Condition Assessment of Rotating Machines (pt2)

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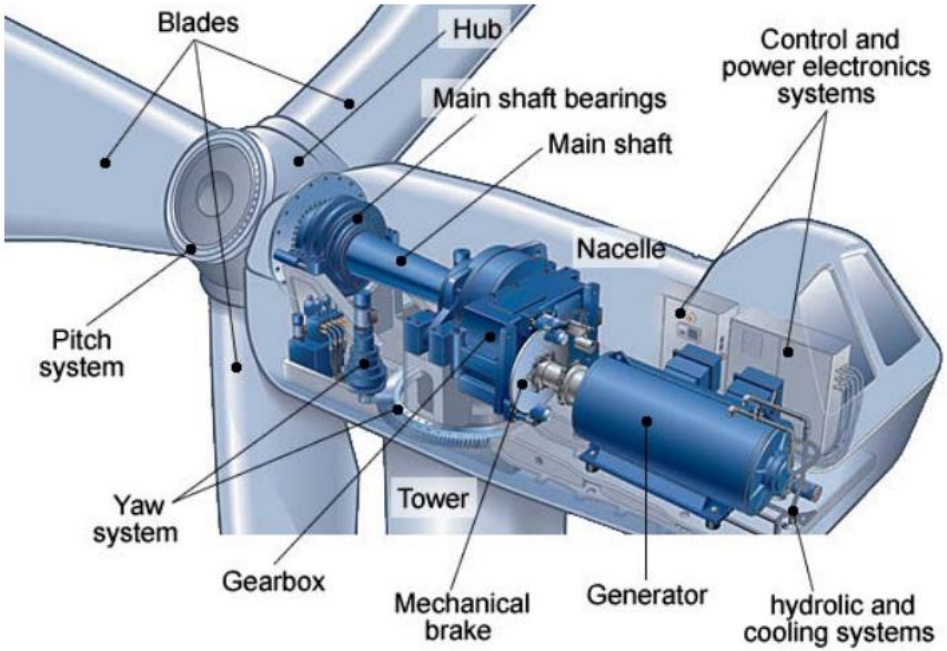
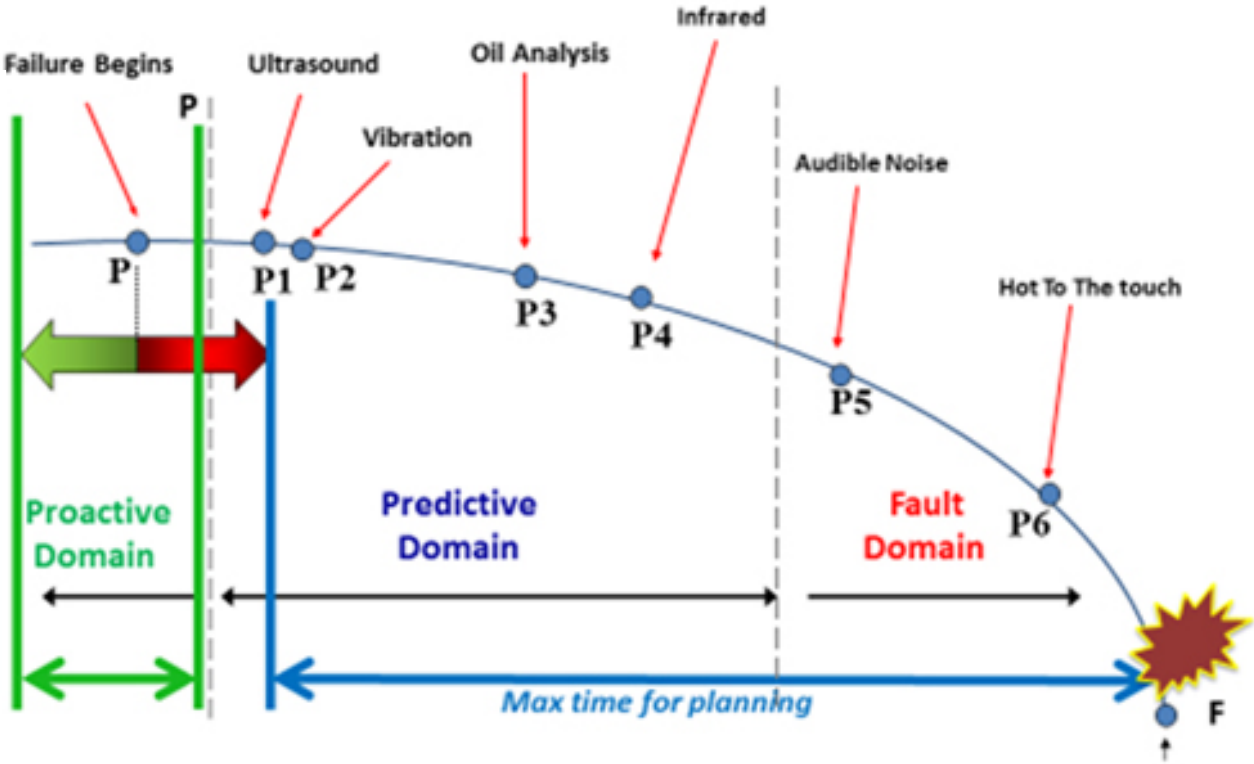
Condition Assessment Techniques

- Thermal (Thermography)
- Vibration
- Oil Analysis
- Acoustic Emissions
- Motor Current Signature Analysis
- Partial Discharge

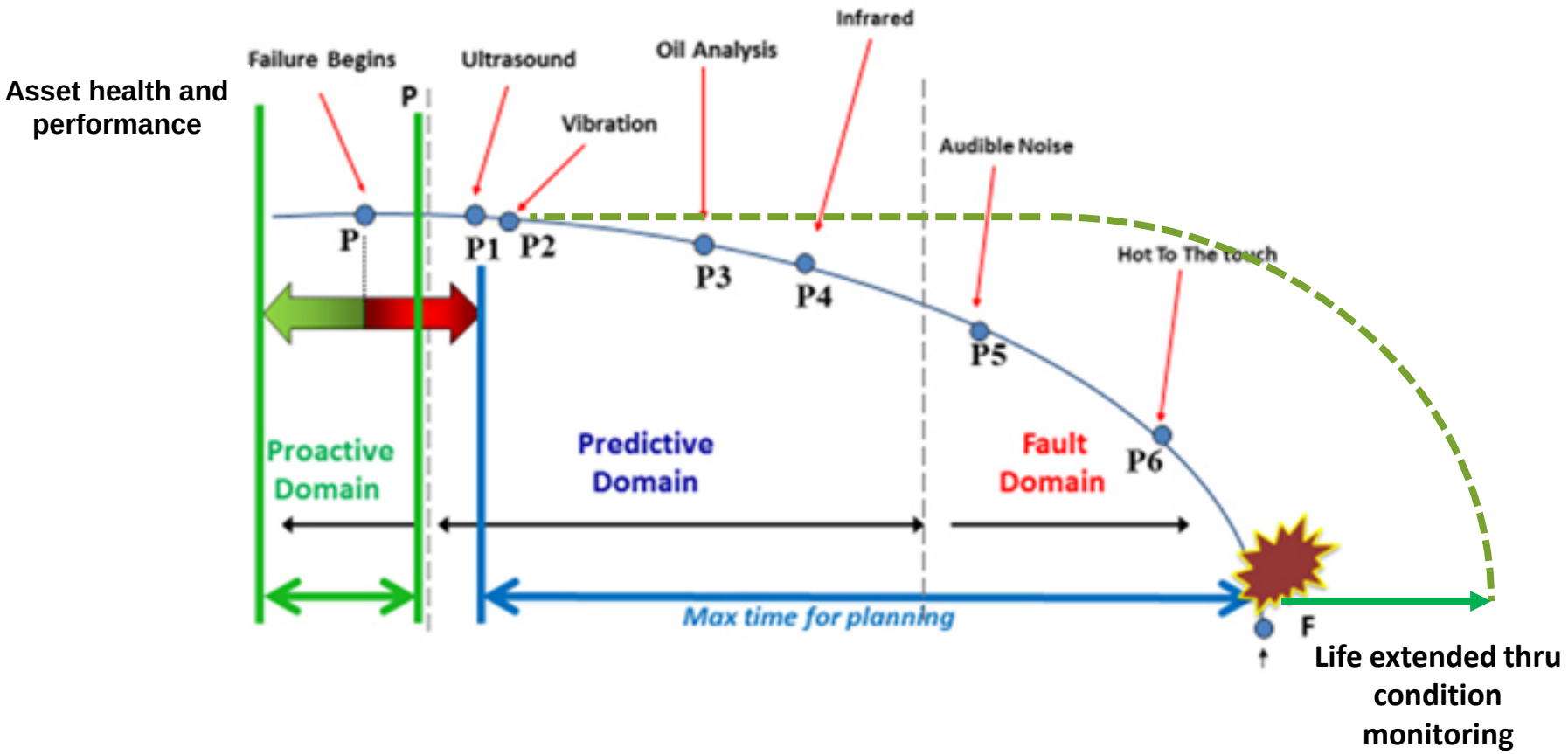


Stages of Condition of the Asset

Asset health and performance

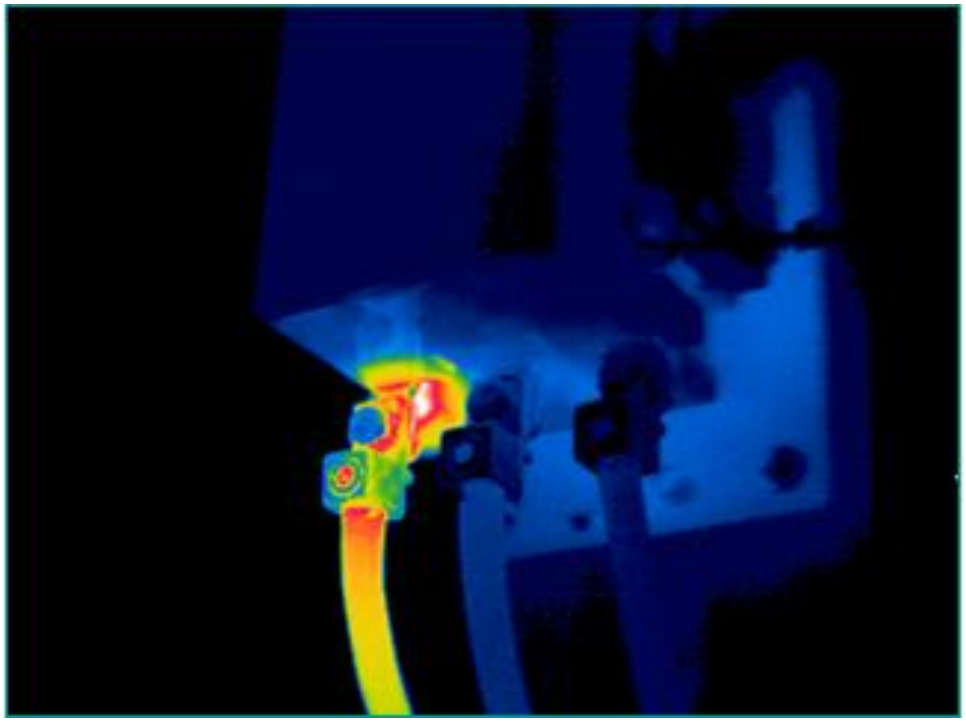


Stages of Condition of the Asset



Thermal

- Infrared (IR) thermography can be defined as the process of generating visual images that represent variations in the IR radiance of surfaces of objects.
- Any object at temperatures greater than absolute zero emits IR energy (radiation) proportional to its existing temperature.
- By using an instrument that contains detectors sensitive to IR electromagnetic radiation, a two-dimensional visual image recording the IR radiance from the surface of an object can be generated.
- Many fault conditions result in changes to a component's temperature.



Thermo-diagnostics is widespread in inspections of electrical switch-gears, high voltage lines, motors, etc.

Types of Equipment

Spot Infrared Thermometer)

Although not generally thought of in the world of thermography, IR thermometers use the same basic principles as higher end equipment to deduce an object's temperature based on IR emissions.

These devices do not provide any image representative of an object's thermal profile, but rather a value representative of the temperature of the object or area of interest.

