1. CM Overview

Electric Power

- easily generated from many sources
- efficiently transmitted and distributed
- 70% electric energy used by electric motors
- 40-45% electric energy used in induction motors

Electric Motors

- DC : traditional variable-speed applications
- Synchronous : constant speed, pf correction
- Induction : low-cost, general purpose

Induction Motor Usage

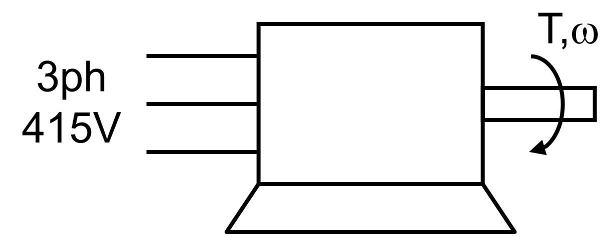
- 10 million large (>80kW) induction motors worldwide
- (6M in the petroleum industry)
- Applications : air-conditioners, fans, pumps, compressors, conveyors, crushers, machine tools, lifts, punch presses, robotics, rolling mills, traction etc
- Industries : manufacturing, petrochemical, mining, power systems, commercial etc

1.1. Induction Machines

induction machines are the most commonly electric motor in industry

characteristics

- operates directly from three-phase AC supply
- self-starting : simply connect to supply
- lowest cost of all electric motor types
- high efficiency
- wide range of sizes : 100W to 10MW
- reliable
- normally relatively fixed speed of operation but option for variable speed



Power	Efficiency
100W	61%
1kW	79%
10kW	88%
100kW	93%
1MW	96%

typical efficiencies
for 4 pole induction motors

1.1.1. Total Cost of Operation

total cost of operation (TCO) = total cost of motor over its lifetime, it includes :

- installation : cost of installing the motor
- purchase cost : cost of motor itself
- cost of repair : cost of maintaining the motor
- reliability : is the cost of the lost production due to failure of the machine
- electricity : cost of electricity to run motor

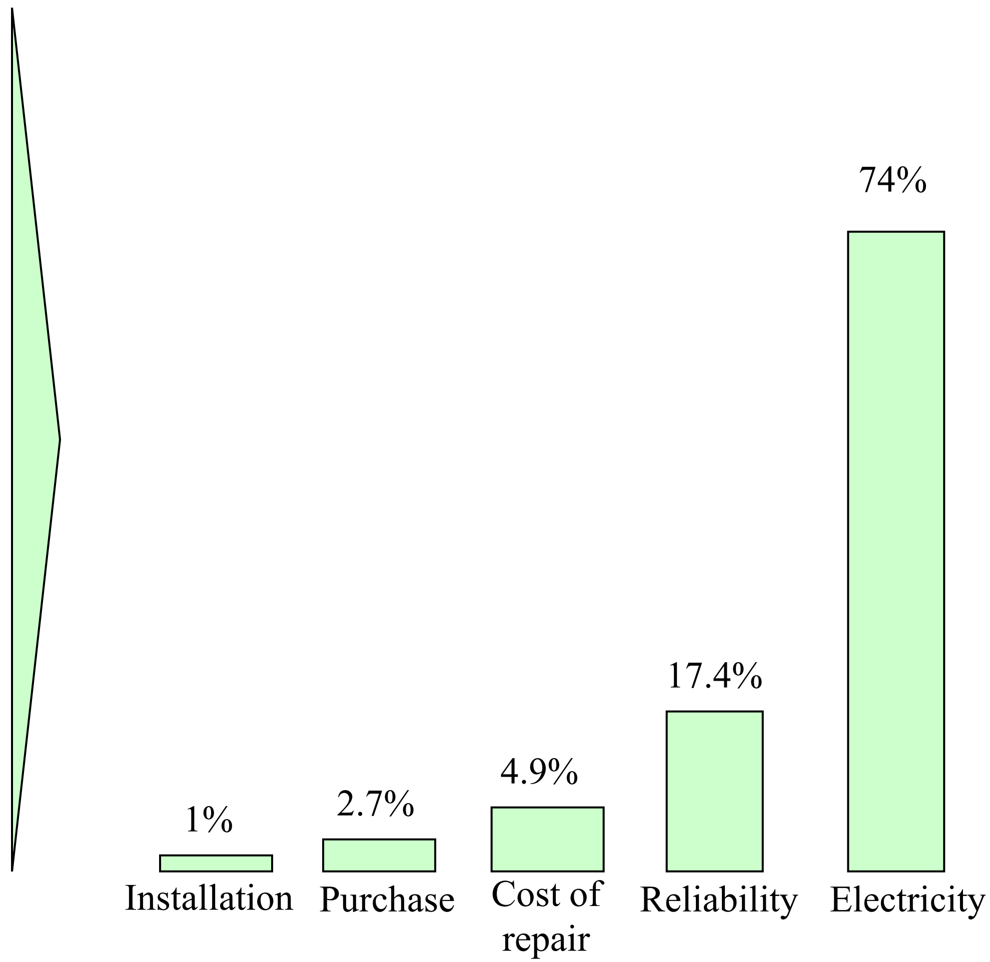
comments

- purchase price is a small part of the TCO for electric motors
- slight variations in efficiency could dramatically affect the TCO through electricity costs
- reliability is difficult to quantify but could be a very important cost

1.1.2. TCO Survey Results

TCO includes:

- •Purchase price
- •Specifications
- •Transportation
- •Storage
- •Installation
- •Quality Assurance
- •Reliability
- •Electricity
- •Repairs
- •Administration
- •Inventory
- •etc



Information provided by Machinemonitor based on survey of 6000 machines

1.1.3. Energy Costs

Energy and Energy Costs

energy = power x time

- 1 joule = 1 watt x 1s
- 1 kWhr = 1kW x 1hr = 1000W x 3,600s = 3.6MJ

for electricity generation and utilisation, energy is often measured in kWhr,electricity is charged per kWhr

the power rating of motors is the output power : Pout = Pin x efficiency

Example : consider a 2.2kW induction motor, cost about A$200, efficiency about 80%, assume

- working at rated output, 8 hrs/day, 7 days/week
- electricity costs $0.20/kWhr

rated input power = 2.2kW/efficiency = 2.75kW

Calculate the electricity costs per year.

- energy/year = power x time
- cost/year = electricity price x energy/year

1.2. Electric Motor Maintenance

General maintenance strategy : taking into account importance of the particular machine, trade-off between

- cost/risk of unexpected failures : downtime/lost production costs
- maintenance related costs : labour/parts costs of maintenance, and lost production time

Types of Maintenance

1) corrective maintenance (non-critical applications)
   - fix it when it fails eg. fridge

2) time based maintenance
   - inspect/overhaul it at a predefined intervals, [overhaul = take motor apart to check for faults, has risk of introducing new failures!] e.g. car

3) condition based maintenance
   - inspect at interval determined by
     - estimate of motor state of health
     - criticalness of motor
     - usage of motor

1.2.1. Maintenance Approaches

What is condition monitoring?

– assessing health of machines using detailed measurements

Condition monitoring advantages : reduced overall cost

– reduce unexpected failures

– reduce maintenance requirements, overhaul only when required

Types of condition monitoring

1) Off-Line : tests done on non-operating motor
   - tests : insulation health, electrical symmetry
   - particularly useful for insulation testing

2) On-Line : tests done on operating motor (main focus here)
   - tests : vibration, current, flux, voltage, partial discharge
   - detection of rotor, stator, bearing, eccentricity faults etc.
   - allows more comprehensive testing

1.2.2. On-line Cond. Mon.

1250kW, 6 pole

>1 MW

Photos courtesy
of RME

1.2.3. Hidden Faults

hidden faults are machine faults which may have only minor symptoms but results in

– lower efficiency and hence higher energy consumption

– poorer performance

– long term degradation

examples

– misalignment, eccentricity etc

even small faults can cause increase increased losses

– reduce efficiency

– increase temperature : will result in reduced insulation life

– increase vibration : may result in reduced bearing life

2. Induction Machine Theory

2.1. IM Construction

2.2. AC Three-Phase Systems

2.3. Rotating Magnetic Fields

2.4. Slip and Slip Frequency

2.5. Torque vs Speed Characteristics

2.1. IM Construction

Stator core : requires good magnetic properties, carries magnetic flux in machine, mechanically strong, consists of iron laminations

Stator winding : three-phase winding connected to mains

• allows electric power input to machine

• generates rotating magnetic field

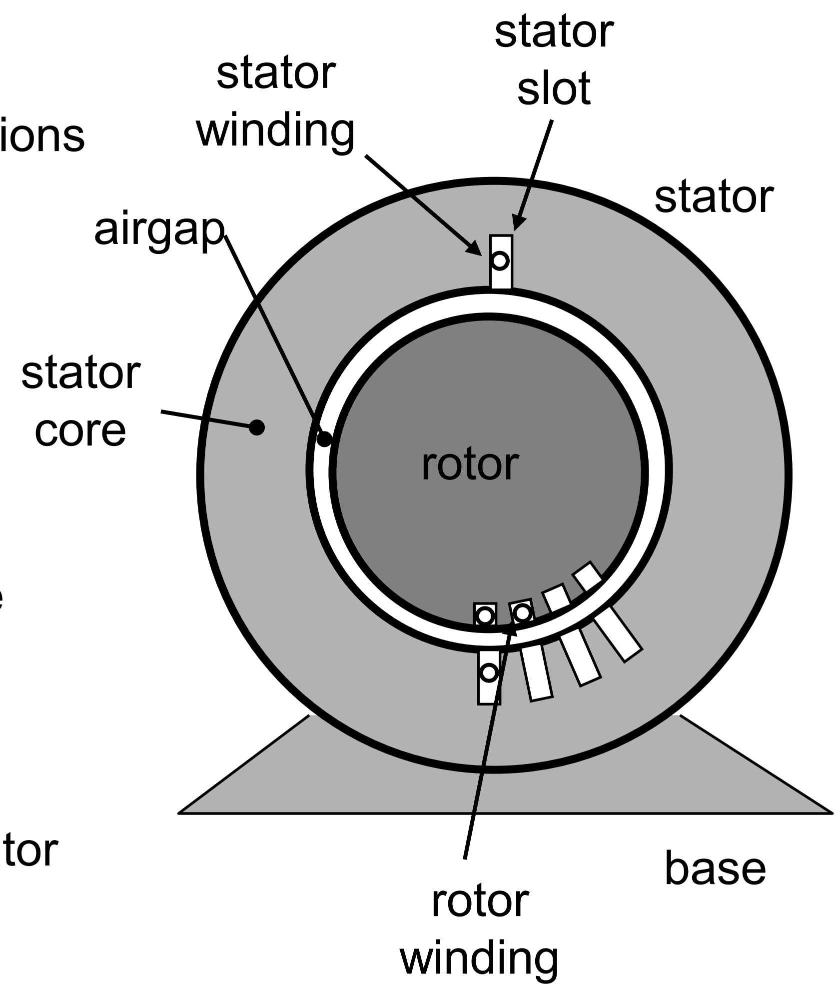
Airgap : physical and electromagnetic gap between rotor and stator

• normally as small as mechanically possible (fraction of percent of rotor diameter)

Rotor winding : magnetic flux from stator induces currents in the rotor winding

• these induced currents interact with the stator flux to produce torque

Rotor core : good magnetic properties, mechanically strong, consists of iron laminations



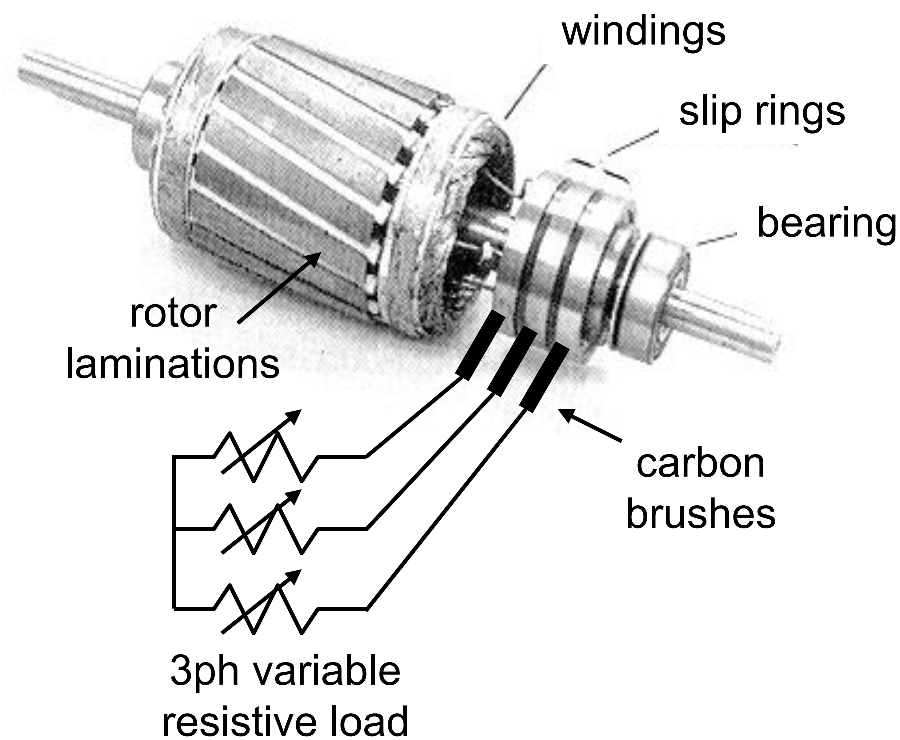
2.1.1. Rotors

Induction motor rotors consist of a stack of laminations with a short-circuited rotor winding. There are two winding types :

a) wound-rotor (slip-ring) : 3ph (copper) winding in slots (similar to stator winding), three ends of windings brought out to three rotating slip-rings. Stationary carbon brushes are used to make contact to rotating slip-rings. The brushes are connected to an external 3ph variable resistance bank.

More expensive than the squirrel-cage and only used for special applications.

slip-ring induction rotor



2.1.2. Squirrel Cage Rotors

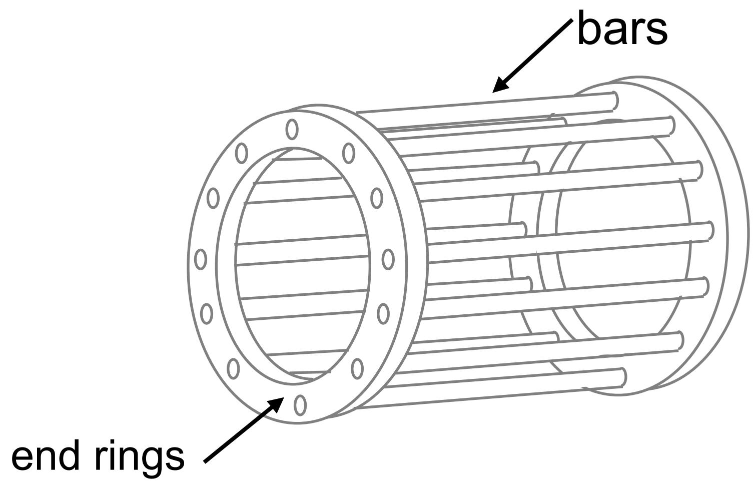
The second rotor winding type is :

b) squirrel-cage : the rotor winding consists of solid metal bars shorted out at both ends of the rotor by circular end-rings. Two types of construction :

i) <u>cast aluminium</u> : bars and end-rings formed by pouring molten aluminium alloy over the rotor laminations. Most common construction, particularly for small to medium size induction machines. Very low cost.

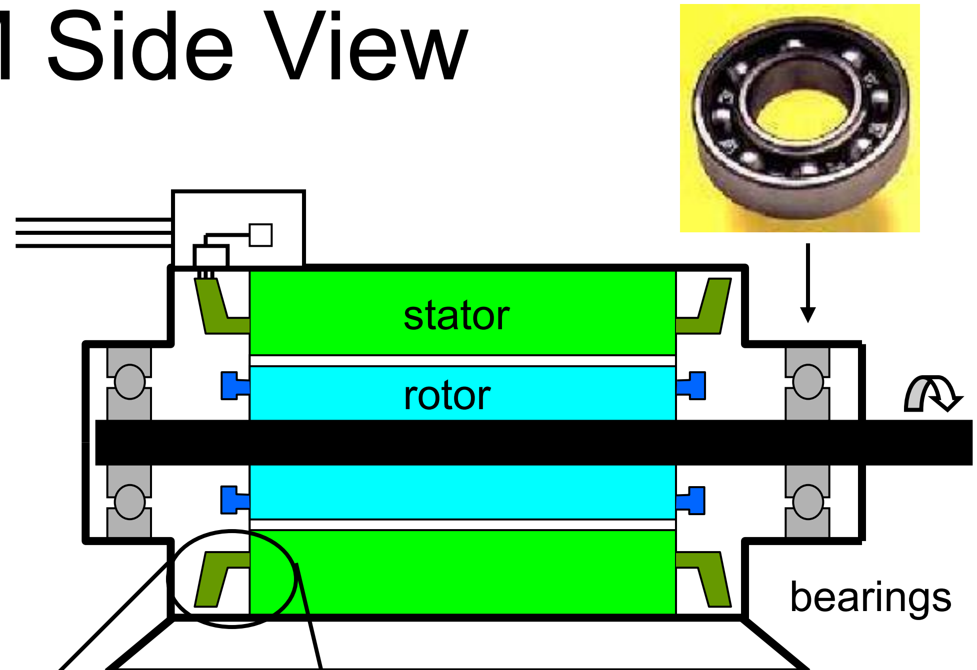
ii) <u>fabricated rotor</u> : rotor made from copper bars and end-rings which are welded or brazed together. Offers the highest efficiency but more expensive. Used on larger machines.

commercial cast aluminium rotor



rotor conductors in a squirrel cage rotor

2.1.3. IM Side View



<u>Bearings</u> : support the rotor, usually constructed using ball bearings, precision device with tight tolerances, sensitive to excessive loads and vibration, most common cause of failure of electric machines

<u>Stator insulation</u> : insulating material between copper windings and the stator core. Operating temperature normally in range 100 to 150^{o}C. Note that raising the operating temperature by 10^{o}C will halve the insulation life. Insulation failure is the second most common electric motor failure mechanism.

stator
end-windings

2.1.4. Cut-Away View

1) **cast aluminium rotor** : showing rotor skew (rotor bars are twisted slightly to make the motor run more smoothly), rotor cooling fins

2) **stator** : three phase windings with circular end-windings at each end

• terminal box for making connections to power cable

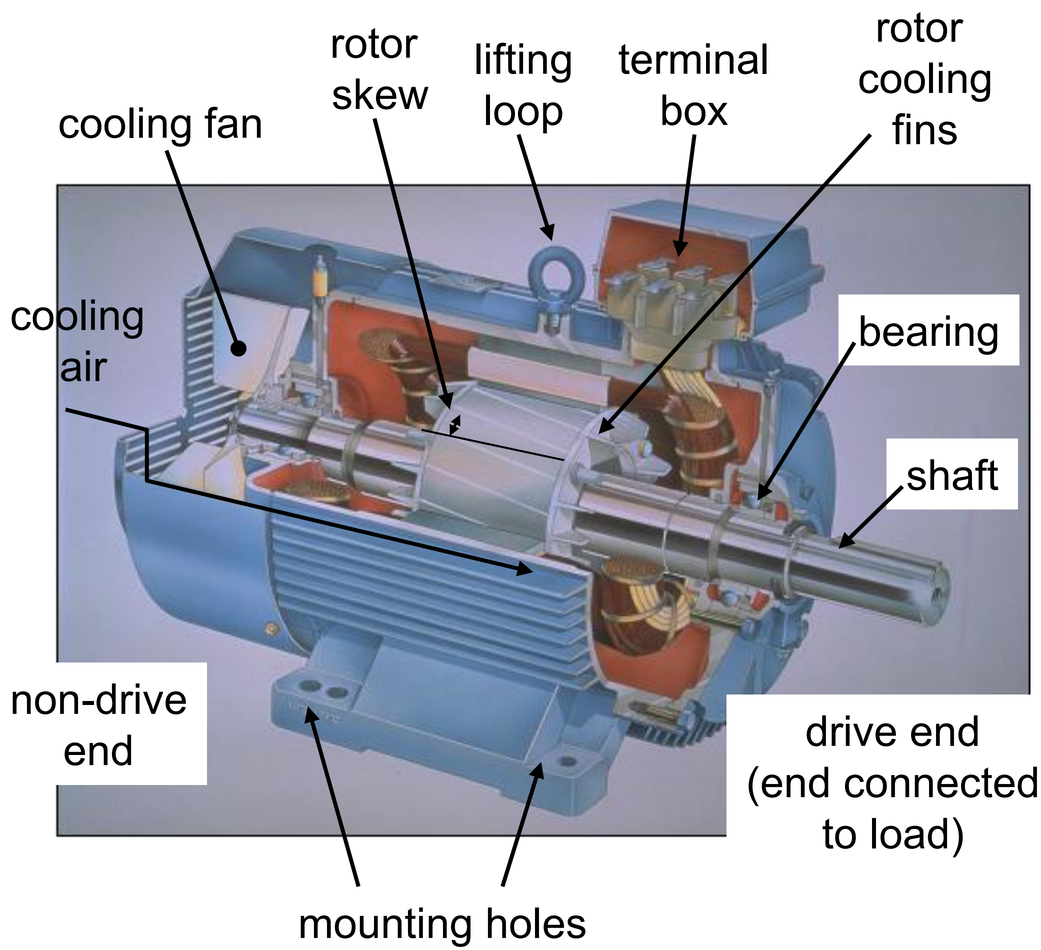
• loop to allow motor to be lifted into position

3) **cooling** : totally enclosed fan cooled (TEFC) motor

• cooling fan at non-drive end

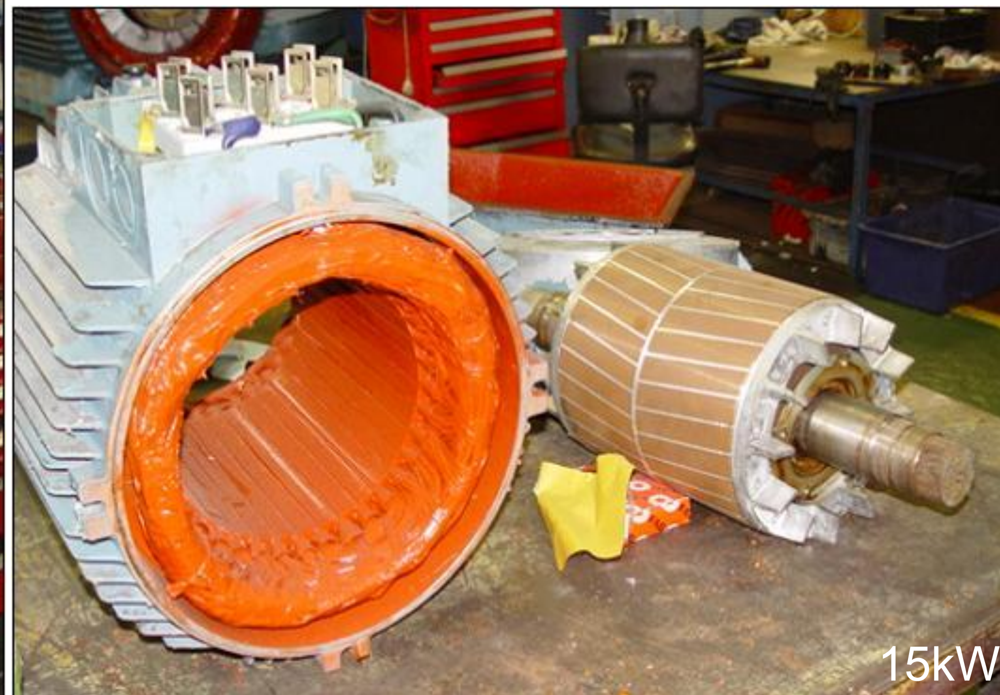
• finned aluminium case to improve cooling

• cooling air does not pass through motor but only on outside of case



2.1.5. 150/15kW Machines

150kW motor with end-cap and bearings removed showing cast aluminium cage rotor resting on inside of stator.



Photos courtesy of RME

2.1.6. Motor Rewinding

Motor rewinding : stator and rotor windings are removed from machine and new windings inserted.

This is done if a large motor develops a fault. Often cheaper than trying to buy an identical new machine. Rewinding is not usually economic for small machines unless not easily replaced.

The photo shows the stator and rotor after the original windings have been removed but before the new winding has been inserted.

260kW, 8 pole Machine

air ventilation (cooling) holes

Photo courtesy of RME

2.1.7. 500kW, 4 Pole Motor

Stator

Rotor

Photos courtesy of RME

2.2. AC Analysis : Signals

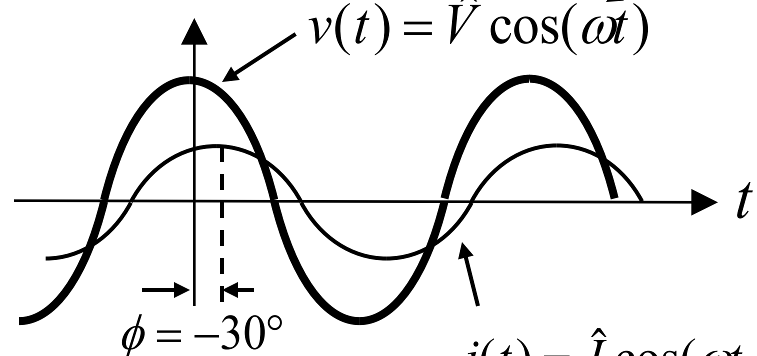
analysis with 50Hz (or 60Hz) AC sinusoidal signals

1) Time Domain

$$v(t) = 240\sqrt{2}\cos(2\pi 50t)\ \text{V}$$

$$i(t) = \underbrace{10\sqrt{2}}\cos(2\pi 50t - 30°)\ \text{A}$$

peak value=rmsx√2



2) (RMS) Phasors

$$\mathbf{V} = 240\angle 0°\ \text{V} = 240\ \text{V}$$

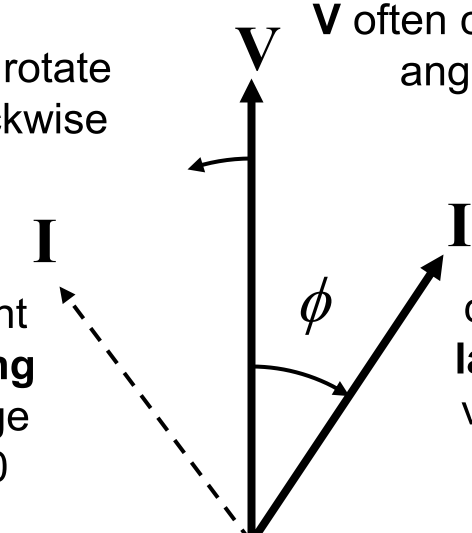
$$\mathbf{I} = 10\angle -30°\ \text{A} = 8.66 - j5\ \text{A}$$

written on board as $\underset{\sim}{I}$

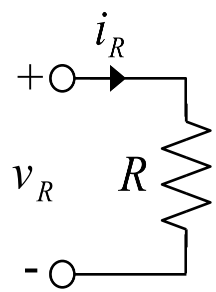
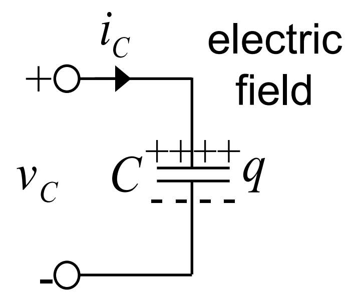
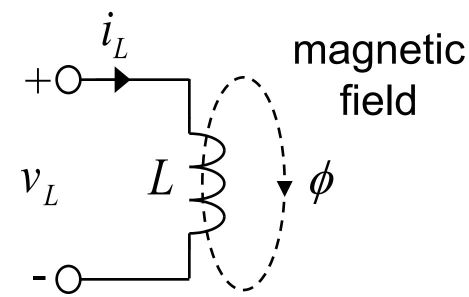
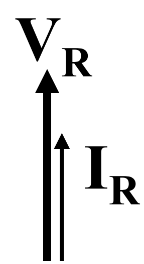
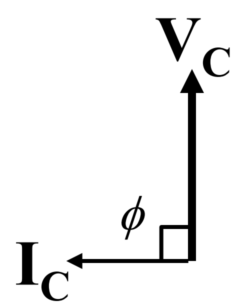
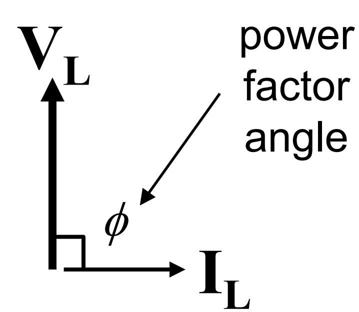
3) (RMS) Magnitudes

$$V = 240\ \text{V}$$

$$I = 10\ \text{A}$$

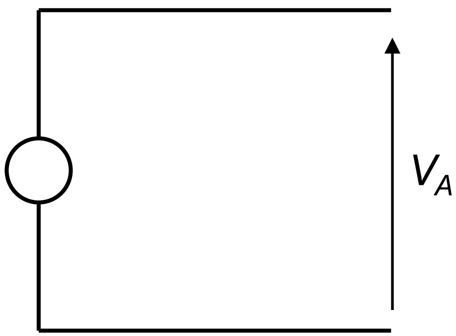


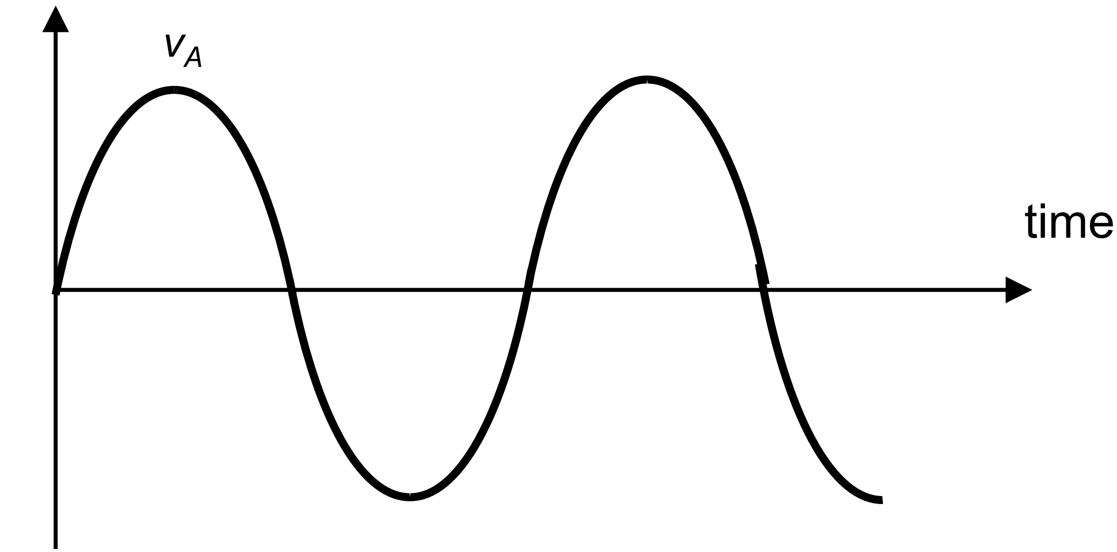
2.2.1. AC Components

	Resistor	Capacitor	Inductor
Principle			
Reactance X		$X = -\dfrac{1}{\omega C}$	$X = \omega L$
Impedance **Z=R+jX**	$Z = R$	$Z = jX, \quad X < 0$	$Z = jX, \quad X > 0$
Phasors $\mathbf{V} = \mathbf{I}Z$ phasors	 $\phi = 0^o$	 $\phi = +90^o$	 $\phi = -90^o$

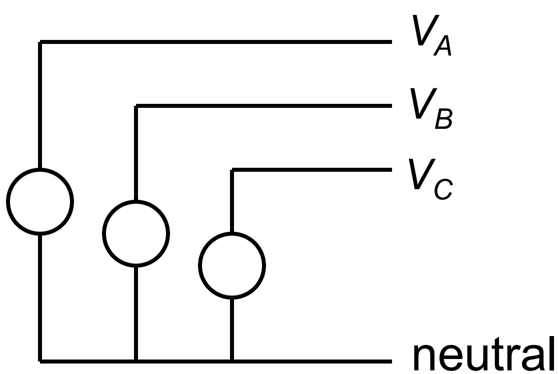
2.2.2. Three-Phase Supply

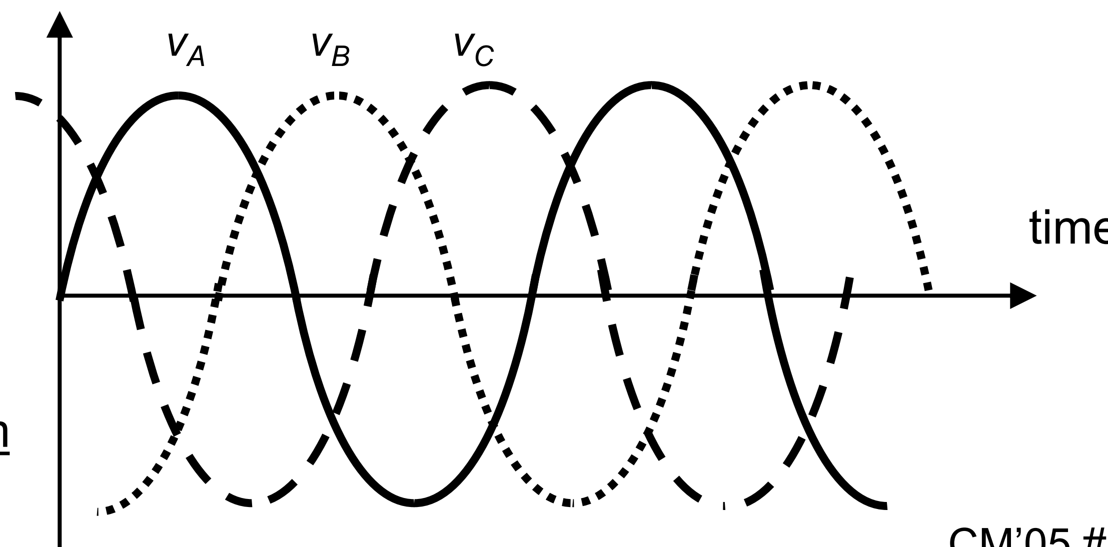
<u>Single-Phase Supply</u>





<u>Three-Phase Supply</u>





<u>balanced three-phase system</u>
voltages equal magnitude
and 120 deg apart in phase

2.2.3. Balanced Three-Phase Supply

Balanced Three-Phase Supply

- equal magnitude voltages
- 120 degrees apart (phase shift)

Can represent as set of three phasors representing voltages between supply lines and neutral.

eg. $V_{AN} = 239.6\angle 0°V$

$V_{BN} = 239.6\angle -120°V$

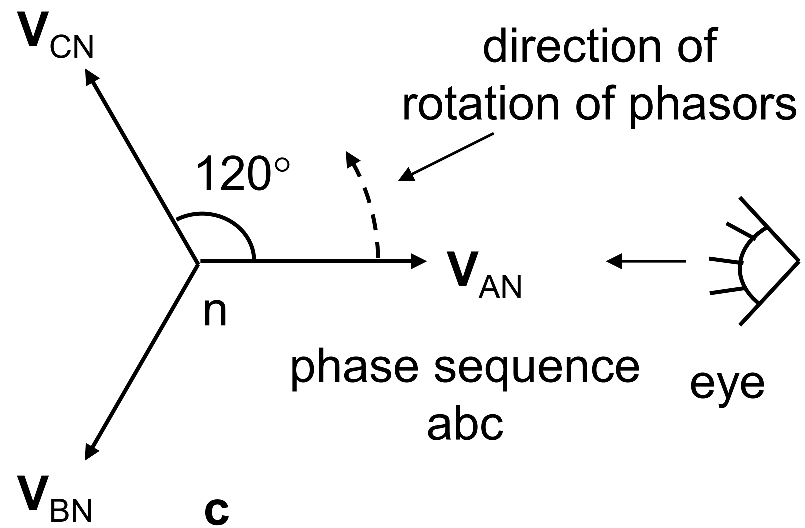
$V_{CN} = 239.6\angle -240°V$

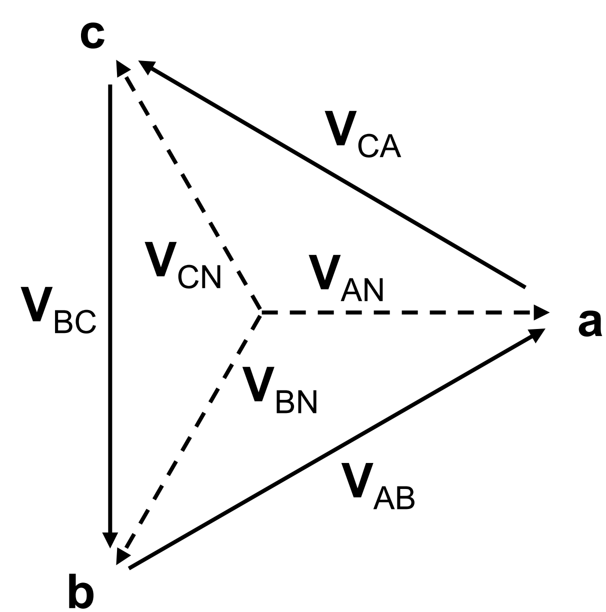
where the magnitudes are equal, that is $V_{AN} = V_{BN} = V_{CN}$

The voltage between the supply lines a and b is :

$V_{AB} = V_{AN} - V_{BN}$

from geometry, the magnitudes are related by $V_{AB} = \sqrt{3}\, V_{AN}$



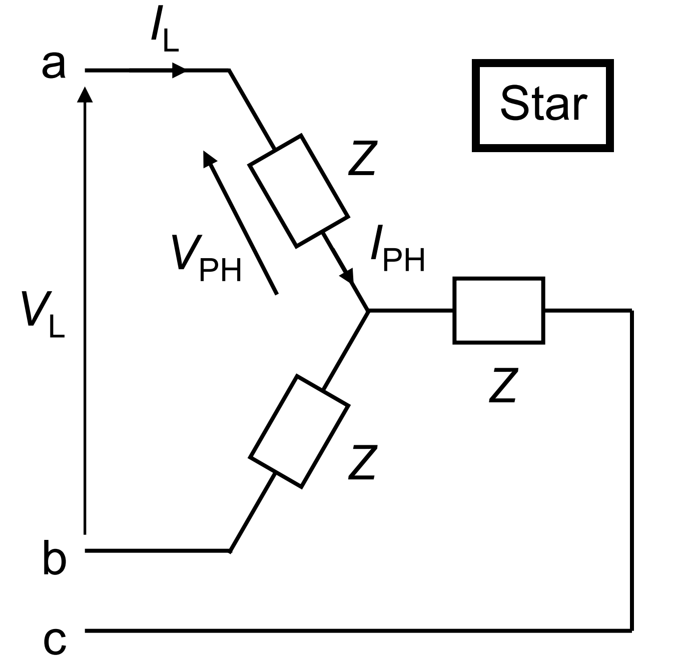


2.2.4. Star/Delta Loads : Definitions

A three-phase system has three supply lines. A three-phase load consists of three separate phase windings (or elements or impedances). These three phase windings can be connected to the supply in two methods :

star : phase windings are connected to a supply line on one end, and are joined together on the other end at the “star” point (most common)

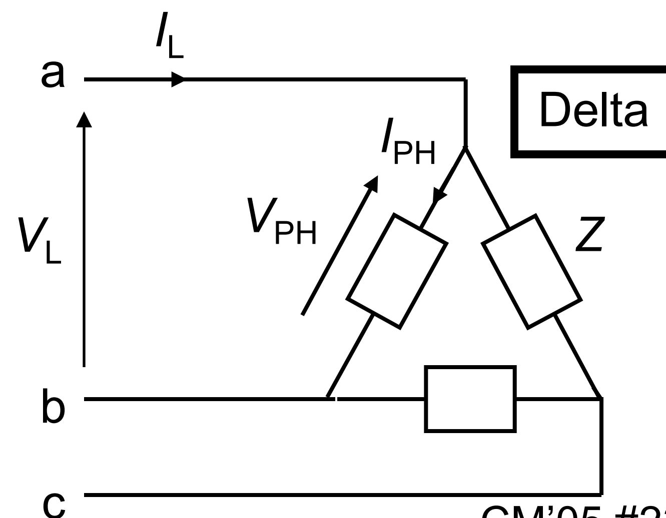
delta : phase windings are connected directly between each combination of supply lines



Other useful definitions :

phase voltage V_{PH} or V_1 and current I_{PH} or I_1 : voltage and current associated with each phase winding

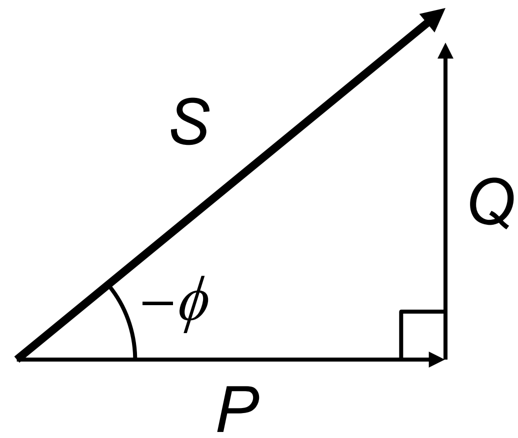
line voltage V_L and current I_L : voltage between two supply lines and current through supply lines



2.2.5. Three-Phase Power

	Star	Delta
Voltage	$V_L = \sqrt{3}\ V_{PH}$	$V_L = V_{PH}$
Current	$I_L = I_{PH}$	$I_L = \sqrt{3}\ I_{PH}$

$V_L I_L = \sqrt{3} V_{PH} I_{PH}$	$V_L I_L = \sqrt{3} V_{PH} I_{PH}$
$V_L I_L = \sqrt{3} V_1 I_1$	$V_L I_L = \sqrt{3} V_1 I_1$



Power Triangle

for balanced systems, the total power is the sum of the phase powers :

for apparent power $S = 3V_1 I_1 = \sqrt{3}(\sqrt{3} V_1 I_1) = \sqrt{3} V_L I_L$

Hence

<u>(total) apparent power</u> $S = 3V_1 I_1 = \sqrt{3}\ V_L I_L$ [VA]

<u>(total) real power</u> $P = 3V_1 I_1 \cos\phi = \sqrt{3}\ V_L I_L \cos\phi = S\cos\phi$ [W]

<u>(total) reactive power</u> $Q = 3V_1 I_1 \sin(-\phi) = \sqrt{3}\ V_L I_L \sin(-\phi) = S\sin(-\phi)$ [VAr]

2.2.6. 3ph Terminology

Standard 3ph Convention

voltages : always given as line voltage

currents : always given as line current

powers : always given as total 3ph power

connection type : assume star-connected unless otherwise stated

electric motors rated as mechanical output power, eg. 2.2kW induction motor

Example : motor nameplate (label) data : 3ph, 220V,15A, 7.5kW

- 220V line voltage
- 15A line current
- 7.5kW output power

Three-Phase Calculations : unless otherwise specified should give answers as line voltage, line current, total power etc.

