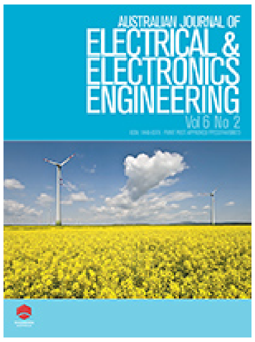

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Hydro generator high voltage stator windings: Part 4 – type and routine production testing *

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***SUMMARY**: A rigorous program of type and routine testing is applied before and during the manufacturing of high voltage (HV) hydro generator stator windings. The purpose of type tests is to qualify the insulation system as suitable for its purpose, and the purpose of routine production testing is to ensure there are no manufacturing defects and deficiencies built into the coils during the manufacturing process. The testing for hydro generator windings is often specified by the purchaser, and quite commonly includes accelerated ageing tests. This paper outlines hydro generator winding type and routine production testing most commonly encountered in modern practice. The electrical tests carried out during and immediately after the winding installation are briefly covered at the end of this paper. The described tests apply equally to the resin rich coils and coils that are Vacuum Pressure Impregnated (VPI) in the coil shop before installation. Given the large physical sizes of hydro generators, globally processed VPI stators are rarely encountered and therefore not covered here.*

1 HYDRO GENERATOR WINDING TYPE TESTING

The hydro generator winding type testing is usually based on two coils or four bars for dielectric breakdown tests, and another four coils or eight bars if accelerated ageing tests are specified. The most commonly used standard in Australia for all general type and routine tests, other than accelerated ageing tests, was BS4999: Part 144 (BSI, 1987a), which is now superseded with BS EN 5029 (BSI, 1999). Below is a description of the most commonly employed type tests.

1.1 Preliminary tests on copper conductor

High voltage (HV) hydro generator windings are manufactured from oxygen bearing or electrolytic tough pitch coppers (alloy number 110 (Standards Australia, 1985)), or alloy number C 101 (BSI, 1987b)). Oxygen bearing tough pitch copper is the copper alloy most common in the electrical industry where extra special characteristics are not required (Znidarich, 2008a).

The insulated copper conductor will be checked, tested and certified in the wire manufacturing facility. Most commonly the test certificate will provide details of copper conductor hardness (the degree of annealing), physical dimensions including corner radius, and the dielectric tests carried out on the strand insulation.

1.1.1 Copper strand hardness requirements

The copper for HV coils is required to be in a "fully annealed soft condition", to ensure its workability during the HV coil manufacturing process. The fully annealed soft copper will also have between 1% and 3% higher conductivity when compared with hard drawn copper, an important consideration regarding winding copper losses. There are two commonly employed methods for assessing the degree of conductor annealing. When subjected to the tensile strength test, the minimum acceptable conductor elongation before break is 35% (BSI, 1987b). The degree of annealing can also be confirmed by measurement of conductor resistivity, which should not exceed 0.017241 μΩm at 20 °C (BSI, 1987b).

1.1.2 Copper strand shape and dimensional requirements

For HV coil manufacturing purposes, the copper conductor with square sharp edges is not acceptable, since sharp edges tend to concentrate the electrical field and may contribute to earlier internal coil partial discharges (PDs) inception. Sharp edges may also cause strand-to-strand short circuits during coil manufacture. Copper strands are therefore

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manufactured with radiused edges, which are a function of conductor thickness, and are prescribed by the standards AS1573 (Standards Australia, 1985) and BS1432 (BSI, 1987b). The conductor manufacturer will examine the conductor profile with a shadowgraph to ensure it conforms to the standard requirements. Table 1 presents the copper conductor dimensional tolerance requirements (BSI, 1987b).

Coil manufacturing facilities are usually not equipped to check conductor corner radius, the copper manufacturer's report is used as a proof of compliance. However, pre-use copper strand dimension verification (width and height) is always carried out.

1.1.3 Copper strand insulation tests

Double-fused dacron glass (D/Glass) insulation is the most common strand insulation material for HV bars and coils. Higher quality multi-turn coils may also use resin rich mica strand insulation.

Strand insulation is always high potentially type and routine tested in the wire manufacturing facility (usually a few samples are type tested before commencement of the production run, followed by routine testing of one sample from each wire reel).

Depending on insulation build, the D/Glass insulation breakdown must exceed 300-500 V AC, whereas mica covered strand is expected to exceed 3000 V AC before breakdown.

1.1.4 Additional tests on copper strand

In some cases the purchaser may request further tests to be carried out on the copper strand. They usually include bending tests on bare and insulated copper strands, and heat ageing and abrasion tests on the insulated copper strand.

1.2 Strand-to-strand testing and strand continuity testing

Strand-to-strand insulation (insulation of conductor laminations) is tested with either 110 V AC (50 Hz rms), or 250 V AC (50 Hz rms) for 3 s. For coils with a larger number of strands automated testing equipment should be used, to both streamline the testing procedure, and avoid human errors. The test is passed if no failure (puncture) of the turn-to-turn insulation occurs (BSI, 1987a, Clause 5.3; BSI, 1999, Clause 3.3).

A continuity of conductor laminations is tested with a current source producing 10 A.

All type test coils are subjected to the strand-to-strand and strand continuity testing.

1.3 Turn-to-turn insulation type testing

Turn-to-turn testing is only applicable to the multi-turn coils. Typically two coils are required for the type testing.

Historically no uniform approach for selection of turn-to-turn test voltage existed. Different manufacturers based it on various design parameters, such as operating voltage per turn or per coil, system voltage, arrangement of turns within the coil, and in some cases on inter-turn and turn-to-ground capacitance.

The modern standardised approach for turn-to-turn testing (IEEE, 1992) is based on the maximum transient over-voltages the machine may be exposed to, and is employing impulse testing of turn-to-turn insulation rather than the traditionally-used surge testing. Even though the hydro generators may be, to some extent, shielded from the system imposed transients by the step-up transformer, impulse testing is more onerous, and will therefore provide the end

Table 1: Copper conductor dimensional tolerance requirements (BSI, 1987b).

	Ordered width or thickness (mm)		Corner radius (mm)	Tolerance (mm)
	Over	Up to		
Copper strand corner radii and tolerances	0.49	1.00	0.50	±0.08
	1.00	1.60	0.50	±0.08
	1.60	2.24	0.65	±0.12
	2.24	3.55	0.80	±0.12
	3.55	10.00	1.00	±0.15
Copper strand tolerances on thickness and width	0.49	3.15		±0.03
	3.15	6.30		±0.05
	6.30	12.50		±0.07
	12.50	25.00		±0.10
	25.00	50.00		±0.14
	50.00	100.00		±0.25
	100.00	160.00		±0.40

user with better assurance of the quality of the coil design and manufacture.

