574

Guide for Consideration of Duty on Windings of Generators

Working Group A1.22

April 2014

cigré

Guide for Consideration of Duty on Windings of Generators

Working Group
A1.22

Members

Michel BERLAMONT (FR) – (Convener), Hideyuki SHIMADA (JP) – (Secretary),
John DOYLE (EI), Sako HIROSHI (JP), Shinobu SEKITO (JP), Aleksander ZIELONKA (PO),
Robert FENTON (US)

ISBN: 978-2-85873-269-2

Table of Contents

INTRODUCTION

Generator life time is significantly related to the ageing of its windings. Several factors such as cyclic duty are contributing. Four previous CIGRE questionnaires have already investigated the ageing processes. This brochure is an update to integrate more feedback based on the experience and latest developments such as higher thermal class insulation or on-line monitoring.

This Guide will review operating practice, ageing processes of generator windings, their consequences and the way to monitor and detect fault appearance, and will propose the condition assessment and maintenance practices according to generator technologies.

1. DESIGN / LIFE TIME / MAINTENANCE

It should be understood that based on the customer requests, the generator design is adapted resulting in different life time expectations and maintenance costs and/or strategy.
To explain the interaction between design, life time and maintenance of a generator, the two opposite cases are considered:

- An Independent Company owning a power station with gas turbines rated 50 MW. Such a customer wants for a quick payback, high availability, low costs for monitoring and maintenance. In the market of air-cooled generators there is a strong competition resulting in low selling prices. Several different technologies are proposed to fit to the requirements.
  As example for the stator design:
  - Global impregnation for the stator winding (price optimisation, no maintenance)
  - Use of higher thermal insulation to allow a better ratio MW per volume of the machine

  Except for the standard thermal and bearings vibrations sensors the generator is not equipped with particular on-line monitoring such as PD measurements.
  For such unit it is accepted that after 25 to 30 years complete retrofit generally with upgrade has to take place. This is in line with the expected life time for the generator windings.
  The investment in a spare rotor is not considered as profitable unless the power plant is composed of several identical units rated above 100 MW.

- A nuclear project for a state public company or large generating company. The unit load is between 1200 to 1800 MW. The customers have nowadays the following requests :
  - Life time of 60 years
  - Optimized maintenance periodicity and durations (major overhaul every 12 years, outage of 25 days)

  Compare to the previous case the economics are completely different: the loss of income for a supplementary outage day is depending on the season but in the range of several million dollars. Also the nuclear island has specific requirements: number of emergency stops is limited, operation time at no load with the nuclear reactor in active condition should be as short as possible.
  In this case the generator design should provide robustness together with maintainability.
  - No global impregnation but re-tighten-able wedging system for the stator winding
  - Compact end windings basket also re-tighten-able depending on design
  - Use of low friction material and/or ripple spring in the rotor slot to reduce the ageing for the rotor winding during operation or in barring mode

  Condition assessment of such generators is required to avoid forced outage and schedule corrective maintenance.

So the generator is equipped to allow a full comprehensive on-line monitoring:

- PD measurements
- Stator end windings vibrations sensors
- Rotor winding insulation resistance measurement
- Rotor flux probe for inter-turn short circuit
- Etc...

For the analysis of the condition monitoring information the operator has to:

- Periodically borrow an external expertise (OEM or specialized companies)
- Or develop his own data acquisition system and train specific staff

Even with optimized design rotor or stator winding will age and a replacement or repair after 30 years of operation has to be planned. OEMs have developed processes to allow fast stator re-winding.
For the rotor a replacement by a new one or a full rewind are options.
Depending on the number of concerned units, the customer considers the acquisition of a spare rotor as worthy in order to secure the duration of scheduled outage or minimize if unscheduled.

All the OEM's technologies, power plant types or practices cannot be individually discussed. Each customer depending on its investment, the payback, the cost of production, quantity of units, etc. should define its maintenance strategy (buying or not of spare rotor or stator, use or not of on-line monitoring and its importance).

2. PROCESS OF DEGRADATION

The stator and rotor windings have different processes of degradation.
The most active operational parameters are the number of start-up cycles and the number of operating hours which reflects the thermal ageing, normal vibration cycles as well as the load cycling (The stator and rotor current variations arising from active and/or reactive power variations).
System disturbances for the stator winding and the number of barring hours for the rotor winding have to be also considered respectively.

Regarding the thermal ageing the international practice is to use the insulation class one step above the permitted temperature rises in order to ensure a 20-25 year lifetime of the insulation.

This aspect has to be considered when a prime-mover upgrade takes place. Such a situation is not unusual especially in gas turbine plants. Rather than encroaching on the thermal margin (e.g. increasing temperatures above class B limits for class F insulation), the better option for longevity of the insulation is to maintain the thermal design margins by upgrading the cooling system or using class H insulation.

For larger capacity units (Hydrogen or Hydrogen/Water cooled turbo generators) different strategies are used to minimize the stresses in the windings due to differential expansion, the most common being to hold the inlet coolant temperatures constant.

The strategy of holding the water temperature over the cold gas temperature would seem to be more directed by avoidance of condensation than at limiting thermal stresses, though depending on how the cold gas temperature was regulated, the stresses could be controlled also.

Maintaining maximum temperatures within the component capabilities will avoid premature loss of life.

2.1. STATOR WINDING

Typical end-winding structures of indirect or water-cooled stator winding are presented respectively with figure #1a & picture #1b and with figure #2a & picture #2b.

