Condition Assessment of Rotating Machines (pt1)

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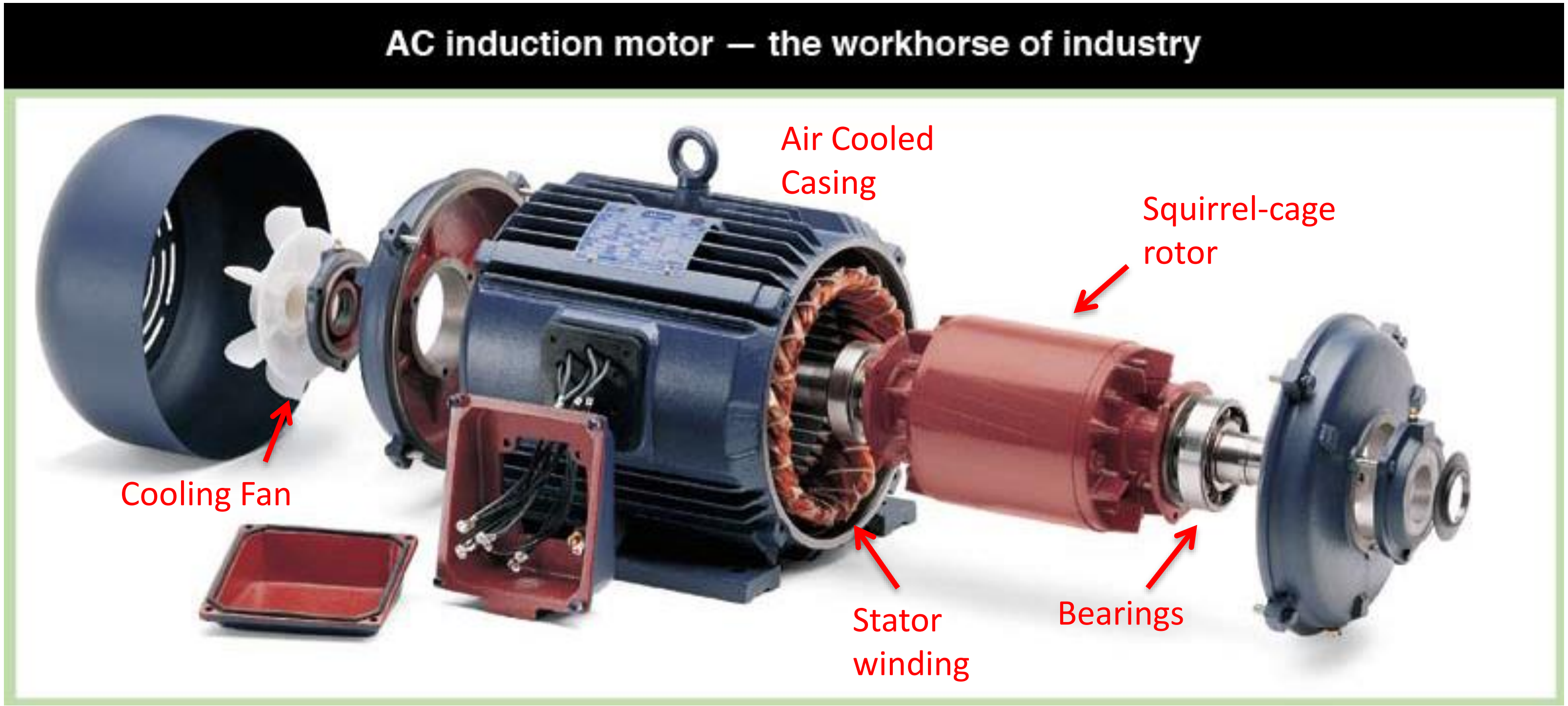
Construction of an Induction Motor



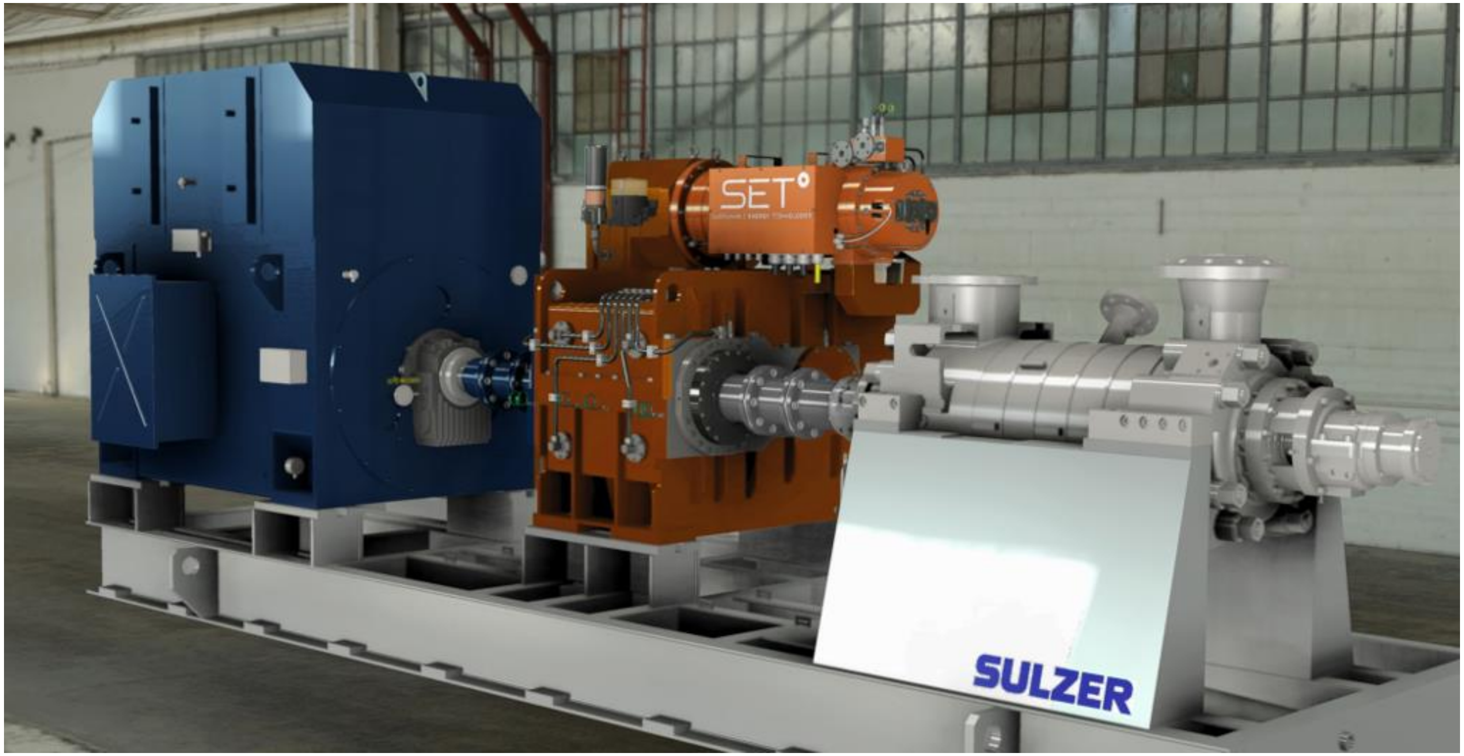
415V, 3-ph, 2 pole, 5kW
squirrel-cage rotor