In addition to normal operating voltages (10-250 V/turn), the generator winding turn-to-turn insulation must be able to withstand transient surge voltages, which are caused by power system disturbances, and may be a few orders greater than the rated voltage, and characterised by their steep voltage rise wavefront, which may vary between 0.1 to 1.2 μs. Typically the steep wavefront voltages rise times produced by the power system disturbances or vacuum circuit breaker switching are of 0.1-0.2 μs duration, while lightning strokes waveform rise times are about 1.2 μs. The transient over voltages do not distribute themselves uniformly across the stator windings. The shorter the voltage rise time, the more uneven the distribution across the windings, with the first few coils dropping most of the transient over voltage. The transients with a rise time of 0.1 to 0.2 μs may be dropped across the first few winding turns only, thus causing severe overstressing of turn-to-turn insulation.

In the past, the turn insulation type testing was carried out by cutting and separating the turns and applying the high AC test voltage until breakdown. For the type test of turn-to-turn insulation, standards BS4999: Part 144, Clause 5.4.1 (BSI, 1987a) and BS EN 5029, Clause 3.4.1 (BSI, 1999) require the coil turns to be cut open at one end, and high AC test voltage of 0.3 of machine line-to-line voltage ($V_{l\text{-}l}$) to be applied between adjacent turns for 60 s. If breakdown has not occurred, the voltage is increased at a rate of 0.5 kV/s until breakdown. There are no criteria for the minimum level of breakdown voltage, the standard just requires that the level of breakdown voltage to be recorded.

As explained above, the modern trends in turn-to-turn insulation testing are based on maximum expected transient over-voltages. IEEE Std 522, Clause 6.3 (IEEE, 1992) specifies the following turn-to-turn impulse voltage test with a positive impulse voltage wavefront rise time of 0.1 to 0.2 μs:

$$V_{ti} = 3.5V_{l-l} \times 10^{-3}\frac{\sqrt{2}}{\sqrt{3}} \quad [\text{kV}_{\text{peak}}] \tag{1}$$

where V_{ti} = recommended impulse testing voltage [kV_{peak}] and $V_{l\text{-}l}$ = machine rated line to line voltage [V].

The author's company uses this voltage level for both the type testing and routine testing of coils, usually in agreement with the winding purchaser. Five voltage pulses are applied for each test. The test failure criteria are actual puncture of turn-to-turn insulation, which is demonstrated by a change (narrowing) of the coil response trace on the impulse tester's screen. The coil impulse test voltage levels for common power system voltages are summarised in the table 2.

It is important to understand the difference between impulse testing equipment and the so-called "surge testers", which are still used by some manufacturers for turn-to-turn testing of HV coils.

Most impulse and surge testers use a capacitor charged to an appropriate voltage level, which is then repeatedly discharged across the coil terminals. The decaying response of this LR circuit is then monitored on the cathode ray oscilloscope (CRO) and compared to a good waveform.

The essential difference between the two is that surge testers do not attempt to simulate the steep-fronted transients. The impulse tester circuitry, however, is adjusted to produce steep-fronted transient impulses, typically with the rise time adjusted to between 0.1-0.2 μs (refer to figure 1). This test therefore better simulates actual transient over-voltages that may be applied to the machine terminals, and is more onerous, ie. because of the faster voltage rise time, it imposes higher stress on the turn-to-turn insulation, when compared to the surge test of the same level.

Considering everything said above, the impulse turn-to-turn type test is gaining in popularity since it is designed to simulate actual conditions of winding exposure to external transient over-voltages.

1.4 Dielectric loss angle type tests (DLA or Tan δ)

The voids are inescapably present in HV insulations due to its heterogeneous structure and varying

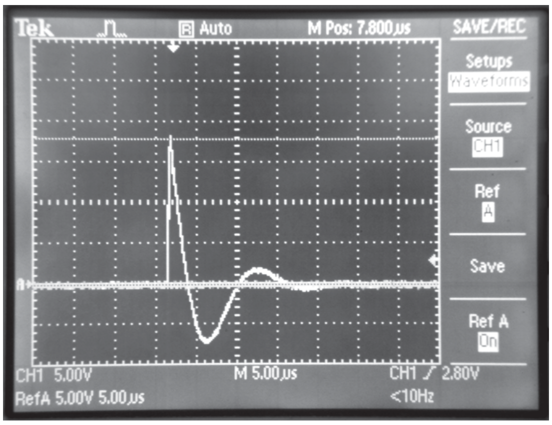

Figure 1: Typical impulse test response trace of a multi-turn HV coil's LR circuit as displayed on the CRO.

Table 2: Summary of coil impulse test voltage levels for common power system voltages.

System voltage [kV rms]	Impulse test voltage [kV_{peak}]	Number of pulses [<0.2 μs]
3.3	9.1	5
6.6	15.7	5
11.0	24.5	5
13.8	30.1	5

physical properties, in particular the coefficients of thermal expansion.

Above the 4-6 kV threshold, PDs in the voids will generate heat, thermally eroding void surfaces, eventually leading to the insulation breakdown.

The practical insulation equivalent circuit is represented as a parallel combination of resistance, which represents the heat loss in the insulation voids caused by PDs, and a capacitor representing insulation capacitance to ground (refer to figure 2).

The ideal condition for a dielectric, would therefore be of zero power factor, ie. the application of an AC current would involve no energy loss, the insulation being a perfect capacitor, with the current vector leading the voltage vector by 90°.

Due to the small resistive current component (I_R), the phase angle (θ) is less than the 90°, by a small angle. For convenience this small loss angle (90°–θ) is called δ (Delta), and the dissipation factor of the insulation is the ratio of resistive current (I_R) to capacitive current (I_C), or Tan δ (refer to figure 3).

The Tan δ test is therefore measuring how much heat loss takes place due to PDs in the insulation voids, relative to insulation capacitance. The larger the ratio insulation resistance/insulation capacitance, the larger is Tan δ (or loss angle), and the higher the power loss within the insulation at a given test voltage.