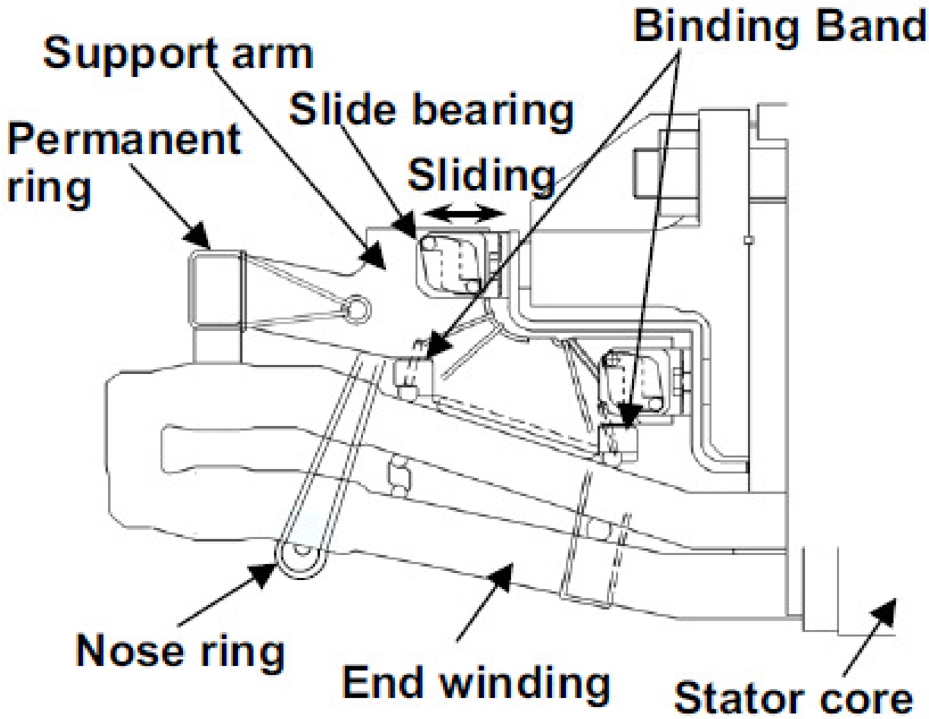


Figure 1a: Stator end winding support structure of Air-cooled generator

Picture 1b: Stator end winding support structure of Air-cooled generator

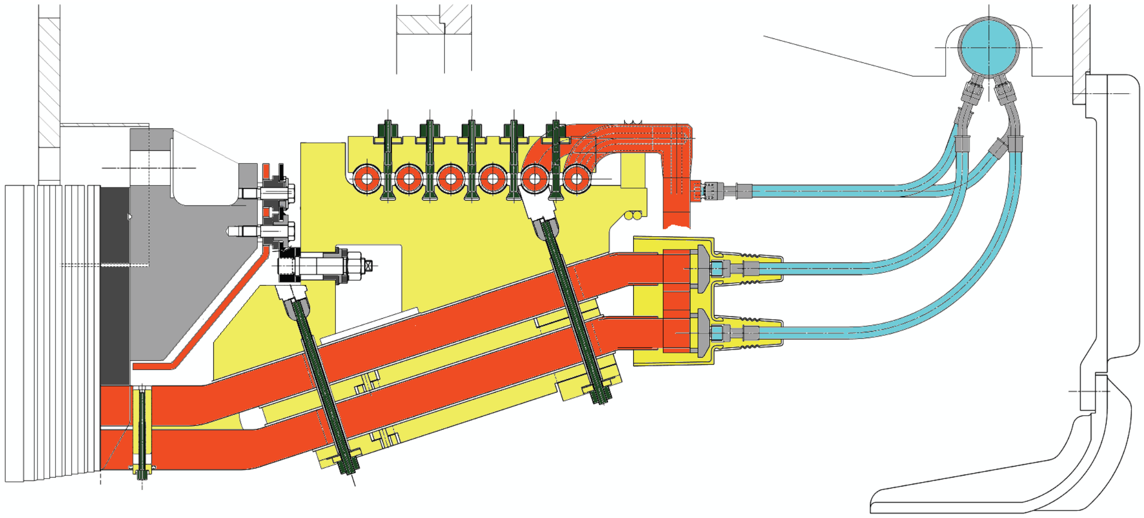
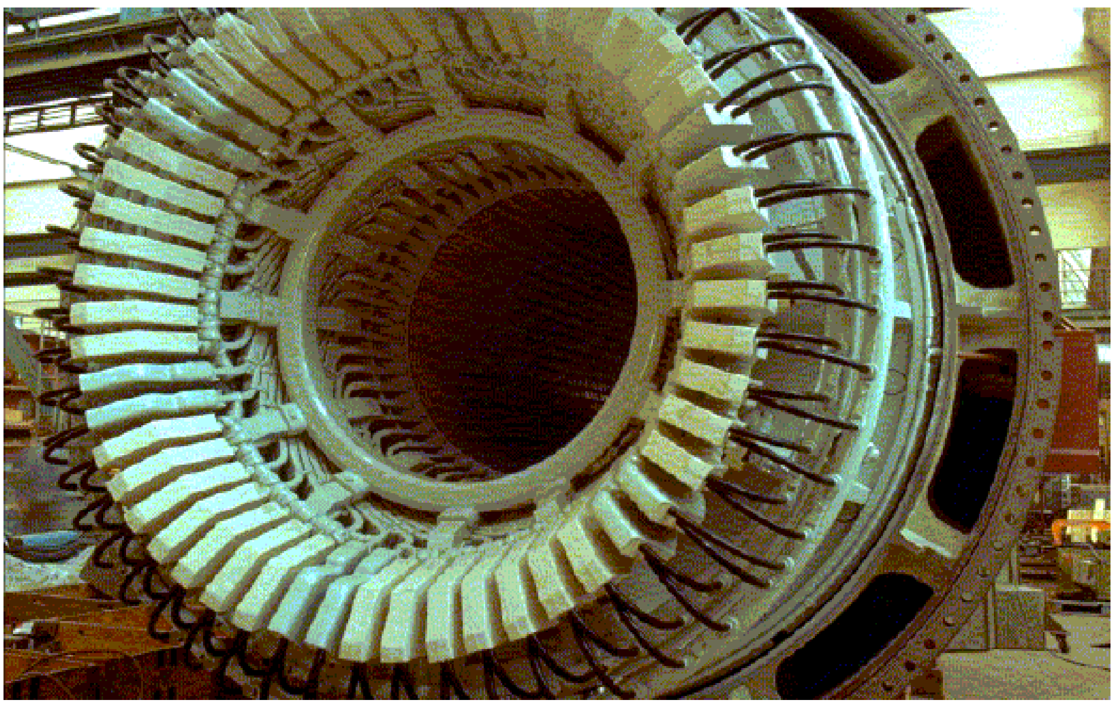


Figure 2a: Water-cooled stator end winding support structure



Picture 2b: Stator end winding of water-cooled generator

Typical stator slot structure is presented with Figure 3 and associated bar cross sections with the pictures # 4a & #4b.