Spot Thermometer

Types of Equipment

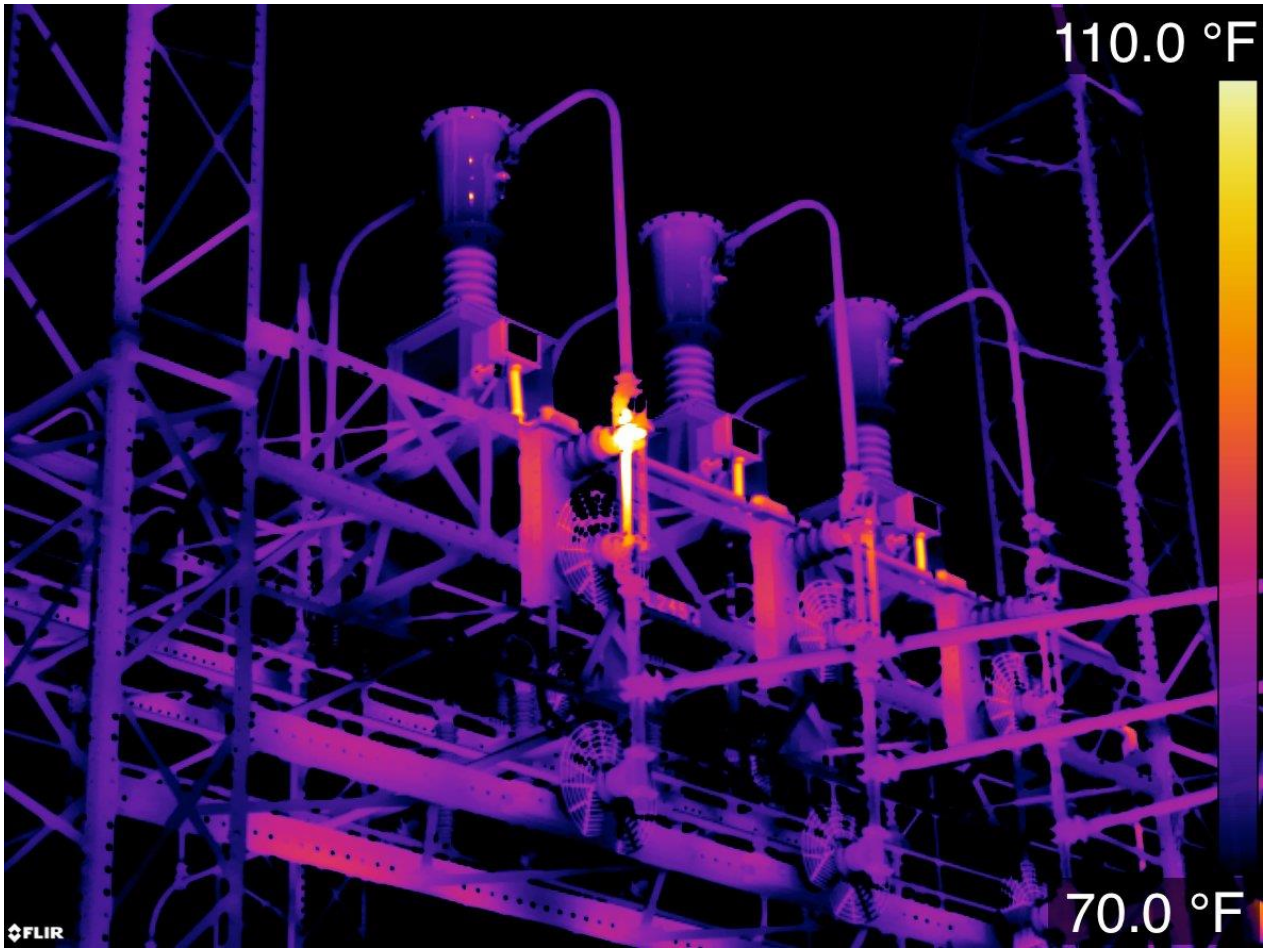
Thermal Imaging camera

- IR cameras with full radiometric capability detect the IR emissions from an object and translate this information into a visible format as in the case of an imager.
- In addition, these devices have the capability to analyze the image and provide a temperature value corresponding to the area of interest.
- This capability is useful in applications where a temperature value is important in defining a problem or condition.

IR Imaging Camera

For example, if an image indicated a difference between a pulley belt temperature and an ambient temperature, the belt may have worn, be the wrong size, or indicate a misalignment condition.

Thermography

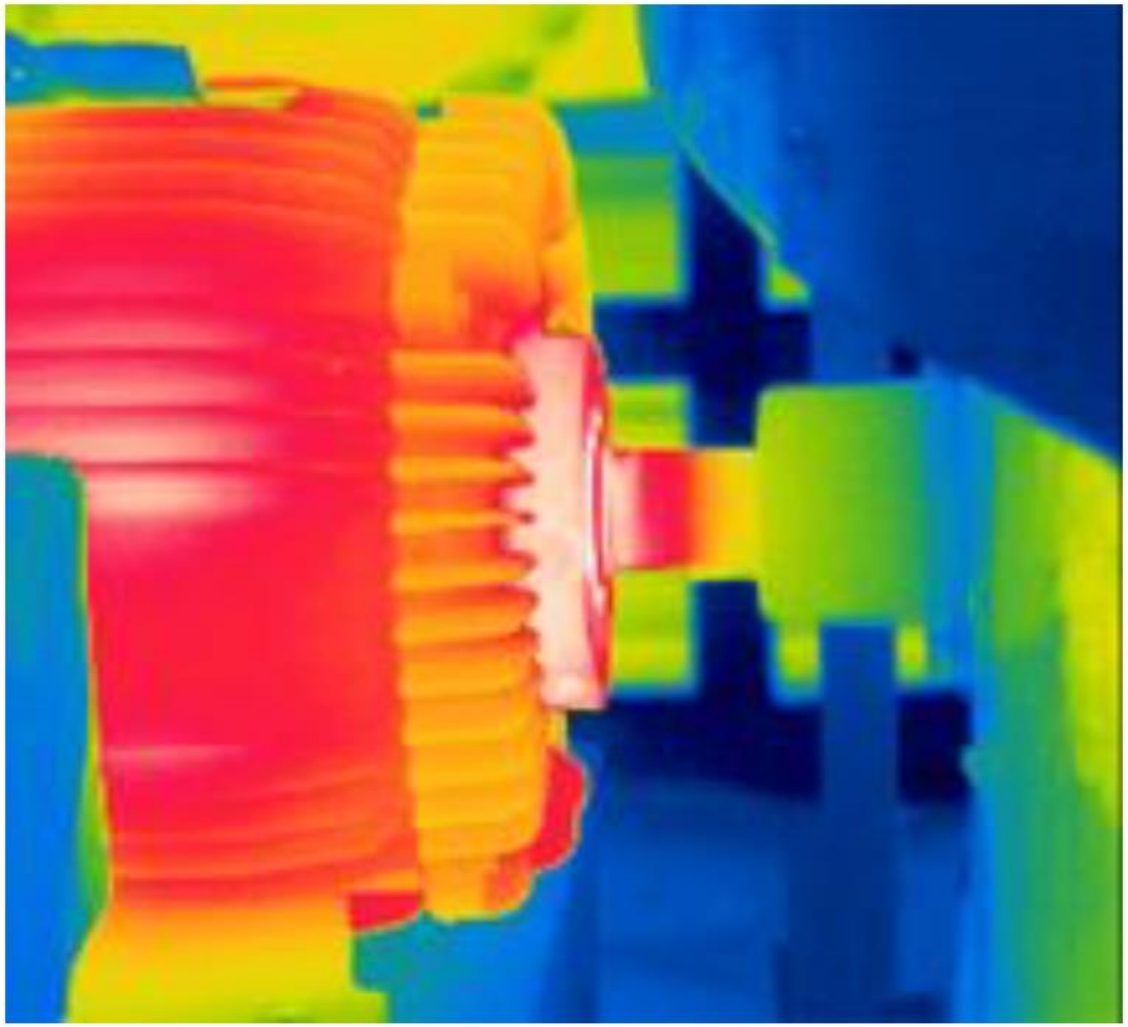


IR Imaging Camera in Operation

Thermography

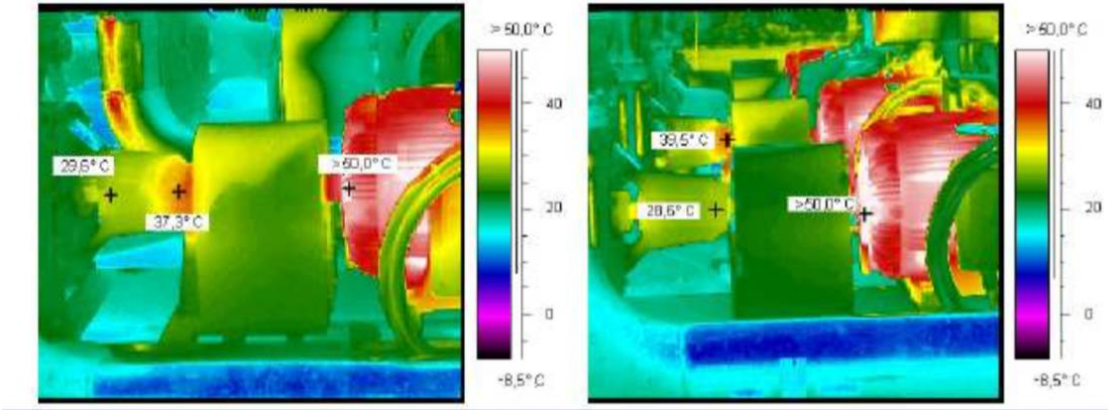
IR Surveillance of Boiler Feed Pump Motor

Thermography



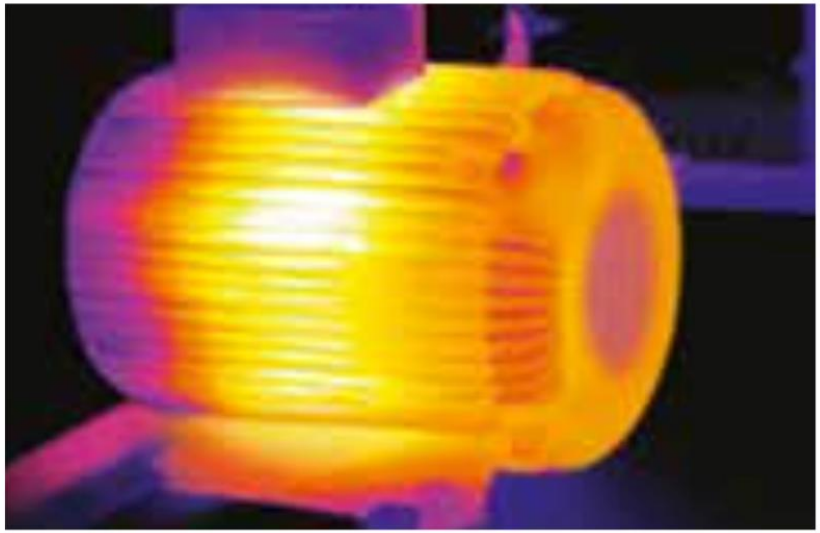
The causes of an abnormally warm motor bearing are not always obvious but infrared is a key means of finding those which are running hot.

Thermography



Example of applying thermo-diagnostics to detect misalignment in coupling (when the coupling is misaligned, greater loss of transmitted power occurs that is converted to heat, warming the coupling and the adjacent bearings).

Thermography



Internal Winding Problem

Vibration

- Vibration diagnostics involves information about the cause of vibration and through its analysis using different methods, an emerging or developing fault can be detected. For rotating machines, this is usually the method that covers most possible faults.

- Vibration diagnostics is described in more detail in ISO 13373-1: *Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 1: General procedures* and ISO 13373-2: *Condition monitoring and diagnostics of machines - Vibration condition monitoring - Part 2: processing, presentation and analysis of vibration data.*

Vibration – Measured Quantities

- In mechanics, movement can be described by *displacement*, *velocity* or *acceleration*, and these variables are linked by mathematical relationships. From this perspective, it does not matter which variable is chosen to describe the vibrational behaviour, it is just a matter of scale and time shift (phase).