If, when all other conditions remain fixed, the voltage stress is raised from one specified level to another, the increase in the dissipation factor percent is called Tip-Up. The Tan δ is usually measured at room temperature in relation to the machine line voltage (V_{l-l}), over the range of 0.2 to 1.0 $V_{l-l,}$ at intervals of 0.2 V_{l-l}. As the voltage goes up, the value of Tan δ will characteristically begin to rise faster than the voltage increases (refer to figures 4 and 5). This bend in the curve (or Tip-Up) of the Tan δ value is compared with some limit prescribed by the standards, as a measure of insulation quality (refer to table 3 for acceptance criteria from BS4999: Part 144 (BSI, 1987a) and BS EN 5029 (BSI, 1999)), which apply equally to the type and routine testing. For the type testing, the usual requirement is to test two coils or four bars. The number of coils/bars subjected to the routine testing is quantified in table 7.

In the author's opinion, the standard prescribed (BSI, 1987a; 1999) maximum values of Tan δ and Δ Tan δ presented in table 3 are too conservative for modern resin rich or VPI insulations. Table 4 is a more realistic representation of what should be easily achievable by any reputable manufacturer, and hence specified

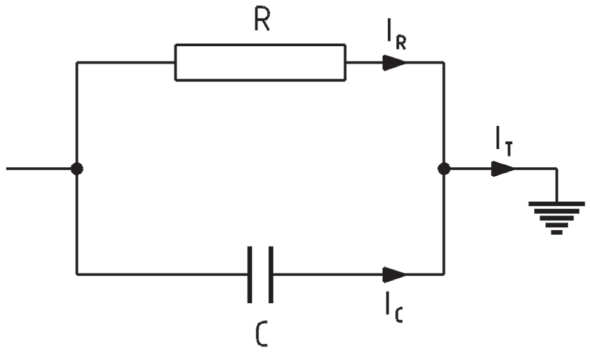

Figure 2: Equivalent circuit for high voltage insulation.

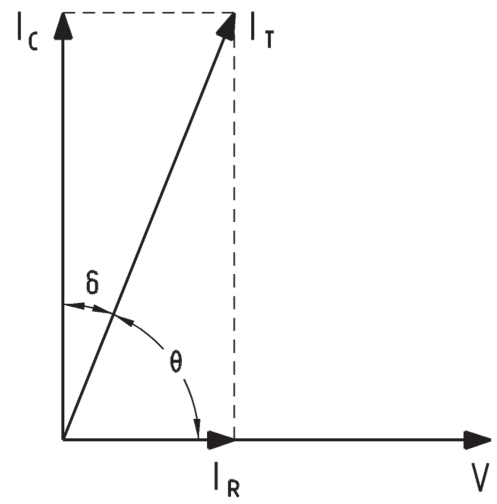

Figure 3: Tan δ representing the ratio of I_R/I_C.

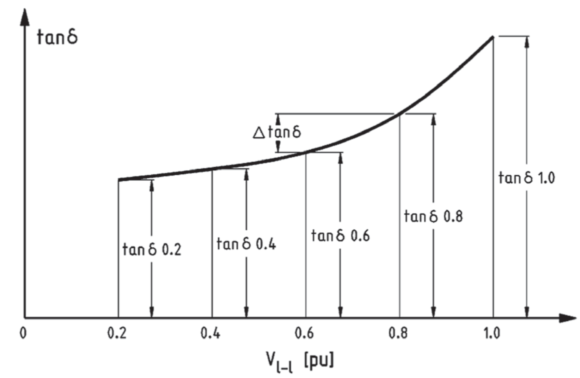

Figure 4: Tan δ curve versus per unit value of applied machine line-to-line voltage (BSI, 1999).

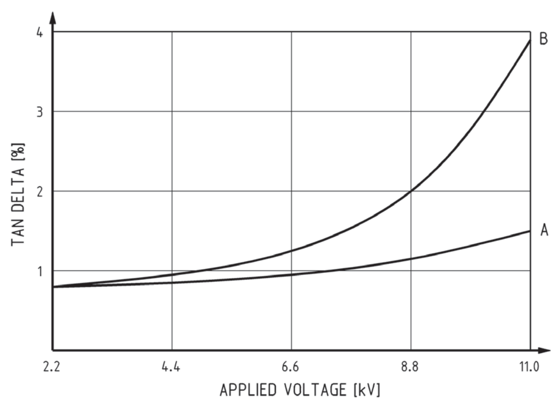

Figure 5: Typical Tan δ plots for acceptable insulation quality (A) and failed test indicating significant void content (B).

Table 3: Insulation quality acceptance criteria (BSI, 1987a; 1999).

Step 1	Step 2	Step 3	Step 4	Step 5
Tan δ at 0.2 V_{l-l}	(Tan δ at 0.6 V_{l-l} – Tan δ at 0.2 V_{l-l})/2		Δ Tan δ per step of 0.2 V_{l-l}	
All samples 30×10^{-3}	95% samples 2.5×10^{-3}	Remain. 5% samples 3.0×10^{-3}	95% samples 5.0×10^{-3}	Remain. 5% samples 6.0×10^{-3}

Table 4: More realistic representation of Tan δ and Δ Tan δ values.

Step 1	Step 2	Step 3	Step 4	Step 5
Tan δ at 0.2 V_{l-l}	(Tan δ at 0.6 V_{l-l} – Tan δ at 0.2 V_{l-l})/2		Δ Tan δ per step of 0.2 V_{l-l}	
All samples 10×10^{-3}	95% samples 1.25×10^{-3}	Remain. 5% samples 1.5×10^{-3}	95% samples 2.5×10^{-3}	Remain. 5% samples 3.0×10^{-3}

when ordering new hydro generator windings. The values in table 4 are approximately 50% when compared with standard prescribed limits listed in table 3.

The Tan δ test has been internationally accepted, and when properly interpreted will give a reliable indication of:

- degree of resin cure for resin bonded or resin filled systems
- how void free the insulation is internally
- bonding of groundwall insulation to the copper/turn stack
- as a production QA tool the Tan δ test is an indispensable tool for assessing solidity, homogeneity and absence of gasses in insulation.

BS4999: Part 144, Clause 5.2 (BSI, 1987a), and BS EN 5029, Clause 3.2 (BSI, 1999), are the most commonly specified standards in Australia for Tan δ testing of HV hydro generator coils and bars. North American utilities use IEEE Std 286, Clause 9.2.8 (IEEE, 2000).

The test is carried out using a variable HV supply, Schering Bridge and standard capacitor (refer to figure 6).

