ON-LINE CONDITION MONITORING OF MOTORS USING ELECTRICAL SIGNATURE ANALYSIS

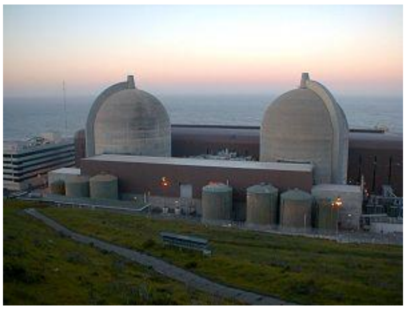
** Presented at the 'Recent Advances in Condition-Based Plant Maintenance' seminar organized by the Indian Institute of Plant Engineers on 17 May 2002 at NITIE, Mumbai.*

PREMISE

Motor current acts as an excellent transducer for detecting faults in the motor. ***Spectrum analysis of the motor's current & voltage signals can hence detect various faults without disturbing its operation.*** Typical faults detectable by this are:

- Rotor bar damage
- Misalignment/ unbalance
- Foundation looseness
- Static & dynamic eccentricity
- Stator core damage
- Interturn shorts
- Defective bearings

HISTORY



Back in the early 70s, the US Nuclear Regulatory Commission felt the need to check the condition of motors located inside the nuclear reactors using non-intrusive techniques. Research for discovering a new technology was initiated by Oak Ridge National Labs & subsequently licensed to Areva NP, which is the largest erector of nuclear plants world-wide. It was found that the motor current signal was always modulated by any fault condition inside the motor. Further (& continuing) research has led to new techniques for conditioning the current & voltage signals in order to analyze these signals & determine the nature of the fault.

INTRODUCTION

Electrical Signature Analysis (ESA) is the procedure of acquiring the motor current & voltage signals, performing signal conditioning and analyzing the derived signals to identify the various faults. The three phase signals are collected either directly (for a LT motor) or through a CT (for a HT motor). Thus, ***motors can be tested from the control panel, enabling easy testing of remote, inaccessible or hazardous area motors***. An FFT (Fast Fourier Transform) analyzer is required for converting the signals from the time domain to the frequency domain.

THEORY

A motor current signal is ideally a perfect sinusoidal wave at 50 Hz. Pictorially; we can represent the current in terms of time as well as frequency (see Fig. 1). Here, the first picture shows the current vs. time while the second shows the current vs. frequency.
The amplitude of the peak in frequency is equal to the RMS amplitude of the sine wave. As this is a theoretical situation with no harmonics, we see only one peak in the frequency spectrum. The conversion of the current from time to the frequency domain is achieved using an algorithm called the Fast Fourier Transform (FFT).

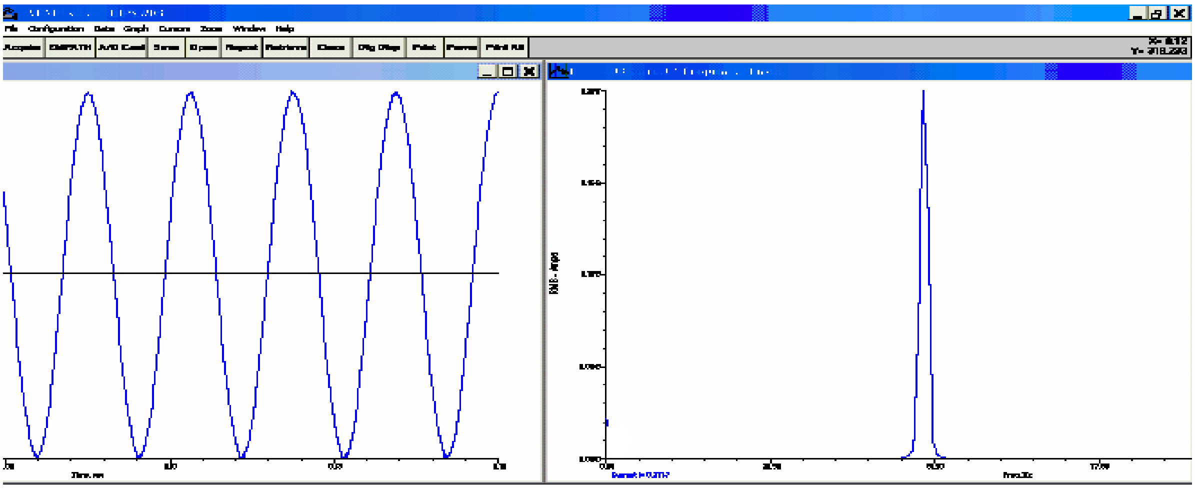


Fig. 1 – A perfect 50 Hz signal in both time & frequency domains

During actual operation, many harmonics will be present in the motor signal, thus an actual signal will show many peaks including line frequency and its harmonics (see Fig. 2). This is known as the motor's current signature. Analyzing these harmonics after amplification and signal conditioning will enable identification of the various motor faults.