High Voltage MW - Induction Motor

Water Cooled

11kV, 3-ph, 2 pole, 5MW
squirrel-cage rotor

Boiler Feed Pump - Induction Motor

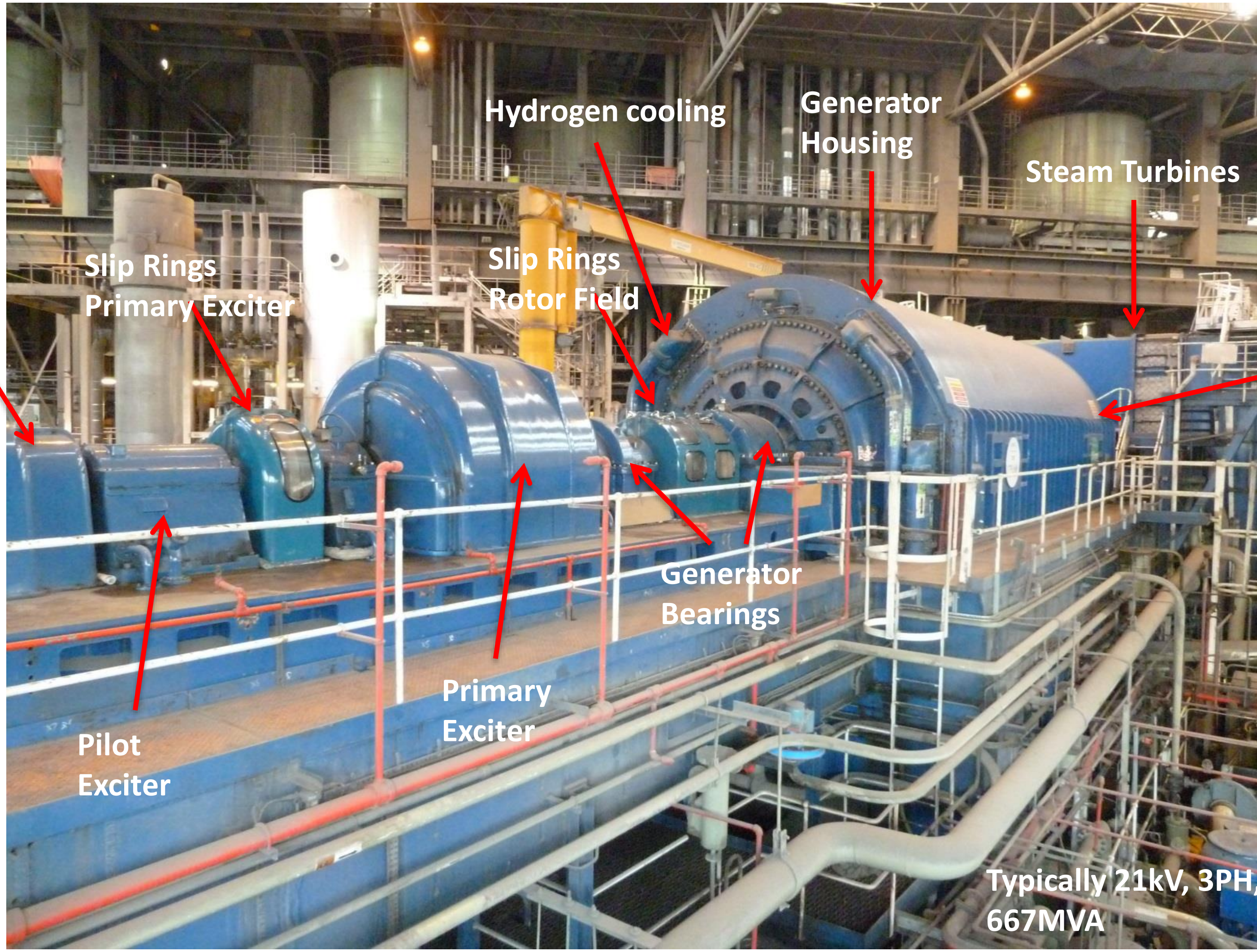


4.1MW
Boiler feed pump

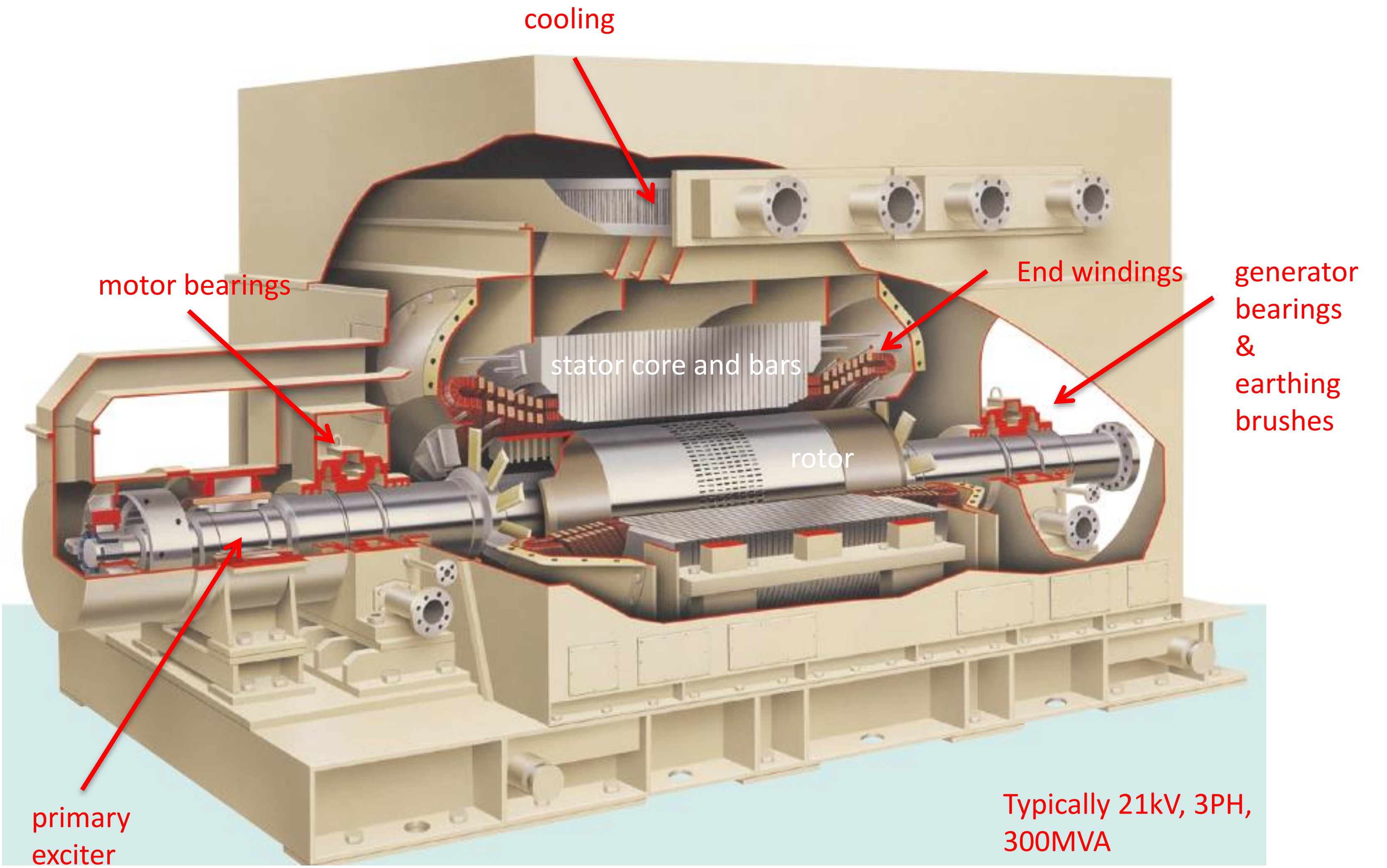
Forced Draft Fan - Induction Motor

2,375 kW / 10 pole / 11 kV / 50 Hz

Synchronous Turbo Generator

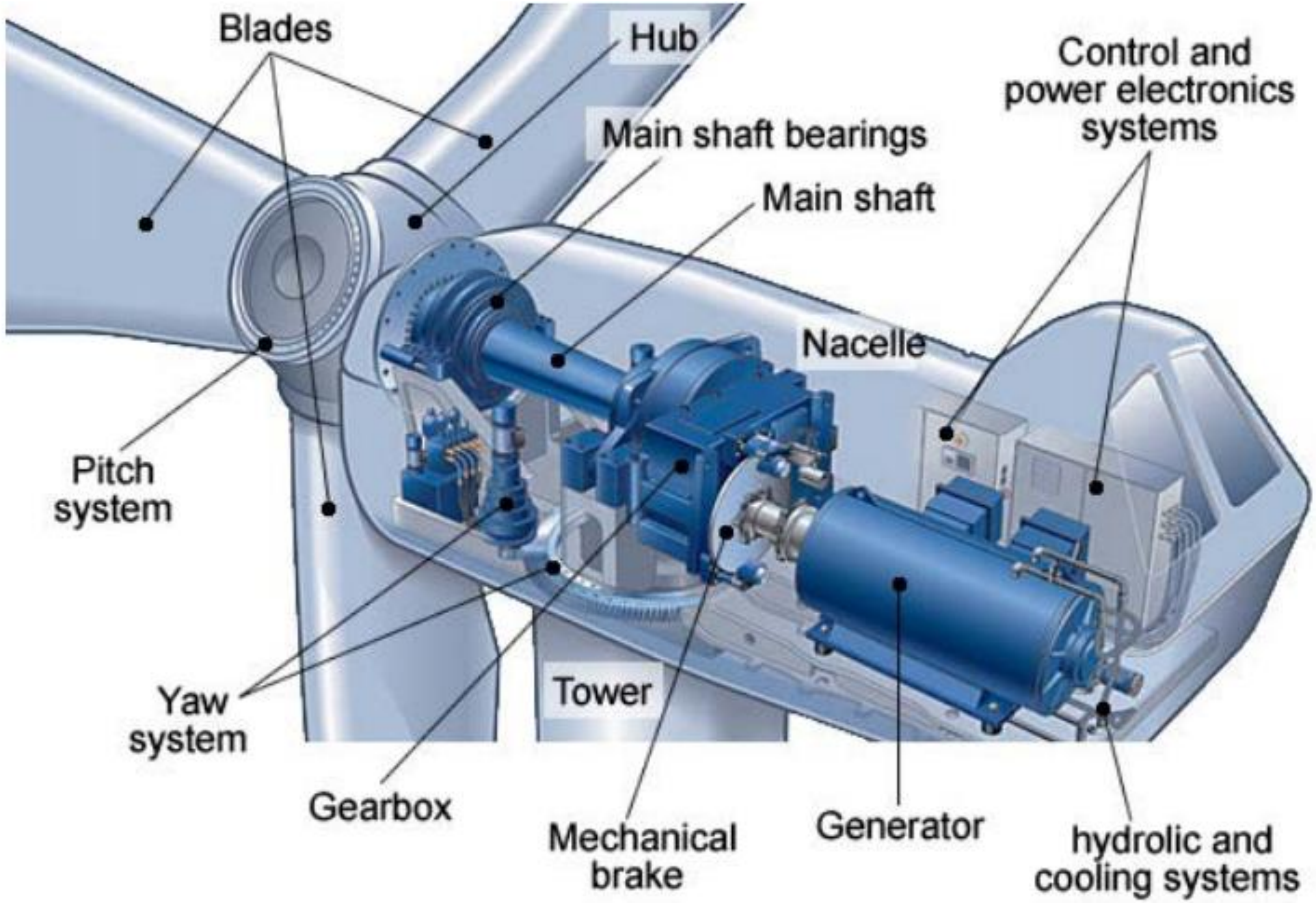


Construction of a Synchronous Turbo Generator