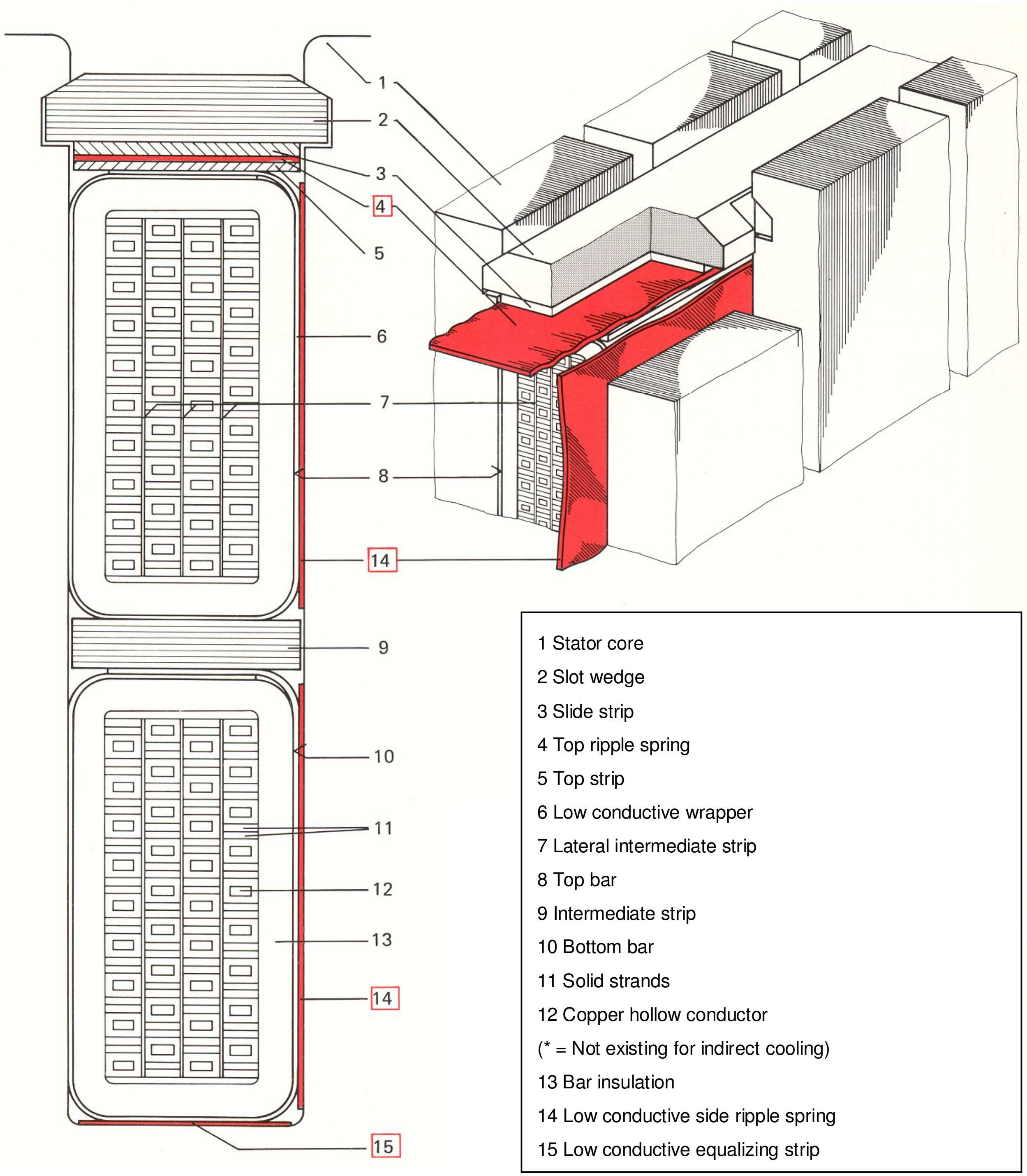
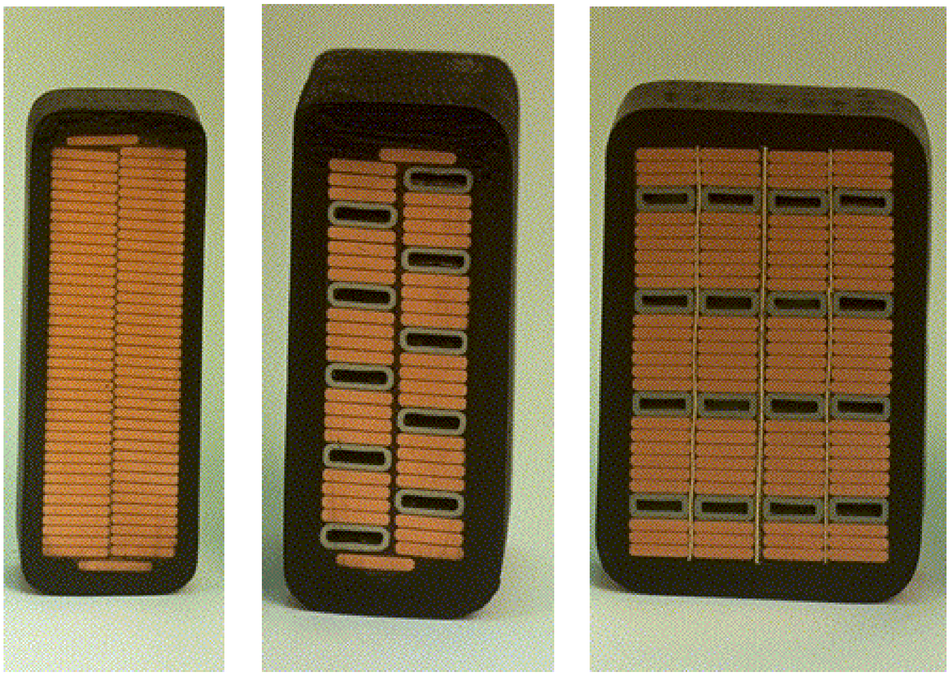


Figure 3: Stator slot cross section



Pictures 4a & 4b: indirect & water-cooled stator bar cross section (single & twin bars)

The possible stator bar insulation degradation processes are shown in the chart #5.

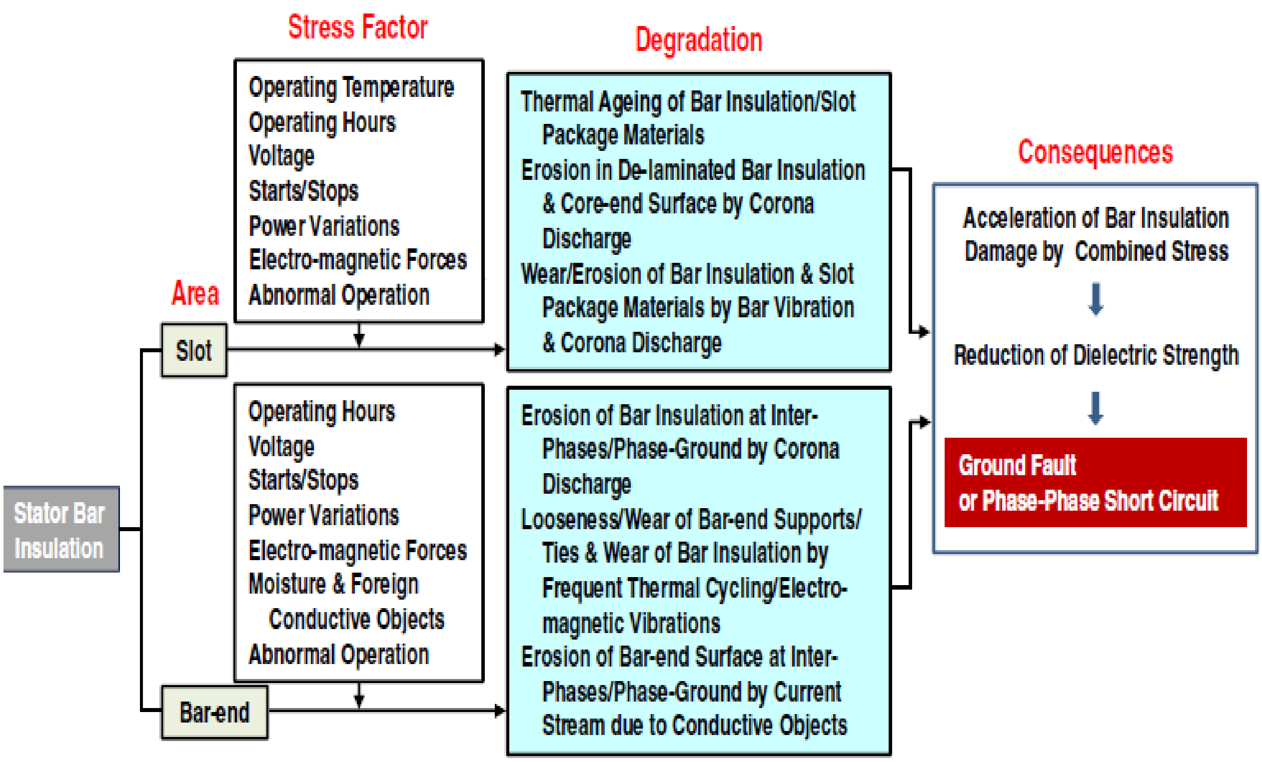


Chart 5: Degradation process of stator bar insulation

The two main processes of degradation are identified as the following mechanical factors:

- Vibrations caused by electro-mechanical forces in stator winding and/or core
- Exposures to mechanical stress surges during system disturbances, out of phase synchronisations, or short-circuits in bus bar system

Both affect all components of the stator winding, including bars in the straight portion and in the end windings, connections of bars and phase rings, ties and blocking in end windings, liquid coolant boxes and piping on liquid cooled stator windings.
In addition the phenomena of discharge in slot could be a concern for air-cooled machines.

These phenomena are discussed in more detail in the following sections.

2.1.1. STATOR CORE VIBRATION

The number of start-up cycles, frequent output power variations and number of operating hours affect the solidity of the slot section and of the winding structure.