- Depending on the measured quantity, sensors are divided into:
  - displacement transducers (proximity probes)
  - velocity probes
  - accelerometers

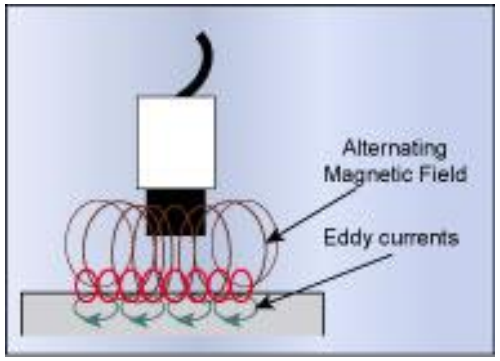
Vibration – Measured Quantities

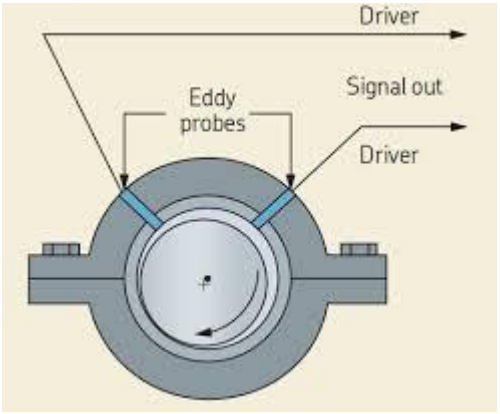
- Frequency range of interest is one of the factors that determine the type of measured value.
- If the measured frequency range includes high frequencies (such as gear mesh frequencies), the best choice would be to measure acceleration.
- Conversely, if the measurement frequency is limited to the running speed, the best choice would be measuring displacement or velocity (depending on application).
- Velocity is used for common measurements in the frequency range 10 Hz to 1000 Hz, acceleration is preferred for higher frequencies and displacement is preferred for lower frequencies.

When measuring the velocity of vibration, there is no need to care about the frequency (speed) at which the value was measured; when measuring the other two variables, it is necessary to indicate at what rotational speed (frequency) the value was measured. Otherwise, it is not possible to assess the condition of the machine.

Displacement Sensors

- Displacement sensors are quite complex systems; so, they are only used for shaft vibration measurement - they measure vibrations of shaft relative to a part of stator, usually relative to the bearing housing.
- The often used type is a non-contact proximity probe sensor based on eddy currents.
- Measures the distance between the sensor tip and a conductive surface.



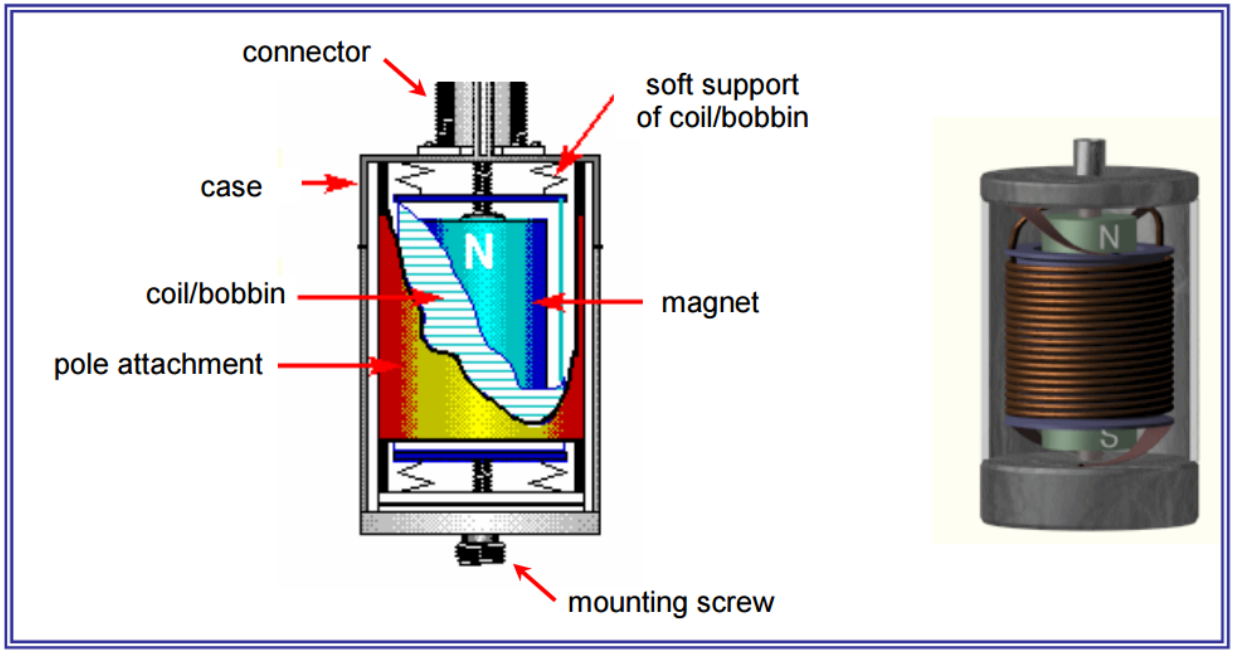


Velocity Transducers

- Velocity transducers operate on the principle of electromagnetic induction: when the coil moves in a magnetic field, voltage is generated on the coil outlets.

- The amount of the induced voltage is directly proportional to the relative speed between the coil and the magnetic field.

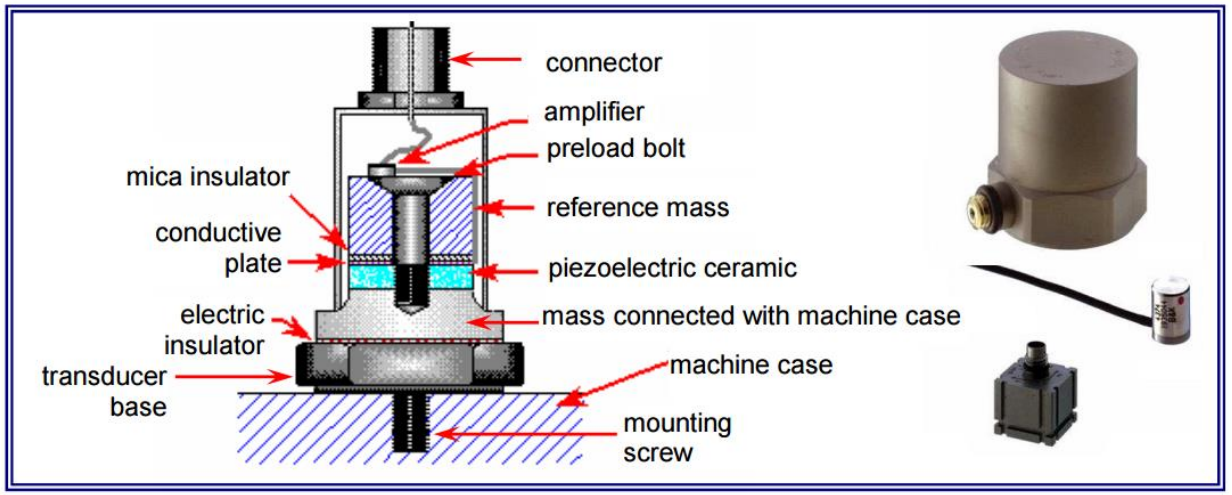
- Velocity transducers are designed so that this relative speed reflects velocity of vibration of the measured machine.



Velocity Transducer.

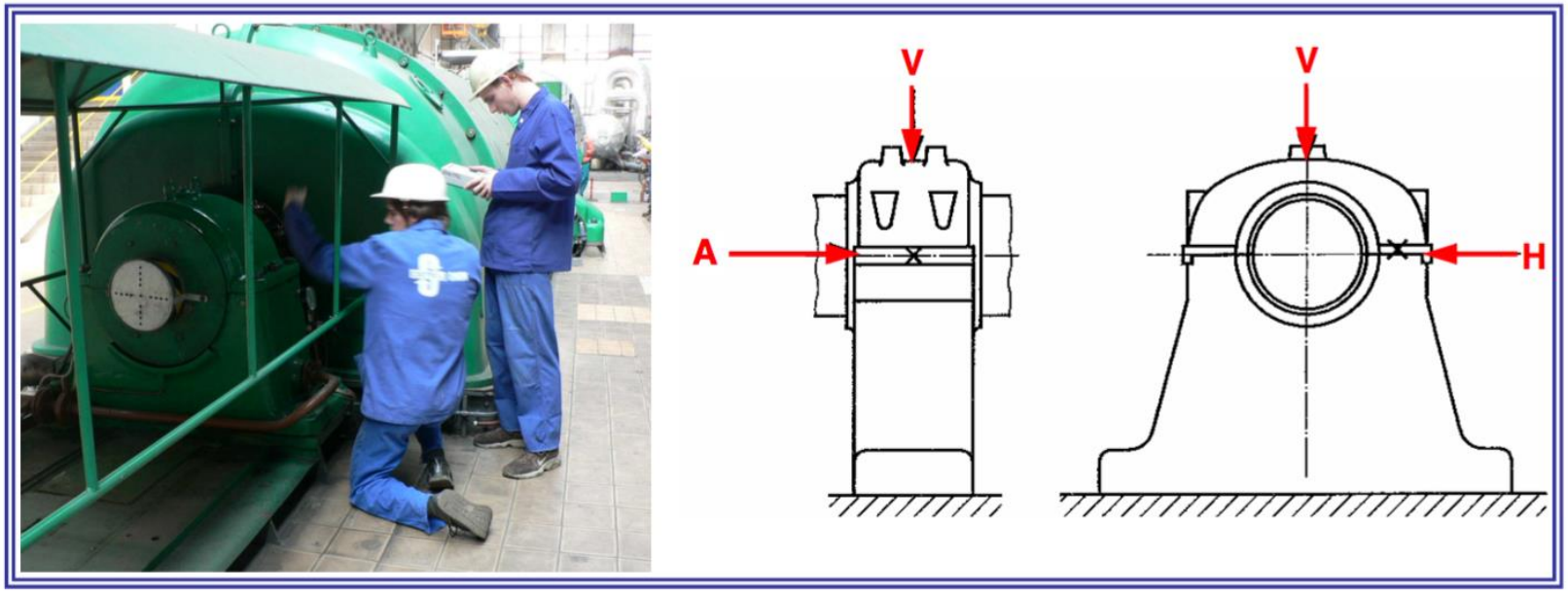
Accelerometer Transducers

- The principle of accelerometer operation is that deformation of a plate of piezoelectric ceramic material creates an electrical charge.
- The ceramic plate is placed between two masses, one of which is inertia (seismic) reference mass and the other is firmly attached to the sensor case and therefore to the case of the measured machine.



- When the measured machine vibrates, the mass firmly attached to the transducer case also vibrates, while the reference inertial mass remains at rest. This creates a force applied to the piezoelectric element that deforms and creates an electrical charge that is proportional to the acceleration of the machine case.

Axial and Radial Monitoring - Bearing

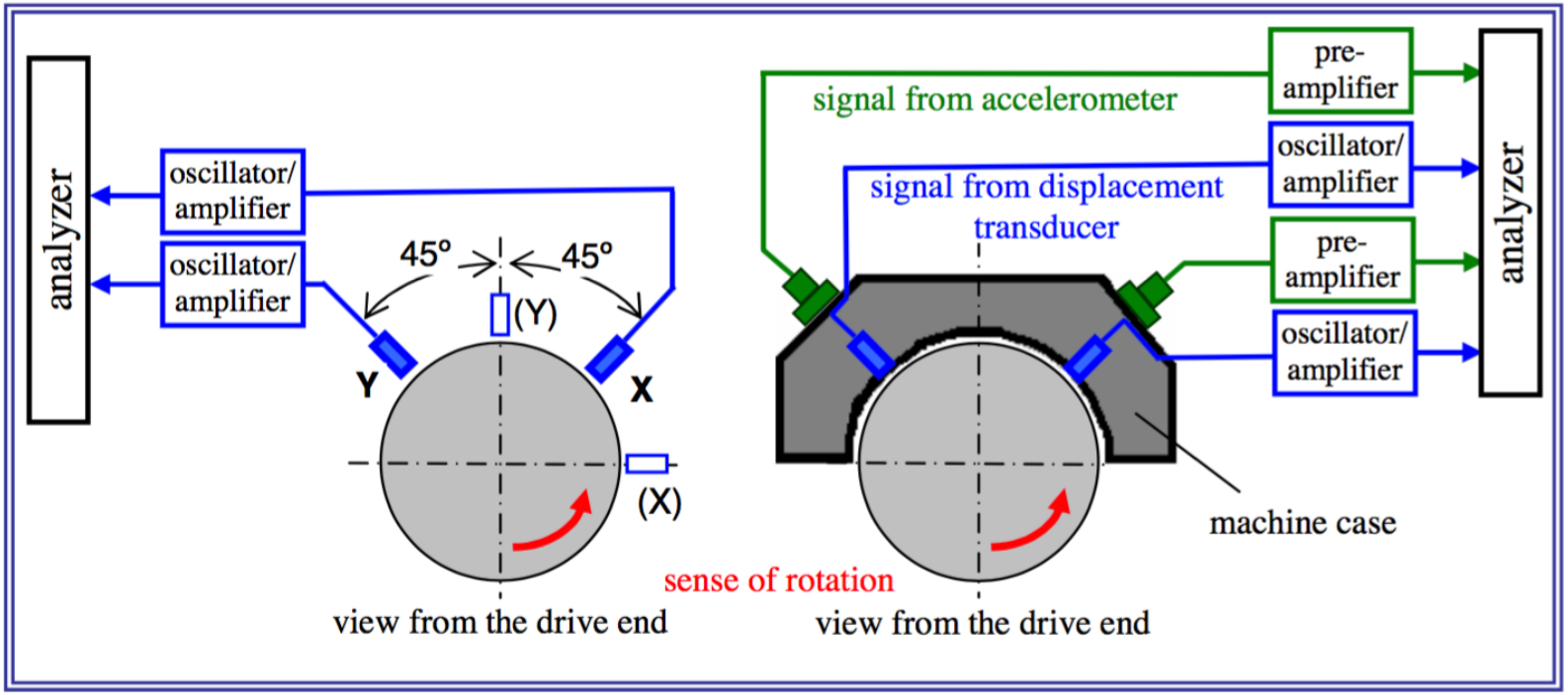


By mounting accelerometers at strategic points on bearings, we can measure axial and radial vibration.