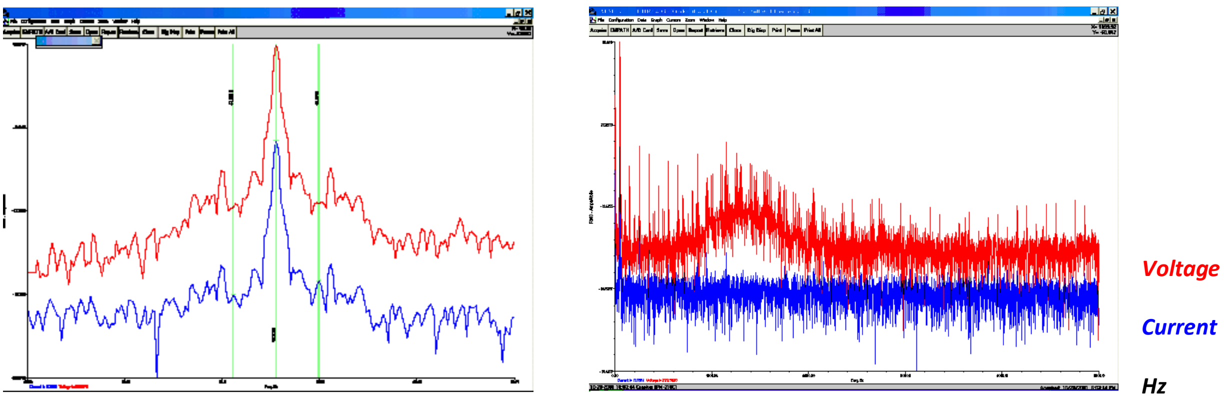


Fig. 2 – Typical low & high frequency spectra of a good motor

Certain harmonics come in on the supply & these are of little consequence. However, harmonics are also generated due to various electrical & mechanical faults. All faults cause a change in the internal flux distribution, thus generating the harmonics. Note that these are intermediate harmonics and cannot be detected by standard harmonic analyzers. ***As fault generated harmonics appear only in the current spectrum (but not in voltage), superimposition of current & voltage spectra can easily identify them.***

Thus, it is crucial to distinguish between Electrical Signature Analysis & Current Signature Analysis. In the latter, voltage is not used as a reference. Thus, supply related harmonics can be misinterpreted as a motor fault, leading to incorrect diagnosis.

ROTOR BAR DAMAGE

In the current signature, the motor pole passing frequency (PPF = motor slip x no. of poles) will show up as a sideband to the line frequency, i. e. we will see peaks at F_L ± PPF. The difference in amplitude between the line frequency peak and the pole passing frequency sidebands is an indication of the rotor bar health. Empirical research has shown that a difference of over 60 dB indicates an excellent rotor bar condition. (A dB scale is used for the Y-axis in order to resolve the PPF peaks clearly. This is very difficult on a linear scale).

As the rotor bars start degrading (i. e. high resistance joints are present or a crack starts developing), the rotor impedance rises. Due to this, the current drawn at the PPF frequency rises, leading to an increase in the amplitude of the PPF peaks in the current spectrum.

A difference of about 48 dB would indicate the presence of high resistance joints whereas a difference of about 35 dB would indicate multiple broken bars. Most cases lie somewhere in between and the exact damage level can be assessed in each case (see table below).

