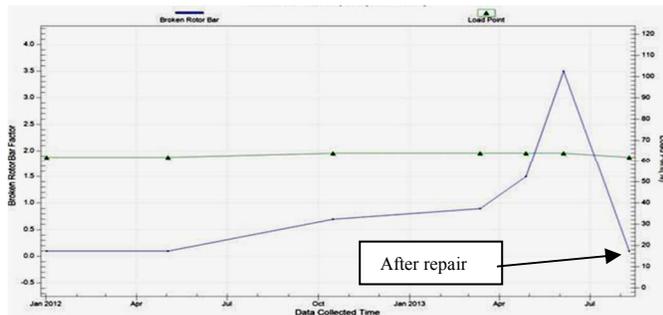


Fig. 8 Broken rotor bar factor trend

III. TECHNOLOGY ADVANCEMENTS FOR EARLY DETECTION

In general, analog to digital converters (ADCs) are selected based on application requirements. For industrial measurement, sigma-delta ADCs satisfy the requirements of high resolution with a reasonable sampling rate to effectively collect stator current signature data. As well, small output

voltages can be digitized directly [4]. With suitable sampling rates and digital filter bandwidths, sigma-delta ADCs allow for supply frequency rejection, meaning no additional signal is introduced due to processing. This is necessary for assessing cage winding faults as severity is based on the difference between a relatively large supply frequency and small twice slip sidebands.

In the 1950s the basic concepts of sigma-delta ADCs were developed and by the end of the 1960s they were well understood [4]. Unfortunately, the digital filters required to effectively use these converters were not available until the late 1980s limiting the practicality. Currently, high dynamic range (up to 24-bit) and high sampling rate (up to 144 kHz bandwidth) sigma-delta ADCs are available on the market exceeding the requirements and providing much more effective current signature analysis.

High dynamic range allows for the detection of current signature fault frequencies riding on a relatively high amplitude supply frequency. Typically a greater than 80 dB dynamic range is required to process air gap eccentricity. Currently, sigma-delta ADCs with 24-bit resolution allows greater than 110 dB signal to noise ratio resulting in earlier detection of these low amplitude frequencies so that preparation can be made well ahead of machine failure. On a logarithmic scale, this 30 dB difference is quite substantial and is especially important for early detection of problems.

In order to capture both cage winding and air gap eccentricity fault frequencies with a single recording, a high sampling rate is required. A reasonable full scale range of 7 kHz will provide a usable range of 3 kHz when considering Nyquist sampling theorem so that the frequencies of interest are recorded. Obviously, one recording during data collection intervals is preferred from a time-management point of view. When considering cage winding faults, this high resolution is also an important characteristic for collecting data on motors with low slip or on low speed motors in order to separate the supply frequency from the fault frequencies.

IV. CONCLUSION

Stator current signature analysis is a proven method to detect cage winding faults and air gap eccentricity issues on induction motors. It is a test that can be performed while the machine is in operation and can be used to confirm the cause of high vibration that may be related to rotor problems or the interaction between the rotor and stator. The fault frequencies that are identified with current signature analysis are trendable and an increasing trend is an indication of a degrading condition.

Cage winding failures are prominent in motors that directly drive high inertia loads such as induced draft and forced draft fans, motors that have frequent starts and stops, and motors with poorly manufactured cage windings. For these machines it is critical that cage winding fault frequencies, i.e. the twice slip sidebands are identified with current signature analysis so that they can be identified prior to failure.

Air gap eccentricity results from poor assembly such that the rotor is not concentric with stator core bore, the rotor shaft is bent, and/or the sleeve bearings are worn. The potential for these issues necessitates a system that can accurately calculate complicated fault frequencies and identify them early

enough to schedule an outage to avoid costly collateral damage related to air gap eccentricity.

Recent technological advancements in analog to digital converters has allowed for the detection of fault frequencies that can identify cage winding faults and air gap eccentricity issues earlier. With early detection of these faults, plant personnel have more time to schedule and plan outages to optimize their process.

V. REFERENCES

- [1] P. Tavner, L. Ran, J. Penman and H. Sedding, "Condition Monitoring of Rotating Electrical Machines," London UK: The Institution of Engineering and Technology, 2008.
- [2] G.C. Stone, I.A. Culbert, E.A. Boulter, and H. Dhirani, *Electrical Insulation for Rotating Machines - Design, Evaluation, Aging, Testing and Repair – Second Edition*, Hoboken NJ: John Wiley and Sons Inc., 2014.
- [3] I. Culbert and W. Rhodes, "Using Current Signature Technology to Reliably Detect Cage Winding Defects in Squirrel Cage Induction Motors," *IEEE PCIC Paper No PCIC-2005-11*.
- [4] W T Thomson, D Rankin and D G Dorrell: "On-line Current Monitoring to Diagnose Air gap Eccentricity – An Industrial Case History of Large HV, 3-Phase Induction Motors", *IEEE Transactions on Energy Conversion*, Dec. 1999.
- [5] W. Kester, "Which ADC Architecture Is Right for Your Application?," *Analog Dialogue* 39-06, June 2005.

VI. AUTHORS' INFORMATION

Ian Culbert has been a Rotating Machines Specialist at Qualitrol-Iris Power since April 2002. Before joining Iris Power he was a motor and small generator specialist with Ontario Hydro/Ontario Power Generation from 1977 to 2002 and prior to then a motor designer with Parsons Peebles, Scotland and Reliance Electric, Canada. Ian is a Registered Professional Engineer in the Province of Ontario, Canada and a Senior Member of IEEE. He has co-authored two books on electrical machine insulation design, evaluation, aging, testing and repair and been principal author of a number of Electric Power Research Institute reports on motor repair. Ian has also co-authored a number of papers on motor electrical component on-line and off-line motor diagnostics testing.