2.3. Rotating Magnetic Fields

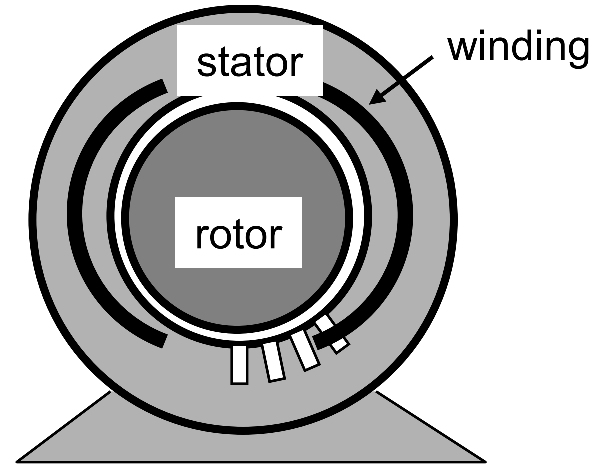
AC machines such as induction and synchronous machines are based on rotating magnetic fields. The stator of AC machines contains three separate phase windings.

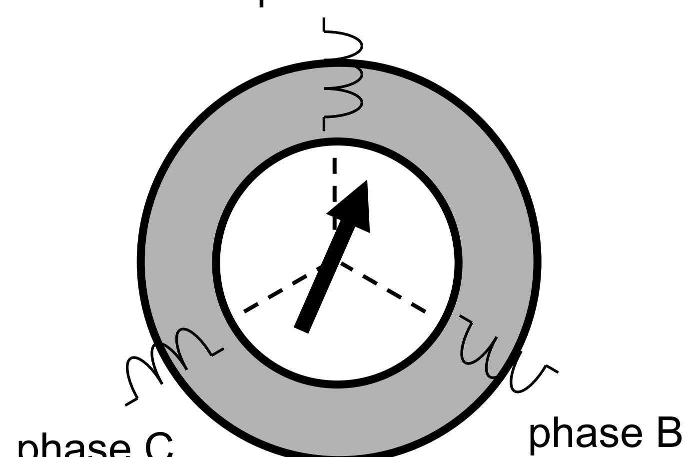
In this section we will ignore the rotor windings.

If the three windings are connected to a three-phase supply then the fields produced by each stator phase combine to produce a rotating magnetic field which has :

• constant amplitude, and

• rotates at constant speed (synchronous speed)





Generation of Rotating Magnetic Field

2.3.1. Synchronous Speed

depends on number of poles P or pole pairs $p = P/2$ of the winding

synchronous speed = speed of rotating magnetic field
$n_S = 60f_1/p$ rpm
$\omega_S = 2\pi f_1/p$ rad/s
where f_1 is the supply frequency

Poles	Pole-Pairs	Synchronous Speed	
P	p	f_1 = 50Hz	f_1 = 60Hz
2	1	3000rpm	3600rpm
4	2	1500rpm	1800rpm
6	3	1000rpm	1200rpm
8	4	750rpm	900rpm

The table on the right shows common values for synchronous speeds of AC machines operated from 50Hz and 60Hz supplies.

Other examples

1) Aircraft commonly use a 400Hz AC power system : a 4 pole machine at this frequency has a

synchronous speed n_S = 60x400/2 pole pairs = 12,000 rpm

2) A low-speed synchronous generator has a synchronous speed of 150rpm. It generates power at 50Hz.

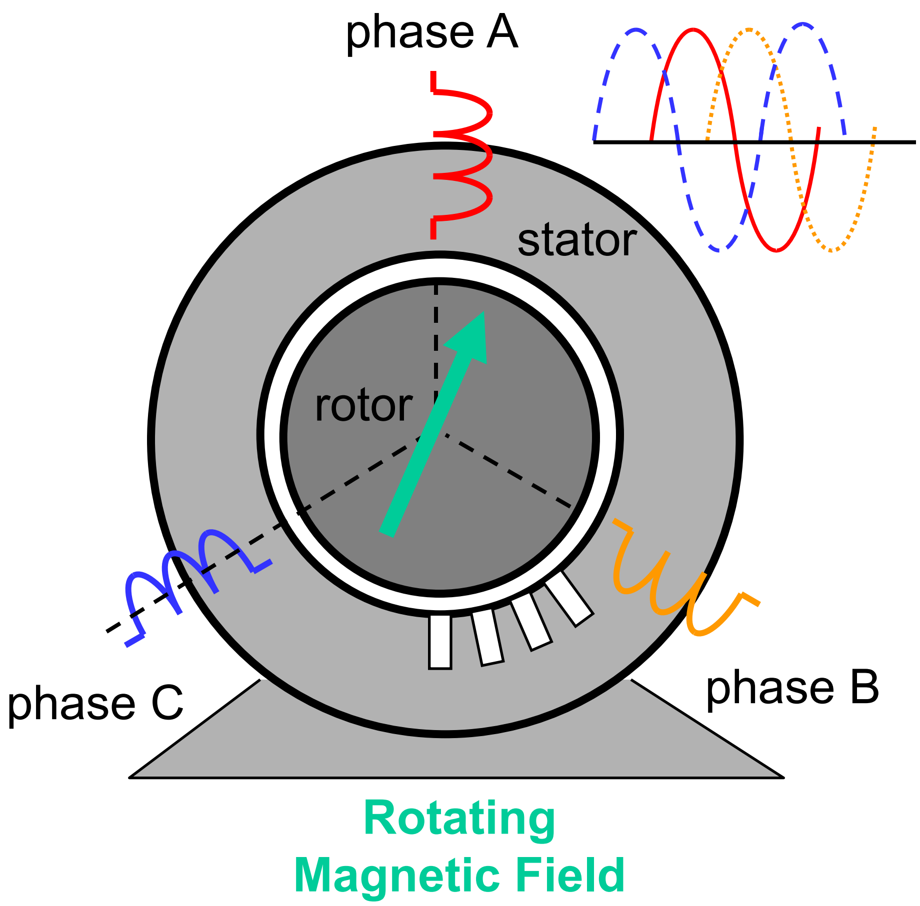
pole pairs = 60x50Hz/150rpm = 20 pole pairs or 40 poles.

2.3.2. Induction Motor Principles

Electromagnetic Description of Torque Production

The stator contains a three phase winding. This winding is connected to a three-phase supply and produces a magnetic field of constant magnitude, rotating at synchronous speed.

The rotor also contains a three-phase winding. This winding is short-circuited. The rotating stator magnetic field induces voltages in the rotor winding. The induced voltages produce currents in the short-circuited winding. These current interact with the rotating stator magnetic field to produce torque.



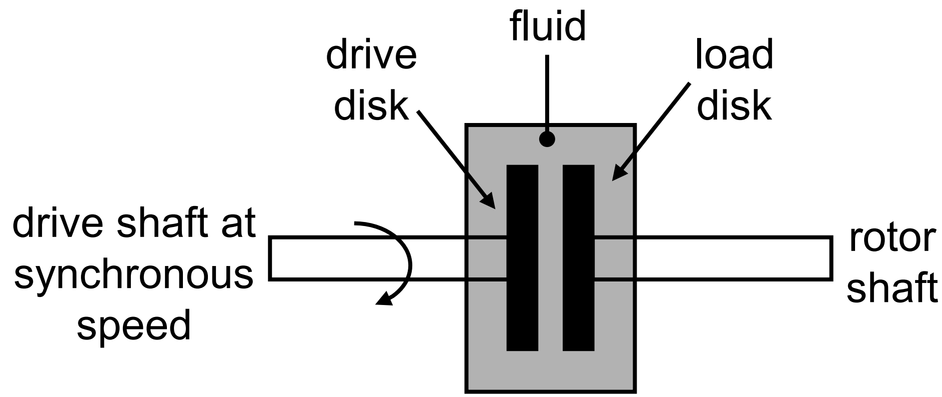
2.3.3. Induction Motor Analogy

Physical Description

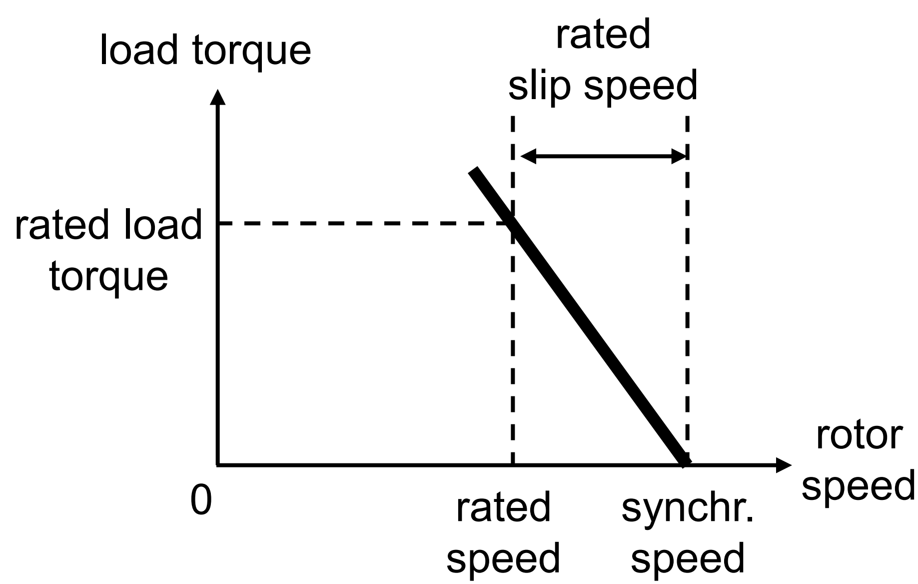
The rotor is “dragged around” by the rotating stator field. In a similar way to a fluid transmission based on two disks in a viscous fluid. Torque is transferred from one disk to the other by viscous drag of the fluid.

Characteristics

- the slip speed is the difference between synchronous speed and the rotor speed
- the torque is roughly proportional to the difference between the rotor speed and synchronous speed
- the rotor normally operates slightly lower than synchronous speed



fluid transmission analogy



2.3.4. Rated Speed

rated speed usually very close (typically 90-99%) to synchronous speed n_S, from rated speed can thus estimate number of poles and synchronous speed

rated torque (and rated output power) occurs at rated speed.

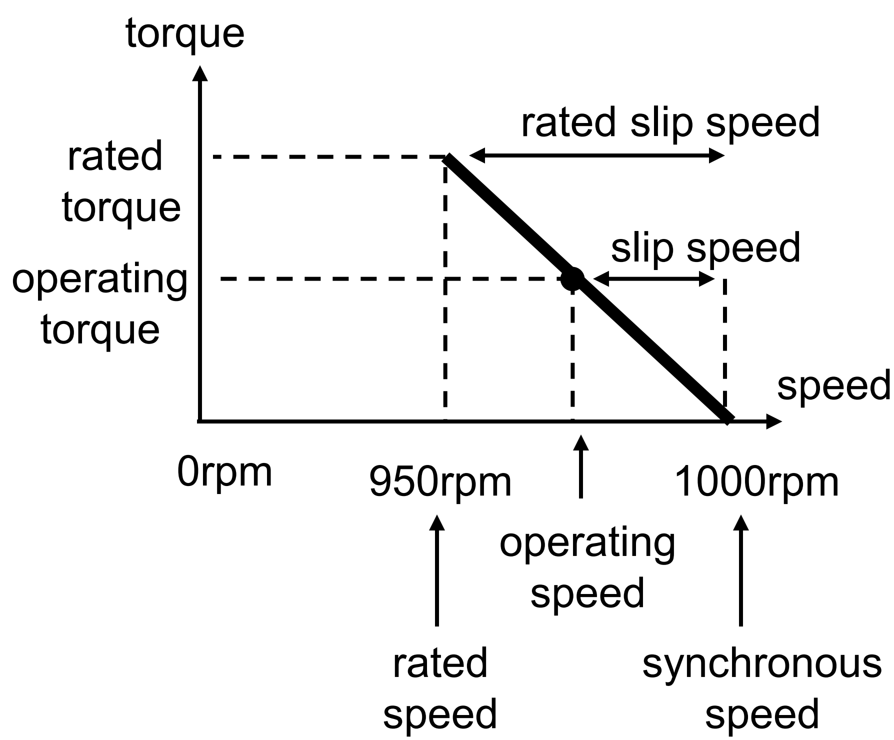
rated torque = rated output power/rated speed

at **synchronous speed** : torque = 0

operating speed range normally between synchronous speed and rated speed (thus nearly fixed speed machines)

torque versus speed curve can be approximated as a straight line between synchronous speed and rated speed. Hence the output torque is proportional to slip speed.

induction motor torque vs speed curve



6 pole, 50 Hz example

2.3.5. Torque/Speed Example

Consider a 37kW, 950rpm, 50Hz induction machine

a) pole pairs $p = 60f_1/n_S \approx 60f_1/n_R$ = 60x50Hz/950rpm=3.158, thus p=<u>3</u>

b) synchronous speed $n_S = 60f_1/p$ = <u>1000rpm</u>, $\omega_S = 2\pi f_1/p$ = <u>104.7rad/s</u>

c) rated slip speed = 1000rpm-950rpm= <u>50rpm</u>

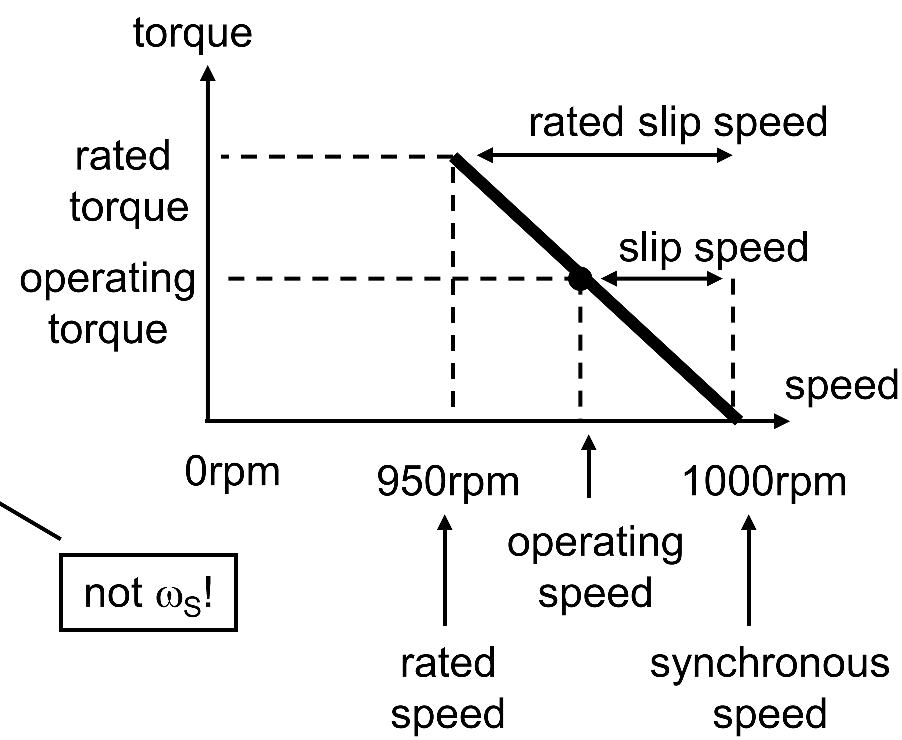
d) rated output torque $T = P/\omega_R$ = 37kW/(950rpm/60x2π)=<u>371.9Nm</u>

not ω_S!

e) the operating speed corresponding to 40% of rated output torque
= 1000rpm-40%xrated slip speed
= 1000rpm-20rpm=<u>980rpm</u>

f) at an operating speed of 965rpm, calculate the output torque. Slip speed = 35rpm, output torque = 371.9Nm x (35rpm/50rpm) = <u>260.3Nm</u>

induction motor torque vs speed curve



2.4. Slip and Slip Frequency

Existing Definitions

f_1 = freq. of stator V and I (Hz), p = number of pole-pairs

n_S, ω_S : synchronous speed n_R, ω_R : rotor speed

slip speed = $n_S - n_R$ (rpm) or $\omega_S - \omega_R$ (rad/s)

Slip

s = (per unit) slip = slip speed/synchr. speed = $(n_S - n_R)/ n_S = (\omega_S - \omega_R)/ \omega_S$

or rotor speed = (1 - slip) x synchronous speed

Slip Frequency

f_2 = slip frequency : frequency of rotor voltages/currents (Hz) = $s\, f_1$

Rotor Frequency

f_R = frequency associated with rotor speed = $n_R/60$

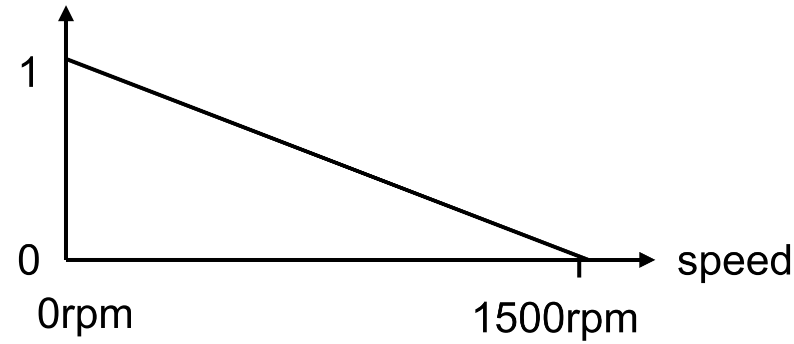
Example : 50Hz, 4 pole machine, synchr. speed n_S = 60x50/2= 1500rpm

Rotor Speed n_R	slip s = $(n_S - n_R)/ n_S$	slip frequency sf	f_R
0rpm	(1500-0)/1500 = 1	1 x 50Hz = 50Hz	0Hz
1410rpm	(1500-1410)/1500 = 0.06	0.06 x 50Hz = 3Hz	23.5Hz
1500rpm	(1500-1500)/1500 = 0	0 x 50Hz = 0Hz	25Hz

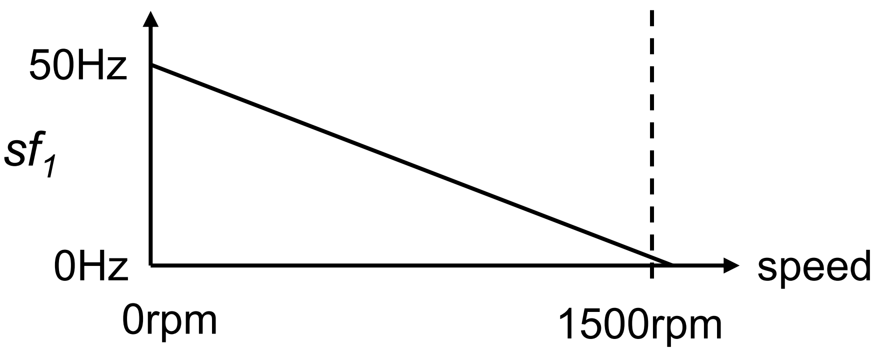
2.4.1. Slip Frequency

four pole
50Hz results

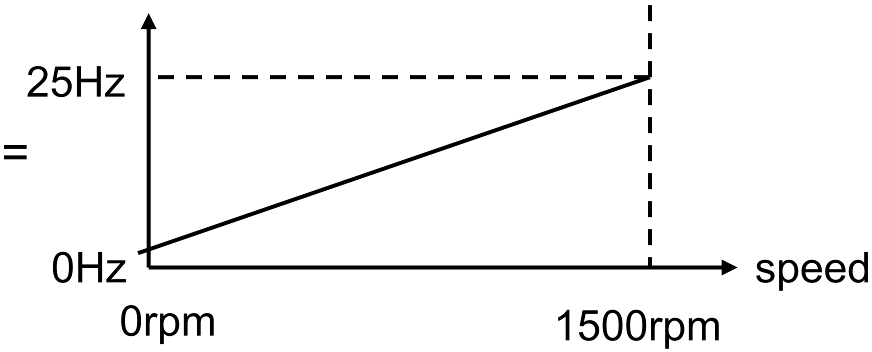
slip $s = (n_S - n_R)/ n_S$



slip frequency $f_2 = sf_1$



rotor frequency $f_R = n_R/60 = (1-s)f_1/p$



2.4.2. Slip Versus Rating

Typical rated speed, rated slip and rated efficiency for four-pole, 50Hz induction machines, n_S = 1500rpm.

Power	Rated Speed	Rated Slip	Rated Efficiency	Rated Slip Freq.
100W	1360rpm	0.09333	61%	4.667Hz
1kW	1410rpm	0.060	79%	3Hz
10kW	1460rpm	0.02667	88%	1.333Hz
100kW	1475rpm	0.01667	93%	0.8333Hz
1MW	1485rpm	0.010	96%	0.5Hz

Notes

- rated slip decreases as the machine gets larger
- for small machines (100W) it is about 10% but drops to 1% for MW size machines
- keep slip to four significant figures
- rated slip frequency is in the range 0.5 to 5Hz

2.4.3. Slip and Slip Freq. Example

Consider a three-phase 415V, 50Hz, 2850rpm induction machine. It is operating at rated voltage at 2915rpm.

a) **pole pairs** $p = 60f_1/n_S \approx 60f_1/n_R = 3000/2850 = 1.053$, one pole pair or two poles

synchronous speed n_S = 3000rpm

b) **under rated conditions**

rated speed n_R = 2850rpm, slip speed = 150rpm, slip s = 150rpm/3000rpm = 0.05, slip frequency sf = 2.5Hz, rotor frequency $f_R = n_R/60$ = 47.5Hz

c) **at the operating speed** n_R = 2915rpm

slip speed = 85rpm, slip s = 85rpm/3000rpm = 0.02833, slip frequency sf = 1.417Hz, $f_R = n_R/60$ = 48.58Hz

output torque at operating speed = 85rpm/150rpm = 56.67% of rated torque

2.5. IM Torque/Speed Curve

The torque speed curve has three main regions :

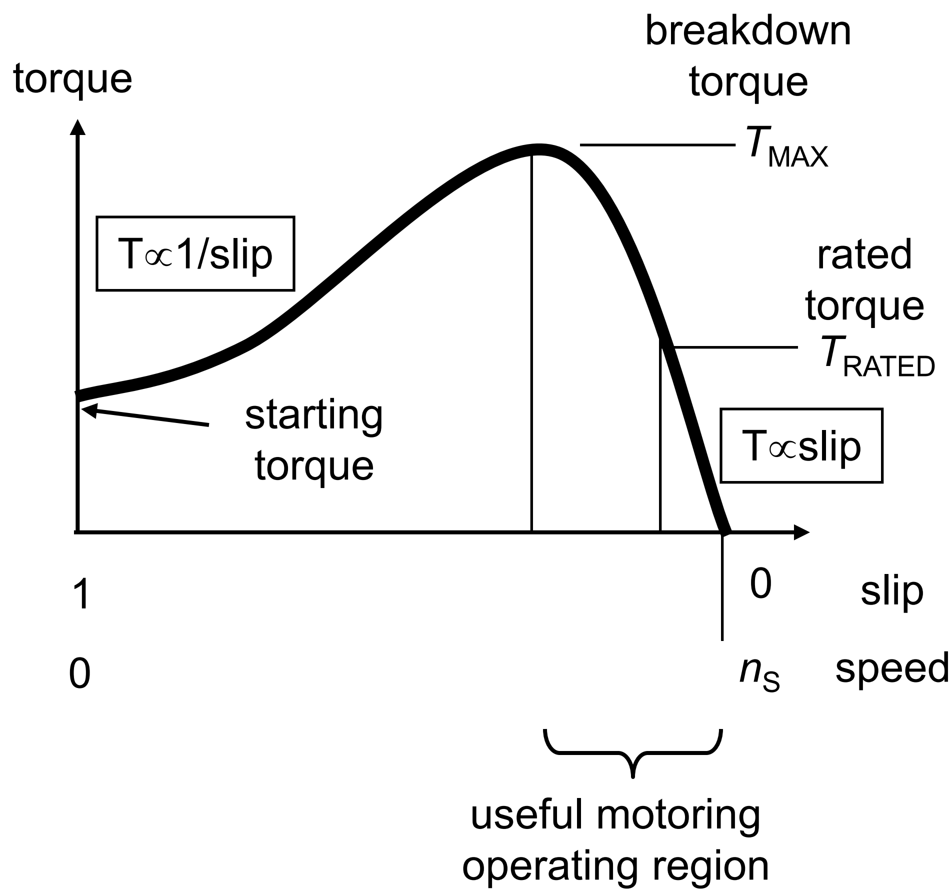
a) small values of slip : torque is nearly linearly proportional to slip or slip speed,

at synchronous speed (s = 0, n = n_S), the torque is zero

b) high values of slip : torque is inversely proportional to slip, at standstill (s =1, n =0), the torque T equals the starting torque

c) middle region : torque reaches a maximum value, called the breakdown torque T_{MAX}

rated torque : is the design value of torque, typically about half of the breakdown torque.

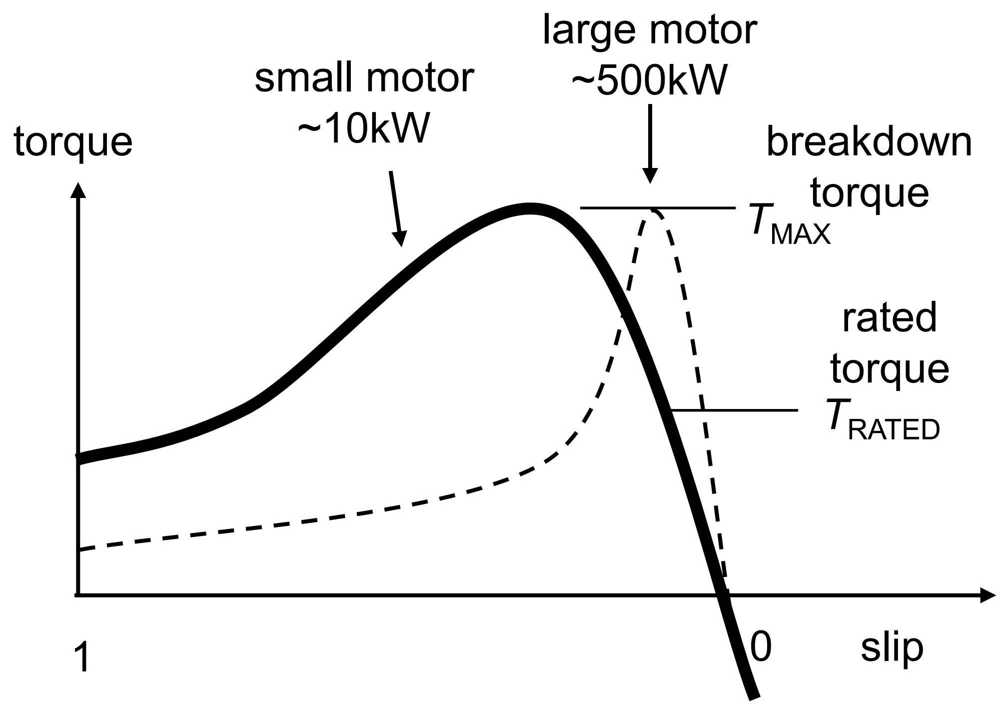


2.5.1. Torque/Speed Curve

The solid line shows the shape of a typical torque versus speed curve for a small motor (eg. 10kW). The dashed curve shows the shape of the torque versus speed curve for a large motor (eg. 500kW). Note that for large motors :

• the rated slip is smaller (and hence efficiency is higher)

• the ratio of starting torque to rated torque is smaller

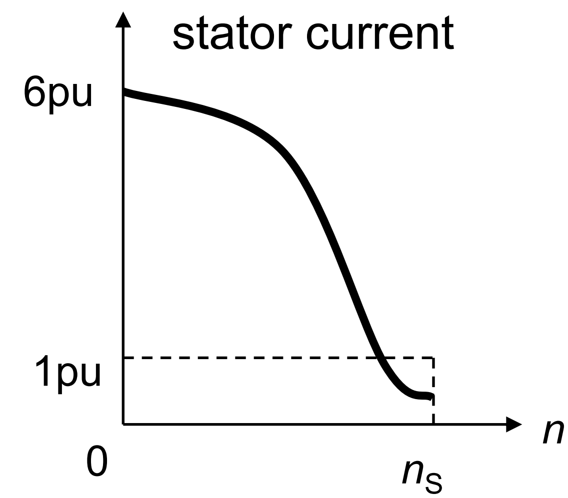


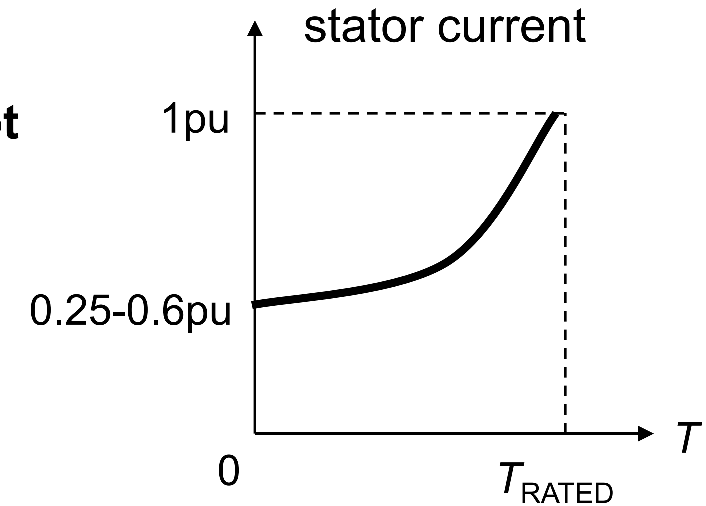
2.5.2. Stator Current

stator current : at standstill, machine currents are very large, typically five to six times rated current, as speed increases the current decreases, [define 1pu = rated current]

direct-on-line starting : motor started by connecting directly to mains, simplest starting means but the high starting currents causes rapid temperature rise of stator and rotor windings. This can cause rotor damage if it is repeated too often without allowing the motor cool down in between starts.

the **stator current of induction machines is not directly proportional to torque**, the no-load current is typically 25-60% of the rated current, thus difficult to estimate the load on an induction motor based on its load current



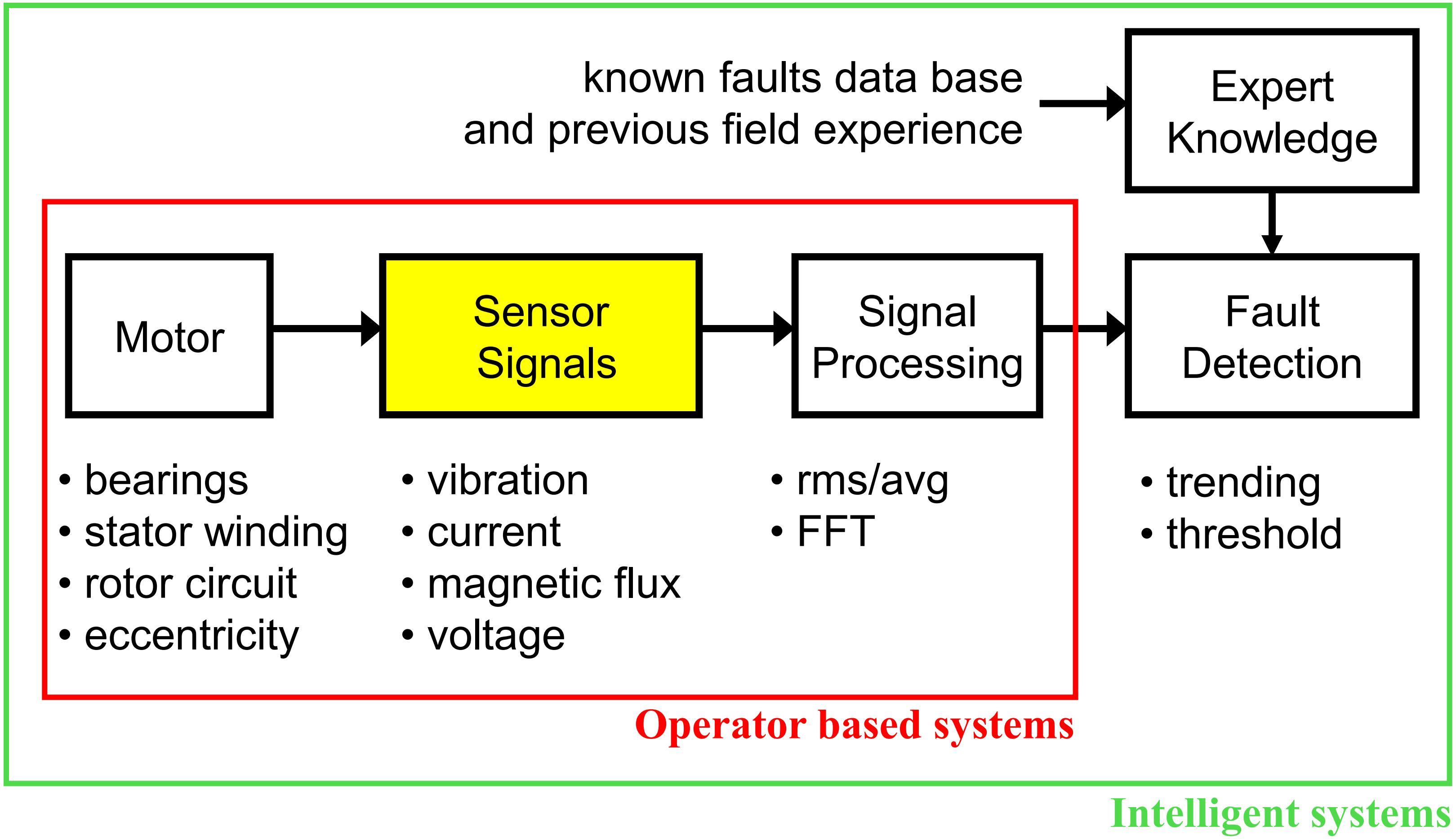


SESSION 3

On-Line Condition Monitoring
: Data Collection

3. On-Line Motor Sensor Types

"while the motor is operating !"



