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Egyptian program for promoting Industrial Motor Efficiency
SAVE TODAY ... POWER TOMORROW

Motor Rewinding Guideline and Repair Facility Work Instructions

May 2022

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UNIDO	United Nations Industrial Development Organization
DE	Drive End
EASA	Electrical Apparatus Service Association
IEEE	Institute of Electrical and Electronics Engineers
IEEESA	The IEEE Standards Association
MLT	Mean Length of Turn
NFAP	National Foundation for American Policy
ODE	Opposite Drive End
OSHA	Occupational Safety and Health Administration
PD	Partial Discharge
RMS	Root Mean Square
RTD	Resistance Temperature Detectors
VPI	Vacuum Pressure Impregnation
WD	Wave Difference

Acknowledgment

This guideline comes as part of the “Egyptian Programme for Promoting Industrial Motor Efficiency” by UNIDO focusing on improving the efficiency of Electric Motor Driven Systems (EMDS) and accelerating the market penetration of energy efficient motors in the industrial sector.

This guideline is developed by *Chemonics Egypt Consultants*, the main consultant of the UNIDO for the assignment of “Recommendation and development of operational policy tools, action plans and guidelines to promote the deployment of energy efficient motor driven systems in Egypt”. The guideline is one of the activities to support rewinding shops in adapting to the changes in the industrial motors market place. The guideline is based on consultant’s experience, literature review, desk research and conducted on-site assessment and interviews with rewinding shops in the Egyptian market. The site visits to rewinding shops included diverse types of rewinding facilities to determine strengths and weaknesses, as well as good and bad practices from their point of view.

This guideline presents step-by-step inspection, testing and maintenance procedures, with the related safety precautions, for both equipment and personnel. It covers the steps of inspection, disassembly, rewinding, repair/replace, and reassembly with illustrative figures and tables.

1. Introduction & Scope of the Guideline

1.1. Background

Electric motors are a major energy consumer in the industry in addition to other sectors such as water & wastewater and domestic sector. Electric motors, like any other device or equipment, are subject to breakdowns and failures. In that case, end users have mainly two options, either to repair the existing motor or to buy a new motor and scrap the old one.

Rewinding the motors is usually the preferred option by the end user compared to the cost of purchasing a new one, especially when the awareness of the feasibility of replacement versus rewinding is absent. Since the bad practices of rewinding could negatively affect the efficiency of the motor, thus enhancing the rewinding and repairing practices of the motor must comply with the standard specifications. This should ensure that the motors run efficiently after the rewinding process, not less than its original state and avoid loss of motor efficiency, which results in a reduction in the waste energy after re-operating the motor and hence enhancement of production cost. Most motor manufacturers recommend that motors should not be rewound more than twice. For good rewinding practices, the motor can keep its original efficiency. However, in practical cases in the Egyptian market, each rewinding time the motor loses 2-5% of its efficiency. In that case, a feasibility study should be done to compare between the cost of repair versus replacement, including the running cost of energy in both cases and operating hours impact. As a general role, if the cost of rewinding the motor properly (i.e. keeping its original efficiency) exceeds 65% of the cost of replacement by a new energy efficient motor, therefore, the replacement should be more feasible than the rewinding.

For electric motors, most the damages occur to or affect the motor windings. Therefore, the repair process typically involves the removal of the damaged windings, making a new set of windings, and installing the new windings along with other necessary mechanical repairs. The process of repairing an electric motor commonly named motor “rewinding” or “refurbishing”.

All types of electric motors can be repaired upon failure. All types of electric motors share the same major construction features except for special purpose machines. Generally, electric motors have wound stator, and a rotor that is one of several types that can be summarized as the following:

- For DC motors: they have wound rotor
- For AC induction motors (IM): they have either wound rotor or squirrel cage rotor
- For AC synchronous motors: they have wound rotor, permanent magnet or solid rotors with saliency for synchronous reluctance motors

The rewinding process can be carried out on the stator or the rotor (in the case of wound rotor) of an electric machine. Also, the repair process is performed to both low voltage motors and medium voltage motors. They share the same general steps or refurbishing and practices of rewinding. However, there are differences in the accepted values of tests according to the standards. This guideline presents the best practices of motor rewinding in general, and focuses on the ***low voltage, squirrel cage induction motors*** as they are the most commonly encountered type of electric motors in the industry and the other sectors (induction motors represent around 93% of the annual Egyptian market of standalone motors, divided as 53% for three-phase IM and 40% for single phase IM)

1.2. Objectives of this guideline

This guideline comes as part of the “Egyptian Programme for Promoting Industrial Motor Efficiency” by UNIDO focusing on improving the efficiency of Electric Motor Driven Systems (EMDS) and accelerating the market penetration of energy efficient motors in the industrial sector.

This guideline highlights the best practices of motor rewinding and the drawbacks of the bad rewinding practices, focusing on what occurs at the Egyptian market context. It focuses on the three-phase induction motors, the most commonly and widely used in the industrial sector. The guideline is not a replacement of any national or international standards, such as IEEE Standard 1068. On the contrary, it builds on their technical data and highlights the importance of refereeing to the standards for the acceptance values and detailed procedures of teste, for instance.

The guideline is based on best practices for motor repair/rewinding, presented in the Electrical Apparatus Service Association (EASA) guidelines and IEEE Standard 1068™-2015, “IEEE Standard for the Repair and Rewinding of AC Electric Motors in the Petroleum, Chemical and Process Industries”.

2. Motor Repair/Rewinding Procedures

Motor rewinding workshops should follow the best practices in motor repair processes to maintain (and may even improve) the efficiency of the motor. Literature studies showed that improper motor repair processes can reduce motor efficiency around 2-5% for each repair.

The main motor repair processes include the following steps, as shown in Figure 1:

1. Data collection and preliminary inspection
2. Dismantling (Disassembly) the motor
3. Internal inspection
4. Removing the old winding
5. Rewinding the motor
6. Reassembling the motor
7. Final inspection and testing

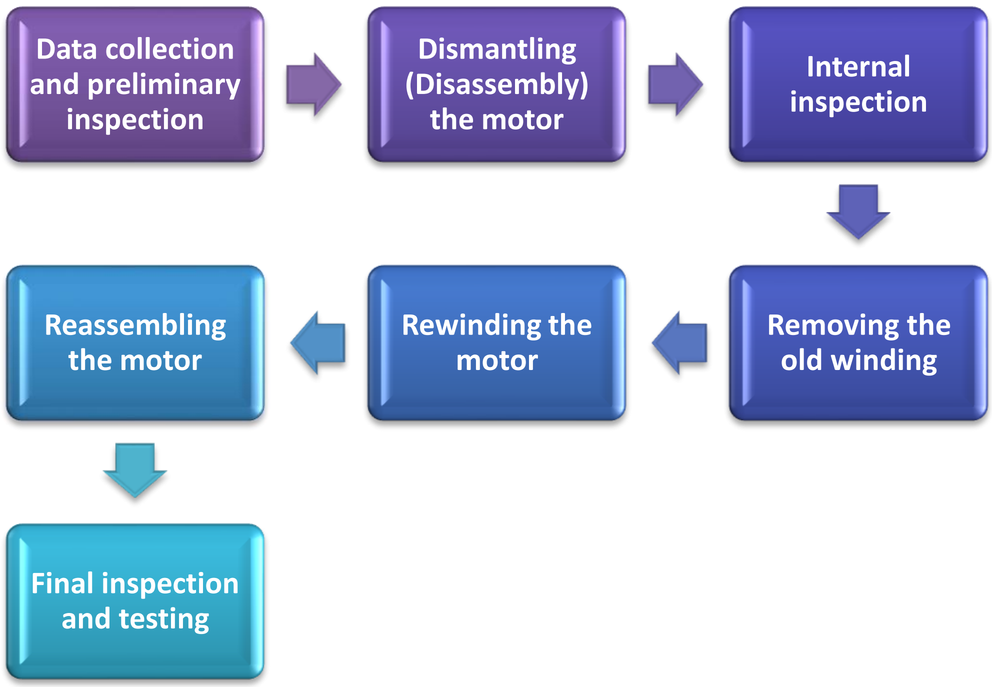


Figure 1: Key steps of motor repair process

The following subsections introduce these processes showing the key activities of each step, best practices to be followed, implementation precautions, as well as the common bad practices to be avoided, illustrating their effect on the motor efficiency.

2.1. Data collection and preliminary inspection

Data collection and preliminary inspection form an important step of the complete motor repair record and may provide indications on the cause of failure. It is important to include all data sources and to be documented. These data shall include nameplate data, external inspections, initial incoming tests and customer (user) input.

2.1.1. Motor nameplate data

Record all nameplate information available. The following data should be obtained:

a) Type of apparatus, such as: horizontal, vertical, partial motor, engine type, etc.
b) Manufacturer and related data, such as motor style, model, type, as well as serial number
c) Rated output, as appropriate
d) Power factor
e) Rated speed
f) Input power; include information for primary and any secondary or field windings as necessary. This shall include voltage(s), frequency, ampere(s), phase sequence, winding connections and starting method.
g) Motor efficiency and efficiency class (either IE1, IE2, IE3 or IE4)
h) Insulation information, including Insulation class, temperature rise, ambient temperature design base
i) Bearing information, such as type, manufacturer and type of used lubricant.
j) Service factor and service duty limits, if any
k) Enclosure type and hazardous (classified) area designation, if any
l) Information available from additional nameplates, such as space heaters and auxiliaries
m) Other information as available from the user

All these data should be recorded and documented, with all other windings and motor design data, on an adequate data card. Sample of data card is presented in Figure 2.

AC Winding Particulars

Customer:

Maker:

Serial No: **Model:** **Enc:**

HP/kW **V** **A** **RPM**

Section	Stator Rotor Existing	New	Checked by
Core Length			
Core Diameter			
No. Slots			
No. Coils			
Turns/Coil			
Sections/Coil			
Size of Conductor			
No. Cond. in //			
Slot Depth			
Tooth Width			
Back Iron Length			
Coil Pitch			
Weight of Coil			
Winding Type			
Slots/Pole/Phase			
Coil Groups			
No. // Circuits			
Connections			
CE Projection			
NCE Projection			
Insulation Class			
Lead Section			

DIAGRAMS OR OTHER DETAILS

PRE-VARNISH TESTS		
WINDING RESISTANCE TO EARTH		
RESISTANCE PER PHASE		
PRESSURE TEST TO EARTH		
PRESSURE BETWEEN PHASES		
STATIC TEST Y Δ TEST VOLTAGE		
amps	amps	amps
POLARITY CHECK		
OTHER TESTS		
DATA TAKEN BY:		
WINDINGS COMPLETED BY:		
CHECKED AND PASSED BY:		
DATE:		

Figure 2: Sample of winding data card for AC polyphase motor[1]

[1] *EASA, Good practice guide to maintain motor efficiency, 2021.*

2.1.2. Customer (user) input

Customers may be able to provide data about the operating condition and load of this motor, as well as the history prior to its fault. Key data that can be provided:

- Operating environment – temperature, vibration, etc.
- Type of driven equipment.
- How many hours/day motor runs.
- Approximate motor load and load cycle.
- How often it is started (i.e. number of starts per day).
- The type of starter used.
- Whether the motor has been rewound before.
- How long the motor has operated since new (or since last rewind).
- Unusual events during its last operations, such as power outage, voltage sag or swell, water damage, problem with driven equipment, etc.

2.1.3. Visual Inspection and Initial Test

Visual inspection may detect some readily observed causes of the fault and issues of the motor. The following procedures can be performed:

- Take photographs of the motor and motor nameplate.
- Inspect windings and adjacent areas for mechanical damage, or discoloured or burned areas visible through access or ventilation openings.
- Rotate the motor shaft by hand, if possible. Check freedom of rotation, absence of rubbing or binding, and excessive end or side play.
- Remove the cover of the terminal box and inspect the leads and the taped lead connections for signs of overheating or mechanical damage. Do not disassemble the taped connections unless there is evidence of damage.
- Check if there are parts missing, damaged or previously replaced/repaired, such as seals, stator cooling ribs, fan, fan cover, terminal box, etc.
- Check cooling air ducts clear/obstructed–may have caused overheating.
- Check shaft discoloured (brown/blue)–sign of rotor overheating or bearing seizure, see Figure 3.

Figure 3: Shaft brown/blue discoloration is a sign of excessive heat damage

2.1.4. Electrical Motor Inspection (Electrical Checks)

At this step, preliminary electrical tests should be performed to check the status of windings of the motor (regarding their resistance and insulation) as well as its capability to run when connected to the supply.

- A full test of the winding condition shall be carried out. Remove the motor terminal box lid and carry out an Insulation Resistance (IR) test using Megohmmeter insulation tester (also known as Megger) and a winding resistance test using a suitable digital multi-meter. The maximum difference in winding resistances of the phases should not exceed 3%.

If possible, and the motor passed the visual inspections and winding status permits that, perform the following checks:

- Perform a run-test to the motor at nameplate voltage, frequency and speed. Check the current drawn per phase.
- Carry out a vibration test in the vertical, horizontal and axial planes using the vibration conformance checker.

Record the measured values of both checks, and ensure they comply with the standard values, such as in IEEE standard.