John Letal is a Rotating Machines Engineer at Qualitrol-Iris Power responsible for supporting rotating machine mechanical monitoring. Prior to Iris, he spent most of his career as a Field Service Engineer troubleshooting large rotating equipment using such tools as current signature and vibration analysis. He was also involved in the implementation and execution of vibration analysis programs. John holds a Bachelor of Science degree in Manufacturing Engineering from the University of Calgary and is registered as a Professional Engineer.



Fig. 1 Failed brazed connection [3]



Fig. 2 Rotor core burning from broken bars



Fig. 3 Die cast rotor with air voids (courtesy of EASA)

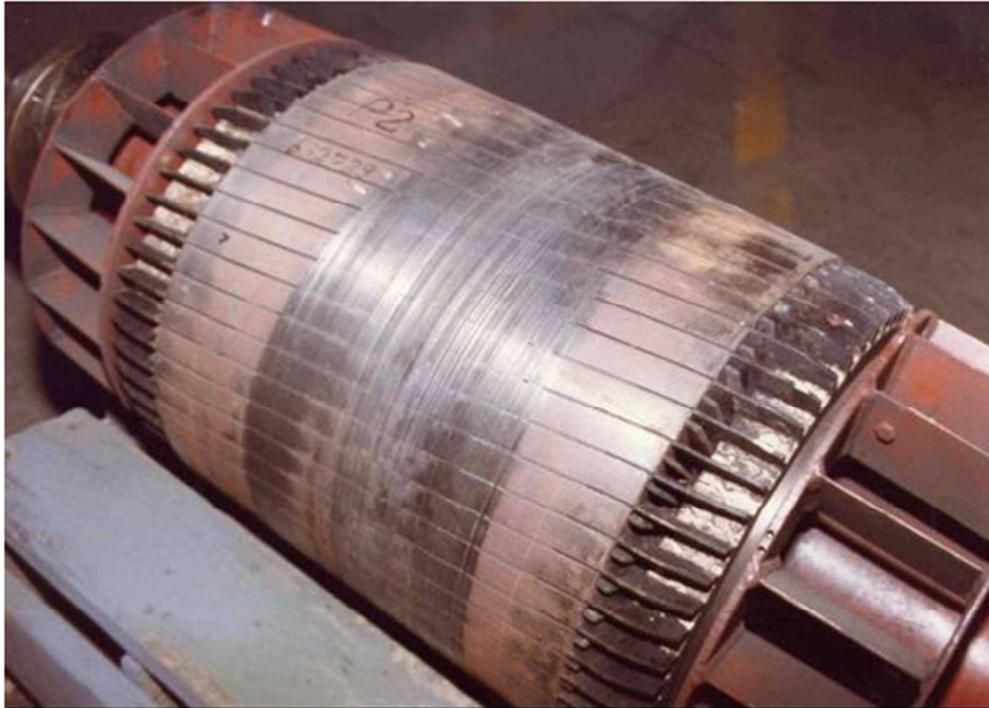


Fig. 4 (a) Rotor surface damage due to rotor rubbing stator

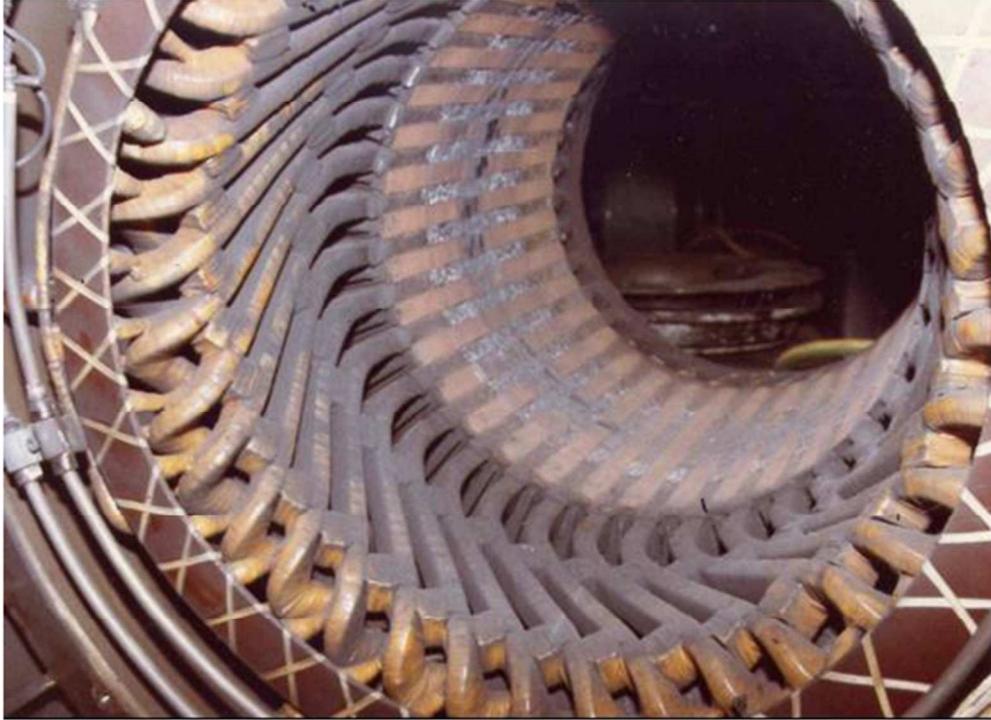


Fig. 4 (b) Stator core damage due to rotor rubbing stator