1 Introduction

A rotating electrical machine can be defined as a machine that converts electrical energy into mechanical energy or vice versa. Such machines either in the form of electric motors or generators quite often constitute the heart in a production unit, whether in the industry or on offshore plants. No matter which maintenance system is utilized the right maintenance of the unit is hence of major importance since any breakdown usually is more or less catastrophic.

The stator- and rotorwindings in electrical machines are often unknown territory to maintenance staff because the windings are well-hidden below shields and covers. Only the output cables in the terminal boxes are usually visible, which unless you have special equipment are difficult for measurement since the winding resistance is fairly low and the windings often are connected in an unknown manner.

2 Why do windings in electrical machines break down?

Depending on design and protection, electrical machines are exposed to many different stress factors. Some of the worst stress factors are the electrical, the thermal, and the mechanical factors.

2.1 Electrical stress factors

The winding insulation is constantly exposed to a transient (excess voltage) bombardment. Due to the transient amplitude of many times nominal operating voltage, the winding insulation can quickly be broken down if it is not completely tight and in order. The transients can come from the supply network, by the re-connection of other equipment, from controls and frequency converters capable of interfering in discordant oscillations, and not least from the winding itself when it is connected to or disconnected from the network.

Contrary to generators, usually connected to or disconnected to the network without any further current change in the windings, it is completely different with electric motors. Motorbreakdowns are frequently noted during the start-up phase, which leads to the presumption that the starting current which can be from 6-14 times the full load current \([I_n]\) is the sinner. This might be true, but electric motors are rarely unloaded before disconnection, which causes the full-load current to be momentarily cut off on its way through the winding. Depending on the connector type and switch construction, substantial transients can occur by disconnection, in the form of voltage \([U_{peak}]\) and not least energy content \([\text{Joule}]\) causing a flashover in the windings.
Unfortunately, the flashover is usually not discovered until the motor is connected again and then it is too late.

![Stress factors for electrical machines](image)

2.2 **Thermal stress factors**

The thermal stress factors occur when the winding expands. When the machine changes from cold to hot during operation both the lamination and the winding expand. The expansion happens as a result from the effect absorbed in the machine as copper and iron losses. The expansion is determined by the accelerating time and thus the initial current progress in rotor and stator windings, respectively. The expansion produces micro-cracks in the isolation, which gives basis for a breakdown in the near future when some of the other stress factors are activated.

2.3 **Mechanical stress factors**

Mechanical stress factors exist in the form of winding vibrations produced by high starting current, operating current, or vibrations from the machines imbalance, etc. Winding vibrations can cause loose winding-overhangs, which will damage the insulation, as well as the risk for loose wedges (slot keys) are present.

The slot keys are locking the coils in the lamination. The slot keys are both manufactured from magnetic as well as non-magnetic material. Besides mechanical power, the magnetic slot keys are exposed to magnetic power, which causes the loosened slot keys to be a very frequently occurring phenomenon. If the loosened slot keys are not detected in time they will be pulled off the slot and pulverized in the machines air gap. Afterwards the winding coils will try to get out of the slot, and a crash is near by.
Especially cage rotors constructed with different kinds of copper rod windings, can be very sensitive to repetitive, long starting attempts as the accumulated energy in the rotor windings will raise the temperature in the winding so much that the welding will melt. As is well known, there are no thermal sensors in the rotor windings to warn us.

2.4 Environmental influence

Electrical machines are cooled by directly supplied air which very often is contaminated by dirt, salt, and any other chemicals. If the machine is constructed as a closed IP 54/55 protection, external cleaning can do the job. If the machine has an open ventilation system in an IP 23 protection, like for instance a number of generators and slip ring motors, it is quite another thing. The electrical, thermal, and mechanical causes mentioned above, offer good reason to be cautious with these machines.

Dirt and salt is deposited everywhere in the machine by the enormous amount of air that is sent through the machine. The winding construction offers an innumerable amount of hiding places which are not readily accessible. When moist and micro-cracks appear at the same time the insolation level will decrease between the windings and the frame, or between two windings, due to the entered dirt and salt. At any number of transients, the insolation value will approach zero, and a short-circuit will crop up at the first occasion with sufficiently high voltage level.

2.5 How it is prevented

The only way to maintain a reasonable insolation level is to supply and maintain a flexible insolation system that keeps out all moist and dirt. Dirty windings necessitate a cleaning before maintenance operation, which in principle is every time.

3 Wash and vacuum drying

For many years different kind of cleaning solvents have been used to remove dirt from the windings. If salt is implied, it is a bad idea to use solvent. The only advantage of solvents is quick evaporation and drying, but solvents do not remove salt. Furthermore solvents wash dirt and oil down into the micro-cracks from where it afterwards can be very difficult to remove. This can produce very poor insolation values, which will require long drying time to become fairly acceptable with the risk of being unacceptable the week after.

In ABB Service we have for many years used water and soap for the washing of windings, and with very good results. The disadvantage of water is the long drying time and an extended consumption of kWh in the drying ovens, but this can be changed. The drying time can be reduced considerably by using vacuum for the removal of water.

After the water- and soap washing, the stator or rotor is placed in a vacuum tank. A vacuum pump lowers the pressure in the tank. The water left in the tank will soon start boiling hence all water evaporates. Water particles and any dirt are whirled up with the water
vapour and sucked out. In only a few hours, the windings are completely dry and ready for impregnation.

With rotors, the great advantage using vacuum instead of drying ovens is that the preheated rotor is cooled by the vaporisation, which allows the assembling of for instance bearings immediately after the rotor has been removed from the vacuum tank. With drying oven, the material has to cool off in several hours before assembling.