3.0.1. On-Line Condition Monitoring

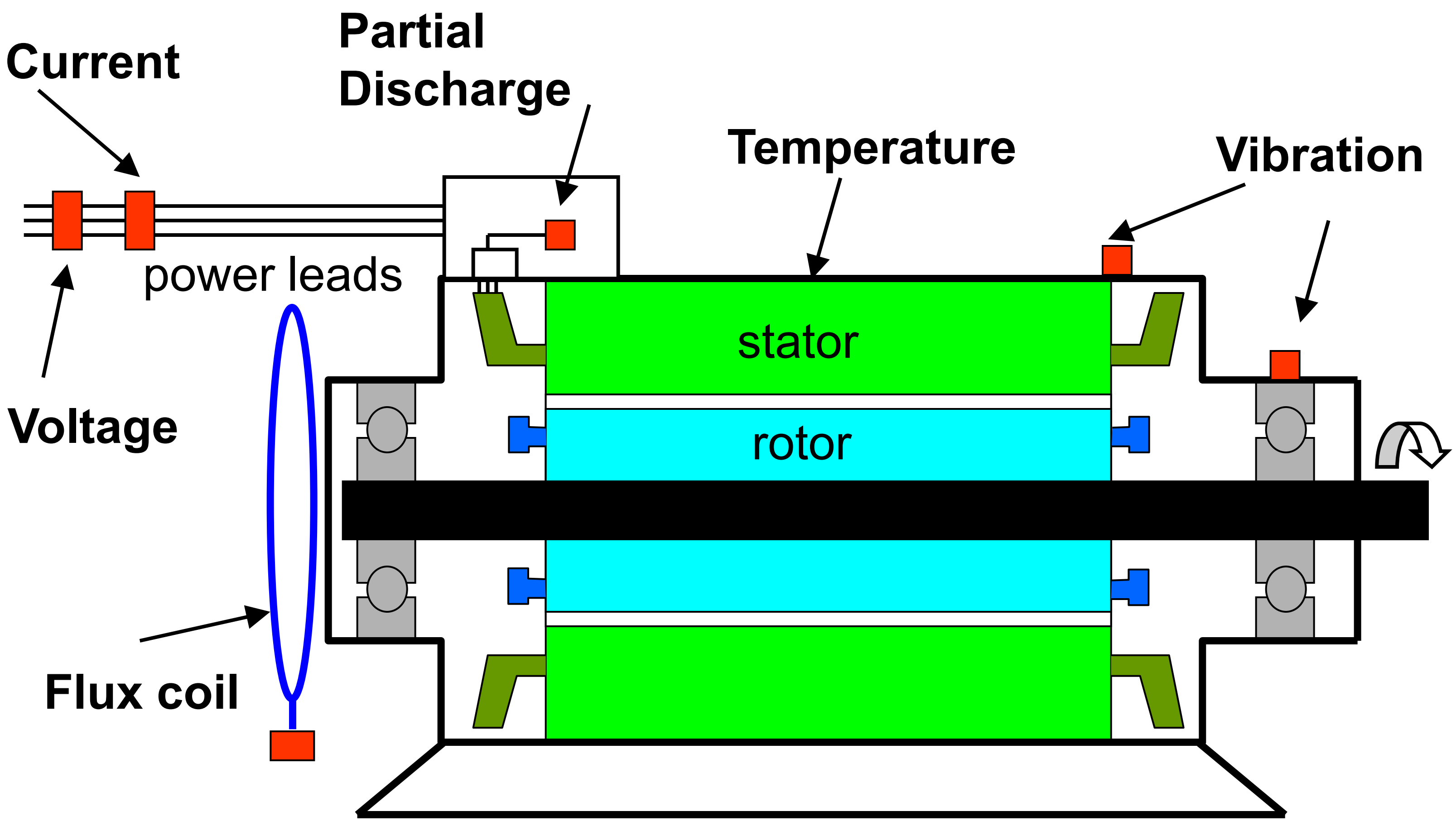
definition : detect faults using measurements when machine is operating

reliable detection requires understanding of the electric, magnetic and mechanical behaviour of the machine in the healthy state and under fault conditions

faults

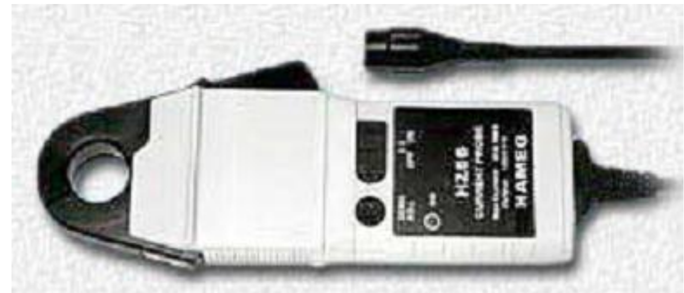
- usually affect symmetry of machine
- produce characteristic fault frequencies in sensor signals
- magnitude of these fault frequencies indicates magnitude of fault
- but even “healthy” machines have some degree of asymmetry
- magnitudes also sensitive to load on motor and motor size
- thus usually requires experienced operator to diagnose faults

3.1. Sensor Types and Locations



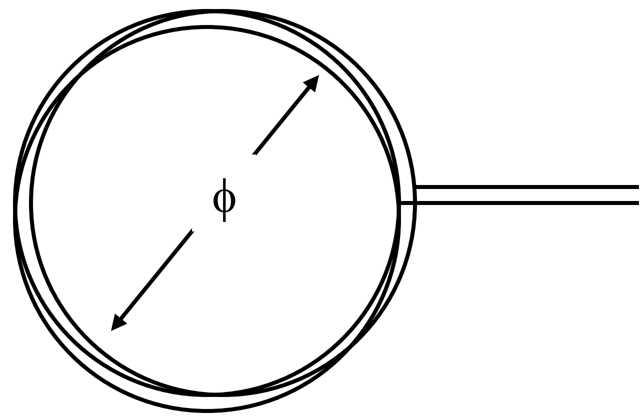
3.1.1. Sensors

vibration sensor (accelerometer)



Hall-effect current probe

differential voltage probe



flux sensing coil

3.1.2. Sensor Specifications

SIGNAL	SENSOR	MAGNITUDE & BANDWIDTH	COMMENTS
Vibration	Piezoelectric	1-2 g 10Hz to 2kHz	•Velocity or acceleration measurement •Frequency spectrum •Sensor sensitivity around 0.1V/g
Current	CT, Hall Effect Rogowski coil	0-500Arms 2,500Hz, 50th harmonic	•Frequency spectrum •Determine instantaneous current phasor
Magnetic field	Magnetic pick up (search) coil Hall sensor	Search coil voltage, 2,500Hz, 50th harmonic	Frequency spectrum Used to estimate motor speed Contains similar fault frequencies to the motor current
Voltage	Diff isolation probes Voltage transformers Isolation Amplifiers	0-11kVrms 2,500Hz, 50th harmonic	Used with the current to calculate both instantaneous power and negative sequence impedance Three phase vector diagram
Partial Discharge	Capacitive sensor or Rogowski Coil	0-500mV 10-100MHz	Histogram and phase distribution of PD
Temperature	Thermocouples, RTDs	0-200 ^{o}C < 1 Hz	Temperature values

3.2. Vibration Sensors

vibration : movement of object, can be described by position, velocity or acceleration

– position is integral of velocity, velocity is integral of acceleration

– acceleration sensitive to high frequency, velocity to lower frequency

– typical acceleration values 1-2g (1g = one gravity = 9.8m/s^2)

sensing methods :

<u>1) accelerometers</u> : piezo-electric crystal

– place probe in contact with object eg. motor stator

– output voltage proportional to acceleration

– typical output 0.1V/g

<u>2) velocity sensors</u> : coil and magnet

– output voltage proportional to velocity

<u>3) position sensors</u> : eddy-current sensors

– do not require direct contact

– useful for check vibration of rotating shafts

– produce output voltage proportional to position

vibration sensor (accelerometer)

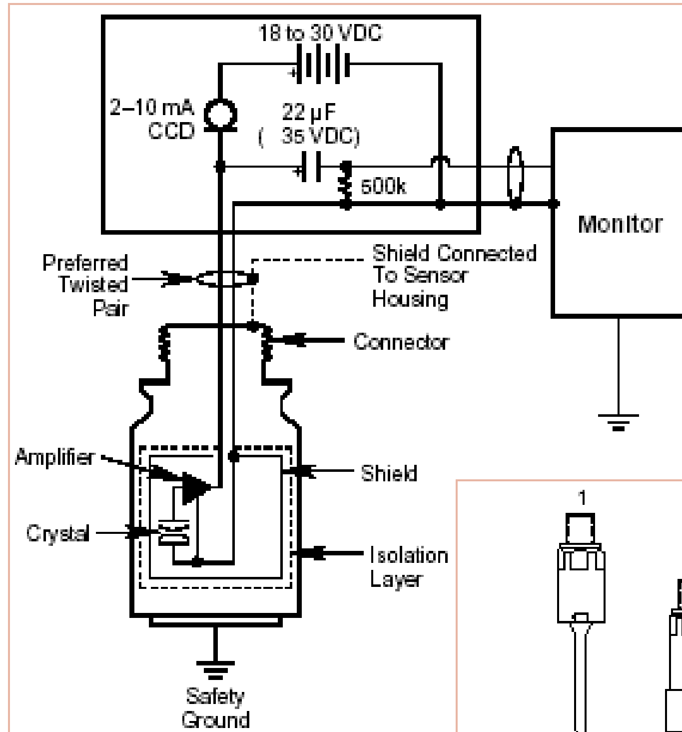
3.2.1. Accelerometers

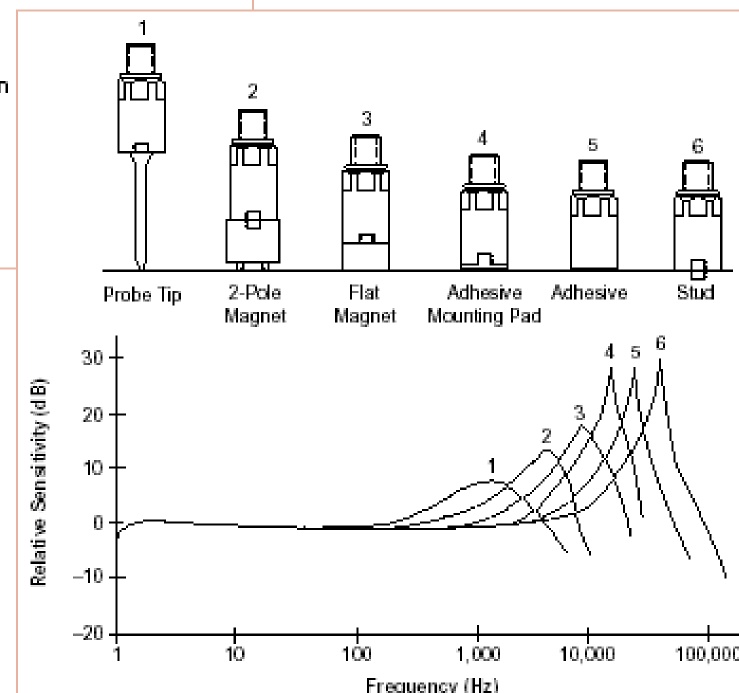
Electrical Circuitry

- two wire device for ease of use
- DC power supplied by current source
- produces AC output signal

Mechanical Connection between sensor and motor

- resonance frequency increases with more solid connection between sensor and object
- higher the resonance frequency the higher the usable frequency





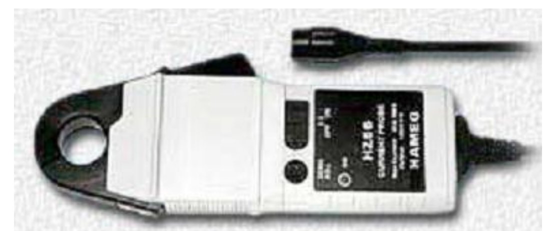
3.3. Current Sensor

typical levels : from 1A to 20kA

sensing methods :

1) current transformer (CT)

- need to interrupt circuit to insert transformer
- provides full electrical isolation
- units available up to any required current rating
- provides output current proportional to input current
- eg. 1kA:5A, 1kA input produces 5A output



2) Hall effect clamp-on current probe

- can clamp on to circuits while operating
- typical ratings : 10A to 500A
- provides output voltage proportional to measured current
- eg. 0.1V/A, 1A input produces 0.1V output
- easy interface to data-acquisition systems
- use directly for low voltages/currents or through CT for higher voltages

3.4. Voltage Sensor

typical levels : from 415V to 11kV

sensing methods :

<u>1) voltage transformer (potential transformer : PT)</u>

- provides full electrical isolation
- provides output voltage proportional to input voltage
- standard output 110V
- eg. 11kV:110V, 11kV input produces 110V output

<u>2) differential voltage probe</u>

- measures up to 1kV
- provides limited electrical isolation
- provides output voltage proportional to input voltage
- eg. 100:1 probe, 200V input produces 2V output
- typical output levels : 5V
- easy interface to data-acquisition systems
- use directly for low voltages or through PT for higher voltages

3.5. Axial Leakage Flux Sensor

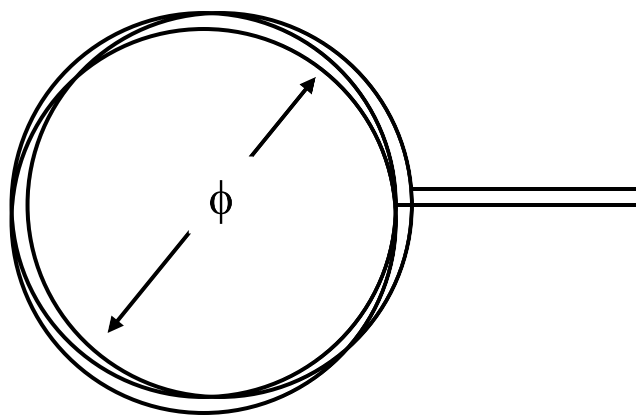
ideal motors : do not produce external magnetic field

practical motors : currents flowing in rotor and stator end-windings produce an axial magnetic leakage field

sensing methods :

1) axial flux search coil

- circular coil of wire placed axially over end of motor
- induced voltage proportional to rate of change of field
- cheap, simple and safe sensing method
- particularly useful for detecting slip frequency of rotor currents



flux sensing coil

3.6. Partial Discharge

stator insulation ages due to electrical, mechanical, thermal and environmental stresses

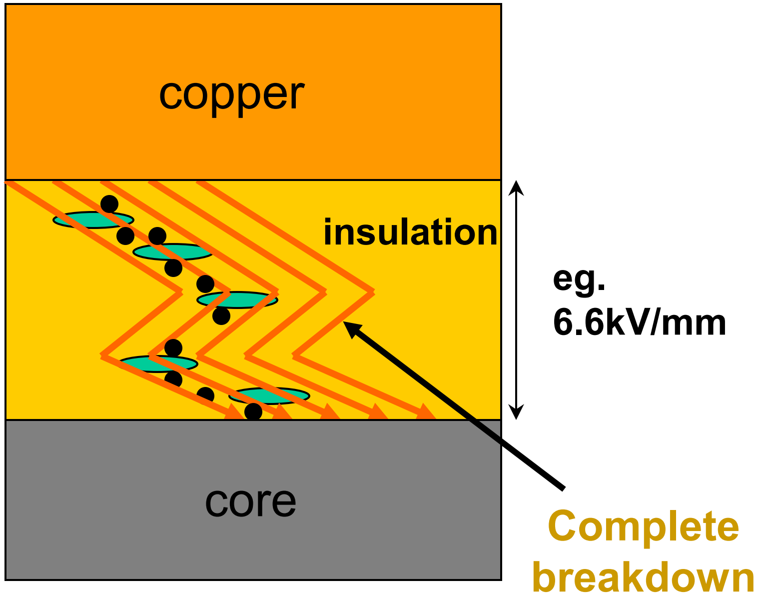
dielectric strength : key parameter of electrical insulation materials

= breakdown voltage/material thickness

dielectric strength of insulation materials usually greater than air (about 3.3kV/mm)

for high voltage machines

- air holes in insulation act as weakest link in chain, cause small amount of arcing (called partial discharges)
- arcing destroys insulation and causing carbonisation
- eventually insulation fails completely

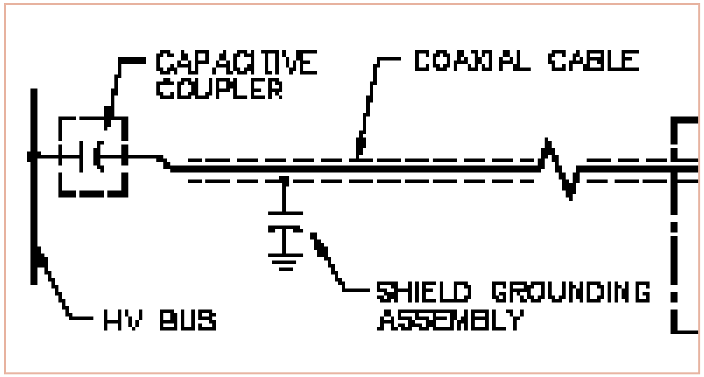


Insulation Breakdown Diagram

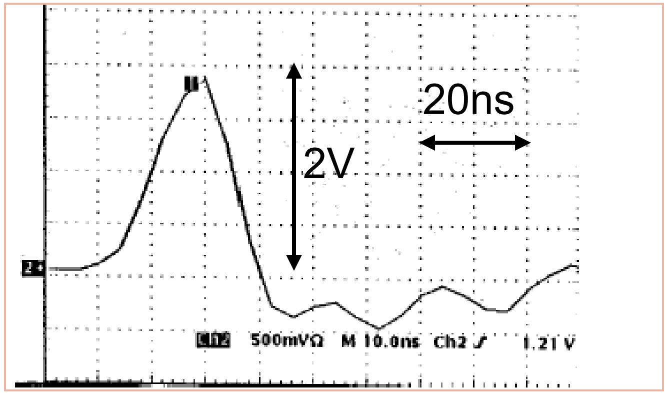
3.6.1. Partial Discharge Sensors

arcing (partial discharges) causes small (V), very fast (ns) voltage spikes on stator terminals

capacitive couplers are used to detect voltage spikes which can be recorded using specialised data acquisition software



Capacitive coupler circuit



A typical PD pulse detected at the winding terminals of an operating hydro-generator by an 80 pF capacitance coupler.

3.7. Sensor Outputs

Need to match the output of sensors to the analog to digital converter input range.

1) Current sensor has gain of 0.01V/A. Used to measure motor rated at 500A.

peak current = 500A√2 = 707.1A

sensor output = 707.1A * 0.01V/A = 7.071V

suitable A/D range +/-8V [or +/-9V]

2) Voltage sensor has gain of 1000:1. Used to measure motor rated at 1.2kV.

3) Vibration sensor has gain of 0.1V/g. Peak expected vibration signal +/-2g.

4. Sampling Theory

The frequency component at half the sampling frequency is referred to as the Nyquist frequency.

Nyquist Sampling Theorem

The Nyquist Theorem states that a signal can be reconstructed from its samples if the sampling rate is greater than twice the frequency of the signal. It follows then that the highest frequency (Nyquist frequency: f_N) that can be analyzed is $f_N = f_S/2$, where f_S is the sampling frequency.

4.1. Aliasing and Filtering

Nyquist freq must be greater than highest input frequency else ...

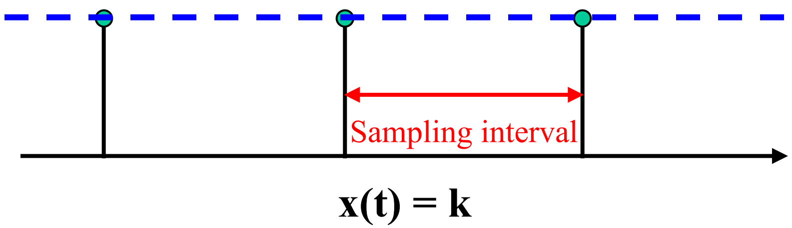
aliasing : misinterpretation of frequencies above the Nyquist frequency as being lower frequencies

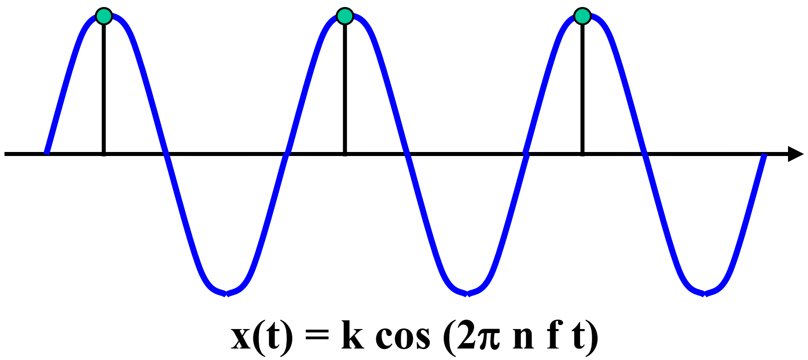
Example 1 : input freq =2 x Nyquist frequency, sampled output = constant output voltage

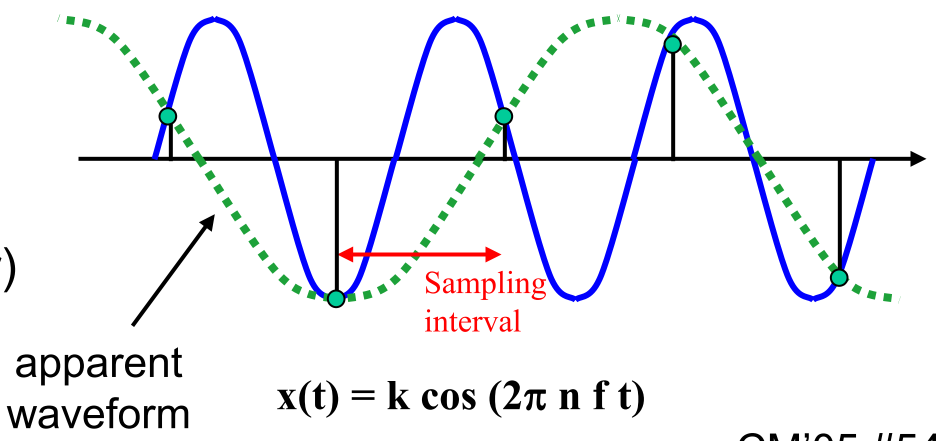
Example 2 : input freq > Nyquist freq, sampled output appears to correspond to a lower frequency than it really is.

Solutions :

- raise sampling frequency, or
- filter out higher frequency components from input signal before sampling (low-pass filter)

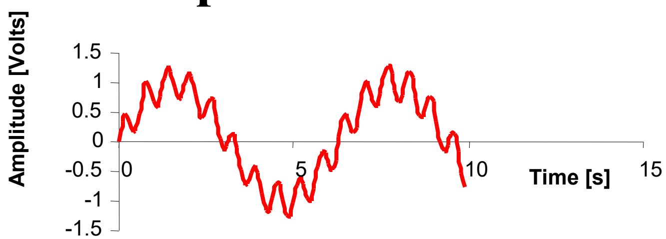


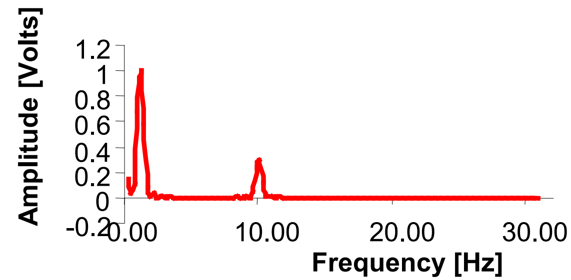


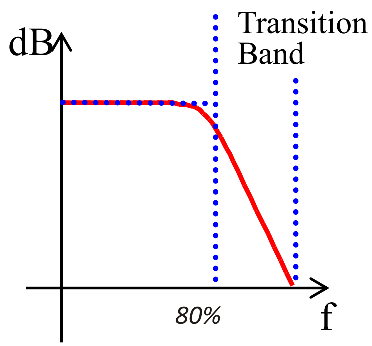


4.1.1. Low-Pass Filter Example

Input to the filter

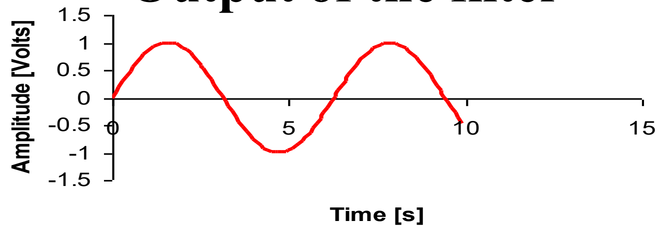


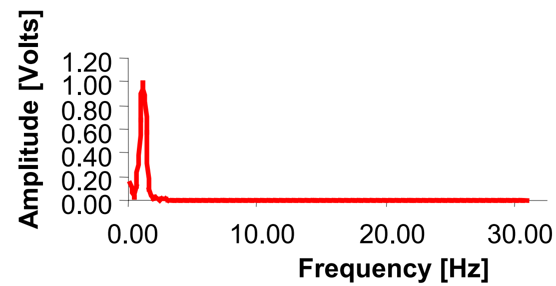




Anti-Aliasing Filter (low-pass filter) : to reduce the amplitudes of the higher frequency components

Output of the filter





“Filtering may change the original signal to some extent. Hence its use must be balanced against the distortions it can remove”

4.1.2. Anti-Aliasing Filter Example

Consider an input signal with components greater than the Nyquist frequency.

Apply low-pass anti-aliasing filter with cut-off frequency below Nyquist frequency, then sample.

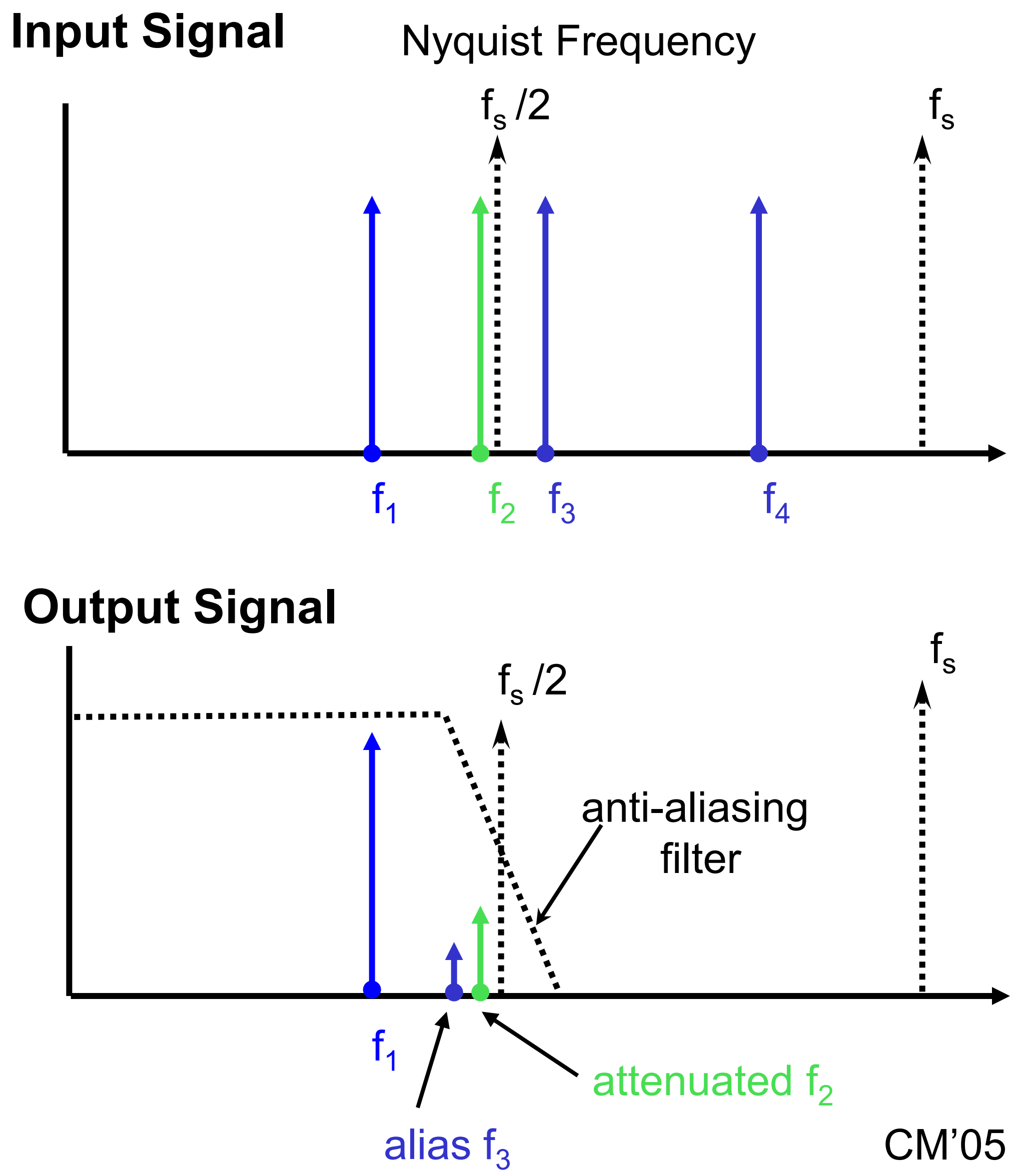
Result :

f_1 : has correct amplitude

f_2 : reduced in amplitude

f_3 : reduced in amplitude and aliased to appear on left of Nyquist frequency by sampling process

f_4 : removed completely by low-pass filter



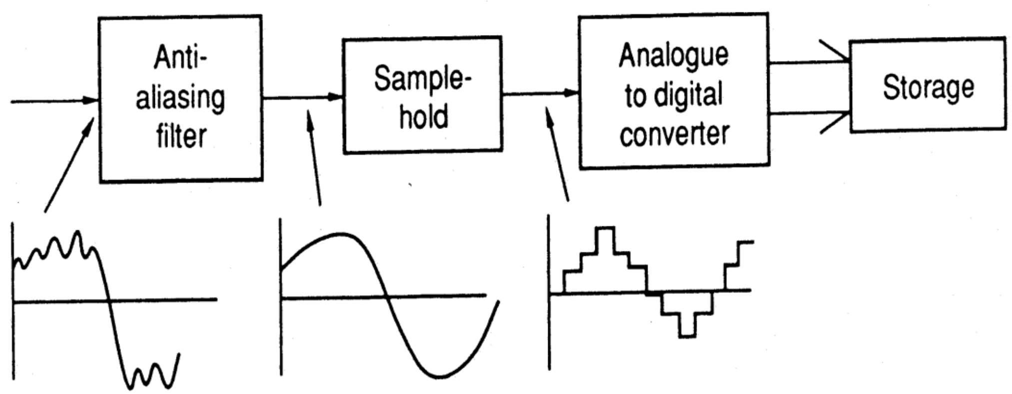
4.2. Analog to Digital Conversion

anti-aliasing low-pass filters to avoid aliasing due to high frequency components e.g. resonance frequency of the accelerometer.

sampling frequency is usually defined by the maximum rotational speed of the motor and the highest order of interest.

high dynamic range : to distinguish a low amplitude signal (fault signals, mV levels) in the presence of high amplitude signals (such as voltage, 100V), which is the key to a successful analysis.

- use high resolution A/D converters
- match expected input signals to A/D input range



4.2.1. A/D Converter Resolution

Resolution determines the smallest change that can be detected.

Specified in bits.

Determines number of output levels, or steps

8 bits = 2^8 = 256 steps

10 bits = 1024 steps

12 bits = 4096 steps

16 bits = 65,536 steps

Typical Resolutions

8-bit – common for high-speed image capture

10-bit – general analog acquisition

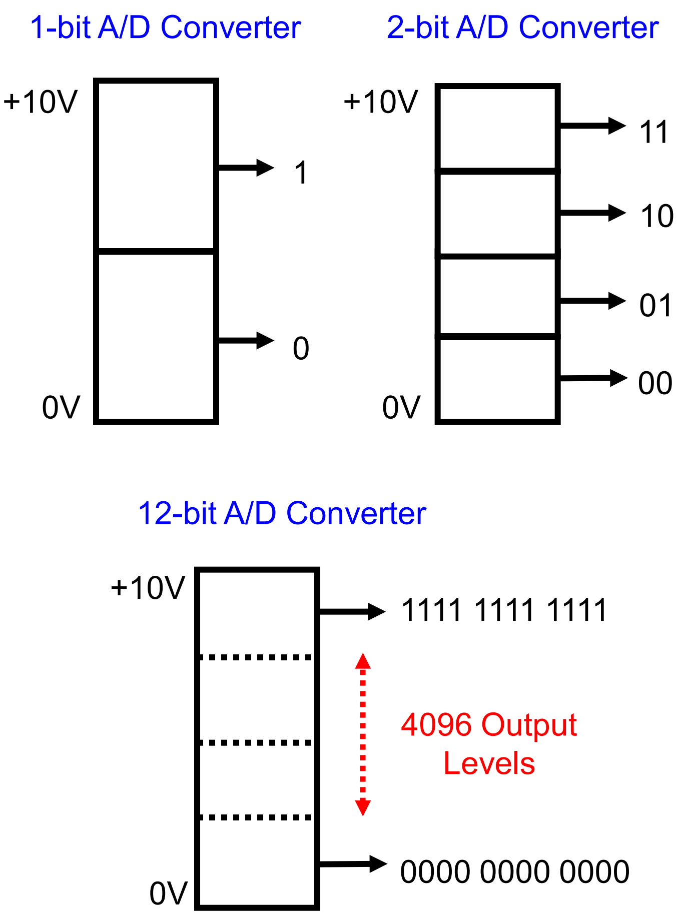
12-bit – general analog acquisition

16-bit – precision analog acquisition

24-bit – high-accuracy analog acquisition

CM

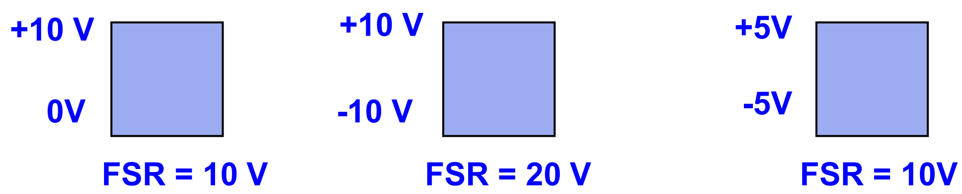
Output Levels



4.2.2. Full Scale Range (FSR)

Full scale range refers to the largest voltage range which can be input into the A/D converter. Typical ranges are based on available sensors:

Uni-polar (positive)	0 to 5 volts
Bipolar	-5 to +5 volts



"Analog input is converted into a digital number, by comparing the voltage with its position within the Full Scale Range (FSR)

With an n-bit A/D converter the number of output levels equals 2^n

e.g. 12-bit converter = $2^{12} = 4096$"

Least Significant Bit (LSB)

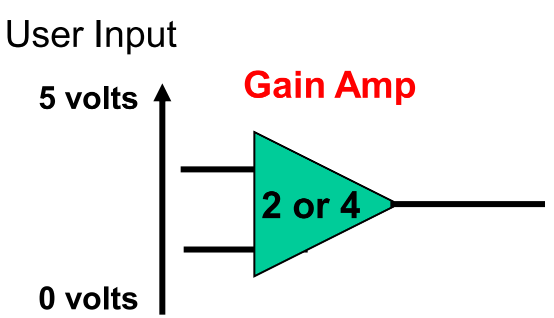
- LSB : the smallest change that can be resolved by the A/D converter
- LSB is the rightmost bit, LSB = Full Scale Range (FSR) ÷ 2^n

4.2.3. Selecting A/D Gain and Range

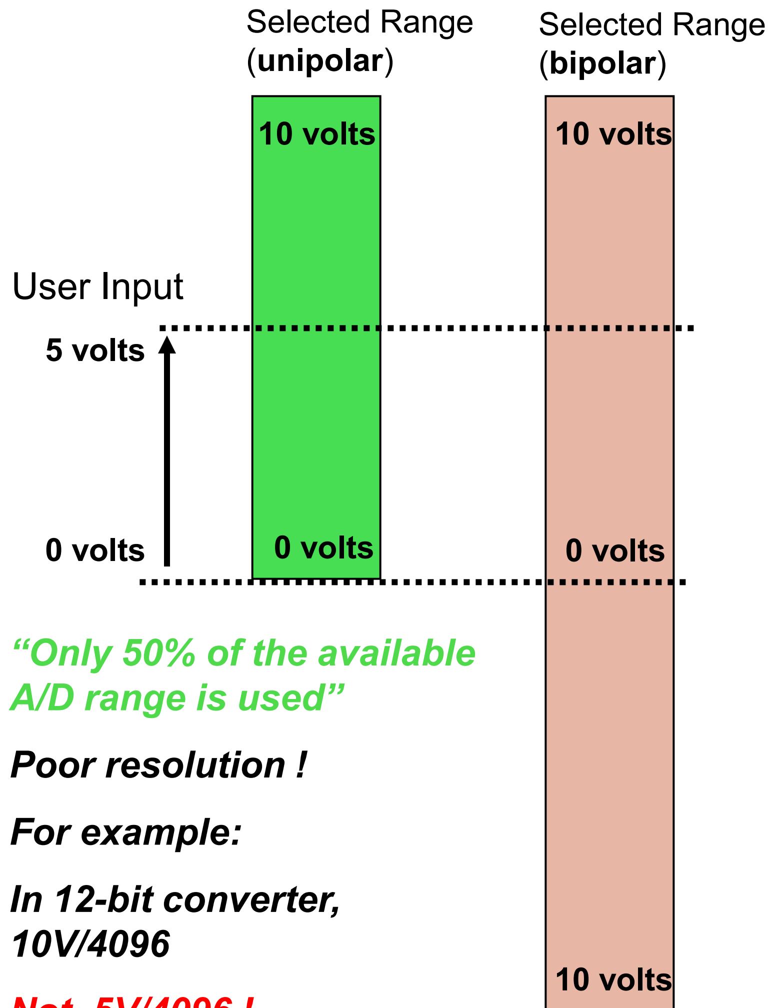
A/D converters offer fixed input voltage range

need to match sensor output voltage range to maximise use of A/D converter range

- more expensive A/D converters have built-in adjustable gain amplifiers, can thus vary input range in software
- alternatively need to add external amplifier



100% of the available A/D range is used!



"Only 50% of the available A/D range is used"

Poor resolution !

For example:

In 12-bit converter, 10V/4096

Not 5V/4096 !

"Only 25% of the available A/D range is used"

4.2.4. Quantizing Error

The number of bits used in A/D conversion control the dynamic range of the analysis.

A digitised series of levels introduces an error referred to as the "quantizing error", which can vary between ±½ least significant bit.

Consider a 10bit A/D converter : has 1024 output levels

the smallest variation = 1/1024 $\approx$ 0.1%, a dynamic range about 1:0.001 or 20log(2^10) dB = 60 dB.

12 bits A/D a dynamic range about 72dB

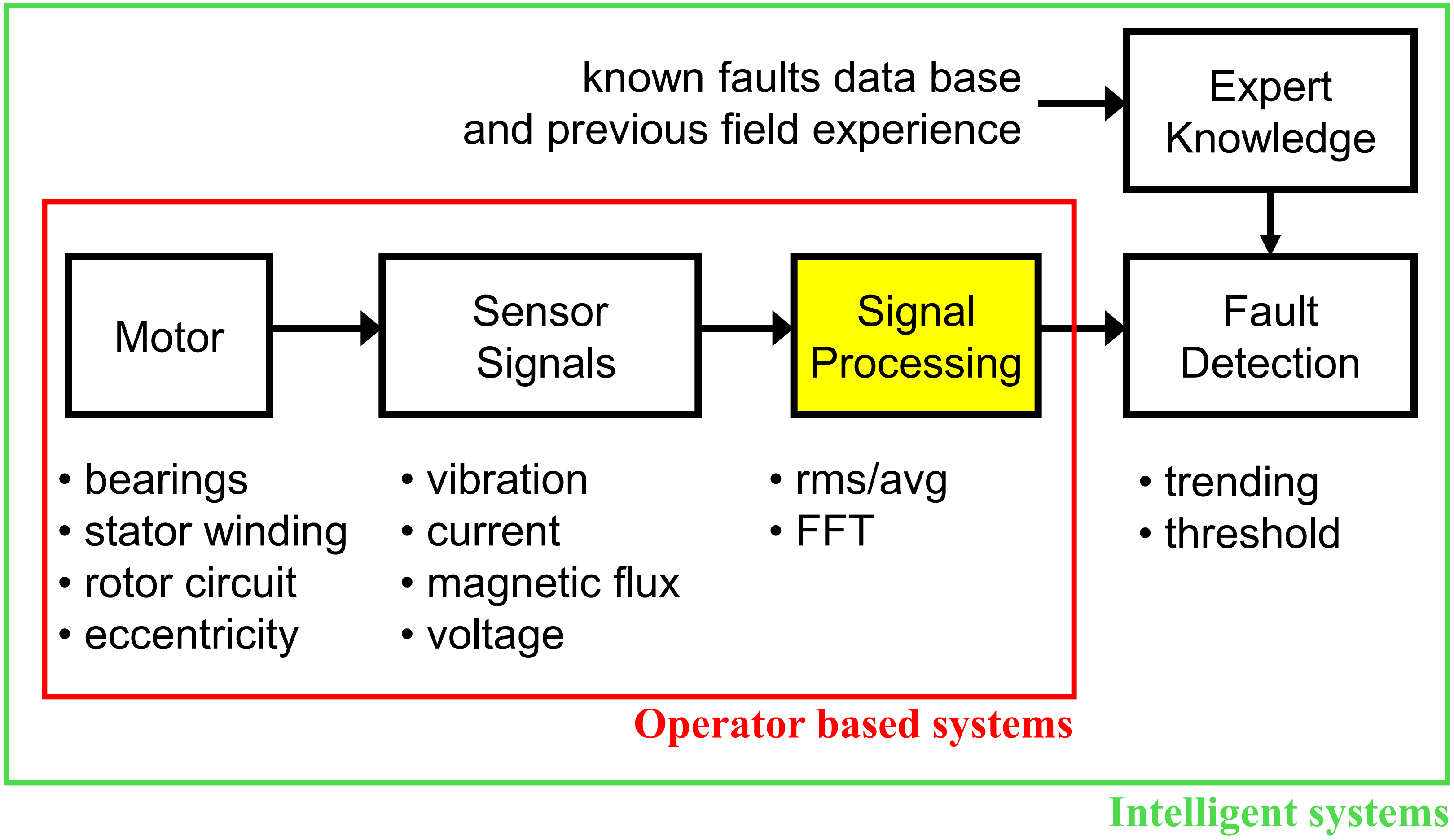
dynamic range increases approximately 6dB for every bit added to the A/D converter.