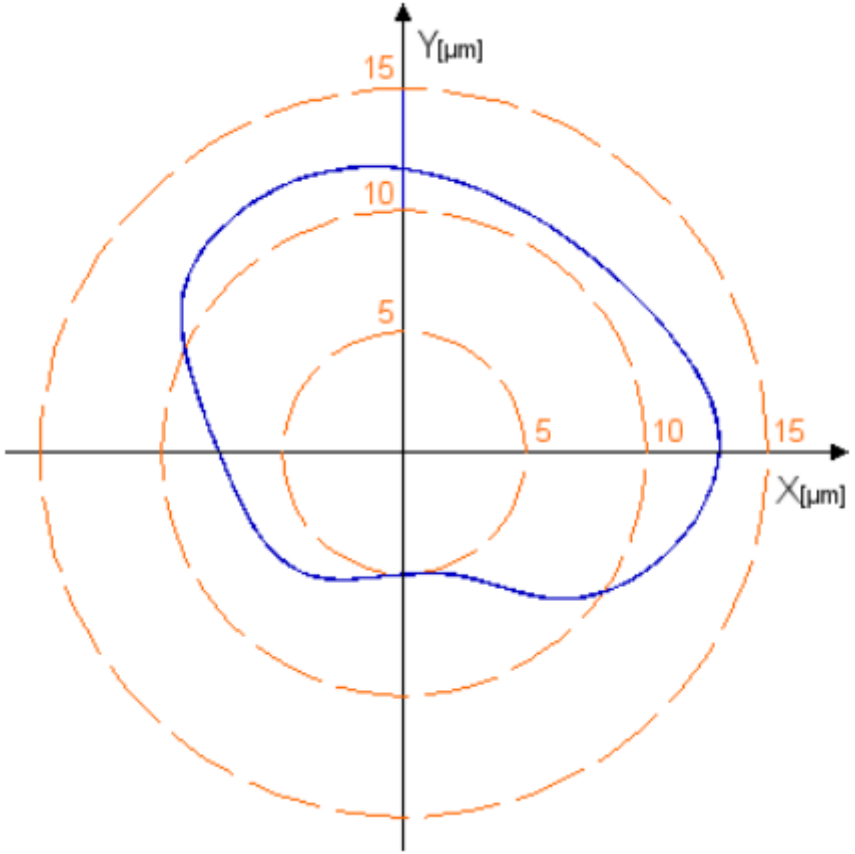
Axial and Radial Monitoring – Motor Shaft

Eddy current displacement probes used to measure rotor shaft displacement and eccentricity relative to the stator.

Probe Arrangement

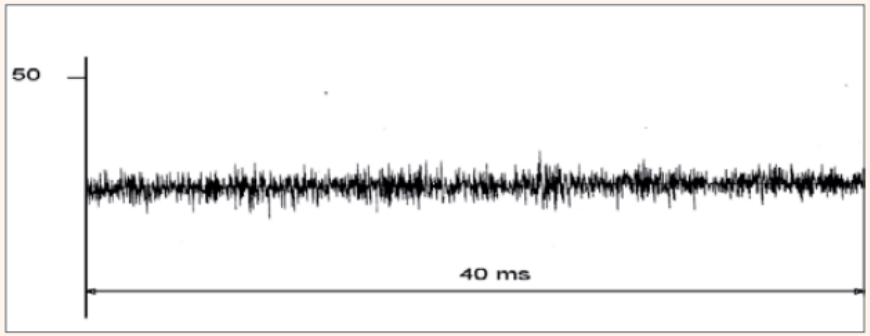


Monitoring Shaft Displacement

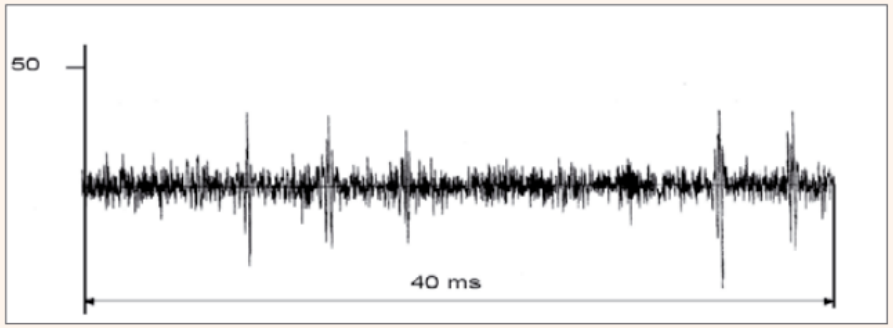


Shaft Orbit: the path of a rotor shaft rotation. (polar plot)

Analyzing Probe Signals in Time Domain



Signal from a good bearing



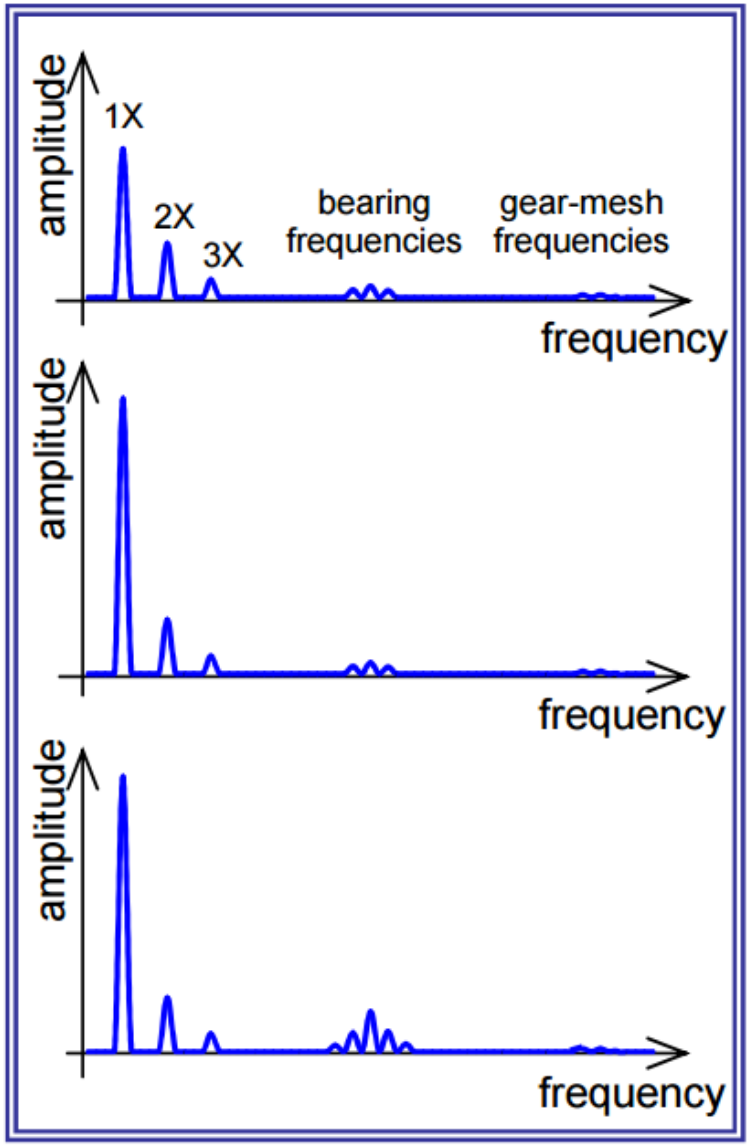
Signal from a damaged bearing

Analyzing Probe Signals in Frequency Domain

FFT Spectrum Analysis

- A method of viewing the vibration signal that is more useful for analysis is to break the signal down into specific amplitudes at various component frequencies.
- These values or amplitudes are then plotted over the frequency scale, the resulting plot is called an FFT spectrum.
- Bearing and gearbox faults and other sources of vibration have specific frequency signatures that can be diagnosed and trended.

Analyzing Probe Signals in Frequency Domain



The top trace is an example of a baseline spectrum.

Beneath there is a situation when the basic rotational frequency 1X has changed and is significantly higher than normal. This indicates that the vibration signal is periodically changed once per shaft rotation. A typical cause for such behaviour use is either unbalance or misalignment.

The last spectrum below shows that in addition to increased 1X, peaks from roller bearing defects have increased as well, which indicates that the problem on 1X gave rise to bearing damage.

Oil Analysis – Basic Concepts

One of the oldest predictive maintenance technologies. Oil analysis is used to define three basic machine conditions related to the machine's lubrication or lubrication system:

1. *First,* is the condition of the oil. Will its current condition lubricate per design?
2. *Second,* is the lubrication system condition. Have any physical boundaries been violated causing lubricant contamination?
3. *Third,* is the machine condition itself. By analysing wear particles existing in the lubricant, machine wear can be evaluated and quantified.

Oil Analysis – Basic Concepts

- Oil condition is most easily determined by testing lubricant viscosity, acidity, base number (ability to neutralise acids), etc.
- Additional tests can determine the presence and/or effectiveness of oil additives such as anti-wear additives, antioxidants, corrosion inhibitors, and anti-foam agents.
- By testing for water content, silicon, or other contaminants (depending on the system design), lubrication system integrity can be evaluated. The presence of silicon (usually from sand) is an indication of contamination from dirt.
- Component wear can be determined by measuring the amount of wear metals such as iron, copper, chromium, aluminum, lead, tin, and nickel. Increases in specific wear metals can mean a particular part is wearing, or wear is taking place in a particular part of the machine.

Oil Analysis – Basic Concepts

- Regardless of whether the analysis is performed by an independent laboratory or by in-house services, accurate results require proper sampling techniques.

- For consistent results and accurate trending, samples should be taken from the same place in the system each time (using a permanently installed sample valve is highly recommended).

Oil observation and sample point

Karl Fischer Test

The *Karl Fischer* Test quantifies the amount of water in the lubricant.

Significance: Water seriously damages the lubricating properties of oil and promotes component corrosion. Increased water concentrations indicate possible condensation, coolant leaks, or process leaks around the seals.

The Karl Fischer technique is based on the oxidation of sulphur dioxide by iodine in a methanolic hydroxide solution. Titration is performed where a solution containing iodine is added until the first trace of excess iodine is present. From this the amount of water present in the solution is determined.

Oil observation and sample point

ICP Spectroscopy

Measures the concentration of wear metals, contaminant metals, and additive metals in a lubricant.

In atomic spectrometry techniques most commonly used for trace element analysis, the sample is decomposed by intense heat into a cloud of hot gases containing free atoms and ions of the element of interest.

- *Atomic Absorption Spectrometry* (AAS) – measures the amount of light absorbed of specific wavelengths to determine the concentration of the elements of interest.
- *Optical Emission Spectrometry* (OES) – measures the amount of light emitted by elements of interest at specific wavelengths to determine the level of concentration.

AAS Spectrometry

Spectrometry Guide

Metal	Transmissions	Gears	Hydraulics
Iron	Gears, disks, housing, bearings, brake bands, shaft	Gears, bearings, shaft, housing	Rods, cylinders, gears
Chrome	Roller bearings	Roller bearings	Shaft
Aluminium	Pumps, thrust washers	Pumps, thrust washers	Bearings, thrust plates
Nickel	Steel alloy from roller bearings and shaft	Steel alloy from roller bearings and shaft	
Copper	Bushings, clutch plates (auto/ powershift), luburication coolers	Bushings, thrust plates	Bushing (bronze alloy)
Lead	Bushings (bronze alloy), lubrication additive supplement	Bushings (bronze alloy), grease contamination	Bushing (bronze alloy)
Tin	Bearing cage metal	Bearing cage metal, lube additive	

Motor Analysis Techniques

- When it comes to motor condition analysis, infrared (IR) and vibration will not provide all the answers required to properly characterize motor condition or winding insulation.