2.1.5. Mechanical Motor Inspection (Mechanical Checks)

- Bearings shall be removed from the rotor and examined for condition and/or failure mode. All failure modes shall be classified in accordance with ISO 15243: 2004, “Rolling bearings – Damage and failures – Terms, characteristics and causes”. Annex 2 – Failure modes of rolling bearings, presents the failure modes as presented in ISO 15243: 2004.
- The bearing housings and journals shall be measured to ensure correct size and fit to ISO 15243:2004 tolerance. Most motor failures are bearing related. The majority of motor repair companies do not go to this level in ensuring correct bearing fits.
- The rotor is to be checked for broken bars, cracked end rings and general condition.
- All mechanical parts are to be thoroughly cleaned and inspected for defects, cracks or damage.

2.2. Dismantling the motor

Dismantling an electric motor involves various steps that should be performed in sequence. It is also essential to keep adequate records of these steps (such as by tables, marking, photographs, etc.) to ensure that the motor is reassembled correctly after being repaired. The motor disassembly process should proceed in the following steps:

1. Documentation of the motor configuration
2. Removal of the end bells
3. Removal of the rotor
4. Removal of the bearings

Figure 4 illustrates the key components of a motor, as a guidance for the upcoming sections.

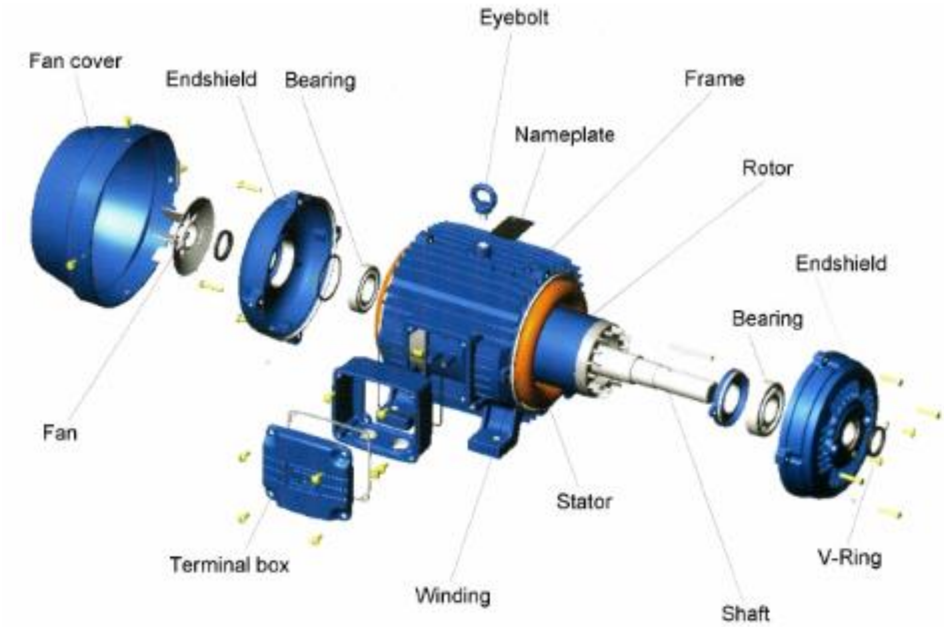


Figure 4: Key components of a motor

2.2.1. Documentation of the motor configuration

Several information should be documented about the motor configuration during the disassembly process. These aspects include:

- ✓ *Terminal box position, layout and connections* – including recording markings on both winding leads and terminals, size and type of lead wire as well as lug size and style. Also, in case of observing any sign of overheating to the insulation of winding leads (sometimes due to poor connection), they should be replaced.

- ✓ *Orientation of shaft with respect to the main terminal box*, should be documented to ensure proper reassembly of the motor. Refer to IEC 60034-7, "Classification of types of construction, mounting arrangements and terminal box position (IM Code)".
- ✓ *Axial position of rotor relative to stator should be marked clearly*, either at drive end (DE) or opposite drive end (ODE), to avoid axial displacement of rotor with respect to stator and hence causing pressure on the bearings.
- ✓ *Orientation of end brackets and bearing caps should be marked clearly and in a lasting way*, to ensure that the end brackets and bearing caps will be installed correctly at the same original position when reassembling the motor.
- ✓ *Bearing sizes, types and clearances* – it is important to replace the bearing with a new one of the same type and characteristics. Key points to be considered in the selection of bearings are bearing enclosure, tolerance, internal clearance, load application and type of lubricant.

Caution

Use the proper and dedicated tools for disassembling the motor and label the removed parts properly. Store them in an orderly arrangement in a safe place. Record the necessary information so that reassembly is done smoothly.

2.2.2. Removal of the end bells

- ✓ *Balance Rings* - Remove the balance rings if they are installed externally to the outer bearing caps.
- ✓ *Bearing Caps* - Remove the outer bearing caps using jacking bolts if available and/or a light mallet, if necessary, see Figure 5 and Figure 6, respectively. Carefully clean and treat the mating surface to remove burrs when necessary. Then, remove inner bearing caps, locknuts and lock washers.

Figure 5: Jacking bolt

Figure 6: Mallet

Caution

Do not let the rotor drop down on the stator lamination while removing the end caps (shields). Use a pipe, longer than the shaft to hold the rotor till the end caps are removed and a packing is inserted between rotor and stator.

- *End Bells*: Loosen the end bells with jacking bolts, if provided. Slide the first end bell over the pipe. Insert packing into the clearance space between rotor and stator. Remove the pipe and end bell after packing is inserted, as in Figure 7. The bearing housings should be a sliding fit on the bearings. If excessive force is necessary to slide a housing, it is either too small or out-of-round. Second end bell can be removed using the same procedure.

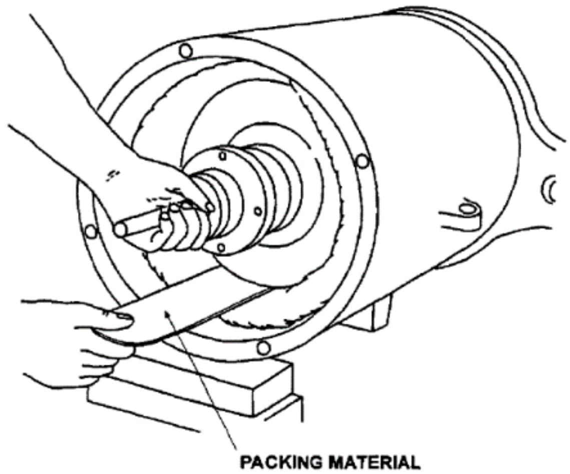


Figure 7: Installing Packing below the rotor

2.2.3. Removal of the rotor

- Insert the packing materials, Figure 7 , into the clearance below the rotor (between rotor and stator).
- Use a suitable pipe on the opposite end of the rotor shaft. It should be long enough to support the rotor till it is completely removed and the shaft is removed from the stator bore.

The rotor presents a considerable overhung load when one end bracket has been removed. Allowing it to scrape along the stator bore during rotor removal can damage the air gap surfaces of both stator and rotor, and hence increase losses, as well as causing winding damage. Rotors should be removed carefully in axial direction. For large motors a rotor handling tool should be used to balance the rotor into the stator in the horizontal plane, see Figure 8.

Figure 8: Rotor handling tool (lifter)[2]

2.2.4. Removal of the bearings

To remove the bearing, the following steps shall be followed:

- ✓ Place the rotor on the workbench in V-blocks. Secure it with a strap wrench to hold it firmly on the bench.
- ✓ Free the tab washer, if present, to permit removal of the bearing locknut. Use a locknut wrench. Be careful not to damage the threads.
- ✓ Use a suitable bearing puller (either manual or hydraulic, see Figure 9) to remove the old bearings. If the bearings are shrunk-fit, use a torch to heat up the bearing taking care to avoid overheating of the shafts or lamination in a way that could damage the rotor laminates. Avoid using angle grinders to cut through the old bearings. Also, avoid hammering or tapping over the old bearings to avoid damaging the bearing housings.

Figure 9: Bearing removal tool: manual (left) and hydraulic (right)

[2] www.rotary.co.uk

2.3. Internal inspection

After the motor disassembly, internal inspection and testing of the motor components are very important. All recorded data, notes and test results must be documented carefully. Before proceeding with this step, thoroughly clean all mechanical parts, and inspect them for defects, cracks or damage.

2.3.1. Visual internal inspection

In this step, look for and note the following:

- *Water or dirt ingress*, on the internal surface of the motor.
- *Condition of stator and rotor cores*, for any damage or overheating. This can be resulted from:
    - **Core rub**, often due to failure of one of the motor bearings or rotor pullover. This damages the laminations from air gap side, and increases the eddy current loss. This type of fault is very common due to the lack of preventive maintenace measures (e.g.: monitoring of bearing temprature and sounds) and operating the bearings beyond their expected life time which is specified by the manufacturer taking into account the running hours and operating conditions (e.g.: vibration levels). Depending upon the level of damage, the motor may not be repairable.
    - **Major mechanical damage to either the stator or rotor core**, due to major electrical faults, such as a short circuit inside the slots. If such damage has happened, usually the core needs to be replaced or restacked, and rewinding the motor is infeasible.
    - **Serious overheating of the stator or rotor cores**. If the inter-laminar insulation is damaged, eddy currents will increase, causing excessive iron losses, thus raising core temperature and reducing the efficiency massively.
    - **Any cracks or breakages in the rotor bars or end rings.**
- *Condition of winding* – inspect any kind of discoloration or damage of the winding, see Figure 10. Rewinder should explore the cause of the failure to avoid its repetition after rewinding the motor. Some of the common reasons are ventilation issue or overloading of the motor.
- *Mechanical damage* - to other components, such as damaged shaft, fan, fan cover or blocked cooling ducts.

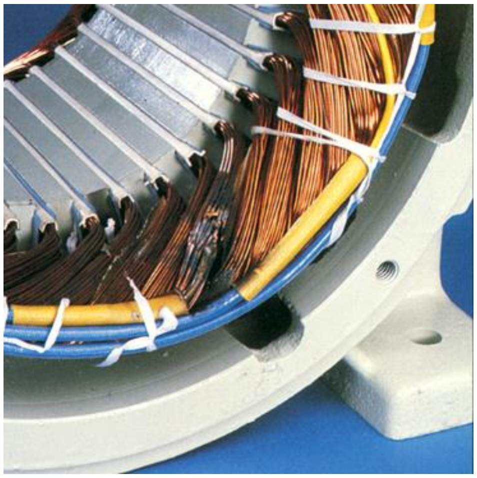


Figure 10: Failure of stator winding, EASA

2.3.2. Internal core and winding design data collection

The following data should be collected and recorded properly in a table, similar to that previously presented in Figure 2. this step is crucial and should be done accurately to return the motor as close as possible to its original performance characteristics. The collected data include:

- ✓ The necessary coil and stator core dimensions.
- ✓ Identify the type of connection and number of circuits used in a 3-phase winding.
- ✓ Recognize whether the winding is connected adjacent pole or skip pole.
- ✓ Determine the coil pitch, the coil grouping and identify whether it is a salient-pole or consequent-pole winding.
- ✓ Determine wire size (or sizes of multiple windings configurations) and the number of wires in multiple that make up the coils in a three-phase winding.
- ✓ Determine the number of turns of magnet wire for each coil in a group.

2.3.3. Core testing

Core loss testing provides a quick and efficient method for determining core losses found in the core steel of stators, rotors, and armatures. The best safeguard against burnout-related problems is to perform a core loss test before burnout and after the core has been stripped and cleaned. Commercial core loss test equipment can simplify the process, or a loop test (also called a “ring flux test”) can be performed using the procedure in Annex 1 – Core Test.

Commercial core loss testers can give an indication of whether the stator core losses have been increased by the rewind process or not. They normally will not record the same core loss as would be measured during a load test on the same machine. One reason for this is that the distribution of the flux induced by the tester in the core is not the same as that induced by the machine’s winding, particularly when the rotor is removed. Core loss testers can be useful provided that the same tester at the same setting is always used for each test on a given core.

Remember

It is recommended to conduct all tests using the same core tester, following the manufacturer’s recommended operating range for the tester being used.
Carry out tests before burnout and after the core has been cleaned prior to rewinding.

If the core loss tests were performed properly with the same tester, and the core loss increases significantly (by more than 20%, according to EASA reports), repair the core or consider replacing it.