The conducting coating of the coil/bar slot portion fitted with one copper bar on each side is used as the bridge electrode. The guard electrodes are applied to stress grading at coil ends, since heat losses in the stress grading silicone carbide coating may be erroneously interpreted as an unsatisfactory Tan δ test result. The guard electrodes must make intimate contact with the stress grading material, without any air voids, which may cause discharges between the two. Some literature reports aluminium foils and conductive pastes used for this purpose. After some experimentation the author has found that satisfactory and uniform results can be achieved by using conductive rubber tape tightly applied over the stress grading surface as a guard electrode. The experience of other coil manufacturers concurs with the author's method. The coil/bar is suitably insulated from earth by using an insulated support

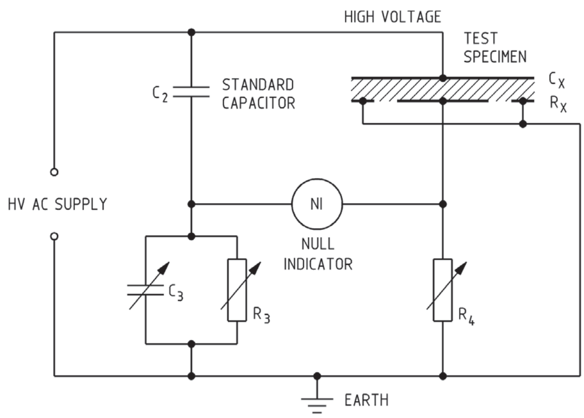

Figure 6: Tan δ Schering Bridge test circuit with guard electrodes.

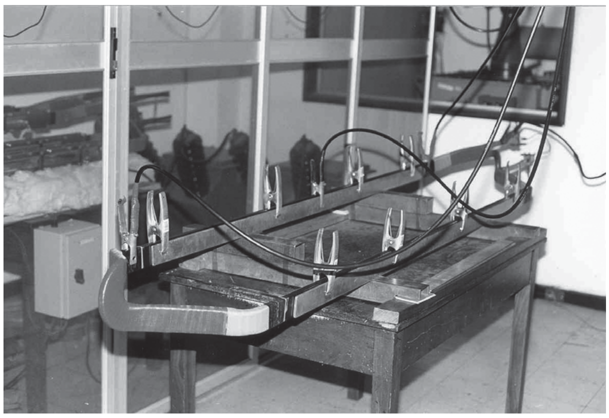

Figure 7: Tan δ testing of 50 MVA, 11 kV HV stator coil.

stand, with all coil copper conductors connected to the HV side of supply. The bridge is balanced by gradually bringing the voltage up to the required value, and then the dials are adjusted until a balance point is reached.

To ensure no insulation delamination takes place when the coil is subjected to thermal stress, the Tan δ type test is often carried out before and after the coil/bar has been subjected to at least one heat cycle (heated up to at least 90 °C and cooled back to room temperature) (BSI, 1987a; 1999). However, this has been largely substituted by a newly developed Thermal Cycling Test.

If increases in Tan δ Tip-Up are higher than normal, and assuming correctly cured insulation, most often some delamination will be present in the insulation. One of the simplest ways to locate the delaminated area is a "tap test". This is carried out by a small piece of metal or a small metallic hammer. Well bonded insulation will respond with a crisp high pitched metallic sound, while porous insulation will return a dull and hollow sound.

Some years previously while trying to promote Australian manufactured hydro generator HV coils overseas, the author had taken a batch of coils for accelerated ageing testing in Canada. When a group of large OEM insulation experts were asked for their initial opinion on the coils, they all responded by pulling large coins from their pockets and carried out a tap test.

The North American practice based on IEEE Std 286 (IEEE, 2000) uses only two voltage test points at 25% and 100% of the line to ground voltage (V_{ph}), with a maximum allowed Tip-Up value of 0.5%.

In the author's experience, the Tan δ test, if carried out in a timely manner, is an indispensable tool for monitoring coil production. The density and homogeneity of applied and consolidated ground insulation may vary slightly due to differences between batches of tapes, climatic conditions, ambient temperatures, etc. Small variations (increases) in Tan δ Tip-Up will therefore indicate a need for minor production adjustments. The author has therefore established a rule of daily testing of all produced coils, and continuous implementation of minor production adjustments for consistent quality of the produced windings.

1.5 High potential testing of insulation

The dielectric strength of an insulation material is defined as the maximum potential gradient that the material can withstand without failure, and it determines the voltage level at which the machine can operate. The dielectric strength is usually expressed in terms of a voltage gradient, such as volts per mil (VPM) or kilovolts per millimetre (kV/mm).

Dielectric strength testing, also known as high potential testing (Hi/Pot) is accomplished by an over-potential test imposed on the winding insulating parts. For in shop single coil testing, the power frequency (50 Hz) AC test voltage is always used. The AC test most appropriately simulates the actual operating insulation stresses and correct functionality of the corona suppression mechanism. An experienced test technician can draw further conclusions relative to the corona system functionality from the magnitude of audible and ultrasonic noise during the AC high potential tests. Excessive audible noise is usually caused by an increased amount of surface PDs due to inadequately processed coil insulation or corona protection system.

The fundamental intent of the test is to break down the insulation if it is weak, indicating defective material or workmanship and permitting replacement prior to actual use.

The AC Hi/Pot test voltage must be of an approximate sine waveform, and during the test the ratio of peak voltage to rms voltage (which can be determined by an oscillograph) should be equal to $\sqrt{2}$ within 3%.

The test is commenced at zero voltage and increased at a rate of approximately 1 kV/s until the desired test voltage is reached. Time is a very important factor when performing HV tests, and the duration of the test must always be specified along with the test voltage. Most commonly the test is of a 60 s duration.

At the end of 60 s, the test voltage is gradually diminished to zero and the test set is switched off.

1.5.1 *High potential testing of end winding insulation*

The Hi/Pot test level for end winding type test is $2V_{l\text{-}l}$ for 60 s at room temperature (BSI, 1987a, Clause 5.5.2; BSI, 1999, Clause 3.5.2). The insulation must pass this test without breakdown taking place.

The test is conducted by wrapping end windings with conductive materials and attaching the earthed side of the Hi/Pot tester to the wrapped end windings. The HV is then applied to the coil leads.

1.5.2 *High potential testing of slot section insulation*

The slot section insulation is first tested at ($2V_{l\text{-}l}$ + 1) kV AC power frequency test voltage level for 60 s at room temperature. The test voltage is then increased at a rate of 1 kV/s until breakdown occurs. The minimum acceptable breakdown voltage is $2(2V_{l\text{-}l} + 1)$ kV AC (BSI, 1987a, Clause 5.5.1; BSI, 1999, Clause 3.5.1), ie. for an 11 kV machine it would be 46 kV. Quite often the breakdown voltage cannot be reached with short end winding hydro generator coils/bars, as surface flashover between grounded coil slot sections and leads takes place.

