Motor Current Signature Analysis and its Applications in Induction Motor Fault Diagnosis

Neelam Mehala, Ratna Dahiya

Abstract---The Motor Current Signature Analysis (MCSA) is considered the most popular fault detection method now a day because it can easily detect the common machine fault such as turn to turn short ckt, cracked /broken rotor bars, bearing deterioration etc. The present paper discusses the fundamentals of Motor Current Signature Analysis (MCSA) plus condition monitoring of the induction motor using MCSA. In addition, this paper presents four case studies of induction motor fault diagnosis. The results show that Motor current signature analysis (MCSA) can effectively detect abnormal operating conditions in induction motor applications.

I. INTRODUCTION

Induction motors are a critical component of many industrial processes and are frequently integrated in commercially available equipment and industrial processes. Motor-driven equipment often provide core capabilities essential to business success and to safety of equipment and personnel. There are many published techniques and many commercially available tools to monitor induction motors to insure a high degree of reliability uptime. In spite of these tools, many companies are still faced with unexpected system failures and reduced motor lifetime. The studies of induction motor behavior during abnormal conditions and the possibility to diagnose these conditions have been a challenging topic for many electrical machine researchers. The major faults of electrical machines can broadly be classified as the following [1]:

Manuscript Received April 16, 2007; Revised Received August 14, 2007. The authors are with the National Institute of Technology, Kurukshetra, Haryana, India

- Stator faults resulting in the opening or shorting of one or more of a stator phase windings,
- Abnormal connection of the stator windings,
- Broken rotor bar or cracked rotor end-rings.
- Static and/or dynamic air-gap irregularities,
- Bent shaft (akin to dynamic eccentricity) which can result in a rub between the rotor and stator, causing serious damage to stator core and windings.

In recent years, intensive research [3-7] effort has been focused on the technique of monitoring and diagnosis of electrical machines and can be summarized as follows,

- Time and frequency domain analysis.
- Time domain analysis of the electromagnetic torque and flux phasor.
- Temperature measurement, infrared recognition, radio frequency (RF) emission monitoring,
- Motor current signature analysis (MCSA)
- Detection by space vector angular fluctuation (SVAF)
- Noise and vibration monitoring,
- Acoustic noise measurements,
- Harmonic analysis of motor torque and speed,
- Model, artificial intelligence and neural network based techniques.

Of all the above techniques, MCSA is the best possible option: it is non-intrusive and uses the stator winding as the search coil; It is not affected by the type of load and other asymmetries.

II. MOTOR CURRENT SIGNATURE ANALYSIS

Motor Current Signature Analysis (MCSA) is a system used for analyzing or trending dynamic, energized systems. Proper analysis of MCSA results assists the technician in identifying:
1. Incoming winding health
2. Stator winding health
3. Rotor Health
4. Air gap static and dynamic eccentricity
5. Coupling health, including direct, belted and geared systems
6. Load issues
7. System load and efficiency
8. Bearing health

III. BASIC STEPS FOR ANALYSIS

There are a number of simple steps that can be used for analysis using MCSA. The steps are as follow:
1. Map out an overview of the system being analyzed.
2. Determine the complaints related to the system in question. For instance, is there reason for analysis due to improper operation of the equipment, etc. and is there other data that can be used in an analysis.
3. Take data.
4. Review data and analyze:
   - Review the 10 second snapshot of current to view the operation over that time period.
   - Review low frequency demodulated current to view the condition of the rotor and identify any load-related issues.
   - Review high frequency demodulated current and voltage in order to determine other faults including electrical and mechanical health.