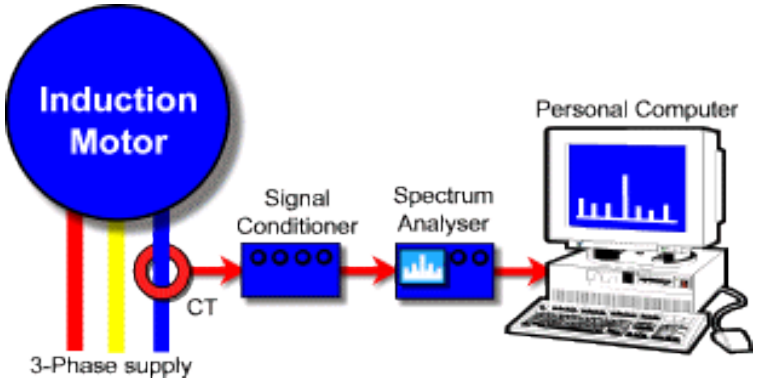
- Over the past several years, motor condition analysis techniques have evolved from simple testing into testing techniques that more accurately define a motor's condition.

- Motor faults or conditions like winding short-circuits, open coils, improper torque settings, as well as many mechanically-related problems can be diagnosed using motor analysis techniques.

- Motor analysis equipment remains fairly expensive and proper analysis requires a high degree of skill and knowledge.

Motor Current Signature Analysis

- Motor Current Signature Analysis (MCSA) is a proven and accepted method for determining the condition of a motor's current carrying components.
- Testing can be conducted without interrupting the normal operation of the motor, and in fact should be performed when the motor is under a minimum of 70% load.
- The process is non-invasive, requiring only that a current transformer (amp-probe or current clamp) be placed around one conductor of the motor power supply cable.
- On three phase motors only one phase need be monitored as characteristic fault frequencies will be equally evident in all three phases.

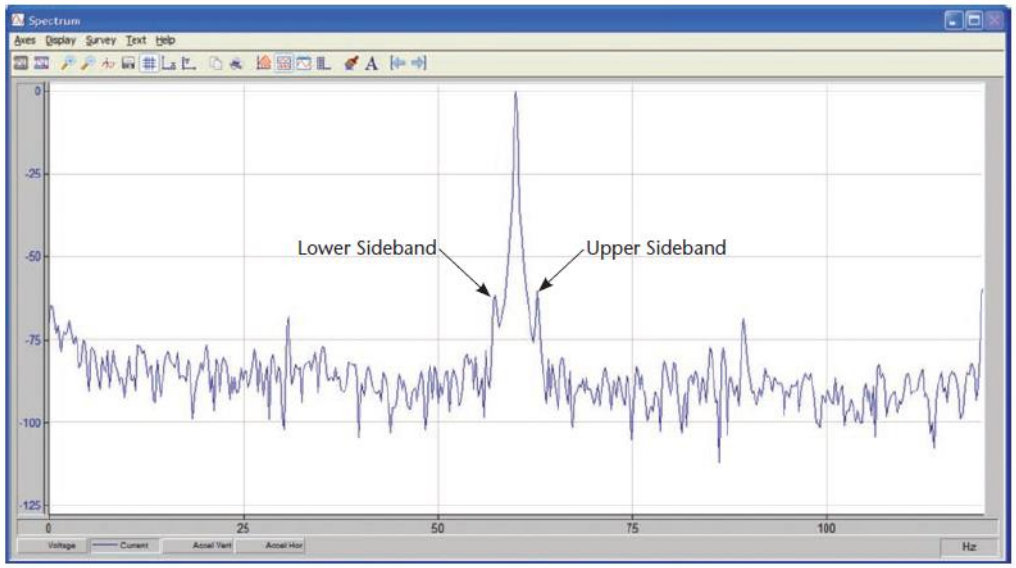


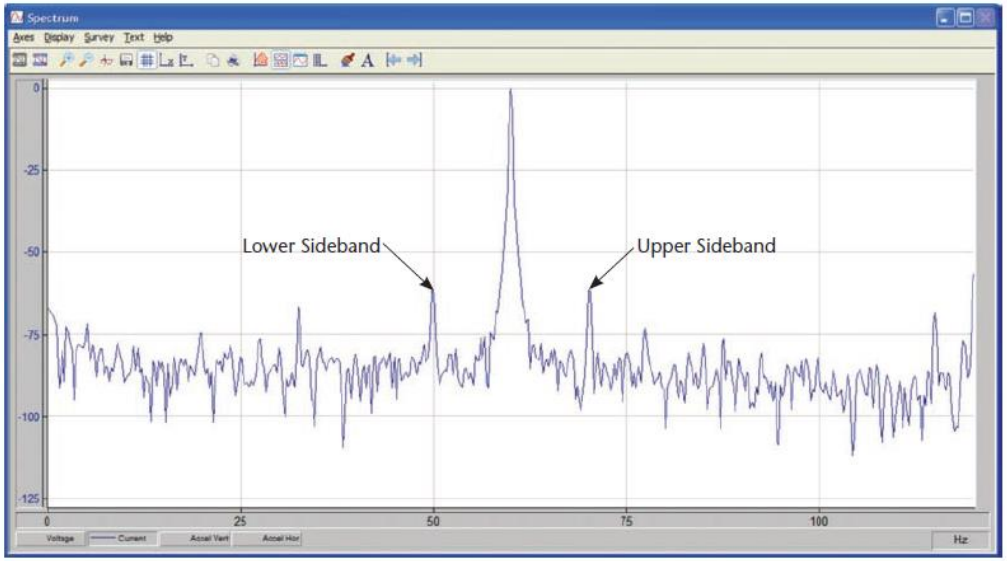
Motor Current Signature Analysis

- The motor (acting as a transducer) senses mechanical load variations and converts them into electric current variations that are transmitted along the motor power cables.
- These current signatures are reflective of a machine's condition and closely resemble signatures produced using vibration monitoring.
- In a healthy inductive motor the flow of current through the stator windings and conductive rotor bars and end rings is consistent and balanced, resulting in constant torque and minimal vibration.
- Damaged conductors cause a reduction or complete interruption of current flow, and a corresponding reduction in torque as that winding is energized.
- This momentary drop in current repeats periodically with each rotation of the rotor, resulting in modulation of the current drawn by the motor.

Motor Current Signature Analysis

- Slip frequency will be visible in the current spectrum in the form of sidebands around the line centre frequency.
- The actual operational speed of the motor will be determined by the load applied.
- As load increases, the operational speed reduces and motor torque increases. The difference between the synchronous motor speed and actual motor speed is termed “slip.”

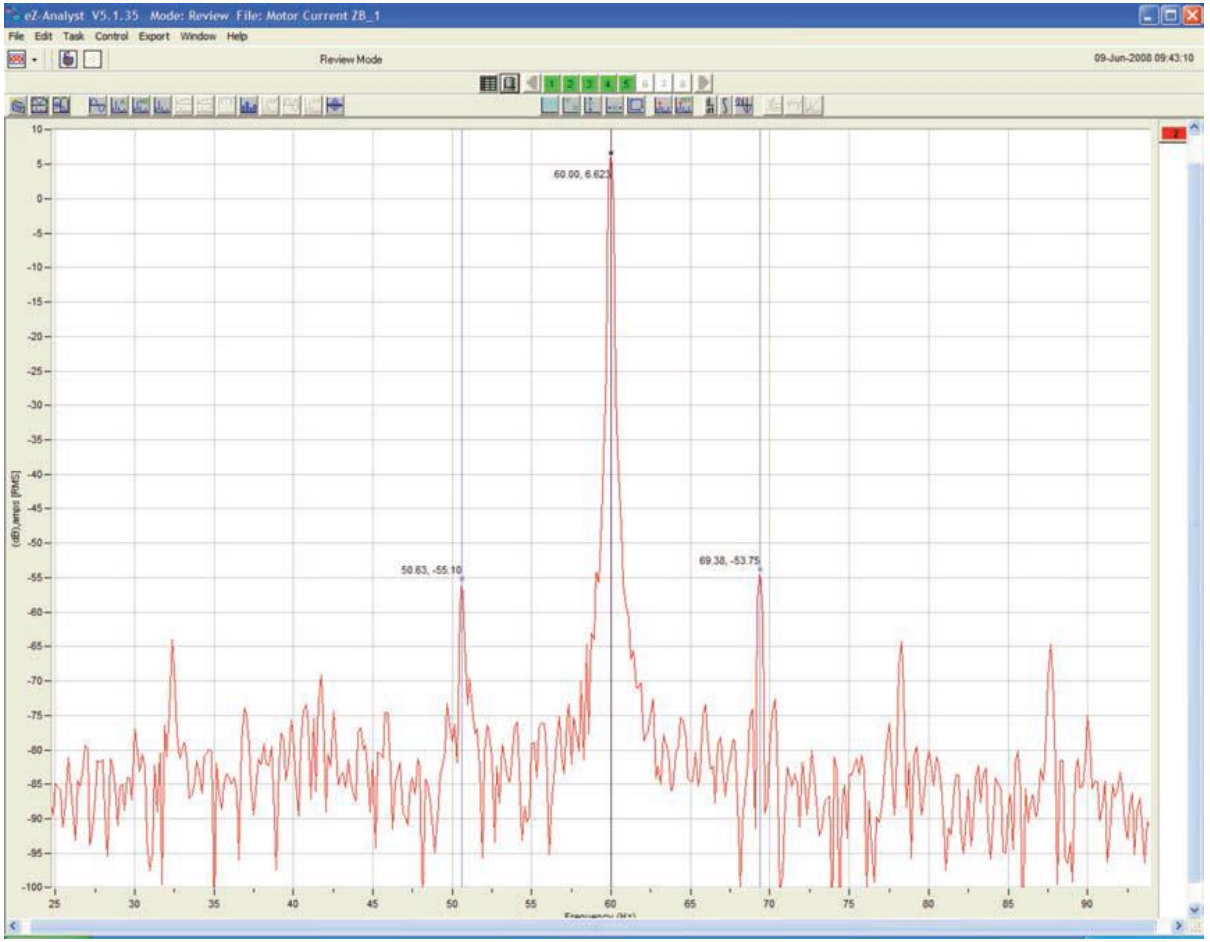




Motor Current Signature Analysis

These current signals are recorded and processed by software to produce a visual representation of the existing frequencies against current amplitude.

Analysis of these variations can provide an indication of machine condition, which may be trended over time to provide an early warning of machine deterioration or process alteration.



When the motor current signal is processed through a spectrum analyser the resultant frequency spectrum can identify and quantify the severity of specific motor faults.

Partial Discharge Monitoring

What is Partial Discharge?

"A **localised** electrical discharge that only partially bridges the insulation between conductors and which can or can not occur adjacent to a conductor" ***IEC60270 Definition***

Why test for partial discharge?

PD activity is an indication of an ***'incipient fault'*** in HV insulation and is widely regarded as the best ***'early warning'*** indicator of the deterioration of high voltage insulation.