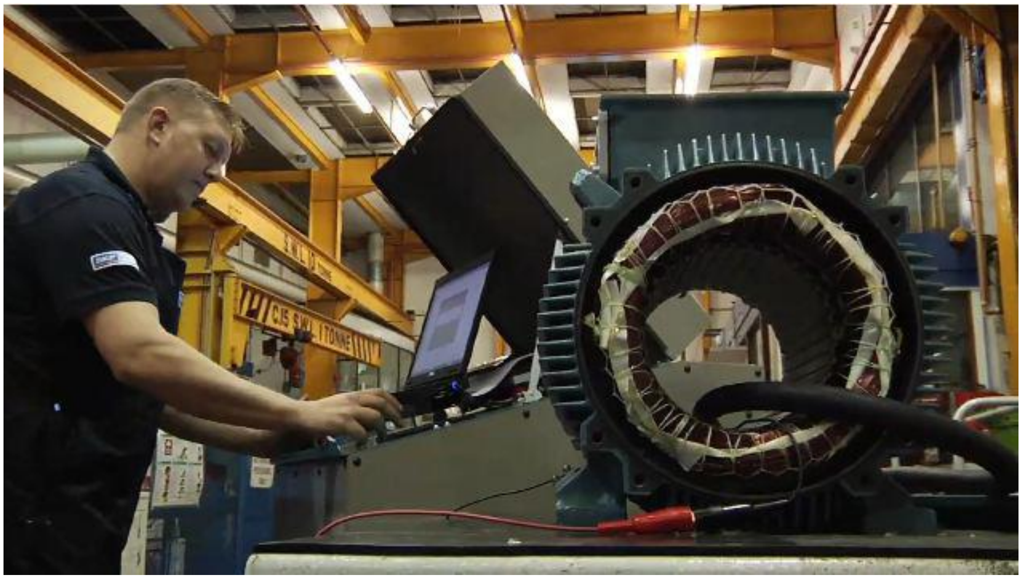


Figure 11: Core Loss Test - FLETCHER MOORLAND Photo

2.4. Removing the old winding and cleaning the core

This step describes the procedures of removing the old winding and cleaning the core. It is important to record the winding details and double check details at each step before and during winding removal. After cutting-off the coil, the coil data should be completed as in Figure 2, including wire size and number of turns in each coil group. Similarly, core loss test is carried out at fixed points throughout the repair process. Figure 12 summarizes the complete activities of removing the old damaged winding till finishing the process of replacement of new the windings. These activities (steps) will be illustrated in detail in the following sections.

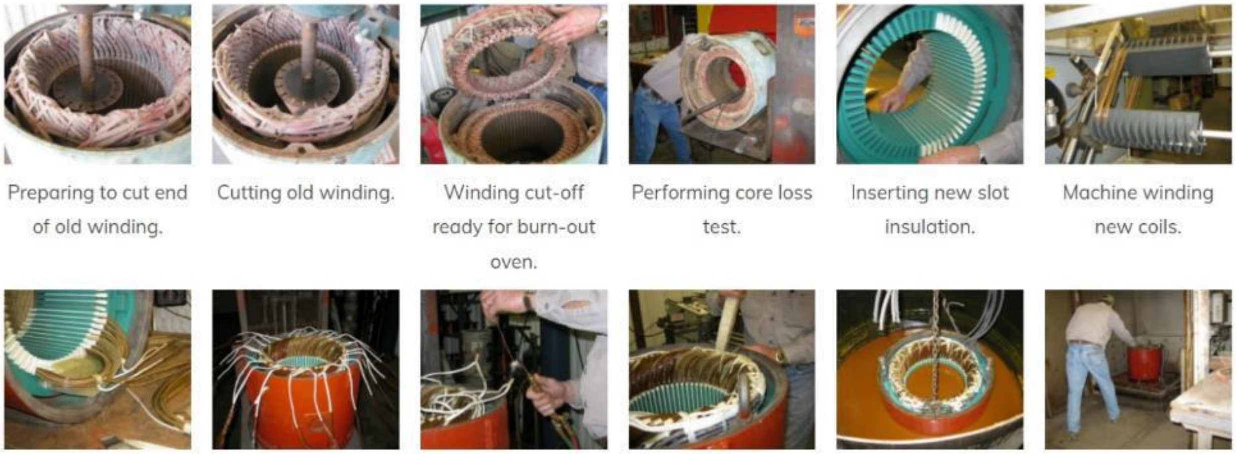


Figure 12: Rewinding complete activities (old winding removal till finishing the new replacement winding) - Photo from Gatewood Electric

2.4.1. Removing the old winding

Removal of the old or failed electrical windings is one of the most potentially damaging procedures in the rewinding operation. If removal is done improperly, it can adversely affect the characteristics of the stator core, thus increasing losses leading to decreased motor performance. The main steps for removing the old windings are: cutting-off the old coil, and stripping the old windings. These steps will be discussed in details in the following sub-sections.

2.4.1.1. Cutting-off the old coil

Stators have semi-closed slots that make it very difficult to remove the windings with the coils intact. Therefore, the first step in removing the old windings from the stator core is to cut off the coil extensions (overhangs), usually on the opposite end connection, see Figure 13. The goal of this procedure is to cut off the coil extensions as close as possible to the laminations without cutting into the laminations. This is typically within 1/4 inch or 6 mm of the laminations, as in Figure 14.

The individual conductors tend to spread apart as the coil exits the slot. Removing as much of this material as possible makes it easier to pull the remainder of the coil out of the slot following the burnout process.

Caution

Some special motors like those with two windings, may have a connection on each end in these cases. Check with your supervisor or more experienced staff before cutting any of the coil extensions.

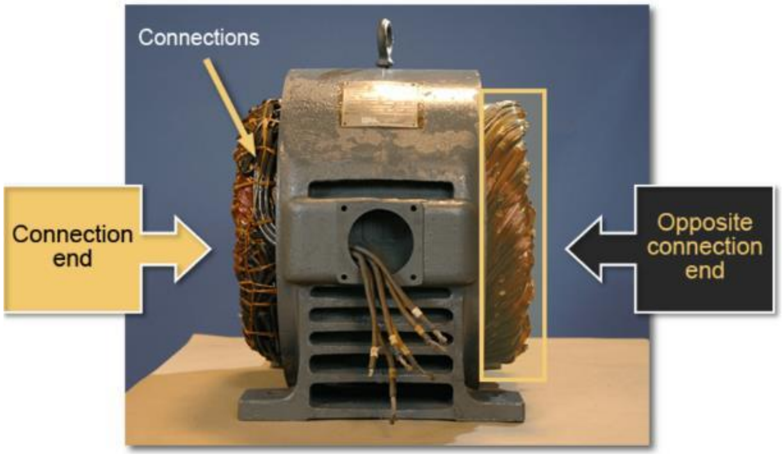


Figure 13: Winding ends in the stator core showing "connection end" and "opposite connection end" – EASA

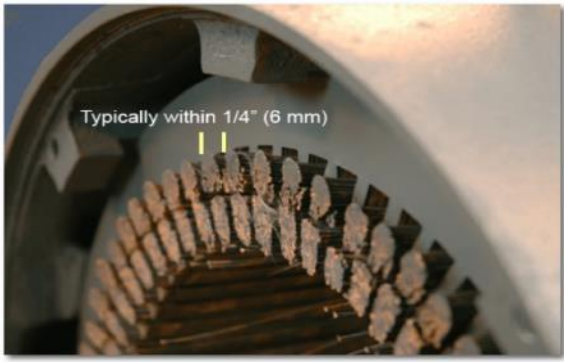


Figure 14: Typical correct procedure for coil cut-off

For optimum cut-off procedure, the following tools and facilities should be used:

- *Winding cut off saw* - a machine designed to cut off coil extensions without damaging the laminations or frame. Cut-off saws come in both vertical and horizontal models as shown in Figure 15. These saws are particularly useful for large motors. Grit-Edge blade designed for cutting metals, which is a safer and more durable alternative to typical abrasive wheels. A die grinder can be used on smaller stators in place of a winding cut off machine.
- *Hoist or crane* to lift and position the stator
- *Data card* - The motor' specific winding data card with all appropriate data recorded to this point in the rewind process.

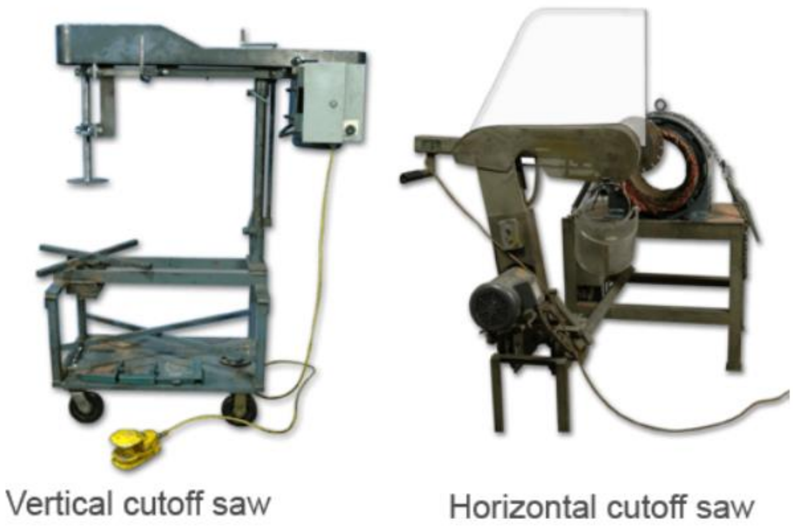


Figure 15: Vertical and horizontal cut-off saws

Having all the above tools, the procedure of the cutting-off is as the following:

- ✓ Verify that initial core testing has been completed and coil extension data has been recorded.
- ✓ Securely position the stator for the type of cut off equipment you will be using.
- ✓ Position the cut off the equipment to cut the coil extensions as close as possible to the laminations without damaging the laminations or frame.
- ✓ Cut off the coil extensions.

2.4.1.2. Stripping the old winding

It is important to remove the coils with minimal damage or displacement of the stator laminations. The less the laminations are disturbed, the less time it will take to prepare the core for rewinding. Damaged laminations may also reduce the efficiency of the repaired motor by increasing the stray load and core losses. There are several methods for stripping/removing the old windings. The most common practices are:

- ***Oven burnout -*** it is a process where the winding and lamination core are placed in a controlled-temperature oven, see Figure 16, at elevated temperatures for a time suitable to "burn out" the insulation system, by turning the insulation to ash and the windings can be easily removed. When done correctly, this procedure breaks down the insulation system of the old winding without damaging the stator core's interlaminar insulation, also known as core plate. Figure 17 illustrates stator coil before and after the burnout process.
  It is considered the simplest, but most time consuming, method of preparing a failed winding for removal. Stator is usually left in the oven for at least 12 hours. The oven temperature during burnout should not exceed 370° C. measured by thermocouple on stator iron.

Figure 16: A typical insulation burnout oven

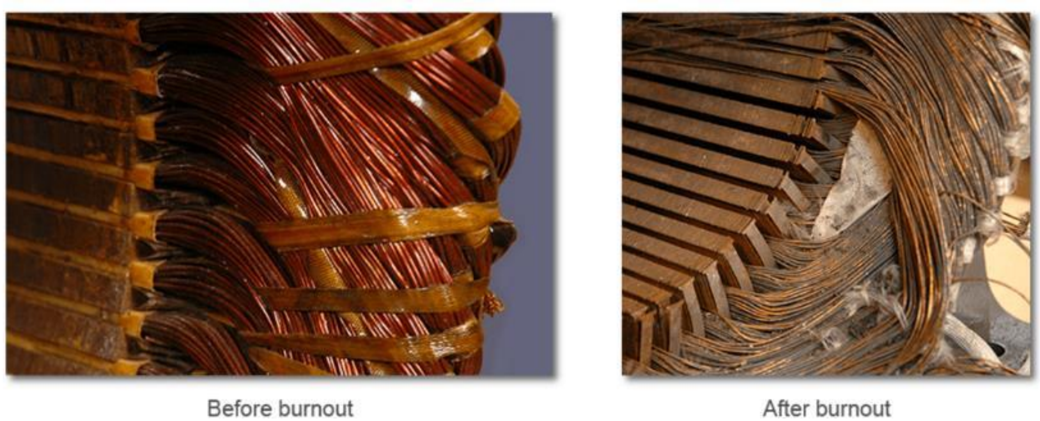


Figure 17: Stator coil before and after burnout process

An optimum "Controlled-temperature burnout oven" for burning out the varnish and slot insulation should have the following features:

- Controller to set oven temperature
- Water suppression system to prevent excessive oven temperature
- Oven chamber temperature sensor to monitor the air temperature within the oven.
- Temperature sensor to monitor the actual temperature of the stator during the burnout process oven.
- Temperature display meters, a chart recorder to monitor and document temperatures during the burnout process, and a timer to control the length of the burnout process.

- ***Water blasting –*** in this procedure high-pressure water is used as a cutting tool to reduce the size and integrity of the coil, allowing the sections or pieces to be removed more easily, see Figure 18. This process is less commonly practiced in Egypt.

Figure 18: Water blast cutting machine

- ***Mechanical (manual) removal -*** which is the most commonly practised method used in Egypt, where coils are stripped manually particularly for small motors. When using mechanical removal techniques, care shall be exercised to not cause the separation of laminations while pulling the windings. Mechanical displacement of the laminations will increase the stator core and stray losses. Heat may be used to soften insulation, however the use of direct flame to burnout the insulation is not recommended.

Regardless the used cutting and stripping procedure, it is important to remove the coils with minimal damage or displacement of the stator laminations. Damaged laminations can reduce the efficiency of the repaired motor by increasing the stray load and core losses. Additional tools are also required to be used in the coil stripping process, such as:

- A mallet or Hammer: used to tap coil extensions to determine if the insulation has been burned out sufficiently to permit easy coil removal
- A pry-bar or crowbar: used to increase leverage when removing tight coils.
- Vise-Grips: used to grasp the coils
- Screwdriver: used to hold lamination teeth in place when removing tight coils.

Figure 19 shows the assortment of tools that should facilitate stripping the old windings. When using any of these tools, be very careful to avoid damaging laminations

Figure 19: Manual tools used for stripping the old windings

2.4.2. Cleaning and preparing the stator core for rewinding

Stator core is made of thin steel laminations that are insulated from one another by an oxide coating or by an organic or inorganic material. This interlaminar insulation can be damaged if the stator core gets too hot during the burnout process. This would cause the rewind motor to run hotter and therefore less efficiently.

