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Hydro generator high voltage stator windings: Part 1 – essential characteristics and degradation mechanisms *

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***SUMMARY**: About 17% of global electricity is generated from hydro power, which is still the only commercially viable renewable energy produced on a large scale (IEA, 2001). Only about 33% of Earth's hydro potential has been developed so far, and given the increased environmental awareness and scrutiny, it is most unlikely that much of the available hydro potential will ever be utilised. The ageing Australian installed hydro generating capacity of approximately 7600 MW is mostly 30-60 years old and approaching its half-life refurbishment. Most of the generators of that vintage were generously sized by today's standards, and offer an opportunity for uprating of their output as part of the refurbishment process. The understanding and correct specification of hydro generator high voltage (HV) stator windings is vital to the success of generator renewal process. The high voltage hydro generator stator windings are exposed to a variety of continuous and transient stresses, all having deleterious effect on the windings' long-term durability. In general, HV winding life expectancy will depend on thermal degradation of insulation, electrical degradation of insulation, mechanical stresses and environmental winding contamination. Most often, the winding degradation occurs as a result of combined stresses, and is often referred to as multi-stress or multi-factor insulation ageing. The author has spent his working life designing and manufacturing high voltage stator windings, and is presenting a series of four informative papers on hydro generator HV stator windings as an Australian contribution aimed at the engineers involved with hydro generator refurbishment and uprates. This paper is the first in this series describing the essential characteristics of hydro generator stator windings and their degradation mechanisms.*

1 HYDRO GENERATOR STATOR WINDING ESSENTIAL CHARACTERISTICS

1.1 Hydro generator stator windings

The hydro generator stator (armature) winding essentially represents the three-phase electrical circuit in which the working EMF of correct magnitude is induced, and through which the electrical energy is supplied to the external power system.

The generated EMF is a consequence of a rotating hetero-polar excitation magnetic field on the rotor, which induces EMF's of equal peak sinusoidal magnitude and correct time-phase displacement in different phases of the armature winding.

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A stator winding consists of suitably insulated copper wire coils fitted into the stator core slots, which are distributed and connected for the best electromagnetic advantage.

The majority of hydro generator windings are three-phase star connected, with earthed neutral. This arrangement imposes line-to-ground voltage between winding conductors and earth, thus allowing the winding ground insulation to be designed for that particular voltage level.

Given the relatively slow speed of rotation, the hydro generator windings are multi-polar, having a large number of coils and pole phase groups in each phase winding. The large number of coils requires an equal number of stator slots and necessarily large stator bore diameters.

All larger hydro generator windings are designed for high voltage operation, with line-to-line voltage levels in Australia mainly varying between 10 to 18 kV.

The modern hydro generator high voltage windings are the double layer, pre-formed type, and depending on the current magnitude per parallel circuit and machine physical size, they can be executed as multi-turn coils, or single turn bars.

The connections within each phase winding can be arranged in a single circuit series connection for smaller machines or multi-parallel circuits for larger machines.

Two basic coil/bar shapes are of lap or wave configuration, with current North American practice favouring lap construction and European practice leaning more towards wave shape. General Electric (GE) in the USA was the first to invent double layer lap winding and subsequent divergence in development was probably influenced by the early patent rights.

To obtain the waveform of induced voltage as close as possible to the pure sinusoidal ideal, the hydro generator windings are constructed as double layer balanced fractional slot windings of distributed type, with fractionally pitched (chorded) coils. Pole phase groups are always arranged with 60° phase belts.

For almost all machines manufactured in the last 60 years, the windings are inserted into the open type stator core slots.

Reduction of extra strand (eddy current) copper losses is accomplished by subdividing the turn copper conductor into suitably sized copper strands and extra circulating current copper losses are mitigated by different types of turn or bar transpositions. More detailed discussion on the subject of stator winding copper losses and their reduction is presented in the second paper of this series (Znidarich, 2008a).

Up to about 500 MVA in size, the hydro generator armature windings are indirectly cooled, where cooling air is directed over the surfaces of the stator windings. For indirectly cooled hydro generator windings, the cooling medium is always air. There are no pressurised hydrogen cooled hydro generators. Machines over 500 MVA have directly cooled stator windings, where the cooling medium (usually deionised water) is passed directly through the single turn stator bars consisting of hollow copper conductors. There are no directly cooled hydro generator windings with multi-turn coils (Stone et al, 2004).

The hydro generator winding must satisfy the following functionality requirements (Ames, 1990):

- The number of turns per phase must be such to generate machine rated voltage with designed flux per pole.
- Copper conductors and winding cooling must be arranged to carry machine rated current without exceeding designed winding temperature rise.
- The groundwall, turn-to-turn and strand insulation must be capable of withstanding their rated operational voltages and maximum expected transient over-voltages, and must be designed and manufactured to minimise internal and external partial discharge (PD) damage.
- The winding must be designed and constructed to resist or eliminate all operational or transient mechanical forces such as forces on coil end winding, slot section and end winding vibrations, and thermo-mechanical forces.
- The winding is expected to provide long-term reliable operation (30-40 years) when exposed to all above mentioned thermal, dielectric, and mechanical stresses and degradation factors.

Hydro generator stator windings are the vital part of the machine, and often the focus of attention and a limiting factor when considering the magnitude of a machine uprate.

1.2 Physical types of hydro generator stator windings

All high voltage hydro generator stator windings are pre-formed (form-wound) multi-turn coils or single turn bars. The pre-formed term refers to the coils or bars that are fully formed and insulated before insertion into the stator core slots. Distinction is made between multi-turn coils, which can only be lap wound, and single turn bars, which can be either lap or wave wound.

1.2.1 Multi-turn pre-formed (diamond) hydro generator stator coils

Multi-turn diamond coils are of the continuously wound closed loop type, consisting of a required number of turns (typically two to 12) to suit the machine design requirements. The term "diamond coil" is derived from the fact that coil end windings

Figure 1: Installation of large hydro generator stator winding.

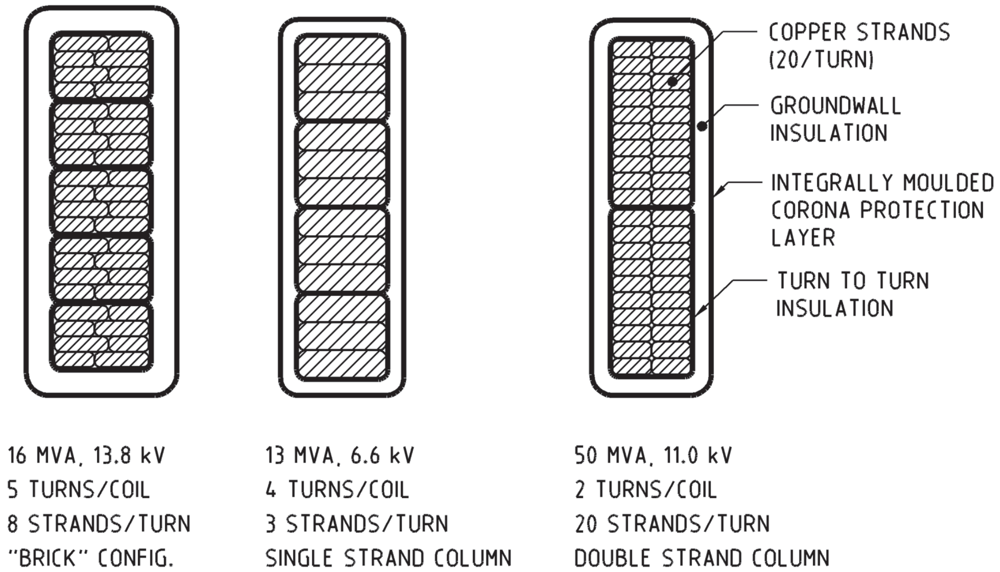


Figure 2: Multi-turn coil cross sections.

resemble a diamond shape. They are mainly used for small and medium-to-large size hydro generators. Each turn is normally divided into a number of strands electrically insulated from each other, primarily to reduce extra strand (eddy current) copper losses, and to a lesser degree from mechanical forming considerations. The circulating current losses are mitigated by the turn transpositions in the coil end winding (twisted turn or 180° semi Roebel turn inversion). The two coil sides are fitted into different slots: one as the top coil side (nearest to the machine bore), and the other as the bottom coil side (furthest from the machine bore). The coil is manufactured by first taking a turn bundle consisting of a designed-number of insulated strands through the turn taping process (application of turn-to-turn insulation over the turn bundle), followed by looping of the coil onto the special loop winding machines. The finished loop consisting of a correct number of insulated turns is then shaped (spread) in the pneumatic or hydraulic coil shaping machines, followed by application and curing of the coil ground insulation. The main components of the multi-turn diamond coil insulation system are strand-to-strand insulation, turn-to-turn insulation, groundwall insulation and surface corona protection system (Stone et al, 2004). The only time the modern multi-turn hydro generator coil is manufactured in two halves (as a top and bottom bar) is when the stator core sections are manufactured and pre-wound in the factory. Following site installation, the ends of these coils situated at the joints of the core sections are manually jointed (strand by strand), insulated and impregnated with air curing resins.