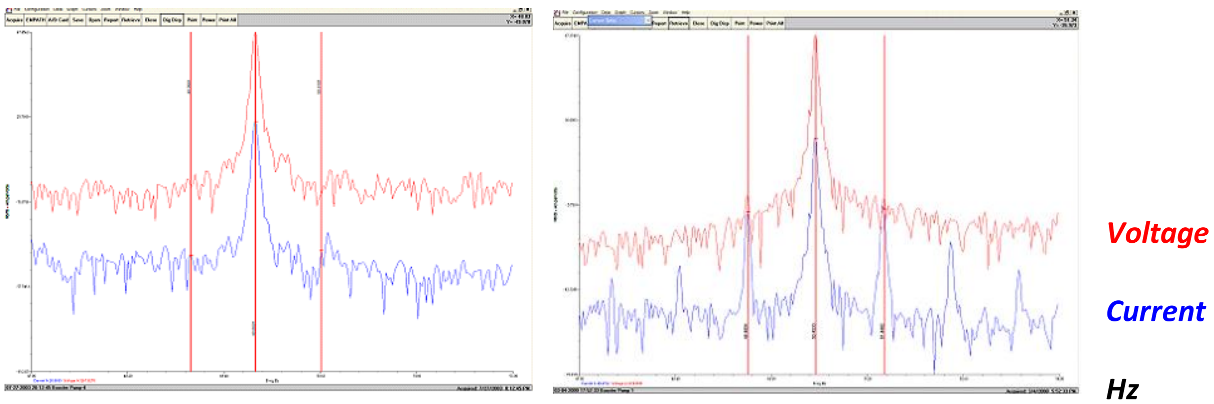


Fig. 3 – Identical 2.3 MW motors; LHS is perfect, RHS has 7 broken rotor bars

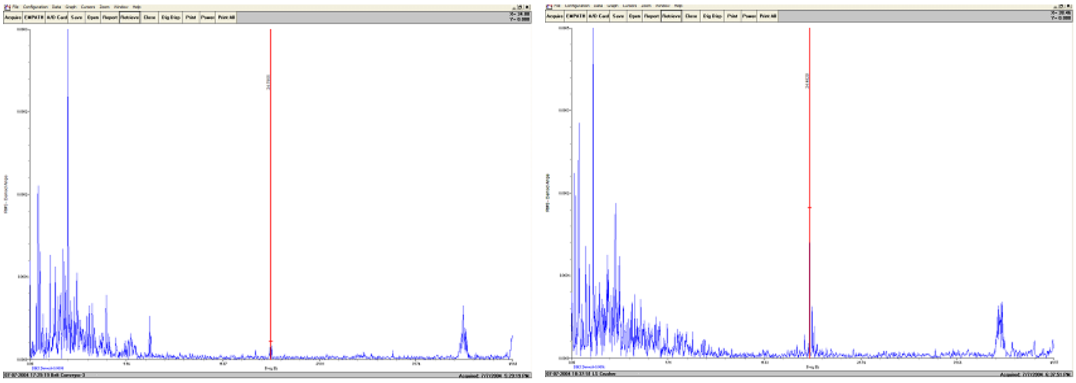
ROTOR BAR DAMAGE SEVERITY LEVEL CHART					
Severity level	**F_L / F_P (dB)**	**F_L / F_P (Ratio)**	**F_P / F_L (Ratio %)**	**Rotor Condition Assessment**	**Recommended corrective action**
1	>60	>1000	<0.10	Excellent	None
2	54-60	501-1000	0.10-0.20	Good	None
3	48-54	251-501	0.20-0.40	Moderate	Trend data
4	42-48	126-251	0.40-0.79	Rotor bar crack may be developing or problems with high resistance joints	Increase trending frequency
5	36-42	63-126	0.79-1.58	One or two rotor bars likely cracked or broken	Perform vibration test to confirm source & severity
6	30-36	32-63	1.58-3.16	Multiple cracked or broken rotor bars	Repair ASAP
7	<30	<32	>3.16	Multiple cracked or broken rotor bars & end-rings	Repair or replace ASAP

The above chart is indicative, but care should be taken in the following cases:

i. Low speed motors – severe bar damage will not give strong sidebands
ii. Fluctuating loads – will raise noise floor & give false indications of rotor damage
iii. Motors coupled to slow speed gears – the gear output speeds may match the PPF & give false indications of rotor bar damage.

MISALIGNMENT/ UNBALANCE

To identify these problems, it is required to perform signal conditioning of the motor current signal. The process is known as RMS Demodulation, which is carried out in order to eliminate the line frequency.