Typically 21kV, 3PH, 300MVA

Nacelle of a Wind Turbine



Condition Based Maintenance (CBM)

- ***High Voltage Rotating Machines***, are prone to breakdowns and failures caused by ***both*** *electrical* ***and*** *mechanical 'wear and tear'.*

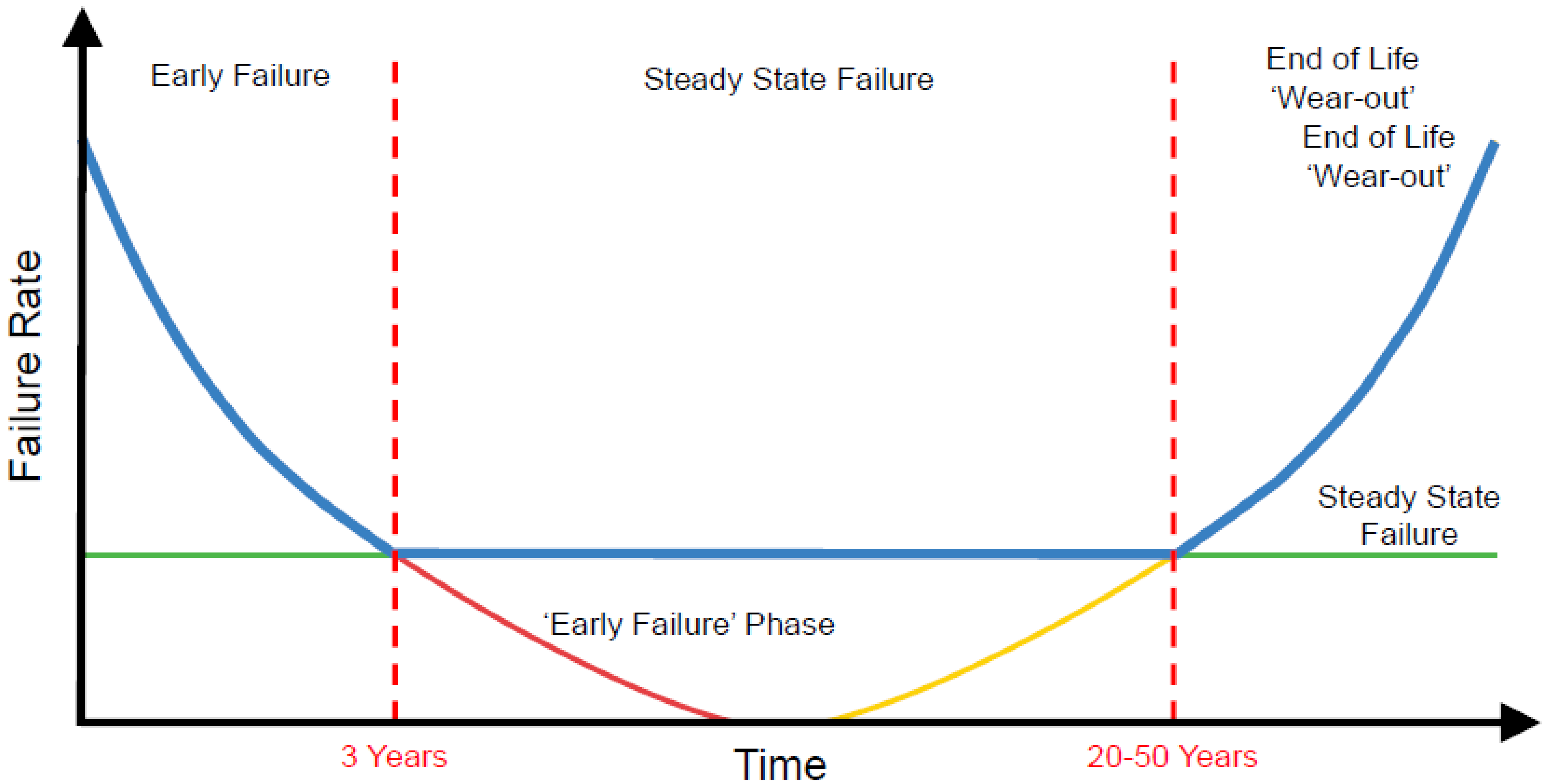
- Breakdowns and failures of the rotating HV machines are therefore inevitable with time in service, it is just a matter of time!