8 bit converter ~ 48dB

12 bit converter ~ 72dB

16 bit converter ~ 98dB

5. Data Analysis : Frequency Analysis



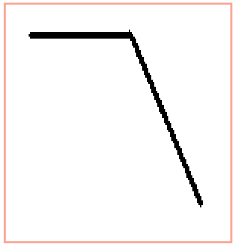
5.1. Analog Signal to Frequencies

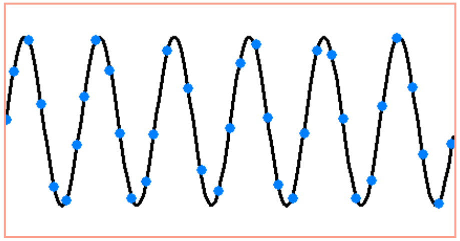
Signal Conditioning

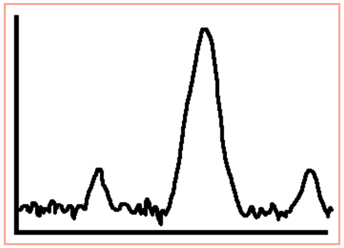
Acquire Waveform

Frequency Analysis

input signal







Anti-Alias Filter (Analogue Low-Pass filter)

Sample Time Domain Signal

Frequency Analysis

5.1.1. Fourier Series

Fourier series : Any periodic function of period *T* can be represented as an infinite series of sine and cosine terms of discrete frequencies of integer multiples of 1/*T*

Mathematically this is the Fourier's Series representation :

$$x(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos n\omega t + b_n \sin n\omega t\right)$$

where

$$\omega = \frac{2\pi}{T}$$

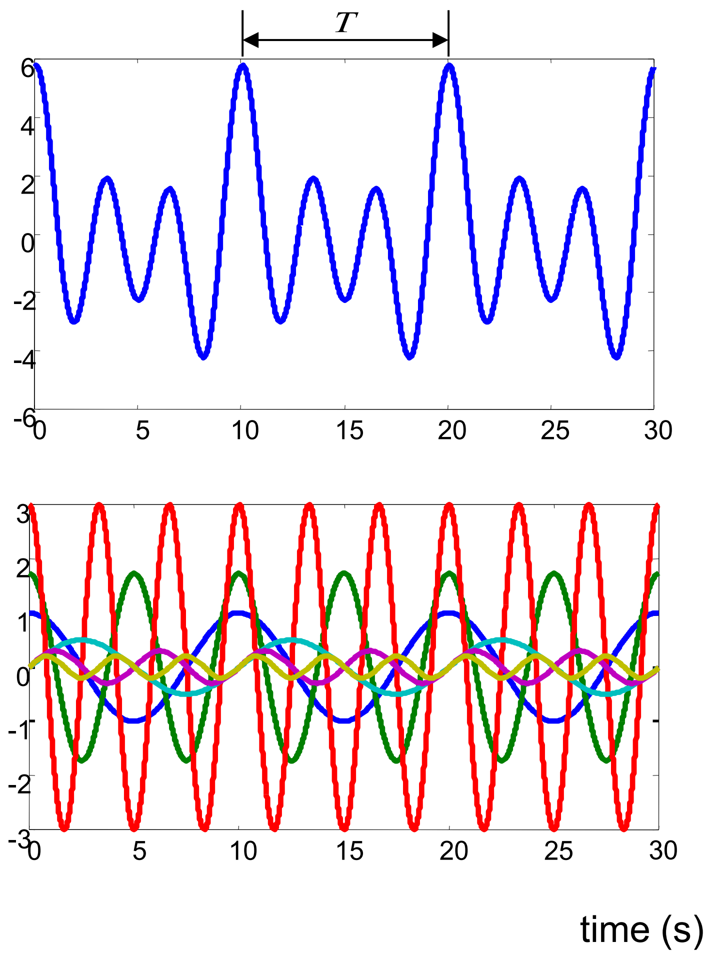
and a_0, a_n and b_n known as the Fourier coefficients

$$a_0 = \frac{1}{T}\int_0^T x(t)\,dt \qquad a_n = \frac{2}{T}\int_0^T x(t)\cos(n\omega t)\,dt$$

$$b_n = \frac{2}{T}\int_0^T x(t)\sin(n\omega t)\,dt$$

5.1.2. Fourier Series Representation

Fourier's theorem states that any periodic waveform in the time domain can be represented by the weighted sum of sines and cosines.



DC component $a_0=0$

	Cos	Sin
fundamental (f=1/T) →	$a_1=1$	$b_1=0.5$
2nd harmonic (f=2/T) →	$a_2=1.73$	$b_2=0.3$
3rd harmonic (f=3/T) →	$a_3=3$	$b_3=0.2$

↑ discrete frequencies

$$x(t) = a_0 + \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \sin n\omega t)$$

5.1.3. Calculation Process

Fourier series applied to a sampled data sequence, assumes it is periodic with period *T*

$$X(k) = \frac{1}{N}\sum_{n=0}^{N-1} x(n)\mathrm{e}^{-j\frac{2\pi kn}{N}} = \frac{1}{N}\sum_{n=0}^{N-1} x(n)\left[\cos\left(\frac{2\pi kn}{N}\right) - j\sin\left(\frac{2\pi kn}{N}\right)\right]$$

where *k* refers to frequency f_k, and *n* to time t_n.

for given input signal v(n)

Procedure for kth harmonic (freq = *k*/*T*)

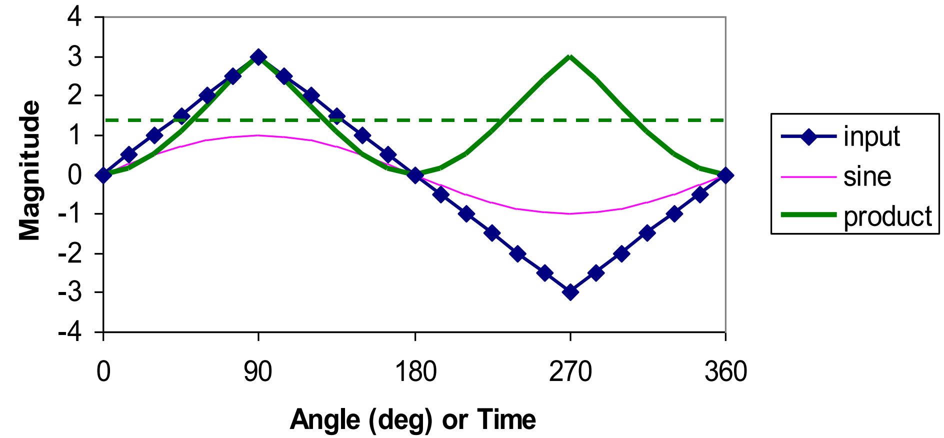
- generate reference sinewave waveform
  - amplitude = 1
  - frequency = k^{th} harmonic
- multiply reference waveform with input signal
- take average of resultant waveform
- amplitude of k^{th} harmonic = 2*average

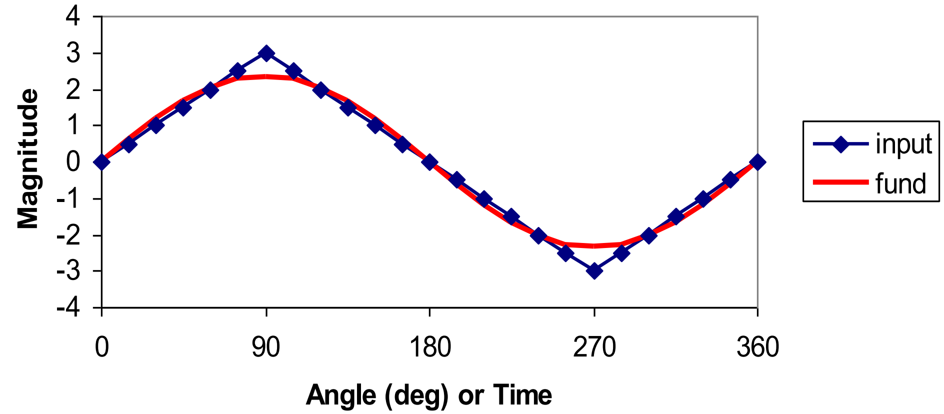
5.1.4. Fundamental (f=1/T)

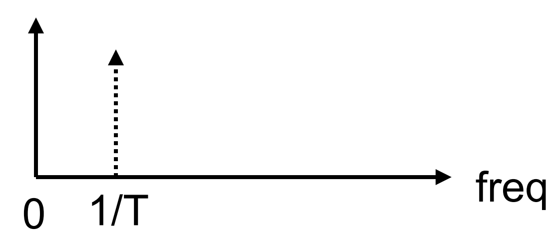
angle theta	input v(theta)	sine sin(theta)	product sin(theta)*v(theta)	fund 2*avg*sin(theta)
0	0	0.000	0.000	0.000
15	0.5	0.259	0.129	0.608
30	1	0.500	0.500	1.174
45	1.5	0.707	1.061	1.660
60	2	0.866	1.732	2.033
75	2.5	0.966	2.415	2.268
90	3	1.000	3.000	2.348
105	2.5	0.966	2.415	2.268
120	2	0.866	1.732	2.033
135	1.5	0.707	1.061	1.660
150	1	0.500	0.500	1.174
165	0.5	0.259	0.129	0.608
180	0	0.000	0.000	0.000
195	-0.5	-0.259	0.129	-0.608
210	-1	-0.500	0.500	-1.174
225	-1.5	-0.707	1.061	-1.660
240	-2	-0.866	1.732	-2.033
255	-2.5	-0.966	2.415	-2.268
270	-3	-1.000	3.000	-2.348
285	-2.5	-0.966	2.415	-2.268
300	-2	-0.866	1.732	-2.033
315	-1.5	-0.707	1.061	-1.660
330	-1	-0.500	0.500	-1.174
345	-0.5	-0.259	0.129	-0.608
360	0	0.000	0.000	0.000

fundamental

avg
1.174





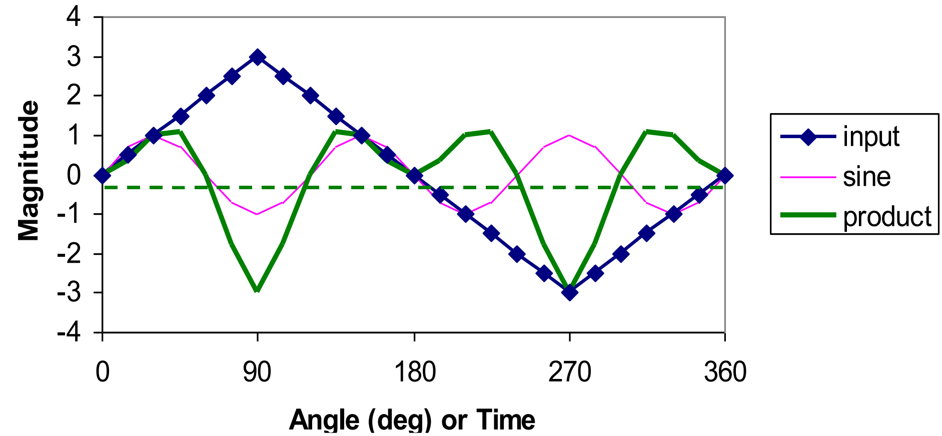


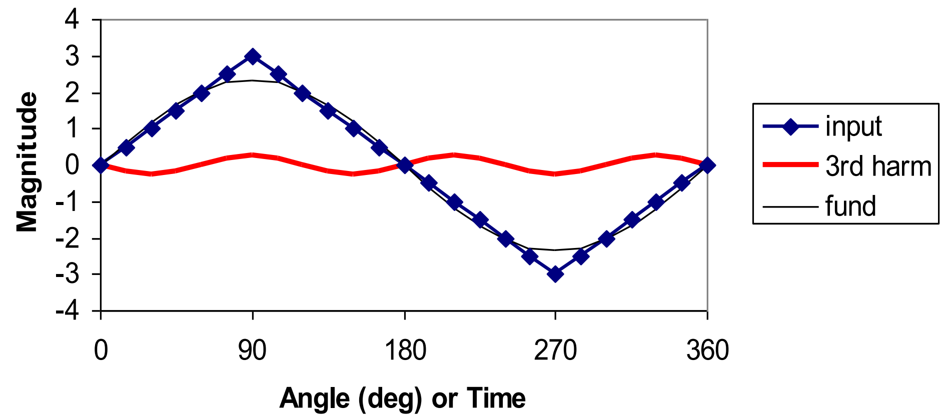
5.1.5. 3rd Harmonic (f=3/T)

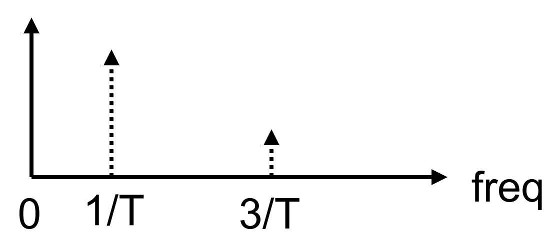
angle theta	input v(theta)	sine sin(3*theta)	product sin(3*theta)*v(theta)	3rd harm 2*avg*sin(3*theta)
0	0	0.000	0.000	0.000
15	0.5	0.707	0.354	-0.193
30	1	1.000	1.000	-0.273
45	1.5	0.707	1.061	-0.193
60	2	0.000	0.000	0.000
75	2.5	-0.707	-1.768	0.193
90	3	-1.000	-3.000	0.273
105	2.5	-0.707	-1.768	0.193
120	2	0.000	0.000	0.000
135	1.5	0.707	1.061	-0.193
150	1	1.000	1.000	-0.273
165	0.5	0.707	0.354	-0.193
180	0	0.000	0.000	0.000
195	-0.5	-0.707	0.354	0.193
210	-1	-1.000	1.000	0.273
225	-1.5	-0.707	1.061	0.193
240	-2	0.000	0.000	0.000
255	-2.5	0.707	-1.768	-0.193
270	-3	1.000	-3.000	-0.273
285	-2.5	0.707	-1.768	-0.193
300	-2	0.000	0.000	0.000
315	-1.5	-0.707	1.061	0.193
330	-1	-1.000	1.000	0.273
345	-0.5	-0.707	0.354	0.193
360	0	0.000	0.000	0.000

now 3rd harmonic

avg
-0.137







5.1.6. Fourier Transform

Fourier transform : represents signal as a <u>continuous</u> frequency spectrum, input signal extends over <u>infinite time</u> and <u>does not have to be periodic</u>, the input signal can be a continuous or a sampled signal in time.

<u>**Continuous time functions**</u>

– Fourier Transform

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt$$

– Inverse Fourier Transform

$$x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi ft} df$$

<u>**Sampled time functions**</u>

– Fourier Transform

$$X(f) = \sum_{n=-\infty}^{\infty} x(t_n) \mathrm{e}^{-j2\pi f t_n}$$

– Inverse Fourier Transform

$$x(t) = \frac{1}{f_s} \int_{-f_s/2}^{f_s/2} X(f) \mathrm{e}^{j2\pi f t_n} \mathrm{d}f$$

where tn = nΔt, ie the nth time sample.

5.1.7. Fast Fourier Transform

Based on using a block of *N* samples of the input signal over a period of time *T*, <u>assumes that the input signal is periodic with period *T*</u>, effectively performs a Fourier Series analysis of the input waveform to find the frequency components at 1/*T*, 2/*T*, 3/*T* ...

– Fourier Transform

$$X(k) = \frac{1}{N}\sum_{n=0}^{N-1} x(n)\mathrm{e}^{-j\frac{2\pi kn}{N}}$$

– Inverse Fourier Transform

$$x(n) = \sum_{k=0}^{N-1} X(k)\mathrm{e}^{j\frac{2\pi kn}{N}}$$

where *k* refers to frequency f_k, and *n* to time t_n.

5.1.8. Fast Fourier Transform

Earlier Fourier series calculation process illustrate the principle of Fourier analysis but is very slow!

For N time samples, has a total of N frequencies to be calculated.

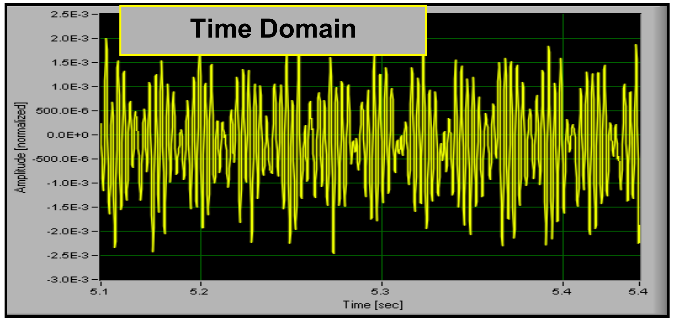
Each frequency requires N multiplications.

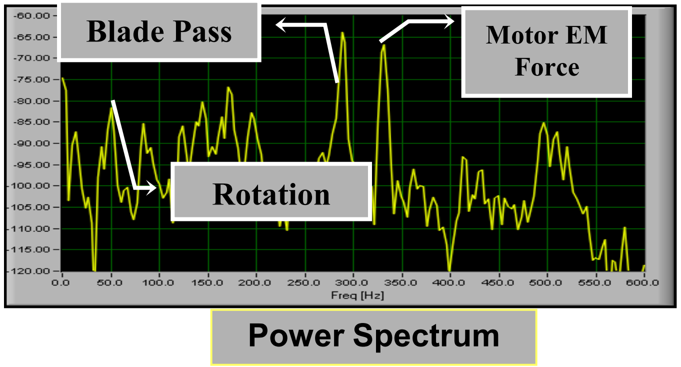
Algorithm thus has an <u>order</u> of N^2, that is, multiplying the number of samples by 10, increases the amount of calculations by a factor of 100.

Fast Fourier Transform (invented 1965)

requires N to be a power of 2, such as $2^{10}=1024$

FFT is a numerically efficient way of performing above calculations (<u>yields same results</u>), reduces number of computations from order N^2 to $N \log_2(N)$. For example: for N = 1024, reduction is >100



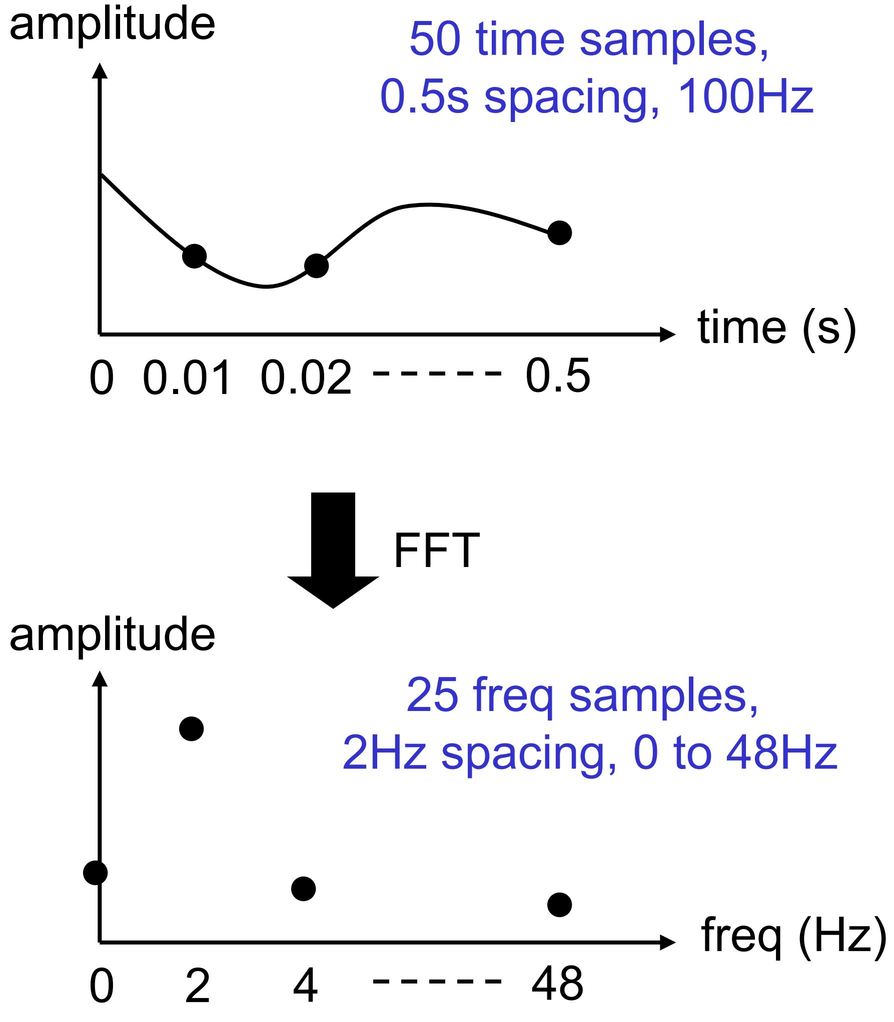


5.1.9. Sampling Freq and Resolution

The FFT converts time points to frequency points

consider a 50 time points taken at a sampling rate of 100Hz, hence over a period of 0.5s

the resultant frequency spectrum will consist of half the number of point [50/2 = 25] with a frequency spacing of 1/0.5s = 2Hz, the Nyquist frequency is 100Hz/2 = 50Hz, highest frequency in output spectrum = 50Hz-2Hz = 48Hz



5.1.10. Sampling Parameters

Condition monitoring usually requires :

- high resolution measurements at low frequencies (<100Hz)
- lower resolution measurements up to higher frequencies say 2kHz (40^{th} harmonic of 50Hz)

which can be more easily met using two data sets, for instance :

	Low Freq	High Freq
Sampling Frequency f_S	400Hz	8,000Hz
Total Sampling Time T	100s	5s
Number of Points $N = f_S T$	40,000	40,000
Nyquist Frequency $= f_S/2$	200Hz	4,000Hz
Frequency Resolution $= 1/T$	0.01Hz	0.2Hz

5.1.11. Sampling Calculation

Formulas

– number of samples N = sampling frequency f_S x total sampling period T

– Nyquist frequency = $f_S/2$

– frequency resolution = $1/T$

Examples

1) take 200 samples over period of 0.2s, find Nyquist frequency and frequency resolution

2) for Nyquist frequency of 500Hz, frequency resolution of 0.1s find sampling frequency, total sampling period and number of samples

5.2. Decibels

consider a 2.2kW motor current spectrum showing

– fundamental 50Hz component of say 4.2A

– a small fault signal at 48Hz of say 0.007A

1) normalisation : convenient to express fault signals as a ratio compared to some reference, such as the fundamental component

– example : 48Hz signal has level 0.007A/4.2A = 0.00167 (0.167%)

2) decibels : fault signals are normally much smaller than reference signal, thus convenient to express in dB (logarithmic scale) where

value in dB = 20 $\log_{10}$(ratio)

– example : 48Hz signal : 20$\log_{10}$(0.00167) = -55.6dB

to convert back to ratio = 10^(dB value/20)

– example : 10^(-55.6/20) = 0.00166

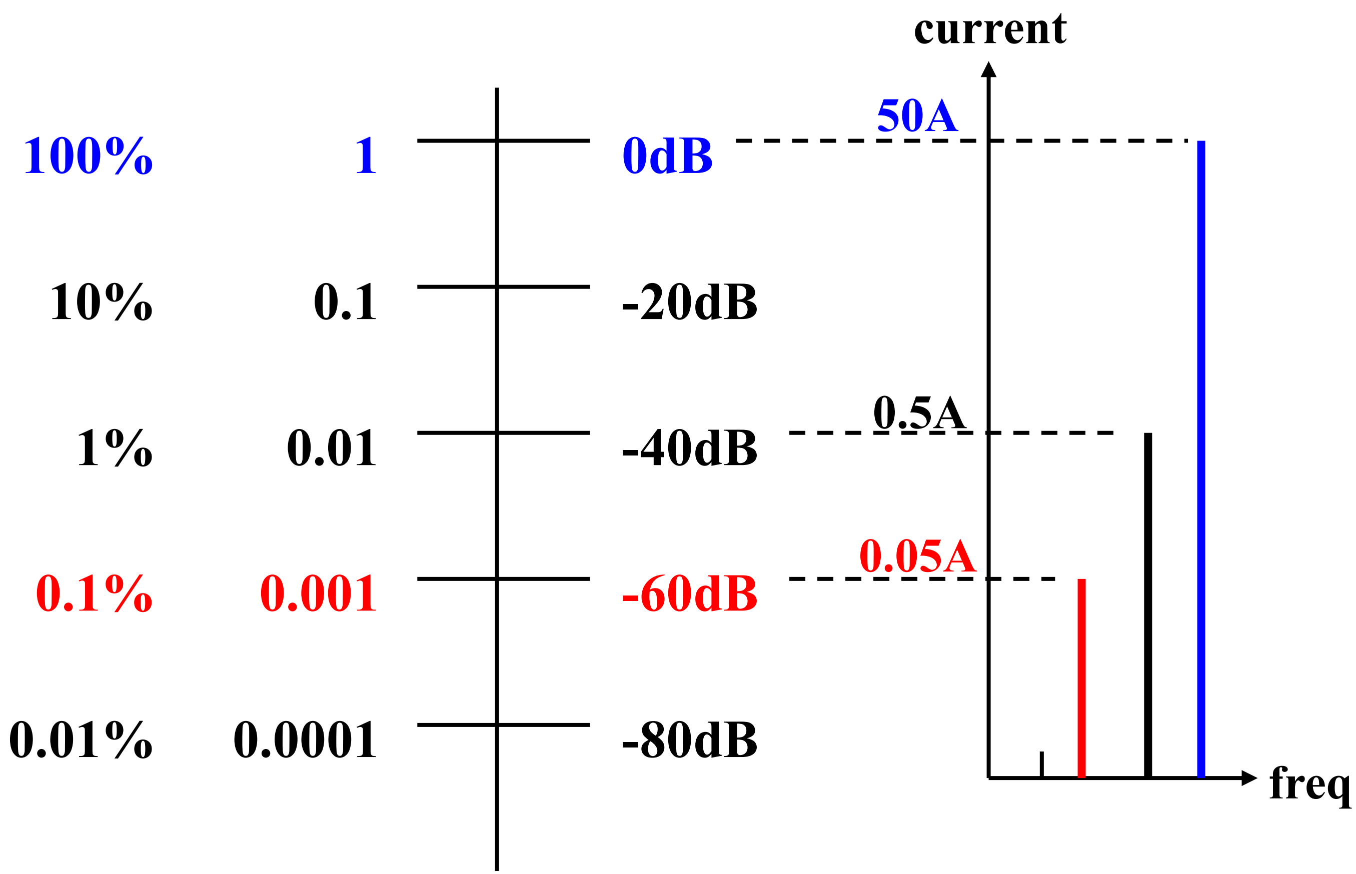
notes

– by definition, value of reference signal is 20$\log_{10}$(1) = 0dB

– ratio of 0.1 = -20dB, ratio of 0.01 = -40dB

– every change in ratio of factor of 10 is equivalent to 20dB

5.2.1. Logarithmic (dB) Ratio Scale



$$dB = 10\log_{10}\left(\frac{x_1}{x_2}\right)^2 = 20\log_{10}\left(\frac{x_1}{x_2}\right)$$

5.3. Windows

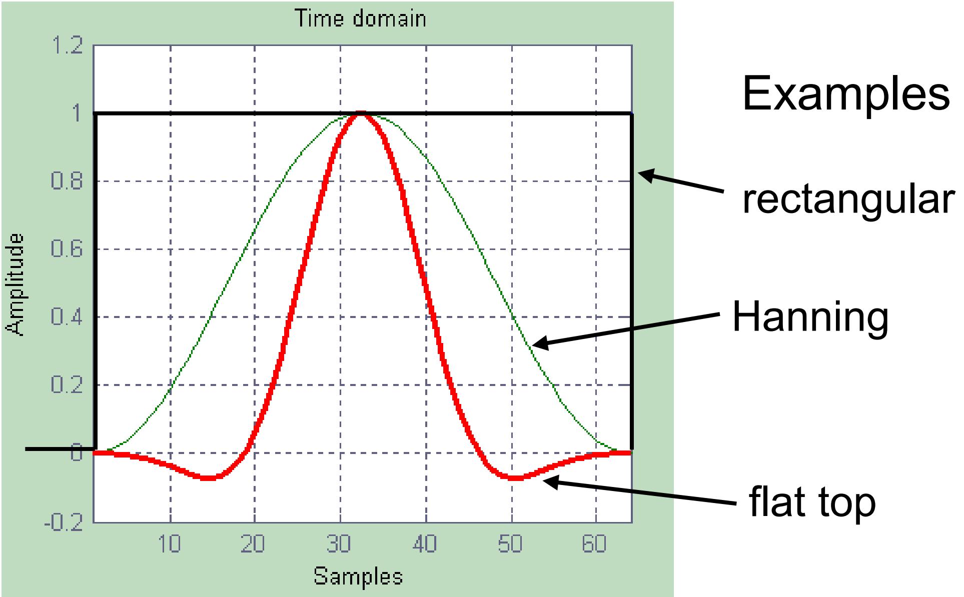
ideal case with infinite long sampling period : if single frequency in input signal, should obtain single, sharp frequency peak in output spectrum

with finite number of points, if frequency is not exact multiple of frequency resolution (1/*T*) then resultant frequency peak is a broader peak which may not have the right amplitude

windowing is a method which trades off accuracy of measurement of

– amplitude of peak

– frequency of peak (also related to minimum frequency separation at which two peaks can be distinguished from a single peak)



Examples of typical window waveforms

5.3.1. Windows

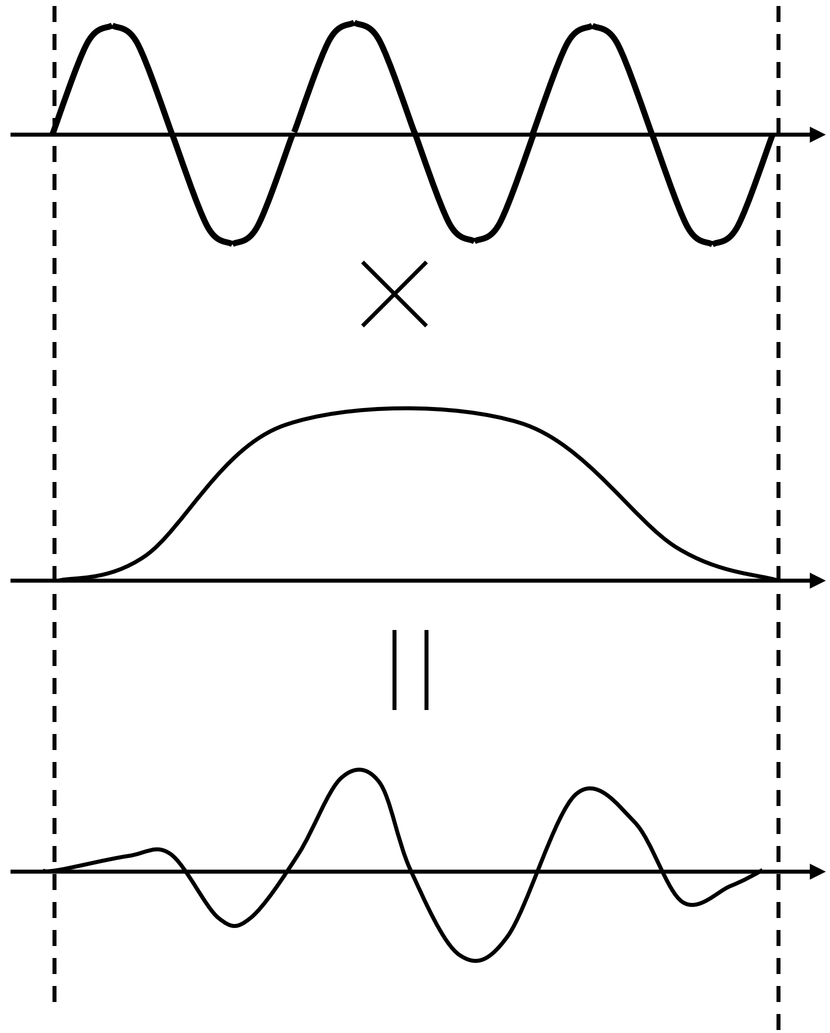
Basic procedure :

1) measure input signal

2) select window function

3) multiply signal by window

4) perform FFT on windowed input signal



5.3.2. Windowing

input signal : consists of sinewave of amplitude = 1, of finite length

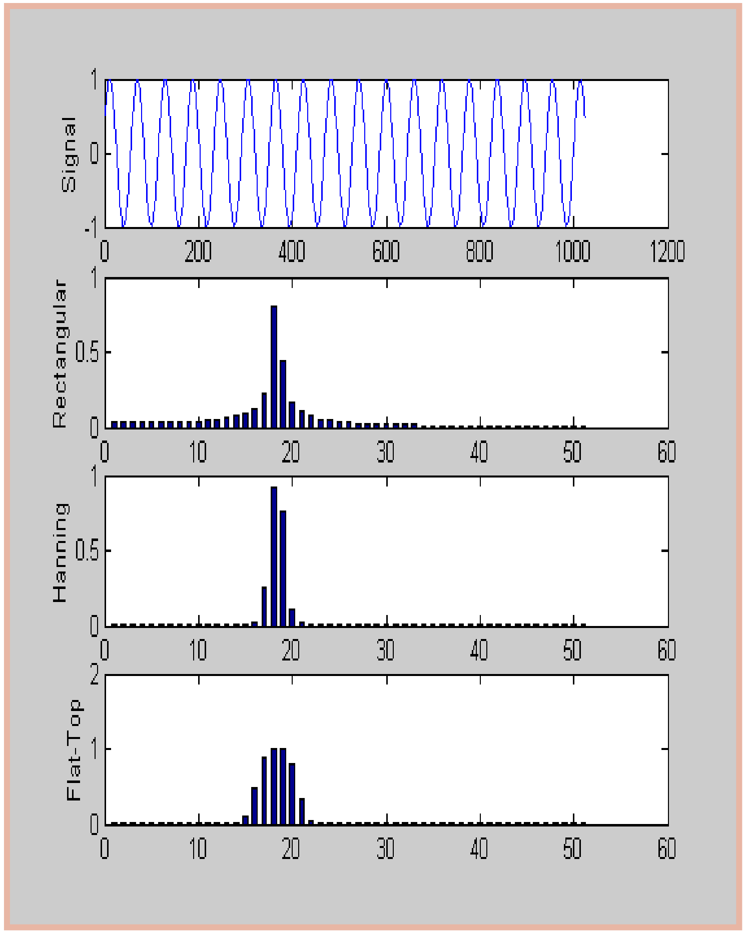
FFT results after passing input signal through different window

1) Rectangular window : effectively no window, sharpest peak : can have up 4dB (about 40%) amplitude error, produces a lot of noise throughout entire spectrum

2) Hanning window : can have up to 1.4dB amplitude error (about 15%) amplitude error, commonly used

3) Flat-top window : amplitude error very small (<0.01dB, less than 0.1%), but broad resulting peak make closely spaced peaks much harder to separate

note - many other types of windows, each has a different amplitude/frequency accuracy trade-off



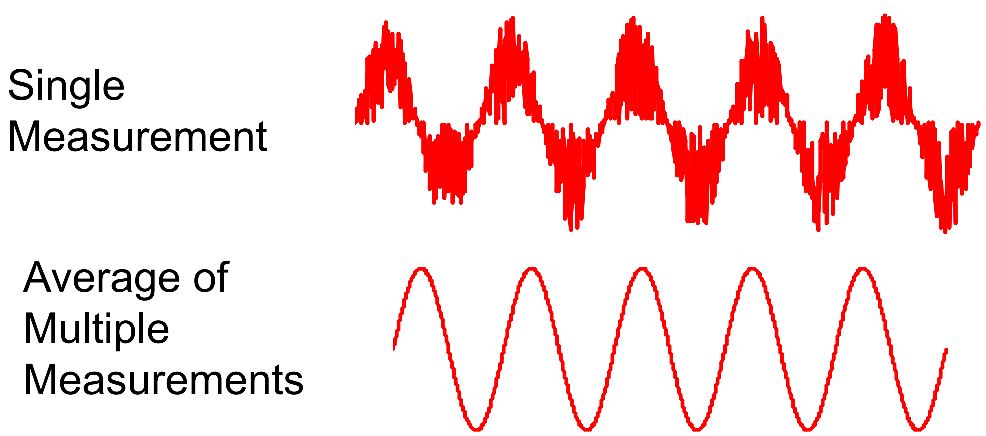
5.4. Averaging

real measurements often noisy, applying averaging to reduce noise

1) time domain averaging : useful where waveform shape is constant with random noise

2) frequency domain averaging : useful where frequency components are constant, but masked with noise