A successful slot restraint system will substantially reduce the speed of ageing from these causes. In contrast movements of the stator conductors lead to ageing of the stator winding through either wear or electrical degradation of the insulation (slot discharge or slot vibration sparking).

Degradation of the properties of the insulation due either to temperature or to fatigue appears as a parameter of second order as long as the thermal design margins are maintained.

Relative motion of the components in the stator end winding is a major factor determining the life of the winding in that area. A resonant vibration condition or loose components in the end winding may either wear into the insulation and lead to failure, or may permit motion of the stator bars that can also lead to failure.

2.1.2. SYSTEM DISTURBANCES

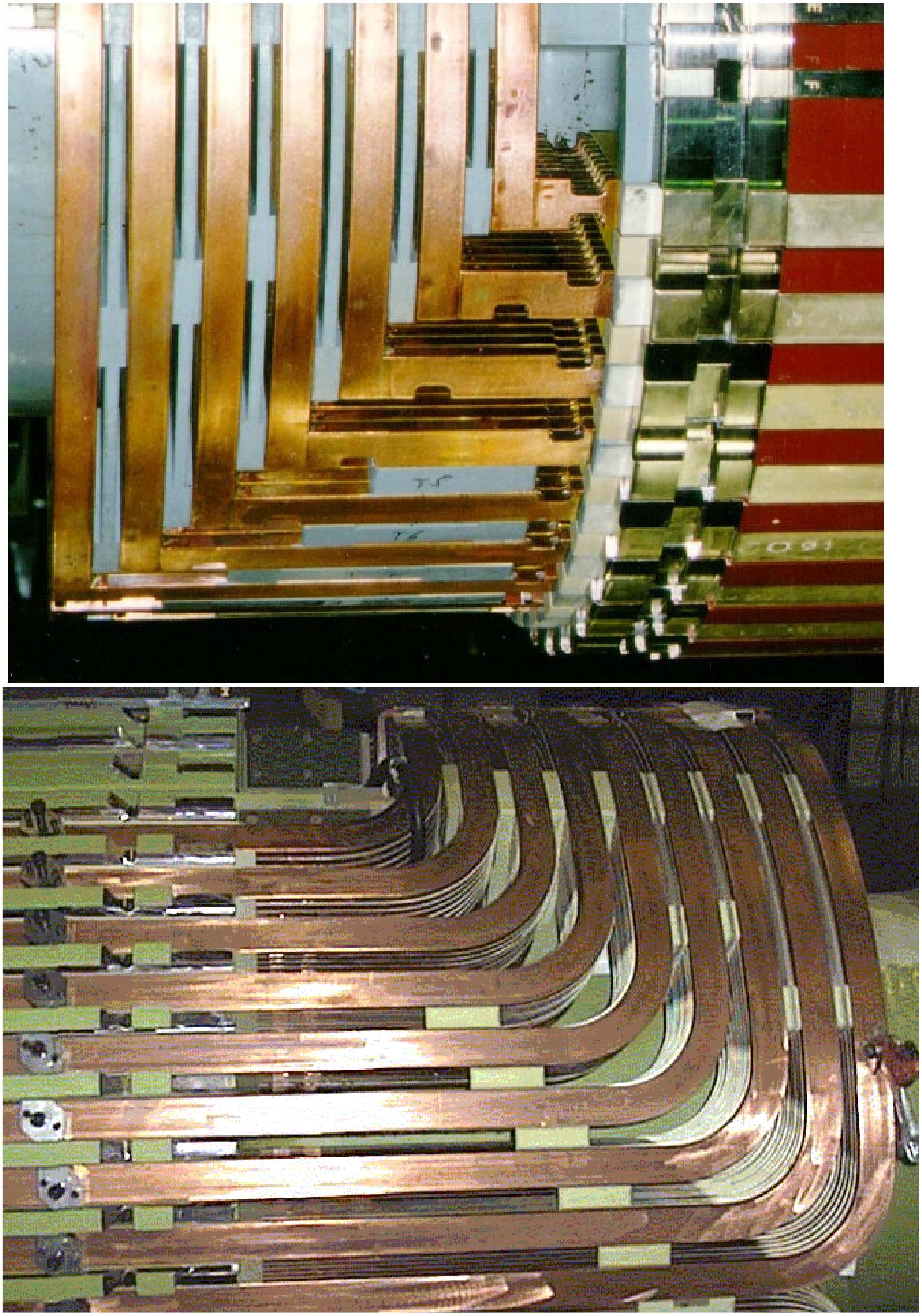
In regard to degradation of stator windings by vibration, system disturbances such as short-circuits and bad synchronisations are rather infrequent, but can result in very high transient currents in the stator windings with subsequently high electro-mechanical forces being exerted on the conductors and support hardware. This can cause loosening of components which in turn may trigger the occurrence of increased vibrations within windings and as a consequence raise the importance of operating hours. A thorough visual inspection of the stator winding is recommended after the generator has experienced such a severe event.

2.1.3. ELECTRICAL DISCHARGES IN SLOT

Partial discharge/Corona discharge is mainly a concern for the air-cooled generators as the breakdown voltage of pressurised hydrogen is higher compared to atmospheric pressure air. In case of air-cooled generators, the ozone gas developed by partial discharge and moisture included in air will accelerate the degradation of insulation materials. The likelihood of partial discharges occurring is depending on the method of insulation, the slot content and stress grading design.

2.2. ROTOR WINDING

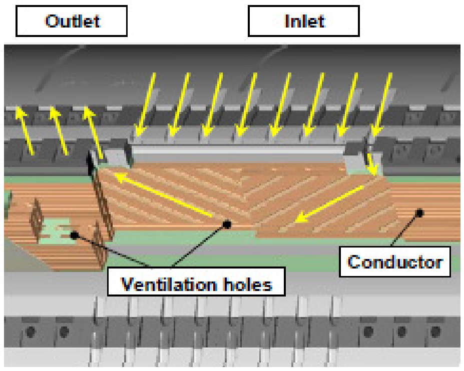
Some typical rotor end windings structures are presented page 10 with the pictures #6a & #6b.



Pictures 6a & 6b: Rotor end windings

Typical rotor slot section vs. ventilation scheme (gap pick-up or radial ventilations) are presented page 11 respectively with figures #7a & 7b and #8a & 8b.