Demod Current

Hz

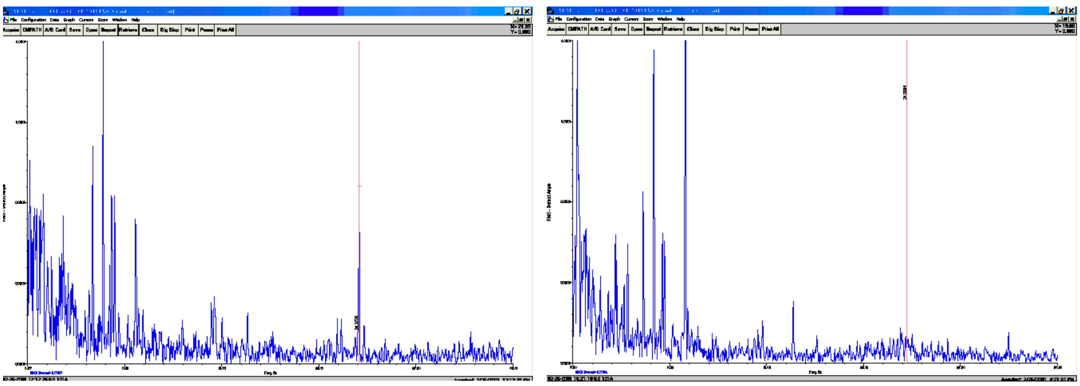
Fig. 4 – Identical 160 kW motors; LHS vibrates at 2.48 mm/sec, RHS vibrates at 15.24 mm/sec

Here, the motor running speed will show up as a peak. For a healthy motor, the running speed peak would be barely visible. In case of misalignment or mechanical unbalance, high peaks will show up at the motor running speed & its harmonics.

Care should be taken while analyzing motors coupled to reciprocating compressors. These will inherently have strong peaks at running speed. Also, note that any vibration that causes running speed vibration (1X) will give a strong 1X peak in the RMS Demod spectrum. Other possible causes could be bent shafts, resonance, structural weakness, etc.

Vibration analysis should thus be combined with ESA whenever strong 1X peaks are observed in the Demod spectrum. This will result in the most accurate analyses every time.

FOUNDATION LOOSENESS



Demod Current

Hz

Fig. 5 – LHS is motor with high vibration. RHS is same motor after tightening the foundation

Uneven foundations or loose foundation bolts will result in looseness. This can be identified by looking at the RMS Demodulated spectrum. The looseness will show up as high peaks at half the running speed of the motor.

ECCENTRICITY

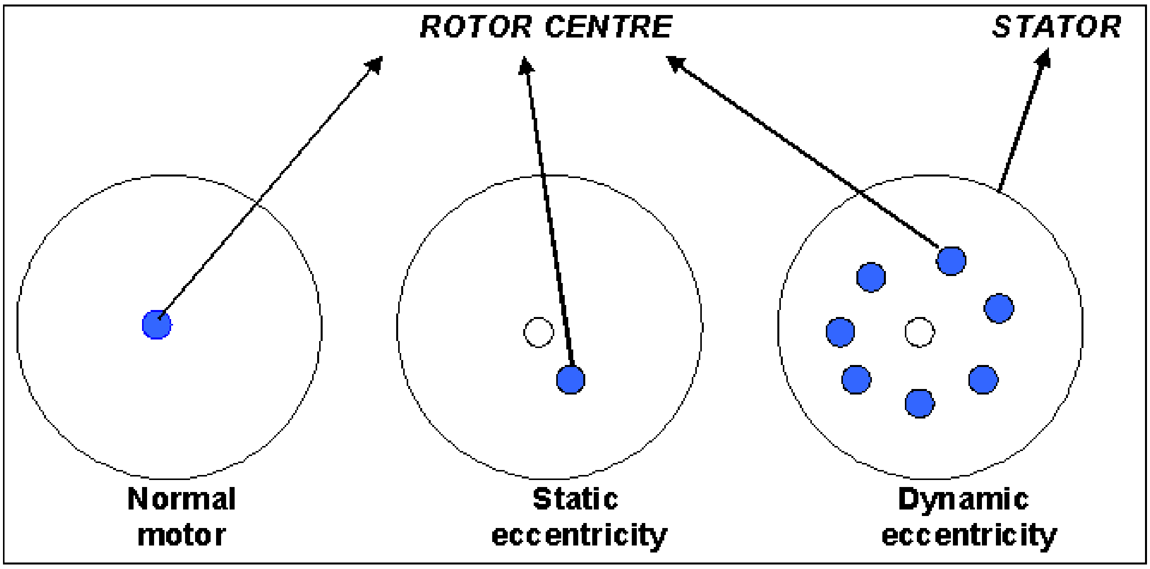


Fig. 6 – The above sketch shows the normal air-gap condition, as well as the difference between static & dynamic eccentricity