IV. FAULT DETECTION

a) Detection of broken bars

It is well known that a 3-phase symmetrical stator winding fed from a symmetrical supply with frequency f_1, will produce a resultant forward rotating magnetic field at synchronous speed and if exact symmetry exists there will be no resultant backward rotating field. Any asymmetry of the supply or stator winding impedances will cause a resultant backward rotating field from the stator winding. When applying the same rotating magnetic field fundamentals to the rotor winding, the first difference compared to the stator winding is that the frequency of the induced electro-magnetic force and current in the rotor winding is at slip frequency, i.e $s.f_l$, and not at the supply frequency. The rotor currents in a cage winding produce an effective 3-phase magnetic field with the same number of poles as the stator field but rotating at slip frequency $f_2= s.f_l$ with respect to the rotating rotor. With a symmetrical cage winding, only a forward rotating field exists. If rotor asymmetry occurs then there will also be a resultant backward rotating field at slip frequency with respect to the forward rotating rotor. As a result, the backward rotating field with respect to the rotor induces an e.m.f. and current in the stator winding at:

$$F_{sb}=f_l\ (1-2s)\ HZ \qquad (1)$$

This is referred to as the lower twice slip frequency sideband due to broken rotor bars. There is therefore a cyclic variation of current that causes a torque pulsation at twice slip frequency ($2sf_l$) and a corresponding speed oscillation, which is also a function of the drive inertia. This speed oscillation can reduce the magnitude (amps) of the $f_l(1-2s)$ sideband but an upper sideband current component at f1(1+2s) is induced in the stator winding due to rotor oscillation. The upper sideband is enhanced by the third time harmonic flux. Broken rotor bars therefore result in current components being induced in the stator winding at frequencies given by [8]:

$$fsb = f1(1\pm 2s)\ Hz \qquad (2)$$

These are the classical twice slip frequency sidebands due to broken rotor bars.

b) Detection of air gap eccentricity:

Air-gap eccentricity in electrical machines can occur as static or dynamic eccentricity. Static eccentricity is defined as a stationary minimum air-gap. This can be caused by stator core ovality or incorrect positioning of the rotor or stator at the commissioning stage. At the position of minimum air-gap there is an unbalanced magnetic pull which tries to deflect the rotor thus increasing the amount of air-gap eccentricity. Dynamic eccentricity is defined as a rotating minimum air-gap. It can be caused by a bent shaft, mechanical resonances at critical speeds, or bearing wear. Either can lead to a rub between the rotor and stator causing serious damage to the machine. The effects of air-gap eccentricity produce unique spectral patterns and can be identified in the current spectrum. The analysis is based on the rotating wave approach whereby the magnetic flux waves in the air-gap are taken as the product of permeance and magnetomotive force (MMF) waves.

c) Detection of shorted turns in LV stator winding

The objective is to reliably identify current components in the stator winding that are only a function of shorted turns and are not due to any other problem or mechanical drive characteristic. There has been a range of papers published on the analysis of air gap and axial flux signals to detect shorted turns and the detailed mathematics can be found in the references [9-10].

d) Detection of mechanical influences

Changes in air gap eccentricity results in changes in the air gap flux waveform. With dynamic eccentricity the rotor position can vary and any oscillation in the radial air gap length results in variations in the air gap flux. Consequently this can induce stator current components given by [11-13]:

$$f_e = f_1 \pm m \times f_r \qquad (3)$$

Where

f1 = supply frequency

fr = rotational speed frequency of the rotor

m = 1,2,3.............harmonic number

fe = current components due to air gap changes

This means that problems such as shaft/coupling misalignment, bearing wear, roller element bearing defects and mechanical problems that result in dynamic rotor disturbances can be potentially detected due to changes in the current spectrum.

e) Influence of gearboxes

Mechanical oscillations will give rise to additional current components in the frequency spectrum. Gearboxes may also give rise to current components of frequencies close to or similar to those of broken bar components. Hence, to perform a reliable diagnosis of a rotor winding for motors connected to a gearbox, the influence of gearbox components in the spectrum need be considered. Specifically, slow revolving shafts will give rise to current components around the main supply frequency components as prescribed by equation (5) where the rotational speed frequency of the shaft, rotating with Nr rpm, may be calculated as:

$$f_r = \frac{N_r}{60} \qquad (4)$$

V. CASE STUDIES

Case I: Current spectrum of a healthy motor

A 100 HP, 440 V standard efficient motor driving a pump was tested in sugar mill. The motor was operating at 95 Amps, corresponding to approximately 75% full load. The full load speed was 1775 rpm yielding a frequency interval of 48.55 Hz to 51.77 Hz for detection of broken rotor bars. Figure 1 shows part of the frequency resolved current spectrum for the motor. The spectrum is completely free of any current components around the main supply frequency, f_1, and consequently, the frequency range in which current components due to broken rotor bars are expected are empty. The motor thus shows no signs of broken rotor bars.