Pre-formed coils are always manufactured from rectangular copper conductors, which allow for the perfect voltage distribution between the coil turns, and make it possible to achieve ground insulation uniform compaction and density, thereby approaching the ideal of a void free structure for prevention of PD.

Strand-to-strand insulation requires a good mechanical strength to resist damaging forces during the coil winding and shaping process. Since strand-to-strand voltages are very low, dielectric qualities of strand-to-strand insulation are of secondary importance. The most commonly used strand-to-strand insulations are fused dacron glass or single serving of thin resin rich mica tape. If mica tape is used for the strand insulation, it can be counted towards the turn-to-turn insulation allowance.

Turn-to-turn insulation prevents short circuits between the coil turns, which always result in winding failure. The shorted turn behaves as a shorted secondary of a transformer, and according to the transformer ratio law, the magnitude of the current in the shorted turn will be the nominal winding current multiplied with the total number of turns per phase. This large current inevitably melts the copper conductor, and results in almost instant ground fault. The normally encountered turn-to-turn voltages range between 10 and 250 V. The main consideration for the design of turn-to-turn insulation, however, is steep fronted transient over-voltages imposed on the coil by power system disturbances, lightning strikes, etc. The turn-to-turn insulation is most commonly manufactured from multiple servings of mica tapes impregnated with epoxy resins.

Groundwall insulation separates copper conductors from the grounded machine core. It is manufactured from multiple servings of mica tapes, impregnated with epoxy resins, and hydraulically pressed to form homogenous void free structure of high dielectric strength. The design of groundwall insulation is subject to conflicting requirements. Thicker insulation provides a better and more durable dielectric barrier, but impedes heat dissipation from the coil causing

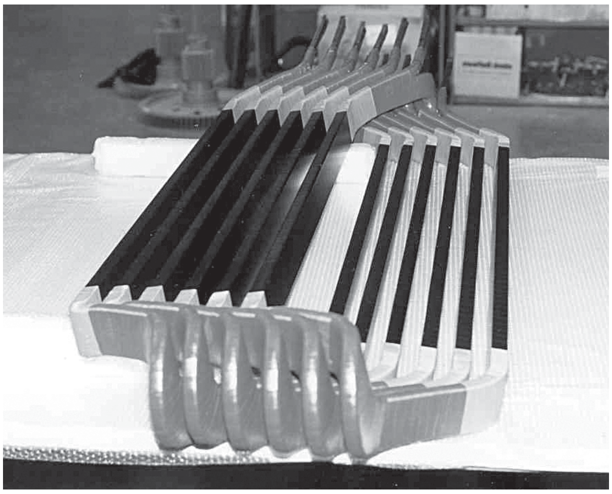


Figure 3: Completed multi-turn pre-formed hydro generator stator coils.

increased winding temperature rise and accelerated thermal degradation. The present compromise is to design the ground insulation with the voltage stress between 2000 and 2600 V/mm. For lower voltages such as 6.6 kV, the insulation thickness giving 2000 to 2200 V/mm stress is common, as the mechanical strength of the insulation must also be considered. For voltages of 11 kV and above, voltage stresses of 2200 to 2600 V/mm are generally employed. The highest end-user specified ground insulation voltage stress for a replacement hydro generator winding that the author has encountered so far in Australian and USA markets was 2700 V/mm.

The surface corona protection system consists of a straight slot section coating with linear conductivity, and a first slot section bend coating with voltage dependant resistivity (VDR). These coatings control surface discharges between the coil slot surface and grounded stator core, and on the coil end winding.

1.2.2 Single turn bars

Single turn bars are employed for the windings of large hydro generators, where the currents per circuit require large conductor cross sectional areas, and where closed loop coils become physically too heavy and mechanically too stiff to be inserted into the stator slots without risking mechanical damage. Two separate bars are normally manufactured to form a coil in a double layer winding, one for the bottom coil side, and the other for the top coil side. Given the large size and handling difficulties, they are inserted separately into the slots, and then joined at both ends by brazing.

The generally adopted method of reducing strand (eddy current) losses is by subdividing the single turn conductor/bar on height, thereby increasing the number of strands above each other in the slot, each of them being insulated from others, and connected in parallel. In order to minimise circulating current losses, the strands are transposed in the slot section.

One of the most commonly used transposition methods for large electrical machines with single turn bars is 360° or 540° Roebel transposition. Everything outlined for the insulation system of multi-turn coils applies, except that there is no turn-to-turn insulation.

Due to the fact that single turn bars are manufactured in two halves (also known as "half bars"), they can be manufactured as lap or wave windings.

In most cases both winding types can be made identical in electromagnetic terms.

The principal advantage of wave windings is their relative simplicity of connections, ie. the absence of pole to pole connections. They are, however, more difficult to produce since they require dedicated forms and have different bar shape ends within connection pole phase groups. Due to their shape more bars need to be removed if replacement of the bottom bar is required.

The opposite is true for the lap bar windings: the connections are more complex and labour intensive,

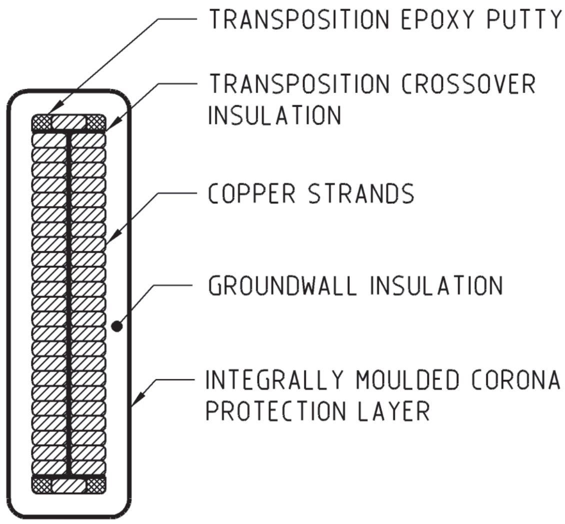


Figure 4: Typical single turn Roebel bar cross section.

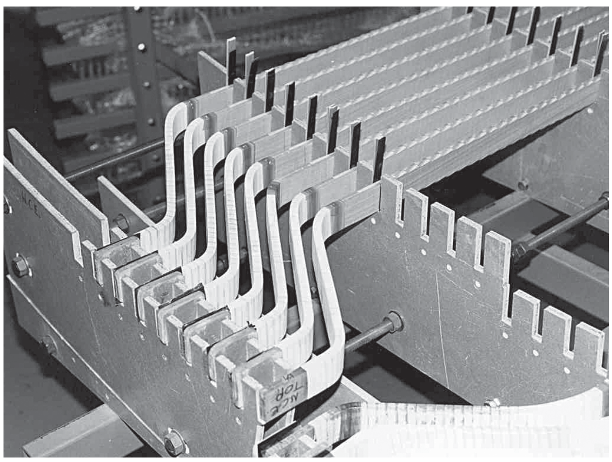
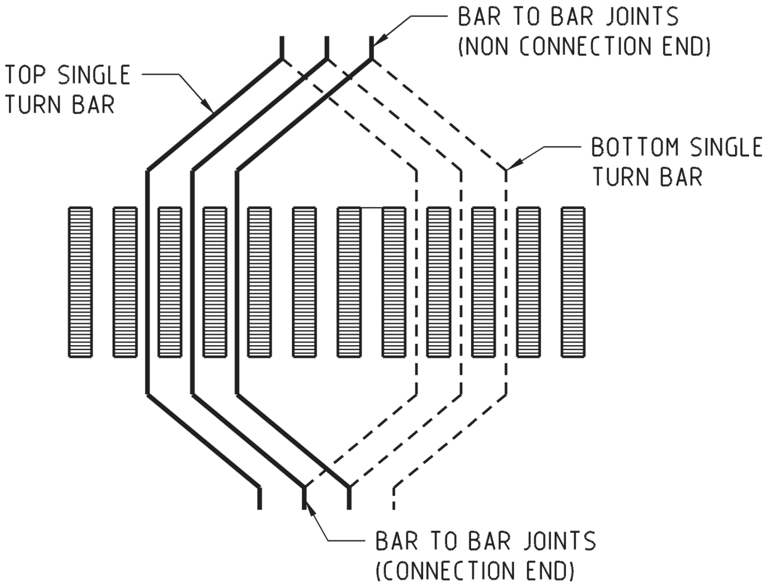


Figure 5: Manufacturing of single turn hydro generator stator bars.