The test is normally carried out by clamping copper bars of an equal length to the stator core on either side of slot section longer edge and attaching the earthed side of the Hi/Pot tester to the copper bars. The HV is applied to the coil leads (refer to figure 8).

1.5.3 *AC versus DC high potential testing*

Although the AC Hi/Pot test provides the best approximation of actual operational conditions, it

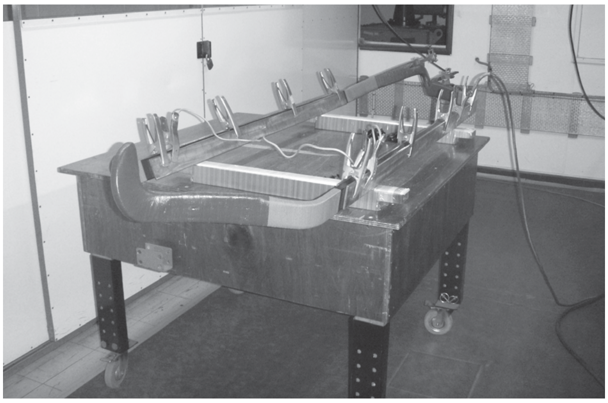

Figure 8: Slot insulation high potential testing of 50 MVA, 11 kV HV stator coil.

is well known that some insulation damage may be incurred during the test. Alternatives to the AC Hi/Pot test are DC and VLF (Very Low Frequency) Hi/Pot tests.

The essential differences between AC and DC Hi/Pot testing are in the degree of insulation ageing during the test and the test voltage stress distribution within the coil/bar insulation.

The AC over-potential test will always instigate significantly intense insulation void PDs, resulting in rather fast insulation degradation and ageing during the test. The reduction of insulation life can be approximated by the inverse power model (Stone et al, 2004), and for the good quality new insulation it may amount to the loss of insulation life in the order of a few hundred hours. Compared to the insulation life expectancy of approximately 30-40 years, that is rather insignificant. Nevertheless, repetition of the AC high potential testing at the same level is avoided. In the contrast, the DC Hi/Pot test does not age the insulation, since only one or two PDs may occur during the voltage application and switching off.

The voltage distribution across the ground insulation for DC Hi/Pot test is essentially proportional to the resistance of the insulation, while the AC Hi/Pot test voltage distribution will be governed by the insulation capacitance (dielectric constant). This essentially means that both tests will stress the slot insulation in approximately the same manner, however, the voltage stress distribution is entirely different in the end winding region. With the AC Hi/Pot test, the voltage stress in the end winding region will reduce when going away from the slot section, whereas with the DC Hi/Pot test, the entire end winding is equally stressed. The author is aware of a case where a particular new hydro generator winding has passed the factory AC Hi/Pot testing, and then repeatedly failed DC Hi/Pot testing on site during the winding installation. The failures were located past the first slot section bend under the voltage stress grading.

Another essential differences between the two tests are in the size of the test equipment, and the amount of damage caused if insulation failure is encountered. For AC Hi/Pot testing, rather large and bulky equipment is required, since it needs to supply high capacitive charging current, governed by typically large hydro generator winding capacitance. Insulation failure encountered during the test may cause quite large damage, including damage to the stator core. In contrast, the DC Hi/Pot test charging current is in order of a few milliamps, which is not likely to cause damage of any significance. The DC test equipment is also correspondingly smaller in size.

Considering the above, the current industry practice is to carry out AC Hi/Pot testing on the new coils/bars in the coil shop, and follow with the DC Hi/Pot testing during winding installation. The final Hi/Pot test at completion of the new winding installation may be AC or DC.

The Hi/Pot test was developed in recent years, which is reported to integrate the best characteristics of both AC and DC testing (IEEE, 1974). The test is named the VLF Hi/Pot test. The test set applies test voltage at the frequency of 0.1 Hz. It is claimed that the voltage distribution across the ground insulation is essentially the same as for AC test, with minimal occurrence of PD (number of bursts of ionisation is 10/min compared to 6000/min for the power frequency Hi/Pot test). The test apparatus is also of a manageable size.

To obtain equivalent voltage stress with AC Hi/Pot test (50 or 60 Hz rms), the long standing research and testing experience indicates that DC test voltage needs to be multiplied by a factor of between 1.6 and 1.7. Current European (and Australian) practice and standards use a 1.6 multiplier, while North American practice uses 1.7. The test voltage multiplier for the VLF Hi/Pot testing is 1.63 for its crest value.

1.6 Accelerated ageing testing

The insulation systems for large HV electrical machines have been rapidly developed in the last three decades, providing for better dielectric properties and higher temperature ratings.

Numerous studies have shown that most of the large electrical machine failures are attributed to the insulation system (Evans, 1981). To achieve long life for HV machines, a proper functioning of the winding insulation system is therefore required.

With increased market competitiveness, there is a constant pressure on electrical machine designers to provide more efficient and smaller machines, relative to the rated output. In regard to the windings, that means increased copper to insulation slot fill ratio (ie. more copper for increased current carrying capacity and less insulation to optimise the machine's physical size). In order to cut costs, designers have reduced insulation, leading to numerous premature failures, even though such windings may have produced excellent initial test results using traditional test methodology (Ward et al, 1987).

To counter this trend, end users (operators of large machines) have commissioned research projects to identify the suitable type tests that would, to a certain extent, predict life expectancy of the newly purchased windings.

This research has indicated various ways of accelerated ageing of the insulations, as the best way of initially predicting longevity and reliability.

Two tests have gained recognition and prominence:

- Voltage Endurance Testing (Ward et al, 1987; IEEE, 1996a; 2002)
- Thermal Cycling Testing (Stone et al, 1991; IEEE, 1996b).

In Australian practice, the Voltage Endurance Test is almost always specified as part of new hydro generator winding type testing, whereas the Thermal Cycling Test (in the author's opinion) should be specified for the generators having longer stator cores (2 m and above). By the client's request, the author has, however, carried out the Thermal Cycling Testing even for machines having relatively short stator cores of around 1 m.

The typically specified requirement is to first subject two coils or four bars to the Thermal Cycling Test, followed by the Voltage Endurance Test on the same coils or bars. In addition, two coils or four bars are subjected to the Voltage Endurance Test only. All preliminary tests are carried out before and after endurance tests (strand-to-strand test, turn-to-turn test, Tan δ test, corona surface resistivity, physical measurements, etc.). The Tan δ test is always carried out upon completion of the endurance tests. Some customers may request high potential testing to destruction to be carried out following the endurance tests. It is customary to carry out coil/bar dissection after the endurance tests, particularly if failure of the coil/bar has occurred.