- Many of the breakdowns can be avoided through the implementation of ***Condition-Based Management (CBM)*** using ***condition monitoring (CM)*** technology to support preventative maintenance interventions.

- It is through the detection of ***'incipient' failure mechanisms*** and developing faults before they occur (using CM assessment and trending) that in-service failures and unplanned outages can be avoided.

- To provide a complete 'picture' of the health of a rotating HV machine it is therefore necessary to apply a ***combination of both electrical and mechanical CM technologies.***

Condition Based Maintenance (CBM)



'Bath Tub' Curve describing the statistics of asset failure

Condition Based Maintenance (CBM)

THERMAL

Loading / duty cycle thermo-mechanical effects and variations.

ELECTRICAL

Localised electrical stresses at the end windings and voids or delaminations in groundwall insulation.

AMBIENT

Temperature and relative humidity, surface discharges can occur with high humidity.

MECHANICAL

Wedge tightness, rotor alignment/concentricity, vibration effects, short-circuit fault forces.

To take into account these variable stresses, ***continuous* electrical and mechanical condition monitoring (CM)** of rotating HV machines is now becoming more widely applied in all sectors of industry.

Condition Based Maintenance (CBM)

Time-Based Maintenance and Replacement

- The oldest is in the worst condition? What is the rotating HV machines' historical service record, total hours of service and maintenance history?

Reactive Maintenance

- Assess similar/nearby plant only after a failure.

Condition-Based Maintenance (CBM)

- Assess the health of plant routinely and/or continuously and then perform maintenance only on plant in the worst condition (e.g. the 'worst 5%').

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Goals of Condition Based Maintenance (CBM)

- Prevent in service failure.
- Focus maintenance on equipment as needed when deterioration is indicated.
- Identify where maintenance is not needed.
- Not over maintain and waste resources.

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There are two common methods used for condition monitoring

- **Trend monitoring:** Trend monitoring is the continuous, regular measurement and interpretation of data. It involves choosing a suitable and measurable indication of machine or component deterioration and studying this trend to figure out when deterioration goes over a critical limit.

For example, trend monitoring is used for routinely tracking airplane engine data to detect and diagnose abnormalities in engine performance, hopefully preventing secondary, more costly damage.

Condition Based Maintenance (CBM)

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There are two common methods used for condition monitoring

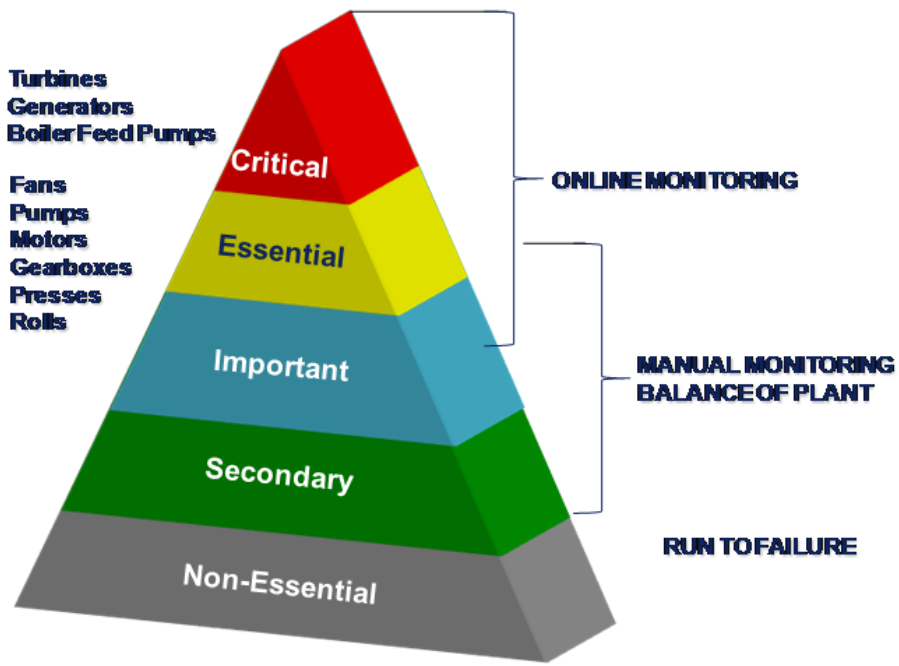
- **Condition checking:** Condition checking involves taking a periodic check measurement with an appropriate indicator while a machine is running. The information from this method is then used to measure the condition of the machine at a given time.

An example of condition checking could be using an oil sight glass like a condition monitoring pod (CMP) to check the condition of a machine's lubricant in real time.

Downsides of Condition Monitoring

- Condition monitoring systems rely on visual data gathered from multiple sensors integrated with a software system.
- This means an added cost of purchasing and installing these sensors, as well as purchasing the tools necessary for condition monitoring
- There's also the added cost of training employees to use condition monitoring technology accurately and effectively.
- Additionally, condition monitoring sensors might have trouble working properly under especially harsh operating conditions. Such conditions can damage sensors, forcing you to replace them on a more regular basis than anticipated.

Asset Criticality Ranking



- In general, rotating assets can be thought of in terms of their criticality to keep the process running and productive.
- The asset pyramid shows the typical criticality distribution of rotating assets in any plant. Usually only the *critical*, *essential*, and more expensive *important* assets are considered for online monitoring.
- Whereas less critical assets would be subject to *surveillance* monitoring at appropriate intervals.
- One important way to discriminate between *critical* and *non-critical* assets is to use *downtime cost* as a discriminator.

Asset Criticality Ranking

Criticality Ranking of Induction Motors

		Downtime Costs	
		Low	**High**
Rated Voltage	**< 11kV**		
	≥ 11kV		

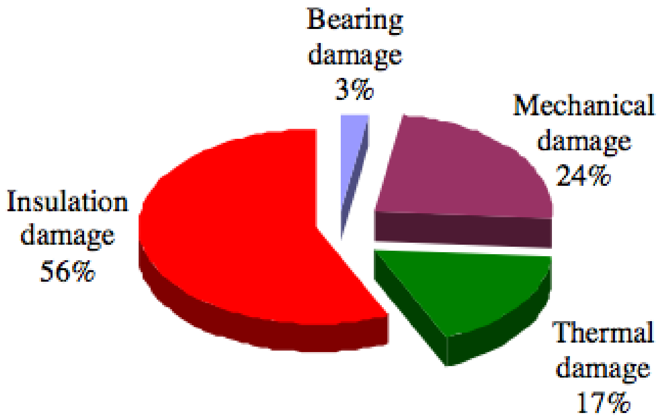
Fault Categories of Rotating Machines

Faults in induction motors can be categorized as follows:

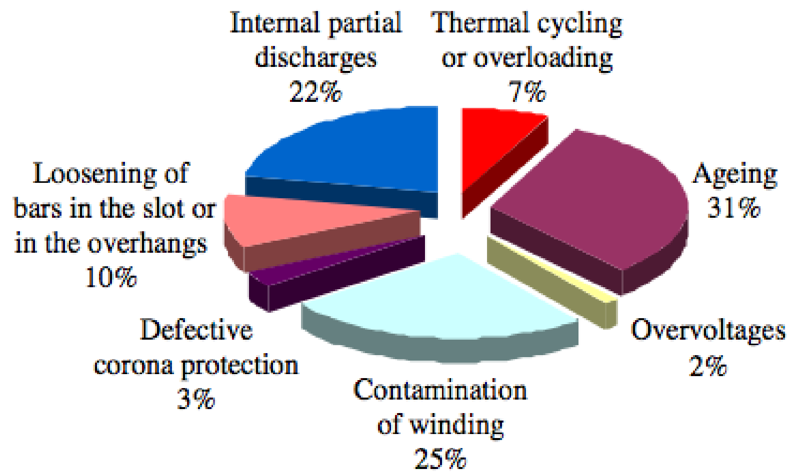
a. **Electrical-related faults**: Faults under this classification are unbalanced supply voltage or current, single phasing, under or over voltage of current, reverse phase sequence, earth fault, overload, inter-turn short-circuit fault, and crawling.
b. **Mechanical-related faults**: Faults under this classification are broken rotor bars, mass unbalance, air gap eccentricity, bearing damage, rotor winding failure, and stator winding failure.
c. **Environmental-related faults**: Ambient temperature as well as external moisture will affect the performance of induction motor. Vibrations of machine, due to any reason such as installation defect, foundation defect, etc., also will affect the performance.