Case II: Rotor Asymmetry

Rotor asymmetry was detected in a 50 HP, 440 volt operating in sugar mill during quality control analysis using MCSA. The full load speed is 940 rpm yielding a frequency interval of 48.55 Hz to 51.66 Hz for detection of broken rotor bars. The motor was operating at 85 Amps, corresponding to approximately 60% full load. Based on the load conditions, the instrument predicted current components due to broken rotor bars to be positioned at 49.0 Hz and 51.0 Hz. A search band is applied around these positions. Figure 2 shows one current component to be present in each search band. The components are distributed symmetrically around f_1, as expected, but different magnitudes, 47.2dB and 58.0dB from the main supply frequency. The components are a sign of initial rotor asymmetry but yet not indicative of an unhealthy motor.

Case III: Damaged Rotor

Figure 3 shows part of the frequency resolved current spectrum for coal mill rated 440 V, 150 HP operating in a utility plant. The full load speed is 955 rpm yielding a frequency interval of 48 Hz to 52 Hz for detection of broken rotor bars. Based on the supply current, the instrument predicted sidebands due to broken rotor bars to be positioned at 49.70 Hz and 50.57 Hz. These frequency positions are close to that of the supply frequency. Figure 3 show the supply frequency to have a somewhat wide declining current component. This is caused by the motor being subjected to smaller changes in load, i.e. smaller changes in supply current, during the data acquisition process. However, the peak detection algorithms embedded in the instrument was able to detect the declining slopes of the supply frequency within the applied search bands

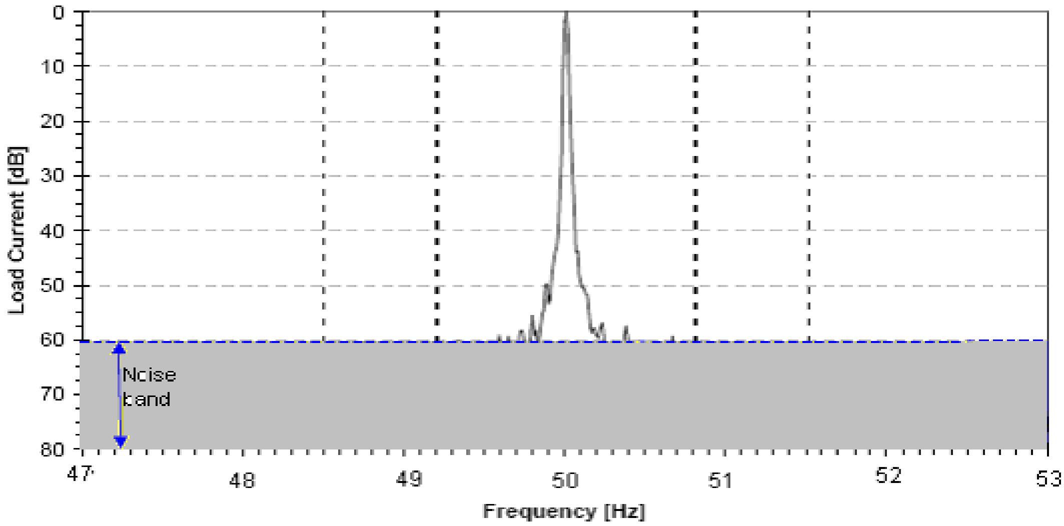

Figure 1: Current spectrum of a healthy motor.