(a)



(b)

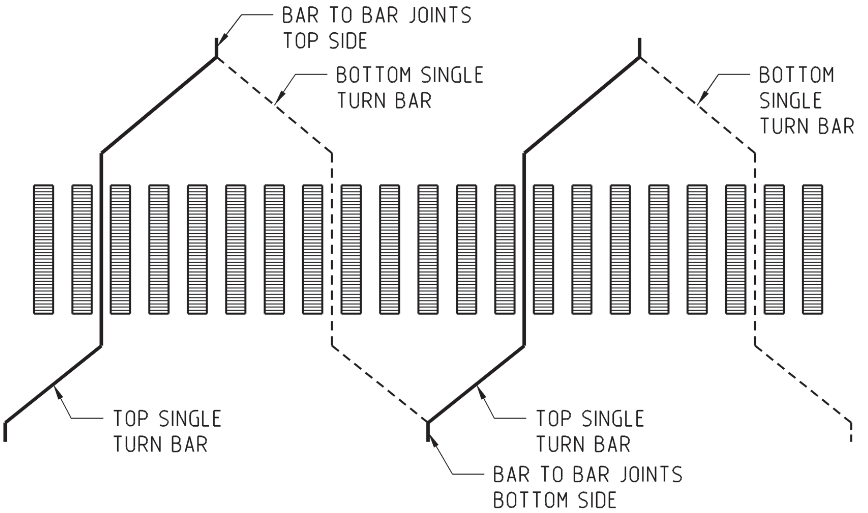


Figure 6: Lap wound single bar winding (a) and wave configuration (b).

they are simpler to produce since all top and all bottom bars have an identical shape, and can be produced two at a time in the adjustable bar spreading machines. Replacement of failed bottom bar requires removal fewer top bars, hence repairs are easier, with a smaller number of spare bars required.

1.3 Stator winding high voltage insulation systems

New HV "resin rich thermosetting" insulation systems, based on mica paper and synthetic resins, have totally replaced the previous generation of HV insulation systems, based on mica and organic binders/impregnants. Mica is generally impervious to the thermal, electrical and mechanical stresses encountered in the operation of electrical machines. None of the new synthetic materials developed by polymer chemistry can yet compare to the overall properties of natural mica for HV insulation applications. The major thrust is therefore towards the development and enhancement of synthetic resins, to give the optimum characteristics for a particular application (Bonnet, 1993), and the development of insulation tape carriers, where polyester films are being substituted for fibreglass carriers (Neal, 1998). An in depth description of the resin rich insulation systems' historical development, followed by the description of system characteristics and integral components are given in Stone et al (2004).

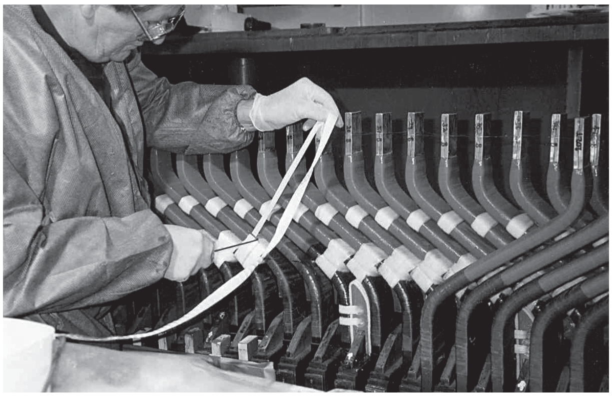


Figure 7: Installation of single turn bar hydro generator winding.

Modern high voltage winding insulation systems utilising mica/synthetic resin based technology offer many advantages:

- superior dielectric properties
- improved voltage and heat ageing
- improved copper content/slot ratio (the thinner insulations allow higher copper content, with reduced copper losses)
- void free fully moulded slot cells, with permanent retention of slot section physical sizes
- improved (more efficient) heat dissipation
- capable of operation at temperatures up to Class "F" (155 °C)
- integrally moulded (taped) corona protection systems.

Two basic systems were developed in recent years – *Resin Rich* Insulation System and *Vacuum Pressure Impregnation* (VPI) Insulation System.

The *Resin Rich Process* utilises mica based insulation, which already possesses high resin content and requires no further resin addition. Naturally occurring resins, previously used in "thermoplastic" insulation systems, have been replaced by synthetic resins, which can be tailor made to give the optimum characteristics required by a particular application. Epoxy resins have now almost entirely replaced polyester resins, which were used in the 60s and 70s.

The insulating tapes are supplied with the resins in the so called "B Stage" (pre-catalysed), which only require a raise in temperature for curing.

Apart from mica paper and "B Stage" resin, resin rich insulating tapes incorporate various combinations of supporting materials, necessary to provide a "carrier" medium for physical application (ie. tensile and flexural properties of the tapes). Carrier materials form an integral part of the insulation system, and often influence the processing mode and final insulation system characteristics. The most common supporting materials utilised for resin rich tapes are glass fabrics, dacron mats and polyester films.

Vacuum Pressure Impregnation involves the application of dry insulation tapes, which are subsequently processed by a vacuum pressure impregnation process, utilising synthetic resins to impregnate between layers of dry mica insulations.

While both resin rich and VPI systems produce high quality insulations, the final choice in their selection depends mainly on an initial capital expenditure and the intended application.

In general, the VPI system requires a large initial capital expenditure, and is more suited for large scale manufacturing. The resin rich system is better suited to "one off" coil set manufacturing, refurbishment and rewinds.

Very few large coil manufacturers actually produce their own insulation materials. They are currently developed and manufactured by a handful of insulation manufacturing companies. The general composition of the tapes and recommendations for their application and use are published by the insulation manufacturers. Resin formulations, however, are proprietary and jealously guarded secrets, not available to the coil manufacturers.

Coil manufacturers are therefore left to purchase insulating materials, which appear to suit their application. With a wide choice of insulating materials currently on offer, manufacturers develop their own combinations that produce the best results with their processing technology. In addition to the initial insulation tape characteristics, the correct processing methodology largely influences the quality and characteristics of the finished insulation system. How this is achieved depends on the manufacturer's ingenuity and expertise, utilising to the fullest the properties and capabilities of modern day materials.

1.4 Copper conductors for hydro generator stator windings

High voltage hydro generator windings are exclusively manufactured from copper. Copper has an outstanding combination of useful properties such as excellent electrical and thermal conductivities, good hot and cold ductility, corrosion resistance, and the ability to be joined readily by soft soldering, brazing and welding. Copper of high purity is commercially readily available, and in this condition is a better conductor of heat and electricity than any known substance, except silver.

The International Electrotechnical Commission (IEC) standard for copper resistivity is 0.017241 μΩm at 20 °C, and copper having this resistivity is said to have a conductivity of 100% IACS (International Annealed Copper Standard). This does not represent the highest possible conductivity, and copper in the annealed condition frequently attains a conductivity of 101% or even 102% IACS.

High voltage hydro generator windings are manufactured from oxygen bearing or electrolytic tough pitch coppers (alloy number 110 (Standards Australia, 1985), or alloy number C 101 (British Standards Institution, 1987)). These coppers contain sufficient oxygen to induce good ductility, combined with the highest conductivity (100% IACS or higher) for electrical conductor applications. Minimum percent copper plus silver (as a trace metal) is 99.9%. Oxygen bearing tough pitch copper is the copper alloy most common in the electrical industry where extra special characteristics are not required.

Only annealed copper is used for HV coil application. In the cold worked condition after drawing and rolling, copper is hard and not easily formed into