Failure Statistics for Generators?

- Operators are not just concerned with the stator insulation system but the overall system.
- A Cigre report[1] of 1199 hydrogenerators indicated that 56% of failed machines showed insulation damage, other major types being mechanical, thermal and bearing damage.



Damage to Hydrogenerators

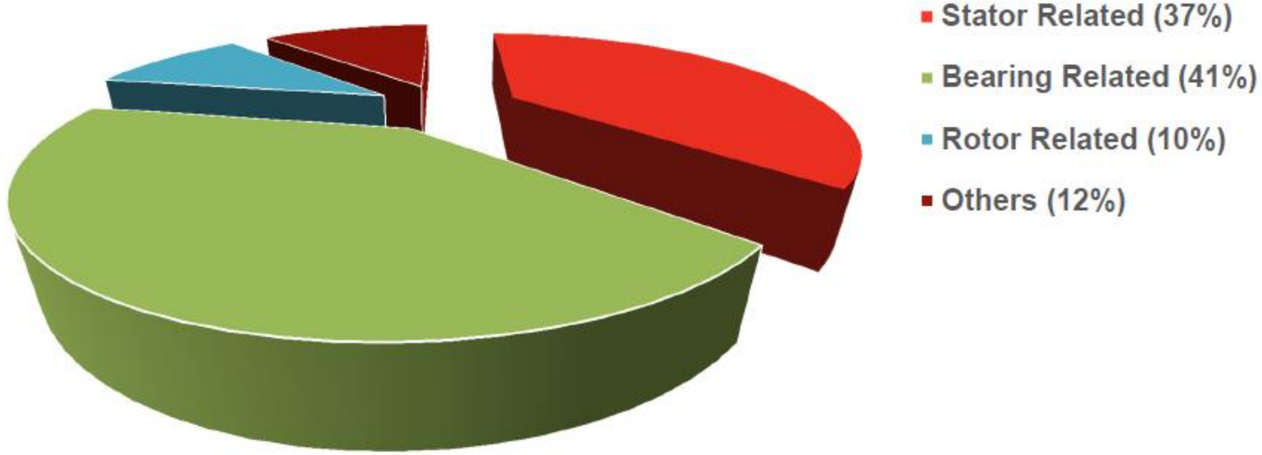


Root cause of insulation damage

[1] CIGRE study committee SC11, EG11.02 "Hydrogenerator Failures – Results of the Survey", (2003)

Failure Statistics for Induction Motors?

- 41% of failures occur due to **mechanical** issues (**vibration or bearings**)
- **37% of failures** are electrical, from **high voltage stator winding failures**
- 10% are **rotor-related** failures
- These three causes cover around **90% of all HV motor failures**.



Damage to Induction Motors

Most Common Faults in Induction Motors

Bearing Faults: can be caused by incorrect lubrication, mechanical stresses, incorrect assembling, drive shaft misalignment, etc. They can affect all the bearing parts such as inner and outer races, cage and balls or rolls.

Stator Winding: normally a consequence of overheating, contamination, shorted turns, shorted coils (same phase), phase to phase or coil to ground. Such failures cause stator electrical imbalance as well as variations in the current harmonic content eventually leading to catastrophic failure.

Rotor faults: usually caused by broken bars or broken end rings, rotor misalignment and imbalance.

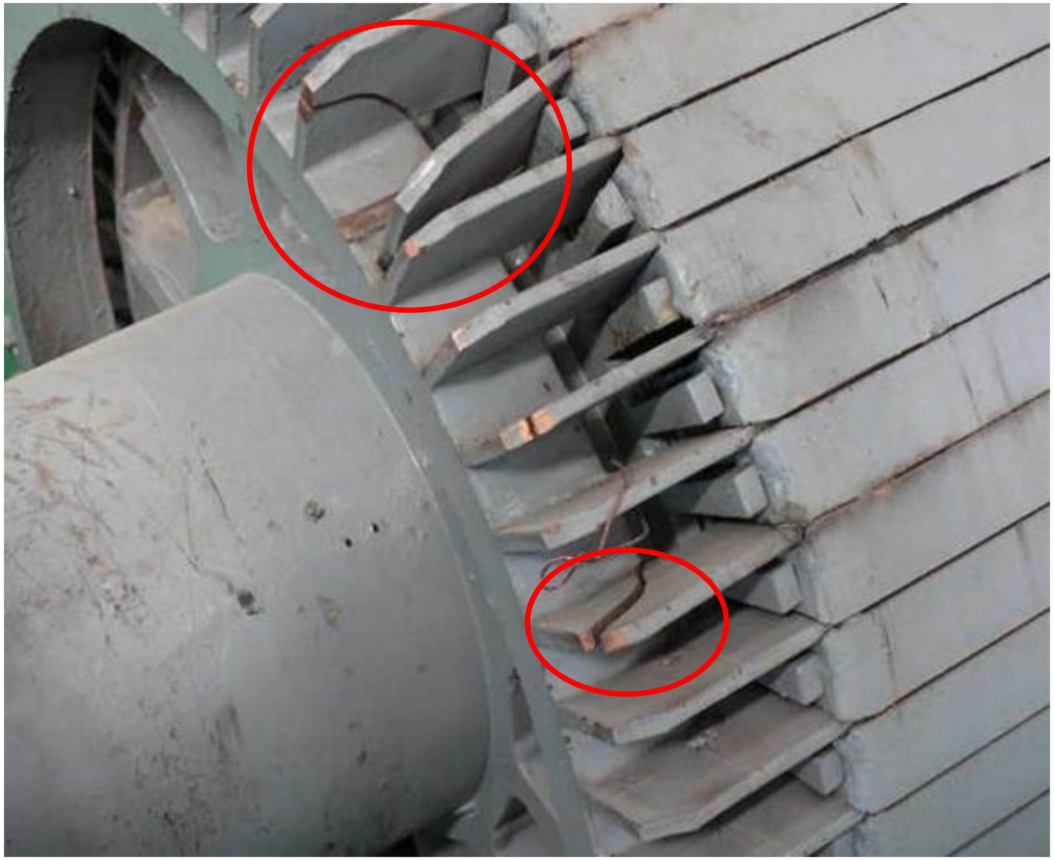
Broken Rotor Bars

The squirrel cage of an induction motor consists of rotor bars and end rings. If one or more of the bars is partially cracked or completely broken, then the motor is said to have broken bar fault.