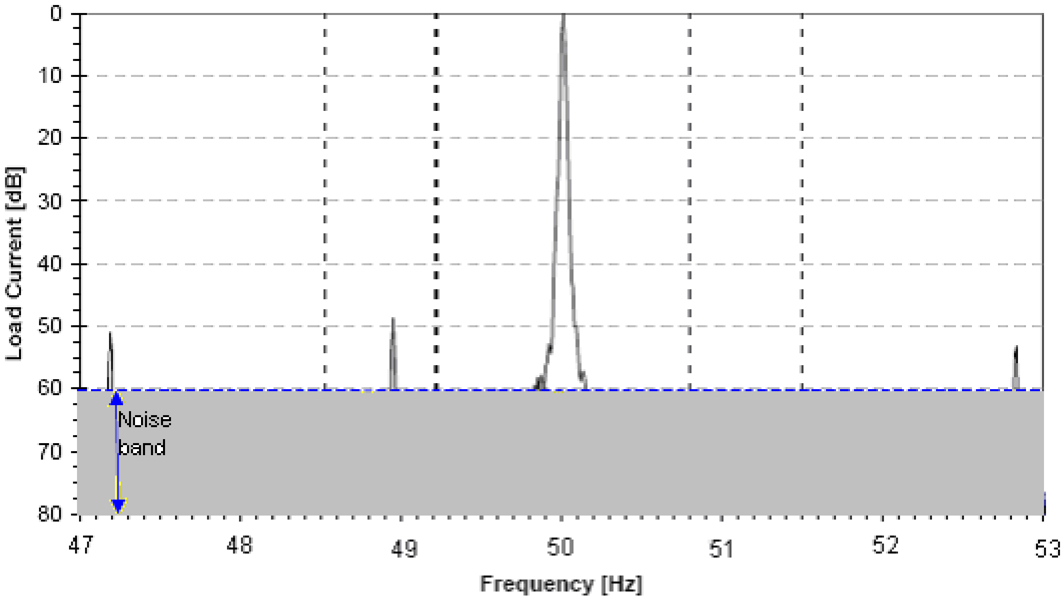

Figure 2: Motor Current spectrum showing signs of initial rotor asymmetry.

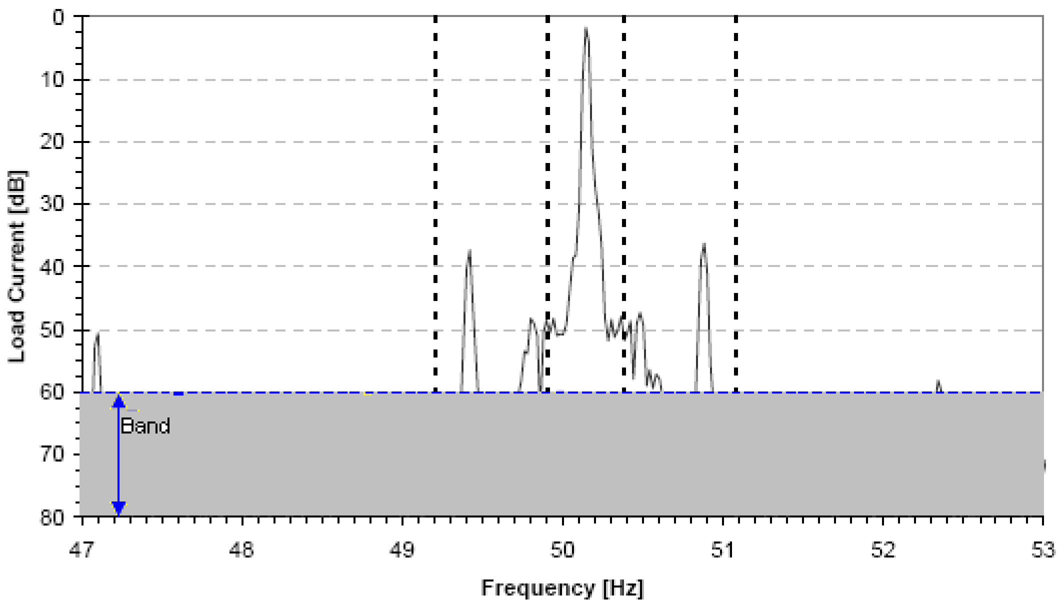

Figure 3: Motor Current spectrum with a damaged rotor

and thus disregard these slopes from the analysis thereby correctly identifying the current components due to broken rotor bars.