Improves the signal-to-noise ratio

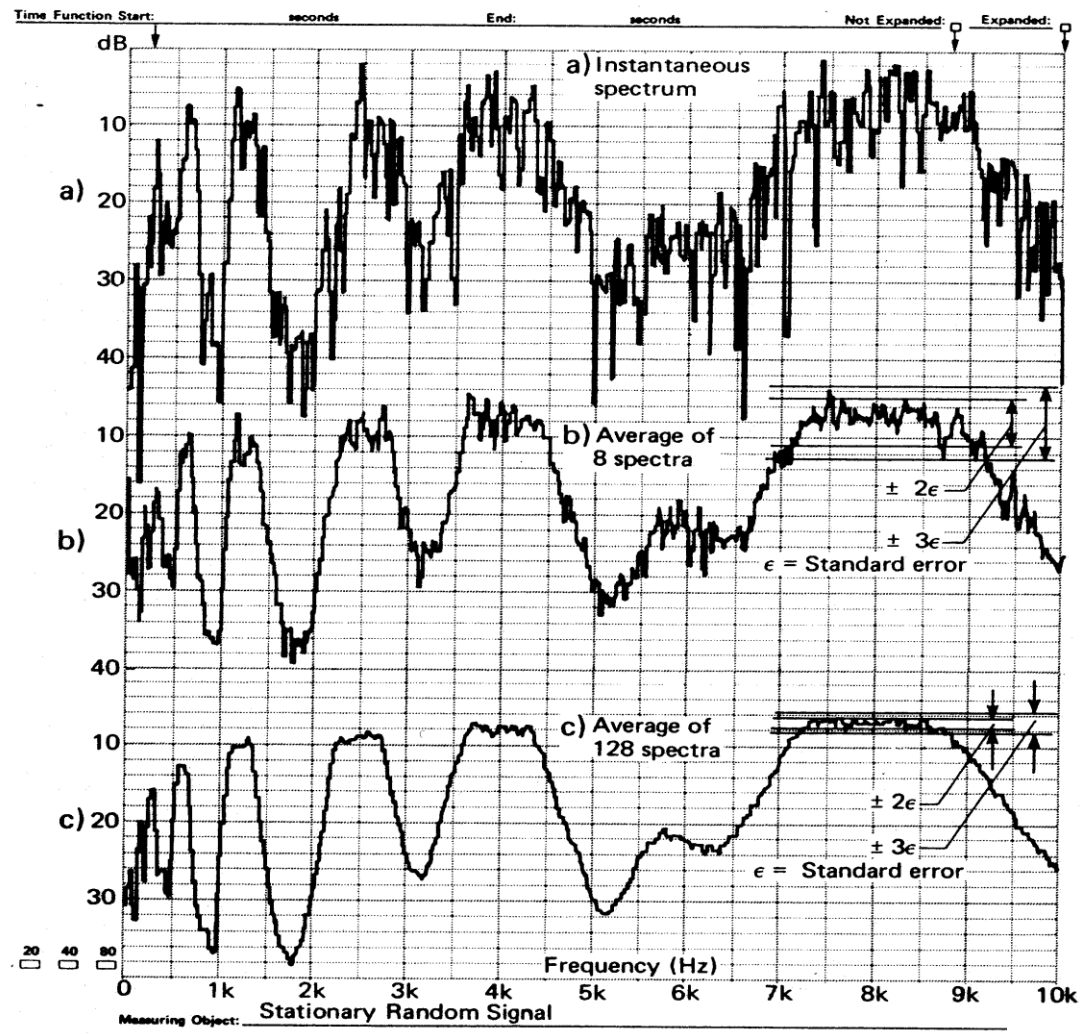


5.4.1. Frequency Averaging

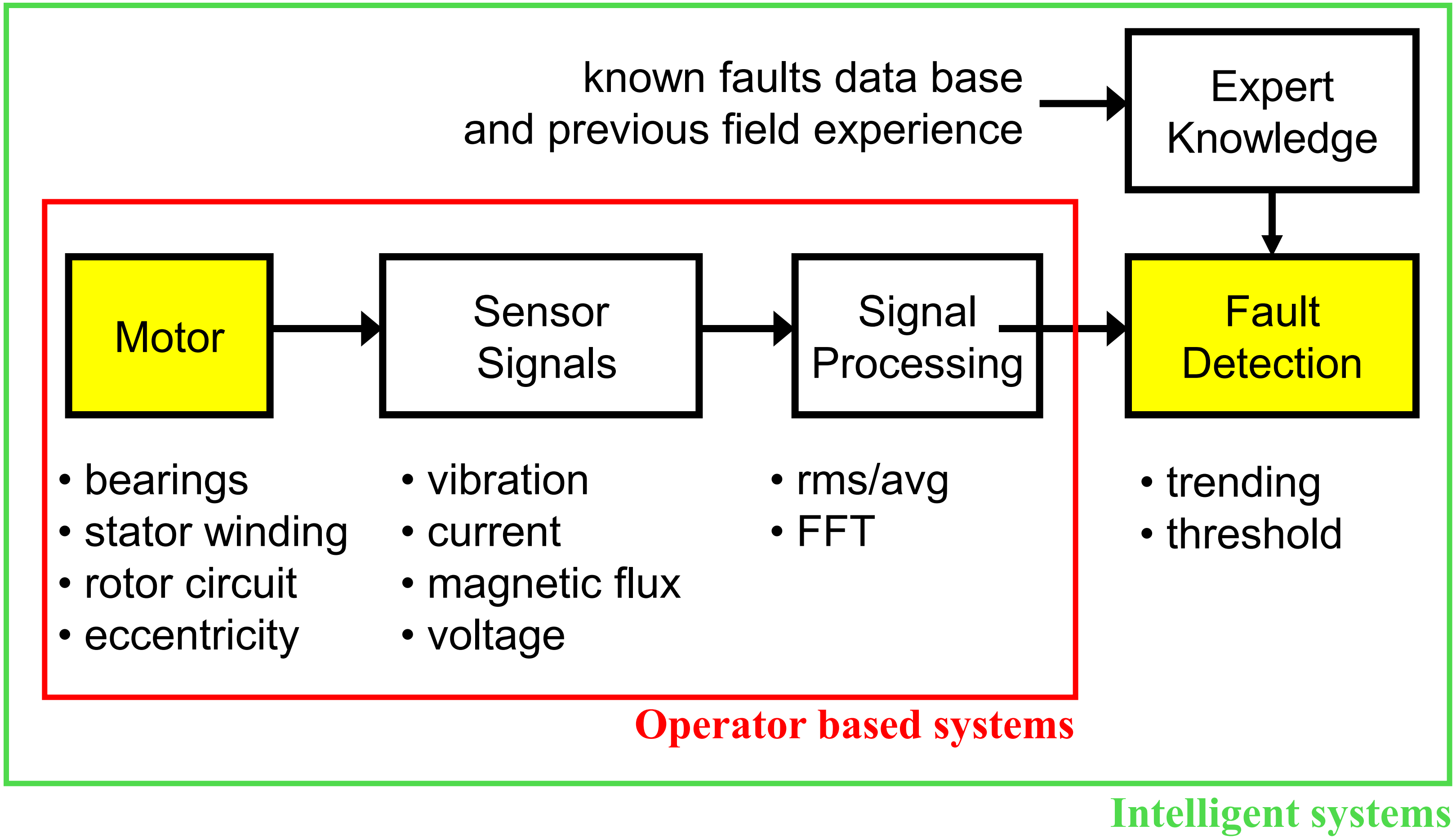
Single Spectrum

Average of 8 Spectra

Average of 128 Spectra



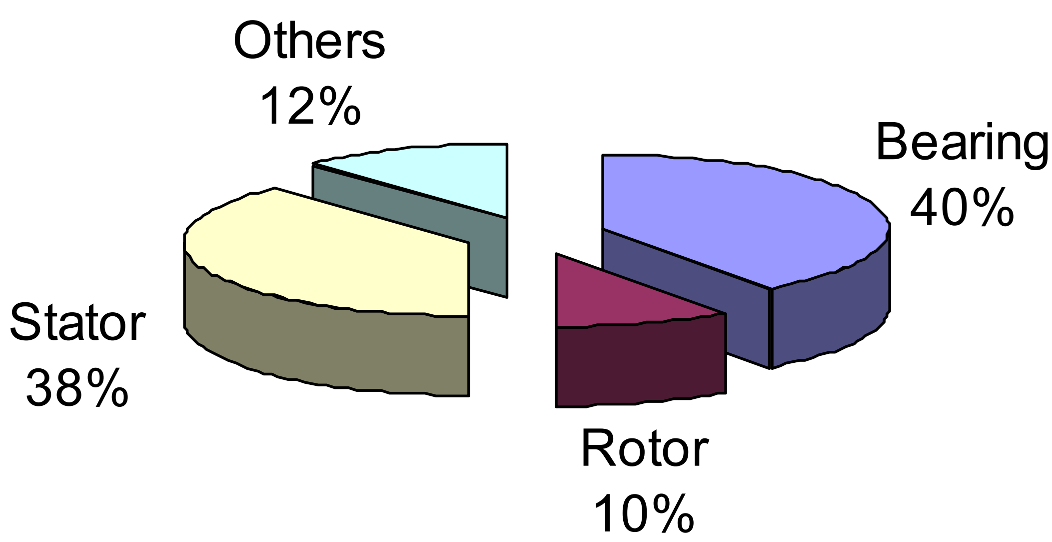
6. Motor Faults and Detection



6.0.1. Induction Motor Fault Surveys

Survey Size (# motors)	EPRI 1052	IEEE 380	IEEE 304
1) Stator Faults : insulation, core	36%	26%	25%
2) Rotor Faults : cage, shaft, core	9%	8%	9%
3) Bearing Faults : elements, sleeve	41%	44%	50%
4) Other	14%	12%	16%

a technical paper gives the following breakdown



EPRI = Electric Power Research Institute
IEEE = Institute of Electrical and Electronic Engineers

6.1. Supply and Slip Frequency

1) number of poles : machine nameplate information gives rated speed and hence number of poles

2) supply frequency : obtain by close examination of largest peak near 50Hz in current, flux or voltage spectra

eg. supply freq f_1 = 50.02Hz

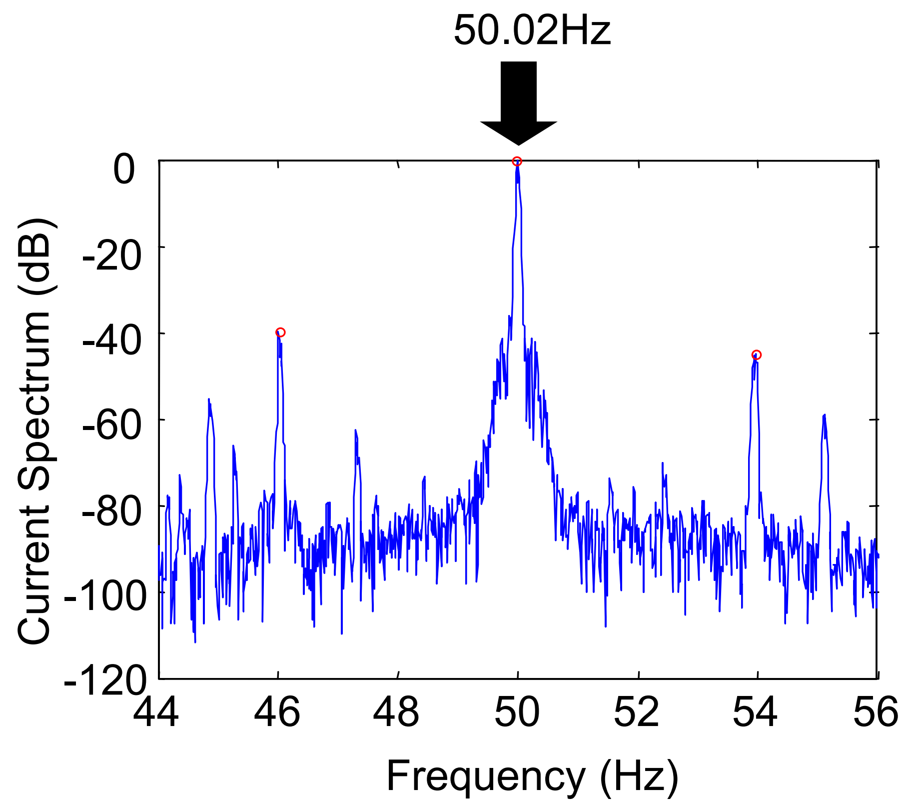
supply frequency usually in range 49.90Hz-50.10Hz

3) operating slip frequency sf_1 find by examining flux spectrum

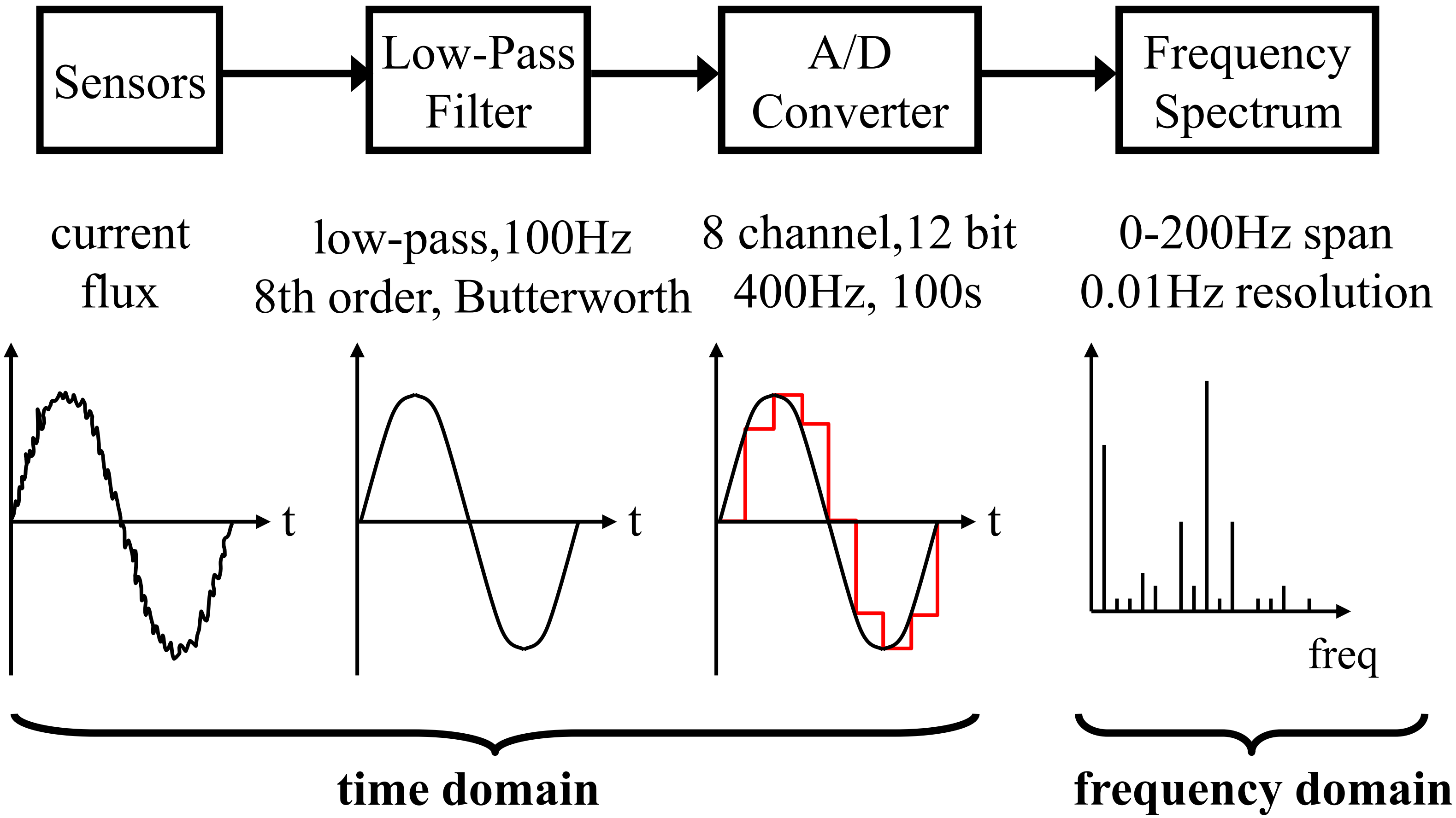
4) calculate operating slip and speed

slip $s = sf_1/f_1$

speed $n_R = (1-s)n_S = (1-s)60f_1/p$



6.1.1. Signal Processing

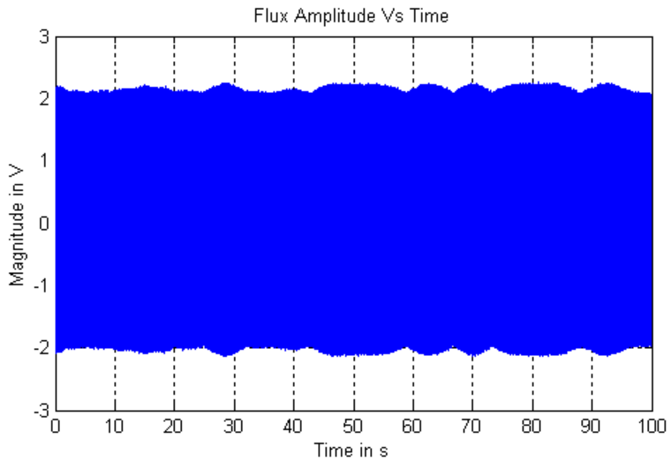


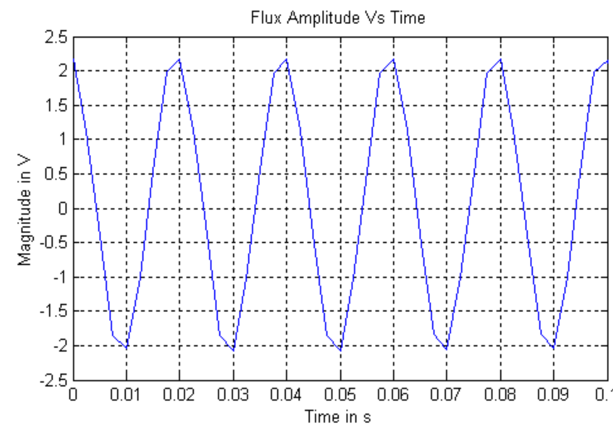
6.1.2. Measured Flux Signals

full time record

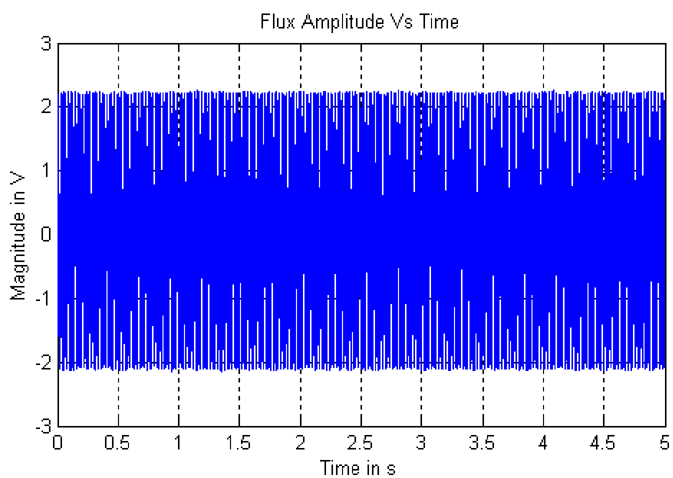
zoomed in segment

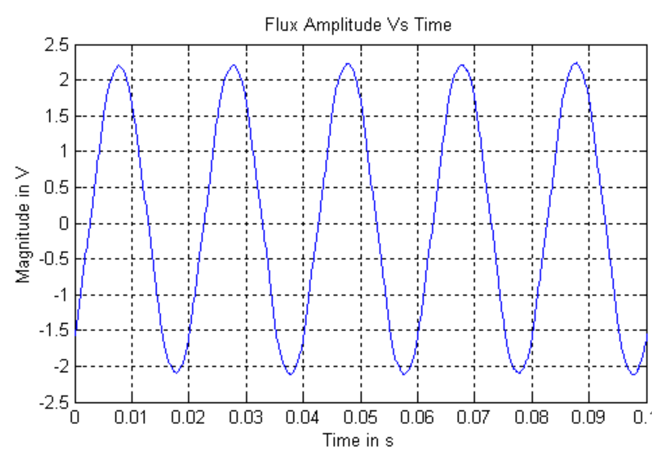
low frequency
sampling 400Hz
100s, 40,000 pts
100Hz low-pass
0.01Hz resolution





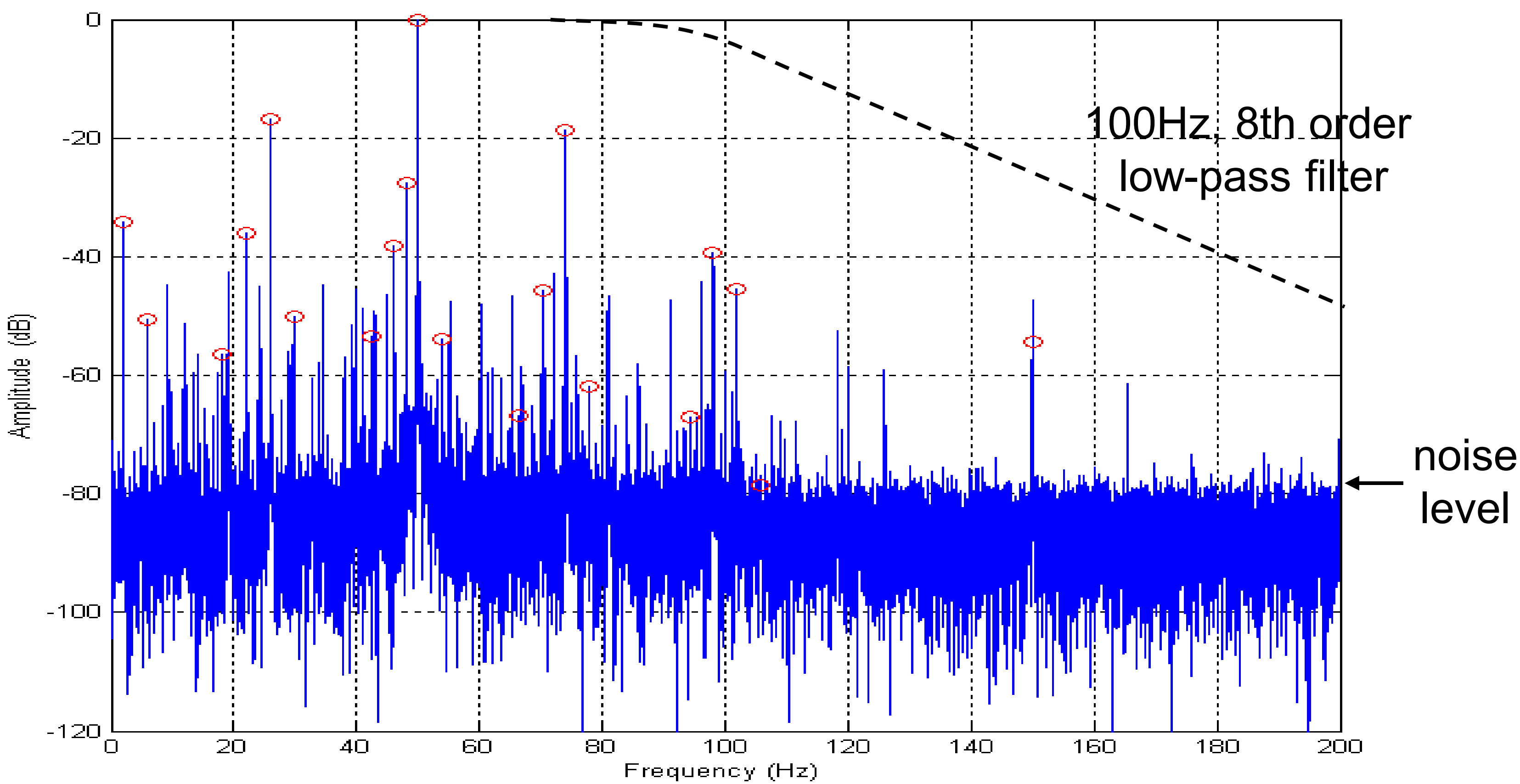
high frequency
sampling 8kHz
5s, 40,000 pts
2kHz low-pass
0.2Hz resolution





6.1.3. Flux Spectrum

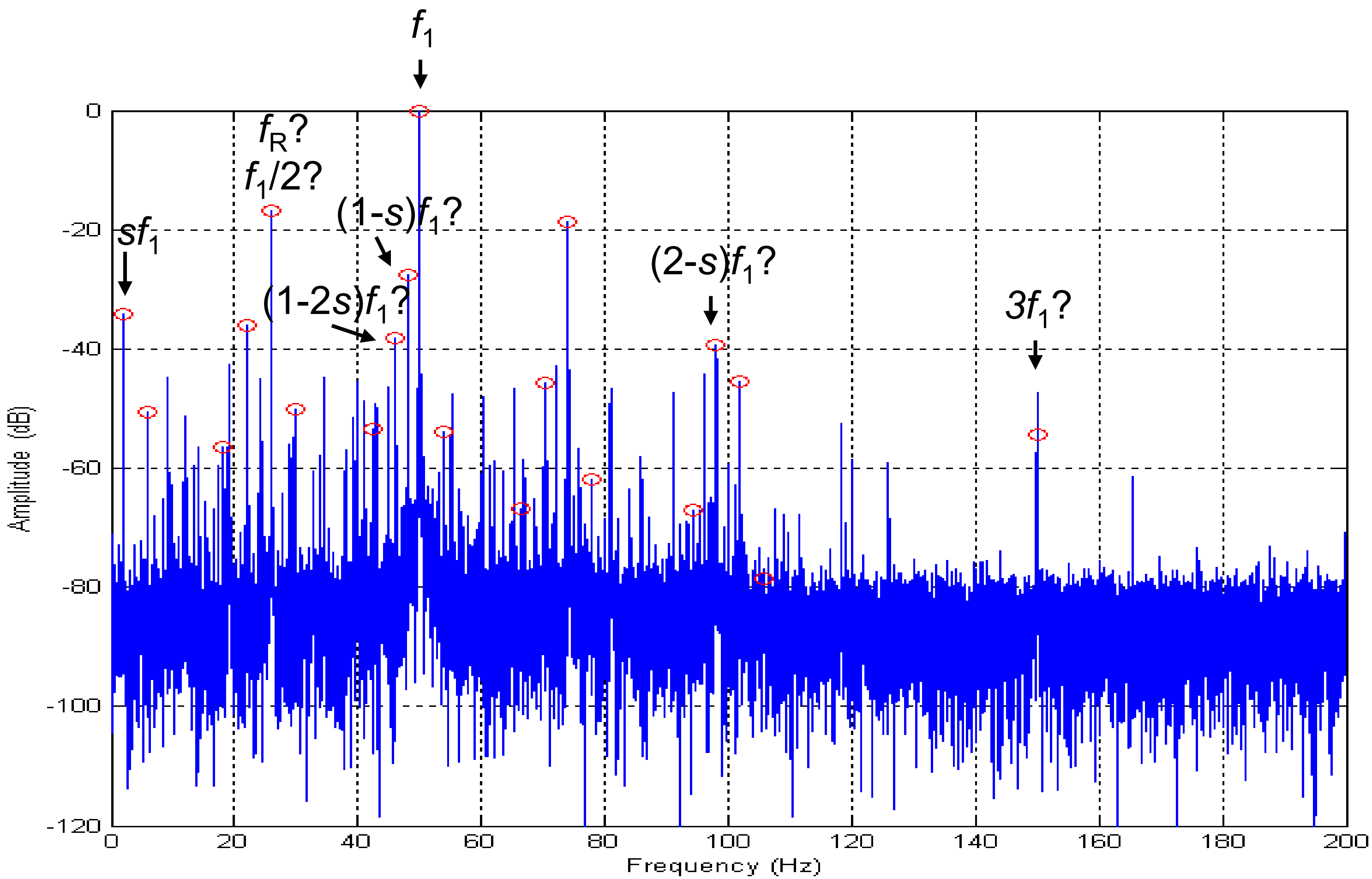
400Hz sampling (100Hz low pass filter) : apply Hanning window, then perform FFT : 0-200Hz spectrum with 0.01Hz resolution, normalise spectrum to highest peak = 1, then convert to dB



6.1.4. Identification of Peaks

key peaks in spectrum usually some multiples of supply frequency f_1 and slip s and pole pairs p,

eg. sf_1, $3sf_1$, $f_R=(1-s)f_1/p$, $f_1/2$, $(1-s)f_1$, $(1-2s)f_1$, $(1+2s)f_1$, $(2-s)f_1$, $3f_1$ ...



6.1.5. Fundamental/Slip Frequency

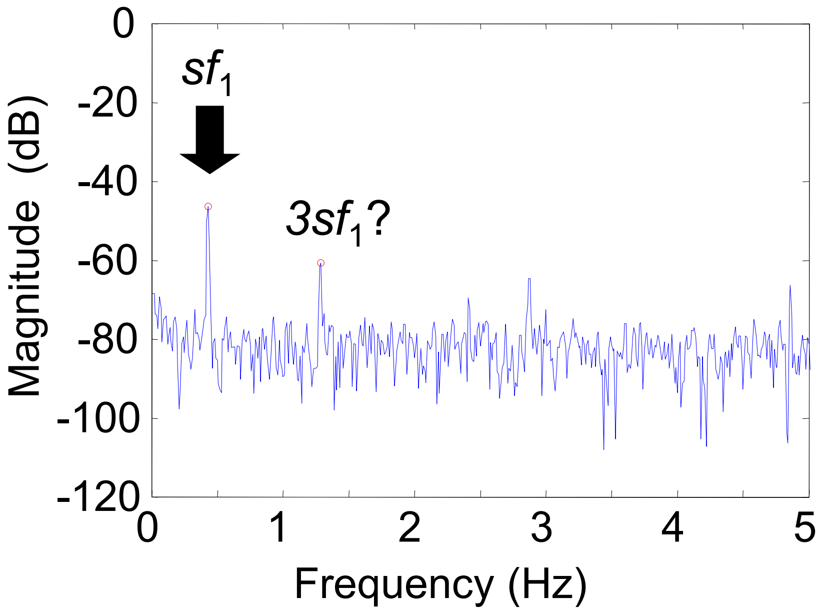
Examine zoomed in flux spectrum, near zero Hz.

Slip frequency (sf_1) component : largest peak in region 0.2-2Hz, eg 1.85Hz

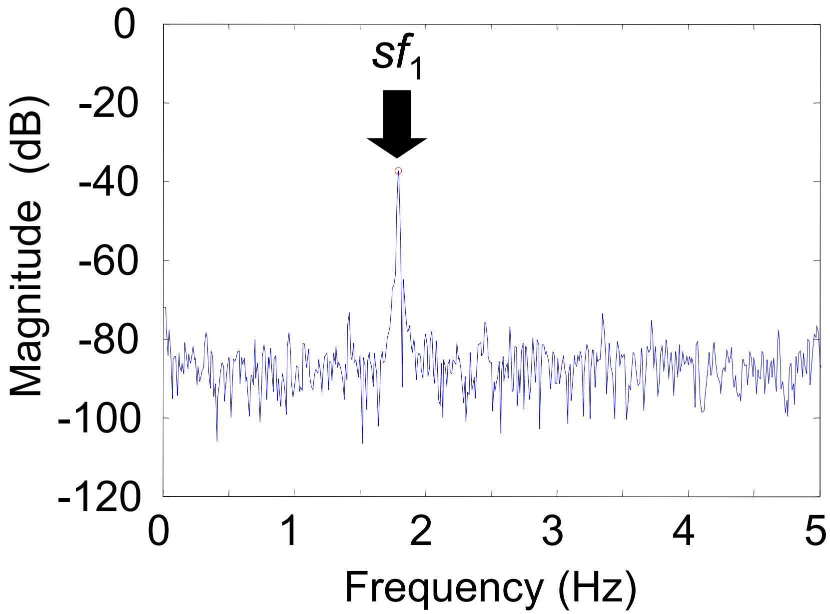
given measured supply frequency f_1, can find slip s

% load (torque) = slip frequency/rated slip frequency = slip/rated slip

20% Load



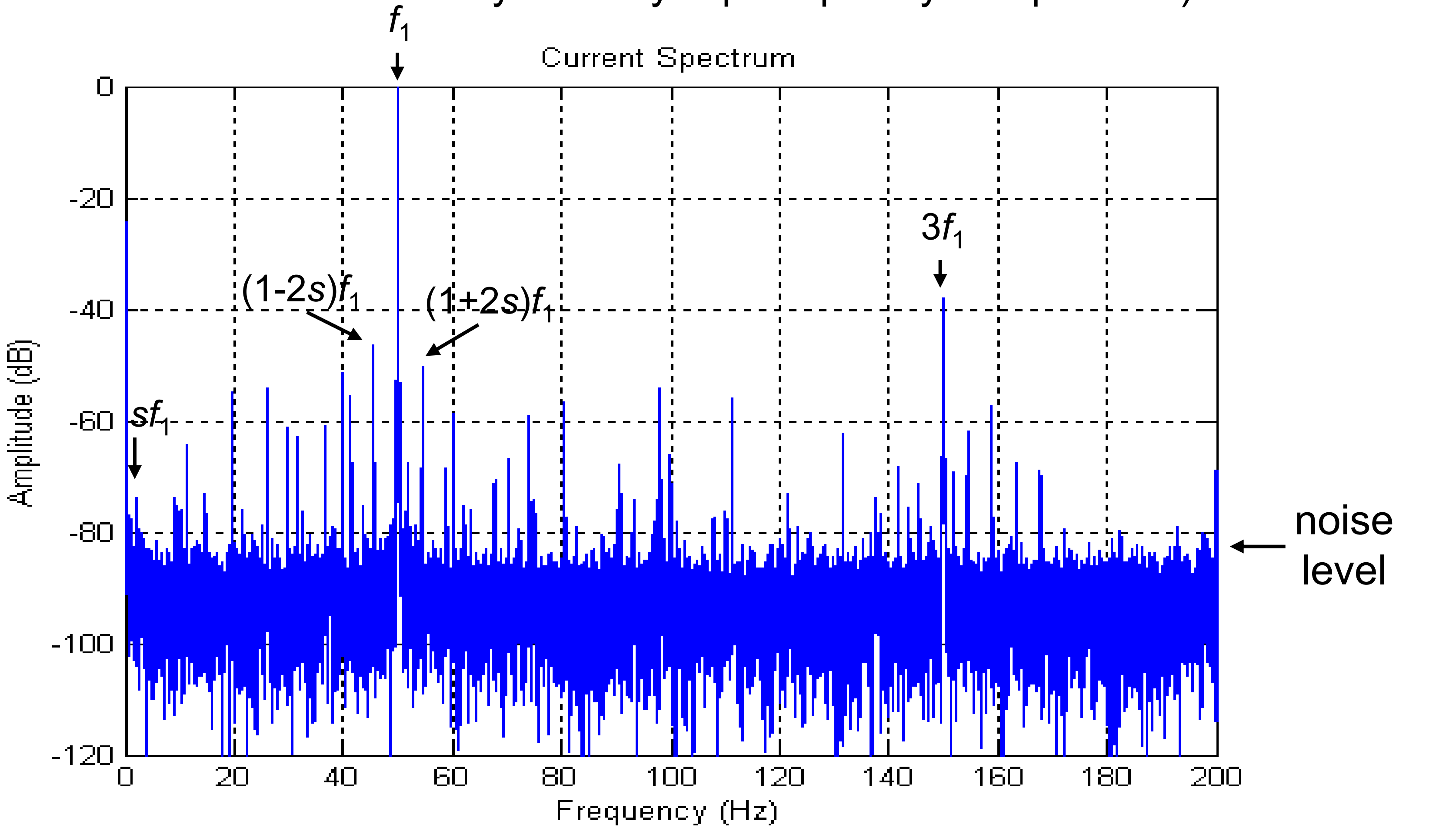
80% Load



6.1.6. Current Spectrum

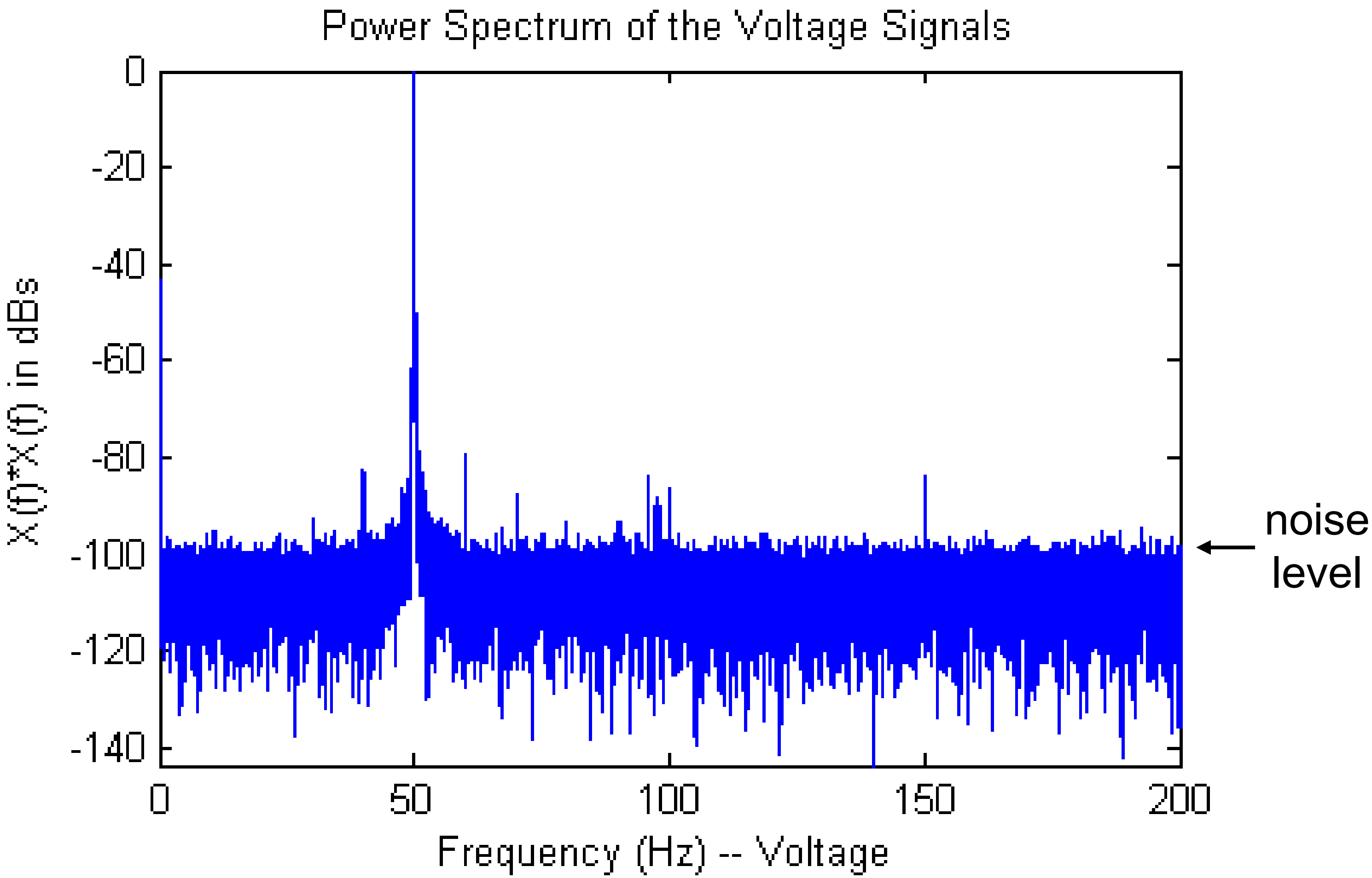
similar to flux spectrum but signals normally lower in amplitude,

slip frequency sf_1 component is very small (flux coil picks up rotor currents, stator currents do not normally see any slip frequency components)



6.1.7. Voltage Spectrum

normally voltage spectrum has very few frequency components, voltage normally used for power calculations or unbalanced voltage measurements



6.2. Broken Rotor Bars

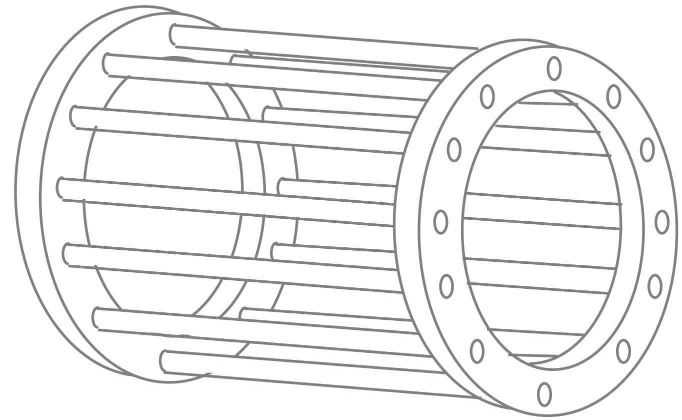
cracks in rotor bars or end cage

Causes

- frequent direct-on-line starting
- pulsating mechanical loads (eg. compressors, coal crushers)
- manufacturing defects
- mechanical stresses (thermal and mechanical)

Effects

- reduction in efficiency and performance
- torque and speed oscillations at twice slip frequency (affects bearings)
- overheating of adjacent bars (spread of damage)
- danger of secondary damage (pieces of rotor damaging stator end-windings or laminations)