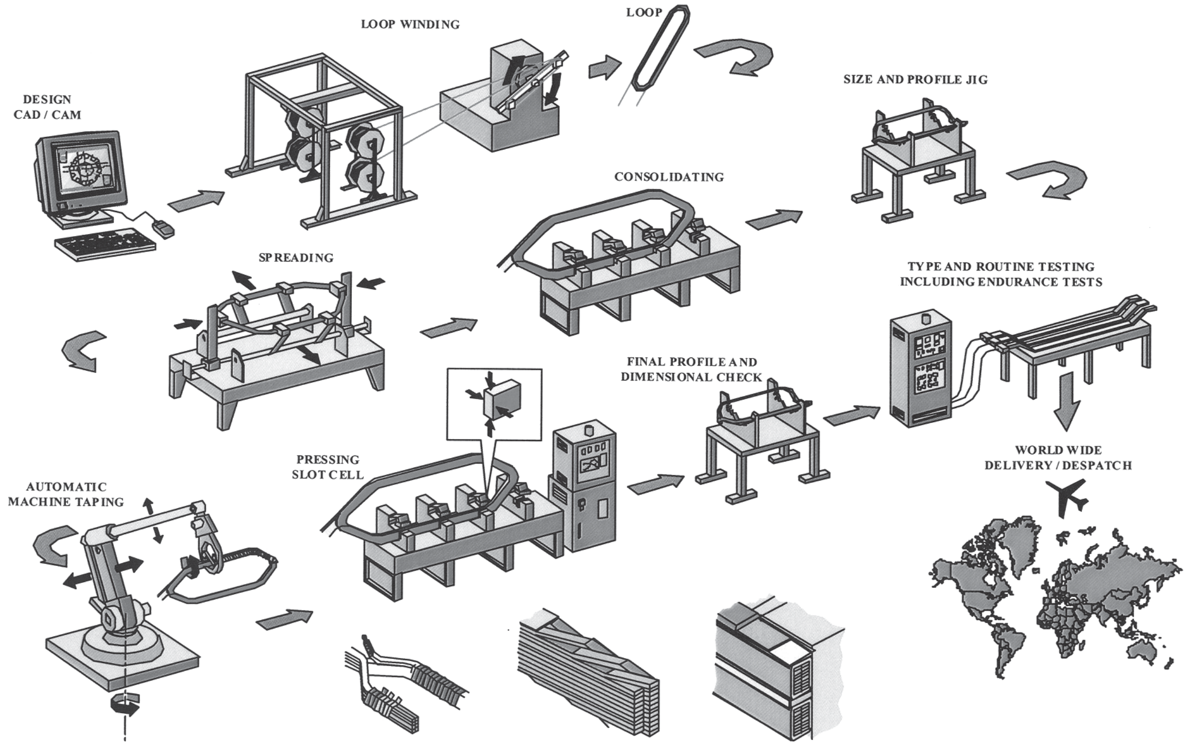


Figure 8: High voltage coil manufacturing process.

the coil shape. Further deformation can only be achieved if the copper is first softened, ie. annealed. The work hardened copper also looses up to 3% of its conductivity compared to the soft annealed condition. Thus, copper, which in the annealed condition may conform to the IEC standard of 100% conductivity, may have only about 97% of that conductivity when hard drawn. This consideration must be kept in mind when specifying the copper conductors and designing the windings which require reduction of I^2R losses. Poorly annealed copper may increase these losses by 1-2%.

2 HYDRO GENERATOR STATOR WINDING DEGRADATION MECHANISMS

2.1 Thermal degradation of insulation

Thermal degradation of insulation is a well researched topic. Every piece of the electrical equipment loses energy due to the current flowing through its internal resistance. In electrical machines, internal resistance is mostly made up of the sum of the resistances of the coils in the windings. The lost energy is referred to as I^2R losses, and it appears in the form of heat. Electrical machines operate with a designed temperature rise, which is a direct consequence of the thermal energy generated by machine losses encountered during machine operation. The principal losses influencing the stator winding operating temperature in the hydro generators are stator and rotor I^2R losses, and stator core losses.

The final operating temperature of the machine depends on the functionality of its cooling system. The problem increases with the size of the machine, where the surface area available for heat dissipation increases approximately as the square of dimensions, but the heat developed by the losses and volume increases approximately as the cube of dimensions.

The operating temperature is closely associated with the life expectancy of the machine insulation, because insulation deterioration is a function of time and temperature.

Insulation deterioration is a chemical change involving slow oxidation, polymer depolymerisation (chain "scission") and cross linking (Stone et al, 2004). At elevated temperatures the thermally induced molecular vibration on organic insulation components tends to break the molecular bonds (bond scission), resulting in shorter and weaker polymer chains (Stone et al, 2004). The insulation suffers from layer delamination and separation, loss of flexural strength, and brittle hardening, leading to the loss of mechanical durability and dielectric strength. Often the rate of decay will be exponential. Loss of dielectric strength will lead to eventual insulation breakdown.

Commonly encountered insulation failure mechanisms due to thermal degradation are (Stone et al, 2004):

- Separated and loosened layers of ground insulation may allow copper strand vibrations caused by electromagnetic forces. This may lead to strand insulation abrasion, with consequential strand to strand, and turn to turn shorts, and resulting winding failure.

- Insulation delamination inevitably results in air voids between the insulation layers. Destructive PD will be formed in the air voids which will accelerate the rate of insulation decay.
- The insulation delamination instigates a "snowballing" exponential degradation. This is caused by reduced insulation thermal conductivity due to the presence of air pockets. The inability to efficiently dissipate heat generated by the coil copper I^2R losses will cause the winding to operate at increased temperature, thus further accelerating the degradation process.

Experience shows that the operational temperature of the electrical machine is one of the major factors governing degradation and life expectancy of the insulation.

In practice it is considered as a long established "rule of thumb" that if the insulation is operating above its thermal ageing threshold, a 10 °C increase in operational temperature of the machine will reduce the insulation life expectancy by 50%. This rule can be approximated by the following equation, which is based on the Arrhenius Rate Law (Stone et al, 2004):

$$L_{ins} = A_k e^{\frac{B_k}{T_{ins}}} \quad \text{(hours)} \tag{1}$$

where L_{ins} is the expected insulation life (hours), T_{ins} is the insulation temperature (°K), and A_k and B_k are constants.

The thermal ageing threshold refers to the temperature below which thermal ageing of insulation material will not occur. Although different for each insulation material, and hence difficult to define globally, the thermal ageing threshold was the subject of numerous research efforts relative to insulations thermal ageing. In practical applications, the insulation engineers consider the thermal ageing threshold to be at the temperature where insulation weight loss as a function of temperature (as tested by a thermo-gravimetric analysis test) is barely measurable and becomes insignificant. For early thermoplastic asphalt impregnated insulations it lies at about 70 ºC, and for later Class B formulations it was about 90 ºC. For Class F epoxy based insulation the thermal ageing threshold is between 120 and 130 ºC depending on epoxy formulation and curing temperature. Below these temperatures the winding will not fail due to thermal aging even in 100 years.

A high voltage winding designer is faced by conflicting requirements, where thinner insulation is better for heat dissipation, and thicker insulation provides safer dielectric characteristics.

Accelerated life (temperature endurance) tests are carried out to classify insulating materials into temperature classes (Dalal, 1981; Nailen, 2000). The result of the temperature endurance tests are thermal endurance graphs, which show the relationship between the insulation test temperature in °C, and time to failure in hours (Stone et al, 2004; IEEE, 1986); see figure 9. The material allocated to the particular temperature class rating will be expected to operate continuously at the maximum temperature for that temperature class for at least 20,000 hours. The allocation of materials is such that the life will be adequate under usual industrial conditions. One of the common assessment methods is to measure material weight loss as a function of time and temperature. The lower the weight loss, the better the temperature endurance is.

Insulating materials are divided into six temperature classes in accordance with their upper stable temperature limit, as outlined in the table 1.

Wherever possible, Class F insulations are used for modern winding design, with the temperature rise limited to Class B, to slow down and reduce thermal degradation of insulation.

2.2 Electrical degradation of insulation (partial discharges)

The high voltage stresses present in air cooled HV hydro generator stator windings cause winding degradation due to PD, represented by the localised breakdown of air, when its breakdown voltage is exceeded. PD can occur in the insulation voids or on the winding surfaces.

The term "partial discharge" is used because the insulation breakdown is limited to only part of the insulation (air space), rather than a complete breakdown or breach of insulation.

In air cooled hydro generator windings the heat generated by ionised air particles contribute to thermal degradation and erosion of insulation. A side effect of the process is the conversion of oxygen into ozone and the formation of nitrogen oxides in insulation voids (Nailen, 1999).

Table 1: Six temperature classes of insulating materials.

Temperature class	Temperature limit
A	105 °C
E	120 °C
B	130 °C
F	155 °C
H	180 °C
C	Above 180 °C

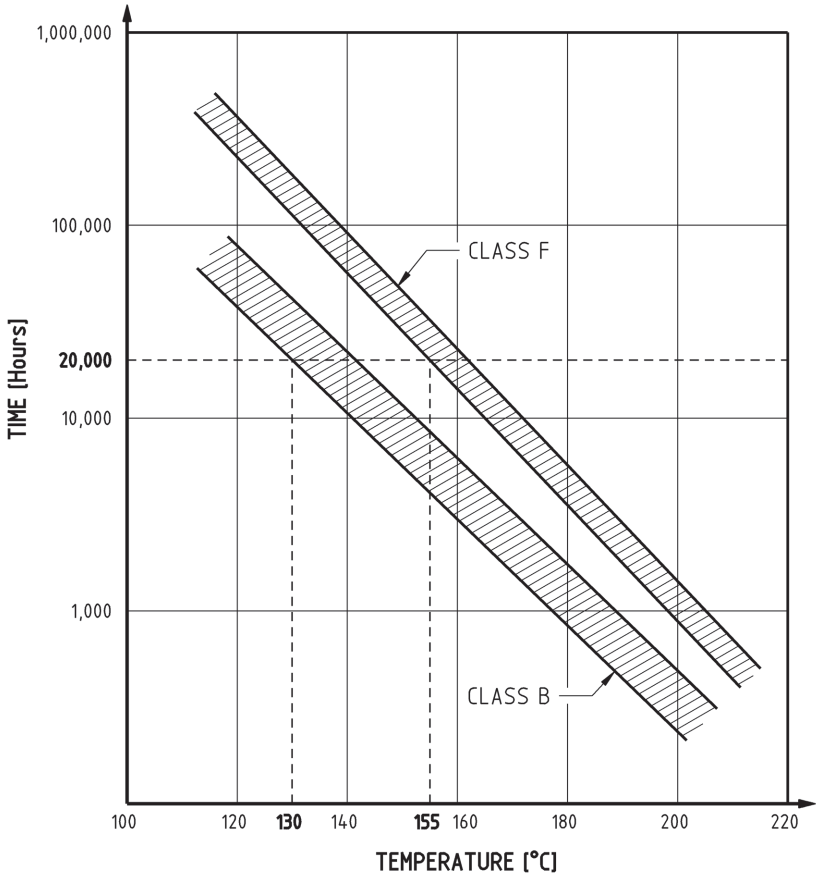


Figure 9: Typical thermal endurance plots for Class B and Class F insulations.