Case IV: Fault in gear box

Figure 4 shows part of the frequency resolved current spectrum for coal mill rated 440 V, 240 HP operating in a utility plant. The full load speed is 885 rpm yielding a frequency interval of 48 Hz to 52 Hz for detection of broken rotor bars. The motor is driving a coal mill through a three-stage reduction gearbox, i.e. the gearbox thus contains three shafts. The output speed of the gearbox at full load conditions is 18.46 rpm and the individual shaft speeds internal to the gearbox are 48.60 rpm and 135.78 rpm at full load conditions.

The fundamental rotational speed frequencies for these shafts at full load conditions are 0.28 Hz, 0.75 Hz and 2.68 Hz respectively. Since part of the spectrum, which may contain current components due to broken rotor bars, span from 48Hz to 52 Hz, only the last two reduction stages may give rise to a series of current components in the part of the current

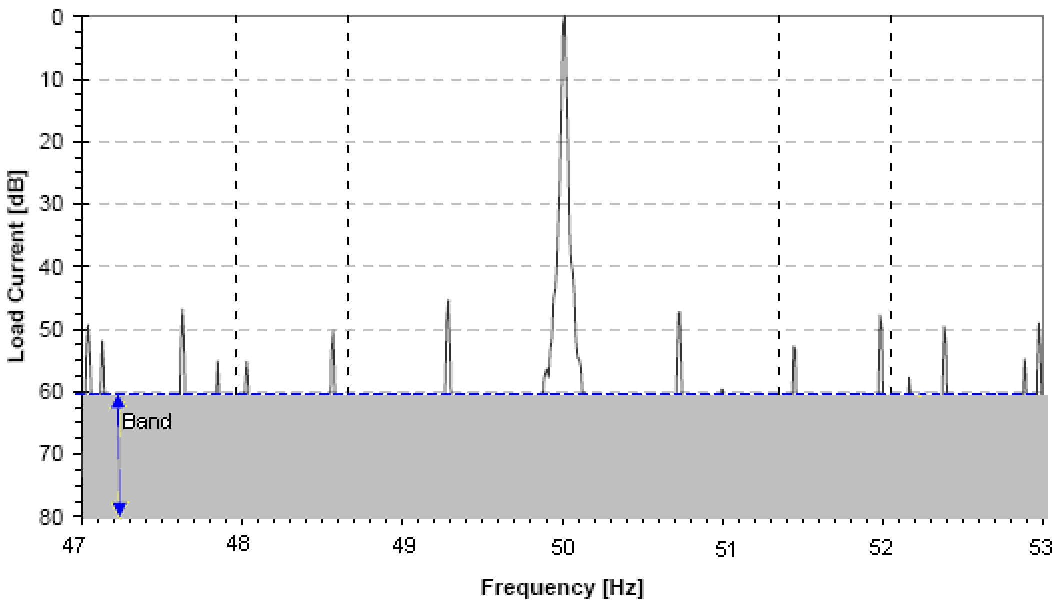

Figure 4: Motor Current spectrum of healthy motor with a gearbox.

spectrum where broken rotor bar components may be present. Specifically, two components may be found in the upper and lower search band.

The motor was operating at 200 Amp corresponding to approximately 80% load. Based on the gearbox name-plate data, the instrument was able to correctly identify the current components caused by the shafts in the gearbox. The positions of these components are displayed in Figure 4. As can be seen, the two current components in each search band are indeed caused by the gearbox. Specifically, the two components in each search band are a 4^{th} harmonic from the 3rd reduction stage and the 2nd harmonic from the 2nd reduction stage. Since the current components in the search band are caused by the gearbox and not by the presence of broken rotor bars, the motor was diagnosed as not being subjected to broken rotor bars. This example clearly demonstrates that gearbox components need be correctly identified and omitted from the analysis. If the influence of gearbox components is not considered when identifying the, presence of broken rotor bar current components in the current spectrum, otherwise healthy machines may be incorrectly diagnosed as unhealthy.

VI. CONCLUSION

Motor Current Signature Analysis is an electric machinery monitoring technology. It provides a highly sensitive, selective, and cost-effective means for online monitoring of a wide variety of heavy industrial machinery. It has been used as a test method to improve the motor bearing wear assessment for inaccessible motors during plant operation. This technique can be fairly simple, or complicated, depending on the system available for data collection and evaluation. MCSA technology can be used in conjunction with other technologies, such as motor circuit analysis, in order to provide a complete overview of the motor circuit. The result of using MCSA as part of motor diagnostics program is a complete view of motor system health.

