Vibration and Motor Current Signature Analysis (MCSA) for Induction Motor Fault Diagnosis

Suri Ganeriwala
SpectraQuest Inc.
8201 Hermitage Road, Richmond, VA, 23228
www.spectraquest.com, suri@spectraquest.com

SpectraQuest, Inc.

Induction Motor Diagnostics

Objective of this work was to investigate the application of Vibration Analysis and MCSA for an Induction Motor Diagnostics

Fault Types:

- **Bearing Faults**
- **Motor with Shorted Turn Faults**
- **Motor with Static Eccentricity Faults**
- **Mechanical Imbalance Faults**
- **Motor with Broken Rotor Bars**

Induction Motor Diagnostics-Motivation

INDUCTION MOTOR DRIVE SYSTEMS

Why so important?

- USA 800,000 MW Generating Capacity
- 40-50% Consumed by induction motors

-320,000MW Plant Systems
-328 Million Horsepower

Induction Motor Diagnostics-Motivation

INDUCTION MOTOR USAGE

USA

Greater than 125HP/93kW

- 400,000
- 12,000 Plants
- 3000 Customers

Greater than 500HP/373kW

- 60,000
- 3,600 Plants
- 1,200 Customers

Induction Motor Diagnostics-Motivation

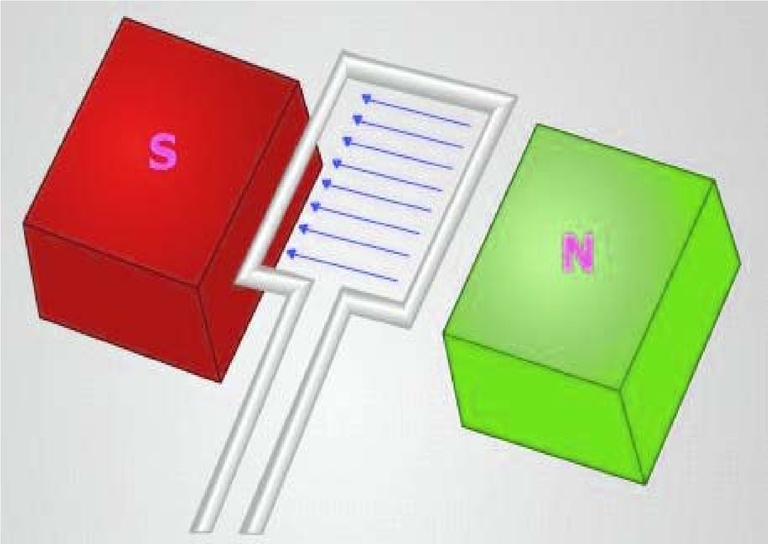
INDUCTION MOTOR USAGE

Power Utilities Greater than 500HP
- 10,000
- 450 Plants
- 150 Companies

- Outside Power Utilities
- Greater than 500HP
- 5 Times the Market

Induction Motor Basics

The movement of the rotor of an induction motor is achieved by a principle called motor action.

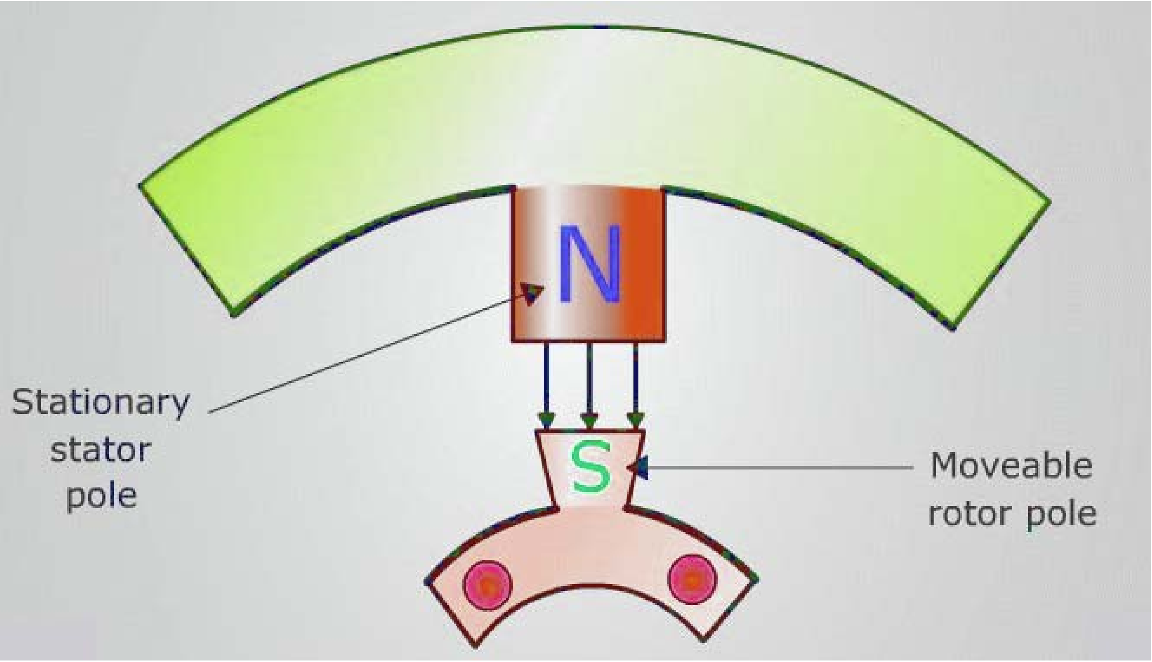


Motor action requires two conditions to exist:

- Current flows through a conductor.
- A force is exerted on the conductor.

Induction Motor Basics

The rotor's magnetic poles at each core are attracted to opposite magnetic poles formed by the stator coils.

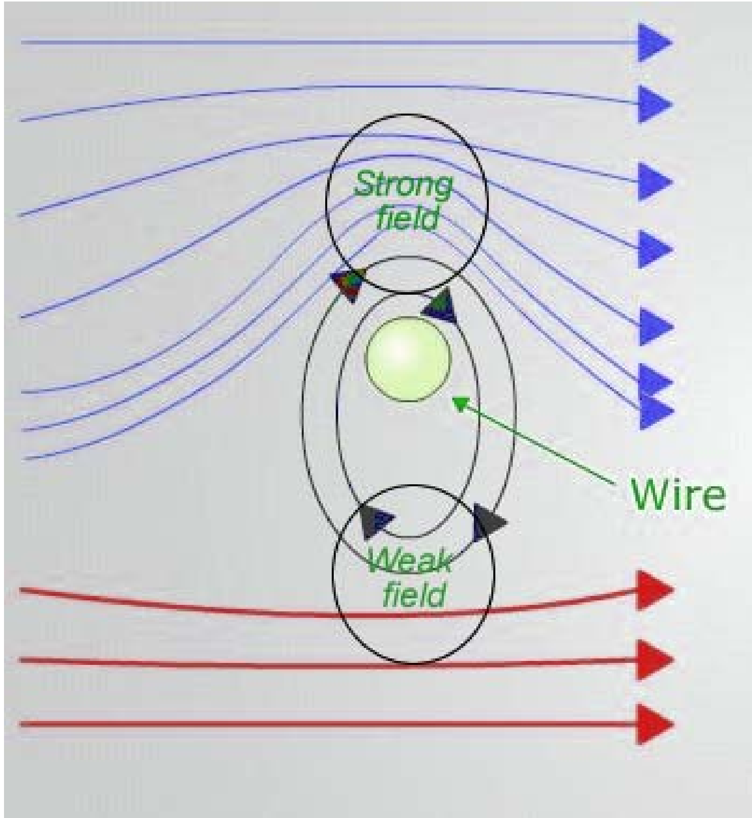


Induction Motor Basics

When the conducting wire is placed inside the main field, the two magnetic fields interact.

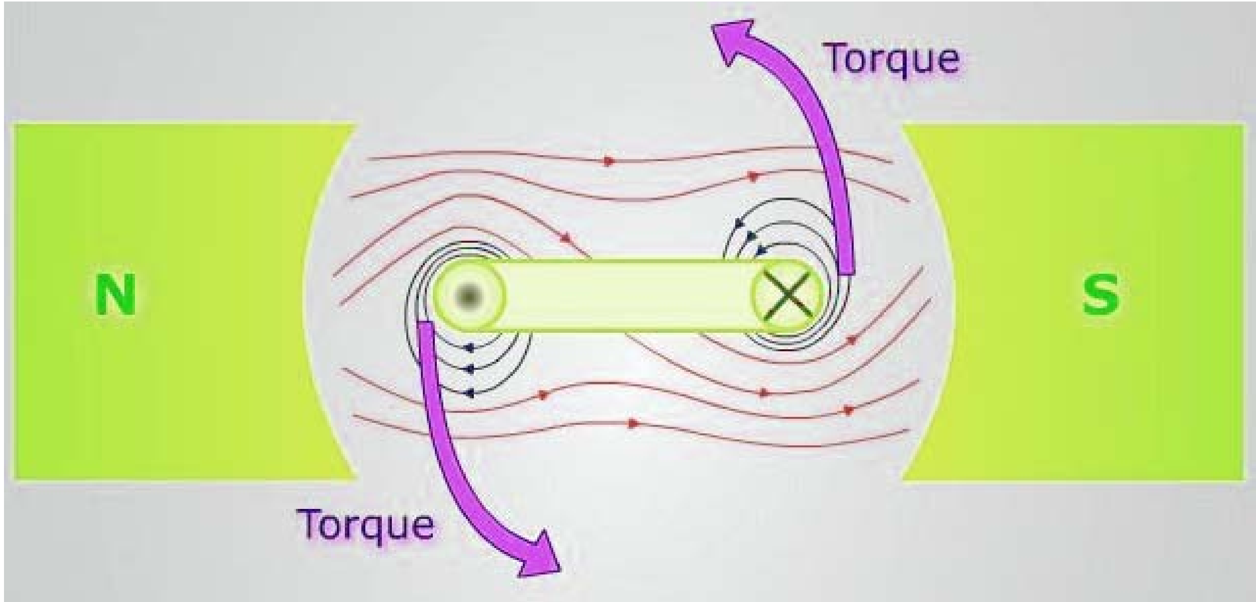
On the side where the magnetic flux lines go in the same direction, the magnetic fields combine and create a strong field.

On the other side, the magnetic flux lines go in opposite directions and cancel each other to form a weak field.