On the other hand, if the stator does not get hot enough to burn out the winding insulation fully, the windings will be difficult to remove. In this case, the force needed to pull the coils out may bend or loosen the laminations in the tooth area. This would require additional time and labor to repair the lamination teeth. If loose or bent laminations are not repaired, stray losses and core losses will increase.

Figure 20: Supporting lamination teeth with a screw driver (left) and a loose stator lamination (right)

After the old winding has been removed from the core, slot insulation and other debris may remain in the slots. This must be removed carefully to avoid damaging the core, this can be done using a wire brush as in Figure *21*, or any other cleaning method such as high-pressure washing. If the teeth of the laminations at the end of the core have been pulled outwards during coil removal, reposition them with minimum force.

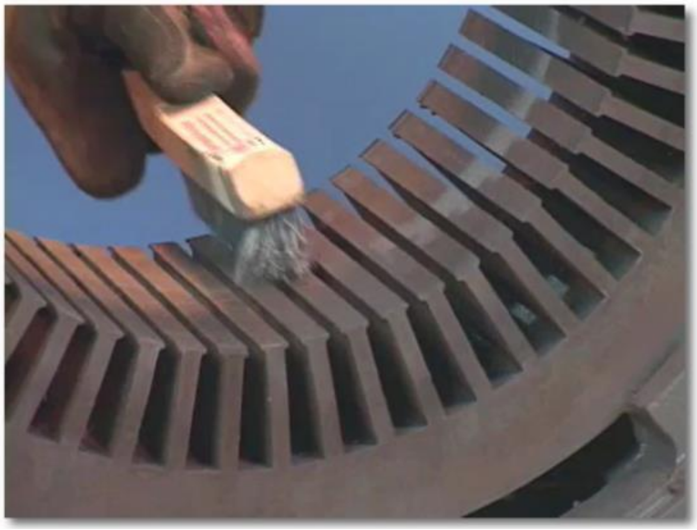


Figure 21 Wire Brush used to clean stator slots

2.4.3. Post burnout test

A core test should be performed post burnout process and the results of this test should be compared to the readings gained from the pre burnout core test. Similar results should be obtained. If the stator has increased core losses, it should be re-stacked and repaired, or scrapped.

2.5. Rewinding the motor

This section covers the steps of making a new winding (coils) to be used in the motor. It is recommended to follow the original winding data table of the motor to return to its original status and maintain its efficiency. The key collected data to be considered are:

- ✓ Old winding original data (manufacturer's data are preferred if available)
- ✓ The same winding configuration and connections, as collected previously in data table of the motor, such as wire size, number of turns of coil group, coil pitch, etc.
- ✓ The length of the coil extension to be the same (preferably less).
- ✓ The same (preferably larger) copper cross-sectional area per turn, to reduce copper losses.
- ✓ The same or shorter mean length of turn (MLT), to reduce copper losses and overhang.

In choosing/making a replacement winding the repairer has two options:

- Copy (duplicate) the winding already in the motor (provided it has the manufacturer's original data).
- Choose a different style of winding that will perform as well as or better than the original. This is a less common practice for small rewinding shops and requires experience and good calculation capacity of the rewinder.

In both options, the main steps of coil rewinding are:

1. Fabrication of the new coils
2. Inserting the coils in the stator slots
3. Lacing and bracing of the windings
4. Inspection and testing of the untreated windings
5. Insulating the new windings with insulating varnish
6. Carrying out the post varnishing tests

2.5.1. Fabrication of the new coils

This section introduces some common terminology and information about the different types of windings, also this section details the tool required to fabricate a new set of coils for any motor.

2.5.1.1. Description of winding types

Either one of two types of coils is used in motor windings: random-wound coils, and form-wound coils. The type of coil used affects the design of the stator core laminations, the motor performance and sometimes it could be possible that both types are not interchangeable.

Random-wound coils refer to round-type wire arranged into coil groups where the individual strands are not fixed in position in relation to the others in the coil. Random-wound coils have a coating for the conductor and turn insulation and are usually inserted into slots that are semi-enclosed where the open top of the slot is narrower than the slot width. For a random wound coil, voltage stress between adjacent turns may potentially equal the coil voltage. This type of coils is more common especially in low voltage motors.

Form-wound coils use rectangular-shaped wire in which the individual conductors are in a fixed position and cannot migrate to a different location. Form-wound coils utilize various strand, turn, and ground wall insulation materials in several layers (e.g., enamel, glass, synthetic polymer, or mica tape). Once finished, the form-wound coil requires an “open” slot so that the open end will not restrict insertion of the rigid rectangular cross-section coils. Voltage stress between adjacent turns is uniform for the form-wound coil. Form-wound coils are normally used in motors with voltage greater than 600 VAC and also in low voltage motors greater than 500 hp[3].

Figure 22 shows an example of random-wound coils and form-wound coils.

[3] *Austin H. Bonnett, Helmuth M. Glatt, “Ten things you should know about installing, operating and maintaining electric motors”, IEEE, 2016*

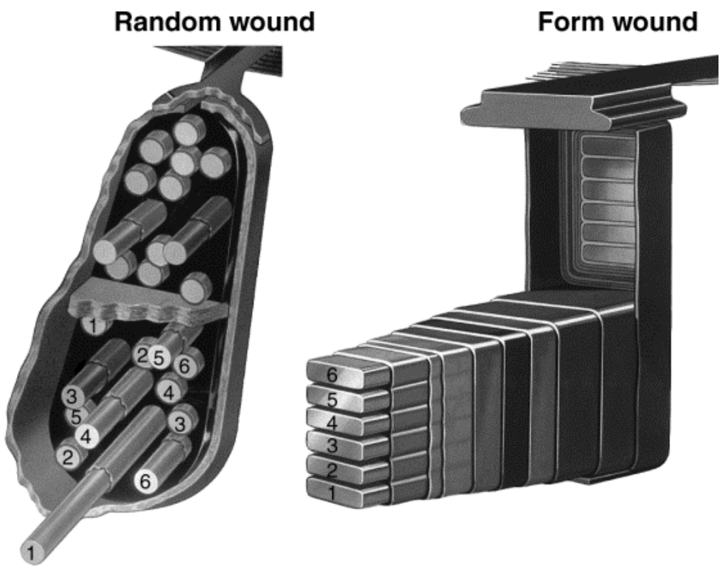


Figure 22 Random wound coils and form wound coils[4]

2.5.1.2. Parts of a coil

The winding of a three-phase stator is made up of individual coils that carry electricity to create a magnetic field. The coils are made from a specially insulated wire called "Magnet Wire". Magnet Wire looks like an ordinary copper wire; however, it is actually coated with a thin film of insulation which prevents electrical shorts between individual coil turns. This insulation is somewhat fragile, so magnet wire must be handled carefully.

The coils lie in the slots of the stator core, the two conductors protruding from a coil are called the coil leads. The coil sides are the straight portions of the coil that lie mostly in the stator slots. They are the active parts of the coil that produce the magnetic field in the stator core. The portions of the coil that extend beyond the core are called the coil extensions, coil ends, coil knuckles, coil noses or end-turns. They are considered inactive conductors, since they do not contribute to the magnetic field of the motor. The overall length of the coil is the distance from one coil knuckle to the other. Figure 23 shows the different parts of a coil.

[4] *Austin H. Bonnett, Helmuth M. Glatt, "Ten things you should know about installing, operating and maintaining electric motors", IEEE, 2016*

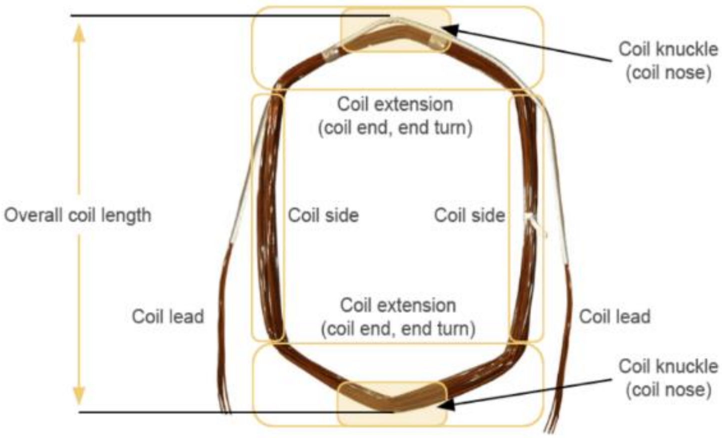


Figure 23: Different parts of a coil – EASA

The width of the coil is the distance between the coil sides. This width is determined by the distance between the slots that the coil sides occupy commonly known as coil pitch. It may also be known as coil span or coil throw. In the example shown in Figure 24 the coil pitch is (1 to 13).

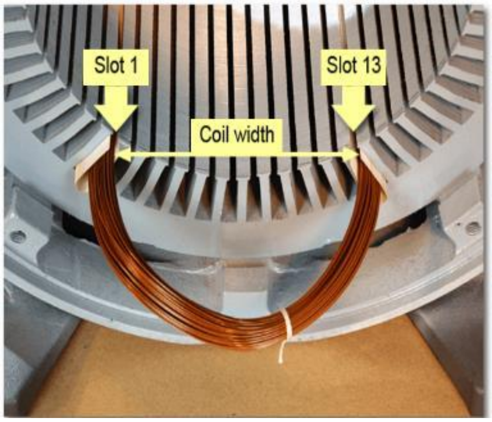


Figure 24: A example illustrating the term "coil pitch"

2.5.1.3. Tools

The coils are made using a coil winding machine which could be manual, semi-automatic, or fully automatic. A basic coil winding machine consists of a rotating shaft to which a "winding head" is installed Winding heads are adjustable devices selected based on the require coil size (pitch and length) and coil shape (diamond, round or concentric). Figure 25 shows a semi-automatic coil winding machine, while Figure 26 illustrates the coil winding process

Figure 25: A semi-automatic coil winding machine

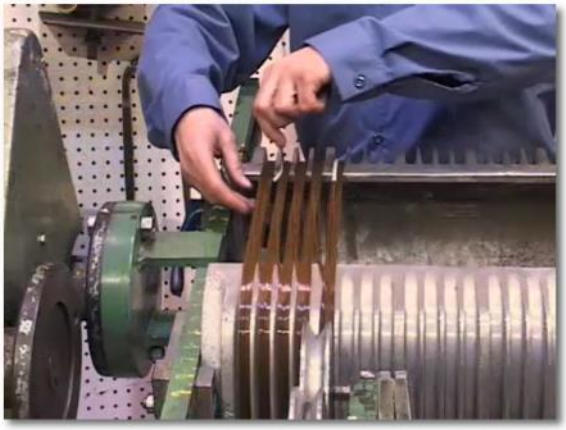


Figure 26: The coil winding process

During the process of making the coils (specifically random wound coils), several hand tools should be available, to support in the process. These tools are illustrated in Figure 27, and include:

- ✓ A coil rack: used to organize and protect the coils from scratches Nicks and other damage.
- ✓ A tape measure: used to measure the coil width and length.
- ✓ A scale: used to weigh the finished coils.
- ✓ Wire cutters: used to cut the magnet wire and group leads
- ✓ A winding horn: used to shape the coil crossovers.
- ✓ A calculator: used to perform wire size conversions, and to determine the total weight of the copper required.

Figure 27: the assortment of tool required for coil making

Finally, in addition to the aforementioned tools, tape string or plastic ties are used for securing the conductors of the finished coils, and a sleeving is used to insulate the group leads.

2.5.2. Coil insertion in slots

After coil making, they need to be inserted into the stator slots. This begins with inserting special paper insulation into the stator slots. After all slots are fully insulated, the coils are inserted in the stator core following the specifications of the winding data cards and the coil ends are soldered. Figure 28 illustrates the process of insulation paper insertion in the slots, followed by the coils insertion using scuff paper.

Figure 28: The process of coil insertion using scuff paper

After coil insertion, specially shaped wedges are used to close off the slots of the motor. The wedges are commonly referred to as slot wedges, slot sticks, or top sticks. Slot wedges are long strips of an insulating material used for securing the coil-sides into the slots and thus prohibits the physical motion of the conductors or worse having the protrusion of conductors outside the stator slot boundaries into the air gap which may result in winding damages, possible short circuits, and mechanical damage to the stator slots and rotor surface. Slot wedges can be constructed of several material which include: wood, Fiber Reinforced Polymers (FRPs), and Nomex™ with each material having its own properties and applications regarding mechanical strength, and temperature range.

Caution

Before proceeding with coil insertion, Always ensure that your winding tools are clean smooth and free of burrs. This prevents damage to the wire, insulation or slot liners.