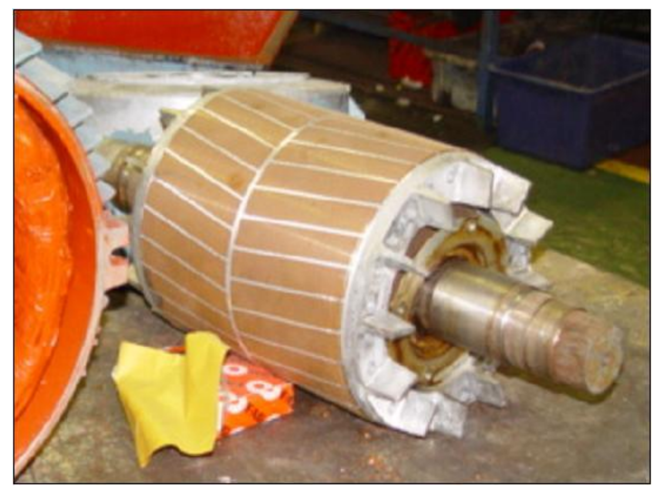
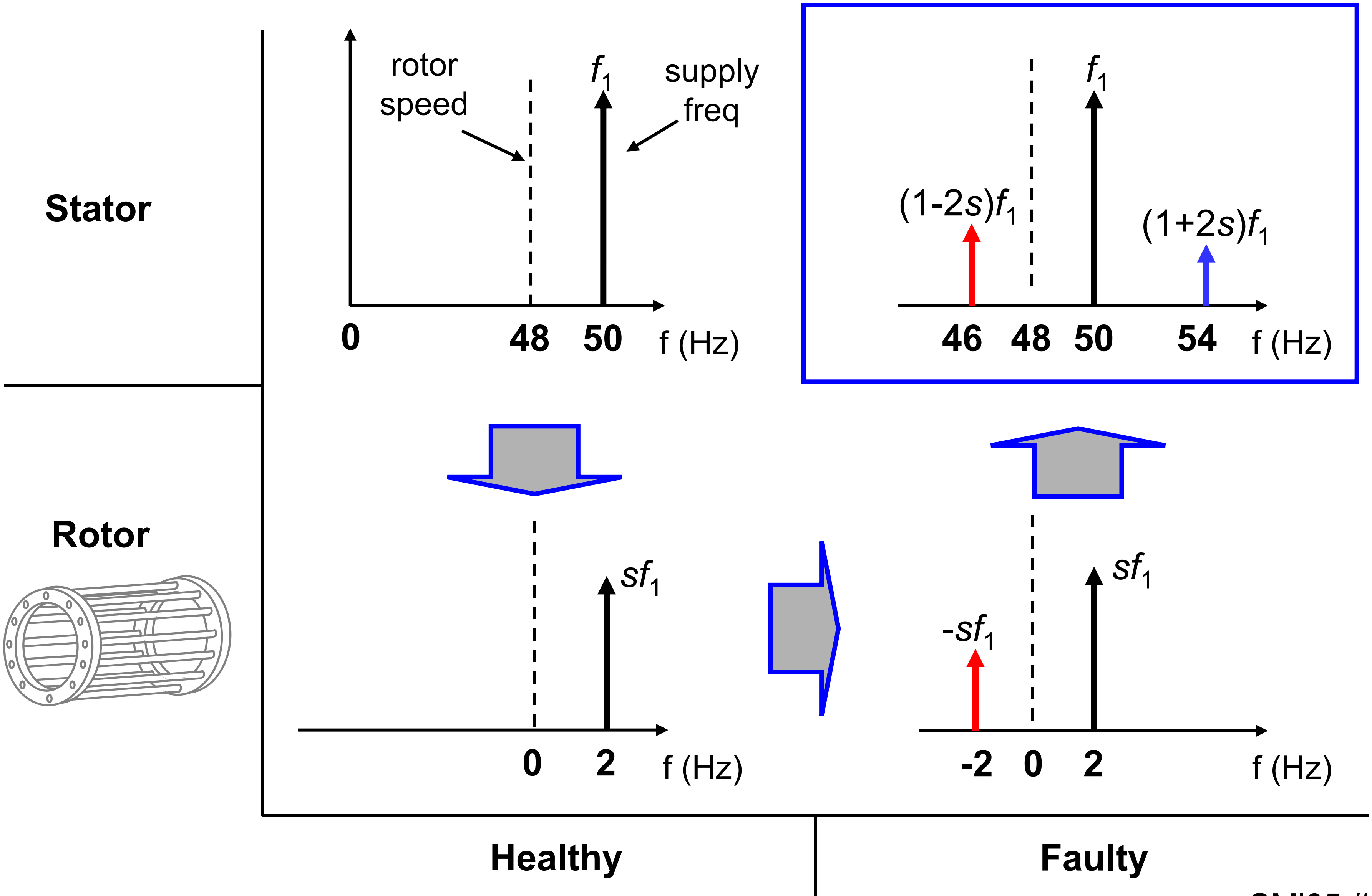


Photo courtesy of RME

6.2.1. Broken Rotor Bar Sidebands



6.2.2. Broken Bar Theory

Consider situation of motor operating under load

- synchronous frequency 50Hz, rotor spinning at 48Hz
- induced voltage in rotor has frequency of 50Hz-48Hz= +2Hz

Healthy Rotor Case

- symmetrical rotor, currents in rotor only at +2Hz
- stator sees rotor currents at frequency of 48Hz+2Hz = 50Hz

Faulty Rotor Case

- broken rotor bars -> assymmetrical rotor
- currents in rotor at frequencies of +/-2Hz
- stator sees rotor currents at frequency of 48Hz+2Hz = 50Hz and 48Hz-2Hz = 46Hz : $(1\text{-}2s)f_1$
- also output torque pulsation at frequency $2sf_1$, causes speed fluctuation at same frequency which produces $(1+2s)f_1$ component
- hence broken bars produce $(1+/\text{-}2s)f_1$ frequency components in current (and flux) spectrum

6.2.3. Identification

Easy fault to find

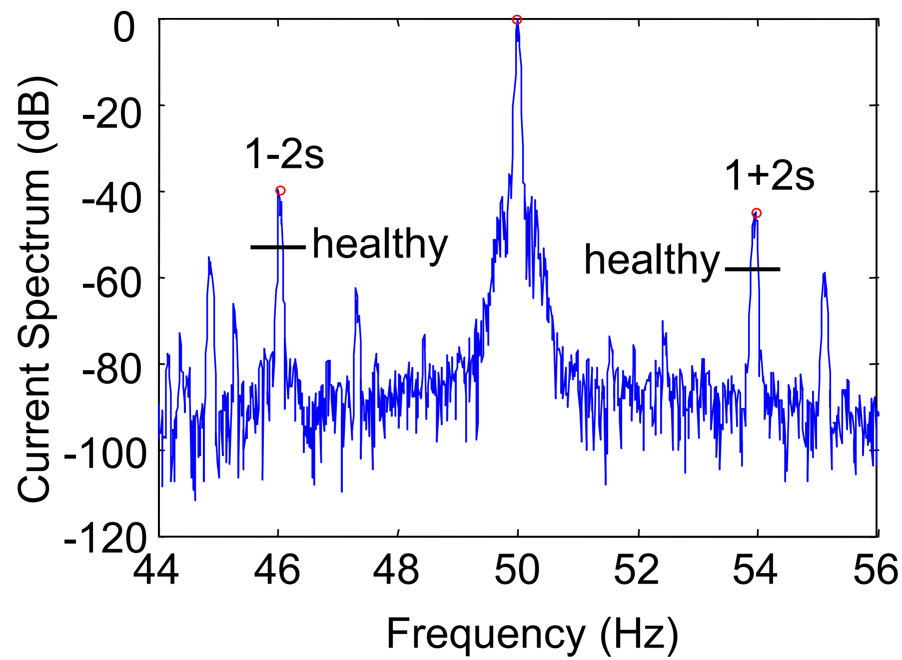
- first fault to be investigated for condition monitoring
- most known about detection using current spectrum

Identification of Broken Bars

- current spectrum : $(1+2s)f_1$ and $(1\text{-}2s)f_1$ components, so called broken bar sidebands
- similar components in the flux and vibration spectrum

Repair

- cast aluminium rotor : usually replace
- fabricated cage rotor : rebraze connections



2.2kW, 4 pole, induction motor, one broken rotor bar out of 32, lines represent sideband amplitudes before fault was introduced

6.2.4. Theoretical Predictions

some researchers have predicted the effect of broken bars on the amplitude of the (1-2*s*)*f* broken bar side-band, consider example predictions for 2 broken bars out of 32 for a four-pole motor (p = 2)

Prediction 1 : Bellini et al.

(1-2s)f sideband amplitude → I_{BB}

fundamental (50Hz) amplitude → I

$$\frac{I_{BB}}{I} = \frac{n}{N}$$

n ← number of broken bars

N ← total number of rotor bars

example : I_{BB}/I = 2/32 = 0.0625 = -24.1dB

Prediction 2 : Benbouzid

$$\frac{I_{BB}}{I} = \frac{\sin\alpha}{2p(2\pi-\alpha)} \qquad \alpha = \frac{2\pi pn}{N}$$

p ← pole-pairs

example α = 2π2*2/32 = 0.7854 rad

I_{BB}/I = sin α /[2*2(2π-α)] = 0.03215 = -29.9dB

Prediction 3 : Thomson

$$\frac{I_{BB}}{I} = \frac{n}{2N-np}$$

I_{BB}/I = 2 /[2*32-2*2] = 0.03333 = -29.5dB

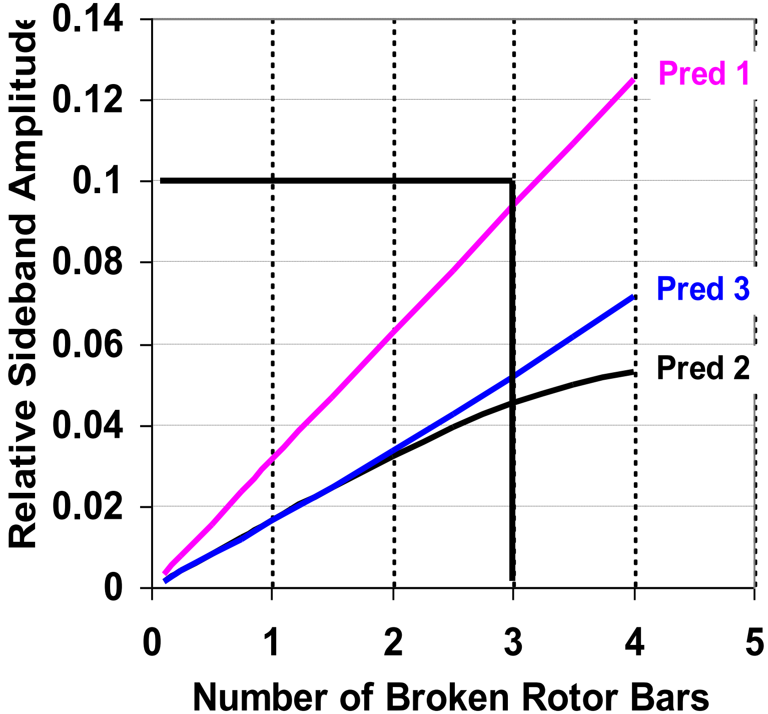
6.2.5. Predicted Sidebands

For induction motor with 4 poles, 32 rotor bars

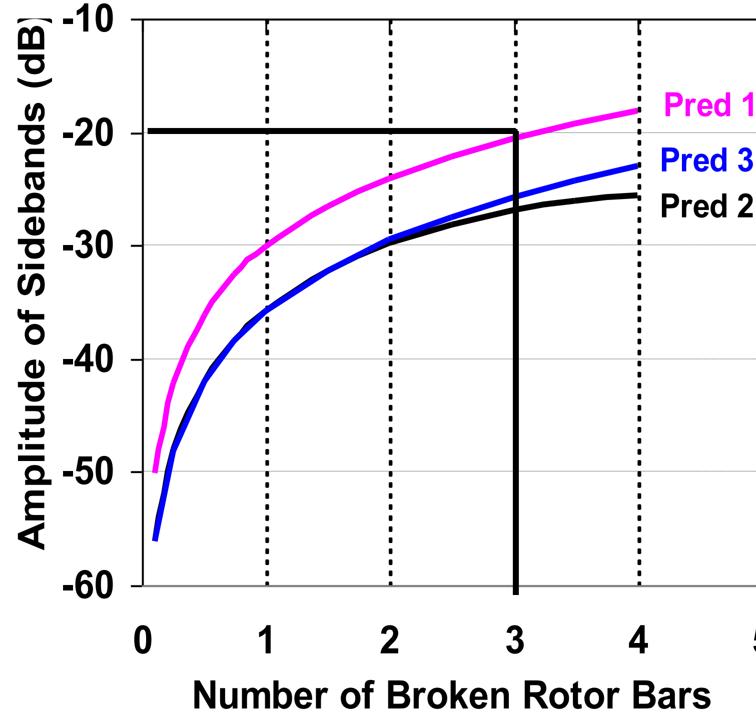
equations can also be used to estimate the number of broken rotor bars given a measured sideband amplitude, eg. for prediction 1, a sideband amplitude of about 0.1 or -20dB corresponds to three broken bars

predictions 2 and 3 are similar for small numbers of broken bars

Linear Scale



Logarithmic Scale



6.2.6. Experimental Testing

Specifications : commercial 2.2kW, 415V, 4.8A, 50Hz, 4 pole, induction machine

Rotor Fault : break bars at end-ring

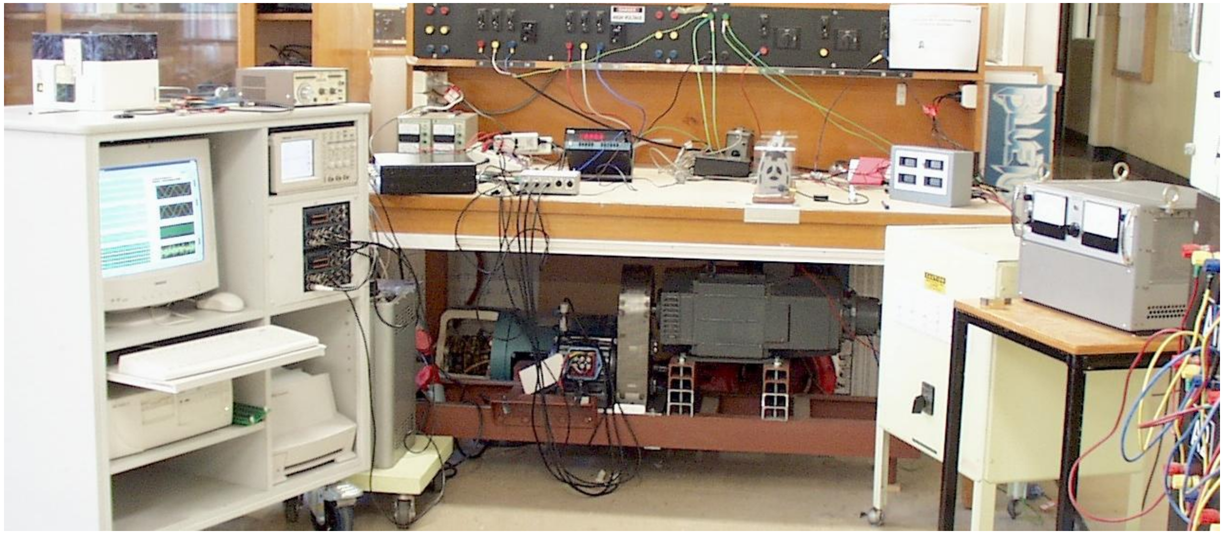
Motor 1 : 0, 0.5, 1, 2, 3, 3.5, 4

Motor 2 : reference

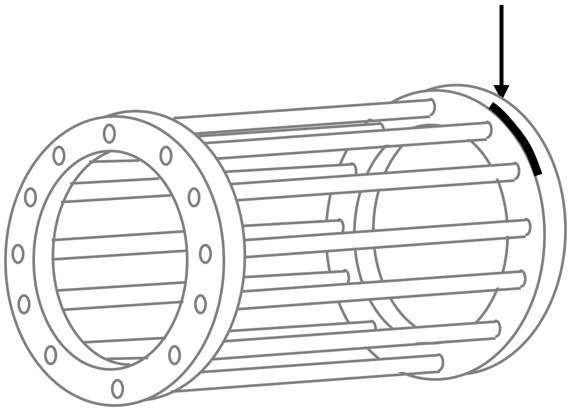
Motor 3 : 0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, 4

test motors

dynamometer arrangement

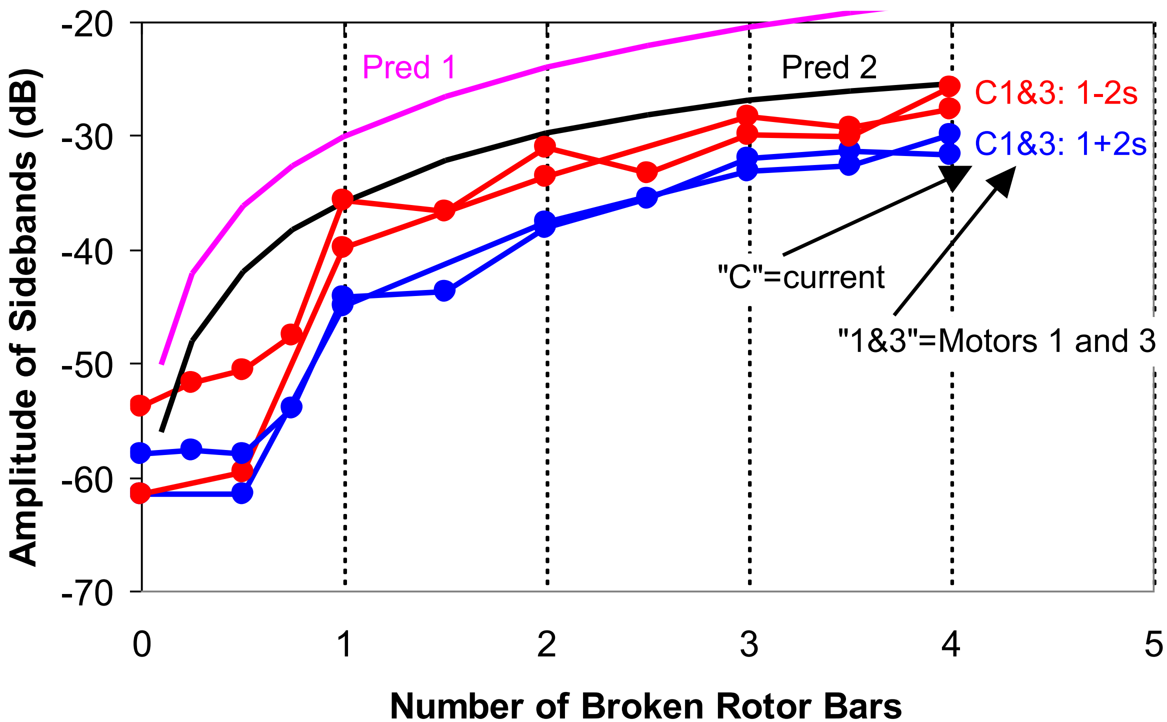


mill slot in end-rings



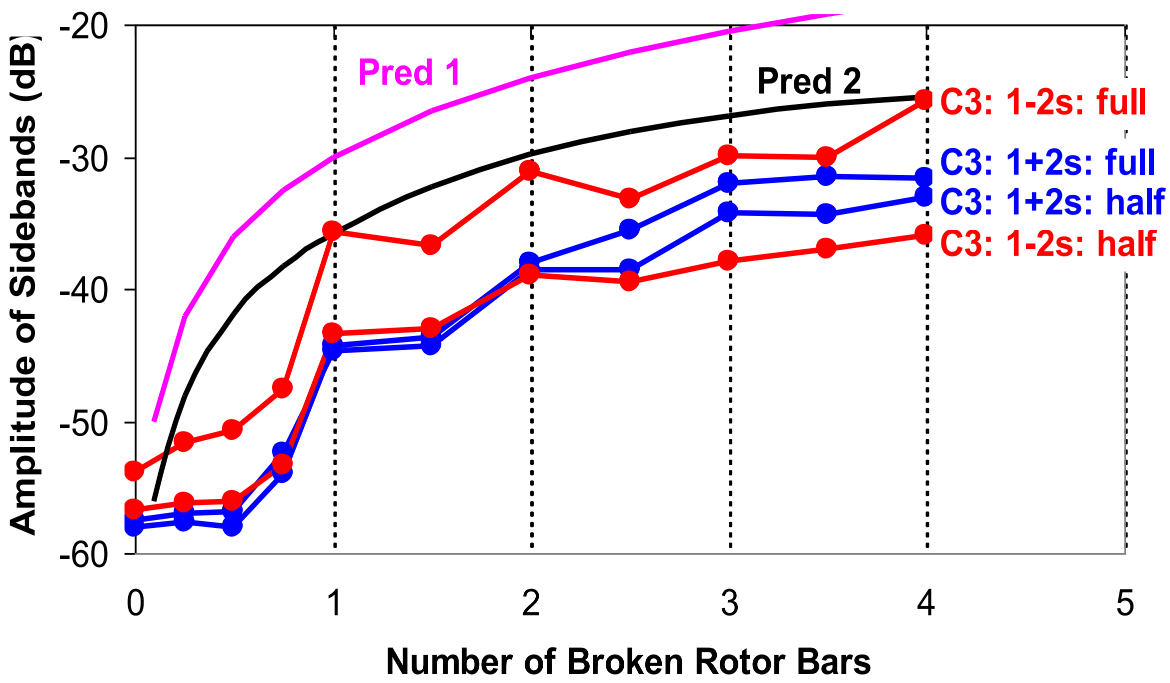
6.2.7. Current : Full-Load

- even "healthy" motors have some degree of sidebands (-50 to -60dB)
- for <u>integer</u> numbers of broken bars, test results follows trends with offset, prediction 2 most accurate, prediction 1 overestimates
- large change from partial to first complete rotor bar breakage
- partial breakages beyond one rotor bar can cause amplitude to drop
- (1+2s)f results follow same trends but about 5-10dB lower



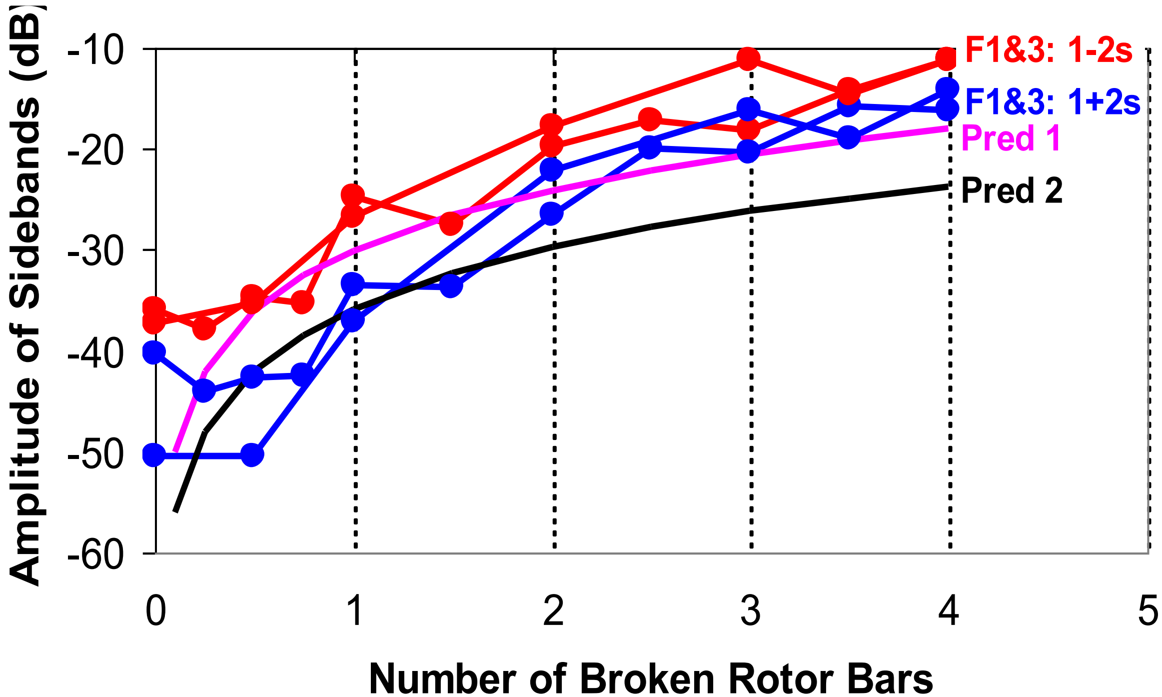
6.2.8. Current : Half-Load

- comparison of full and half load current sideband results for Motor 3
- at half load, both sideband amplitudes fall, 1-2s : 5-10dB, 1+2s : 1-3dB
- for this motor : amplitude of 1-2s sideband appears is sensitive to loading, 1+2s current component is less sensitive to loading
- difficult to make generalisations, need more data



6.2.9. Flux : Full-Load

- similar trends to current spectrum
- amplitude of sidebands are higher in flux relative to 50Hz component than in the current, sidebands larger than Prediction 1
- monotonic trend with integer broken bars, partial breakages can cause sideband amplitudes to fall
- smaller changes between healthy and fault levels make it more difficult to detect broken bars than using current



6.2.10. Broken Bar Thresholds

(from SKF Condition Monitoring)

sideband amplitudes in current spectrum

-54 to -60dB : excellent

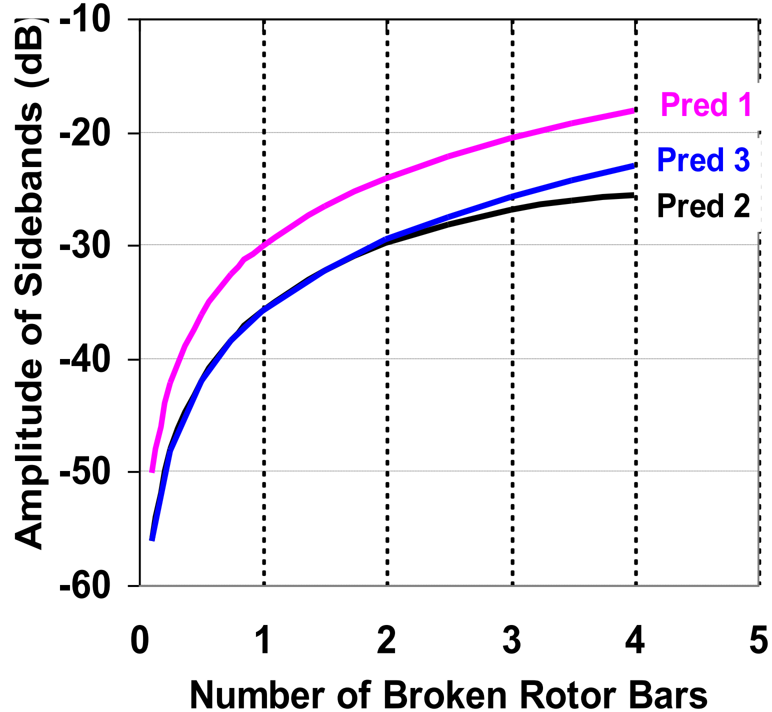
-48 to -54dB : good

-42 to -48dB : moderate

-36 to -42dB : cracked rotor bars or other source of high resistance

-30 to -36dB : multiple sources of high resistance

over -30dB : severe damage



6.2.11. Estimating Broken Bars

Can invert broken bar sideband amplitude predictions to estimate number of broken bars :

Prediction 1 : $$\frac{n}{N} = \frac{I_{BB}}{I}$$

Prediction 2 : difficult to invert due to sin term

Prediction 3 : $$\frac{n}{N} = \frac{2(I_{BB}/I)}{1 + p(I_{BB}/I)}$$

<u>example</u> : for (1-2*s*)f_1 sideband of -30dB, 4 poles, 32 rotor bars

6.3. Stator Winding Faults

1) Turn to Turn Faults (shorted turn), part of winding shorts out, generates very high currents in shorted part of winding=> high temp, fault spreads

- larger, high voltage machines : fails in fraction of second
- small, low voltage machines : much longer time to fail

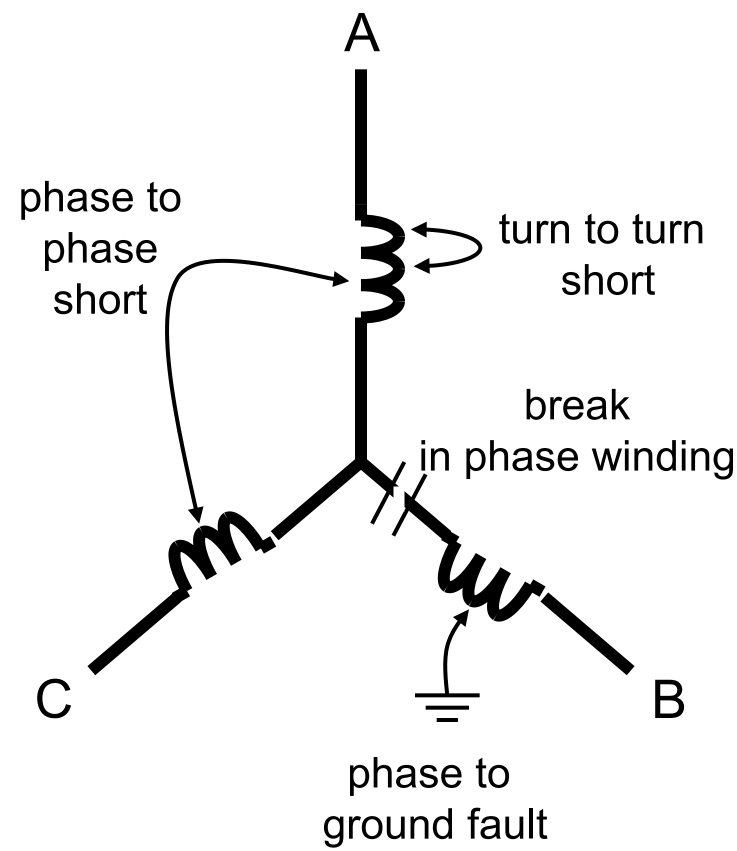
produces imbalances in three-phase supply currents

2) Phase to Phase Short-Circuit/Phase to Ground Fault

produce large line currents which will rapidly trip out the circuit breaker

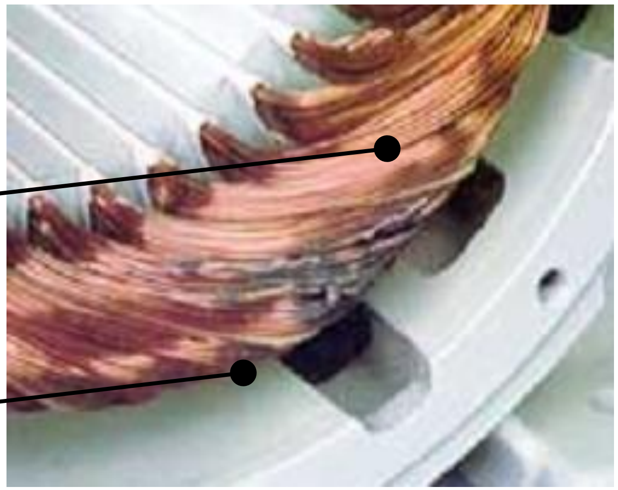
3) Open-Circuit in one Phase Winding (Single-Phasing)

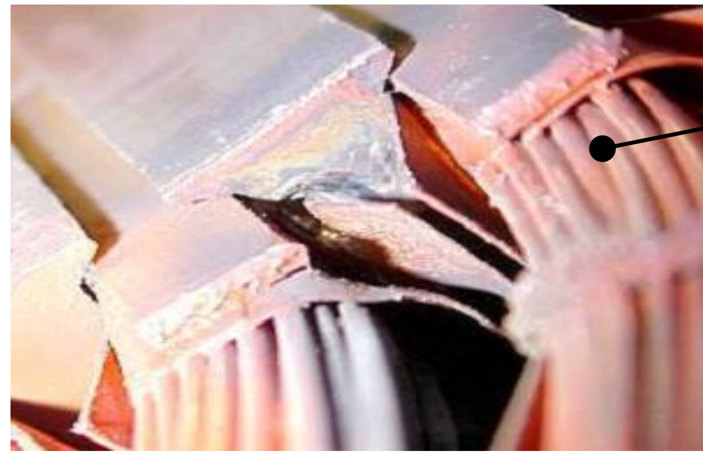
machine does not start by itself, but will start if rotated by hand, reduced output power



6.3.1. Stator Winding Photos

Photos courtesy of RME





6.3.2. Stator Winding Fault Causes

rotor and stator rubbing (contact)

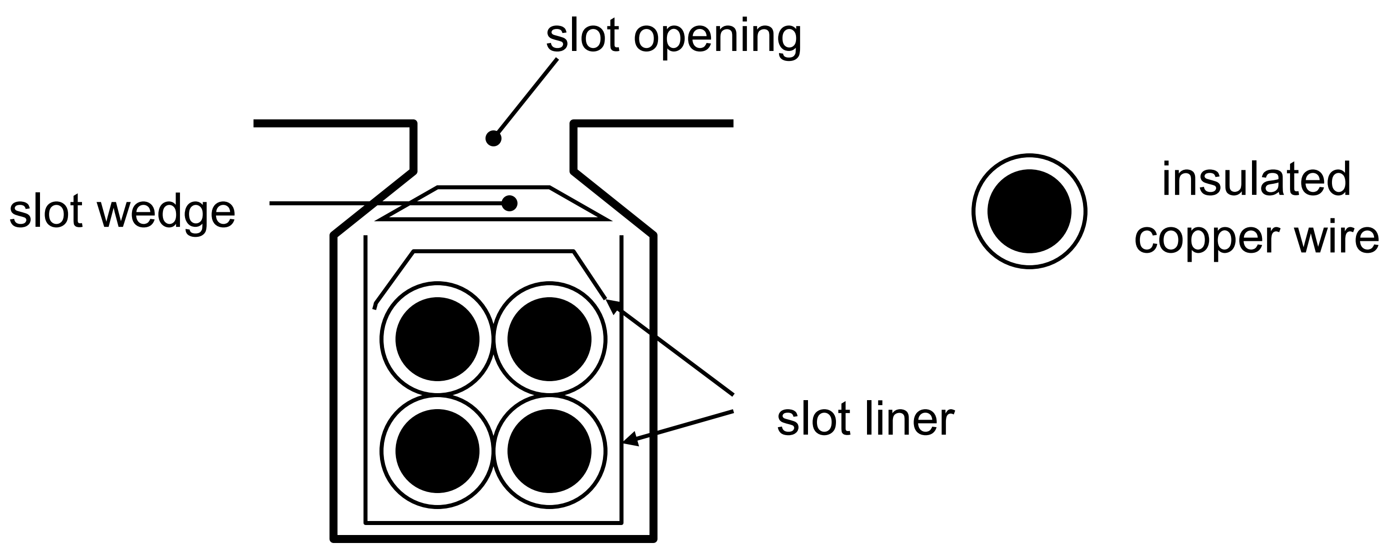
manufacturing problems : air voids in HV insulation

transient voltages (switching, inverter, lightning) : high voltage breakdown of insulation

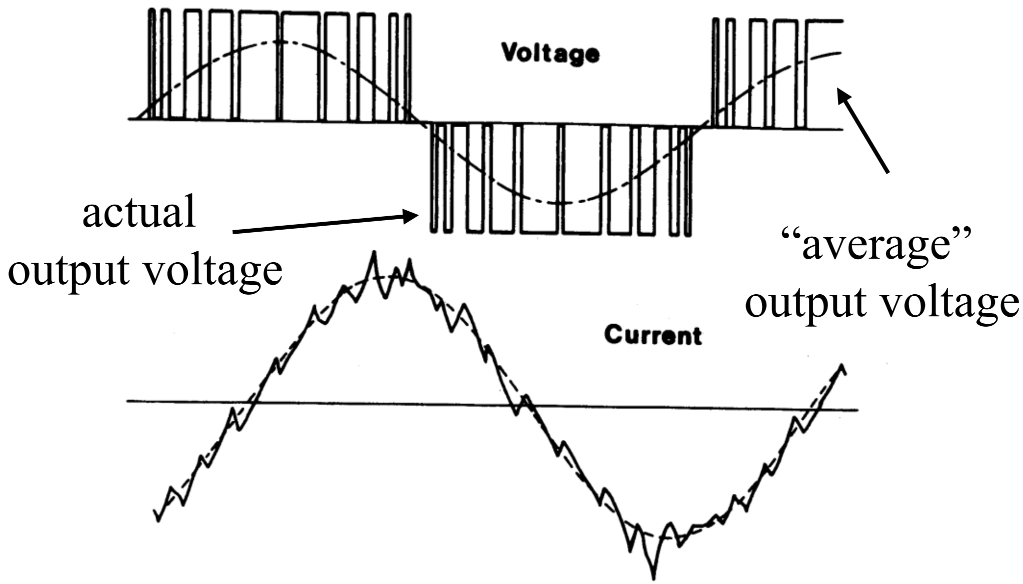
contamination of insulation : water, chemicals

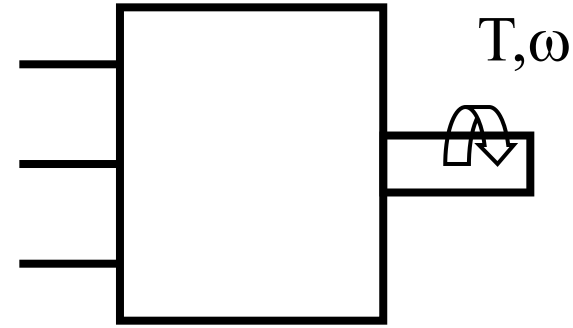
overheating : life reduced by overheating

coil movement : vibration causes wear of insulation



6.3.3. Inverter Operation





inverters : can generate variable output frequency, thus change synchronous speed and hence operating speed (variable speed operation)

but applies high frequency switching signals to motor winding

- high peak and high rate of change of voltage (dv/dt) can reduce insulation life
- peak voltages can be even higher if there is a long cable between the motor and inverter

some motors have special insulation designed for inverter use

6.3.4. Insulation Lifetime

Standard insulation classes

Class A : 105 degC	Class B : 130 degC
Class F : 155 degC	Class H : 180 degC

expected insulation life is 20,000 to 40,000hrs at stated temperature (2 - 5 years continuous)

Arrhenius Law

– typically insulation life expectancy halves for every 10 degC rise in temperature

Example :

Consider a class A insulation with an expected life of 20,000hours. Estimate life if operated at class F temperatures.

6.3.5. Detecting Shorted Turns

1) **vibration** : $2f_1$: twice supply frequency, that is 100Hz for 50Hz systems

2) **current imbalance** : currents in all three phases are not the same, even though the line voltages are the same

3) **current fault frequency** components :

$f_1((n/p)(1-s) +/- k)$

- n = 1,2,3 ...
- k = 1,3,5,7 ...

example : 6 pole machine, 60Hz, slip s = 0.01

ignore negative sign

60Hz [$(n/3)(0.99)$ +/-k] = 60Hz [n0.33 +/-k]

– n=1, k=1 : 60Hz[0.33+1] = 79.80Hz, 60Hz[0.33-1] = (-)40.20Hz

– n=2, k=1 :

6.4. Eccentricity

Eccentricity : airgap is normally uniform around the stator. Eccentricity occurs if this airgap varies in length around stator.