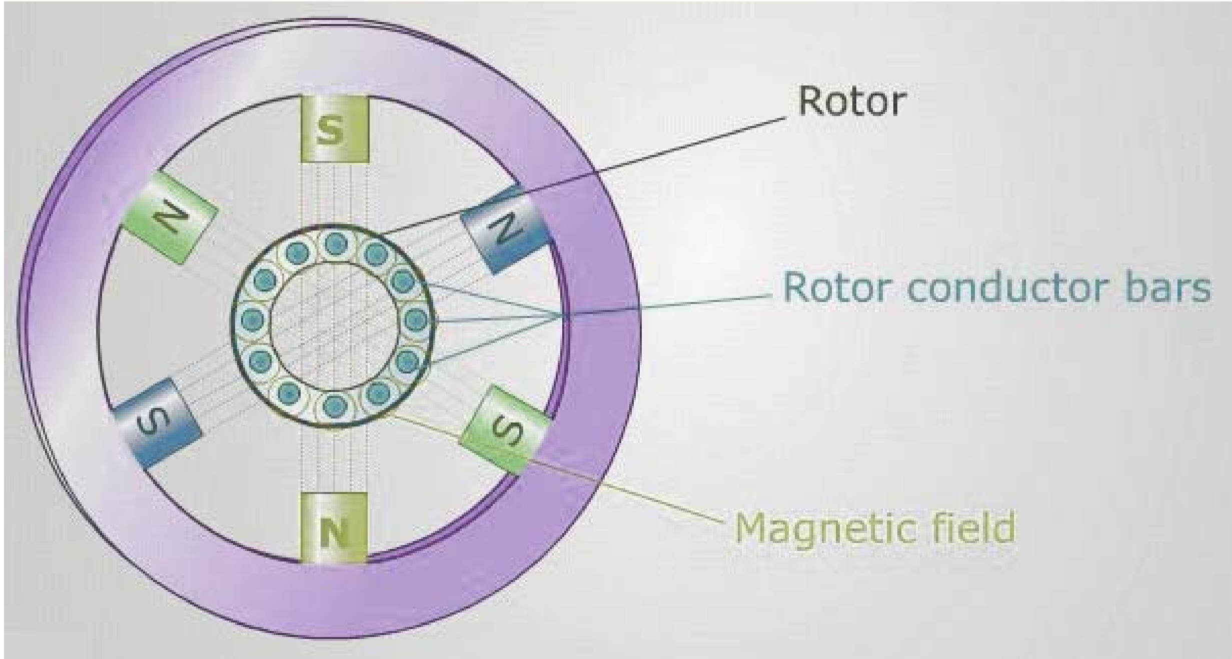
Induction Motor Basics

The armature of the AC induction motor consists of loops of wire.
A single loop of wire is inside the main field.

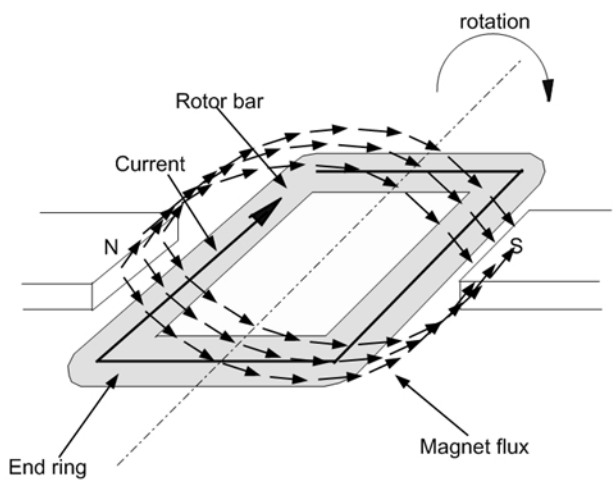


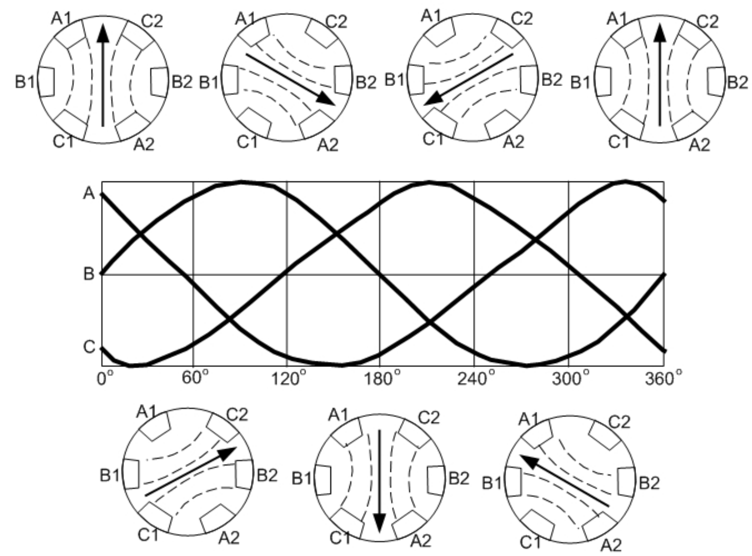
Induction Motor Basics

With an actual induction motor, several stator fields are always rotating. The armature consists of a large number of rotor bars/wire loops with magnetic fields that form around them.

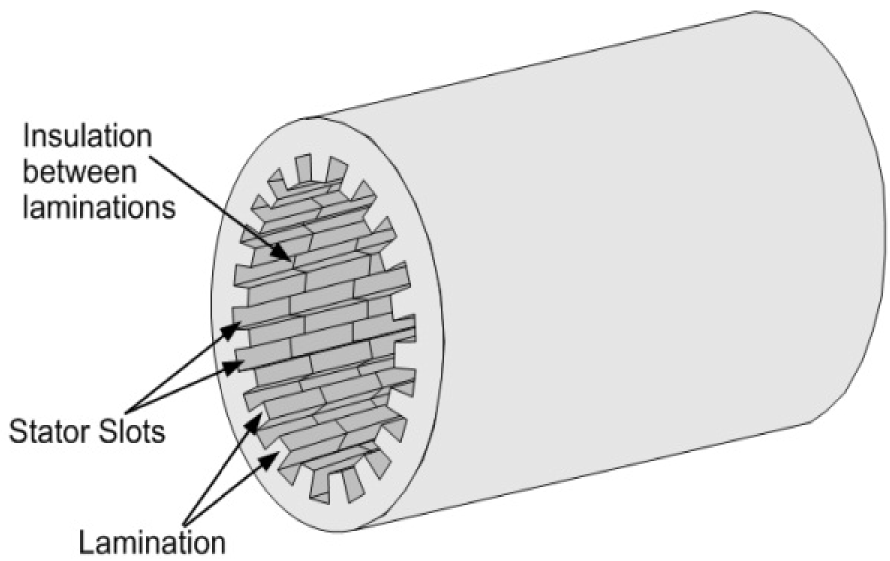


Induction Motor Basics

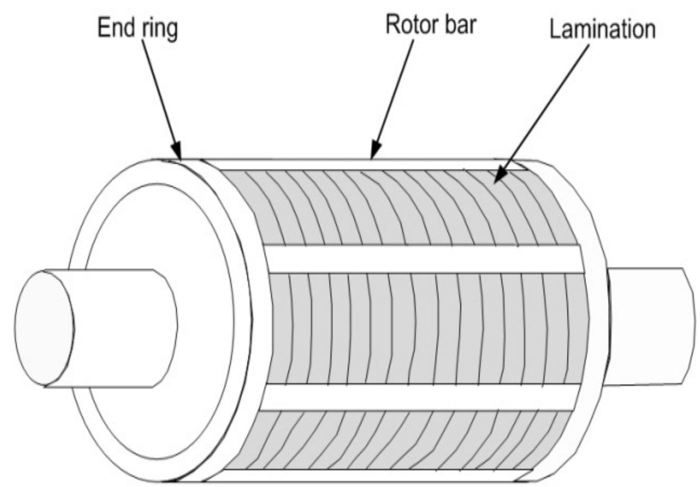




Induction Motor Basics



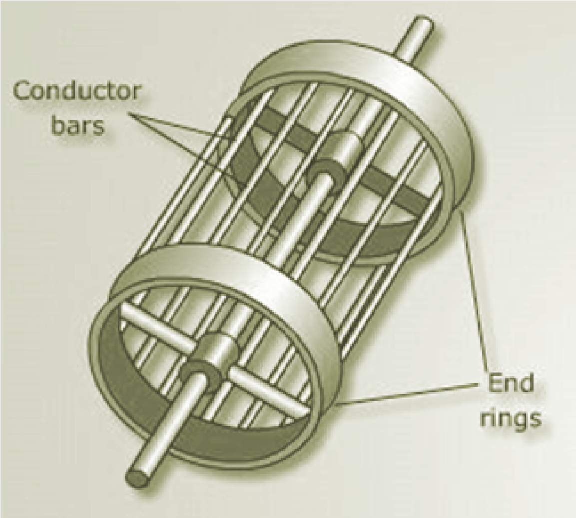
Stator

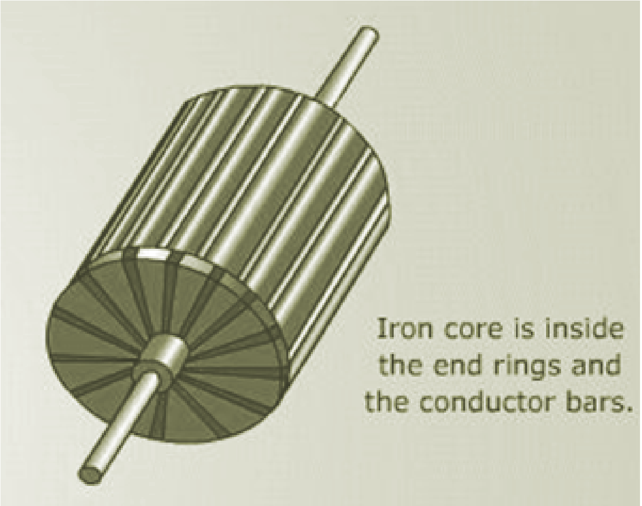


Rotor

Induction Motor Basics

The rotor of the motor is placed inside the rotating magnetic field of the stator.





The rotor of the induction motor consists of end rings connected by the conductor bars.

The Shaft of the motor that drives the load is physically connected to the rotor.