2.2.1 Partial discharges in insulation voids

If the HV coil insulation is not fully void free (a practically impossible aspiration), the air in the insulation voids will become ionised, and if the voltage is above the air breakdown threshold (3 kV/mm), PD will result. Given the much lower dielectric constant of air when compared to the surrounding insulation, and the fact that voltage divides in inverse proportion to the materials' dielectric constants, the voltage stress appearing across the void will be much higher than the voltage appearing across the equivalent distance of winding insulation. Ozone, nitrogen oxides and, under certain circumstances, nitric acid will be formed. Ozone's strong oxidising action, combined with nitric acid, will attack and progressively destroy most of the organic insulation materials, causing insulation decomposition and degradation. PD also produce heat, further contributing to insulation destruction. Ultimately, PD will propagate the area of the void, forming partially conducting discharge channels (void treeing), thus further accelerating the insulation chemical and mechanical degradation, and ultimately leading to insulation failure.

The void discharge repetition rate is not a function of frequency of the applied voltage. Rather, the PD involves a repeated charging and discharging of the capacitance within the void. Charging does occur at a rate proportional to supply frequency, but discharge then follows almost instantly as the void breakdown voltage is reached. At that time, the applied voltage will still be rising along the same waveform cycle, at the same rate, so the process occurs again many times per cycle depending on the remaining space charges and electrical field (typically up to 100/cycle).

The "internal corona" problem was very evident in old type bitumen coils, which would swell in service, thus creating cavities and air voids in insulation. Total internal coil insulation degradation would take place, leading to turn-to-turn failure, which would then cause failure of groundwall insulation.

Internal PD problems can only be eliminated by manufacturing the fully pressed coils, which are as void free as practicably possible. Correct insulation density and composition (ratio of resin content to mica), as well as processing, are of critical importance for insulation system durability and reliability.

Dielectric loss angle (DLA), or tanδ testing, is one of the best methods of detecting and quantifying void content in the insulation during winding manufacture.

2.2.2 Slot surface discharge effect

PD are formed in the small air spaces between the core steel laminations that are normally at ground

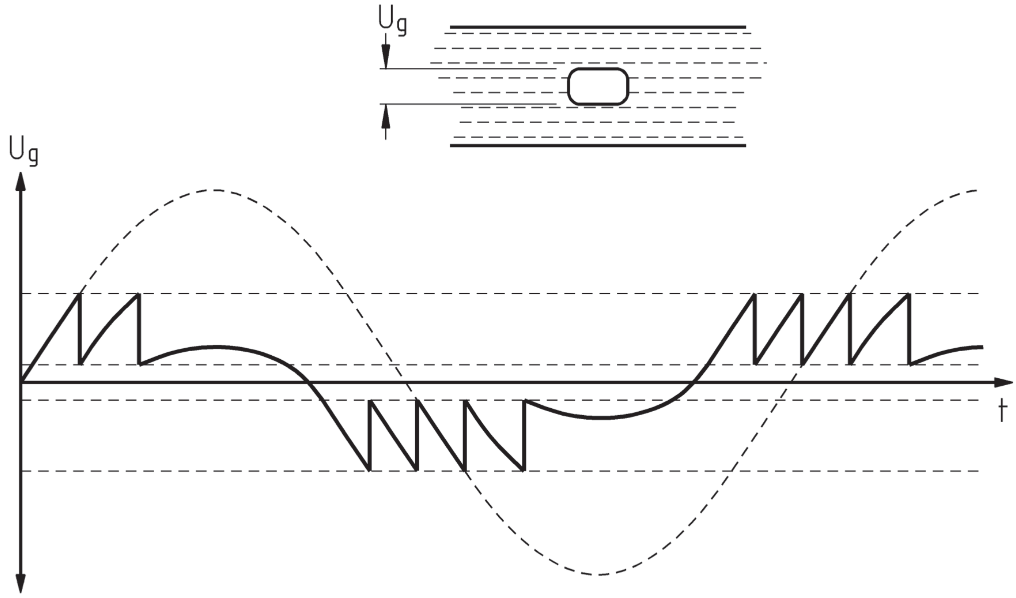


Figure 10: The recurrence of PD in a small insulation void.

Figure 11: Complete destruction of turn-to-turn insulation by internal partial discharges.

potential and the HV coils connected to the line end where the voltage stresses are higher. The principle of air breakdown between the coil insulated slot section and grounded slot wall is exactly the same as outlined for the air voids in the insulation groundwall. Any abrupt discontinuities, such as air vent ducts, will also contribute to the formation of PD, as sharp corners normally produce high voltage stress points (Weddleton et al, 1972).

The machine's operation with line-to-line voltages below 4 kV normally will not experience this problem, and do not require surface corona protection. The higher the machine operating voltage, the more important and necessary it is to provide some form of corona protection.

The solution to this problem is to apply to the HV coil slot section surfaces a conductive layer coating (0.5-40 kΩ/square surface resistivity), and to make sure this conductive coating is in good contact with the core steel laminations. Since both surfaces are now at the same potential, PD can not be formed between them. The surface resistivity of the conductive layer must be carefully controlled. If it is too low (close to 1 Ω), the shorting out of stator core laminations may occur, causing additional heat losses. If it is too high, it may not function to effectively bring the slot surface to ground potential (Nailen, 1980). The modern resin rich insulation systems employ conductive tapes that are integrally moulded with the slot section groundwall insulation during the hydraulic pressing process. This system has proven to be more durable and have a more uniform surface resistivity than comparable painted on corona protection systems. The tapes are usually manufactured from polyester fleece uniformly impregnated with graphite particles.

To ensure positive electrical contact between the coils' slot section conductive surface and the core slot wall, conductive side fillers or side packing is used. Also to ensure good contact between the top and bottom coil sides in the slot, HV machines also utilise conductive vertical slot fillers. Even if there are small breaks between contact points of the coil surface and slot wall (ie. coil surface is not touching core slot wall continuously), the resistance limits of the slot surface coating of 0.5-40 kΩ/square will be low enough to keep the complete coil slot surface close enough to ground potential to prevent surface PD.

2.2.3 End winding surface discharges

The slot surface conductive coating is normally extended about 50 mm past the end of the core to prevent PD between abruptly ended stator core and the coil slot surface (abrupt changes in shape and sharp corners tend to concentrate the electrical field). The end of very thin coil conductive coating also gives rise to a very high localised electrical field (Stone et al, 2004). Referring to figure 12, the small leakage currents pass through the insulation along the whole end winding area. These currents continue to flow on the surface and they naturally find their way toward the low potential (ie. the ground), the closest grounded point being the end of the slot section's conductive layer. These surface currents add together and their magnitude increases the closer they are to the end of slot section conductive layer. Although the absolute magnitude of these surface currents is relatively small, the surface resistivity of good insulation is very high, and close to the stator core, their IR volt drop product may become high enough to ionise the surrounding air, and cause PD. The typical "ring of fire" is formed at the end of the slot section conductive coating.

To prevent these PD the special voltage grading conductive layer is fitted, overlapping the slot section conductive layer, and extending around the first coil slot section bend (Brammer et al, 1998; Moore et al, 1984). The material consists of silicone carbide and has VDR. Silicone carbide resistivity is inversely proportional to the voltage, ie. the higher the voltage, the lower the resistivity, and vice versa. This unique property produces a nearly uniform voltage distribution around the coil first bend, thus keeping all surface voltages low enough to prevent PD.

2.2.4 End winding coil to coil discharges

Correct minimum end winding spacing between adjacent coils is essential for cooling air circulation and prevention of end winding PD.