Gap pick-up ventilation



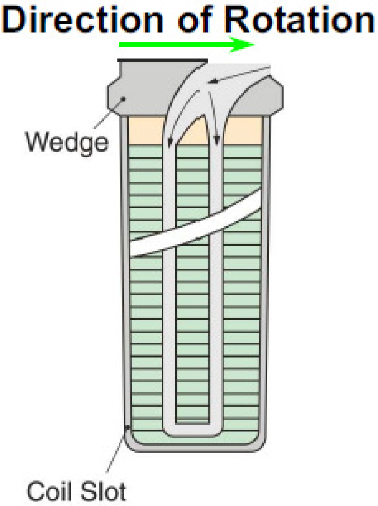


Figure 7a: Rotor ventilation scheme Figure 7b: Rotor slot section

Radial ventilation

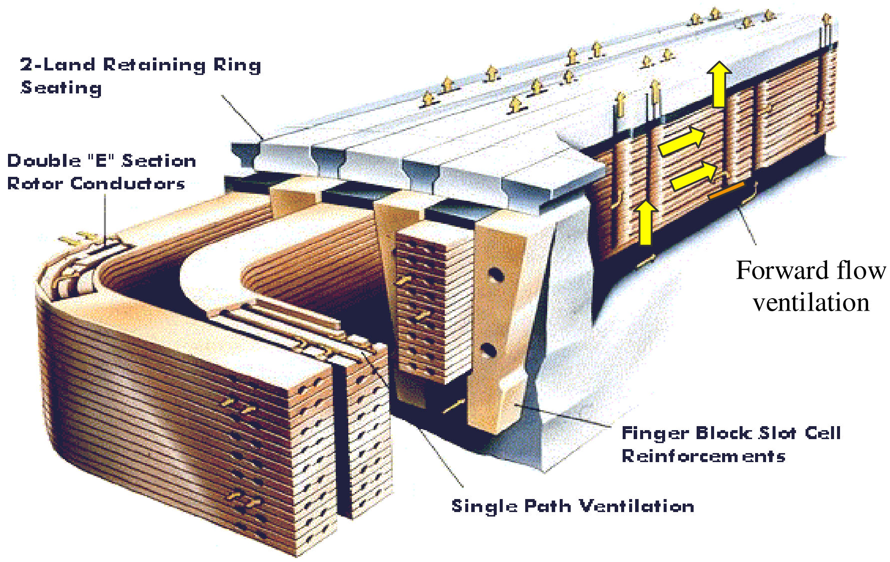


Figure 8a: Rotor ventilation scheme

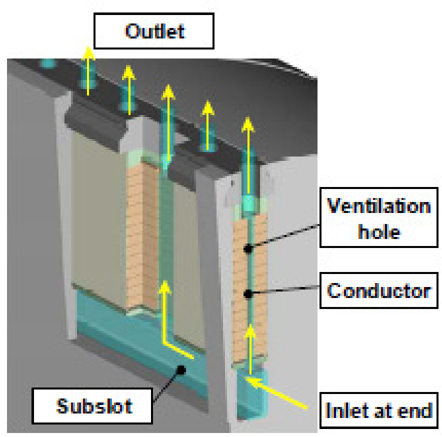


Figure 8b: Rotor slot section

The possible rotor winding insulation degradation processes are shown in the chart #9.

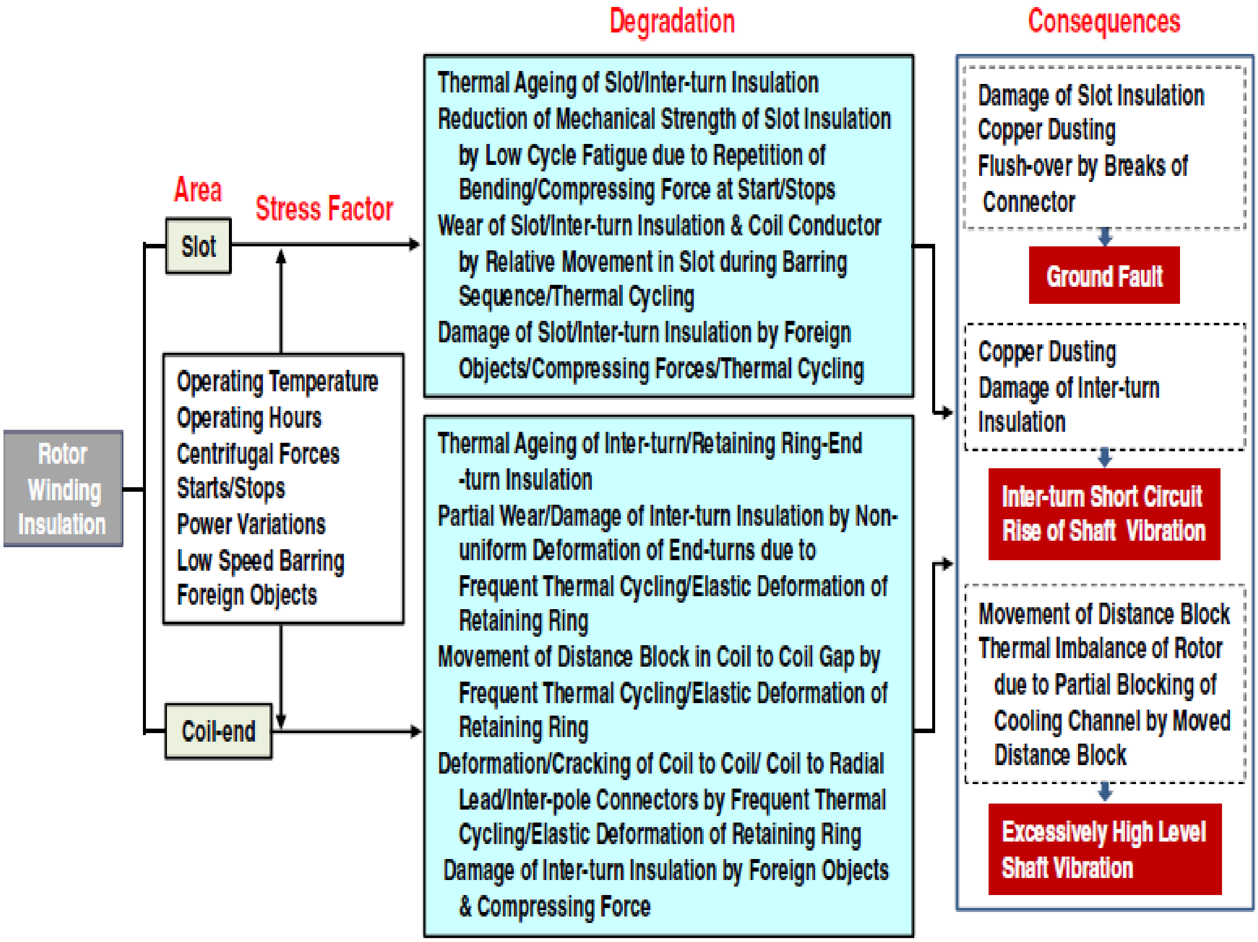


Chart 9: Degradation process of Rotor winding insulation

The two main processes of degradation are identified as the following mechanical factors:

- Low cycle fatigue resulting from a succession of rotor start-ups and shut downs, the components being subjected to changing centrifugal forces.
- Mechanical stresses resulting from the conductor thermal expansion due to the excitation current and the associated friction forces as the various wedging between coils in the end windings acting to various degrees against this expansion.

The thermal expansion of the winding in respect to the shaft is the most important ageing parameter for the axial parts of the conductors and the insulation in the slot (inter-turn and ground insulation).

The low cycle fatigue due to start-up cycles mainly affects the conductors at the end of the body and under the retaining rings, all the connections between coils and the inter-polar connection. This is a consequence of the increase of the retaining ring diameter with the centrifugal force, resulting in tangential movement between the coils. The current inlet and outlet of the winding (radial leads and axial conductors between the central bore connection and the coils) are also affected by low cycle fatigue due to centrifugal force.

In practice, the influence of these two mechanisms is combined.

Another process of degradation is the relative movement between winding and shaft during barring sequences. This phenomenon is important for the slot ground insulation, the inter-turn insulation, the top packing strip, but also for the axial part of the conductors in the slot and at the end of the body. Also certain rotor winding designs incorporate copper-to-copper contact within a single turn. During normal operation centrifugal forces keeps elements tight, however during barring the forces are lower and copper dusting can be generated at the copper-to-copper surface. This dust can create inadvertent conductive paths within the winding and can lead to short circuits between turns or winding to ground faults.

The frequent start/stop (thermal cycling) and repetition of increase/decrease of retaining ring diameter can result in permanent deformation of rotor coil-end and movement of distance block assembly in coil to coil gap. This can result in partial blocking of cooling channels and inter-turn short circuits due to non-uniformity of individual turn conductor deformation. Consequently thermal imbalance can arise and the shaft vibration levels increase.