The tools used for coil insertion include:

- *Needle nose pliers*: used to insert separators and wedges. Keep a pair of needle-nose pliers just for handling the winding. This will help prevent burring or other damage to the tool that could scratch the magnet wire insulation.
- *A tape measure or pocket ruler*: used to make sure the winding extensions are symmetrical with the correct coil extensions on each end. This is critical in some cases to keep other parts of the motor from damaging the winding.
- *A pair of scissors*: used to trim phase insulation and to cut various other pieces of insulation and material needed for installing coils into the stator core.
- *A Winding Mallet*: used to shape the coil extensions to position the coils properly and to ensure adequate clearance for the rotor are baffles and in brackets. The Mallet head must have a non-marring surface to prevent damage to the coils. Keep the edges of Rawhide or nylon inserts trimmed because rough edges can snag wires and pull them out of place.
- *Tamping tools*: used to compress the bottom coils in the slots making it easier to insert the top coils. They must be free of burrs to prevent scratched, wires and cut slot, liners. Tamping tools are available in several widths. A tamping tool that is too wide may damage the slot liner in a place where it is difficult to notice that could shorten the life of the winding.
- *Winding horns:* are useful for shaping coil extensions.
- *Scuff paper or feeder paper*, consists simply of two pieces of smooth insulation. Its purpose is to help the winders slip the wires of the coils into the slots more easily. It also keeps the magnet wire insulation from being scratched from insertion. A piece of heavy protective paper will keep the top coils from getting scratched. While you insert the coil bottom sides. Figure 28 showed an illustration of this process

The assortment of tools is illustrated in Figure 29.

Figure 29: Assortment of tools usein in coil insertion

2.5.3. Lacing and Bracing Windings

Lacing and bracing extend the life of the winding by improving varnish retention. This increases mechanical strength and minimizes coil movement. Strength is important to withstand electromagnetic forces on coil extensions, which can be 30 to 40 times greater during startup than during normal operation.

There are two methods for securing coil extensions, Continuous Lacing and the Lock-Stitch Lacing. Both methods may be used with the stator in the horizontal or vertical positions. Figure 31 shows the difference in between these methods. If lacing the stator in the vertical position, be sure to support it in a way that will protect the coil extensions.

Lacing materials include cord and string. Lacing cord is wider than string, so it has more contact area with the coil extensions. Absorbent materials, like Dacron lacing cord and untreated string bond to the winding better than non-Absorbent materials, like waxed string. Something to consider is that most lacing materials shrink about 5% in length when the winding is baked, which further tightens the lacing. Another material is the surge robe, which is an absorbent material used in addition to lacing to increase the mechanical strength of the coil extensions. This may be needed to minimize coil movement on larger machines that start across the line. Figure 30 and Figure 31 show the material used for lacing motor windings and their application

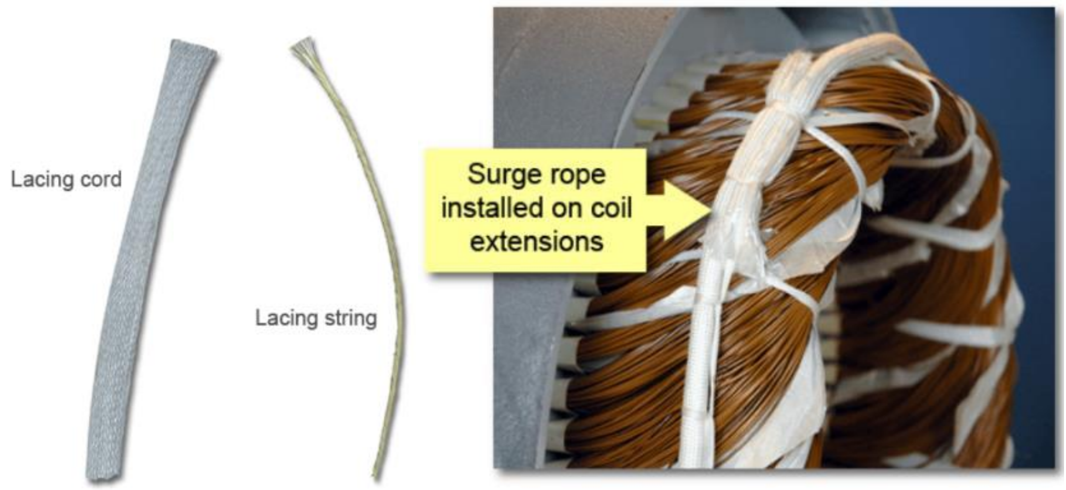


Figure 30: Lacing material used for lacing motor windings

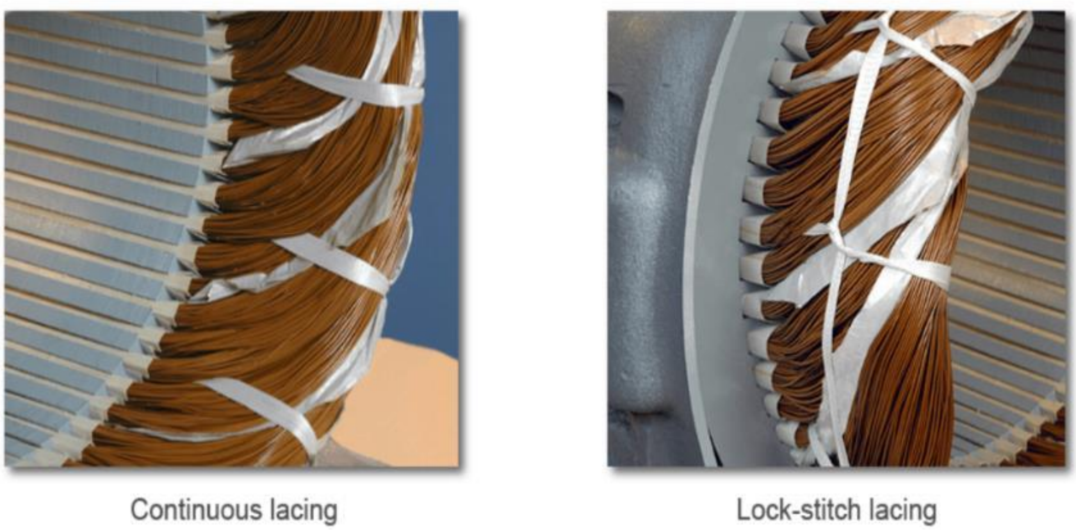


Figure 31: Continuous and lock-stitch lacing

The tools and equipment used for lacing motor windings include:

- A winding needle, which can be made from a length of stainless-steel wire, rod or from scrap. magnet wire
- A pair of scissors or a knife
- A tape measure.

Figure 32 shows the assortment of tool used for lacing motor windings.

Figure 32: Tools used for lacing motor windings

2.5.4. Inspection and Testing Untreated and Treated Windings

Careful inspection of an untreated winding is a critical step in the rewind process. Undetected mistakes could lead to a winding failure. Testing should be performed before the winding is treated with insulation, as defects discovered after the winding has been treated with varnish or epoxy may be difficult to fix without stripping and rewinding the stator.

Testing, untreated and treated windings, as a quality control measure that identifies problems, such as grounds shorts, opens circuits, and incorrect connections, that could lead to premature winding failures. The tools needed to perform the required tests are:

- A Megohmmeter, also called a Megger
- A Surge tester
- A high-potential tester
- A milli-ohmmeter.

Figure 33 shows the equipment need to perform winding tests

Warning

Most of the required tests involve the use of high voltages. Always make sure that the personnel carrying out these test are properly trained to use the test equipment safely and correctly.

Figure 33: Testing equipment used for winding tests

Tests on untreated and treated windings should be performed in this order:

1. Megohmmeter test
2. Surge comparison test
3. High potential test.
4. The winding resistance test (need only to be performed on untreated windings).

The following sections discuss each of these tests.

2.5.4.1. Megohmmeter test (Megger test)

This test measures the insulation resistance to ground, and verifies that the winding is suitable to proceed with the remaining potentially destructive tests. The test proceeds as follows:

1. Remove about half an inch (13 mm) of insulation from the end of each motor lead with a wire stripper.
2. Bundle all the motor leads together with a scrap piece of bare Magnet Wire.
3. Then wrap a second piece of bare Magnet Wire around the bare conductors. An alternative is to use an alligator clip.
4. Check the Megohmmeter by touching the tests' leads together, the dial should read zero.
5. If the meter is okay, connect one Megohmmeter lead to the motor leads, connect the other to the stator frame using the ground lead. If it is identified run the test at 500 volts DC for one minute and then record the Megohmmeter' reading
6. Untreated windings should have a minimum reading of 100 Mega Ohms at room temperature, which is assumed to be 20 degrees Celsius. On the other hand, treated windings should have a minimum value of 100 Mega Ohms and will probably be much higher (typically above 500 Mega Ohms).

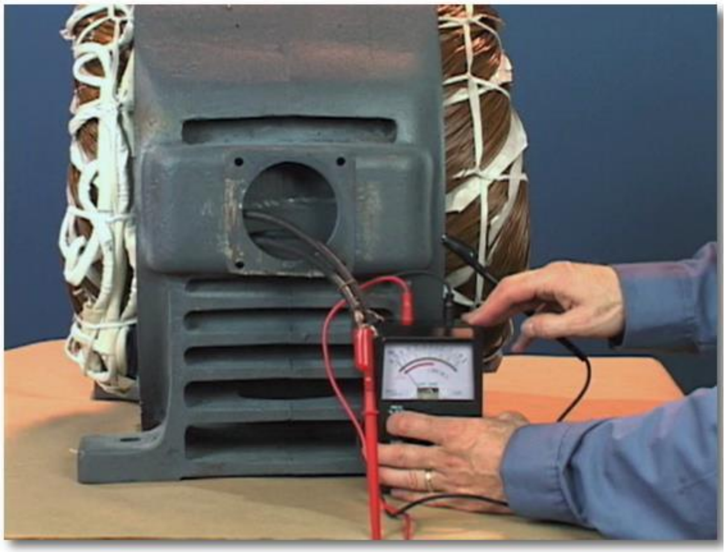


Figure 34: Megohmmeter (Megger) test

2.5.4.2. Surge comparison test

Surge tests are critical because they are the only test that finds turn-to-turn insulation weaknesses. These weaknesses start at voltages above the operating voltage of the motor and are precursors to serious failures and shutdown of a motor. Surge tests are also used to find hard shorts and a number of other mistakes in windings and coils. Figure 35 shows a typical surge tester.

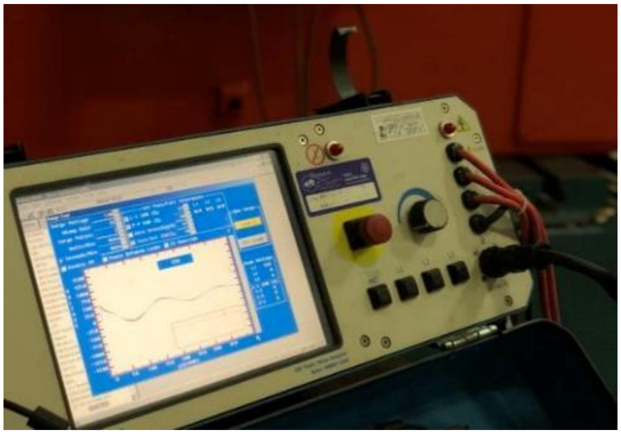


Figure 35: A typical surge tester

Surge tests are also known as surge comparison tests because the result from a coil or phase is compared to the result from another coil or phase. Coils are designed to be identical so the surge test results should be nearly identical. When windings or phases are not identical or there is nothing to compare to, operators use the pulse-to-pulse surge test.

The test proceeds by applying a set of fast rising pulses passing through the coil or motor. The operator sets the voltage of the surge test pulses based on standards and best practices. The test voltage ranges from the peak operating voltage of the motor to around 3.5 times the operating voltage of the motor.

The most common testing voltage is 2U+1000V (where U is the operating RMS voltage of the motor). The surge pulses produce a decaying wave form by the oscilloscope channel in the tester. Each wave is compared to the wave from another coil or to the waves from the other motor phases. All wave forms display on the screen. The waves are nearly identical if the coils or windings are identical. If one has a fault or insulation weakness, the wave will have a different frequency from the others and appear separate. The tester should calculate the percentage wave differences (%WD) which is also called Error Area Ratio (%EAR).

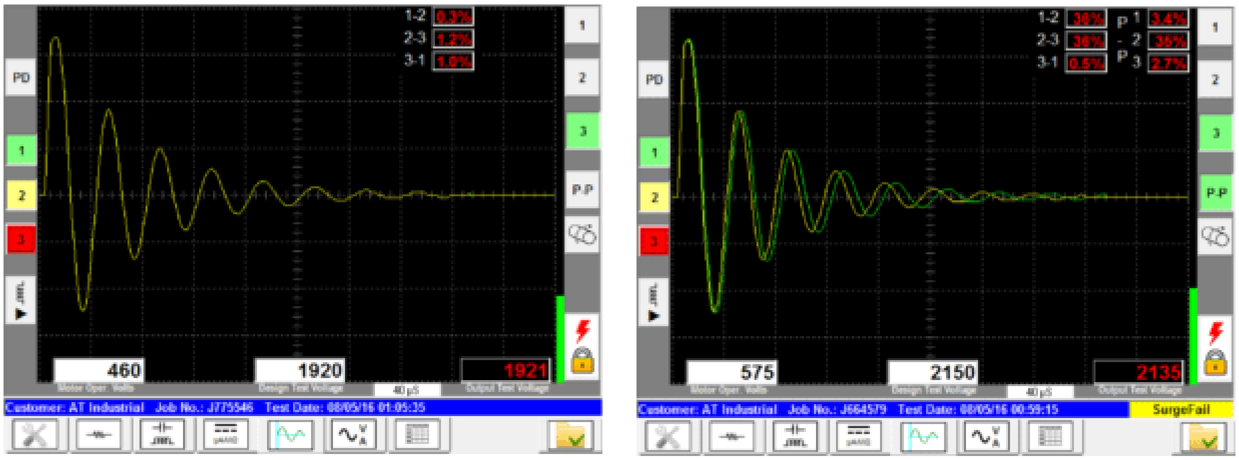


Figure 36: Three nearly identical waves (left) of good test versus non-identical waves (right) of a 3-phase motor - ELECTROM INSTRUMENTS

Another variant of this test is the pulse-to-pulse surge test. This test is used in applications with normal differences in the surge waves but when the tolerance for pass/fail is unknown. This is the case with some assembled motors and many concentric wound stators. It is also used when there are no other coils/phases to compare to. The situations where Pulse-to-Pulse tests are used are:

1. Concentric wound stators with a %WD above expectations
2. Assembled motors (rotor installed) with rotor influence on the stator inductance that creates different surge test waves in the 3 phases
3. Single phase motors
4. Any test where there is nothing to compare the standard surge test to
5. Any time the surge test results are questionable or in the “grey zone”
6. To find the Inception Voltage in Partial Discharge (PD) Measurements

The exact method of testing depends on the standard according to which the test is performed. Some of these standards are discussed below.