Basic Principles for Induction Motor Diagnostics

- Pole pairs of the stator creates a main magnetic field
- Secondary magnetic field of the rotor interacts with the main field
- On one side flux lines of both fields go in the same directions, fields combine and concentrate. On other side fields go in opposite directions and cancel each other. This difference in field strength creates a rotating torque
- The rotating toque reaches maximum twice in one revolution, once at south pole and once at the north poles.
- This fluctuation in torques in proportional to the current and hence the current variations also occurs twice per revolution

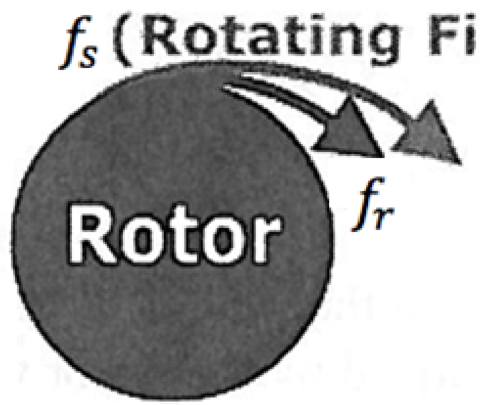
Basic Principles for Induction Motor Diagnostics

- Rotor Always rotates slower than the synchronous speed of the rotating field from the stator
- Rotor speed is frequency of the rotor current and is function of load
- Difference between stator field and the rotor speed is called slip; an exact measurement of slip is probably the most important parameter for diagnostics
- The rotor in a 2-pole motor is subjected to a maximum current flow (or torque) twice for each revolution of slip.
- Increase in load requires more torque and consequently more slip
- Increase in slip is also an indicator of the deteriorating motor health

Induction Motor Diagnostics

- There is normally only a one or two RPM difference between the no-load speed and synchronous speed.
- Under these conditions the rotor is only required to produce sufficient torque to overcome windage and friction.
- The difference between the speed of the rotating magnetic field (f_s) and the actual rotor speed (f_r) is called the slip speed:

$$Slip\ speed = (f_s - f_r)\ in\ r.p.m\ (or\ revs/sec)$$



Induction Motor Diagnostics

Synchronous Speed: the speed at which the magnetic field rotates

$$f_s[Hz] = \frac{2f_l}{p}$$

f_s = synchronous speed of induction motors
f_l = line frequency
p = number of poles

Slip Frequency (S): the speed at which the magnetic field rotates

$$S = f_s - f_r$$

Per unit slip:

$$s = \frac{f_s - f_r}{f_s}$$

S = slip frequency [Hz]
s = per unit slip
f_r = motor running speed

Induction Motor Diagnostics

Diagnostics and condition monitoring minimizes machine downtime, and save time and money.

Induction Motors

Mechanical Faults

- **Bearing Faults**
- **Rotor Misalignment & Eccentricity (static, dynamic)**
- **Mechanical Imbalance**

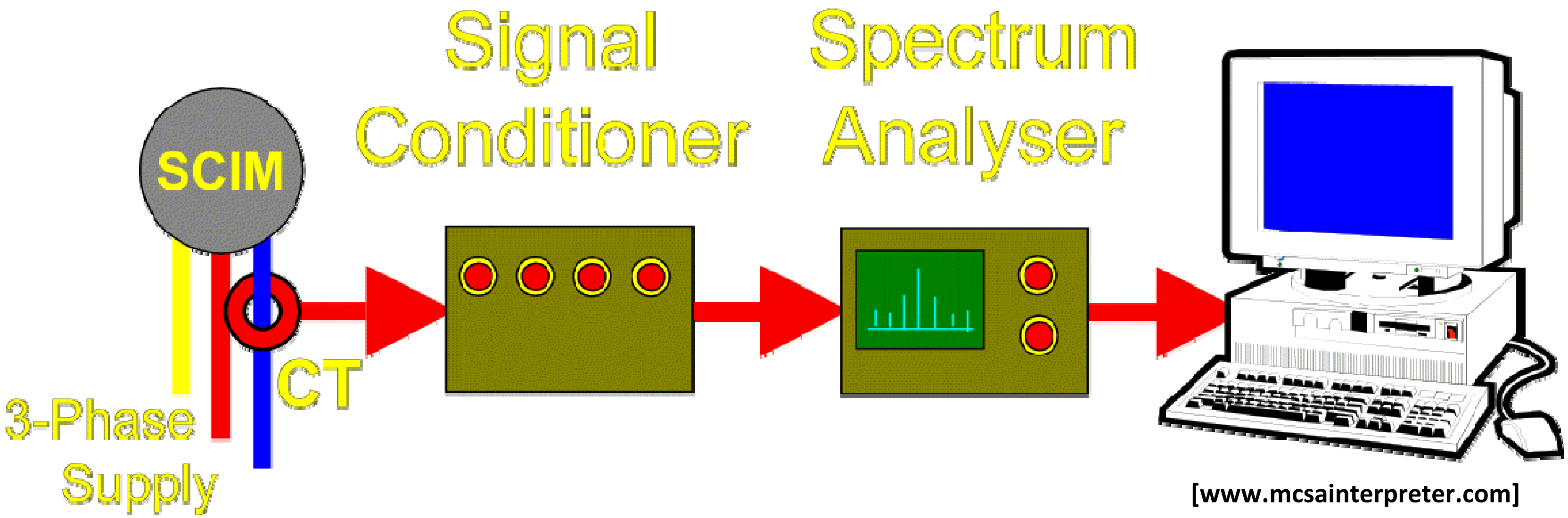
Electrical Faults

- **Shorted Turn**
- **Phase Imbalance**
- **Single Phasing**
- **Broken Rotor Bar**
- **Ground Fault**

Mechanical or electrical faults can change measurable physical or electrical parameters of the motor reflecting in Vibration and/or current signals.

Motor Current Signature Analysis (MCSA)

MCSA is the procedure of capturing a motor's current and voltage signals and analyzing them to detect various faults of the motor.



[www.mcsainterpreter.com]

Advantages:

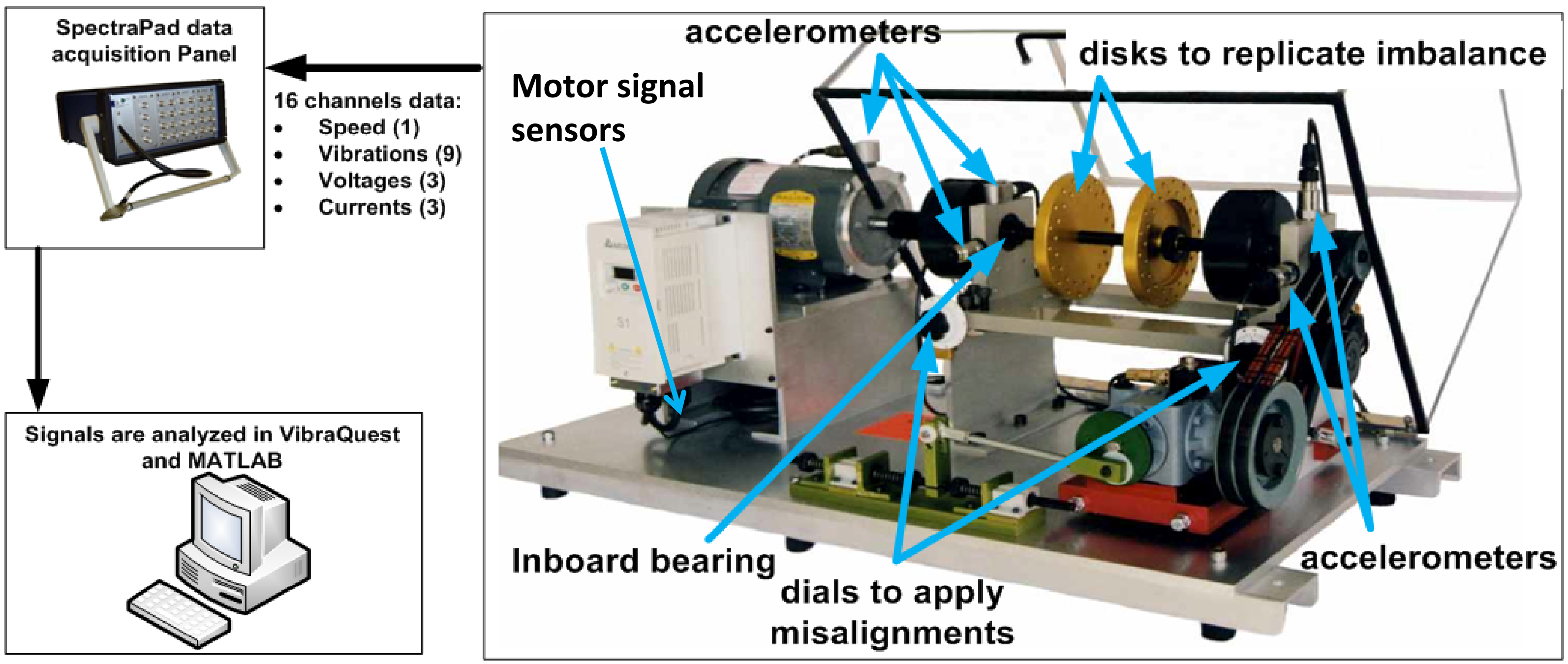
- non-invasive technique
- Online, no stoppage
- Remote monitoring
- Accurate detection of electrical signals

Induction Motor Diagnostics

Test Rig: SpectraQuest's Machinery Fault Simulator (**MFS**)

Data Acquisition using **SpectraPad:** acquiring data simultaneously up to 32 channels

Data Analysis using **VibraQuest:** A comprehensive data analysis software for diagnosis



Experiment Parameters and Specifications

Parameter	Value	Parameter	Value
Induction Motor, Marathon	0.5 HP	Rolling element bearings	MB ER-10K
Number of rotor bars	34	Number of balls	9
Number of stator slots	24	Ball Dia. [mm]	7.94
Shaft diameter [in]	0.625	Outer race Dia. [mm]	31.38
Shaft length [in]	21	Inner race Dia. [mm]	47.26
Rotor bearings span [in]	14.1	Bearing pitch Dia. [mm]	39.32

Experiments Setups

<table>
<tr><th>Faults</th><th>Description</th><th>16 Channels:</th></tr>
<tr><td rowspan="4">Rolling element bearing faults</td><td>Inner Race Fault (IRF)</td><td rowspan="17">Tachometer
Acceleration of motor, vertical
Acceleration of motor, horizontal
Acceleration of inboard bearing, vertical
Acceleration of inboard bearing, horizontal
Acceleration of outboard bearing, vertical
Acceleration of outboard bearing, horizontal
Acceleration of gearbox, axial
Acceleration of gearbox, vertical
Acceleration of gearbox, horizontal
Currents (3 phase)
Voltages (3 phase)</td></tr>
<tr><td>Outer Race Faults (ORF)</td></tr>
<tr><td>Ball Faults (BF)</td></tr>
<tr><td>Combined Faults (CF)</td></tr>
<tr><td rowspan="3">Shorted turn faults</td><td>Level I</td></tr>
<tr><td>Level II</td></tr>
<tr><td>Level III</td></tr>
<tr><td rowspan="4">Eccentricity faults</td><td>Level I: 25%</td></tr>
<tr><td>Level II: 50%</td></tr>
<tr><td>Level III: 75%</td></tr>
<tr><td>Level IV: 100%</td></tr>
<tr><td rowspan="2">Mechanical imbalance</td><td>Static imbalance</td></tr>
<tr><td>Coupled imbalance</td></tr>
<tr><td rowspan="4">Broken rotor bars</td><td>3 broken bars, load 0.5 lb-in</td></tr>
<tr><td>3 broken bars, load 10 lb-in</td></tr>
<tr><td>6 broken bars, load 0.5 lb-in</td></tr>
<tr><td>6 broken bars, load 10 lb-in</td></tr>
</table>