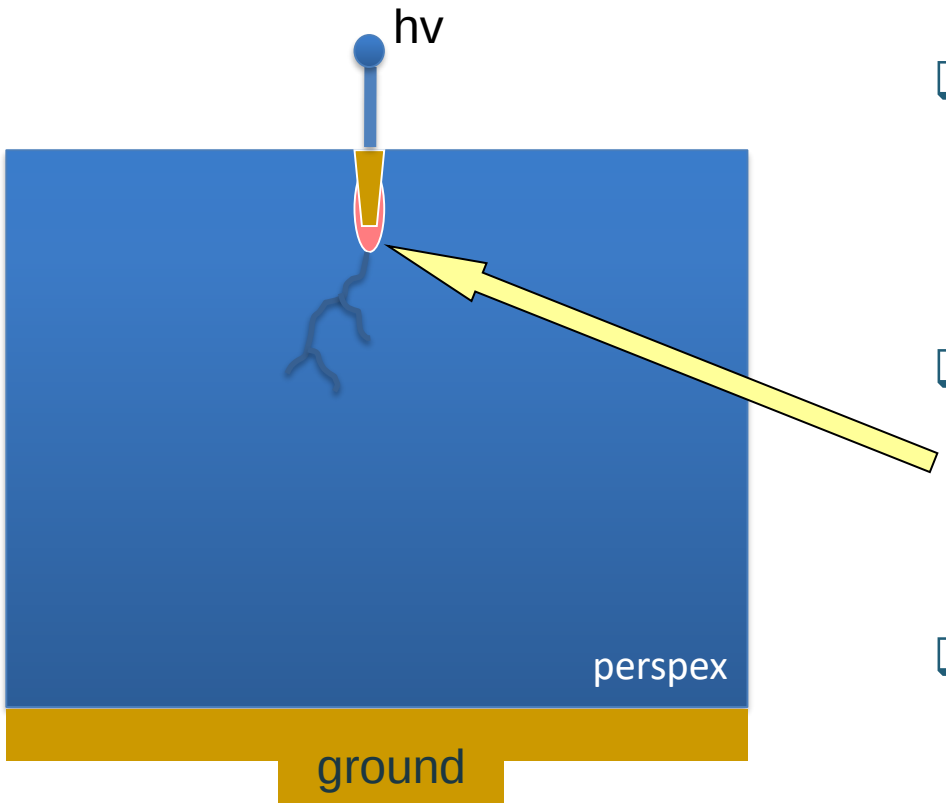
Partial Discharge Monitoring

- PD occurs when insulation defects exist which produce distorted and enhanced electric field stress.
- Causes of PD in insulation system:
  - Voids in epoxy resins, polymers, paper
  - Bubbles and gas layers in liquids/oils
  - Delamination of insulation surfaces
  - Metal depositions/irregularities/contaminants
  - Electrodes and insulation surfaces
  - Poor terminations/loose joints

Partial Discharge Monitoring

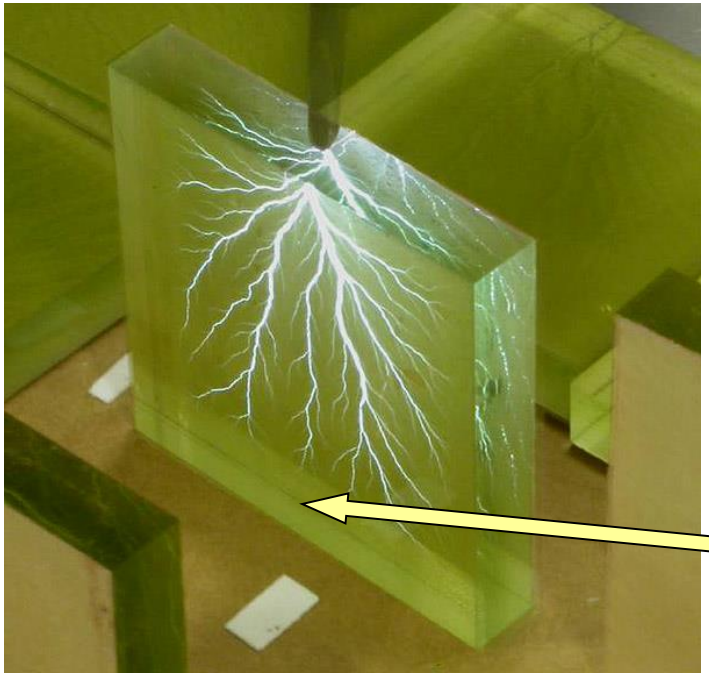
- Can also arise through:
  - Poor design and manufacture
  - Damage of equipment
  - Poor installation processes
  - General “ageing” or deterioration of materials
  - Accelerated aging of the insulation as a result of transient-over-voltages resulting from
    - natural phenomena such as lightning strikes, overloading,
    - load switching,
    - variable speed drives (VSDs),
    - invertors

So What is Partial Discharge (PD) ?



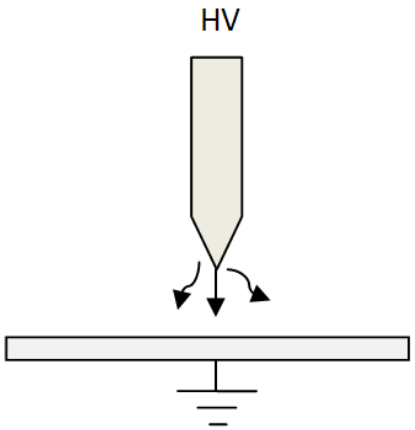
- This block of perspex has electrodes on two faces – with: a needle as one; the second a ground plane.
- There is a high electro-mechanical stress in the perspex around the needle tip.
- It eventually leads to a void at the needle tip, PD and then local breakdown in the perspex.
- The tree then starts.

Tree Growth – a model study in perspex



- The structure of the perspex will break down to form free carbon. So the branches will become carbonised, and eventually more will form and extend through the perspex as a tree.
- The material ahead is still insulating and high impedance. This prevents any significant current flow in the carbon track and a power follow-through is prevented.
- Thus the discharges are low current events and only **partial breakdowns.**
- Eventually the stress at the tips will become critical and a leader will form the puncture track.

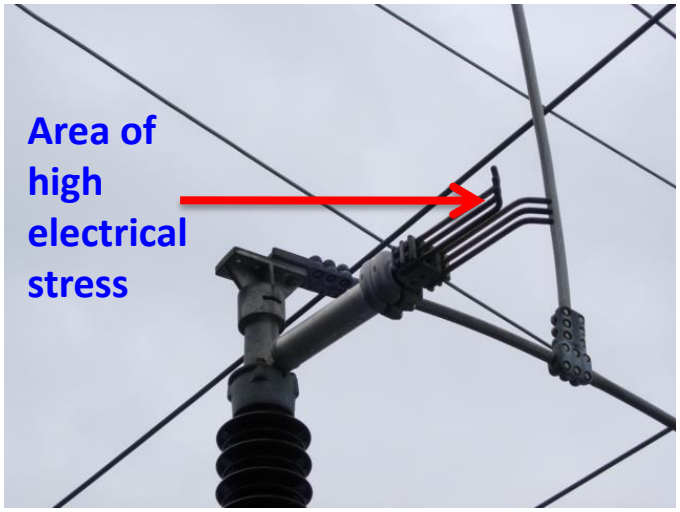
Corona Discharge

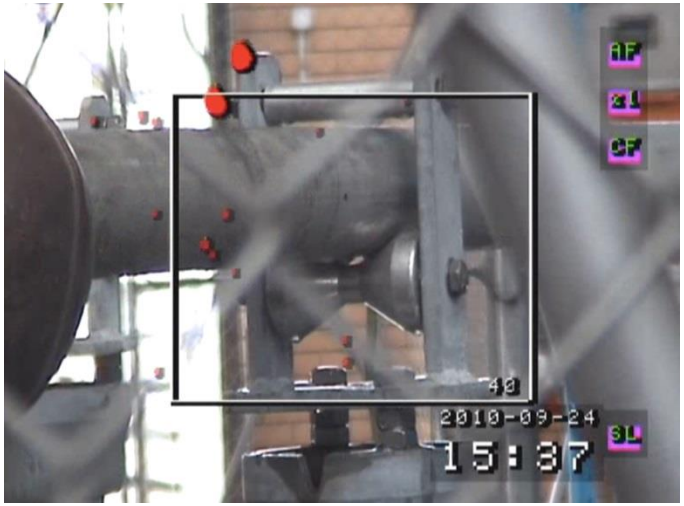


Corona Discharge

Non-uniform electric field distribution around the sharp point – divergent lines of electrical force

Causes avalanche of free electrons and streamer formation



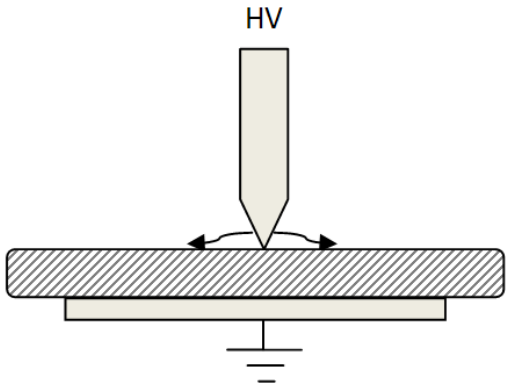


Sources of Corona visualised using a UV DayCor Camera

Corona Discharge

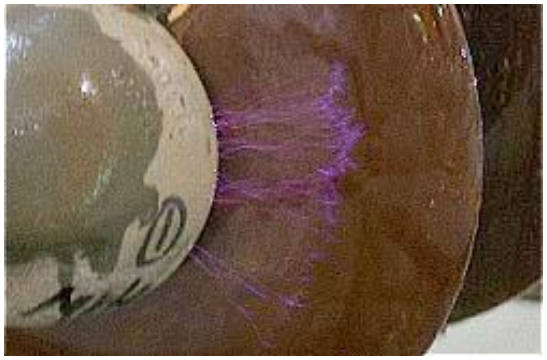
Corona emission from energized parts of a transmission line suspension insulator

Surface Discharge

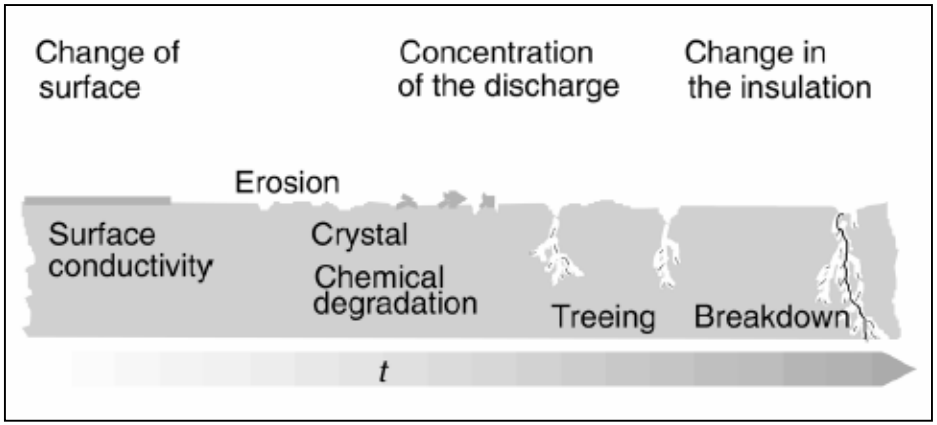


Surface Discharge

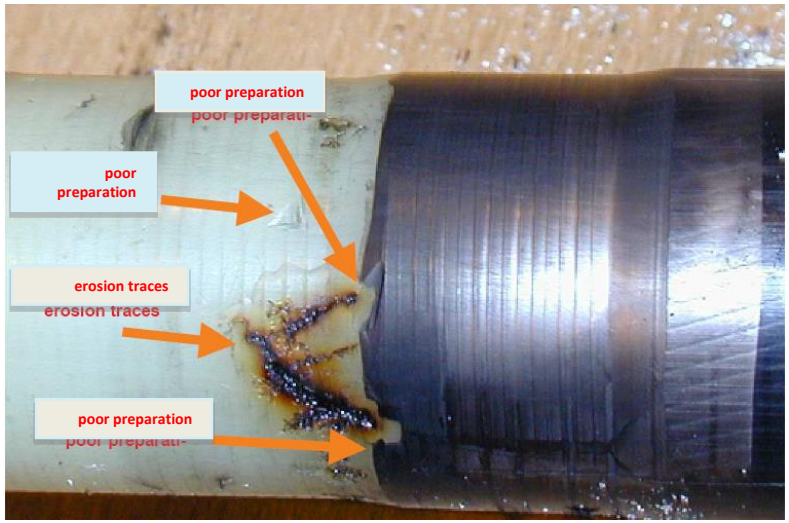
500kV GIS Insulating Support



Connection Spout

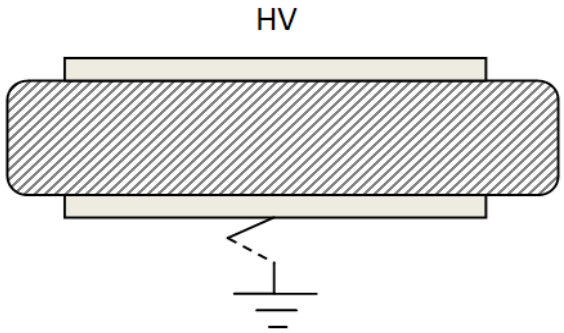


Morshuis (2005)