- ***ANSI/EASA AR100-2015*** - This standard dictates a test voltage that is equal to (2*U + 1000 V), where U is nominal rated Line to Line voltage of the motor. This is the most commonly used test voltage formula for windings, stators, assembled motors and generators of all kinds. The standard does not distinguish between new and used machines, and is used for both random wound and form wound stators and assembled machines.

- ***IEEE 522-2004*** - This guide applies to:
  - Individual stator coils after manufacture.
  - Coils in completely wound stators of original manufacture.
  - Coils and windings for rewinds of used machinery.
  - Windings of machines in service to determine their suitability for further service (preventive maintenance testing).

  The standard stats that coils may be tested at one or more of the following steps:
  - Prior to insertion in the stator
  - After coil installation, wedging and bracing, but before any connections are made. Each coil should be tested.
  - After series connections are made, but before insulation them and before making connections between phase groups.
  - After connecting into phase groups, but before connecting phase groups to each other. This can be done before or after insulating the series connections.
  - After all connections are made and insulated. Maintenance tests are normally made in this condition.
- ***IEC 60034-15 Edition 3.0 2009*** - This standard applies to sample tests of form coils, typically of at least two form coils, "carried out on coils in new condition which adequately represent the configuration of the finished item to be used in the machine for the purpose of evaluating the manufacturing procedures and processes incorporated in the insulation system." Note that these coils are not yet installed in a stator.

2.5.4.3. High potential test

High potential or "Hipot tests" can highlight and provide early warning for several types of faults in the motors by indicating:

- Early warnings of weak ground-wall insulation.
- Dielectric strength to ground.
- The dielectric strength of the phase-to-phase insulation.
- When the mega ohms measured in an IR test are lower than expected, a DC Hipot Step Voltage test can indicate if the motor) is dirty and/or moist, or if the insulation is breaking down.

A Hipot test is performed using AC or DC voltage, when using DC voltage, the test voltage used is 1.7 times the AC test voltage as indicated by equations below

$V_{AC} = 2*U + 1000$ V

$V_{DC} = (1.7)*(2*U + 1000)$ V

Where U is the nominal motor operating voltage, V_{AC} indicates AC test voltage and V_{DC} indicates the DC test voltage.

AC Hipot tests are sometimes more preferred as they better match the conditions under which the motor operates and do not neglect the effects of capacitive currents, however DC test equipment are simpler and the effects of arcing, should the insulation fail, are less severe in DC test. Thus, the rest of this section will discuss the DC Hipot test.

How a DC Hipot test works:

For low voltage motors, the DC Hipot test is normally a 1-minute test at a specified DC voltage that is higher than the peak lead to lead operating voltage. The test is referred to as an over-voltage test since the voltage is higher than what the motor normally sees.

During the test, the DC test voltage is applied to open (disconnected) windings by the Hipot tester or motor analyzer. The DC voltage potential in the windings is rapidly raised to a predetermined level, or raised in steps up to this level, depending on what test method is used.

As the voltage is raised, several currents will flow into and possibly out of the windings to ground, and the combined total of these currents are measured by the Hipot tester. The currents are the same currents present in an insulation resistance test:

- Capacitive current, or geometric capacitive current (I_c): This is also called inrush current. This current charges the windings capacitance. This current typically drops to zero within seconds after the test voltage provided by the motor tester is stable.
- Absorption current (I_A): This current is present during the atomic and any molecular polarization of the insulation, and is the current one is interested in during a Polarization Index test. This current will drop to zero, or near zero, over a period of time that varies by motor. It can happen in seconds or may take 10 minutes or more.
- Volume Conduction current (I_G): This is the current that flows through the entire volume of the insulation between ground and the conductors. In good windings, this current is usually zero or near zero, and depends on the composition and condition of the insulation system. People sometimes think of this current as the “leakage” current.
- Surface conduction current (I_L): This is often referred to as surface leakage current. The surface conduction current runs over the end winding surfaces of the insulation. It is a result of surface contamination, dirt and moisture on the windings that are connected to ground. As the contamination level increases the current increases. As the voltage increases, the current increases more or less proportionally with the voltage applied by the motor tester. For used, good motors, this current will minimize the absorption and volume conduction currents because of the relatively lower resistance in the surface contamination. For new, totally clean, and dry motors this current should be zero or near zero.

A motor tester measures the sum of all the above currents in micro-Ampere (μA) and displays it along with the test voltage. To add to the list of what “leakage current” may mean to people, the total current measured by IR/Megohmmeter and Hipot testers is also often called “leakage current”. IEEE 95 calls this the “measured current”. Figure 37 shows an illustration of the aforementioned currents.

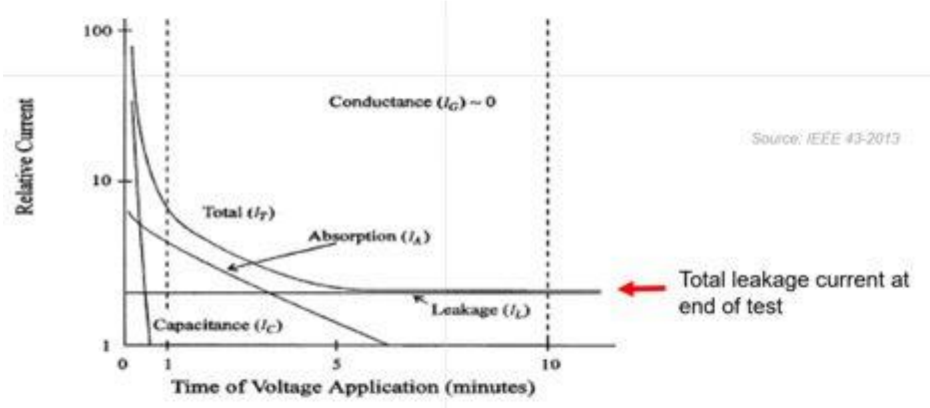


Figure 37: Typical currents associated with DC Hipot tests

The types of Hipot tests:

- *Hipot step voltage*: In a Hipot step voltage Test the voltage is usually raised in equal steps. At each step the voltage and measured current are recorded after 1 minute per IEEE 95. The number of steps is determined by the test operator, and can be anything from 5 to 30 or more voltage steps. The Hipot step voltage is done on motors with any operating voltage when more information than what a 1-minute Hipot test provides is needed. Hipot step voltage tests provide much more information than a 1-minute Hipot test because the data is recorded as the voltage is raised. By charting a current vs. voltage curve, one can usually tell if the leakage current is mainly due to contaminated dirty windings, or due to a breakdown of the insulation.
- *Hipot ramp voltage*: The ramp test is performed with a slowly rising voltage. The final voltage is the Hipot test voltage indicted by equation A. The voltage and measured current is recorded every second or few seconds during the ramp test. The initial increase in the current is mainly due to capacitive inrush current, IC. This current quickly stabilizes and remains constant throughout the test as long as the voltage increase is constant. There may also be some absorption current throughout the ramp test. At the end of the voltage ramp, the voltage is held steady for a short while. The capacitive inrush current rapidly drops to zero, and the remaining measured current is mainly due to surface currents and conduction leakage currents if the winding insulation is breaking down.

Interpreting the Hipot test results

Good windings will have a test voltage vs. measured current curve that is more or less a straight line since a higher voltage typically produces a proportionally higher measured current. The magnitude of leakage current depends on how contaminated the windings are. However, typical leakage current should be in the range of micro amperes.

The increase in the current as the test proceeds is due to surface leakage current. If the insulation is weak or breaking down, there will also be an accelerating volume conduction current through the insulation. An acceleration in the total measured current after the initial current inrush has settled indicates a breakdown of the insulation.

With rapid acceleration of the current, the chance of an arc increases significantly. In general, any deviation from a smooth curve should be viewed as a potential warning. A very sudden drop in conduction current is rarely found, but when it occurs above the peak operating voltage for the winding, it may indicate approaching insulation failure. Mechanical abrasion and cracking may cause abrupt and unexpected insulation breakdown.

Precautions for conducting the Hipot tests

- Before starting an over-voltage test like the DC High Potential Test, the following components should be shorted to ground:
  - Stator resistance temperature detectors (RTDs) or thermocouples
  - Other devices associated with the stator windings
  - Objects close enough to become charged
  - Motor tester chassis ground
- If surge arresters and surge capacitors are installed these must be disconnected prior to any over-voltage tests. Surge arresters have resistive elements and, Surge capacitors have discharge resistors. They are in parallel with the winding under test and will invalidate the current measurements.
- For single phase motors, start and run capacitors should be disconnected.
- With a step voltage test the motor tester should be able to shut down the test before an arc happens using the current acceleration limit. The test operator can also manually abort the test if the leakage current appears to accelerate. Modern Hipot and motor testers have arc detection that will shut off the test immediately when an arc is detected instead of continuing to ramp up the voltage with more and more severe arcing.

2.5.4.4. Winding resistance test

Motor winding resistance test uses the “Four-wire” (Kelvin) measurement method. This method provides the best possible measurement results since it ensures that the resistance of the connecting current cables is not included in the measurement.

In this test, the test current is passed through the windings using the high current cables. The voltage drop across the windings is measured using the sensing cables. Figure 38 shows the layout of this test. Winding resistance of three-phase AC motors is measured between their terminals (all three combinations).

The value of a test current should be selected according to the nominal winding current. Information about nominal winding current could be found on the nameplate of the test object. The test current should not exceed 10% of the nominal winding current. Because of cables heating, higher values of test current will significantly increase the winding resistance.

Placement of the cables is very important in this test. The current cables should always be placed outside of the sensing cables. That way, the resistance of both cables and clamps is almost completely excluded from the resistance measurement. The resistance is calculated using Ohm’s law and is equal to the resulting voltage drop divided by the test current.

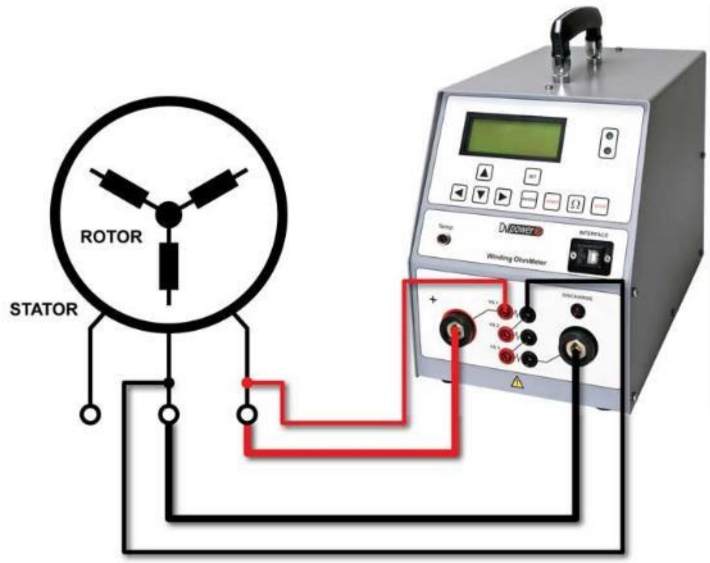


Figure 38 Winding resistance test and test layout

2.6. Varnishing of the motor

Varnishing of motor windings can be done by various method that can be summarized as the following:

a) ***Vacuum Pressure Impregnation (VPI)*** – it is a process by which a fully wound electric apparatus stator or rotor is completely submerged in a Resin. Through a combination of dry and wet vacuum and pressure cycles, the resin is absorbed throughout the insulation system. Once thermally processed, the impregnated windings become a monolithic and homogenous structure. In the VPI process solventless epoxy impregnating resin is forced into the windings under vacuum and pressure processes through removing moisture and air pockets from the stator body, thus filling all voids with epoxy and allowing no voids or gaps for moisture to enter the motor – see Figure 39. The benefits of this process are;

- Higher Dielectric Strength
- Increased Mechanical Strength
- Greater Thermal Inductivity
- Superior Protection against the Ingress of Water, Chemical and Containments

A proper global vacuum pressure impregnated winding will have superior characteristics, which will support a longer and more maintenance free life span.

The main steps of the VPI process is as the following:

1. Place stator or rotor inside impregnation vessel.
2. Securely lock tank and initiate vacuum process.
3. Once pressure is developed to 50mbar the vacuum pump allows resin to enter impregnation vessel.