Rolling Element Bearing Faults

Bearing fundamental fault frequencies:

ball passing frequency outer race $$BPFO = \frac{nf_r}{2}\left\{1 - \frac{d}{D}\cos\phi\right\}$$

ball passing frequency inner race $$BPFI = \frac{nf_r}{2}\left\{1 + \frac{d}{D}\cos\phi\right\}$$

fundamental train frequency $$FTF = \frac{f_r}{2}\left\{1 - \frac{d}{D}\cos\phi\right\}$$

Ball spin frequency $$BSF = \frac{D}{2d}\left\{1 - \left(\frac{d}{D}\cos\phi\right)^2\right\}$$

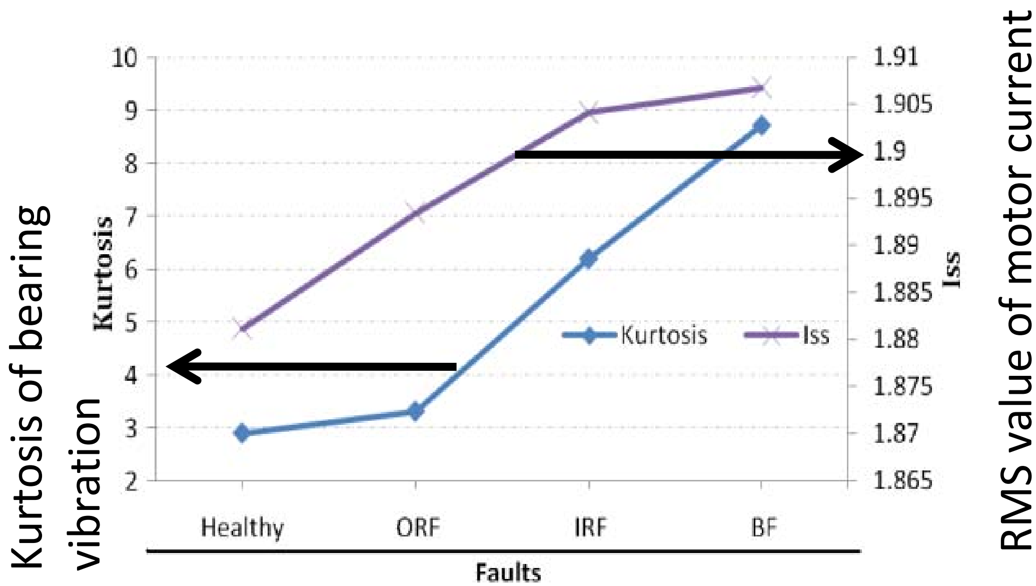
D = pitch dia; d = ball dia; ϕ = contact angle;
n = no. of balls

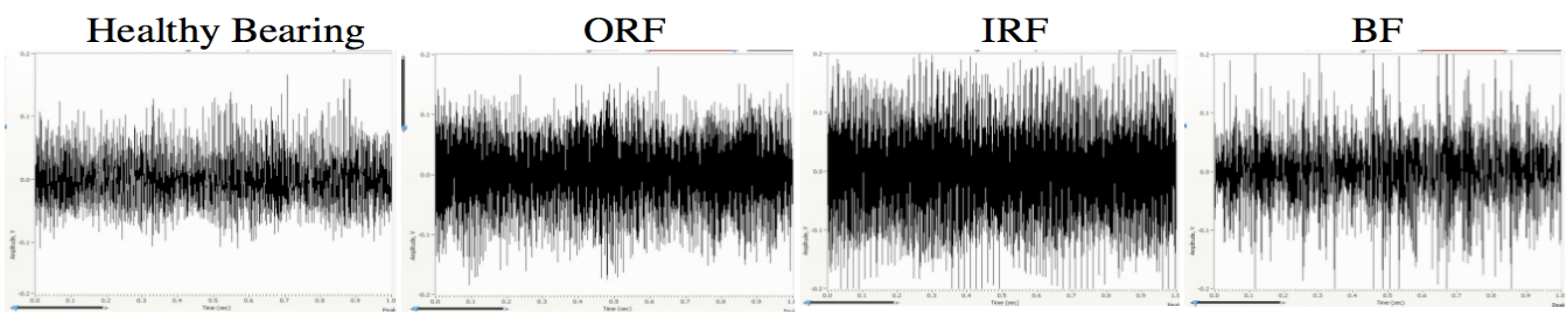
In MCSA, bearing faults can be detected as harmonics of fault frequencies (f_{brg}: BPFO, BPFI, 2×BPF), with line frequency (f_l) sidebands in current spectra.

$$f_{brg}^{MCSA} = Kf_{brg} \pm f_l \quad ; \quad K = 1,2,3,\ldots$$

Rolling Element Bearing Faults (fr=60 Hz, Beam coupling)

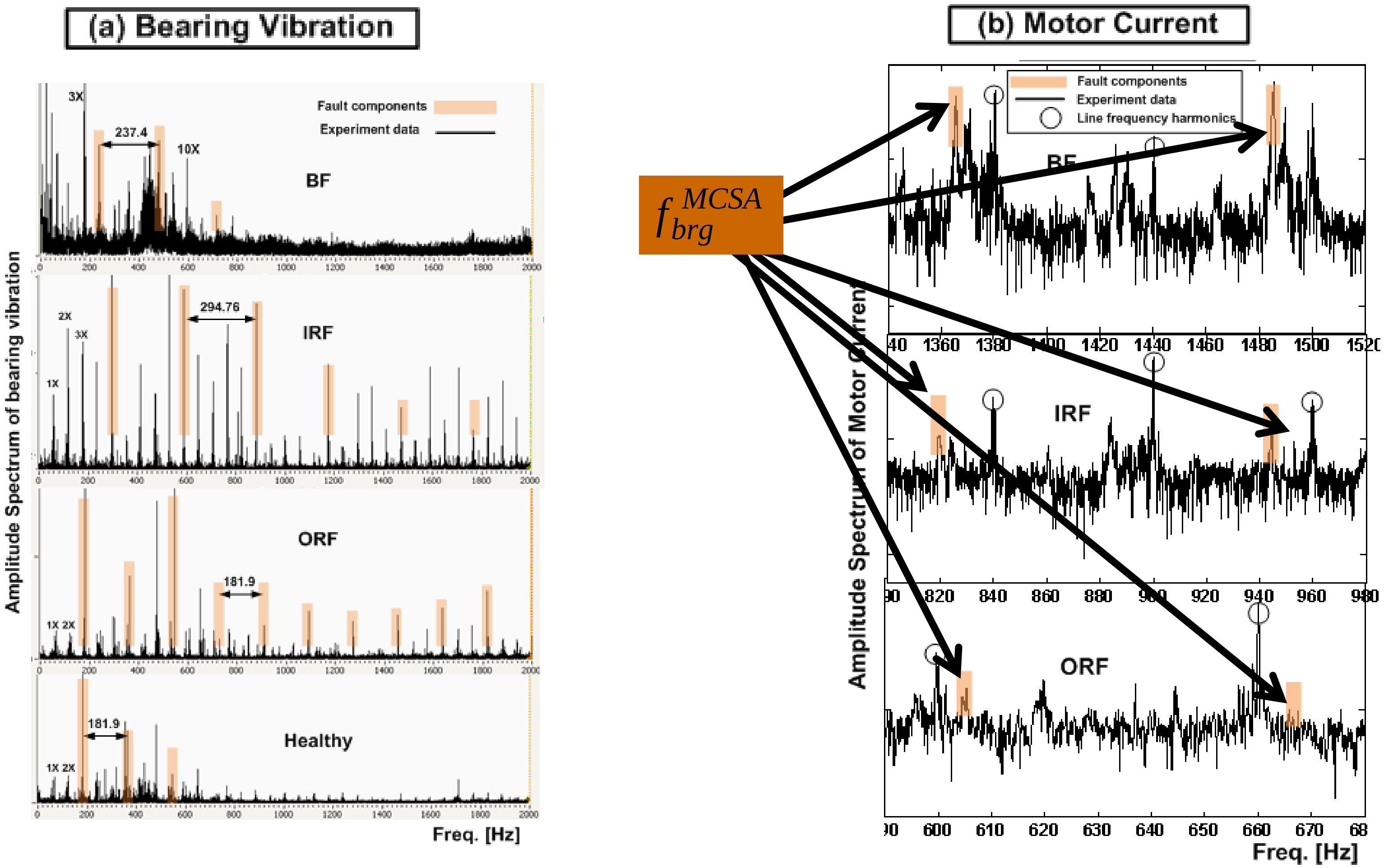
Bearing vibrations significantly are increased with faults.





Rolling Element Bearing Faults

Rolling Element Bearing Faults



Broken Rotor Bars

Fault frequency components:

$$f_{br} = (1 \pm 2ks)f_s$$

f_{br} = frequency components of broken rotor bars
$k = 1, 2, 3, \ldots$
s = per unit slip
f_s = synchronous speed of induction motors

For a 2-pole motor with f_l = 60 Hz $\Rightarrow$ $\boxed{f_{br} = f_l \pm 2kS}$

It represents sidebands of twice of the slip frequency (2S) around the line frequency.

