Written by Hasnain Jivajee and Ian Culbert, Iris Power Engineering Inc.
Monday, 01 November 2004 14:58

With advancements in digital electronics and reduced component costs in recent years, monitoring instruments for use in condition-based maintenance programs have become more cost-effective and dependable. Machinery does not need to be taken out of service as many tests are done online, and in many cases very little expertise is required for testing and data interpretation. This enables the user to make well-informed decisions for planning maintenance and repairs, which ultimately leads to increased productivity.

This article concentrates on one technology that has been developed to reliably detect broken rotor bars, abnormal levels of air gap eccentricity, and other problems in squirrel cage induction motors and driven components using motor current signature analysis (MCSA).

Consequences of broken rotor bars

Rotor windings in squirrel cage induction motors are manufactured from aluminum alloy, copper, or copper alloy. Larger motors generally have rotors and end-rings fabricated out of these whereas motors with ratings less than a few hundred horsepower generally have die-cast aluminum alloy rotor cages.
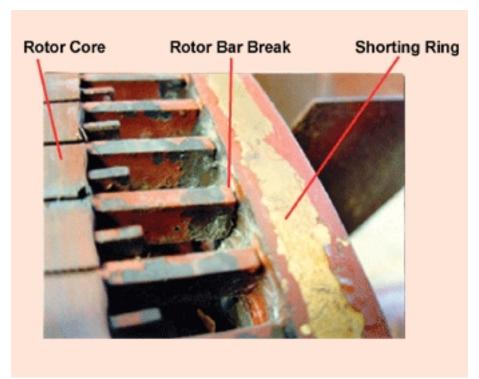

Fig. 1. A 1700 hp motor with broken rotor bar Broken rotor bars (Fig. 1) rarely cause immediate failures, especially in large multi-pole (slow-speed) motors. However, if there are enough broken rotor bars, the motor may not start as it may not be able to develop sufficient accelerating torque. Regardless, the presence of broken rotor bars precipitates deterioration

in other components that can result in time-consuming and expensive fixes.

Replacement of the rotor core in larger motors is costly; therefore, by detecting broken rotor bars early, such secondary deterioration can be avoided. The rotor can be repaired at a fraction of the cost of rotor replacement, not to mention averting production revenue losses due to unplanned downtime.

Some of the more common secondary effects of broken rotor bars are:

• Broken bars can cause sparking, a serious concern in hazardous areas.

• If one or more rotor bars are broken, the healthy bars are forced to carry additional current leading to rotor core damage from persistent elevated temperatures in the vicinity of the broken bars and current passing through the core from broken to healthy bars.

• Broken bars cause torque and speed oscillations in the rotor, provoking premature wear of bearings and other driven components.

• Large air pockets in die-cast aluminum alloy rotor windings can cause nonuniform bar expansion leading to rotor bending and imbalance that causes high vibration levels from premature bearing wear.

• As the rotor rotates at high radial speed, broken rotor bars can lift out of the slot due to centrifugal force and strike against the stator winding causing a catastrophic motor failure.

• Rotor asymmetry (the rotor rotating off-center), both static and dynamic, could cause the rotor to rub against the stator winding leading to rotor core damage and even a catastrophic fault.

MCSA technology
Motor current signature analysis technology has existed for many years to help diagnose

problems in induction motors related to broken rotor bars, air gap eccentricity, drive-train wear analysis, and shaft misalignment. The technology relies on the fact that each of these problems produces recognizable frequency patterns in the motor load current that can be predicted by using empirical formulae and measured. These problems give rise to magnetic asymmetry in the rotor air gap that produces current components at specific frequencies in the load current.

A trace of the motor supply current is obtained by using a clamp-on current probe either from one of the main phase leads to the motor or from the secondary side of a motor CT. A Fast Fourier Transform is performed on the time-domain data to obtain a frequency spectrum. Depending on the device used, this can be done either by the datalogger itself or by computer software.