STATIC ECCENTRICITY

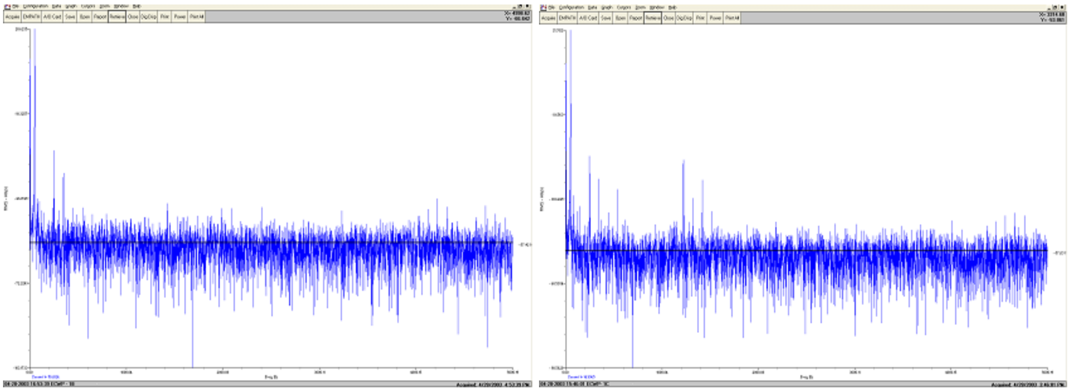


Fig. 7 – Identical 300 kW motors; LHS vibrates at 1.14 mm/sec, RHS vibrates at 8.64 mm/sec

Static eccentricity is the phenomenon of uneven stator-rotor air-gap, typically caused due to soft foot in the foundation, cocked bearing or an improperly adjusted air-gap for plain bearings. It will show up as high peaks at the principal rotor bar passing frequency appearing as sidebands to the line frequency and its harmonics.

Static eccentricity = RB x RS ± nF_L

where RB = no. of rotor bars; RS = running speed; n = 1, 3, 5, etc.; F_L = line frequency

Many motors will inherently show static eccentricity even at the manufacturing stage. Thus, some level of eccentricity is considered acceptable by many motor vendors. Thus, a static eccentricity call should only be made after comparing identical motors OR after trending a particular motor's data over a period of time.

Also, an eccentricity call should only be made if two or more peaks of the rotor bar pass frequency rise 15 dB or more over the background level.

DYNAMIC ECCENTRICITY

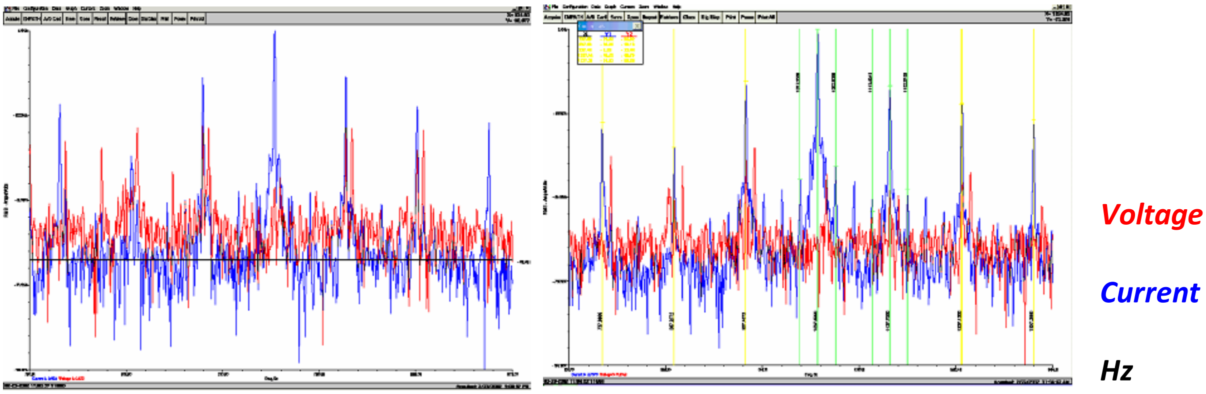


Fig. 8 – Identical 95 kW motors. RHS had a worn-out bearing housing.

Dynamic eccentricity is the phenomenon of a variable stator-rotor air gap, typically caused due to worn out bearings or housings. It will show up as high peaks at principal rotor bar passing frequency and its harmonics along with the running speed sidebands around these.