Broken Rotor Bars

Causes and Failures in Induction Motors

Broken Rotor Bars in Squirrel Cage Rotors

Working Torque
Centrifugal Forces
Torsional Vibration
Transient Torques

Magnetic Forces caused by Slot Leakage Flux

$$f_b = \mu_0 {I_b}^2 / 8w$$

Frequency = $2sf_1$

Thermal stresses – end ring heating

Axial Bar growth

Unbalanced Magnetic Pull acting on bars/rotor

Residual Forces from casting, welding, etc

Broken Rotor Bars

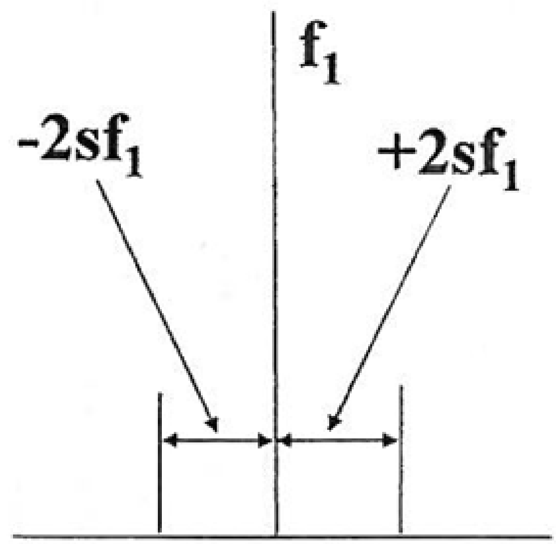
Signature Pattern Due to Broken Bars

$$F_{sb} = f_1 \pm 2sf_1$$

USA : $2sf_1$

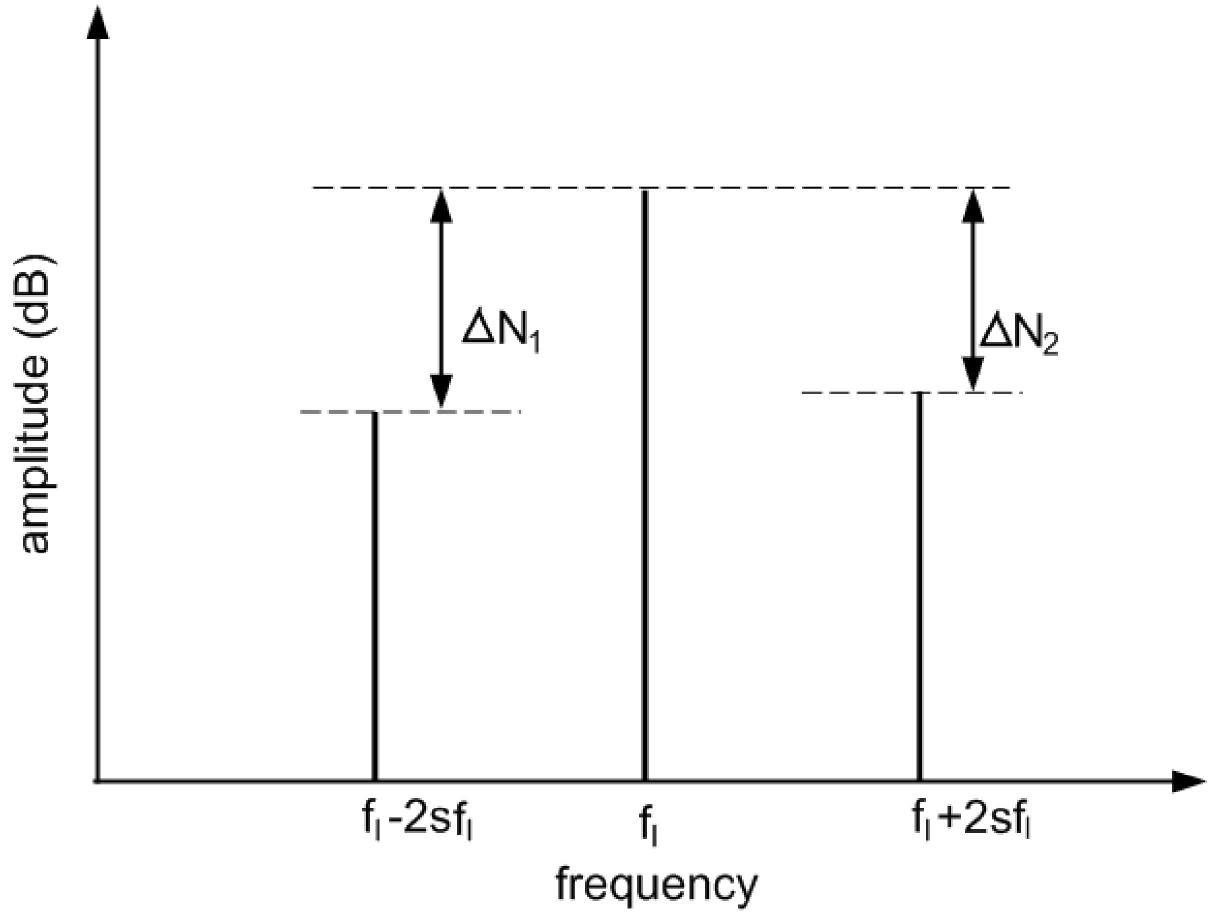
POLE PASS FREQUENCIES

- Slip Frequency sf1
- Rotor Currents and induced e.m.f. in rotor winding



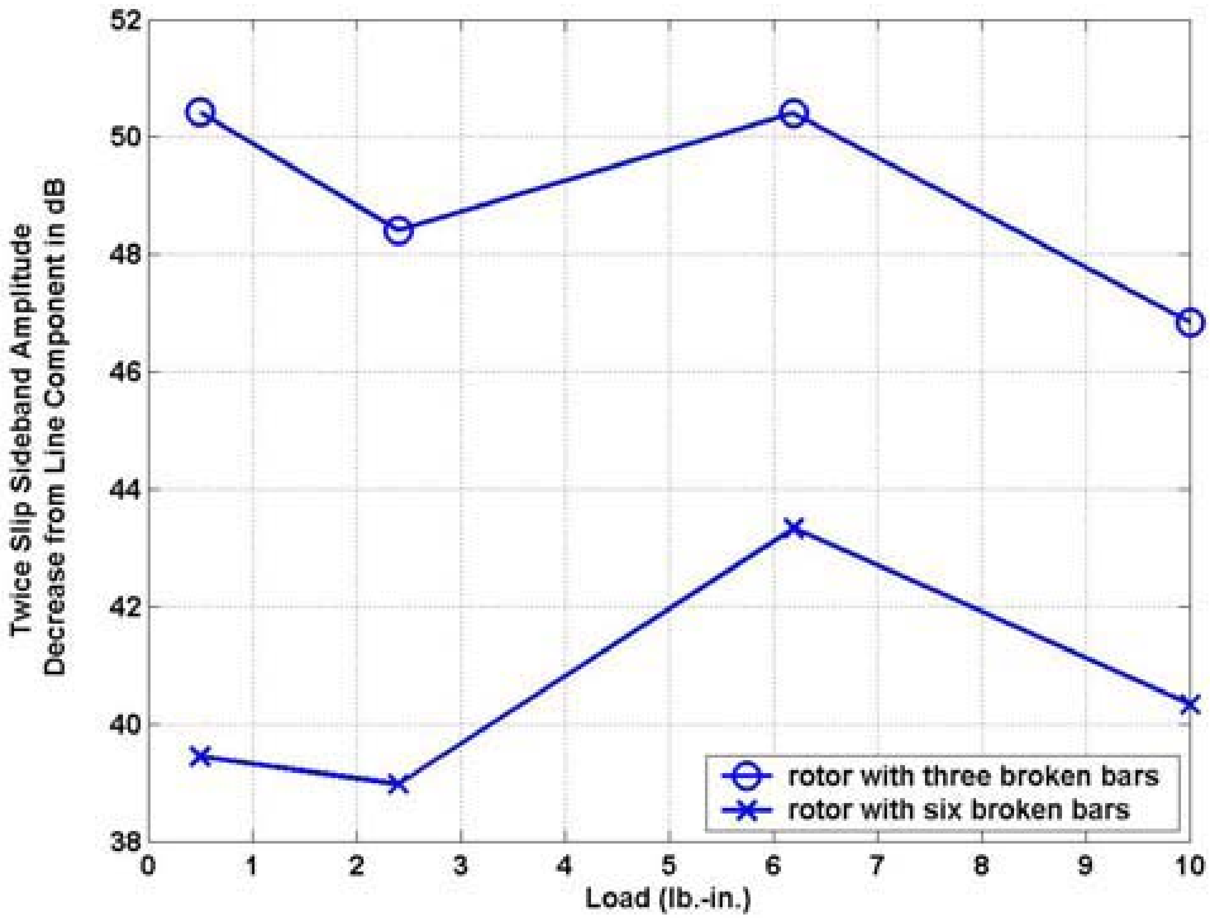
Broken Rotor Bars

Severity is given by the amplitude difference between twice slip sidebands with line component