Once the frequency spectrum is obtained and stored, empirical formulae are used to look for frequency signatures in the spectrum within various frequency ranges depending on the problem to be diagnosed. For example, broken rotor bar frequencies (also called sidebands or pole-passing frequencies) usually can be found within ±5 Hz of the motor supply frequency; for air gap eccentricity a wider range is required for the search, from a few hundred Hz up to a few kHz. If the predicted frequency patterns are present in the spectrum, a positive diagnosis is returned.

In all cases, accurate estimate of the operating slip of the motor is a prerequisite to reliable diagnosis as the predictor equations require operating slip as one of the input parameters. In an induction motor, slip is dependent on the load and increases with increased load. In most cases, the only knowledge a tester would have regarding slip is that at full load; the motor nameplate data contains the rated speed at rated horsepower and the slip can therefore be easily derived when the motor is running at full rated load. However, as motors rarely operate at exactly full load, determining the operating slip becomes a challenge.

There are several ways to determine operating slip—a stroboscope or axial flux measurement are two examples. However, between the time the speed is determined using these techniques and the current measurement taken the load can change, leading to an inaccurate slip estimate. Not to mention the fact that these methods are cumbersome and time consuming.

Much work has been done in recent years to make MCSA technology reliable and user-friendly by calculating the slip based on motor nameplate parameters and measured load current.

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Depending on the MCSA instrument vendor, several algorithms may be employed to calculate slip. Some algorithms rely on deriving slip from the torque and some from operating current. Such algorithms do not need an external speed input.

Advances in pattern-recognition technology have now made it possible that systems rely less on expert knowledge, thereby making these systems useable by nonexperts who may not have in-depth knowledge of current signature analysis.

Detection of broken rotor bars

The location of the frequency components of the current due to broken rotor bars in the frequency spectrum is given by the formula:

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

where:

f_{sb} = frequency components of the current due to broken rotor bars, also known as sidebands

f_1 = power supply frequency (Hz)

s = operating slip (per unit)

Figure 2 illustrates the current spectrum from a 13.8 kV primary air fan motor with broken rotor bars operating in a fossil power station. The motor supply frequency is 60 Hz. Frequencies due to broken rotor bars are clearly visible.

**Frequency spectrum from motor
with broken rotor bars**

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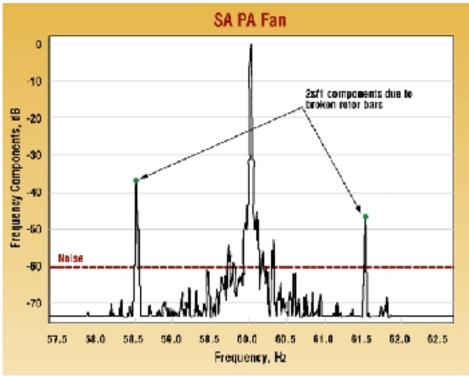Monday, 01 November 2004 14:58

Fig. 2. Frequencies due to broken rotor bars are clearly visible, as is the influence of load changes durin

The influence of load

Figure 2 also illustrates the influence of load changes during the data acquisition   process. Note the skirting effect at the base of the 60 Hz spike. Keeping in   mind that the slip is dependent on load one would, in fact, expect such a skirting   effect as the current components are recorded in multiple positions on the x-axis.

The influence of gearboxes

Speed-reducing gearboxes or belt drives connected to the motor also may induce   frequency components of the current in the spectrum and also have been a cause   of false alarms. The position of such components depends on the rotational frequency   of the individual gearbox shafts. Often the frequencies of these components   are very close to positions that are expected from broken rotor bars.

Take the case of a coal-mill motor for which the current spectrum is shown   in Fig. 3. This motor is rated at 300 hp, 575 V, 295 A, 885 rpm, and is connected   to a 3-stage gearbox for which the output shaft rotates at 19.39 rpm (0.32 Hz)   at full load (nameplate data). Speeds of

the individual shafts internal to the motor are 52.8 rpm (0.88 Hz) and 141.69 rpm (2.36 Hz), respectively. Table 1 depicts the location of the frequency components of the current due to each shaft rotational speed at full load.