The bending stresses due to the deflection of the rotor are considered as a secondary parameter, affecting essentially the conductors at the end of the body, the radial leads and the current leads to the coils.

The influences of the active operating parameters in these degradation processes are:

- The number of operating hours affects mainly the inter-turn and ground insulation, through a process of thermal and mechanical ageing.
- The number of start-up cycles, as well as the number of over-speeds, is considered as one of the most important cause of ageing by mechanical fatigue and deformation of the winding ends, current leads, and connections between coils, inter-polar connection, various brazed joints and also conductors at the end of the body.
- Cycles of current changes, because of the resultant thermal expansion, are the main cause of the ageing of the winding in the slot, and in a less extent under the retaining rings. However the ageing of the winding under the retaining ring may be the primary ageing mechanism in some OEM designs. The addition of a low friction coefficient coating on retaining ring insulations is one solution as it prevents sticking and distortion of conductors and insulation and allows the thermal expansion.
  Rate of change of current can be considered secondary, however it is still an important driver in mechanical degradation. A faster rate of change will produce higher shear forces between coil and core due to different rates of thermal expansion. A very slow rate of change would produce low shear forces.
- The number of barring hours is identified as active parameter on the ageing of insulating materials in the slot and also under the retaining rings for certain rotor winding designs (where copper-to-copper contact is present). To prevent degradations the choice of barring speed is also important.
  Two options are present:
  - Very slow barring speeds (a few rpm) when considering that the wear is related to the total number of cycles
  - High speed barring to limit the micro movement of the winding in respect to the shaft.

  There is no recommendation, the risk depending on the rotor technology. The use of ripple spring in the slot content is one solution to restrain conductors' movement at low rotation speed.
  The design of the turbine is also to be considered in the choice of the barring speed.

3. CONSEQUENCES OF DEGRADATION OF WINDINGS

3.1. STATOR WINDING

3.1.1. Broken conductor

The consequences of conductor cracking are ranged from the melting of joints with breakdown of stator ground insulation and limited damage of the windings, to some minor damage, with gas in coolant leaks that could be repaired in-situ.

3.1.2. End winding loosening

Dusting and abrasion in end windings are in most cases related to mechanical causes such as loosening and vibration of parts. This is a long-term degradation for all type of generators. The end windings status are detected on regular overhauls and rectified by cleaning, retightening, rebracing or possibly complete refurbishment of the winding and its support structure. Some failures with forced outages have been also experienced.

3.1.3. Short circuit fault

Short circuits between phases are experienced on all types of generators.

Causes of the short circuit failures are:

- Corona degradation leading to tracking in the slot portion particularly on air cooled generators
- Foreign metal pieces
- Humidity in end windings particularly on air cooled generators (the hydrogen indirect cooled, hydrogen inner cooled and liquid cooled types are fitted with hydrogen dryer to prevent water condensation during the operation),or on the stator water cooled generators subjected to water boxes leakage
- Leakage water short circuiting terminals

Consequences of short circuits inside the generator are very high electro-mechanical forces causing loosening and damage to windings, wedges, end winding supports & blocking, etc…. There will be localised severe overheating/burning with consequent damage and loss of material at the short circuit location, the extent of damage being dependent on protection tripping time.

3.1.4. Faulty synchronizing from standstill

Even though infrequent such an incident is extremely prejudicial to the generator. Regarding the stator winding it induces large torsional forces and can impact its mechanical integrity. Mechanical forces can cause loosening and damage of end winding components in particular.

3.1.5. Ground fault

Ground faults are experienced more often than short circuits.
Such faults occur also on all types of generators in different parts: slot portion, end windings (see below picture #6), terminals.

Picture 10: Insulation failure in end winding

Causes for the failure are:

- Lamination pieces of core cutting through insulation of bars
- Water leakages
- Cracking of bar to bar connection; broken copper strands
- Core heating damage
- Obstructing coolant passage of stator conductor
- Foreign magnetic particle within ties
- Broken conductor in slot
- Electric discharges

Consequences of ground faults are similar to short circuits faults, with the extent of damage being dependent on protection tripping time and the neutral earthing arrangement. For more information on this topic see the CIGRE Technical Brochure: **'Guide on stator grounding systems on Turbo-generators'.**

3.2. ROTOR WINDING

3.2.1. Broken conductor

Broken conductors are experienced, rarely in the slot, but more frequently in the coil ends and also broken radial leads to winding or to slip rings have to be considered.

The most frequent consequence is a local overheating leading to arcing, burning of the insulation, and finally earth fault with local melting of steel (shaft or retaining ring).

Some consequential damages to stator can also result from a broken radial lead.

Partial or total cracking of the inter-polar connection and deformation have to be mentioned.

It is considered that the risk of damage depends on the protection level setting.

3.2.2. Cracking of insulating materials

Cracking of insulating materials can result in a ground fault or in inter-turn short-circuits.

Ground insulation:

A ground fault of the rotor winding has no detrimental consequences in operation, but two ground faults can result in a severe melting of copper and steel. The function of the earth fault protection is to stop the generator before this occurs.

In the particular case of 4-pole generators, ground faults can also result in more or less severe vibrations due to the corresponding magnetic unbalance.

Inter-turn faults:

They result in an increase of the field current, thermal imbalance and a more or less apparent change in the vibration behaviour of the rotor (progressive thermal unbalance for 2-pole rotors, magnetic unbalance for 4-pole rotors). Also a risk of overheating is possible, resulting progressively in a ground fault.

3.2.3. Policy in respect to Ground fault

The policy in case of ground fault depends on the utilities. Some apply a standard procedure for high rated units and the unit is stopped for inspection and repaired when the winding insulating resistance comes below a predetermined level. For the majority, the decision depends on the circumstances and the unit is generally kept in operation with an increased monitoring up to the next scheduled maintenance.

It is to be noted that manufactures and utilities have often a different view in respect to the risk of operating a generator with a low rotor winding insulation level.

The minimum insulating level accepted varies from a few kΩ to a few MΩ.

The decision depends on the level of risk accepted by each utility, and of several factors such as:

- Level of protection
- Difficulty to measure permanently the insulation level with a brushless exciter
- Availability of a spare rotor

3.2.4. Operation with inter-turn faults

It is generally acceptable to operate a generator with a limited number of inter-turn faults, the consequences being often minor (acceptable increase of field current and vibrations).

A site rebalancing can be carried out to improve the behaviour of the rotor. After some time of operation with inter-turn faults, when the vibration level becomes unacceptable, or the field current out of the limitations, the winding has to be totally or partially removed for repair.

3.2.5. Faulty synchronizing from standstill

Asynchronous currents flowing through the rotor body and the retaining rings occur on faulty synchronization. Consequently removal of the retaining rings and slot wedges for inspection is the minimum, however repair or replacement of a rotor winding, slot wedge and shaft teeth are sometimes necessary.

4. FAULT DETECTION - SERVICING - CONDITION ASSESSMENT

4.1. STATOR WINDING

4.1.1. Fault detection

Routine high voltage testing is a common method to ultimately test the dielectric strength of windings. For AC testing the normal range is 1,25 to 1,5 x U nominal, 1 min, with the exact level depending on condition and history of the unit. Traditionally in some countries a lower test voltage of 1.25 X U/√3 to 1.25 X U is applied depending on agreement of utility and manufacturer.