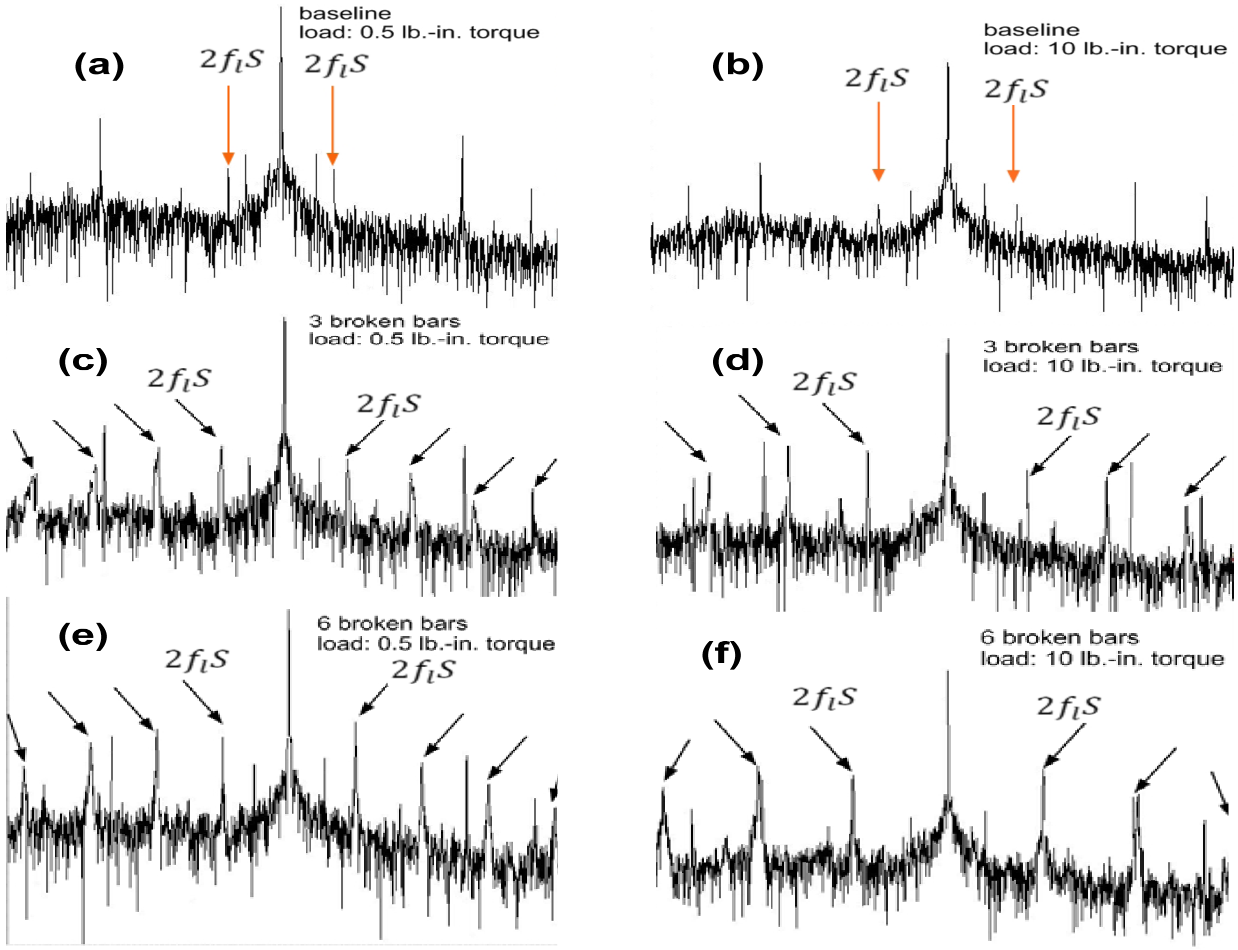


Broken Rotor Bars

Effect of Load on Amplitude Decrease between Twice Slip Sideband and Line Component



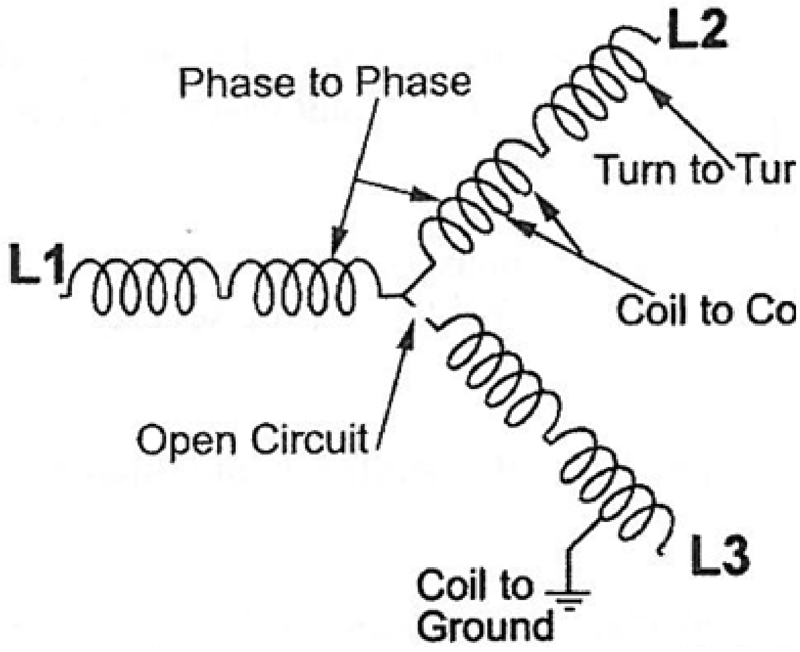
Broken Rotor Bars



Stator Winding Fault

Stator Winding Failure Modes

- Turn to Turn Shorts - Shorted Turns
- Coil to Coil Shorts - Shorted Coils (Same phase)
- Phase to Phase
- Phase or Coil to ground
- Single - Phasing



Shorted Turn Faults

- Turn to turn shorts within a coil
- Short between coils of the same phase
- Phase to phase short
- Phase to ground short (ground fault)

$$f_{st} = \left\{2k\left(\frac{1-s}{p}\right) \pm v\right\} f_l$$

f_{st} = Fault components that are a function of shorted turns
k = 1, 2, 3 … and v= 1, 3, 5…

$$\Rightarrow \quad f_{st} = f_l(k \pm v) - k.S$$

It generates a regular pattern of left sideband around line frequency harmonics.

For even harmonics of line frequency, left sideband are odd multiple of slip speed and for odd harmonics of line frequency, left sidebands are even multiple of slip speed.

Shorted Turn Faults

Low Voltage Stator Winding Problems - Failure Modes

➢ How long does it take for shorted turns within a coil to develop into a phase-to-phase or phase-to-earth fault.

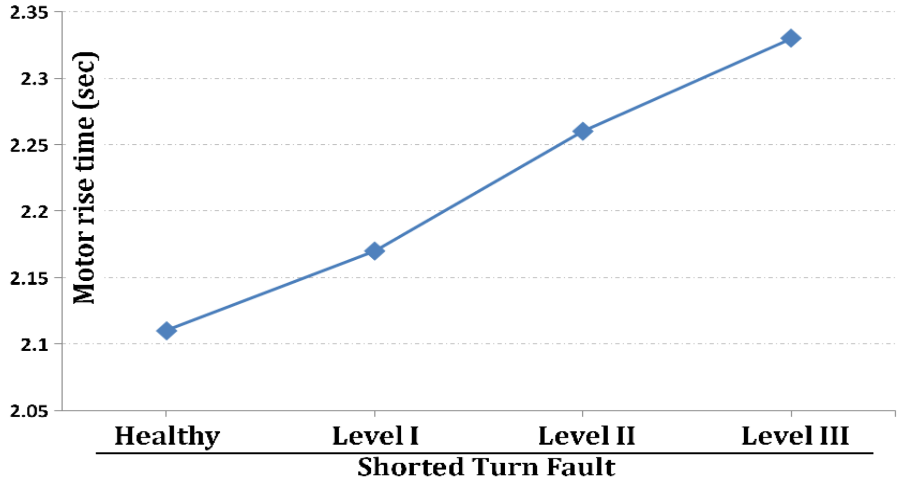
➢ Is it worth diagnosing shorted turns or coils in LV stator windings since the lead time to a failure may be too short.

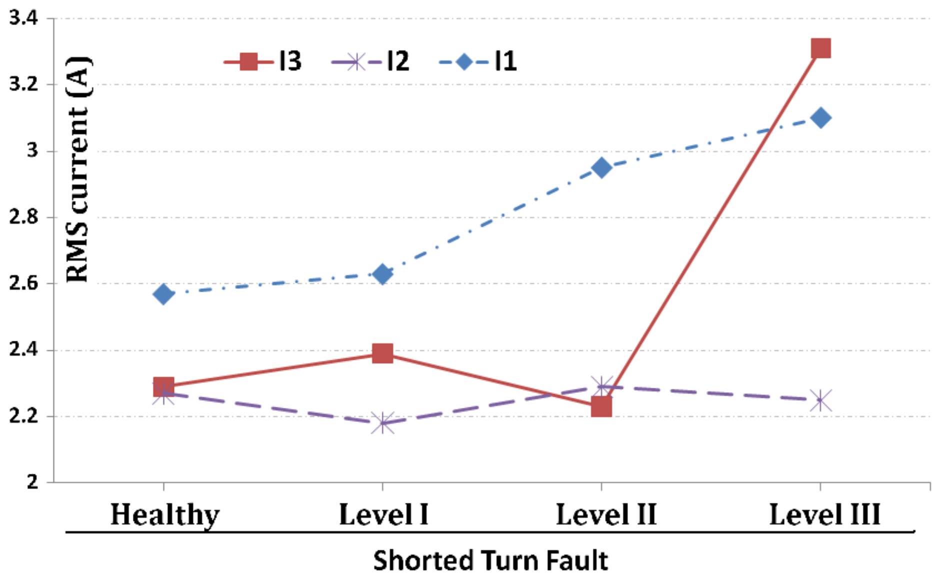
➢ The concept that the motor has already developed a fault and will need to be repaired has prevailed.

➢ In modern production processes then any lead-time can be extremely advantageous.

➢ Unexpected failure of a drive can be very costly and in some industries it can also be a serious safety hazard.