In addition to fundamental speeds of shaft rotation, harmonics also can produce frequency components that occur at locations in the spectrum where broken rotor bars are expected (see Table 2). It can be seen from Table 2 that gearbox shaft rotation, especially the rotational harmonics from the 2nd and 3rd stages, induces frequency components of the current at locations very close to where components from broken rotor bars are expected to occur. Keep in mind that Table 2 depicts conditions at full load.

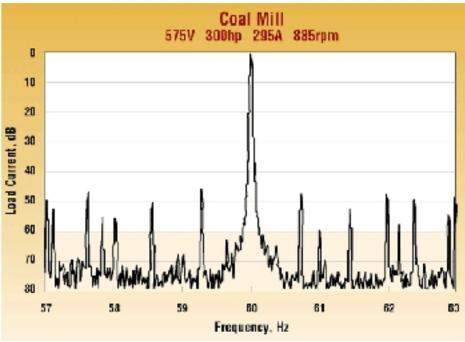**Spectrum from a motor connected to a gearbox**

Fig. 3. Several current components are present in the spectrum. The question is which ones are due to l

In this case study, the motor was operating at less than full load with a current of 250 A and therefore at lower slip (higher speed). Even at this load, the harmonics from shaft rotation may lead a user to raise a false alarm of broken rotor bars if not correctly identified as such. Whereas frequency components due to the gearbox are expected to remain at almost the same location for full load (295 A) as well as reduced load (250 A), components due to broken rotor bars move "inwards" at reduced load, i.e., toward the fundamental 60 Hz component. As a corollary, if it is possible to collect data at two different loads, chances of misdiagnosis

can almost be eliminated as this would help identify   twice-slip-frequency components from mechanical components. In fact, the motor   in this case study did not have broken rotor bars.

Problems due to gearbox interference are easily circumvented by embedding intelligence in the instrument that enables it to predict such interfering frequencies. This requires that the reduction stage ratios are known and fed in prior to processing the data for diagnosis.

The importance of high resolution
 This case also highlights the necessity of using high resolution in data acquisition   and spectrum analysis. A resolution of 10 MHz would generally be sufficient   to discriminate between distinct sidebands and therefore enable reliable diagnosis.   High resolution is particularly important when testing low-slip and/or low-speed   motors where the sidebands do not move as much as high-slip or high-speed applications   and therefore could make frequency discrimination difficult.

One of the problems encountered when acquiring high-resolution data is the acquisition and processing time. However, with modern processors and digital technology this problem has largely been overcome due to high-speed sampling and processing capabilities.

Motor current signature analysis technology can reliably be used to detect problems in induction motors. Advancements in technology have made devices intelligent enough to minimize false alarms while at the same time minimizing need for expert interpretation and reducing time for testing and diagnosis. **MT**

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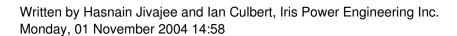[*Iris Power   Engineering Inc.*](#)
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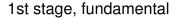
**Table 1. Expected Frequency Positions from
 Broken Rotor Bars and Gearbox at Full Load**

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Broken rotor bars at

58 and 62 Hz

1st stage

60 ± 2.36 Hz = 57.64 and 62.36 Hz

2nd stage

60 ± 0.88 Hz = 59.12 and 60.88 Hz

3rd stage

60 ± 0.32 Hz = 59.68 and 60.32 Hz

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**Table 2. Expected Frequency Positions of
Gearbox Harmonics at Full Load**

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1st stage, fundamental

60 ± 2.36 Hz = 57.64 and 62.36 Hz

2nd stage, 2nd harmonic

$60 \pm 2 \times 0.88$ Hz = 58.24 and 61.76 Hz

3rd stage, 6th harmonic

$60 \pm 6 \times 0.32$ Hz = 58.1 and 61.9 Hz

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