For DC testing the following voltages are used:

- 1,7 x 1,5 x Un (line to line)
- 2,2 x Un (line to line)
- 2,5 x 1,7 x Un (line to line)
- 1 or 2 kV with direct voltage injection apparatus
- 1.7 X (1.25 X U/√3 to 1.25 X U)

Note the factor 1.7 is an internationally used multiplier from AC test voltage to equivalent DC voltage

Detection of clogging conductors is practiced for water-cooled stator windings. The most common procedures are listed as follows:

- In operation
  - Inlet-outlet temperature monitoring of water for each single bar
  - Pressure drop versus flow measurements of complete winding
  - Hydrogen-inner cooled windings are supervised by H2 flow or temperature monitoring
  - Temperature monitoring of elements in slots
- At standstill
  - Individual conductor coolant flow test with water or air flow on suspected bars
  - Individual conductor flow test with Doppler device and coolant in operation
  - Endoscopic probes

Blocked and partly blocked hollow conductors are commonly experienced. Experience demonstrates that clogging has never occurred in windings with stainless steel hollow tubes. Change of dissolved oxygen content regime of water is considered as the main cause of the clogging of the copper hollow conductors.
A direct correlation with water pH condition cannot be concluded. For more information on this topic see the CIGRE Technical Brochure: **'Guide on Stator Water Chemistry Management'.**

An important parameter in context of hollow conductor blocking on liquid cooled stator windings is the water treatment practice:

- Low level of dissolved oxygen content or saturated condition
- Neutral pH or basic pH condition

Wedge tightness checking methods are becoming more significant and important since retightening actions require having the rotor removed which, as a trend, is routinely less frequent in time period.

In most units, the first check after commissioning is made 2 to 3 years after commissioning. Later, wedge tightness checking is performed on major overhauls, which results in interval between 6 to 9 years. The test intervals can be reduced to 3 or 4 years (intermediate overhauls) by using air gap robots.

Re-wedging activities depend largely on the operation mode of generators. Some need partial re-wedging after 1 to 2 years of operation after commissioning. Later, partial re-wedging activities may become necessary in intervals of 6 to 8 years and total re-wedging actions may be necessary in intervals of 10 to 25 years.

Checking of end winding support structures can be performed in most units without rotor removal and is therefore practiced whenever end covers are removed or access to the end windings is provided through manholes etc. Intervals can vary between 1 to 4 years. The need for re-tightening varies between 2 to 10 years.

Re-tightening can consist of lacing work, adjusting of brackets or by re-torqueing pre-stressing bolts on larger units. On air-cooled generators re-tightening of end windings is reported to be reasonably common.

In other stator end-winding support designs, generally re-tightening of the support system is not common.

Although most of the windings are protected with insulation, some designs still are exposing bare un-insulated metal components. Experience in regard to a reduction of stator winding integrity due to such un-insulated parts demonstrates this is not a critical issue, if appropriate care is taken in operation. As an example a ground fault could be caused by leakage water tracking along terminals. In order to detect degradation of end winding insulation due to water from leaking, mapping of local capacitance or surface potential can be quite effective depending on the stator bar insulation design.

4.1.2. Servicing

Overhaul planning can be performed based on time or on condition.
Presently most utilities use a mix of both systems.

More and more units are inspected during short outages and the timing of major activities is synchronized with maintenance work on other components (integration in gas or steam turbine maintenance program) or with the refuelling outages of nuclear power plants.

The scheduling of generator overhauls is moving from time based to condition based planning and intervals between major overhauls have been extended to 9 to 12 years with intermediate overhauls and short outages made every 3 to 4 years.

An important factor in overhaul planning is given by the condition assessment technologies.

In major overhauls, visual inspection, slot wedge tightness testing, interlamination testing of low flux density and core tightness testing are common procedures along with some type of dielectric testing.

Six dielectric tests are commonly used to validate the stator winding condition.
Five allow by the analysis of the past and present results to define predictive maintenance.
The last one is more challenging: it will pass or fail without any warning.

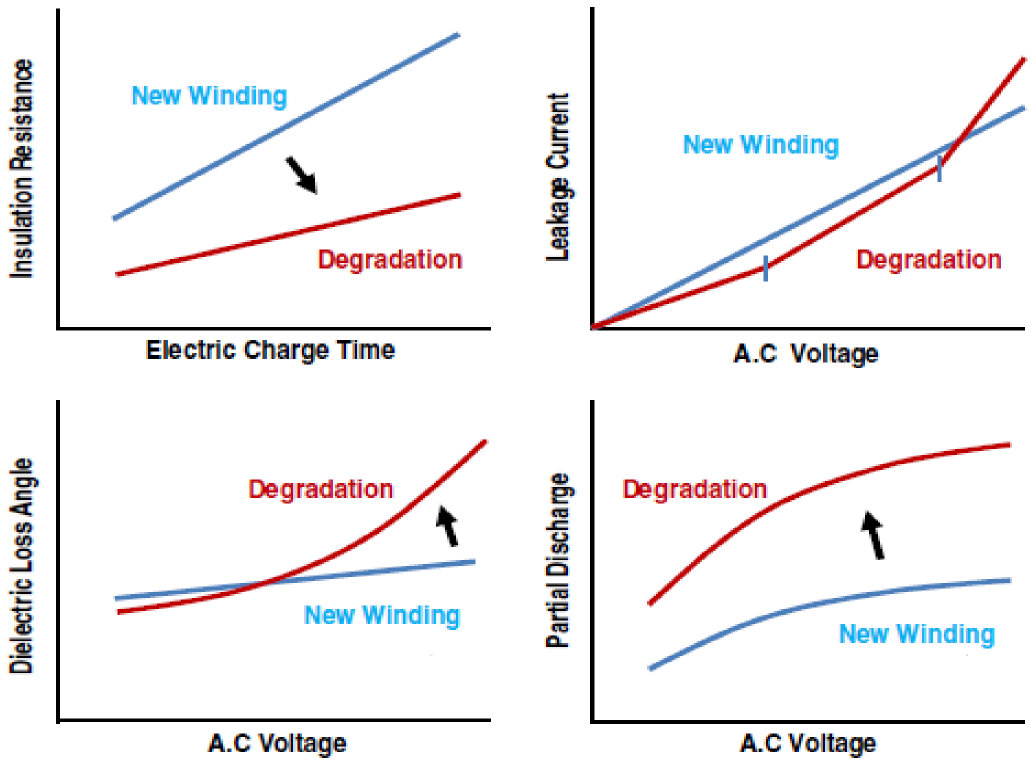
- Insulation resistance & Polarisation Index with applied voltage from 500 to 1000 or 2000 V dc
  This test can reveal:
    - Ageing of insulation, see typical curve on the figure #11 of page 18.
    - Or presence of humidity / pollution which has to be eliminated.

  A correct polarization index (> 1.5 for indirect-cooled winding, >2.0 for direct water-cooled winding) must be obtained prior to any further dielectric test.
- Ramped DC leakage current measurements with voltage increased gradually up to an elevated voltage. Unless a significant fault is present on the insulation (heavy wet condition, large damage area), this test is not effective and the AC voltage test method is the preferred one.
- AC leakage current measurements to check the change of increasing rate of leakage current with step change of applied voltage: see typical degradation curve on the figure #11 of page 18.
- AC loss factor measurements: see typical degradation curve on the figure #11 of page 18.

Note: the applicability of this method is largely depending on the design of the end potential grading system.

- Partial discharge measurements and observation of pulse distribution: see typical degradation curve on the figure #11 of page 18.
  The picture #12 of page 18 shows a typical on-site PD test (use of a Corona probe).
- High voltage testing 1 min. This is a good or no good test:
  - If good it is assumed that no failure will occur during the next period of operation
  - If not the defective bar has to repaired / replaced without eliminating the risk of a further failure. So the maintenance outage can be highly impacted in term of delay and cost.