Causes of Broken Rotor Bars

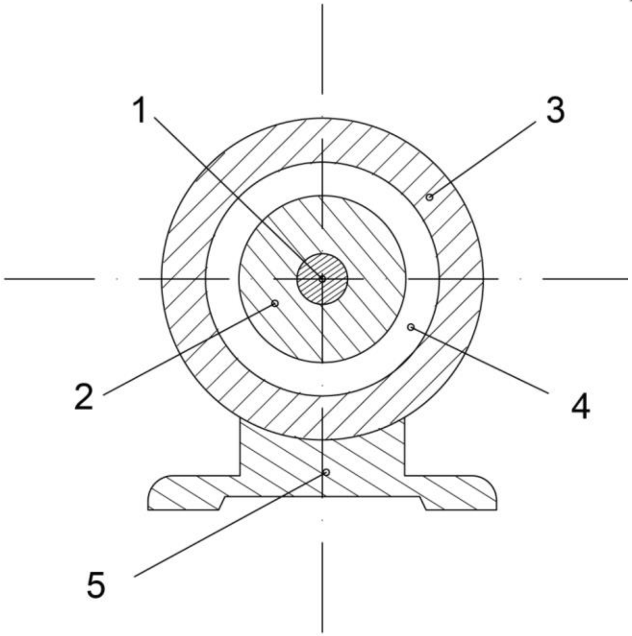
The main causes of rotor broken bar of an induction motor :

- manufacturing defects
- thermal stresses
- mechanical stress caused by bearing faults
- frequent starts of the motor at rated voltage
- due to fatigue of metal of the rotor bar.

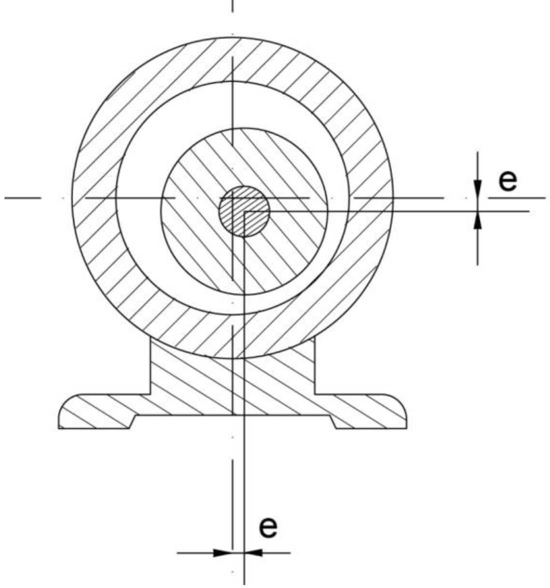


Rotor Mass Unbalance

In a healthy motor, the rotor is centrally aligned with the stator and the axis of rotation of the rotor is the same as the geometrical axis of the stator. This results in identical air gap between the outer surface of the rotor and the inner surface of the stator.



However, if the rotor is not centrally aligned or its axis of rotation is not the same as the geometrical axis of the stator, then the air gap will not be identical and the situation is referred as air-gap eccentricity. Air-gap eccentricity is common in rotor faults in an induction motor.

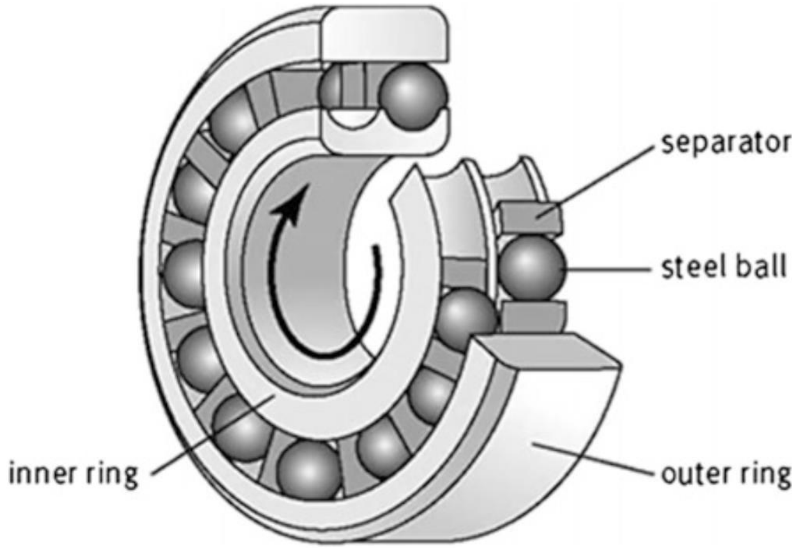


Air-Gap Eccentricity

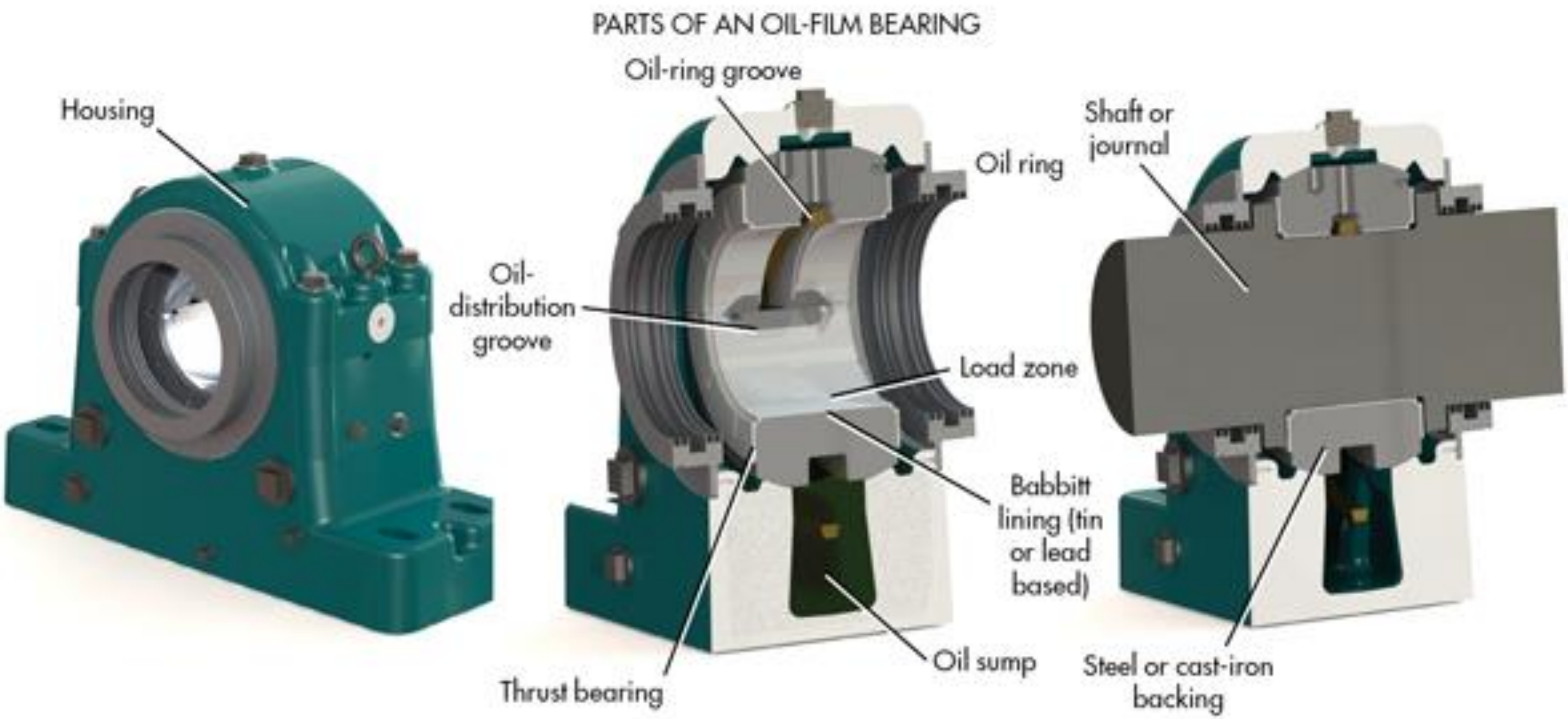
- ❑ Air-gap eccentricity may occur due to any of the rotor faults:
  - Rotor mass unbalance fault
  - Bowed rotor fault, etc.
- ❑ Due to air-gap eccentricity, electromagnetic pull will be unbalanced.
  - The rotor side where the air gap is minimum will experience greater pull, and
  - the opposite side will experience lower pull and as a result rotor will tend to move in the greater pull direction across that gap.
- ❑ In severe cases the rotor may rub the stator which may result in damage to the rotor and/or stator.
- ❑ Air-gap eccentricity can also cause noise and/or vibration.