1) Static Eccentricity : position of minimum airgap is fixed in space with respect to the stator, possible causes :

- stator core is oval in shape
- incorrect positioning of rotor with respect to stator

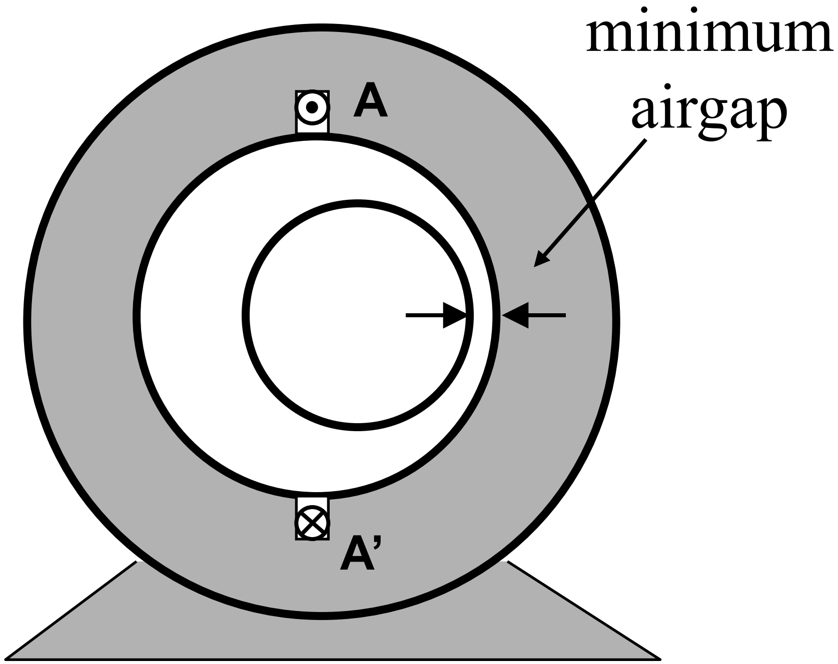
2) Dynamic Eccentricity : position of minimum airgap rotates with rotor, possible causes :

- rotor outside diameter not concentric with centre of shaft
- bearing wear and movement

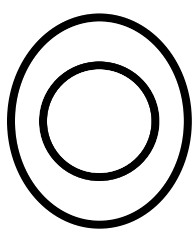
Effects : distortion of the magnetic field distribution around the airgap which produces large radial forces

- reduces performance and efficiency
- causes noise and vibration
- reduces bearing life
- if severe, can cause the rotor and stator to hit one another resulting in damage to the laminations and windings

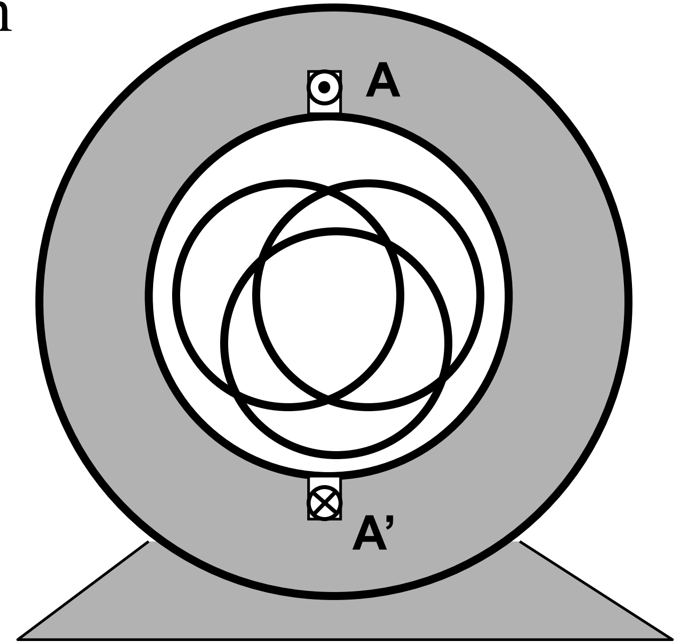
6.4.1. Eccentricity Diagram



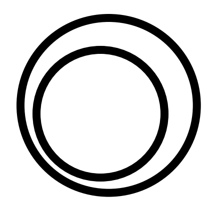
Static Eccentricity



oval stator



Dynamic Eccentricity



non-concentric rotor

6.4.2. Airgap Length

electromagnetically prefer smallest possible airgap length, practical length is limited

- manufacturing tolerances on rotor and stator diameters
- assembly tolerances of locating rotor within the stator
- bearing tolerances
- bending of rotor and thermal expansion of rotor during operation

typically airgap length is a fraction of a percent of the rotor diameter

Eccentricity : sum of the static and dynamic eccentricity

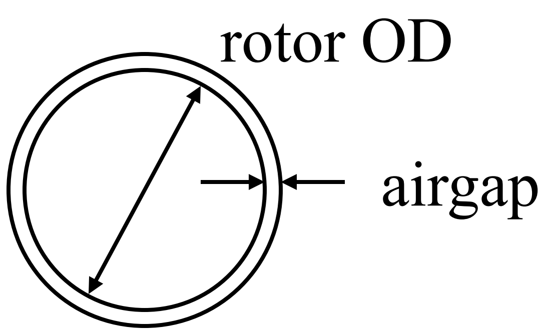
- typical tolerances on eccentricity is 5% to 10%
- when eccentricity reaches 25-30% it is considered severe

6.4.3. Example Airgap Lengths

Rating	Rotor OD	Airgap	% of Rotor OD
2.2kW, 4 pole	92mm	0.39+/-10% mm	0.42%
11kW, 4 pole	127mm	0.51+/-10% mm	0.40%
1.5MW, 8 pole	~ 1 m	2.5 +/- 5% mm	0.25%
5MW, 2 pole		5mm +/- 5-10% mm	

Eccentricity :

for 11kW machine, tolerance of 10% in airgap is +/- 0.051mm!



6.4.4. Rotor Slot Passing Frequency

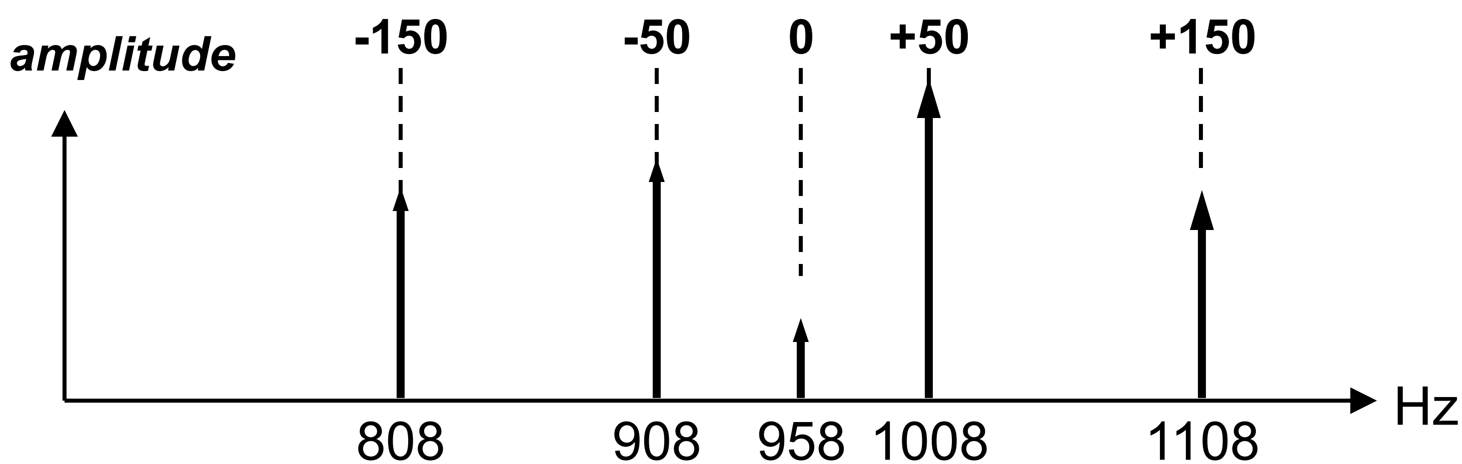
consider machine with number of rotors slots $R = 32$

machine is rotating at rotor frequency $f_R = (1\text{-}s)f_1/p$

stator sees the rotor slots passing by at frequency of number of rotor slots x mech rotational frequency $Rf_R = R(1\text{-}s)f_1/p$

eccentricity creates components in flux and current spectra at sidebands of +/-50Hz, +/-150Hz, +/-250Hz of the rotor slot passing frequency

example spectrum shown below (see next slide for calculations)



6.4.5. Detecting Eccentricity

<u>example</u> : 2 pole rotor has 20 slots, slip frequency sf_1 = 2.1Hz, supply frequency is 50Hz

<u>1) vibration</u> : 2 f_1 : twice supply frequency

example : 100Hz

<u>2) current</u> : $f_1((R/p)(1\text{-}s) +/\text{-}\ k) = Rf_1(1\text{-}s)/p +/\text{-}\ kf_1 = Rf_R +/\text{-}\ kf_1$

- R = number of rotor slots
- f_R = rotor frequency
- k = 1,3,5,7 ...

example : rotor frequency $f_R = f_1(1\text{-}s)/p$ = (50-2.1)/1= 47.90Hz

rotor slot passing freq Rf_R = 20 slots x 47.90Hz = 958Hz

sidebands :

<u>3) current</u> : $f_1 +/\text{-}\ f_R$

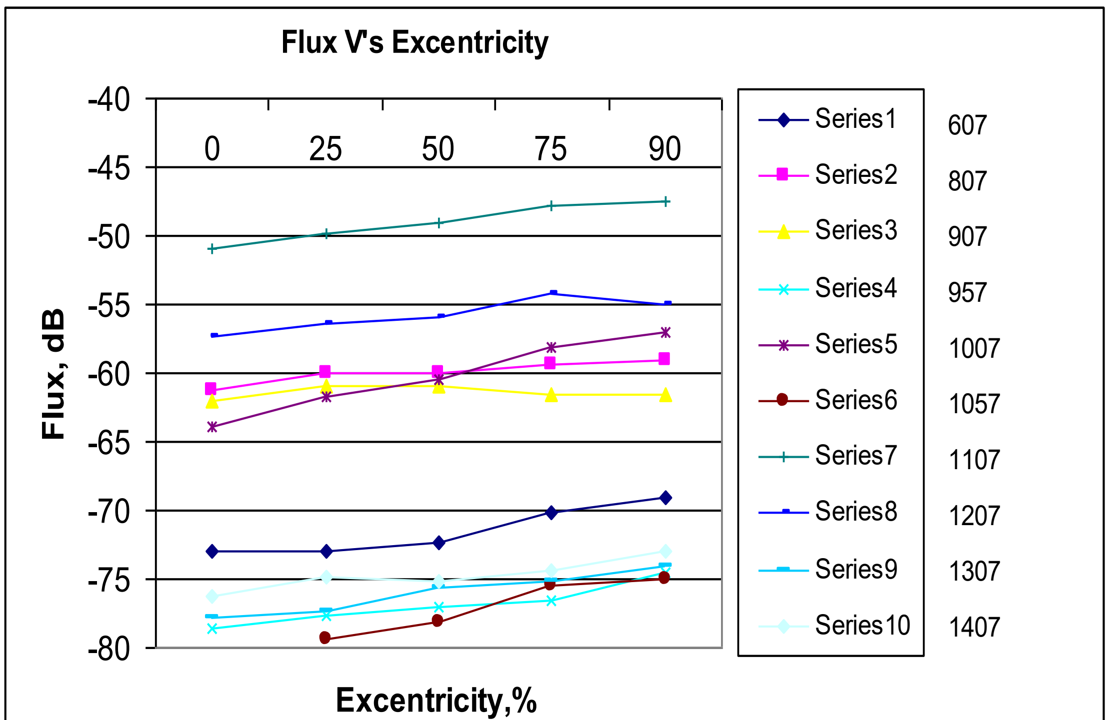
example : 50Hz +/- 47.90Hz = 2.10Hz, 97.90Hz

6.4.6. Eccentricity Test Results

experimental data taken on a small 2 pole induction machine with eccentricity being varied from 0% to 90% (unfortunately 2 pole machines not very sensitive to eccentricity!)

– rotor slot passing sidebands increase in amplitude with increasing eccentricity

– relatively small effect in this machine (about 4dB change)



Excentricity	0	25	50	75	90
Frequency					
607	-73	-73	-72.4	-70.2	-69
807	-61.3	-60	-60	-59.4	-59
907	-62	-61	-60.9	-61.5	-61.5
957	-78.6	-77.7	-77	-76.6	-74.5
1007	-63.9	-61.7	-60.5	-58.16	-57
1057		-79.4	-78.1	-75.5	-75
1107	-51	-49.9	-49.1	-47.8	-47.5
1207	-57.3	-56.4	-56	-54.2	-55
1307	-77.8	-77.4	-75.6	-75.1	-74
1407	-76.3	-74.8	-75.2	-74.3	-73

6.4.7. Eccentricity Fault

Case Study

observed high vibration amplitude at twice the stator frequency (100Hz)

eccentricity can be a cause of such symptoms

measurements showed problem with machining of end shields (ends of machines which support the bearings)

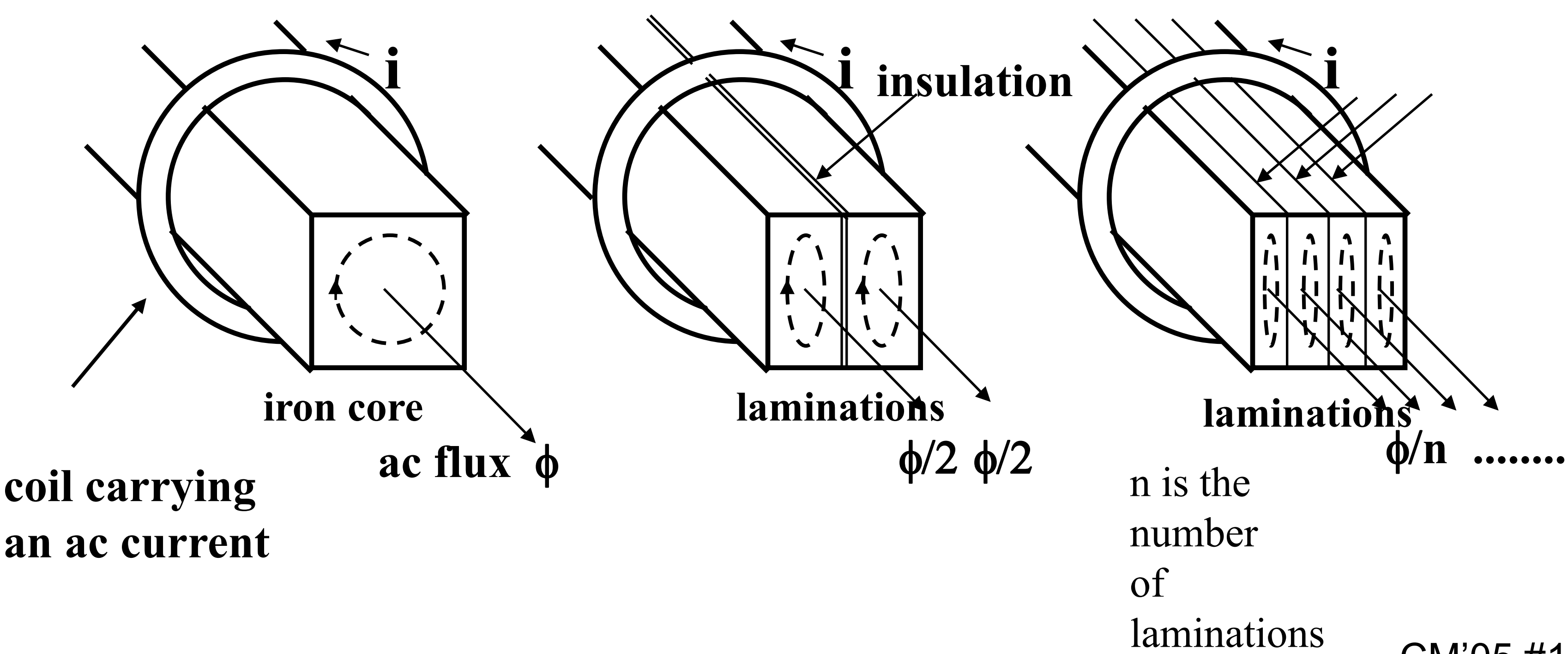
960kW, 6 pole, 3.3kV
Excessive eccentricity !

Photo courtesy of RME

6.5. Lamination Faults

eddy-current loss : resistive losses resulting from circulating electric currents produced by changing magnetic fields in conducting magnetic materials

Motors consist of thin metal sheets (laminations) to reduce eddy-current losses



6.5.1. Lamination Damage

Damaged insulation between laminations can cause large eddy currents which :

- cause extra losses
- result in local heating of the laminations causing further insulation damage

Detection of Lamination Faults

- vibration : $2f_1$
- current : high imbalance between phases

rotor lamination damage

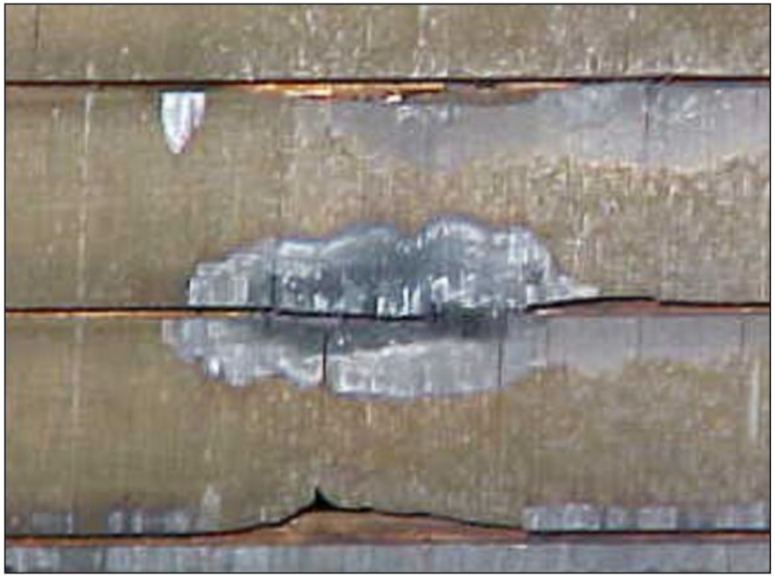
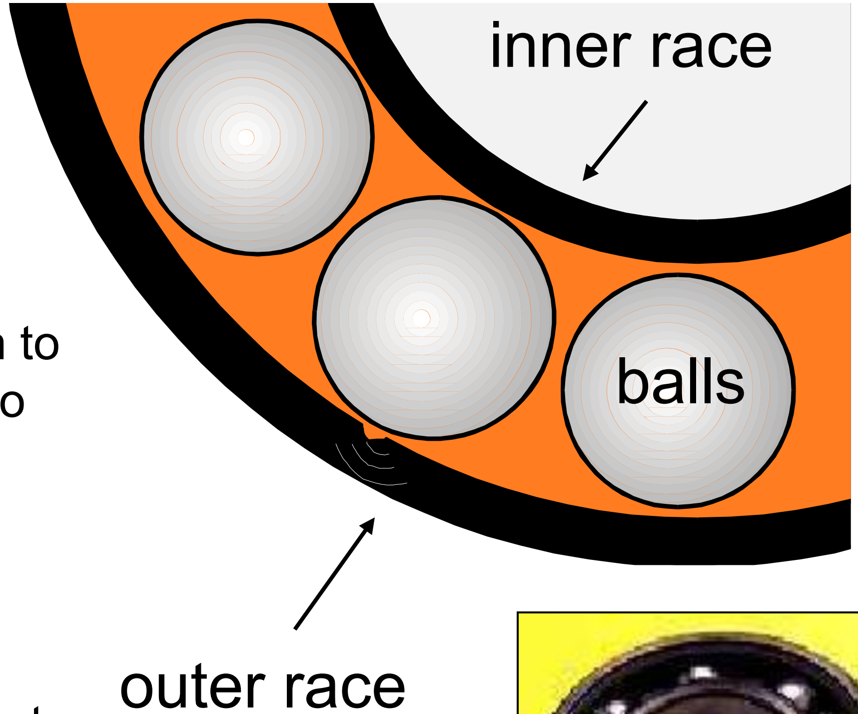


Photo courtesy of RME

6.6. Bearings

1) **Journal Bearings** : used in large or older machines (not considered in this course)

2) **Rolling Element Bearings** : more common, especially on smaller or newer machines, outer race is stationary (fits on to stator housing), inner race is connected to rotor shaft, balls rotate



problems

a) lubrication : too much, too little, contaminated

b) excessive load caused by: misalignment, imbalance, bent shaft etc.....

c) old age

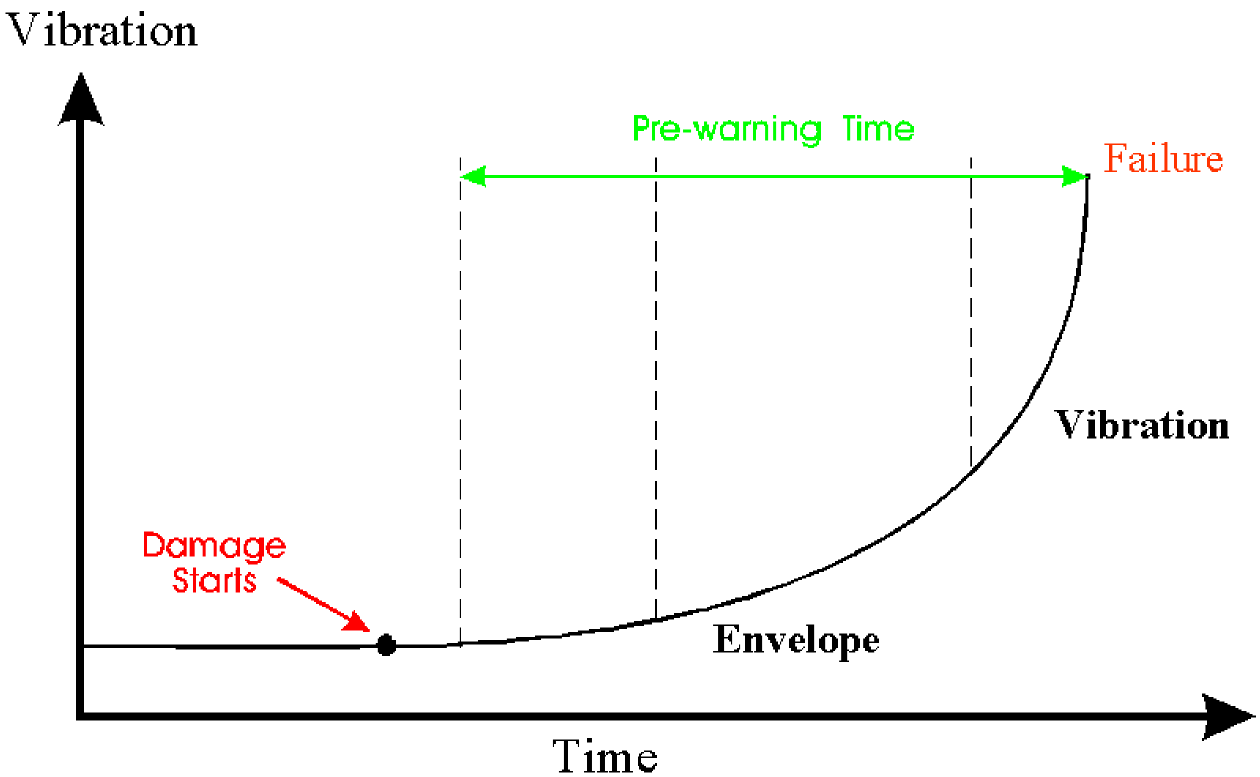
bearing failure often caused by other influences, if these are not corrected and the bearing simply replaced, the new bearing will not last very long!

6.6.1. Bearing Failure Curve

bearing faults can cause excessive vibration

increasing vibration versus time can indicate worsening bearing fault

often bearings give symptoms ahead of time of impending failure, if vibration shows increasing trend, should check motor more frequently



6.6.2. Detecting Bearing Failure

faulty bearings produce characteristic fault frequencies in vibration (and current)

exact formulas require detailed knowledge of the bearing construction

typical bearing fault frequencies about (5 to 10) x f_R

most commercial instruments have a database of characteristic frequencies based on the bearing manufacturer and bearing model number

6.7. Unbalanced Supplies

in an ideal balanced power system, the line voltages have same magnitude

voltage unbalance factor (VUF)

IEEE definition VUF = $\Delta V/V_{AV}$

V_{AV} = average of line voltages

ΔV = maximum deviation of line voltage from V_{AV}

example : measured line voltages are 412V, 420V and 409V

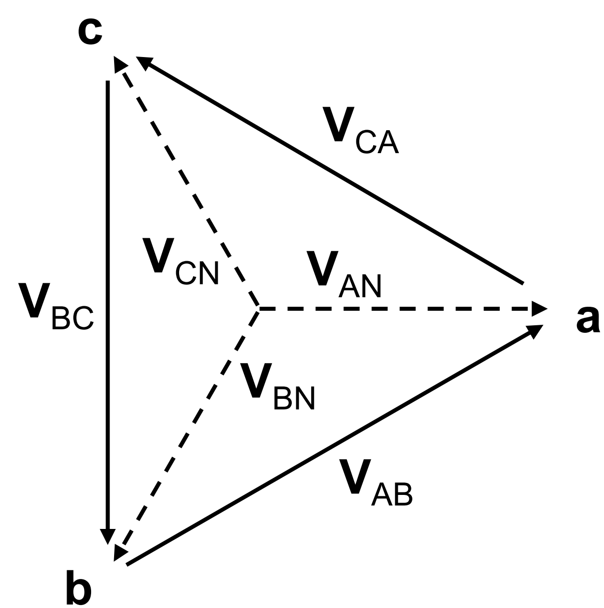
V_{AV} = (412V + 420V + 409V)/3 = 413.7V

420V-413.7V = 6.3V

413.7V-409V = 4.7V

ΔV = 6.3V

VUF = 6.3V/413.7V = 1.5%



6.7.1. Effects and Symptoms

effects : induction motors very sensitive to voltage imbalance, even small voltage imbalances can result in large current imbalances (rough rule of thumb 1:5 ratio, e.g. 1% voltage imbalance will produce a 5% current imbalance)

- produce extra resistive losses (I^2R) in machine
- stator and rotor temperature rise and efficiency reduction

usually prefer to keep VUF to less than 2% to avoid problems with induction machines

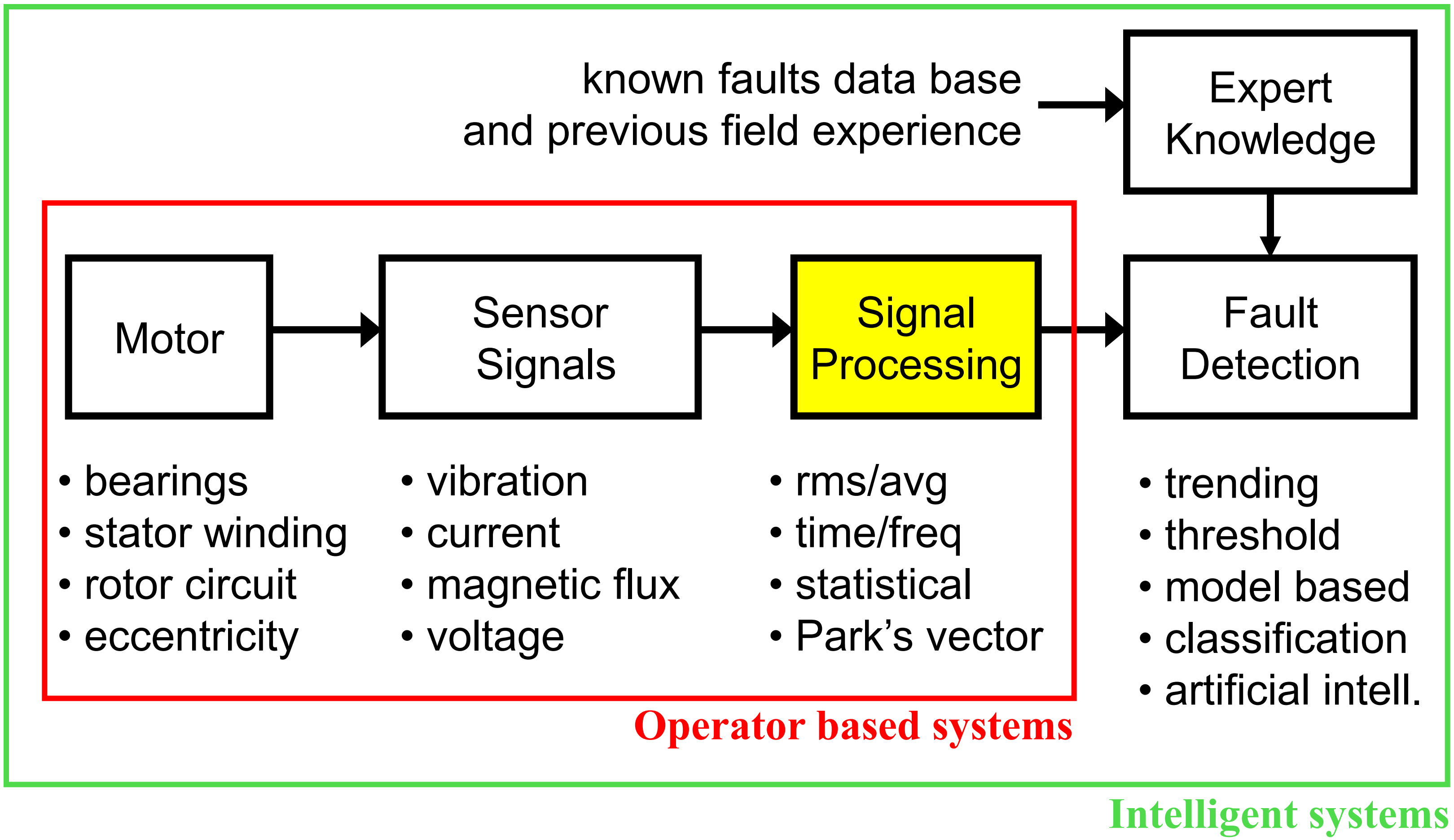
H. Penrose "Motor Circuit Analysis" indicates than a 2% voltage imbalance can result in a 10^{o}C temperature rise (halves stator insulation life)

symptoms

1) voltage and current imbalances

2) vibration : $2f_1$: twice supply frequency

7. Signal Analysis Methods



7.0.1. Signal Analysis Methods

so far largely focussed on use of frequency spectral analysis (FFTs) to detect faults

most popular method but are other methods being investigated :

1) Frequency Analysis Methods

- FFT
- time-frequency
- wavelet

2) Statistical Methods

- rms
- probability density function

3) Graphical Methods : Park's vector

7.1. Frequency Analysis

a) FFT

- most common analysis approach
- assumes frequency content does not vary with time

however for waveforms with time-varying frequency content can use ...

b) time-frequency analysis

- splits input signal into short time segments and performs FFT on each segment
- hence shows variation of frequency spectra with time
- the short time segments however limit frequency resolution

c) wavelet

- most commonly used when signal contains repetitions of basic pulse waveforms, eg. human speech processing, detecting radar pulses
- have been applied to highly transient waveforms such as motor starting current

7.1.1. Time-Frequency Analysis

consider a time record of 100s

<u>1) apply FFT to entire record</u>

single frequency spectrum :

freq resolution 0.01Hz,

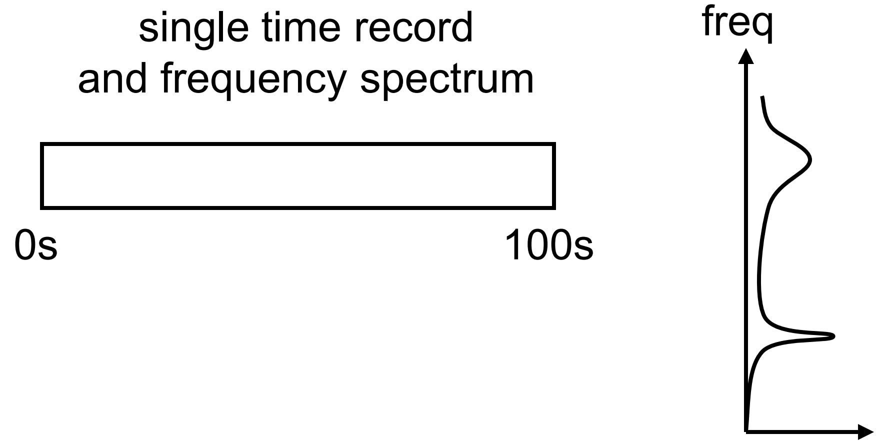
time resolution 100s

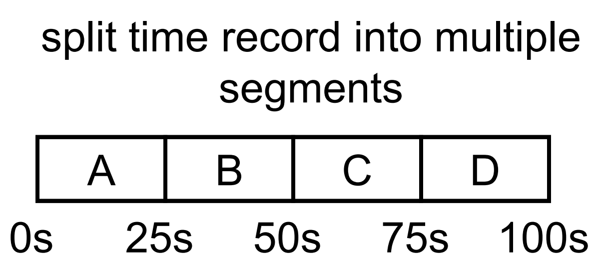
<u>2) divide up time record into four equal segments of 25s</u>

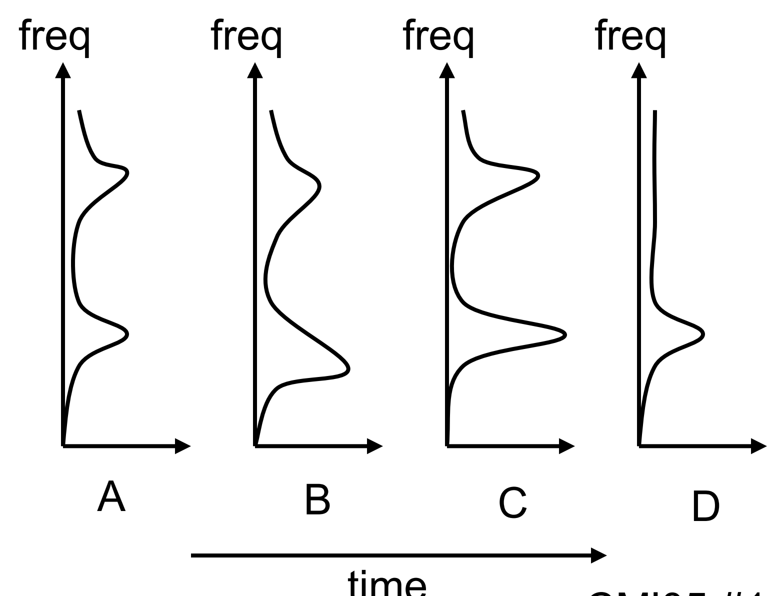
frequency resolution : 0.04Hz

but now have information about change in frequency spectrum over time : 4 samples

time resolution 25s



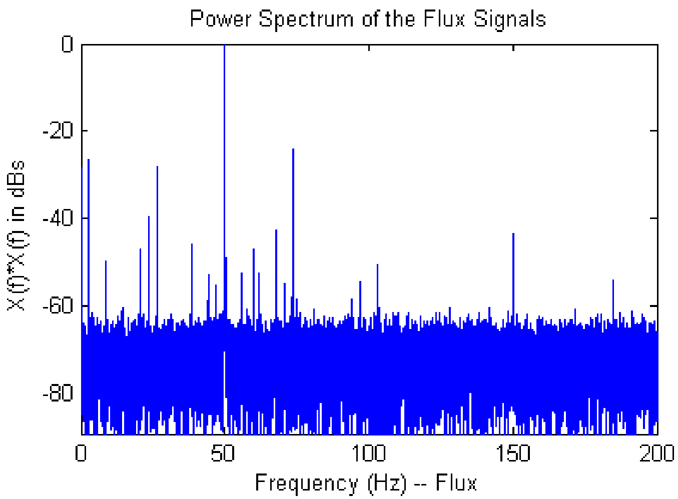


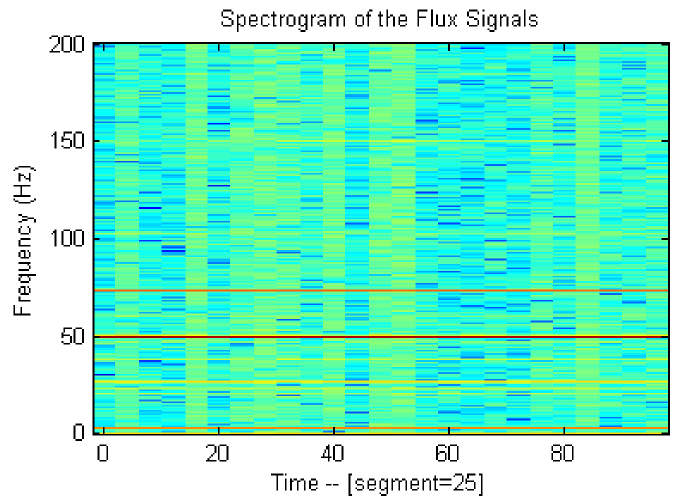


7.1.2. Time-Frequency Examples

spectrum using entire time data-set

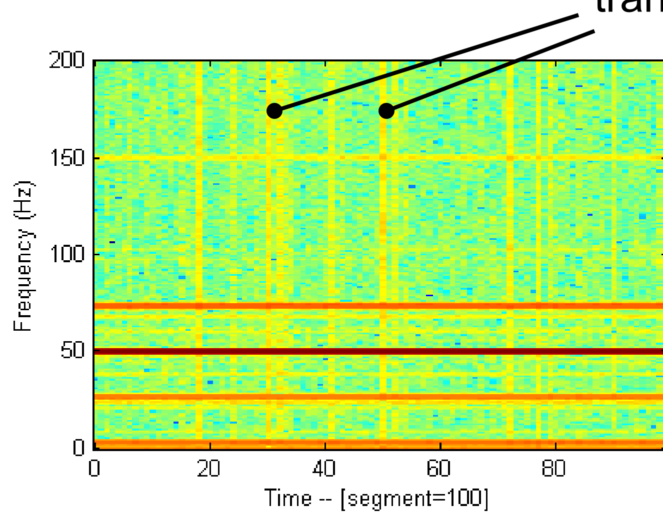
time-frequency analysis from subdividing data-set
showing time/frequency resolution tradeoff