This paper discusses the fundamentals of MCSA and demonstrates through industrial case studies, how motor current signature analysis can reliably diagnose rotor cage problems in induction motor drives. Traditional methods of measurements can result in false alarms and/or misdiagnosis of healthy machines due to the presence of current frequency components in the stator current resulting from non-rotor related conditions such as mechanical load fluctuations, gearboxes, etc. Theoretical advancements have now made it possible to predict many of these components, thus making MCSA testing a much more robust and less error prone technology. Based on these theoretical developments, case studies are presented which demonstrate the ability to separate current components resulting from mechanical gearboxes from those resulting from broken rotor bars. The case studies show that MCSA can effectively detect broken rotor bars and other high resistance faults.

REFERENCES

[1] VAS, P. “Parameter Estimation, Condition Monitoring, and Diagnosis of Electrical Machines”, Clarendon Press, Oxford, 1993.

[2] Kilman, G. B., KoegL, R. A., Stein, J., Endicott, R. D., Madden, M. W. “Noninvasive Detection of Broken Rotor Bars in Operating Induction Motors” , IEEE Trans. Energy Conv. (1988), 873–879.

[3] Cardoso, A. J. M., Cruz, S. M. A., Carvalho, J. F. S., Saraiva, E. S. : Rotor Cage Fault Diagnosis in Induction Motors by Park’s Vector Approach, IEEE, IAS’95 Orlando Florida, Oct. 1995, pp. 642–646.

[4] Hsu, J. S. “Monitoring of Defects in Induction Motors through Air-Gap Torque Observation”, IEEE Transactions on Industry Applications 31 (1995), 1016–1021.

[5] Thomson, W. T., Stewart, I. D. “On-line Current Mon- itoring for Fault Diagnosis in Inverter Fed Induction Motors” , IEE Third International Conference on Power Electronics and Drives, London, 1988.

[6] Bellini, A., Filippetti, F., Franceschini, G., Tassoni, C., Kliman, G. B. “Quantitative Evaluation of Induction Motor Broken Bars by Means of Electrical Signature Analysis”, IEEE Trans. Ind. Applicat. Vol. 37 (2001), 1248–1255.

[7] Lebaroud, A., BentounsI, A. “NDT of Faulty Induction Motor, 11th International Symposium on Applied Electromagnetic”, ISEM 2003, 12–14 May, Paris, France.

[8] R R Schoen, B K Lin, F G Habetter, H J Shlog and S Farag: “An Unsupervised On-line System for Induction Motor Fault Detection Using Stator Current Monitoring”, IEEE-IAS Transactions, November/December, Vol. 31, No 6, 1995, pp 1280-1286.

[9] W T Thomson and A Barbour: “On-line Current Monitoring and Application of a Finite Element Method to Predict the Level of Airgap Eccentricity in 3-Phase Induction Motors”, IEEE

Transactions on Energy Conversion, Vol 13, No 4, December 1998, pp 347-357
[10] S Fruchenecht, E Pittius and H Seinsch: "A Diagnostic System for Three-Phase Asynchronous Machines", Proc IEE Conf, EMDA'89, Vol. 310, IEE Savoy Place, London, 1989, pp 163-171.
[11] J Penman, J G Hadwick and B Barbour: "Detection of Faults in Electrical Machines by Examination of the Axially Directed Fluxes", Proceedings ICEM'78, Brussels
[12] J Penman, H G Sedding, B A Lloyd and W T Fink: "Detection and Location of Interturn Short Circuits in the Stator Windings of Operating Motors", IEEE Transactions on Energy Conversion, Vol. 9, No 4, December 1994
[13] W T Thomson: "On-Line MCSA to Diagnose Shorted Turns in Low Voltage Stator Windings of 3-Phase Induction Motors Prior to Failure", IEEE, PES&IAS IEMDC, MIT, Boston, June, 2001.