1.6.1 Thermal Cycling Testing

The Thermal Cycling Test is intended to model thermo mechanical phenomena and failure mechanisms occurring within large electrical machine HV coils and bars. Particular problems have been experienced with large electrical machines and hydro generators, which are 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. The full rated load is often applied within 2 to 3 minutes from starting of machine rotation.

The failure mechanism is attributed to a faster rate of heating for a stator bar copper stack, relative to its surrounding insulation, during a suddenly applied load. Given different coefficients of thermal expansion for copper and insulation (copper coefficient is higher), copper will expand much more rapidly in an axial direction. Considerable shear stress is therefore imposed at the interface of copper and insulation that could lead to breakage of the bond between them and formation of insulation voids. Voids in HV insulation (particularly at line end coils) will lead to formation of PDs and accelerated winding deterioration, eventually causing winding failure.

The Thermal Cycling Test has been developed to simulate operating conditions of the cyclically loaded machine. A number of rapid heating/cooling cycles are applied to the stator bars (500 cycles) by means of injected circulating AC or DC currents and cooling air, or water-cooled platens. The temperature/time profile is adjusted to correspond to the actual conditions for the rapidly loaded machine. Typically the hydro generator coils operated within Class B (130 °C) temperature rise will be cycled from 40 to 100 °C and back to 40 °C slot surface temperature within 80-90 minutes. It was found experimentally that due to the very fast copper temperature rise during the thermal cycling test, the slot surface temperature of 100 °C corresponds to the copper temperature of approximately 125-130 °C. During the normal machine operation, with all temperatures stabilised, the difference between copper and insulation surface temperature is smaller, usually between 5 and 10 °C (Stone et al, 2004).

The degree of delamination is assessed by periodic Tan δ testing, and physical measurements of the slot sections, after the first 10 cycles, and then after 50, 100, 150, 200, 250 and 500 cycles. Although the Tan δ failure criteria are not explicitly defined in IEEE Std 1310 (IEEE, 1996b), an increase in Tan δ Tip-Up values of 0.5% should be considered significant (Stone et al, 2004).

The HV windings capable of passing the Thermal Cycling Test are more likely to be immune to the insulation delamination caused by rapid thermal stress and should have a better life expectancy (Stone et al, 1991).

The author has developed a variation of the Thermal Cycling Test suited for Australian climatic conditions. Instead of using cold air blown over the test specimens for the cooling part of the thermal cycle, as suggested in the standard, the author had developed water cooled platens attached to the test specimen slot sections. The obvious reason for this is a difficulty and expenses involved in generating cold air with ambient temperatures often reaching 40 °C and above. The block diagram of this Australian version of the Thermal Cycle Test is presented in the figure 9. The authors opinion is that Australian version of the test provides better resemblance of the stator core thermal inertia (heat sink), and is therefore more onerous when compared to IEEE (1996b) test, which uses cooling air instead. This test has been accepted in Australia for all thermal cycle tests on hydro generator stator windings carried out to date by the author (refer to figures 10 and 11).

1.6.2 Voltage Endurance Testing

The Voltage Endurance Test combines voltage and thermal stress to simulate and accelerate the insulation ageing and failure mechanisms occurring during normal machine operation. The AC test voltage is approximately four times line-to-ground voltage, applied at operating temperature, and the test is usually carried out for 250 or 400 hours. This test has been well researched during the past 50-60 years by North American power utilities, and Ontario Hydro HV Insulation Lab in particular (Ward et al, 1987).

Research experience shows that insulation that takes a longer time to fall in a voltage endurance test will generally last longer in service (Ward et al, 1987).

In the research stage, two pass/fail criteria were proposed. The first was based on a test voltage stress imposed on the ground insulation, and the second one on the voltage class of the winding being tested.

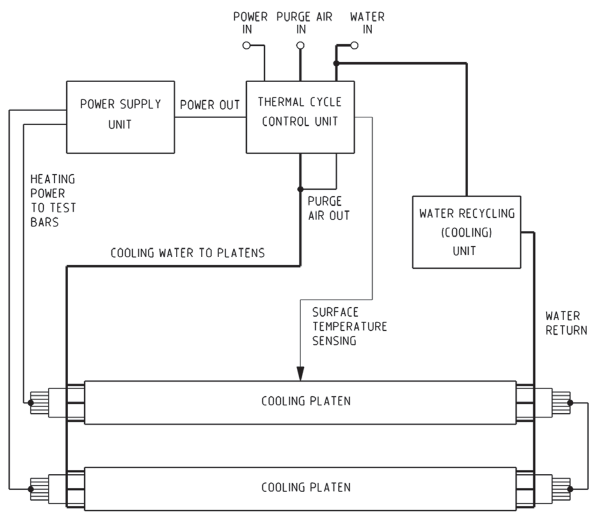

Figure 9: Block diagram of Australian (TGE Energy Services) Thermal Cycling Test equipment.

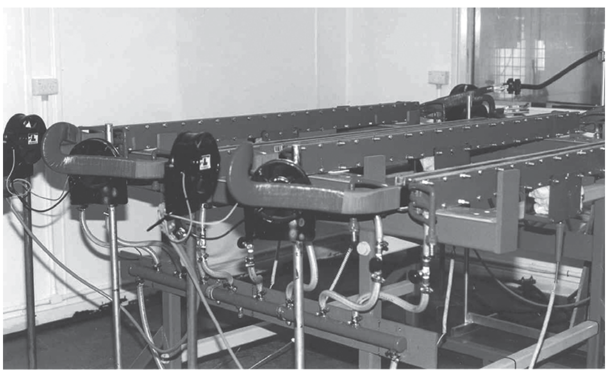

Figure 10: Thermal Cycling Test arrangement for multi-turn hydro generator coils.

From numerous tests over a 20-year period between the 1950s and 1970s, Ontario Hydro developed a voltage endurance curve depicted in figure 12 (Ward et al, 1987). The curve is based on test voltage stress, and the inverse power law, and was statistically developed by using a lower confidence level and comparing the performance of insulation systems on test and in actual service. If combined test stress and time to failure fall onto the right side of the curve, the bar or coil is considered to have passed the test.