Referring to figure 13, two end windings and an air gap between them can be represented by an equivalent series circuit of three capacitances, capacitance of ground insulation of coil A, capacitance of air gap, and capacitance of ground insulation of coil B. If the air gap between the coil end windings is insufficient, or if the insulation of the end winding is thin, the bulk of the voltage between them will be dropped across the air gap due to the different dielectric coefficients between air and insulation material, causing PD activity.

Given unfavourable conditions such as air contamination, high humidity or high altitudes, the

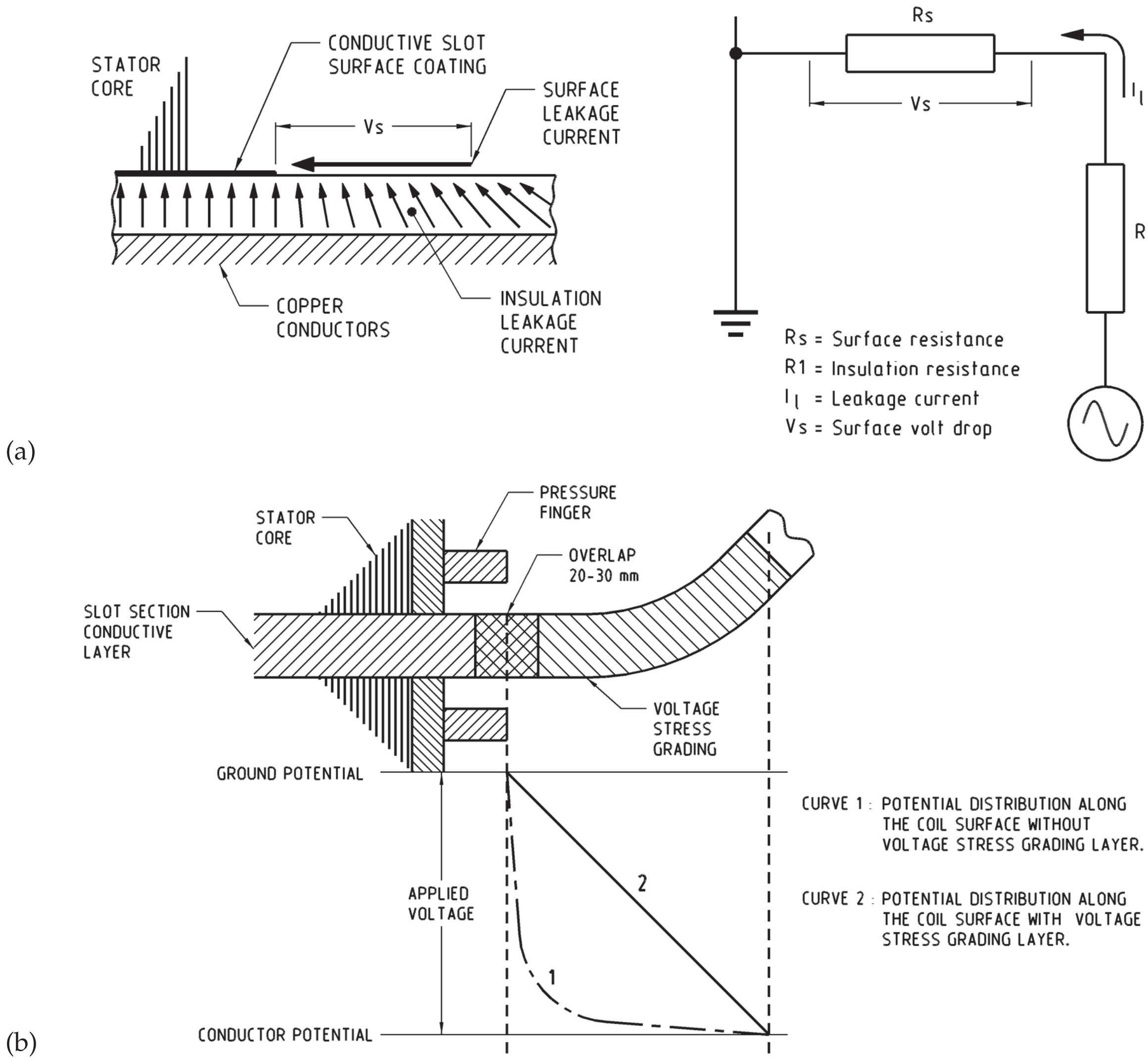


Figure 12: End winding surface leakage currents and their equivalent circuit (a) and stress grading system functionality (b).

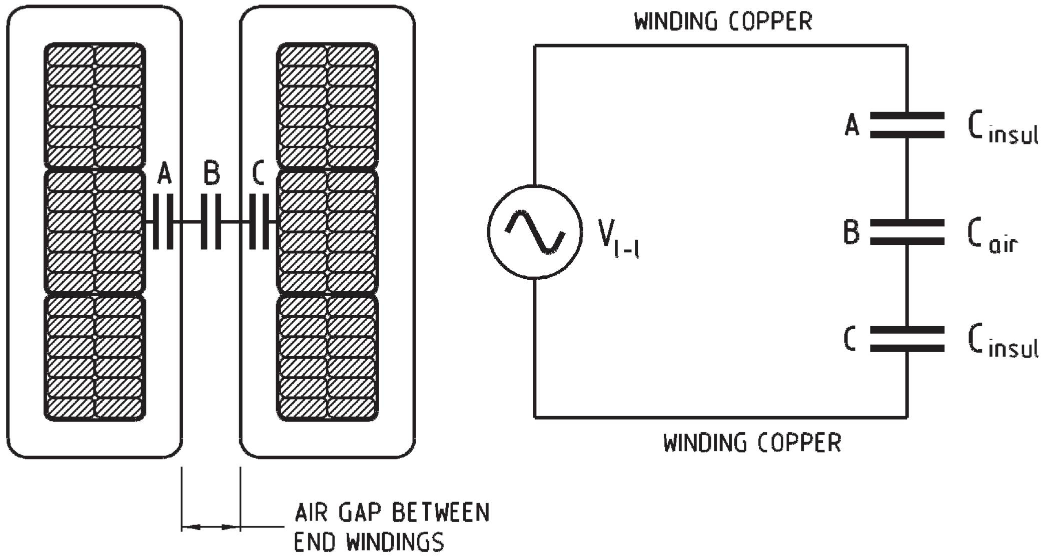


Figure 13: Equivalent circuit for end winding partial discharges.

air will most certainly break at the calculated voltage stress, causing harmful PD. The PD in open air will generate poisonous ozone gas and nitric acids, which add chemical decomposition dimensions to the process. In addition to chemical attack on insulation, the ozone is a poisonous gas, and cases are on record for some large open ventilated machines with high levels of PD in the end windings, being rewound on occupational health and safety grounds. The levels of ozone in power station air were considered too high (above 1 part/million is considered harmful and is readily detectible by smell). According to Paschen's Law (Stone et al, 2004), the air at high altitudes, being at lower pressure, will also break down at lower voltages. The electrical machines designed for operation at high altitudes must, therefore, have increased coil-to-coil gapping in the end winding region.

Considering that the winding voltage gradient to earth is highest at the HV output end, and almost zero at the neutral end, the HV end coils will be exposed to the highest deterioration due to combined PD effects. To prolong the winding life, in some cases it is possible to reverse (swap) the generator HV and neutral leads after some years of operation (IEEE, 1999). Since the neutral ends of the windings are exposed to exactly the same thermal and mechanical degradation mechanisms as the HV ends, and considering the relative expenses and technical difficultly associated with the procedure to change bus work on large synchronous generator, this practice should only be implemented after ensuring by testing and inspection that the neutral winding end is in much better condition than the HV end. The most important decision making factor regarding the reversal of stator leads is the remaining degree of bonding at the copper insulation interface and any damage to the surface of the ground insulation as a result of mechanical abrasion at neutral end.

2.3 Mechanical degradation of insulation

In addition to thermal and electrical stresses, the stator windings in rotating electrical machines are subjected to a variety of mechanical forces that require a suitable means of wedging, bracing and blocking of the winding if satisfactory service is to be obtained.

The primary forces that occur are the result of the following conditions:

- forces on coil end winding
- coil slot section vibration within core slots
- coil thermal expansion
- stator core vibration.

2.3.1 Forces on coil end winding

Significant forces are exerted onto the coil end windings due to the current flow in adjacent coils and current carrying members of the electrical machine. These forces tend to either pull conductors together or separate them depending upon the direction of the current flow. Coils within the same pole phase group will be pulled together because the direction of the current is the same, whereas adjacent coils in different pole phase groups will be strongly repelled because of different current directions. The second acting force pushes the coils away from the bore. This force appears as a "rotating wave" spinning around the stator circumference at synchronous speed stressing each coil in turn, as it passes.