If a stator winding insulation problem can be predetermined (high PD values, wet insulation from water box leak …), it is preferred to avoid such test or to perform it at reduced voltage.



Picture 11: Typical ageing of stator insulation

Picture 12: Off-line PD test with Corona probe

Besides these tests, additional measurements are carried out in different countries as follows:

- Winding resistance measurement
- Ohmic resistance to ground in slot
- Gas flow in hydrogen tubes
- Test to detect and localize water leaks; pressure and vacuum testing, tracer gas, mapping of local capacitance or surface potential on the end-winding
- Hydraulic tests on stator winding

Bump testing to detect changes in natural frequencies and hence loosening of end windings is performed regularly by some utilities: see below the picture #13.

Picture 13: Stator end winding tightening control

Retightening of end structures during overhauls is considered as being necessary, with special emphasis donated in this respect to the larger generators. Retightening is not necessarily restricted to certain types but depends largely on the type of bracing and operating practices (system disturbances etc.)

Some OEM design larger generators are equipped with adjustable clamping systems using pre-stressing bolts which can be retightened if deemed necessary; on other types wedges can be retightened. If no such means are available for retightening eventually ties have to be remade if necessary.

During intermediate or short outages a visual inspection is usual.

For the investigation of slot wedge tightness and core lamination condition, systems are available for measurements with the rotor in place and are used more and more frequently.

Depending on the design core bolts can be inspected in regard to proper torque.

Depending of the generator condition and the customer practice, dielectric measurements can be made but with a reduced program as well as additional controls (see pages 17 to 19).

4.1.3. Condition assessment

On line monitoring is used more and more to assess the stator winding integrity, especially on larger generators. Several types of system are in use or in a validation phase: they have been developed by OEMs, specialized suppliers or even by some utilities.

They include:

- Gas detection system in coolant circuit
  This allows early detection of conductor cracking or braze leak. Detection methods include not only monitoring of gas leakage into coolant but also RF monitoring and temperature measurement of conductor bars and coolant outlet.
- Temperature monitoring of water outlets and slot temperatures in combination with generator condition calculator
- PD monitoring and RF monitoring
  Nowadays partial discharge (PD) measurements are the state of the art for evaluation of the condition of a high voltage insulation system. But there are many PD testing systems with different characteristics, as measuring frequency, bandwidth, available and these systems have their advantages and disadvantages with regard to the possible detection of different flaws in the winding. Furthermore the use of PD measurement systems requires experience regarding the interpretation of the results of tests. Knowledge about the tested insulation system is also needed to prevent misinterpretation. Additionally it would be recommendable that for subsequent measurements on a winding the same PD testing method should be used again to allow comparisons concerning changes in the PD behaviour.
- Core condition monitoring which could include special coatings for fault tracking
- Fibre optic monitoring on end windings and vibration monitoring on support structures using piezo acceleration systems.
  Such vibration monitoring is generally fitted on larger generators but for smaller units is installed only at the special request of customers.

For more information on this topic see the CIGRE Technical Brochure: "**Guide for On-Line Monitoring of Turbo-generators**"

4.2. ROTOR WINDING

4.2.1. Fault detection

Detection of crack initiation

There is not any available method to detect crack initiation in the winding, except visual inspection. Some use measurement of ohmic resistance, rotor heating test, correlation with vibration measurements, indication of overheating with a core monitor, and surge wave test, these last methods being applicable to rotor in rotation.

Detection of electrical faults

Several classical methods can be used to detect earth faults:

- At standstill, the insulation resistance of the rotor winding is measured by direct voltage injection apparatus, DC voltage with high current, AC impedance or surge wave test
- In operation, various systems of earth fault protection based on the measurement of current flow to earth give a permanent information or can initiate alarms
- Brushless exciters are usually equipped with auxiliary slip rings. Telemetric system exists nowadays principally for small air-cooled generators.

Detection of inter-turn faults is possible by well-experienced methods, rotor at standstill (impedance, recurrent surge test) or in rotation (search coil in the air gap, impedance, recurrent surge test). Also stray field distribution on the surface, or indirect information obtained from measurements in operation (as increase of field current or vibrations, or no load and short-circuit characteristics) can be analysed.

4.2.2. Periodicity of the controls – Servicing procedures

The recommendation to remove periodically the retaining rings to check the condition of the winding applies to old rotors, in some cases motivated by the inspection of the retaining rings themselves.

The retaining rings are not removed if no particular doubt exists and the operational behaviour of the rotor is satisfactory.

The periodicity of inspections does not change for a cycled rotor for most of the cases.

The evaluation of the winding condition is done by:

- The electrical tests mentioned before
- RSO test of rotor winding to detect inter-turn short circuit
- NDT testing on retaining rings
- Inspection of ventilation channels
- Visual inspection under the winding ends (boroscope or optical fibre).

Such controls are normally included in major overhauls.

During intermediate or short outages a visual inspection under the winding ends (boroscope or optical fibre) is usual. Electrical tests are done in case of fault suspicion.

It is possible to remove the retaining rings on site. It is not considered as systematically necessary, if precautions are taken at refitting of the retaining rings, to complete the operation with a rebalancing.

Detection of possible conductor cracks, with retaining ring removed, is normally done by visual inspection and dye penetrant test, plus occasionally by other techniques as Eddy current, resistance measurement, Gamma rays.

It is not always considered that conductor deformations are a premonitory sign of crack initiation; even though it is an indication of high stresses in the copper.

When a rotor is opened, the opportunity is taken to change damage and aged insulating materials, and also the insulation under the retaining rings. Many utilities carry out this operation systematically after some time of operation which means a spare rotor with brand new or retrofitted winding is at disposal.

The decision to rewind a rotor depends on the operational behaviour of the rotor before inspection, and on the mechanical condition of the copper and of the insulating material. It is also dependent on the policy of the power station (how long it is required to last, or change of duty, for example 2 shift operation). In case of rewinding, some OEMs recommend to prepare in advance new coils with their inter-turn insulation.

The original copper is sometimes refurbished and reused when in satisfactory condition (economical choice). Soft copper is generally not reused.

The mechanical characteristics of the copper used (silver alloyed copper and hardening) are generally considered as having an influence on the further deformation of the conductors, and in a less extent on the initiation of cracks.

4.2.3. Condition assessment

For larger generators on line monitoring to assess the stator condition includes also modules for rotor winding condition assessment.

They include:

- Temperature monitoring of hydrogen in combination with generator condition calculator
- Air gap flux monitoring
- Vibration monitoring of shaft and generator bearings
- Overheating detection with core condition monitoring if special coating has been fitted
- Shaft voltage monitoring
- One OEM considers that such monitoring can predict ground fault or inter-turn faults on rotor winding.

For more information on this topic see the CIGRE Technical Brochure: “**Guide for On-Line Monitoring of Turbo-generators**”

5. REFERENCES

WG A1.01.03 “Stressing Turbine Generators beyond their Established Thermal Limits”

WG 11.01 “Report on Stator Winding Integrity (Questionnaire 93-1)”

WG 11.01 “Report on Rotor Winding Integrity”

WG 11.01 “Ageing of Machines with respect to Load or Field Current Cycling”

WG A1.07 “Generator Maintenance, Inspection and Test Programs”

WG A1.11 “Guide for On-Line Monitoring of Turbo-generators”

WG A1.15 “Guide on Stator Water Chemistry Management”

WG A1.16 “Guide: Generator Coil Retaining Ring”

CIGRE Paris Session 2008, Group A1 “Giga-Watt Generation” Panel Session