From examination of figure 12, it is obvious that the bars or coils with thinner insulations will have a higher voltage stress imposed on them at a particular test voltage, and will therefore require shorter time on test when compared with bars or coils with thicker insulation under the same voltage stress. It

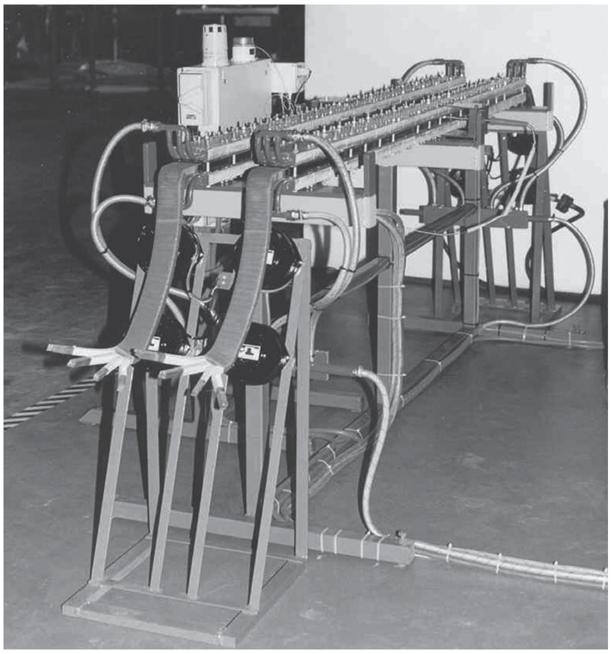

Figure 11: Thermal Cycling Test arrangement for single turn bars.

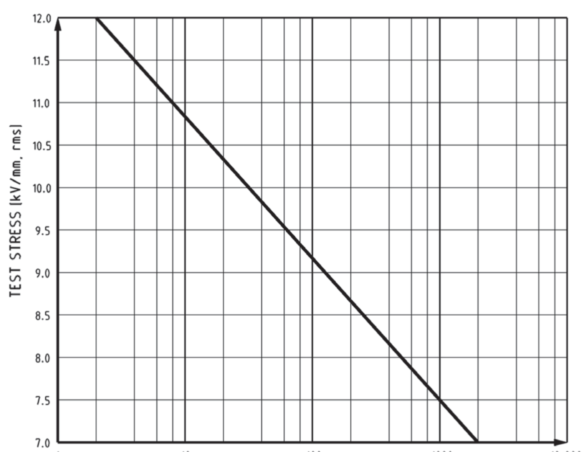

Figure 12: Ontario Hydro empirically derived Voltage Endurance Curve (Ward et al, 1987).

was, however, found from practical life testing that bars with thicker insulation will, under the same conditions almost always last longer in service.

The voltage stress pass/fail criterion was therefore abandoned, and the voltage class of the winding criterion is now universally prescribed in the Voltage Endurance standards (IEEE, 1996a; 2002). Essentially, and irrespective of insulation thickness, the voltage class criterion prescribes the test voltage level, and the time for test based on the winding's rated voltage.

The full size specimen slot sections (and most often complete coils) are fitted within temperature controlled heating plates, which also provide a ground surface similar to the stator slot in the machine, while the constant value sinusoidal AC HV is applied between coil leads and grounded heating plates (refer to figure 13).

The HV supply must provide a stable voltage (±2% variation) (IEEE, 1996a), with a good quality sinusoidal waveform.

The Voltage Endurance Test voltage stresses are adjusted to levels that still represent the ageing mechanisms the coil will experience in service, without going too high into the area where different excessive degradation mechanisms may not be a close representation of the actual operating conditions. IEEE Std 1553 (IEEE, 2002) prescribes two different voltage levels relative to the Voltage Endurance test schedules (hours). The voltage level of 3.76 times the line to ground rms voltage is used for 400 hours test duration, and a voltage level of 4.39 times the line to ground rms voltage is used for 250 hours test duration (refer table 5). The suggested temperature is equal to the machine operating temperature as measured by slot embedded temperature detectors (ETDs), or alternatively, it is negotiated between the vendor and the purchaser (IEEE, 2002).

Referring to table 5, an 11 kV insulation system will be expected to withstand 23.9 kV AC at 110 °C for a duration of 400 hours (16.6 days), or 27.9 kV AC, for a duration of 250 hours (10.4 days), without coil insulation or slot corona protection system failure. As a comparison, the standard rewind insulation acceptance test for an 11 kV insulation is 23 kV AC, for 60 s at room temperature.

The test samples are deemed to have failed the test if puncture of insulation has occurred. The criteria relative to the failure of the corona protection system is not as clear in the standards, and room has been left

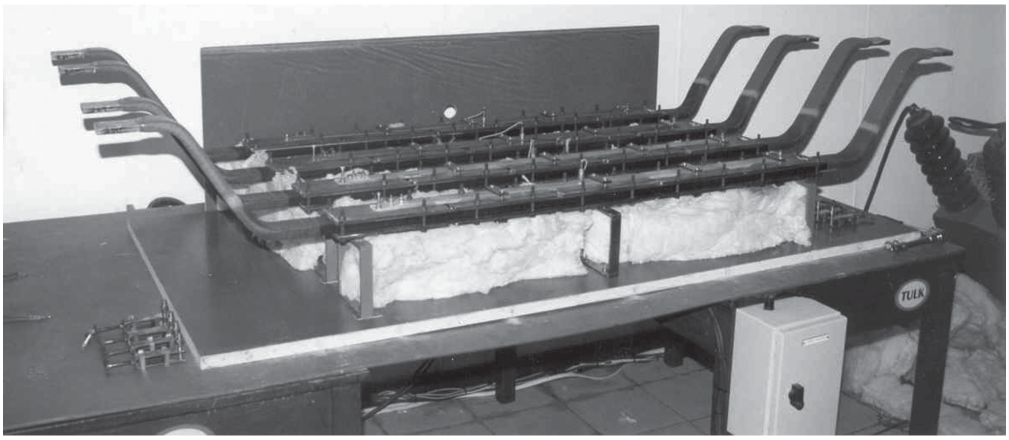

Figure 13: Voltage Endurance Test arrangement for multi-turn hydro generator coils.

Table 5: Voltage levels relative to the Voltage Endurance test schedules.

Rated line-to-line voltage [kV]	Rated line-to-ground voltage [kV]	Schedule A 400 hours	Schedule B 250 hours
		VE test voltage [kV]	
3.3	1.91	7.2	8.4
6.0	3.46	13.0	15.2
6.6	3.81	14.3	16.7
11.0	6.35	23.9	27.9
11.5	6.64	35.0	29.1
12.0	6.93	26.1	30.4
13.8	7.97	30.0	35.0
16.0	9.24	34.7	40.6
17.0	9.82	36.9	43.1

for negotiated test criteria to be agreed upon between the winding manufacturer and the purchaser. Current opinions are that stress relieve silicone carbide voltage grading is expected to deteriorate from increased heating losses due to the much higher currents it needs to carry at the elevated test voltage level, and that overheating will probably include the interface with the slot section coronal layer. Most purchasers' specifications encountered by the author so far permitted periodic repair of voltage grading during the test, but consider any damage to the slot section corona layer as a failure of the test.