The forces between coils are proportional to the current squared, so the machine exposed to the short circuit resulting in 12-times rated current, will experience attracting or repelling forces in the overhangs 144 times of the normal full load level. The winding bracing and blocking system consisting of spacer blocks between coils, winding support rings and end support arms must be designed to

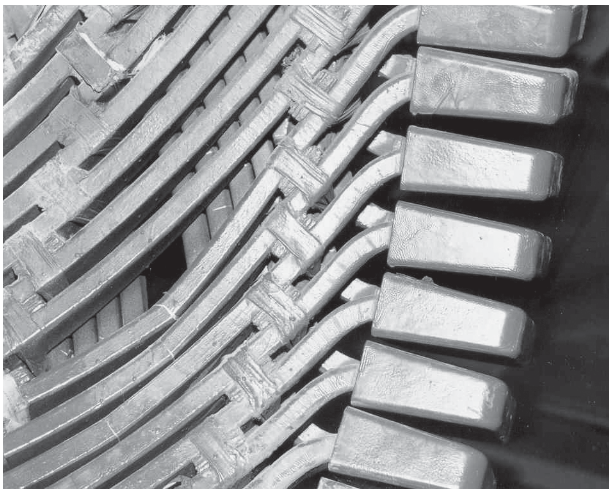


Figure 14: Catastrophic destruction of generator end winding by three-phase short circuit on machine terminals.

withstand maximum currents resulting from short circuits imposed on the machine without damage to the windings.

Due to the 3D geometrical complexity of the end windings and infinite number of possible failure modes, the end winding forces are difficult to calculate. The designs of presently employed end winding support mechanisms are based on numerical modelling, finite element analysis, model type testing and experience with previous designs.

2.3.2 Coil slot section vibration within core slots

Loosening of the slot contents due to insulation thermal degradation (shrinkage and weight loss) may lead to in-slot winding vibrations due to slot bar electromagnetic forces, which are produced by the interaction of a magnetic flux produced by a current flow in the conductors of coils/bars and cross slot leakage flux. There are also significant in-slot axial and radial differential thermal expansion effects.

The slot wedge systems used in rotating machines are designed to prevent slot section bouncing and vibrations, and to ensure that the radial pressure on the coils fitted into the slot is maintained throughout the insulation life span. They have had considerable attention over the years and various systems were developed such as spring loaded wedges, two part tapered wedges and a combination of the two.

Slot side packing within the slot is also important to ensure adequate contact of the corona suppression system with the core, as well as to prevent bar sideways movement and vibration. The methods

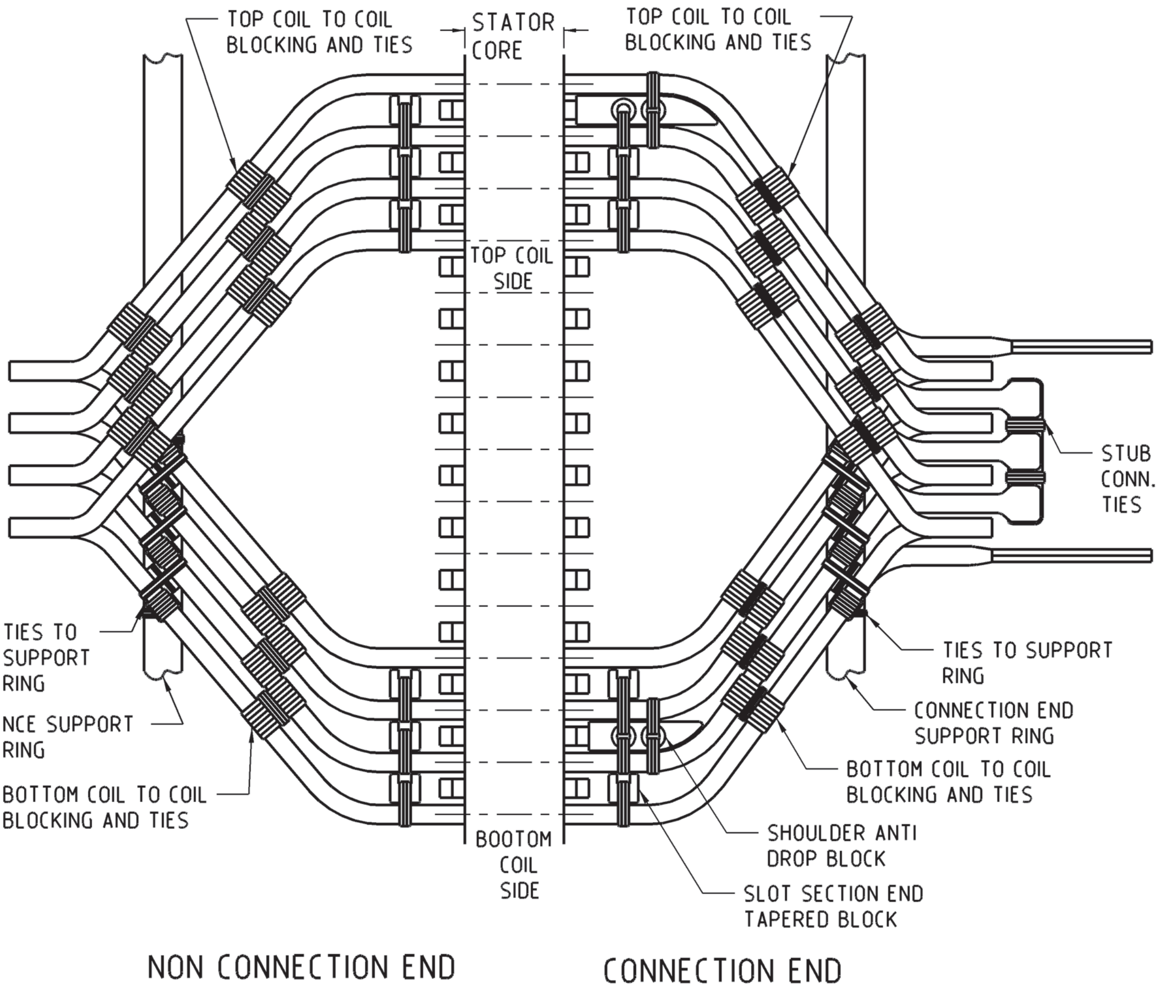


Figure 15: Typical hydro generator end winding bracing and blocking.

vary from the traditional conductive solid side packing, to interference fit conductive silicone rubber or conductive slot side springs. The slot supporting mechanisms (slot wedges, and slot radial and side packing) are discussed in more detail in the third paper of this series (Znidarich, 2008b).

2.3.3 *Coil thermal expansion*

Particular problems with coil thermal expansion have been experienced with the large electrical machines exposed to a severe cyclic duty (ie. rapidly loaded and unloaded), especially if the machines have long stator cores. Large numbers of hydro generators being used for peaking duty belong to this category, where full rated load may be applied within a few minutes from initiation of machine rotation. The rapidly heating copper stack will expand faster than the surrounding groundwall insulation, which takes a longer time to heat up. Given copper's higher coefficient of thermal expansion when compared to ground insulation, a considerable shear stress is imposed at their interface leading to a possible breakage of the bond, formation of the voids and destructive PD. In recent years, the thermal cycling test had been developed to ensure newly manufactured windings will be able to cope with this onerous operating regime (IEEE, 1996). The fourth paper of this series presents a detailed summary of hydro generator winding type and routine production testing (Znidarich, 2008c).

Long-term running under load does cause end turns to thermally expand and grow from 0.5 to 2 mm depending on winding temperature and end coil length. The coils within slots will also expand thermally more than the core (steel thermal coefficient of expansion is approximately 1/3 less than the copper coefficient). Again, the problem is more pronounced for the machines with long stator cores.

Coil bracing systems must be flexible enough to cope with the end winding axial growth, otherwise potentially dangerous stresses may result.

Historically, attempts were made to design end winding supports so rigid, as to prevent any axial movement. Experience has proven that to be impossible, and the modern school of thought is not to restrict end winding axial expansion.

This is usually accomplished by designing in required axial movement for the coil support mechanism (refer to figure 16).

2.3.4 *Stator core vibrations*

The rotor of a generator can be regarded as a large rotating magnet, the stator laminations surrounding this magnet in the form of a ring. The electromagnetic force produced by the rotating field winding is proportional to the square of the flux density.

There is thus a large electromagnetic force tending to pull the ring into the shape of an ellipse. This ellipse revolves at twice the speed of the rotor and sets what is known as "double frequency vibration of the stator core". For example, in a two-pole machine, a four-node vibration will be set, and an eight-node vibration for the four-pole machine will result.