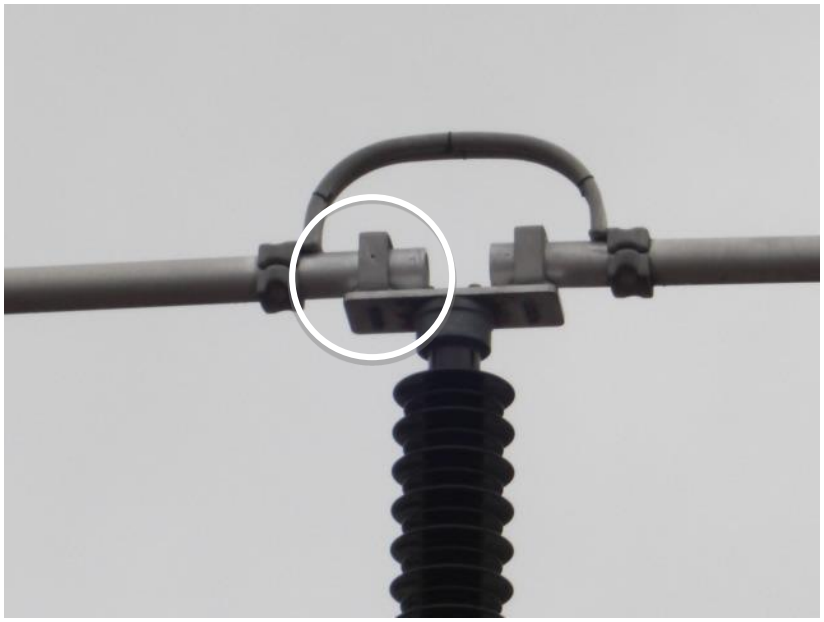
Poorly Prepared Cable Joint

Loose Connection



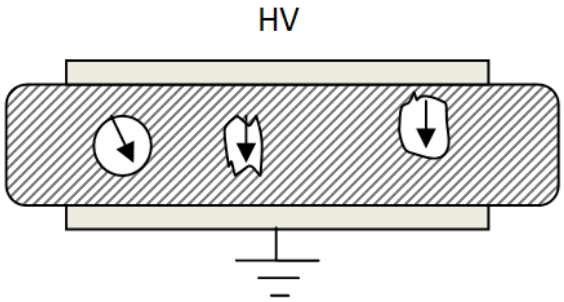
Loose Connection

Poorly Completed Connection

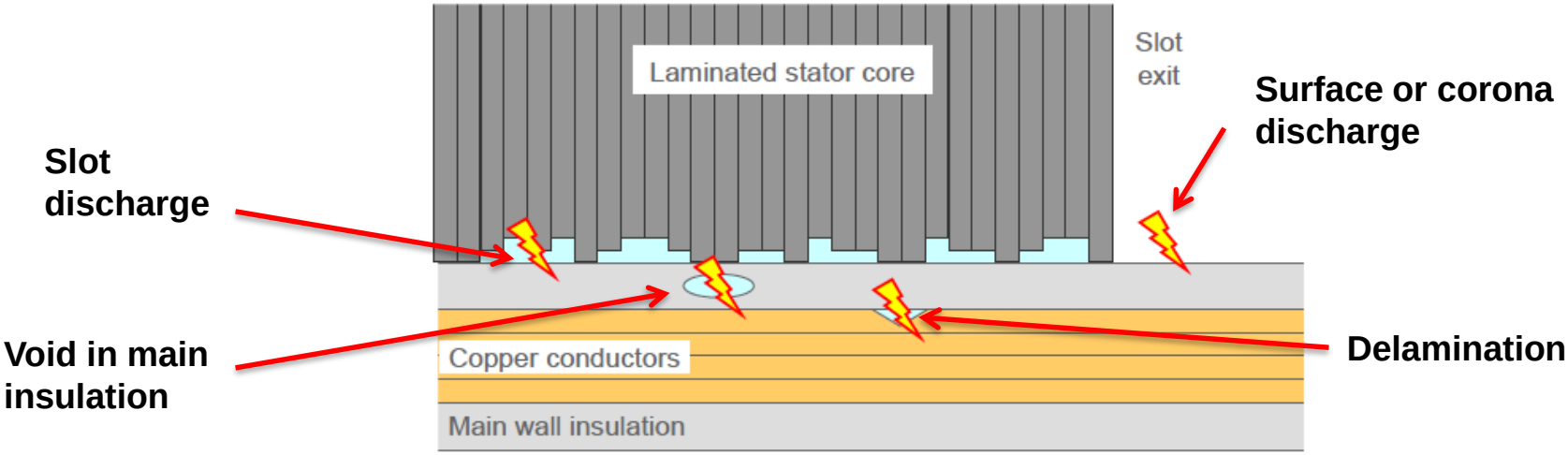


Busbar Expansion Joint and Support

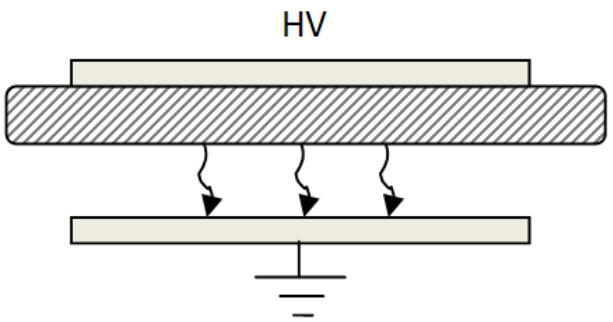
Cavity Discharge



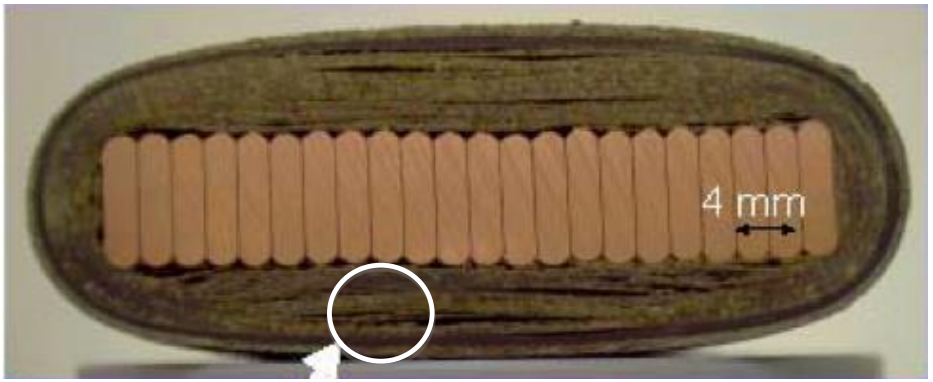
Cavity Discharge



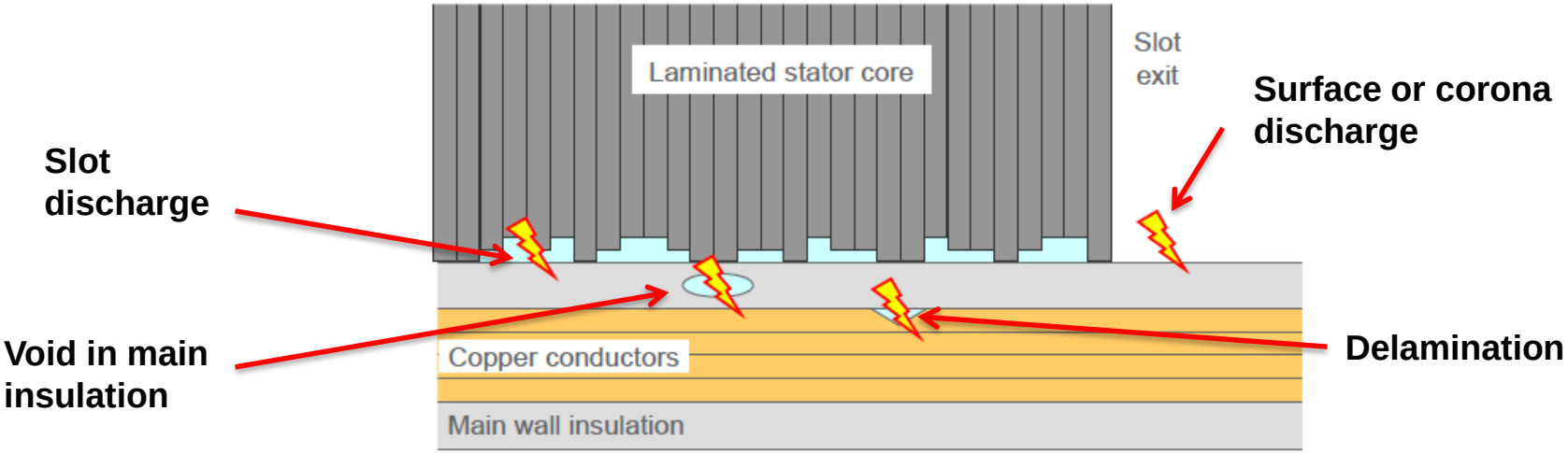
Lamination Discharge



Lamination Discharge



Insulation Delamination



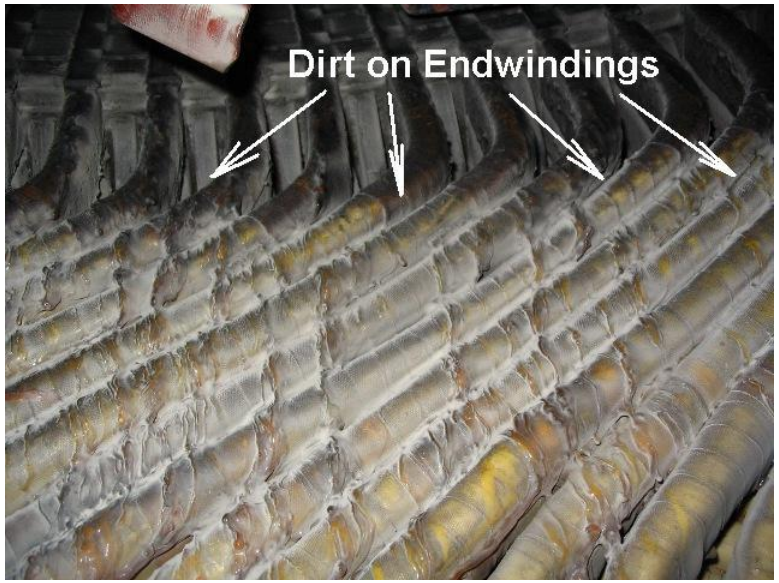
What Does PD Depend On?

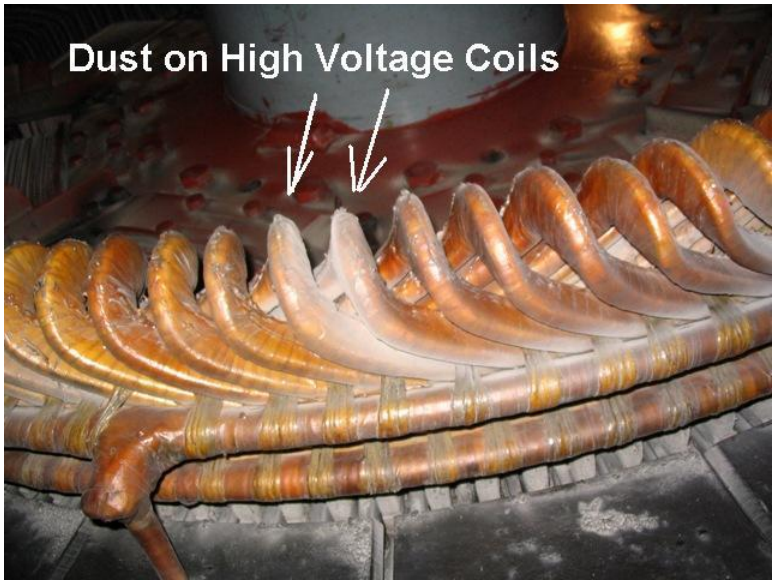
- PD can exist for months to years before failure.
- PD depends on for example:
  - electrical field stress
  - shape/size/deterioration level of fault condition
  - environment conditions - temp and humidity
  - load/current
  - mechanical vibration
- Important to have early stage detection of PD – onset of risk.
- PD can be trended to monitor transitions in level and severity of degradation – escalation of risk.