Dynamic eccentricity = RB x RS ± nF_L ± RS

Close trending is recommended on detection of this condition. This is a significant problem as it can quickly lead to the rotor rubbing with the stator.

STATOR MECHANICAL FAULTS

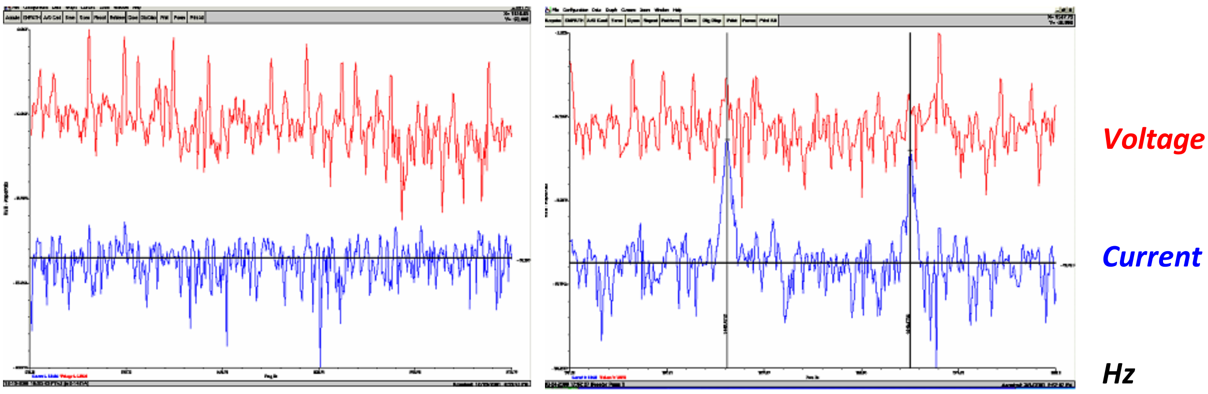


Fig. 9 – Identical 410 kW motors. LHS is excellent; RHS has severe hot spots.

These faults are typically hot spots or stator lamination damage. In some cases, extremely loose wedges too have shown up. The theory behind these patterns is still unexplained, the data is purely empirical. Typical fault frequencies are stator slot pass frequencies.

Stator mechanical faults = SS x RS ± F_L

where SS = no. of stator slots; RS = running speed; F_L = line frequency

Core damage results in shorted stator laminations, causing localized eddy currents that heat the core locally. This will eat away at the motor insulation and destroy it over time.

Loose wedges damage the coil insulation mechanically and also erode the conducting varnish on the coil sides, leading to corona. The corona discharges then start degrading the motor insulation.

INTERTURN INSULATION DEGRADATION

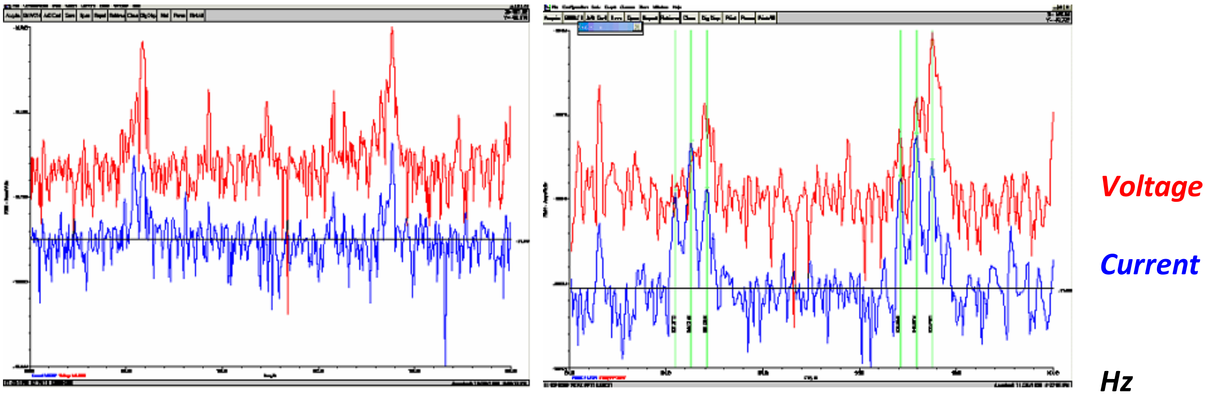


Fig. 10 – Identical 1100 kW motors. LHS is excellent; RHS had degraded interturn insulation.