Bearings

- Bearings are placed at both the ends of the rotor of an induction motor to support the rotating shaft.
- Each bearing consists of an inner and an outer ring called races and a set of rolling elements called balls in between these two races.
- Normally, in case of motors, the inner race is attached to the shaft and the load is transmitted through the rotating balls—this decreases the friction. Using lubricant (oil or grease) in between the races friction is further decreased.



Oil Film Bearings



Oil Film Bearings are bearings in which the load is supported by a thin layer of rapidly moving pressurized liquid or gas between the bearing surfaces

Fluid bearings can catastrophically seize under shock situations.

Oil Film Bearings

Oil film formation

Bearing failure due to oil starvation

Causes and Effects of Bearing Failure

1. **Excessive loads, tight fits, and excessive temperature rise**. All of these can anneal the two races and ball materials. They can also degrade, even destroy, the lubricant.

2. **Fatigue failure**: this is due to long run of the bearings. It causes fracture and subsequently removal of small discrete particles of materials from the surfaces of races or balls. This type of bearing failure is progressive. For this bearing failure, vibration and noise level of motor will increase.

3. **Corrosion**: this results if bearings are exposed to corrosive fluids (acids, etc.) or corrosive atmosphere. If lubricants deteriorate or the bearings are handled carelessly during installation, then also corrosion of bearings may take place.

Causes and Effects of Bearing Failure

4. **Contamination**: it is one of the leading factors of bearing failure. Lubricants get contaminated by dirt and other foreign particles which are most often present in industrial environment. High vibration and wear are the effects of contamination.

5. **Lubricant failure**: for restricted flow of lubricant or excessive temperature this takes place. It degrades the property of the lubricant for which excessive wear of balls and races takes place which results in overheating.

6. **Misalignment of bearings**: for this, wear in the surfaces of balls and races takes place which results in rise in temperature of the bearings.

All of which causes rise in temperature of the bearings and increase in vibration of the concerned machine.

For this, bearing temperature and vibration can provide useful information regarding bearing condition and hence machine health .

Construction of Stator Winding

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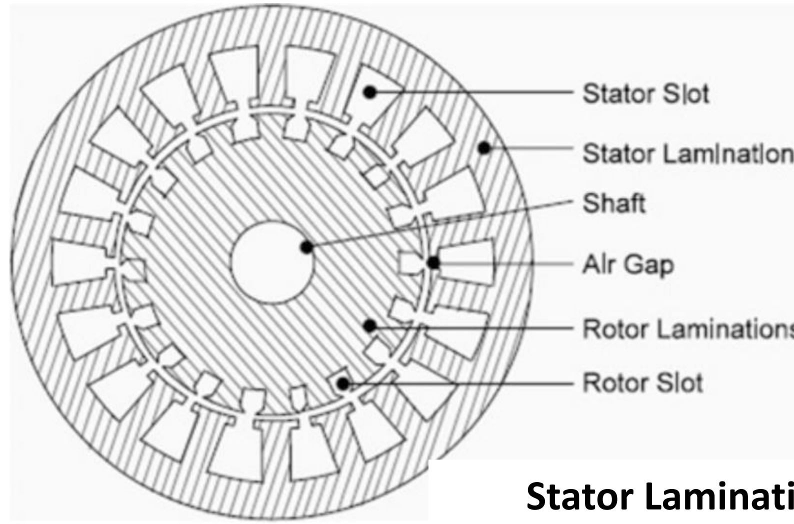
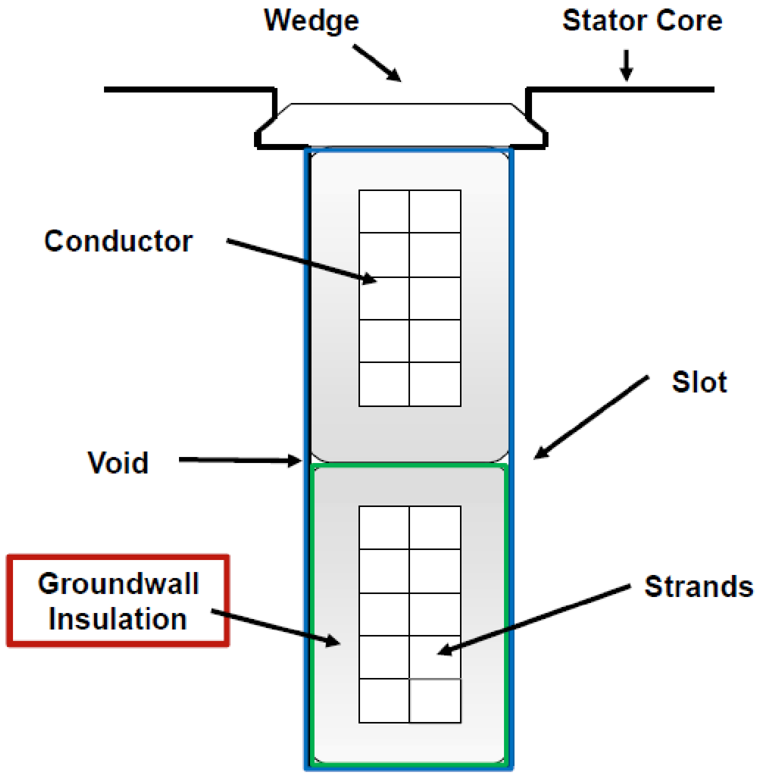
Stator Winding

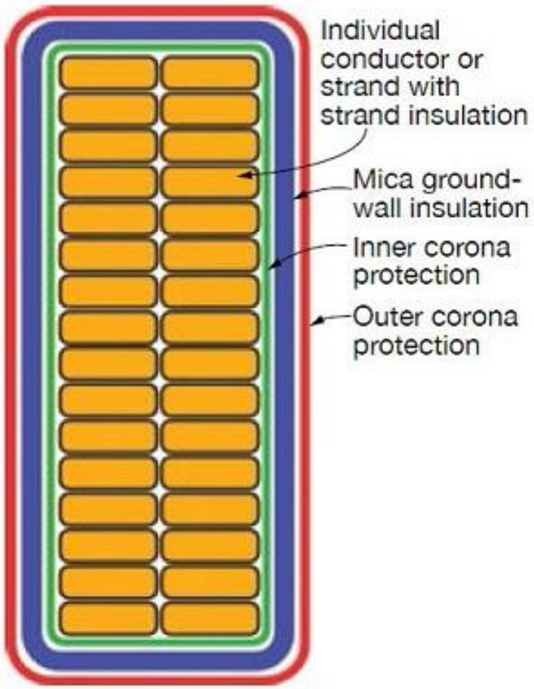


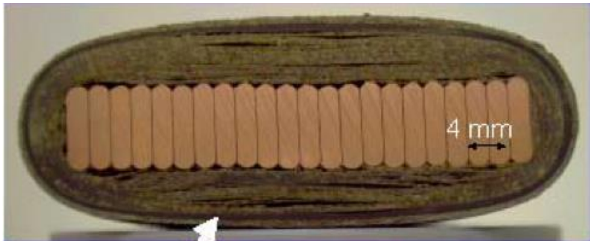
Stator Laminations

Stator Winding Construction

Stator Bar Cross Section







Stator Faults

The stator of an induction motor is subjected to various stresses such as mechanical, electrical, thermal, and environmental.

Depending upon the severity of these stresses stator faults may occur.