4. Once the unit is submerged in resin, a wet vacuum is created.
5. Upon completion of wet vacuum, the electrical apparatus is pressurized at 6bar/84psi.
6. VPI process duration is relative to the unit rotor/stator/coils size.
7. Once the VPI process has been completed, a reverse vacuum is created in the resin tank to empty the impregnation vessel.
8. The impregnated unit is then left to drip, pre-curing.
9. Finally, a full report of the process should be produced including date, time duration of process, applied pressure, etc.

Figure 39: Vacuum Pressure Impregnation (VPI) system

b) ***Trickle impregnation***- it is a process for impregnating the windings of stators and rotors with insulating resin. It is characterised by the fact that the resin is trickled in a continuous stream and at a controlled rate directly onto the windings, usually without it being applied to the iron core. The trickle impregnation machines are designed to apply varnish or epoxy onto parts as they are held and rotated. These trickle impregnating systems work by dispensing resin over the part in specific locations at controlled volumes and flow rates. As a result, resin can be applied very accurately with little or no excess resin lost or coating deposited on the part in an undesirable area. The machines are usually controlled by PLCs and linear motion actuators to accurately locate the varnish trickles – see Figure 40.

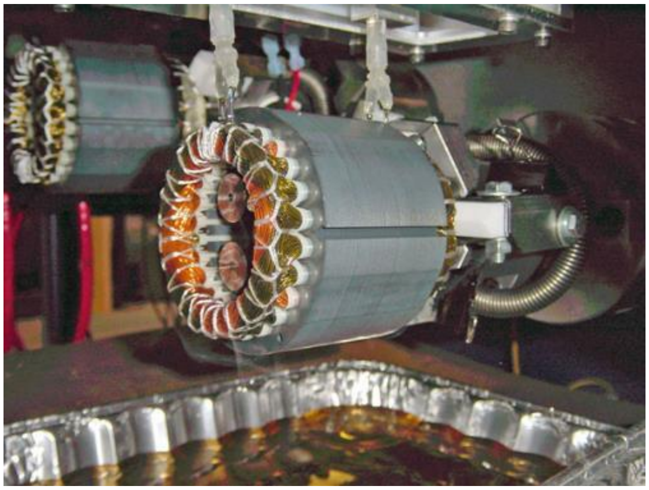


Figure 40: The trickle impregnation machine[5]

c) ***Dip and Bake*** – it is a standard varnishing technique where the motor windings are dipped into a varnish tank and then set to cure in an oven. Typically, a new motor winding should be dipped twice (double dip and bake) to ensure the varnish fully covers the windings. However, it is not the most recommended process of varnishing. Most rewinders do not wait so that the windings gets cooled once they are cured in the oven after the first dip and before the motor is dipped a second time. Because the windings are still hot during the second dip, the varnish becomes more viscous and runs off the motor easily. This results in a less effective second dip of varnish. In addition, parts in varnish is that removal of the varnish in unwanted areas is required after baking, thus adding to the cost of the finished assembly.

2.7. Mechanical repairs

Perform the required mechanical repairs when needed, to ensure the proper and efficient operation of the motor after the rewinding process. Mechanical repairs include:

- Repairs to cores - for stator, make sure to keep the inner surface free of burrs, reposition splayed teeth properly with no excess forces as well as apply proper restacking. For the rotor, maintain same number of ensure correct air gap length and treat any broken bar or end-ring.
- Repairs to shaft – use correct size of bearing seats according to the shaft size, and ensure replacing the shaft with a new one (if needed) with the same magnetic properties of the original one.
- Repairs to housing – adjust stator frame and end bells to reduce stator-rotor eccentricity. In addition, remove any obstructions or dust in the air ducts or fan cover.
- Repairs to fan – replace new fan similar to the material and dimensions of the original fan. Replace the fan cover if needed and tight it properly. Also, ensure that the air inlet of the fan is dust and dirt free.

[5] https://www.heattek.com/

- Repairs to bearings – replace the old bearings by new similar ones with the same characteristics and specs. Perform bearing fitting and lubrication properly as per manufacturer's recommendations.

2.8. Coating of the motor body

As a final step, the outer surface of the motor frame should be re-coated and returned in a good condition. Make sure not to use excess painting to avoid painting entering the terminal box, bearing or any other spots where it should not be painted.

Place and fit the nameplate ensuring that all data are clear and free of paint.

2.9. Motor Assembly

To assemble the motor, follow the following key steps:

- Select a clean work area large enough to permit easy movement around the motor.
- Place the motor frame at a suitable comfortable working height in the clean work area.
- Assemble all needed tools and materials, as well as all motor components.
- Line the bore of the motor stator with gasket material to protect the lamination and windings.
- Place the rotor in the bore carefully (avoid getting slipped in the stator to prevent lamination and winding damage)
- Place long studs in the inner bearing cap bolt holes.
- Position one end bell on or near the shaft. Lift the end bell onto the bearing and ensure good alignment. Tighten end bell bolts manually.
- Slide the outer bearing cap into place, using the studs as a guide. Catch the inner bearing cap by installing bolts in two or more vacant holes. Place all bearing cap bolts into position and tighten them by hand.
- Place studs in the inner bearing cap on the other end of the motor, and then place the other end bell on the motor shaft.
- Support the motor shaft and end bell. Use a pipe slipped over the shaft and an appropriate lifting device.
- Raise the motor shaft until the rotor is clear of the gasket material or NOMEX protecting the lamination.
- Remove the packing material or NOMEX from between the rotor and lamination.
- Slide the end bell toward the motor frame. Insert the inner bearing cap studs through bearing cap bolts on the end bell.
- Align the matchmarks.
- Slide the end bell over the motor bearing and catch the end bell bolts. Tighten them finger tight.
- Remove the pipe and lifting device.
- Install the outer bearing cap.
- Pull the cap up tight and then tighten bearing cap bolts by finger.
- Remove the studs. Catch the remaining bearing cap bolts.
- Check to ensure that the shaft turns freely.

- Pull the end bell bolts down in several steps. Use a crisscross pattern, shifting from one end bell to the other.
- Torque the bolts properly.
- Tighten the bearing cap bolts. Use a criss-cross pattern, shifting from one bearing cap to the other.
- Reinstall the balance rings (if applicable).
- Check for free rotation of the rotor shaft by hand.
- All motor internal surfaces as well as the terminal box are to be coated with an anti-tracking paint.
- Only use an approved bearing induction heater, temperature controlled and with a degaussing function, see Figure 41. Lubricate the bearings in accordance with the manufacture's guidelines.

Figure 41: Correct bearing fitting methods

2.10. Motor Testing

The following final test are to be performed as final checks:

- ✓ Motor testing is to be carried out on an isolated test bed. Megger test to be carried out before test run. Insulation resistance test (Megger test) must be carried out before any test run.
- ✓ The motor is to be run at nameplate voltage, frequency and speed. Record the current drawn per phase and document.
- ✓ The motor shall be vibration acceptance tested. and the vibration spectrum for each position measured and recorded. The vibration test should be carried out on a specialized test bed using calibration equipment. Record the vibration spectrum for each position measured. Accepted result of vibration test are shown in Figure 42.
- ✓ Bearing temperatures to be measured using a non-contact tool (ex: an infrared thermometer or an infrared camera) and recorded once stabilized.

Machine		Class I Small Machines	Class II Medium Machines	Class III Large Rigid Foundation	Class IV Large Soft Foundation
Vibration Velocity Vrms in/s	mm/s				
0.01	0.28				
0.02	0.45				
0.03	0.71		GOOD		
0.04	1.12				
0.07	1.80				
0.11	2.80		SATISFACTORY		
0.18	4.50				
0.28	7.10		UNSATISFACTORY		
0.44	11.20				
0.70	18.00				
1.10	28.00		UNACCEPTABLE		
1.77	45.9				

Figure 42: Vibration Severity - ISO 10816-1, image from Fluke

In addition, after completion of the motor repairs, the repair facility shall submit a report that contains the following:

- Condition of the motor upon receipt, electrical and/or mechanical as appropriate
- A detailed description of the work performed
- Sufficient test data demonstrating that the motor was appropriately repaired
- Condition of the motor when returned, electrical and/or mechanical as appropriate
- Copies of other records (e.g., photographs, sketches or drawings) deemed necessary for clarity

3. Safety Instructions and Cautions

This chapter presents general safety instructions and cautions that should be followed by the rewinding technicians and considered in the rewinding facility to ensure safe work environment for both personnel and equipment. This chapter is not a replacement of any national or international standards, however it provides general instructions related to the rewinding process, which includes both electrical and mechanical processes.

Some useful safety resources and standards are listed below:

- 3003.2-2014 - IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems
- 1584-2018 - IEEE Guide for Performing Arc-Flash Hazard Calculations
- OSHA 29 CFR 1910.132, Personal Protective Equipment (General Requirements)
- OSHA 29 CFR 1910.137, Electrical Protective Devices
- Manufacturers' and suppliers' datasheet and safety instructions of each equipment/tool.

The following are the main health and safety instructions for a motor rewinding facility and process.

A) <u>General</u>

- Always follow the manufacturer's instructions regarding cleaning, operation and safety.
- Use proposer personal protective equipment (PPE) suitable for the used equipment or the performed activity. Standard PPEs for workspace include overall, safety rubber shoes, safety eyeglasses, safety gloves and helmet, see Figure 43.

Figure 43: Standard safety PPEs for workspace

- For larger motors with gearboxes or other attachments, do not use motor eye bolt only for lifting, ensure the weight is fully supported.

- Cleanliness - Facilities should be clean and orderly, and tools and equipment should be in good condition. Proper labelling and signs should be used for different working areas, such as winding, storage and insulation areas.
- Lighting - Health and safety recommendations suggest having the lighting range between 600 – 750 lux for precision work areas.
- Safety program - The rewinding facility should have a safety program and ensure that all workers and technicians are properly trained. Employees should be trained and qualified in safe operation of all electrical equipment within their responsibility. Training should be provided by use of relevant equipment operational manuals, hands-on training and other multi-media methods. Employees should be informed of the relevant safety rules, and employers should enforce compliance.
- Ventilation - Rewinding facility should have good ventilation, especially when dealing with chemicals, such as solvents and varnish, which may be flammable and toxic.
- Personnel should be trained in the procedures for first aid, cardiopulmonary resuscitation (CPR), and securing emergency medical aid.
- Fire extinguishers and first aid equipment should be readily available and personnel should be trained in their use.
- The rewinding facility should have a safety manual outlining the "Do's and Don'ts", and also addressing company procedures for workplace safety such as:
    - Regular communications, education, training, and safety meetings
    - Mandatory compliance with NFAP and/or OSHA regulations
    - Workplace hazard safety and emergency response plans
    - Documentation and record keeping process
    - On-going evaluations, safety audits, and job safety inspections
    - Corrective action process to identify safety hazards or deficiencies
    - Employment related medical requirements
    - The process for handing an accident or illness

B) <u>Electrical</u>

- Electric Shock - People working around energized electric circuits and equipment must always observe safety precautions. Injury may result from electric shock.
- Short circuits can be caused by accidentally placing or dropping a metal tool, flashlight case, or other conducting article across an energized line. These short circuits can cause an arc or fire on even relatively low voltage circuits and may result in extensive damage to equipment and serious injury to personnel.
- Do not touch a conductor, until it is tested, to be sure it is deenergized. Use a voltmeter or voltage tester to ensure that equipment or circuits are deenergized.
- Obey all warning signs and read equipment warning labels before use.
- Wear rubber gloves when using metal-cased portable electrical equipment, or when using electric handheld portable tools in hazardous conditions, such as wet decks and bilge areas. Figure 44

shows rubber gloves that should be used when testing or dealing with electrical hazardous conditions.

Figure 44: Safety rubber gloves

- Insulation testing involves the application of high voltages to motor windings. These windings have capacitive and inductive properties that can lead to hazards. Please refer to the relevant standards, manufacturer's instruction manuals, and other safety standards as may be applicable.
- Never use outlets that appear to be burnt, or damaged cords; See Figure 45.

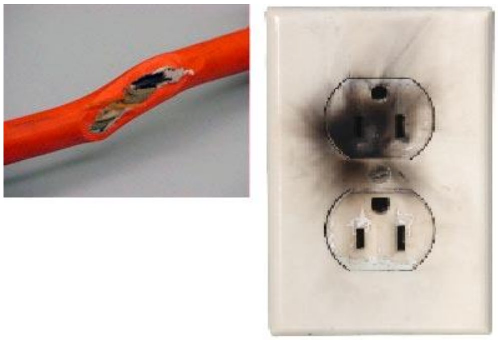


Figure 45: Damaged cords and burnt outlets that must be avoided

C) <u>Tools and Equipment</u>

- Check the portable electrical equipment has been inspected and has a current inspection label affixed.
- Do not use equipment with worn or damaged cords, or crushed or damaged plugs.
- Crane equipment capacity - The capacity and condition of lifting equipment must be adequate to handle large motors safely and smoothly.
- Earthing - The equipment must be grounded separately before use, otherwise, it may malfunction and cause electric shock accidents in the event of electric leakage.
- Wear safety eyeglasses or goggles when grinding, see Figure 46.