Sources of Partial Discharge in Motors and Generators

- Loose stator bar, stator bar vibration
- Phase-to-earth discharges in the slot section
- Damaged HV conductors
- Surface degradation (e.g. at the end windings)
- Corona ring stress relief degradation
- Phase-to-phase discharges at the end windings
- Delamination of mica-based insulation
- Voids in resin/VPI insulation
- PD in the accessories (e.g. CT / VT / cable terminations)

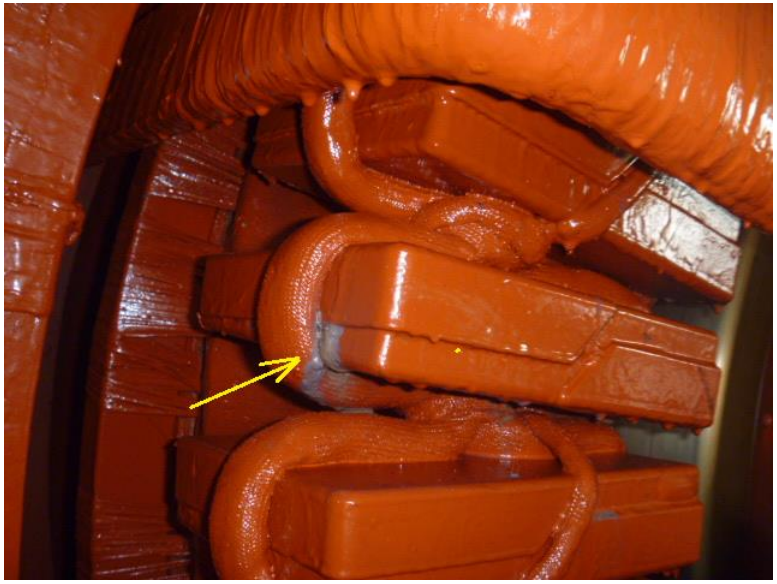
Example 1- Endwinding Contamination





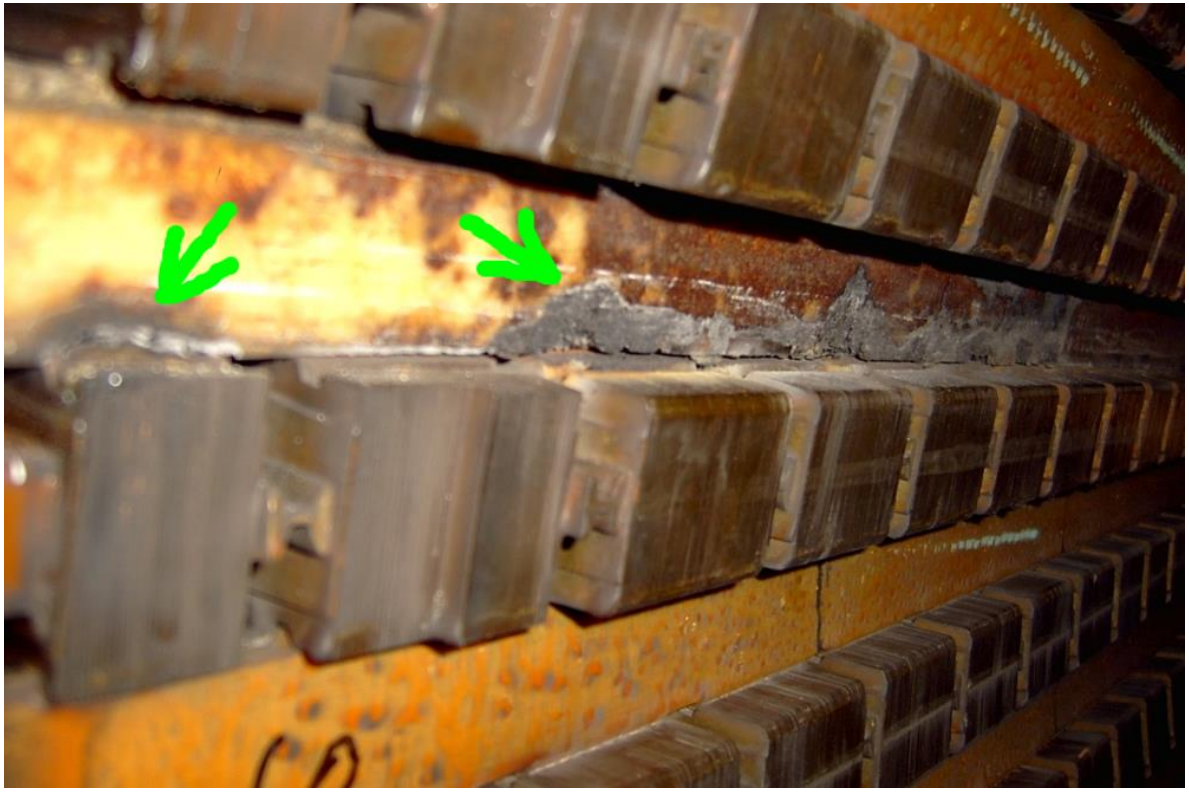
Courtesy of Doble Engineering Company

Example 2 – Loose Endwinding



Courtesy of Doble Engineering Company

Example 3 – Groundwall Discharge



Courtesy of Doble Engineering Company

Sensors used in Measuring PD

High Voltage Coupling Capacitor (HVCC)

- 80 pF / 500 pF / 1 nF rating
- High sensitivity (when installed in the machine's cable terminal box).
- The higher the capacitance, the better lower frequency response (to sub-10 MHz)
- to enable detection of PD deep into the HV windings.

High Frequency Current Transformers (HFCT)

- Available in a range of sizes to fit most confined spaces.
- Ex/Atex-certified, saturation currents of up to 1000 A.
- **High sensitivity at low frequencies** and capable of detecting PD in the machine **remotely** with the sensor installed at the switchgear.

Rogowski Coil Sensors (RC)

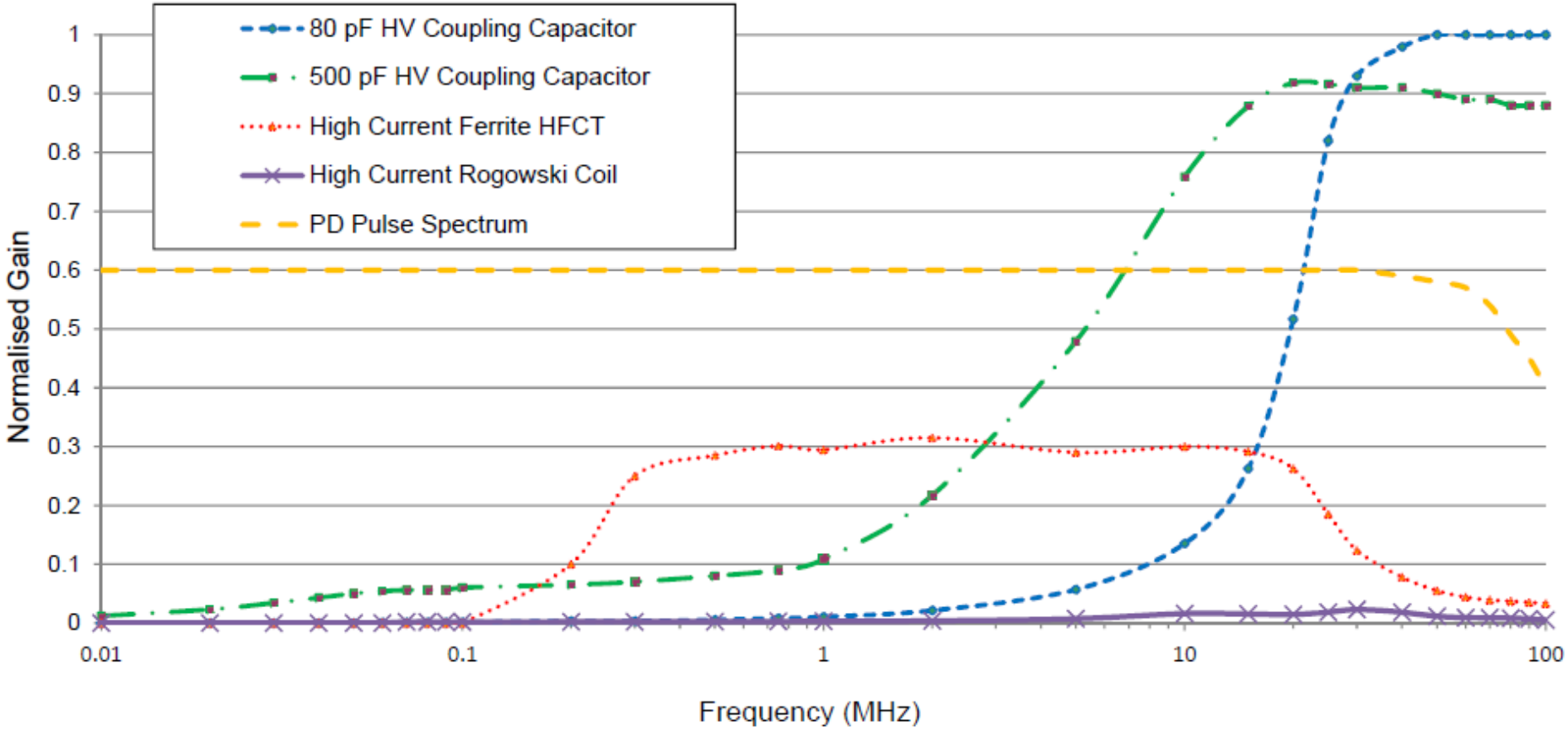
- Does not saturate with high current (>5000 A).
- Ex/Atex-certified (for use in hazardous gas zones).
- **Very low sensitivity** and thus does not detect low levels of PD i.e. only significant PD activity

Sensors used in Measuring PD

Sensor	PD Sensor Options		
	Picture	Coupling Method	Relative Sensitivity at 10MHz
High Voltage Coupling Capacitor		Capacitive	100
Ferrite-cored High Frequency Current Transformer		Inductive	30
Transient Earth Voltage		Capacitive	5
Rogowski Coil		Inductive	1

Relative Sensitivity at 10 MHz of the 4 types of OLPD sensor

Bandwidth of Sensors



Placement of PD Sensors

The choice of PD sensor depends on:

- The rating of the machine
- The size of the cable box
- Whether it is bus-fed (HVCC) or cable fed (HFCT)

Providing Alerts on Winding Condition using OLPD

Reference	Comments	PD Monitor Trend	Condition
GT2	Slot/End-Winding PD Local Switchgear PD	Increasing PD	Unreliable
WATER INJECTION PUMP 2	End-Winding PD	Increasing PD	Unreliable
HP COMPRESSOR 2	End-Winding PD Local Switchgear PD	Increasing PD	Unreliable
AMINE PUMP	Slot Section PD	Increasing PD	Probable Inspection
HP COMPRESSOR 1	Slot/End-Winding PD	Increasing PD	Probable Inspection
TRANSFER PUMP	Slot/End-Winding PD	Stable PD	Probable Inspection
LP COMPRESSOR 1	Slot Section PD	Stable PD	Acceptable
GT1	Slot/End-Winding PD	Increasing PD	Good
WATER INJECTION PUMP 1	Slot/End-Winding PD	Stable PD	Excellent
LP COMPRESSOR 2	Slot/End-Winding PD	Stable PD	Excellent

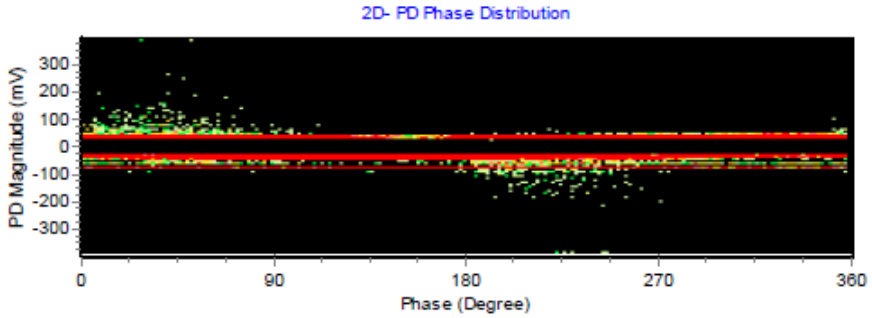
Providing Alerts on Winding Condition using OLPD

The analysis of OLPD test results is based on:

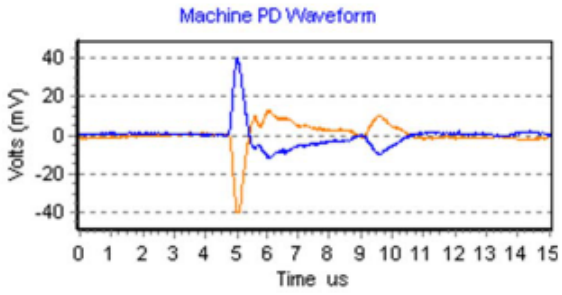
- **PD level trends** – e.g. the PD activity doubling in 12 months is a sign of severe insulation deterioration.

Jan 2009	June 2009	Jan 2010
8 nC	10 nC	17 nC

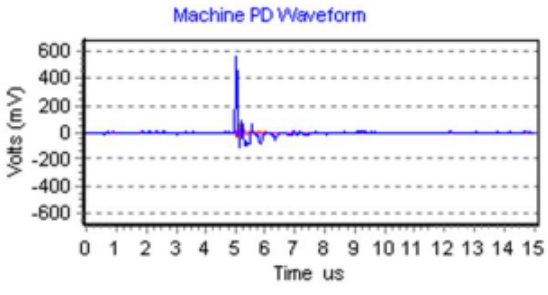
- **Phase Resolved PD (PRPD) patterns** – different defects have different phase patterns across the 50/60 Hz power cycle.



- **PD pulse *'waveshape'*** this can identify both phase-to-phase and phase-to-earth PDs and different PD sites within the machine's stator winding.



Phase-to-Phase PD



Phase-to-Earth PD