These vibrations are obviously reflected at the interfaces of the winding and the core, ie. at the slot

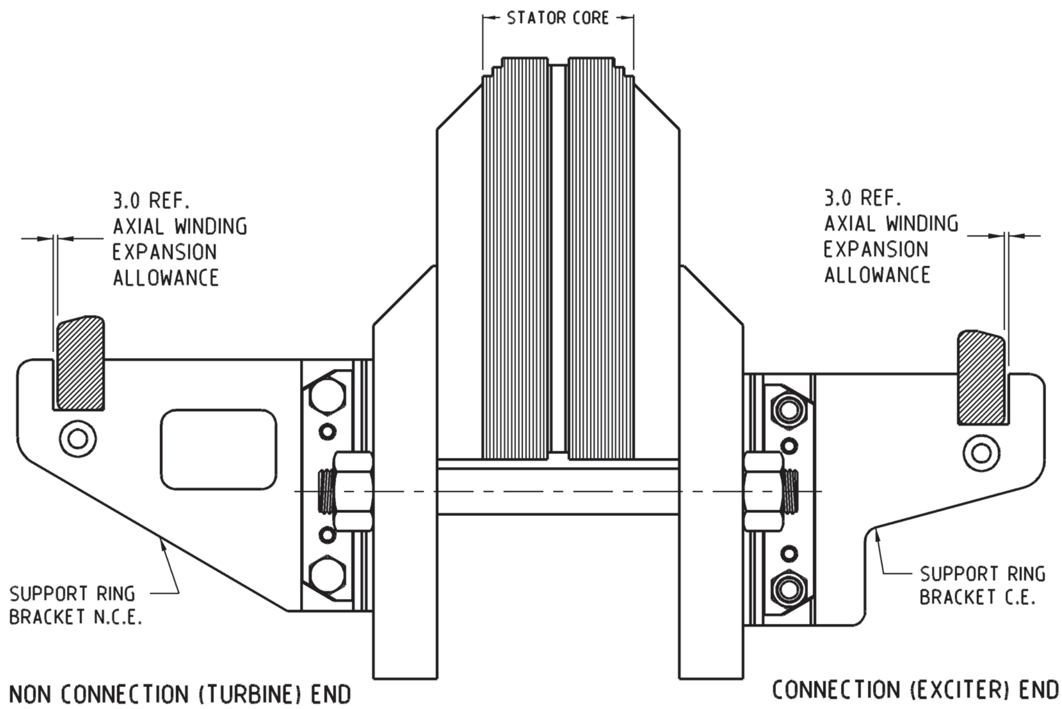


Figure 16: Typical allowances for the end winding thermal expansion.

section fits and end winding supports, leading to the insulation's mechanical abrasion.

Various ways have been devised to deal with the problem, such as making the core's outside diameter larger and stiffer, and increasing mechanical stiffness of the stator frame (Havley & Richardson, 1970).

2.4 Environmental winding degradation

Environmental ageing is due to the winding exposure to adverse environmental conditions. Although modern HV insulation systems are designed to meet specified operating conditions and environmental hazards, a reliable trouble free operation will only be achieved if the machine is not subjected to more adverse operating conditions and environmental exposure than is allowed by the machine design.

Contamination is one of the most common causes of HV winding failures.

Dirt, causing winding contamination, can be defined as "matter out of place" – the material that belongs elsewhere, not on the machine windings.

The major environmental hazards affecting HV insulations are (Nailen, 1983):

- ingress of moisture
- contamination with dirt and harmful chemicals.

Without the corrective maintenance measures, any of the above factors can lead to rapid mechanical and electrical winding degradation, eventually resulting in insulation failure.

The age old rotating machine insulation maintenance idioms: "Keep it Dry", "Keep it Clean" and "Keep it Cool" are still very much applicable today, especially when dealing with the environmental contamination of the HV winding surfaces (Nailen, 1983).

Moisture is an "age old" natural enemy of HV insulations. All insulation materials are to some degree hygroscopic, and will absorb moisture. The older insulating material based on organic binders and varnishes are more susceptible to moisture absorption when compared to the modern systems based on inorganic carriers and synthetic resins.

Internal absorption of moisture can lead to *"hydrolysis"*, which is a mechanism that causes rupture of the chemical bonds of the insulation (Stone et al, 2004). This process results in de-lamination and swelling of the insulation, where PD may be initiated. The most common symptom of moisture presence in the windings is a low insulation resistance to ground that responds, and can be raised by the dry-out process.

The external wetting of the winding surfaces (which is usually accelerated by the presence of dust, dirt, salt, oils or chemicals) can lead to surface electrical tracking. The capacitive charges on the winding surface cause leakage currents to flow on the surface of a contaminated winding, forming permanent conductive paths, which are manifested as visible carbonised tracks on the winding surface, extending between winding phases, or between phase windings and the ground.

The permanent conductive/carbonised paths on the insulation surface often lead to surface flashovers, causing insulation ground or phase to phase failures.

REFERENCES

Ames, R. L. 1990, *AC Generators: Design and Application*, 1st Edition, Research Studies Press Ltd, John Wiley & Sons, Inc.

Bonnet, P. 1993, "Trends in resin rich type high voltage insulation systems", ISOTEC Workshop 93, Zurich, November.

Brammer, R., Bengtsson, K. & Rudolfsson, D. 1998, "Coil end corona protection studies", INSUCON/ISOTEC 98, The 8th BEAMA International Electrical Insulation Conference, Harrogate, May.

British Standards Institution, 1987, BS 1432:1987 Copper for Electrical Purposes: High Conductivity Copper Rectangular Conductors with Drawn or Rolled Edges.

Dalal, M. V. 1981, "Thermal stability of micaceous insulation of high voltage machines", *IEEE Transactions on Electrical Insulation*, Vol. EI-16, No. 4, February.

Havley, R. & Richardson, P. 1970, "Vibration of large generator stators and windings", *Electrical Times Magazine*, July.

IEEE, 1986, *ANSI/IEEE Std 1 – 1986 IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation*.

IEEE, 1996, *IEEE Std 1310 – 1996 IEEE Trial Use Recommended Practice for Thermal Cycle Testing of Form-Wound Stator Bars and Coils for Large Generators*.

IEEE, 1999, *IEEE Std 492 – 1999 IEEE Guide for Operation and Maintenance of Hydro-Generators*.

International Energy Agency (IEA), 2001, *Guidelines for Hydroelectric Generator Upgrading*, Technical Report, The Hydro Power Upgrading Task Force.

Moore, V. A., Mulhall, V. R. & Bernard, J. R. 1984, "Stator bar end arm line discharge – menace or nuisance?", Presented at Canadian Electrical Association Rotating Machines Subsection, March.

Nailen, R. L. 1980, "How conducting surface coatings protect high voltage coils", *Electrical Apparatus Magazine*, August.

Nailen, R. L. 1983, "How to Recognize – and avoid – chemical damage to electric motors", *Electrical Apparatus Magazine*, September.

Nailen, R. L. 1999, "Corona: What it does; how to detect it – Part 1", *Electrical Apparatus Magazine*, January.

Nailen, R. L. 2000, "What tests of insulation's thermal life really mean", *Electrical Apparatus Magazine*, March.

Neal, J. E. 1998, "Resin rich technology today and trends", INSUCON/ISOTEC 98 – The 8th BEAMA International Electrical Insulation Conference, Harrogate, May.

Standards Australia, 1985, *AS 1573-1985 Copper and Copper Alloys-Wire for Engineering Purposes*.

Stone, G. C., Boulter, B. A., Culbert, I. & Dhirani, H. 2004, "Electrical insulation for rotating machines – design, evaluation, aging, testing, and repair", *IEEE Press Series on Power Engineering*, 1st Edition, Wiley Interscience, A John Wiley & Sons, Inc. Publication.

Weddleton, R. F., Brown, C. N. & Shields, C. R. 1972, "Corona protection for high-voltage stator windings", *Doble Rotating Machinery Publication*.

Znidarich, M. M. 2008a, "Hydro generator high voltage stator windings: Part 2 – design for reduced copper losses and elimination of harmonics", *Australian Journal of Electrical & Electronics Engineering*, accepted for publication.

Znidarich, M. M. 2008b, "Hydro generator high voltage stator windings: Part 3 – Stator winding slot support systems", *Australian Journal of Electrical & Electronics Engineering*, accepted for publication.

Znidarich, M. M. 2008c, "Hydro generator high voltage stator windings: Part 4 – type and routine production testing", *Australian Journal of Electrical & Electronics Engineering*, accepted for publication.

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Michael was born in Croatia, where he completed his electrical apprenticeship in 1968. Since emigrating to Australia and for the past 32 years he has worked with TGE Energy Services in Perth, Western Australia. TGE Energy Services (formerly F. R. Tulk and Co) is a joint venture between Transfield Services Australia and GE Energy Services (Australia). In the early 1980s, Michael was instrumental in the establishment and development of a high voltage coil and bar manufacturing facility, which now has clients in 22 countries around the world. He is currently engineering manager for all three TGE Energy Services facilities (Perth and Bunbury in Western Australia, and Sydney in New South Wales). Michael's current interests are focused on design of high voltage windings for large electrical machines, applied research on high voltage insulations for rotating electrical machines, and applied engineering for upgrades and uprates of hydro generators.

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