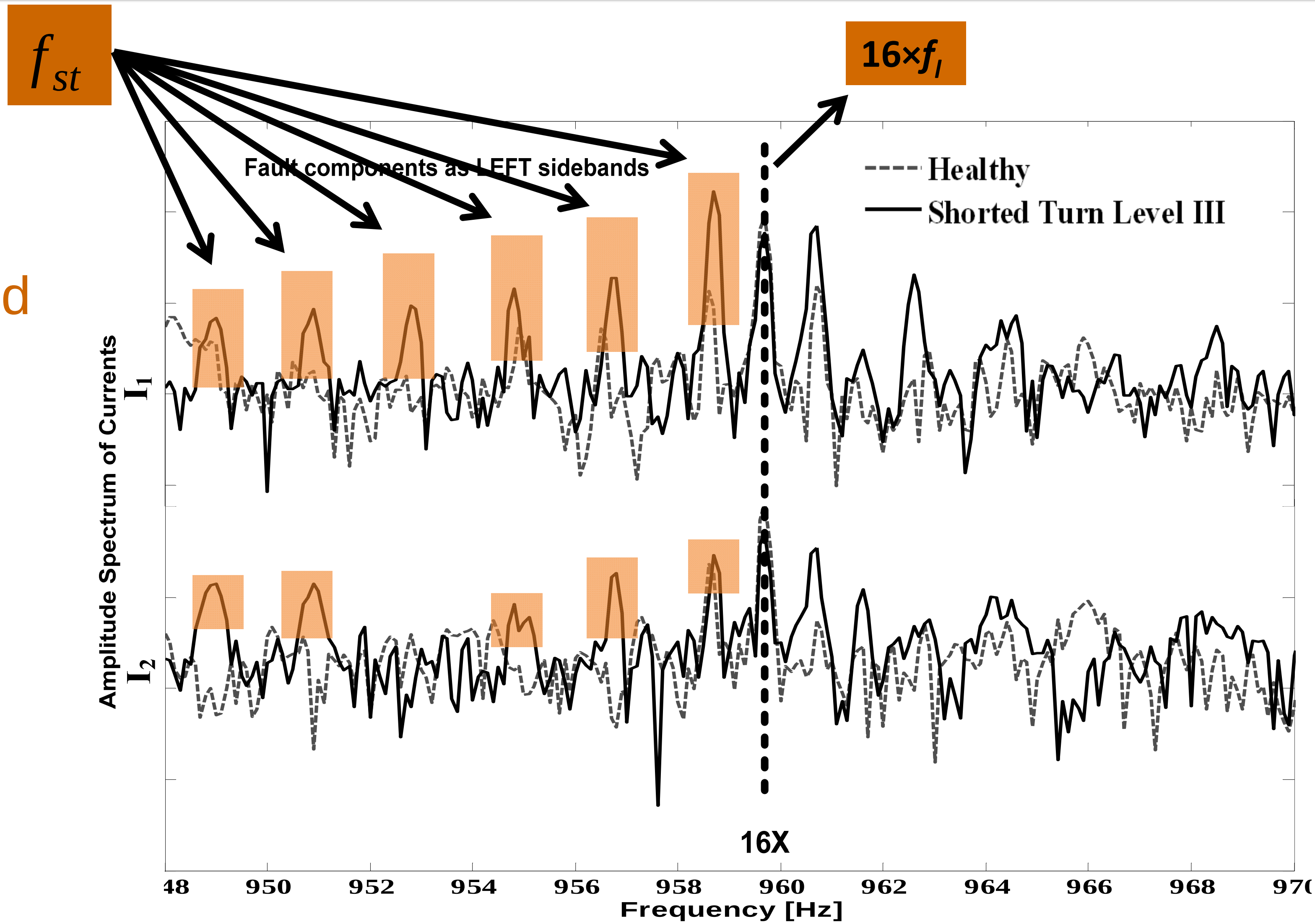
Shorted Turn Faults





Shorted Turn Faults

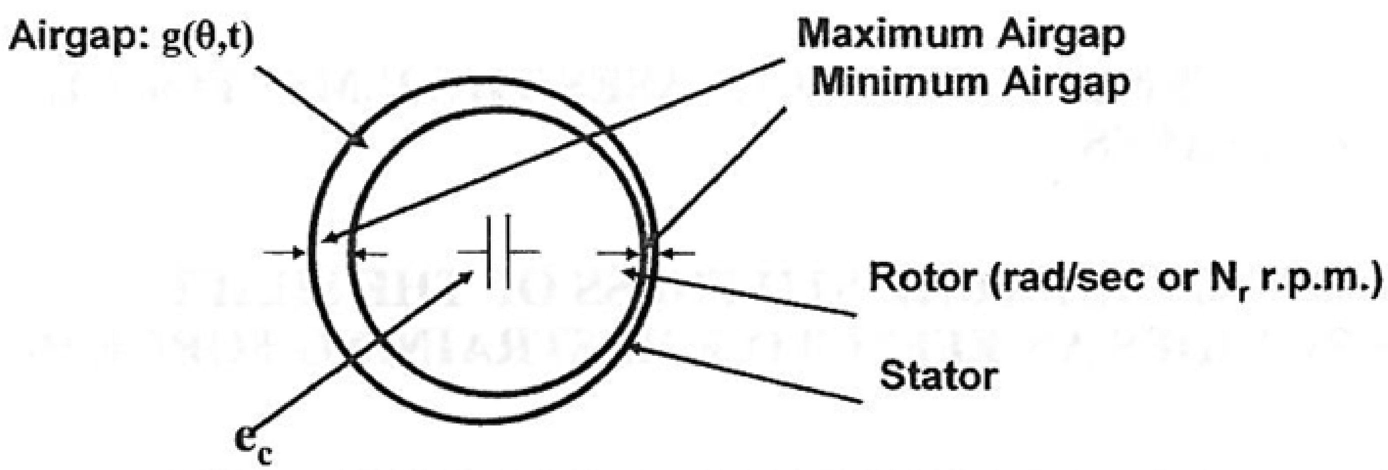
Shorted Turn Faults



Airgap Eccentricity Faults

Causes and Effects of Airgap Eccentricity Problems in 3-Phase Induction Motors

Airgap Eccentricity: Airgap is not a Uniform Radial Length between Rotor surface and Stator bore



For completeness the airgap length as a function of both static (e_s) and dynamic eccentricity (e_d) can be expressed as :

$$g_{(\theta,t)} = g(1 - e_s \cos\theta - e_d \cos(\omega_r t - \theta))$$

Airgap Eccentricity Faults

Effects of Airgap Eccentricity

- An unbalanced magnetic pull (U.M.P.) between the rotor and stator at the minimum airgap
- As eccentricity increases the U.M.P. force increases
- The mechanical Stiffness of the shaft provides an effective restraining force: K
- Rotor to stator rub occurs when the U.M.P. force > K

Airgap Eccentricity Faults

Eccentricity Faults

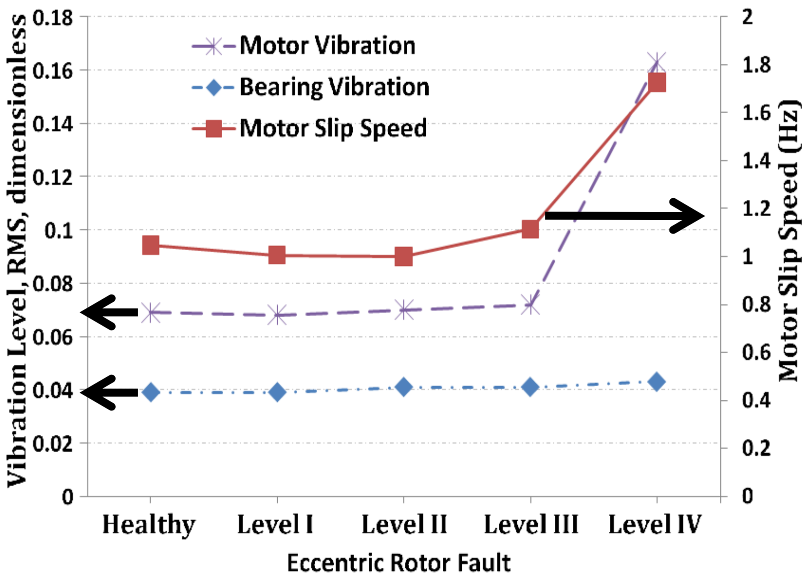
- **Dynamic eccentricity:** the rotor axis is shifted to one side while rotational axis still lies on stator axis. This fault causes whirling motion of the rotor.
- **Static eccentricity:** both rotor and rotational axes are shifted to one side.

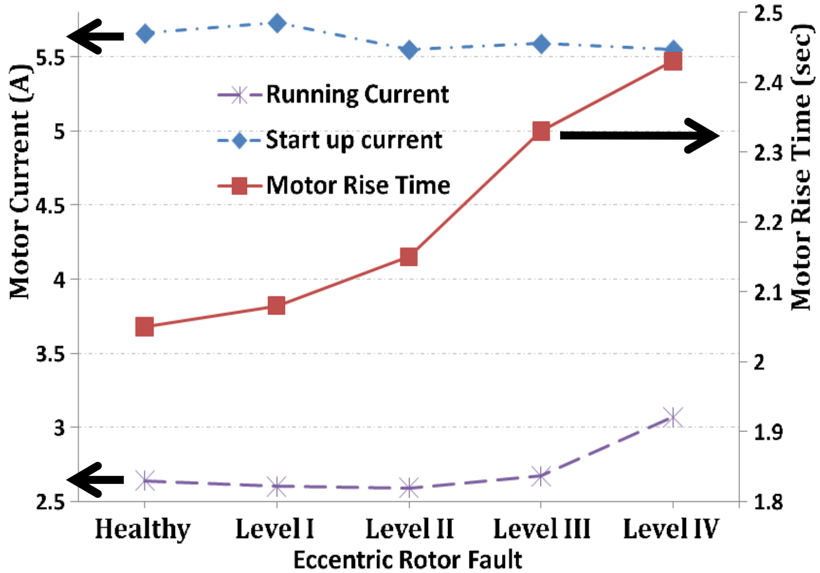
$$f_{ec} = \left\{2(R.k \pm n_d)\left(\frac{1-s}{p}\right) \pm v\right\} f_l$$

f_{ec} = frequency components of eccentricity faults
k = positive constant or zero
$n_d = 0$ for static eccentricity and 1, 2, 3 … for dynamic eccentricity
R = number of rotor bars
$v = 1, 3, 5...$ denotes for line frequency sideband harmonics

$p = 2$, & static eccentricity & $k = 1$ $\Rightarrow$ $\boxed{f_{ec} = R.f_r \pm v f_l}$

Static Eccentricity Faults



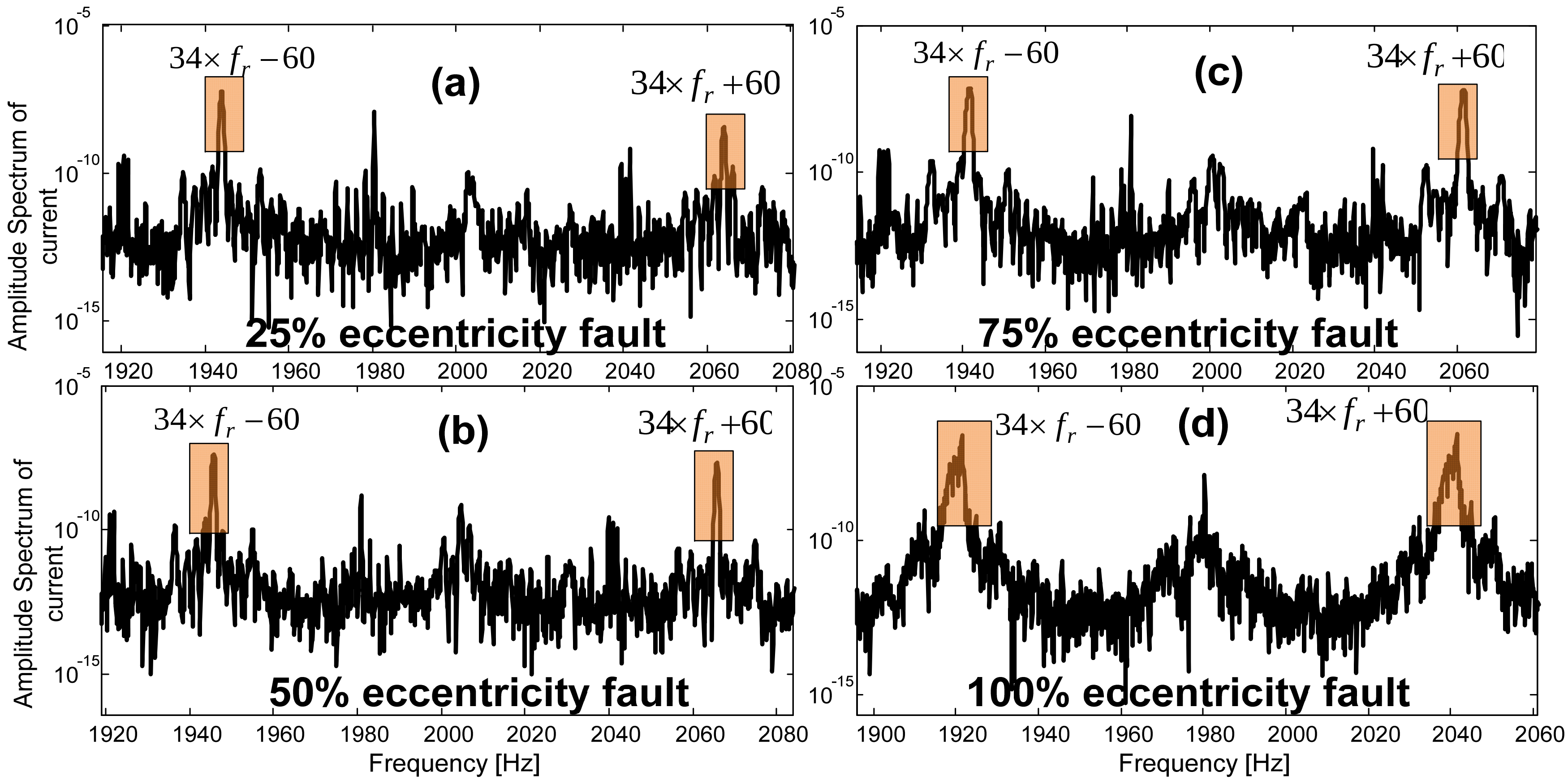


Eccentricity faults in induction motors increase motor rising time, motor slip, and motor running currents.