Figure 46: Safety googles

- Clean all components thoroughly, using approved methods and solvents or detergents as dictated by safety regulations. Once cleaned, store parts in a clean, dust-free area until needed for assembly.
- Solvents must be used with extreme care while following all applicable safety precautions for the type of solvent used. Most solvents are toxic and can be harmful to personnel if vapours are breathed or if the liquid comes into contact with the skin. Avoid using solvents in contact with open flame or extremely hot surfaces because of the danger of fire or the generation of toxic fumes.
- Always use insulated tools to protect worker from electric shock and reduce the possibility of arc faults caused by short circuits, see Figure 47.

Figure 47: Sample of insulated hand tools, (Fluke.com)

Annex 1 – Core Test

Core loss testing provides a quick and efficient method for determining core losses found in the core steel of stators, rotors, and armatures.

Equipment used in test:

- <u>Temperature detector</u>
  A temperature detector is used to measure the temperature rise of the stator core during the test, as well as to identify hotspots temperature. Detectors that work well include the infrared and thermocouple types
  Do not use mercury filled, thermometers, or bearing are winding are keyed. He's never use your hands to detect, hot spots.

Figure 48: Infrared thermometer

- <u>Commercial core loss tester</u>
  This test can be performed using a commercial core loss tester. If this equipment is not available. You will need to digital multi-meters and ammeter and a watt meter that read true RMS values. You also need a suitable power supply.

Figure 49: Key equipment and tools used for loss testing

If you will not be using a commercial tester, a length of insulated unshielded lead wire to make a loop coil and a length of 14 to 18 AWG or 1 to 2.5 mm, lead wire to measure the voltage induced into the stator core. The test setup is shown in Figure 50. The data obtained from this test should be recorded in a stator core test form, an example of which is shown in Figure 51.

Figure 50: Core loss testing using an non-commercial core tester

STATOR CORE TEST FORM

kW					
Hp	RPM	Manufacturer		Frame	Type
Phase	Hz	Volts	Amps	Model	Serial No.

CORE DIMENSIONS ☐ Inch ☐ mm	Length less air ducts L =	Inside diameter D_i =	Slot depth S =	Back iron depth B =

POWER SUPPLY FOR TESTING
V_s = Volts f = Hz

Remarks

Use this section when core dimensions are in INCHES.

Mean Dia. (D)	D_i + (2 x S) + B = + (2 x) + =	in	Mean Dia. (D)
Loop turns	$\frac{279 \times V_s}{f \times L \times B} = \frac{279 \times}{\times \quad \times}$ =		Loop turns
Estimated amperes	$\frac{28 \times D}{\text{Loop turns}} = \frac{28 \times}{}$ =		Estimated amperes
Calculated induced voltage (V)	V_i x 0.003585 f x L x B (indicates desired core flux of 85 kilolines/in²) =		Calculated induced voltage (V)
Core weight*	0.82 x D x L x B = 0.82 x x x =	lb	Core weight*

*Note: Weight calculation is based on back iron only and does not include teeth.

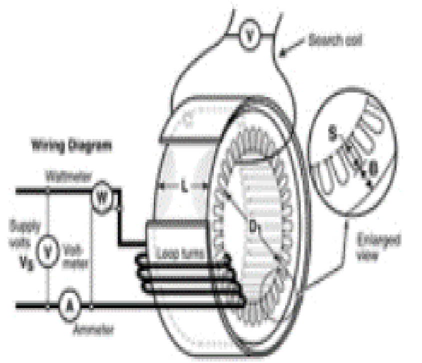
Use this section when core dimensions are in MILLIMETERS.

Mean Dia. (D)	D_i + (2 x S) + B = + (2 x) + =	mm	Mean Dia. (D)
Loop turns	$\frac{180000 \times V_s}{f \times L \times B} = \frac{180000 \times}{\times \quad \times}$ =		Loop turns
Estimated amperes	$\frac{1.1 \times D}{\text{Loop turns}} = \frac{1.1 \times}{}$ =		Estimated amperes
Calculated induced voltage (V)	V_i x 0.000005557 f x L x B (indicates desired core flux of 1.32 Tesla) =		Calculated induced voltage (V)
Core weight*	$\frac{D \times L \times B}{43821} = \frac{\times \quad \times}{43821}$ =	kg	Core weight*

*Note: Weight calculation is based on back iron only and does not include teeth.

LEAD WIRE SELECTION																	
Size AWG	18	16	14	12	10	8	6	4	3	2	1	1/0	2/0	3/0	4/0	LEAD SIZE	
Amperes†	18	22	25	30	40	50	70	90	105	120	140	155	185	210	235		
Metric size mm²	1.0	1.5	2.5	4.0	6.0	10	16	25	25	35	50	50	70	95	120		

†Note: If estimated amperes fall between table's values, use next higher value for selection of lead wire or cable.



CORE TEMPERATURES ☐ °F ☐ °C					TEST DATA	(Use only meters that read true RMS value.) METER READINGS				CORE ASSESSMENT $\frac{W_2}{W_1}$ = =	
Ambient	At start	At end	Rise	Time elapsed (minutes)		Volts	Amps	Induced Volts	Watts	Disposition of core: ☐ Use ☐ Repair ☐ Scrap	
					Before stripping				W_1	Watts/lb**	Watts/kg**
					After stripping				W_2	Watts/lb**	Watts/kg**

** Note: Watts loss per pound (per kilogram) calculations are based on back iron only and do not include teeth.

Job No.	Customer	Date	Tested by	Verified by	Ref. Tech Note 17

Rev 0314RCP1M

EASA The Electro-Mechanical Authority

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Figure 51: Sample of example of a stator core test form, EASA

Importance of testing stator cores - By testing the core before and after the winding removal process and comparing the results, the technician can identify areas where the insulation between laminations has been damaged by a motor failure or the burnout process. Such damage will manifest itself as excessive core heating and hot spots at the damaged spots. This infrared image clearly shows areas that has excess of heating that would adversely impact the rewound motors efficiency and reliability, unless detected and repaired.

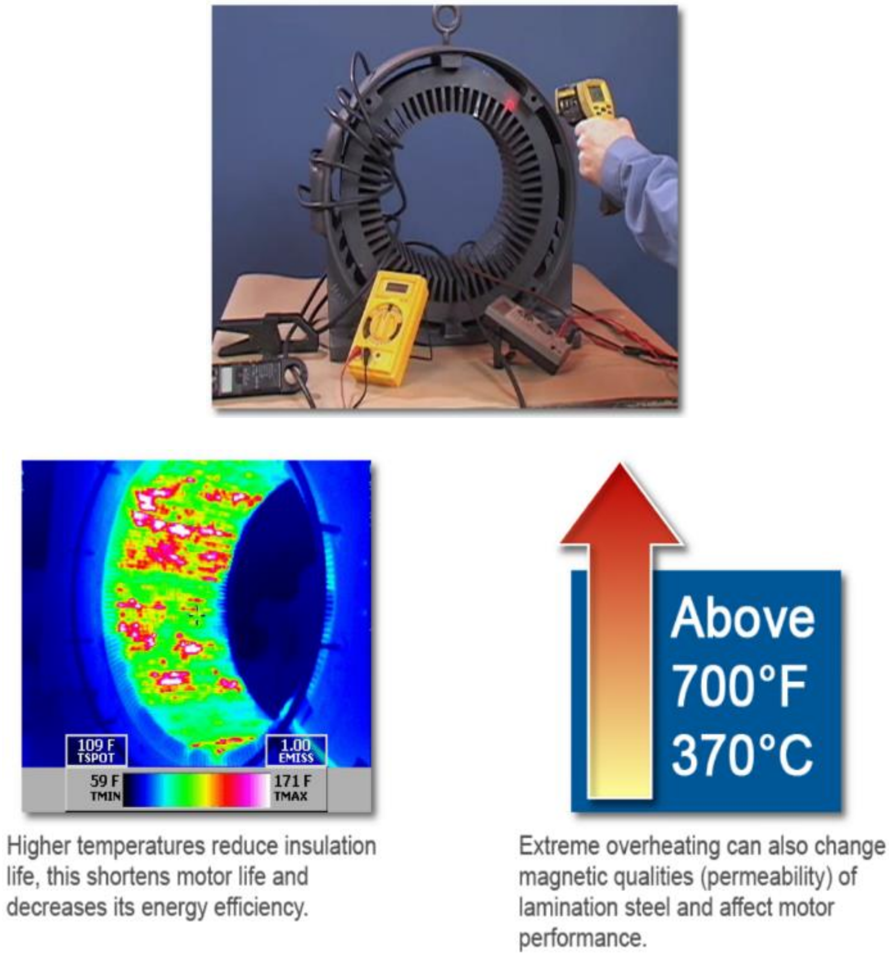

Figure 52: measuring stator temperature using infrared cameras. Bottom: Hot spots in the stator core indicated by camera measurements

Causes of core degradation - Anything that changes the characteristics of the lamination steel or core plate can increase a motor's loss and result in heating of the core. Generally, this is caused by excessive temperature or physical damage.

Overheating can damage some or all of the insulation between the laminations. This could be due to motor failure or excessive temperatures, normally above 370° C . During the burnout process physical damage can weld laminations together resulting in electrical shorts. Higher temperatures, reduce insulation life that shortens motor life and decreases its energy efficiency.

Annex 2 – Failure modes of rolling bearings

The ISO 15243: 2004, "Rolling bearings – Damage and failures – Terms, characteristics and causes" defines, describes and classifies the characteristics, changes in appearance and possible causes of failure of rolling bearings while in service. The standard classifies the failure mode in six main groups and various sub-groups as presented in Figure 53.

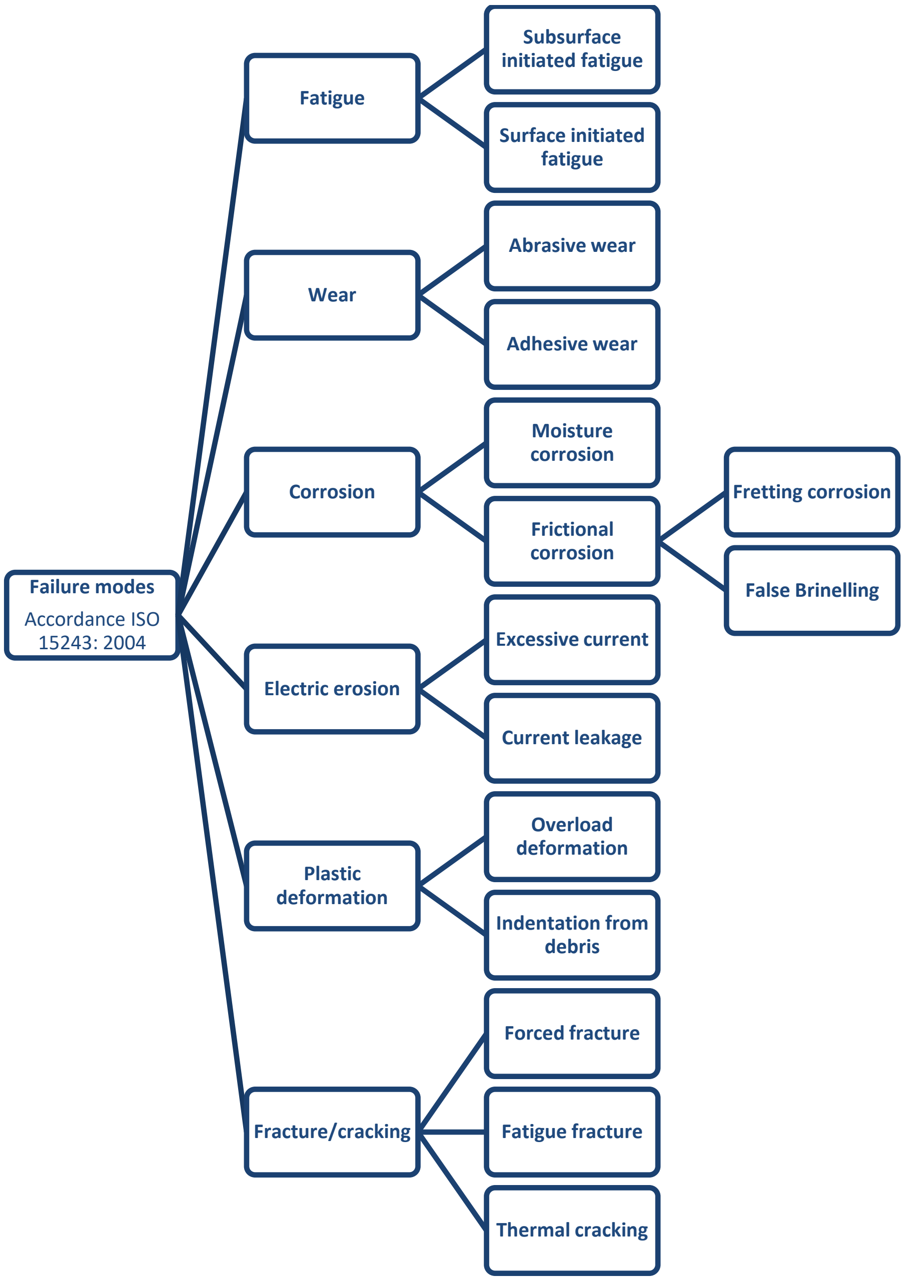

Figure 53: Classifications of failure modes of rolling bearings[6]

[6] *ISO 15243: 2004, "Rolling bearings – Damage and failures – Terms, characteristics and causes"*

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