The stator faults can be classified as:

(i) faults in laminations and frame of the stator, and
(ii) faults in stator winding.

Out of these the second one is the most common stator fault.

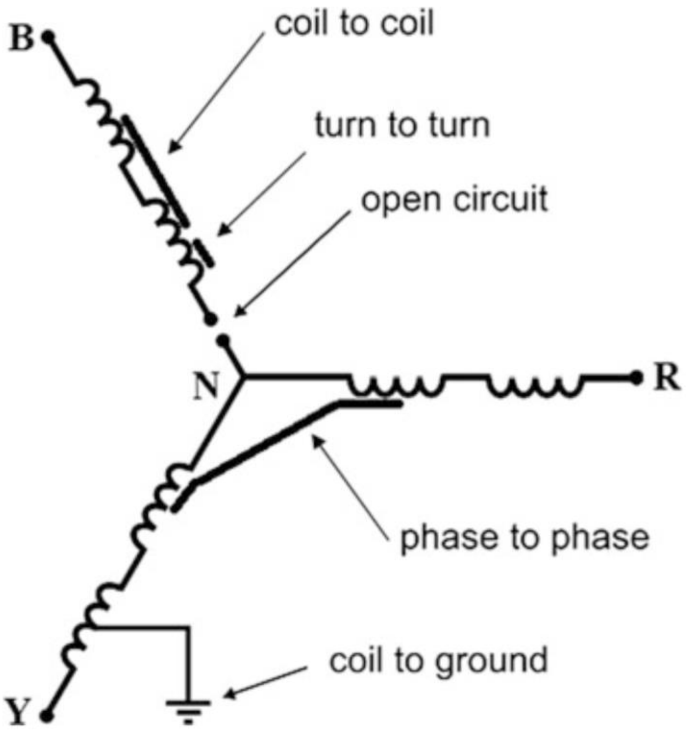
Stator Winding of MW HV Induction Motor

Stator Faults

These faults are due to failure of insulation of the stator winding.

Different types of stator winding faults are:

- ❖ short circuit between two turns of same phase—called turn-to-turn fault,
- ❖ short circuit between two coils of same phase—called coil to coil fault,
- ❖ short circuit between turns of two phases—called phase to phase fault,
- ❖ short circuit between turns of all three phases,
- ❖ short circuit between winding conductors and the stator core— called coil to ground fault, and
- ❖ open-circuit fault when winding has a break or high impedance connection.



Causes and Effects

Mechanical Stresses - these are due to movement of stator coil and rotor striking the stator.

- Coil movement which is due to the stator current (as force is proportional to the square of the current) may loosen the top sticks and also may cause damage to the copper conductor and its insulation.
- Rotor may strike the stator due to rotor-to-stator misalignment or due to shaft deflection or due to bearing failure and if strikes then the striking force will cause the stator laminations to puncture the coil insulation resulting coil to ground fault.
- High mechanical vibration may disconnect the stator winding producing the open-circuit fault.

Causes and Effects

Thermal stresses - these are mainly due to thermal overloading and are the main reason, among the other possible causes, for deterioration of the insulation of the stator winding.

- Thermal stress happens due to over current flowing due to sustained overload or fault, higher ambient temperature, obstructed ventilation, unbalanced supply voltage, etc.
- The thumb rule, in this regard, states that for every 10 °C increase in temperature above the stator winding temperature limit, the insulation life is reduced by 50 %.

Ambient in °C	Insulation life in hours
30	250,000
40	125,000
50	60,000
60	30,000

Causes and Effects

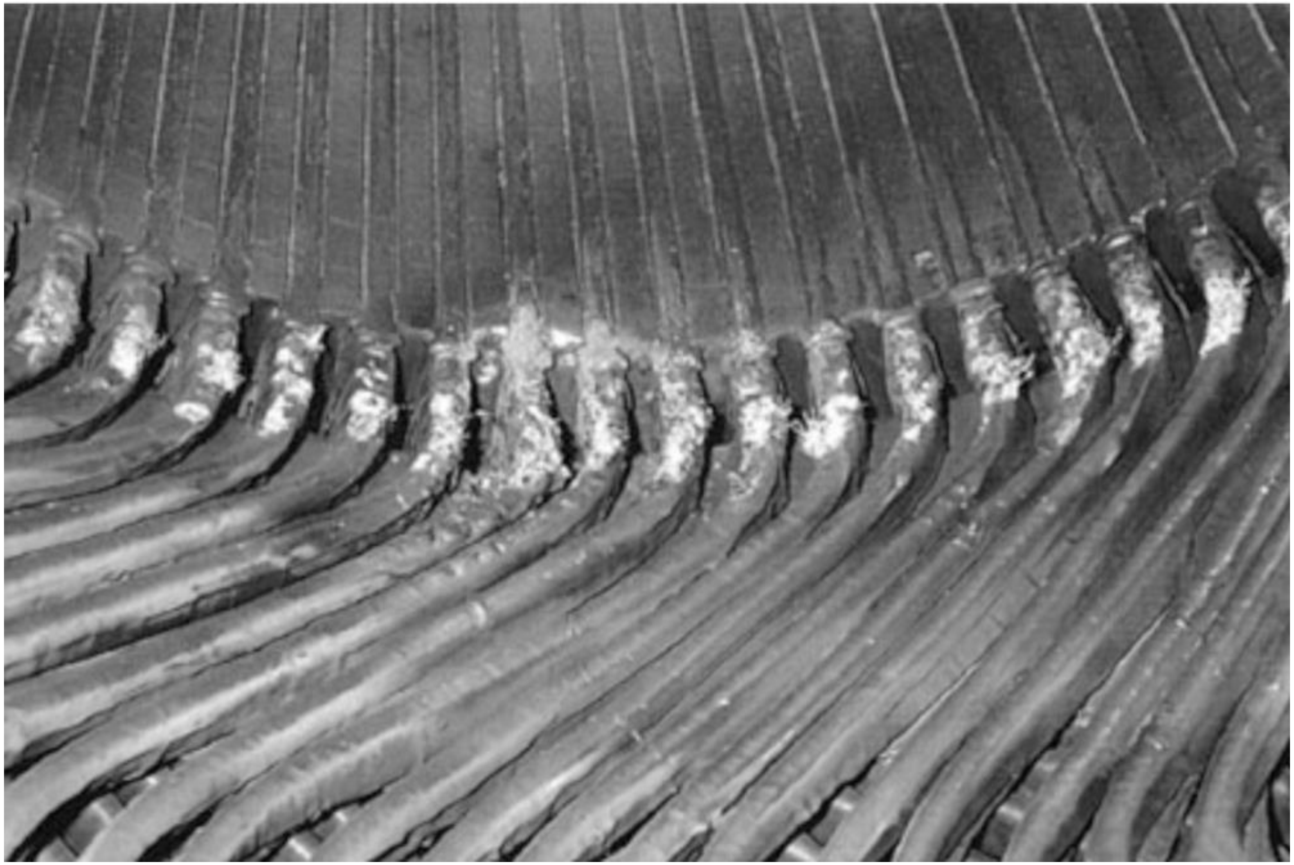
Electrical Stresses - these are mainly due to the supply voltage transient.

- These transient arises due to different faults (like line-to-line, line-to-ground, or three-phase fault), due to lightning, opening, or closing of circuit breakers or due to variable frequency drives.
- These transient voltages reduces life of stator winding and in severe case may cause turn-to-turn or turn-to-ground fault.

Environmental stresses - these stresses may arise if the motor operates in a hostile environment with too hot or too cold or too humid.

- Humid conditions and/or the presence of foreign material can contaminate the insulation of stator winding, and
- May reduce the rate of heat dissipation from the motor, resulting in a reduction in insulation life.

Causes and Effects



Stator End Winding Damage Resulting from Surface Discharge resulting from deposits on the End Winding