Airgap Eccentricity Faults

Static Eccentricity Faults

$$f_{ec} = R.f_r \pm v f_l$$



Mechanical Imbalance Faults

Imbalance weights on disks make the **rotor unbalanced** and creates lateral force and motions of the rotating shaft.
In induction motor, lateral motion of the rotor causes **rotating non-uniform air gap** acting as **dynamic eccentricity**. Therefore, in MCSA, mechanical imbalance can be treated as dynamic eccentricity.

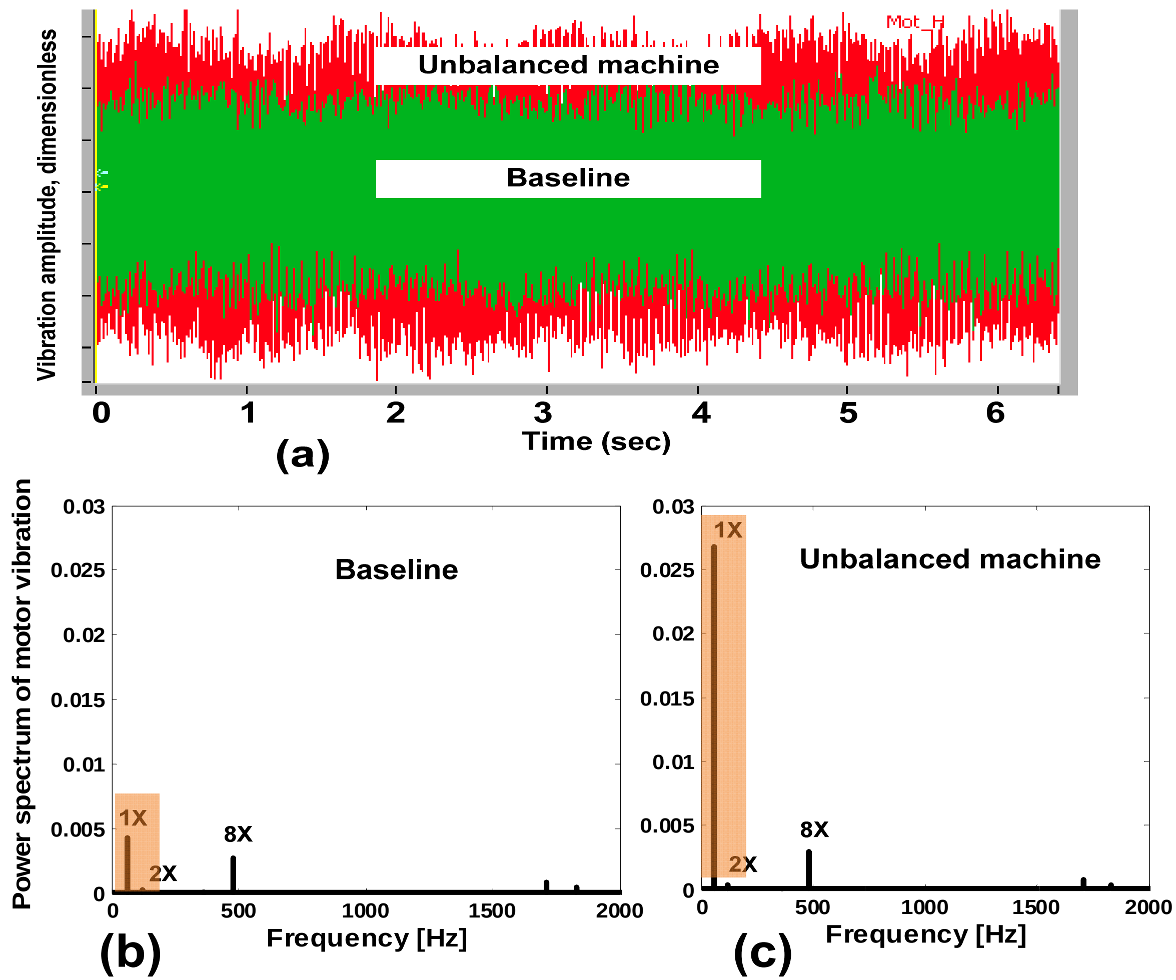
$$\Rightarrow \quad \boxed{f_{imb} = (R \pm n_d) f_r \pm v f_l}$$

f_{imb} = frequency components of mechanical imbalance faults
R = number of rotor bars
$n_d = 1, 2, 3 \ldots$
$v = 1, 3, 5 \ldots$

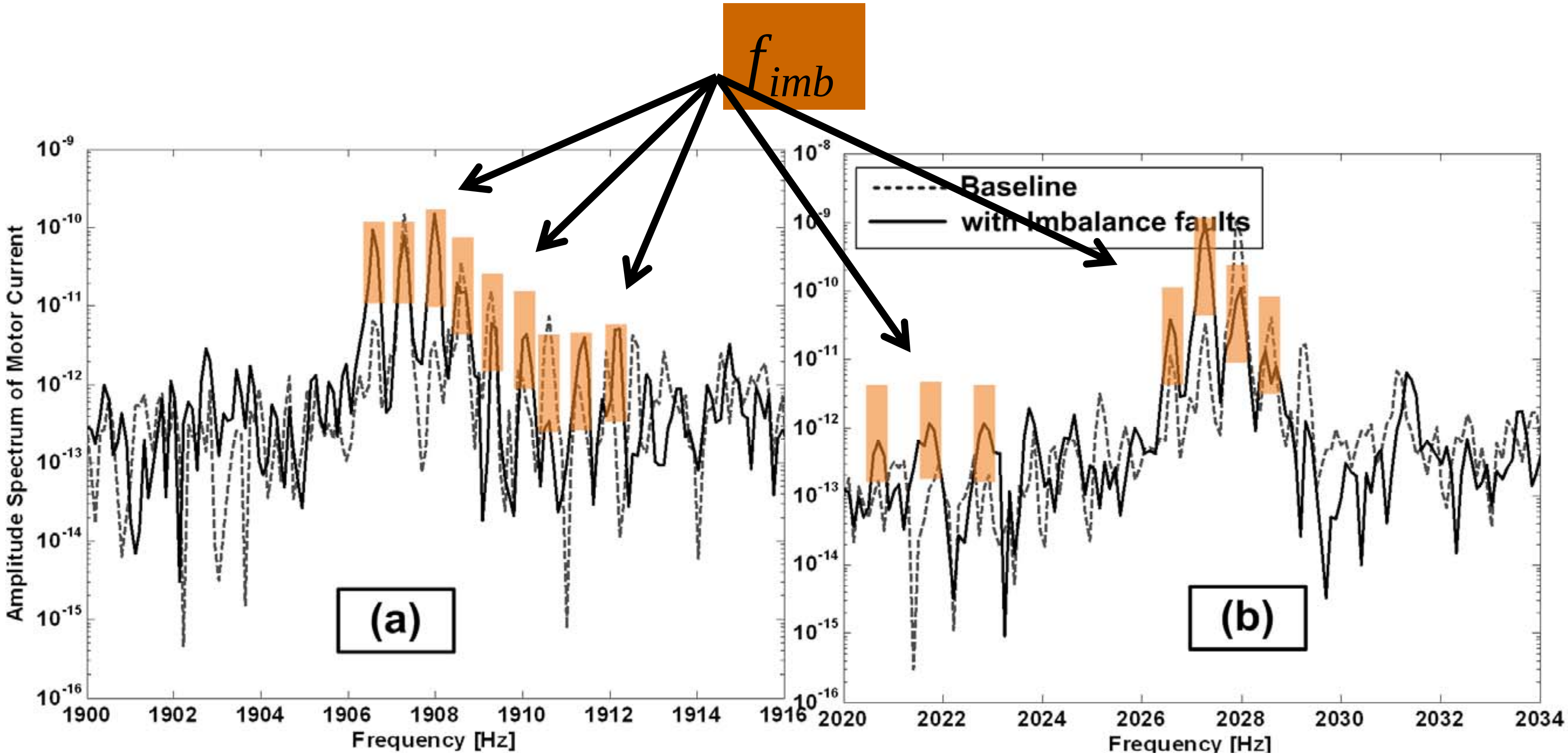
Mechanical Imbalance Faults

Time series of vibration signal

FFT of vibration signal



Mechanical Imbalance Faults



Fault components are slightly increased with mechanical imbalance faults. However, these components are observed even in the baseline spectrum showing the presence of dynamic eccentricity in the healthy motor.

Induction Motor Fault Diagnostics

Conclusions

-Bearing faults: fault frequencies are clearly observed in vibration signals. however in MCSA, fault components are not very clear.

- Shorted turn faults: With MCSA, fault components can be seen as left sidebands around line frequency harmonics. Vibration seems ineffective

-Eccentricity faults: In MCSA, fault signals are not strong and advanced signal processing techniques. Not much is seen in vibration data.

- Mechanical imbalance faults: can be easily detected from vibration. However, fault components are observed if the symptoms is big enough to change the motor air gap.

- Broken rotor bars: generate side bands of twice of the slip frequency (2S) around the line frequency. Surprisingly loading effect was not much.