Interturn shorts cause current imbalance. This will lead to localized heating, reduced output and eventually result in a ground fault. The current spectrum can pick up interturn shorts as well as interturn insulation degradation (in severe cases).

Stator interturn deterioration $fst = f1[\frac{n}{p}(1-s) \pm k]$

where f1 = line frequency; n = 1, 2, 3…; p = pole pairs; s = per unit slip & k = 1, 3, 5…

LT motors & HT motors rated upto 3.3 kV can run for some time even with an interturn short. However, HT motors of 6.6 kV & above will fail almost immediately in the event of an interturn short. As a result, detecting interturn insulation degradation in advance is vital.

ESA is the only known technology that is capable of doing this on-line. The only other way of doing this is to carry out Motor Circuit Analysis or Surge Testing of the motor, which require that the motor be switched off.

LIMITATIONS

While the ESA technology is extremely powerful, the following limitations too should be kept in mind while applying it:

- Will not work unless motor is loaded by atleast 25 % (over the no-load power).
- Rotor bar assessment for slip-ring & slow speed motors is rather different from the rules given here.
- Die-cast aluminium rotors will often show rotor degradation but will run for years.
- Will not distinguish between the various mechanical problems that give rise to 1X vibration.

- Will not work unless the load current is steady (less than 10 % variation during the data acquisition period).
- Will not work unless the motor speed is steady (less than 10 % variation during the data acquisition period).
- Sensitivity for interturn insulation deterioration is nowhere near the sensitivities of Motor Circuit Analysis & Surge Comparison Analysis.
- For VFD motors, data has to be acquired at the output of the drive. Analysis is often difficult due to the extremely noisy signals generated by the VFD.
- ESA can detect stator mechanical faults but cannot pinpoint their location.

ADDITIONAL APPLICATIONS

The motor current is modulated by any form of vibration, which causes pulses in the torque & results in harmonics. Hence, ESA can also be used to detect problems in the driven loads. Typical detectable problems include:

- Fan blade damage,
- Belt looseness,
- Gear tooth damage,
- Gear shaft unbalance,
- Load bearing problems, etc.

The technology is extremely ***popular in USA for assessing the condition of motorized valves (MOVs)***, in which following problems can be detected:

- Variations in stem taper,
- Worm gear tooth wear,
- Stem nut wear,
- Degraded worm gear & valve stem lubrication,
- Obstructions in the valve seat area,
- Motor pinion disengagement, etc.

In case of motors that cannot be physically accessed, ESA can also be used to assess the bearing condition. The bearing defect frequencies (BPFI, BPFO, BSF & FTF) will modulate the current spectrum when the bearing deterioration is significant. Thus, bearing faults can be predicted. The bearing defect frequencies are often rather low in amplitude & not easy to distinguish from the noise floor. Vibration analysis is the preferred method of bearing analysis if motor is accessible.

While this paper has mostly covered faults in induction motors, the technology is equally applicable for generators & DC motors.

For DC motors, ESA can detect commutator & brush faults, along with problems in the firing circuitry (faulty SCRs, blown fuses, faulty comparator cards, etc.).

For generators, the applicable rules are similar to those for AC motors. Note however, that the analysis is done using the voltage spectrum instead of the current spectrum. Also, the signal has to be captured from the generator PT, not the bus PT. As the rotor winding is DC, it is generally not possible to assess faults in it using the AC signals from the stator.

Most of the ***above analyses are now available commercially using an automated expert system***, which has greatly simplified the technology. This expert system is known as the EMPATH, which has been developed by Framatome, USA & is now ***available in India through our organization.***

CONCLUSION

This is a highly versatile & proven technology for condition monitoring of motors. It solves the biggest hurdle of any Plant Manager, i.e. to obtain a shutdown for testing his machines. We believe that it will revolutionize Condition Based Maintenance in the years to come.

ABOUT THE AUTHOR

Aditya Korde is the Managing Director of Diagnostic Technologies India Pvt. Ltd., an electrical testing services company. After completion of his graduation in electrical engineering, he been involved with motor & generator repairs and condition monitoring of these as well as transformers & cables for the last 24 years. He specializes in the fields of electrical signature & partial discharge and is actively involved in the development of these technologies. He can be contacted at aditya.korde@diatech.in.

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