### 3.1 Quick repair

Vacuum drying of electrical windings offers great advantages. The repair time is reduced considerably which minimizes long-term and inconvenient interruptions in operation. The vacuum drying guarantees a completely cleaned and dry winding and thus greater dependability. The energy used for removal of water content is reduced with up to 90%, which benefits both the clients as well as the environment.

### 3.2 Vacuum drying with great advantages

- Quicker repair flow
- Better insolation level
- Greater dependability
- Longer service life
- Better overall economy

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**Vacuum-Drying**

1. Energysavings < kWh.
2. Timesaving - drying time < 5 timer.
3. Less temperature = less waitingtime
4. Extended cleaningproces.

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ABB Service A/S
3.3 Post-impregnation
After washing and drying, it is necessary with some kind of sealing of the insolation system to close the entries of moist to the windings just as when a car is undersealed. Without sealing, the insolation level will slowly decrease depending on air humidity, and that could quickly set us back to the starting point.

3.4 Spray impregnation
Many maintenance companies utilize fairly light-fluid anti-leakage current protection lacquer with a high content of solvents when they impregnate electrical windings. The lacquer is usually sprayed directly on the visible windings with aerosol cans or paint sprayers. In field service work, it can be useful for repairing minor damages. However, the biggest impact is usually only for the sake of appearances since the high content of solvent which evaporates during the drying contributes to a lacquer layer that is extremely leaky. Utilized with a minimum of solvents and in generous amounts it can be used on round wire windings (random wound) found on small standard asynchronous motors.

3.5 Dip impregnation
If the repairshop has a dip impregnation vessel it is possible to submerge the entire winding. This allows the entire winding to be post-impregnated. However, the result is extremely dependent on the lacquer type utilized. Good penetration ability requires low viscosity, which means a large content of solvents. If the dipping leaves 10 kg of lacquer on the winding, the 5 kg will evaporate during the hardening at a solvent percentage of 50. Furthermore, the 5 kg must be burned off during the drying to ensure that the birds do not catch a headache…

Lacquer with low viscosity only leaves a sparse wear layer on the outside of the winding where a thick layer is desirable. Apparently, we are facing a job that requires several procedures and different lacquer systems.

3.6 Requirements for impregnation systems
The following requirements can be made on an impregnation system for insolation systems in electrical machines:

- It should be possible to impregnate each single winding at form coil windings
- The viscosity of the lacquer should be as high as is necessary to fill in any airspace in partial windings and below wedges as well as to leave a fair, thick wear layer on the winding overhangs, etc.
- The viscosity of the lacquer should not be too high, causing the air circulation in the cooling hoods of the lamination packets to stop.
- The lacquer should be so resilient that it can endure the expansions in the windings without crazing.
- The lacquer should not contain more than 10% solvents.
At first, the job seems insoluble although the technique has been known for years. But it has only been utilized in the production of electrical machines designed for rated operating voltage higher than 3kV and for the impregnation of special rotors for e.g. traction motors.

4 Vacuum – Pressure – Impregnation [ VPI ].

To remedy the deficiencies and imperfections of the dip impregnation, we have introduced the VPI technique at ABB Service.

4.1 Procedure
After washing and vacuum drying, the pre-heated winded components are placed in a pressure vessel. The pressure in the vessel is lowered to 0.6 mbar. In this vacuum, a specially developed styrene-free one-component special lacquer is led to the vessel, whereby the windings are submerged. The vacuum ensures that any air bubbles are sucked out of the lacquer. The special lacquer contains less than 4% solvent and thus it is avoided that the substance will start boiling in this low pressure.

4.2 The lacquer makes its way
The vacuum is then changed to a positive pressure of 6 bar, i.e. a pressure ratio of about 10,000 times which ensures that the lacquer is pushed into the core of each partial winding and encircles all coils, windings, and wedges. After approximately 60 minutes, the pressure is removed and the component is transferred to an electric heated oven in order to harden the lacquer.

4.3 Substantial improvement of dependability
A substantial advantage in utilizing this impregnation method is the possibility of using a special lacquer with high viscosity without solvents. The high viscosity ensures that a thick layer of lacquer is applied to the windings and thus a high level of insolation is attained.

This impregnation technique ensures optimum heat dissipation from the winding and with it an increased load capacity. All air leaks in the winding are filled with special lacquer, which has a considerably better thermal conduction ability than air, and therefore the condition of good heat transfer is optimum. VPI impregnated windings thus sustains much more overload also because the number of the so-called hot spots, i.e. poorly cooled winding parts, is minimized.

Experiences show that VPI treated electrical machines are substantially better protected against mechanical, electrical, thermal, and environmental influences.
4.4 VPI is a good investment

VPI gives a better dependability due to:

- Supreme insolation level
- Increased mechanical stability
- Increased load capacity
- Reduction of magnetic and electric noise
- High protection against corrosion
- Longer total service life
- Reduced risk of break down
- Repaired and overhauled motors and generators can become better than new motors and generators

VPI impregnation of electrical machines in the effect range from 100 kW to 4000 kW has increased considerably in recent years since more and more manufacturers have discovered the advantages of VPI. What especially makes VPI attractive is the greater effect that each machine can be loaded with due to the improved heat conduction.

For the purpose of maintenance it is the supreme insolation ability and the high viscosity utilized which at the same time ensures both the windings and the wedges in an easy way. Once the break down in the heart of the factory is a fact, it often takes the maintenance staff by surprise that (special) electrical machines, both small and large ones, are not kept in stock for delivery in a few minutes.
A complete rewinding of a 3 MW stator designed for 10 kV takes 3 to 4 weeks. The smaller machines are handled more quickly. To avoid total breakdowns, checking the mechanical and electrical condition on the electrical machines are a really good idea, because:

One measurement is better than 100 opinions.