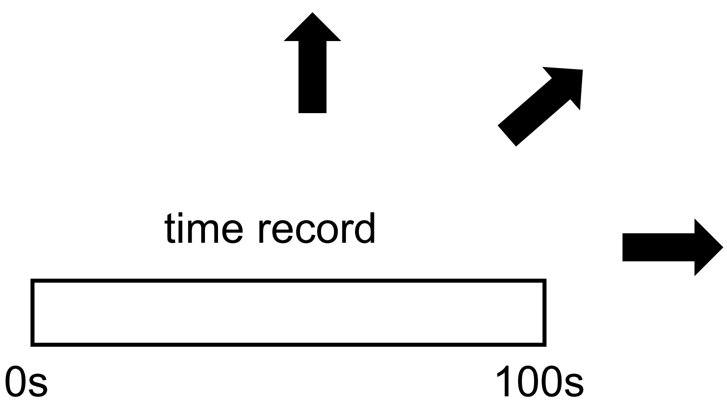


25 segments
each 100s/25
=4s long
resolution :
0.25Hz/4s

transient events



100 segments
each 100s/100
=1s long
resolution :
1Hz/1s



Results from J. Grieger and R. Supangat

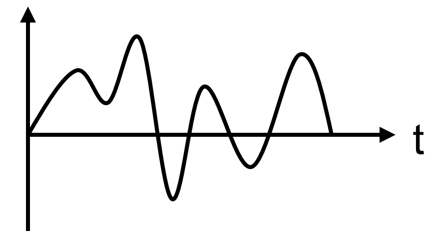
7.1.3. Wavelet Analysis

alternative means for examining signals with time-varying signal components

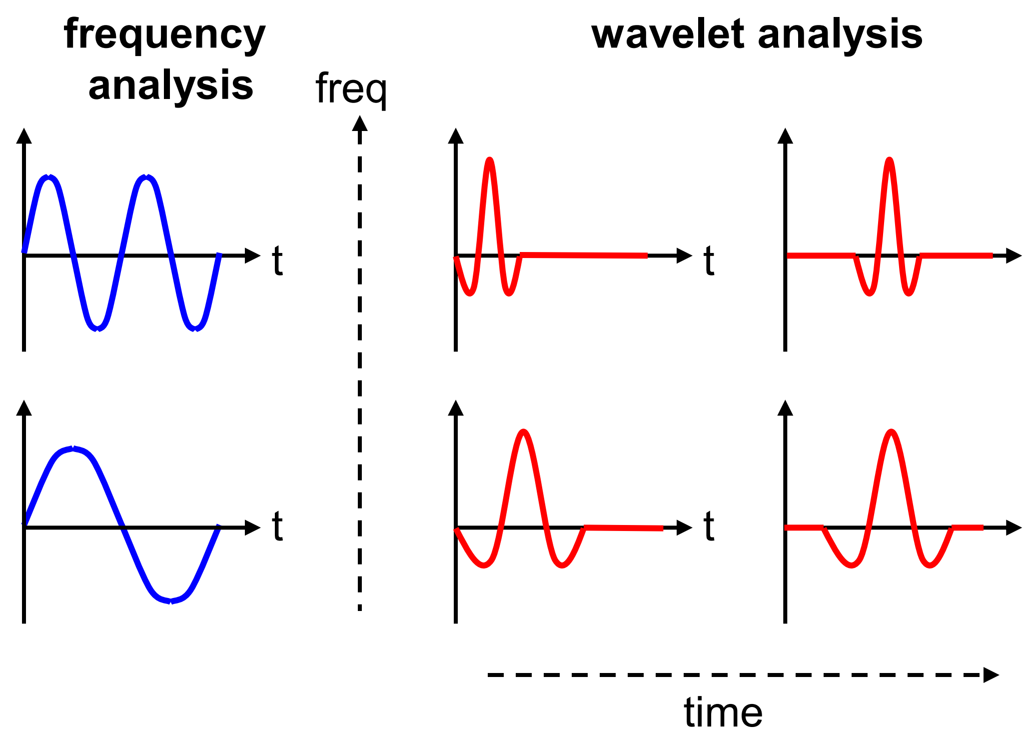
a) <u>frequency analysis</u> : involves multiplying input waveform with sinusoids of varying frequencies, provides only frequency information (obtain time information by dividing time record into segments)

b) <u>wavelet analysis</u> : involves multiplying input waveform with pulse waveforms of various time shift (time axis) and various time scaling ("frequency" axis), provides both time and "frequency" information

input waveform



multiplied by reference waveforms below :



7.1.4. Wavelet Analysis Example

detection of broken rotor bars using $(1+/-2s)f_1$ sidebands difficult at no-load ($s \approx 0$) as rotor currents are small, under starting conditions have large rotor currents

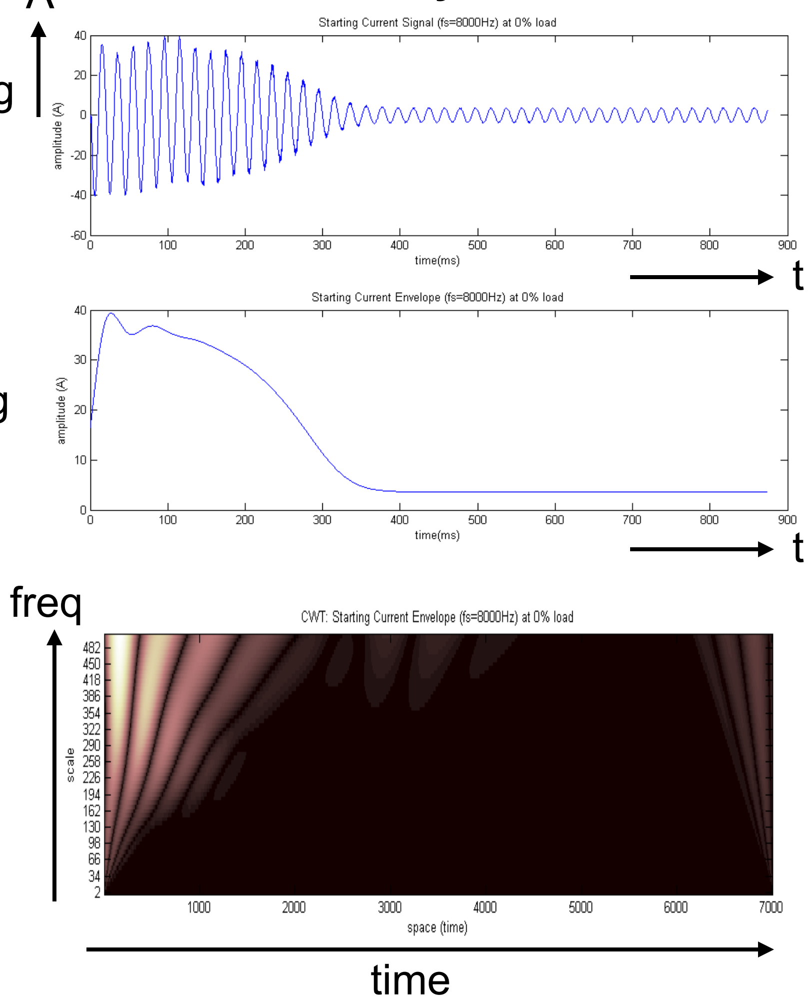
motor starting current waveform (no load)

envelope of motor starting current waveform

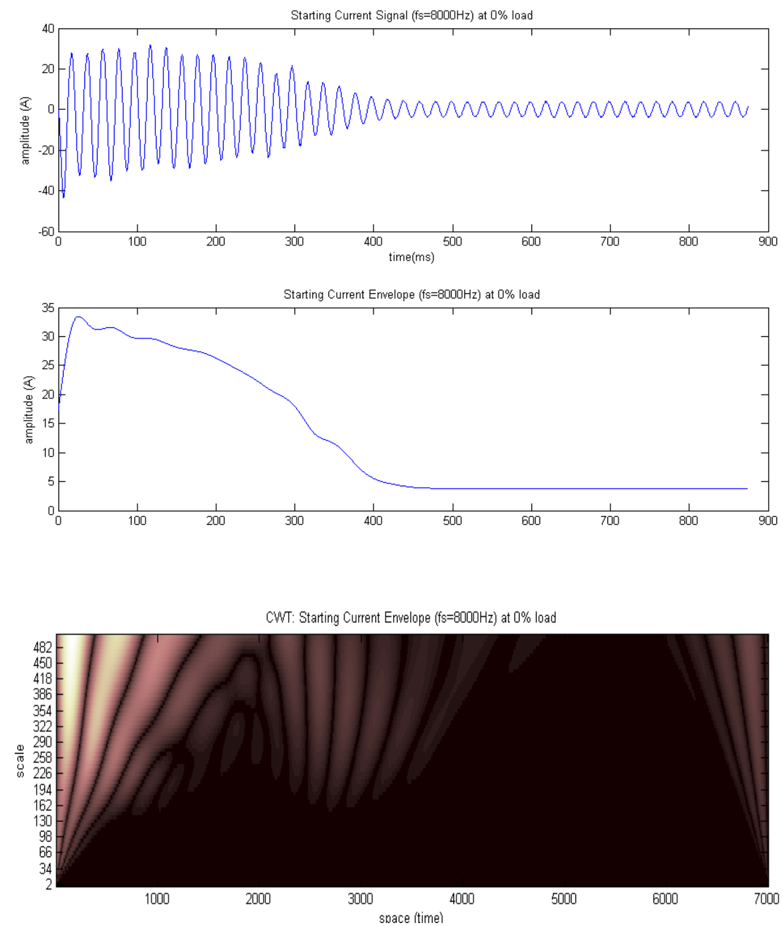
wavelet analysis of envelope

Healthy Motor

A



Motor with Four Broken Rotor Bars



Results from R. Supangat

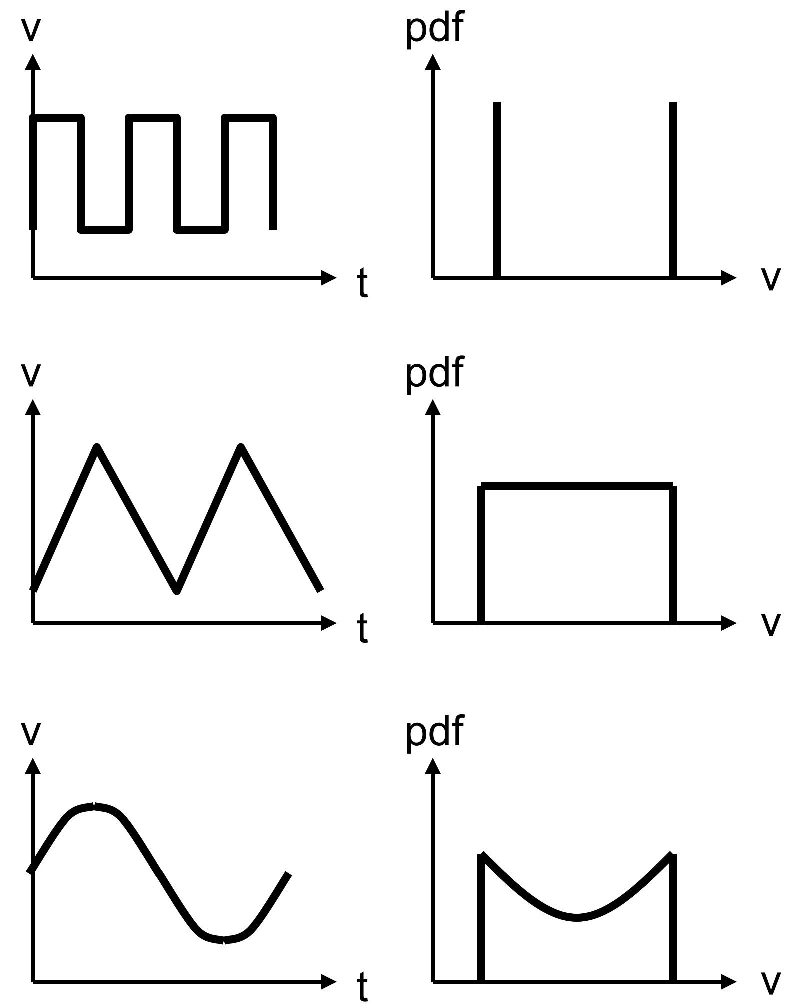
7.2. Statistical Methods

<u>rms values</u>

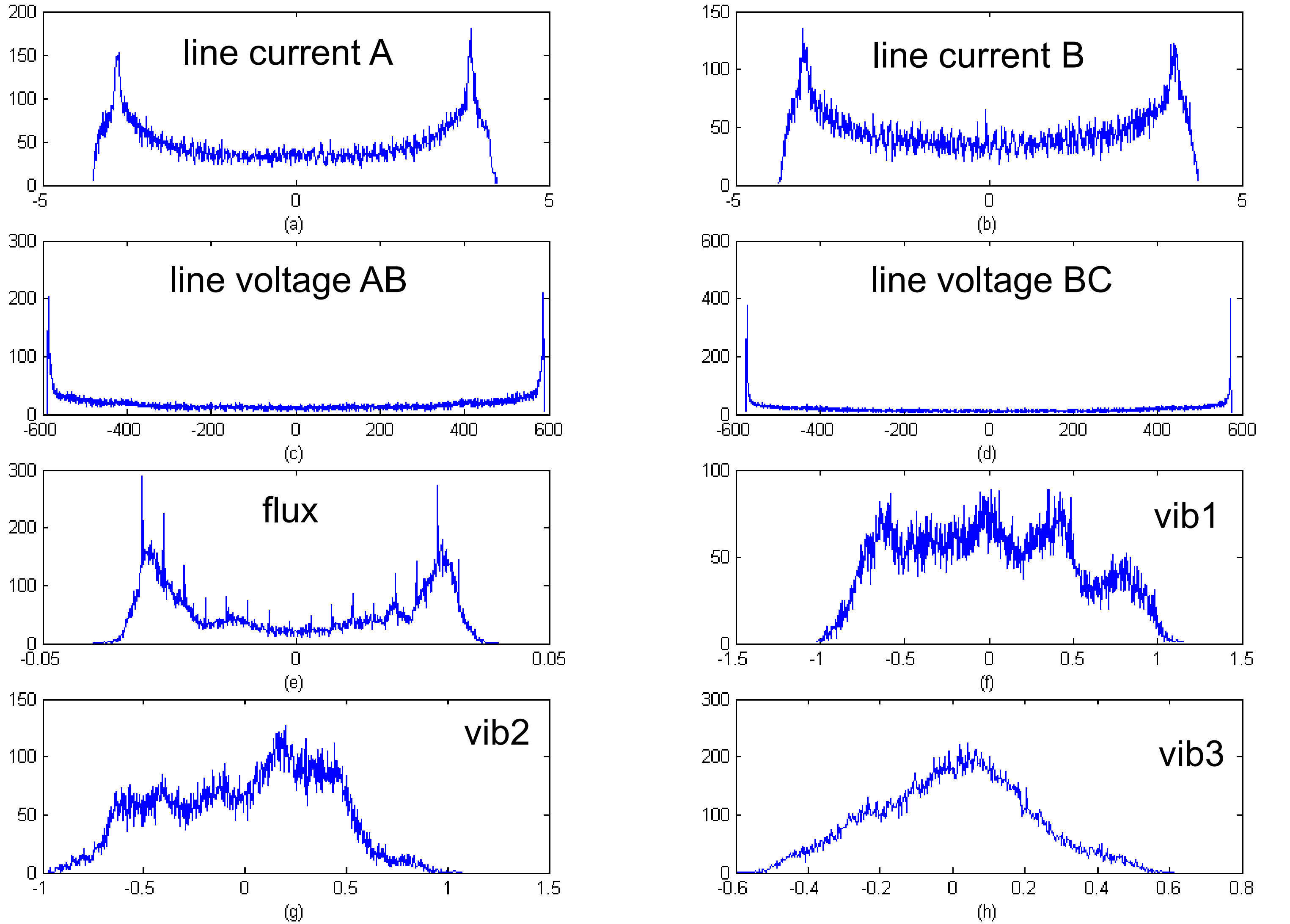
- vibration : gives indication of overall vibration level
- voltages and currents
  - check within rated values
  - examine balance of three-phase voltages and currents

<u>probability density function</u> (pdf) shows the likelihood of signal having a given magnitude (effectively a histogram of signal values)

researchers have investigated the use of the shape of the pdf to detect faults in machines



7.2.1. Prob. Density Funct. Examples



Results from J. Grieger and R. Supangat

7.3. Park's Current Vector

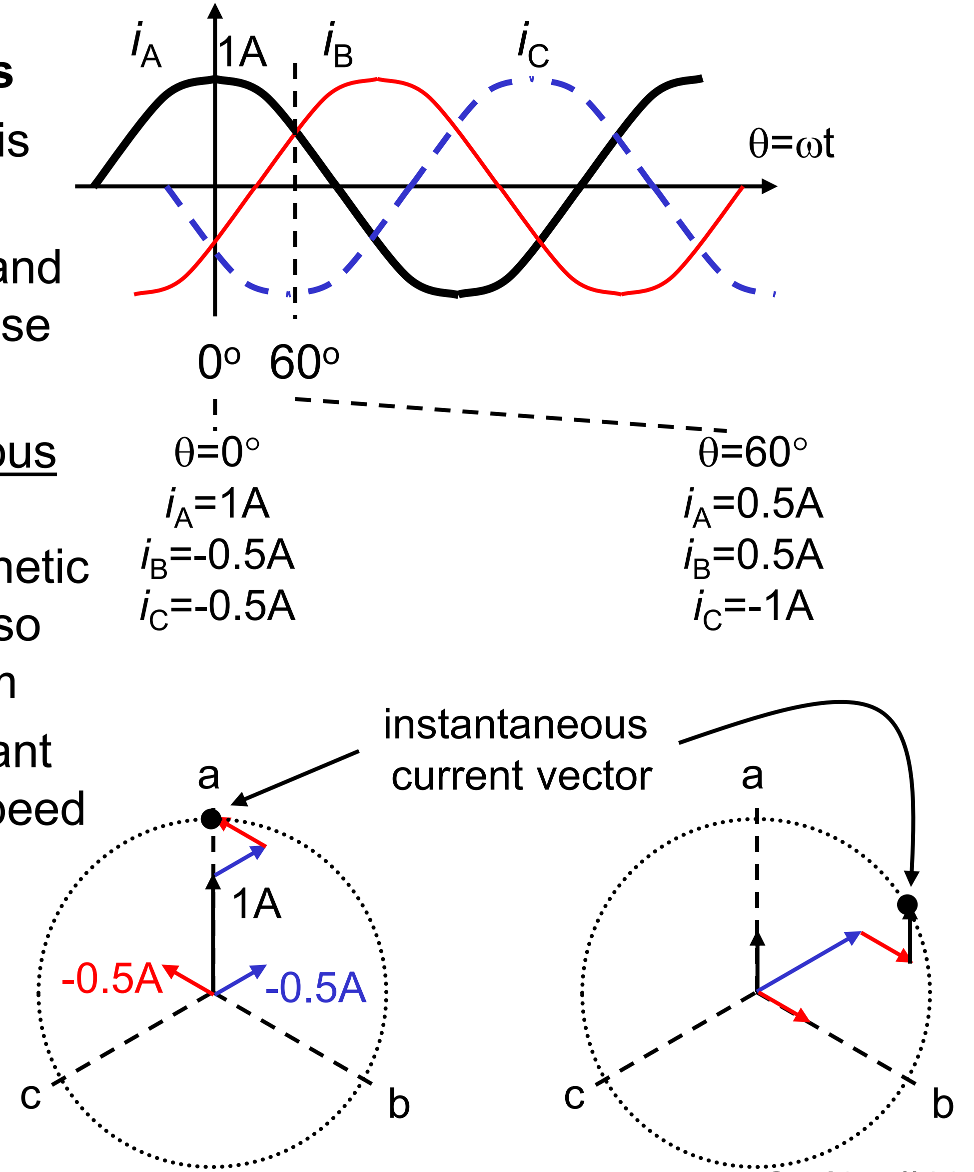
revision of rotating magnetic fields

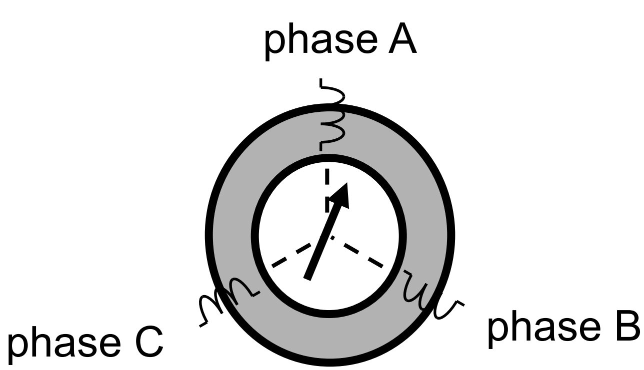
each stator phase winding has an axis which is 120 degrees apart in <u>space</u>

<u>balanced</u> three phase currents i_A, i_B and i_C are 120 degrees apart in <u>time</u> (phase angle)

total magnetic field is the <u>instantaneous</u> vector sum of the magnetic fields produced by each phase, since magnetic field is proportional to current, can also plot instantaneous current vector sum

ideally total magnetic field has constant magnitude and rotates at constant speed





7.3.1. Park's Vector Implementation

implementation

for each time sample, calculate total current vector as the vector sum of the three measured phase current values and plot point on x-y axis

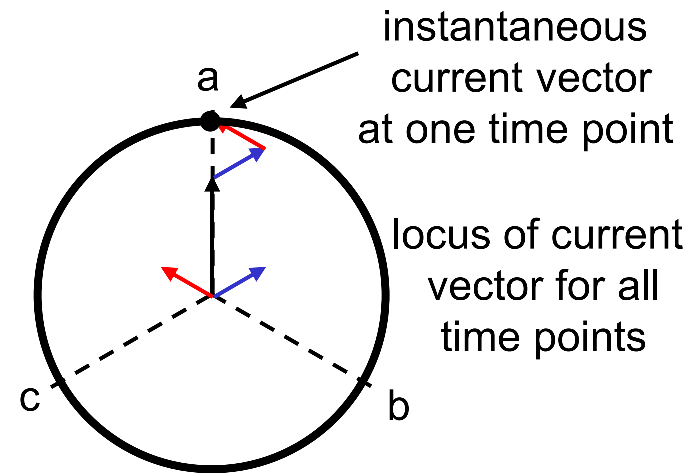
application

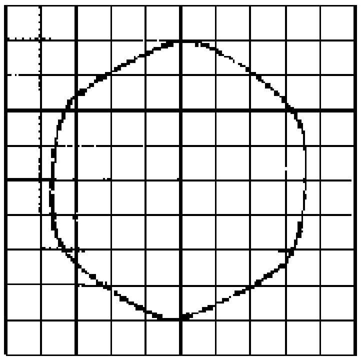
- examine shape of the locus of the stator current vector (ideally a circle)
- detection of broken rotor bars, shorted turns, air-gap eccentricity

<u>examples</u> shown on right

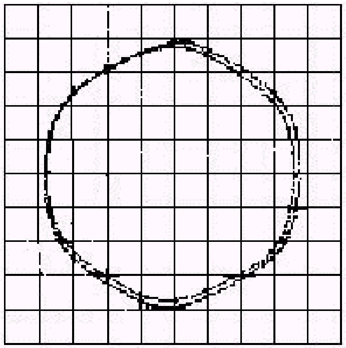
even in healthy machine, locus shows some distortion, probably due to harmonics in stator current waveform due to saturation

dynamic airgap eccentricity causes fluctuations in stator currents causing the locus shape to vary with time





healthy machine



with air-gap eccentricity

7.3.2. Park's Vector : More Examples

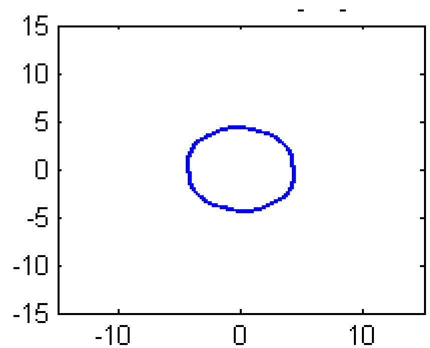
examples from measurements taken in laboratory showing effect of :

a) load on healthy machines

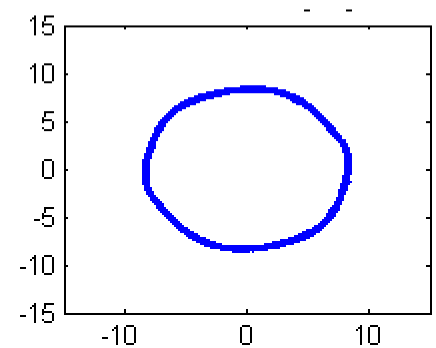
b) broken bars : causes amplitude modulation of current waveforms resulting in "thickening" of locus

c) unbalanced supply : resultant unbalanced currents cause locus to become elliptical

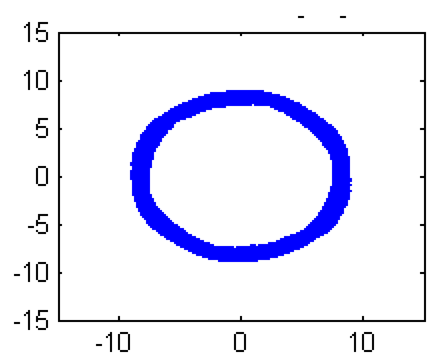
Park's vectors : 2.2kW, 8kHz sampling



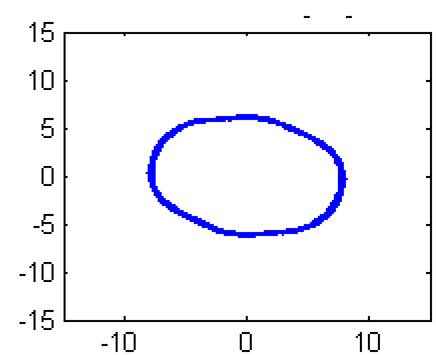
Healthy : no-load



Healthy : full-load



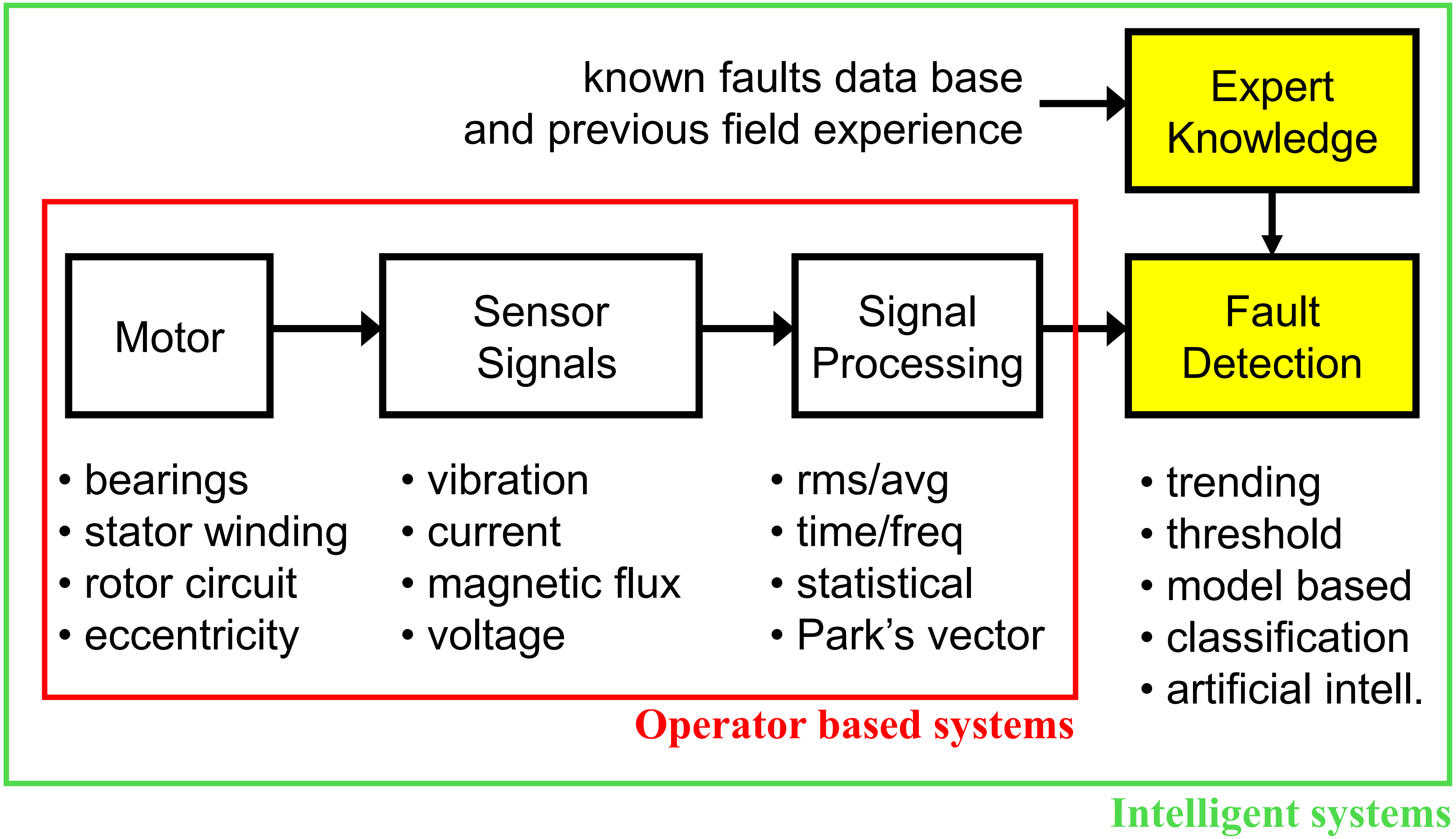
4 broken bars



unbalanced supply

Results from R. Supangat and J. Grieger

8. Fault Detection Methods

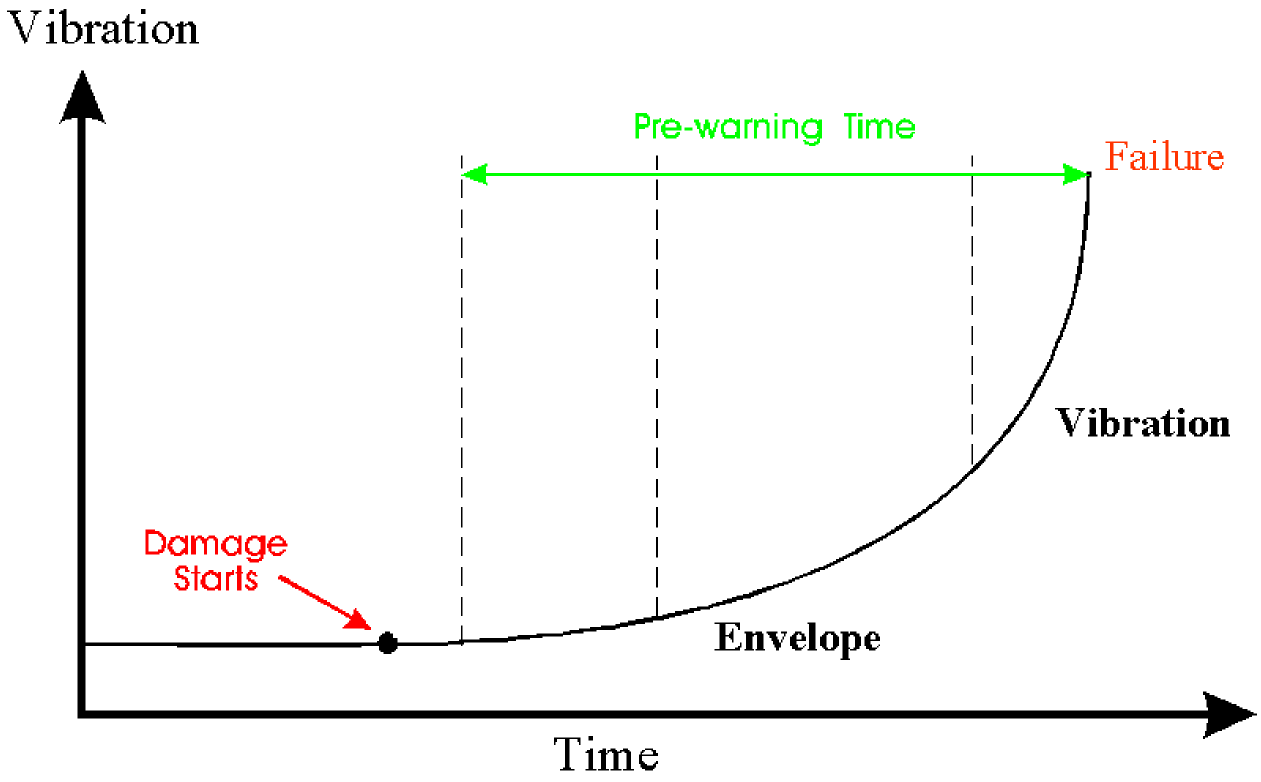


8.1. Trending

take measurements at regular intervals (usually of order of weeks or months) and plot results on graph

if results are relatively stable, machine is good

if results show increasing trend then perform a more detailed examination to see if a fault exists, inspect machine more frequently



8.2. Thresholds

use guidelines developed by experience to set thresholds for levels corresponding to faulty machine

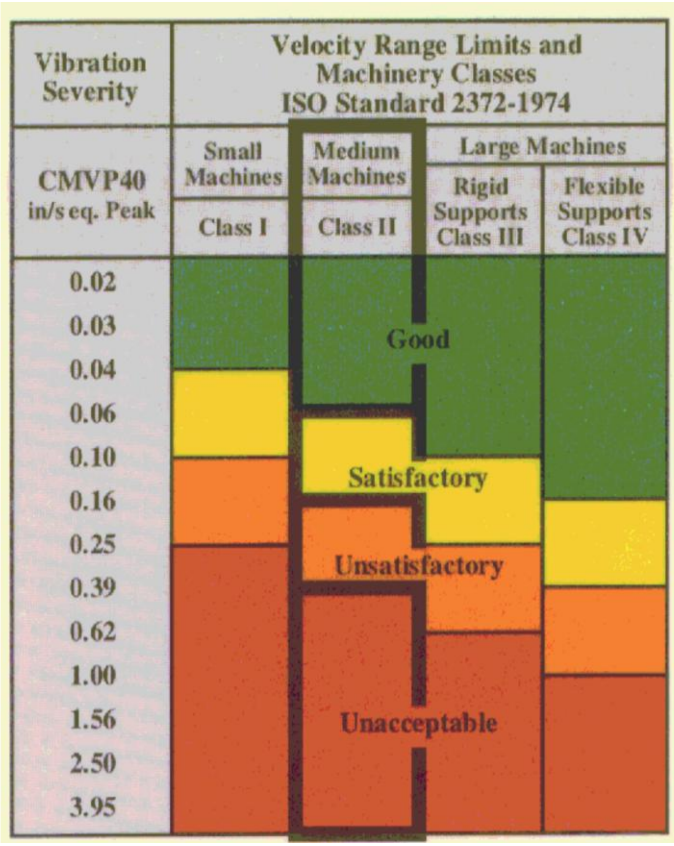
<u>examples</u>

1) broken bar sideband thresholds below (from SKF)

2) vibration thresholds for peak velocity readings for different size machines (from SKF)

sideband amplitudes in current spectrum
-54 to -60dB : excellent
-48 to -54dB : good
-42 to -48dB : moderate
-36 to -42dB : cracked rotor bars or other source of high resistance
-30 to -36dB : multiple sources of high resistance
over -30dB : severe damage

Vibration Thresholds (SKF)

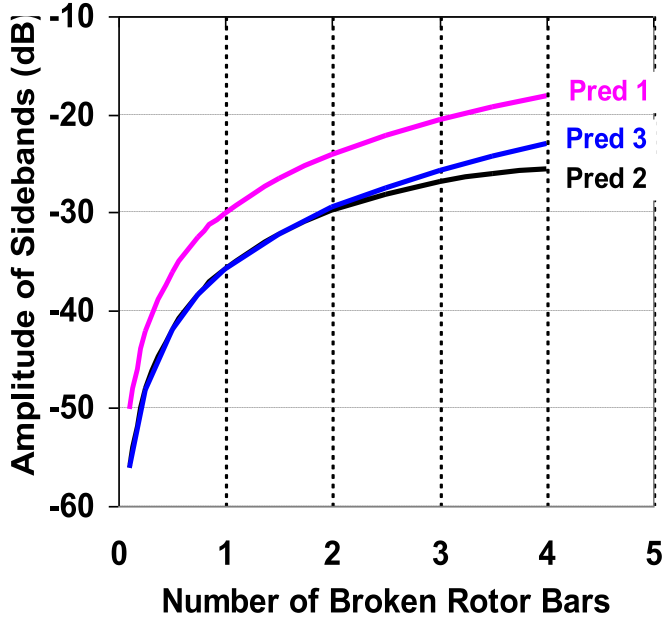


vibration : velocity : peak value

8.3. Model Based Approaches

use a mathematical model for the induction machine to predict how the amplitude of fault frequency components will vary with fault severity

e.g. broken bar sideband amplitude formulas



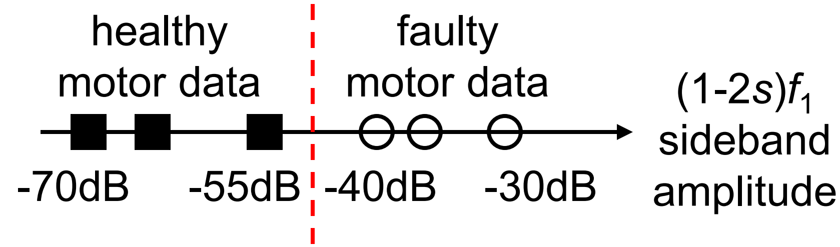
8.4. Classification Methods

problem : given “training” sets of data of parameters for healthy machines and for faulty machines develop means to classify new data as either healthy or faulty

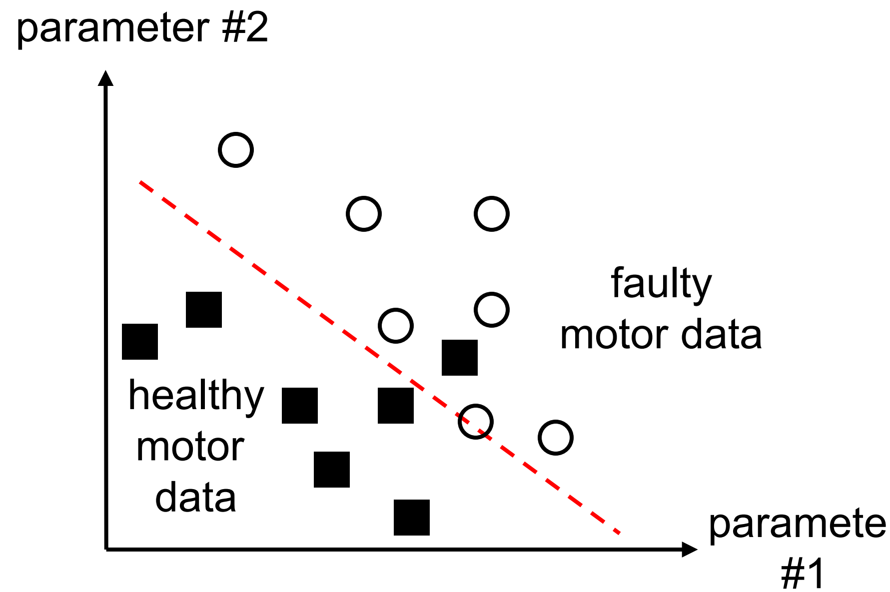
one-dimensional example :broken bar side-bands, can try to set thresholds to distinguish healthy and faulty motors

two-dimensional example : have two parameters, try to set straight line to separate healthy and faulty motors

can extend to multi-dimensional case



one-dimensional example



two-dimensional example

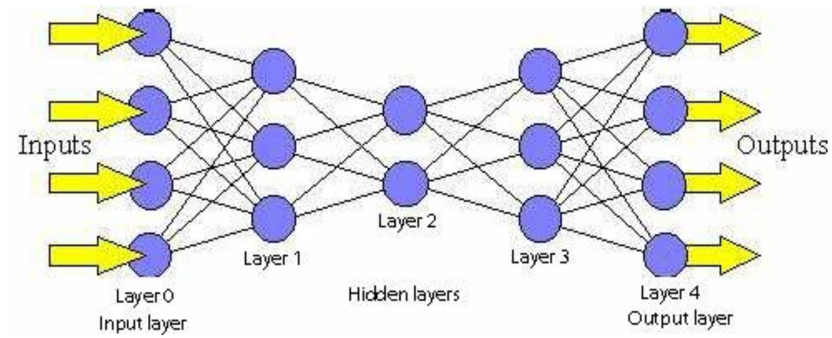
8.5. Artificial Intelligence Methods

Use algorithms developed for artificial intelligence applications to distinguish faults

a) **neural networks** : tries to model function of the neurons in the brain, use healthy and faulty training data to “teach” the neural network to give the right response

b) **expert systems** : tries to capture human experience in fault finding by sets of “rules”

e.g IF (current broken bar sideband amplitudes >-45dB) AND (flux broken bar sideband amplitudes >-30dB) THEN (broken bar fault)



neural network