To fully exploit information available at the end of the accelerated ageing testing, particularly if the failure has occurred, it is customary to carry out dissection of the coils or bars. An experienced examiner can draw useful conclusions regarding the quality of the insulation system and manufacturing procedures including:

- causes of failure and failure mechanism
- quality of tape application and pressing, including tape lapping, tape tension, tape wrinkles, excessive resin content and excessive void content
- correct alignment of copper conductors within the slot section structure
- uniformity of insulation thickness on all four sides of the slot section
- excessive roundness or sharpness of insulation on the slot section corners.

Some examples of Thermal Cycling and Voltage Endurance testing carried in Australia by the author's company are presented in table 6.

The author has never encountered a failure on either Thermal Cycling or Voltage Endurance testing. An interesting observation was made that Tan δ readings following endurance tests generally improved (lower initial readings and Tip-Up). This was particularly noticeable after the Voltage Endurance testing. The conclusion was reached that prolonged insulation exposure (250 hours) to temperatures of 110-120 °C resulted in further curing and polymerisation of epoxy resins in groundwall insulation.

To further enhance the realism of accelerated ageing tests, one test should be developed, combining as many insulation degradation factors as possible, ie. combined Thermal Cycling, Voltage Endurance and mechanical vibrations. This is justified since they do occur simultaneously within an electrical machine. For further simulation of actual operating conditions, full size HV stator coils should be fitted into full size replicas of the actual stator slots, incorporating the latest technology slot side packing and wedging (Znidarich, 2009e).

2 HYDRO GENERATOR WINDING ROUTINE PRODUCTION TESTING

Although BS4999: Part 144 (BSI, 1987a) and BS EN 5029 (BSI, 1999) prescribe the number of bars and coils to be routine tested relative to the machine size and number of poles (refer to table 7), the author's company usually applies routine tests, listed below, to all hydro generator coils at the end of the manufactured cycle.

Table 6: Some examples of Thermal Cycling and Voltage Endurance testing carried in Australia by the author's company.

Thermal Cycling Testing					
Machine rating		**Core length [m]**	**No. of thermal cycles**	**Temp. range [°C]**	**Cycle time [min]**
MVA	**kV**				
72.0	11.0	2.35	250	40-100	70
50.0	11.0	1.65	250	40-100	75
26.3	11.5	1.40	250	40-100	75
24.0	11.0	1.02	250	40-100	80
Voltage Endurance Testing					
Machine rating		**Design stress [kV/mm]**	**Test voltage [kV]**	**Test temp. [°C]**	**Test time [hrs]**
MVA	**kV**				
72.0	11.0	2.397	28.0	110	300
66.7	11.0	2.075	28.0	120	250
50.0	11.0	2.490	28.0	110	250
26.3	11.5	2.354	28.0	110	250
24.0	11.0	2.294	28.0	110	250
18.5	11.5	2.270	28.0	120	250

The final routine production testing and inspection carried out on hydro generator coils/bars usually includes:

- coil/bar shape verification
- strand-to-strand testing
- strand continuity testing
- turn-to-turn impulse testing
- Tan δ testing of slot groundwall insulation
- Hi/Pot testing of slot groundwall insulation
- surface resistivity measurement of slot section conductive corona protection layer
- physical dimensional measurement of the slot sections
- final visual inspection.

Coil/bar shape verification is carried out on all coils and bars. The author has developed a unique way of final curing and shape checking of all hydro generator coils and bars produced at the TGE plant. The coils or bars produced each day are fitted into accurate replicas of hydro generator stator cores (dummy stators), which also include essential end winding support components (surge rings) (refer to figure 14). The coils/bars are accurately positioned and fully blocked exactly as they will be in the actual machine. All relevant shape parameters are then checked including coil pitch, slot angles, end winding gapping, clearances with the support rings, etc. The coils/bars are then finally oven cured while being held in the precisely required position. Following final cure and testing, the coils/bars are fitted into packaging crates in the reverse order relative to their location in the dummy stator, so they can be wound into the generator stator core straight out of the boxes in the same order as they were fitted into dummy stator. The author proposes this to be the best and most comprehensive way of checking the final coil shape. This was proven on numerous hydro generator rewinds carried out by the author's company. Badly fitted coils were never encountered, and there is not a single high potential failure of a hydro generator coil or bar following installation recorded in the company's history.

The author insists on daily testing of produced coils/bars immediately following final curing. This allows for continuous monitoring of production quality, and implementation of minor "fine tuning" of production to ensure the best possible quality.

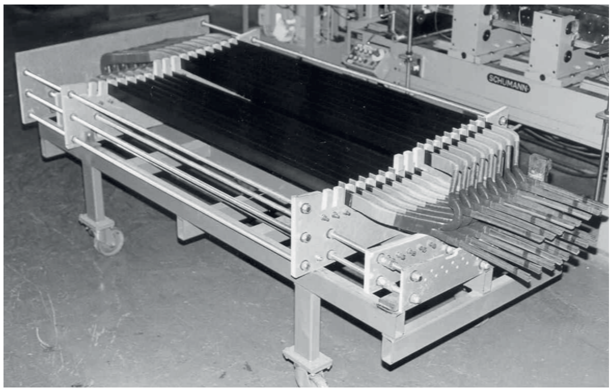

Figure 14: A batch of hydro generator coils fitted into dummy stator for dimensional evaluation.

The routine *strand-to-strand* and *strand continuity tests* are identical to type testing described in section 1.2 (refer to figure 15). The routine *turn-to-turn impulse test* is identical to the impulse type turn-to-turn test as described in section 1.3. The routine *Tan δ test* is as described in section 1.4, except it is carried out at room temperature, without prior thermal cycling requirement.

The routine *Hi/Pot testing of slot groundwall insulation* is negotiated between vendor and purchaser. The standard does not exist, but the test is usually made considerably higher than the final on-site winding test following winding installation of $(2V_{l\text{-}l} + 1)$ kV. This is designed to arrive at the final winding test voltage during the stator rewind through a series of intermediate tests, each having a downward sloping test voltage level.

The authors company uses the following voltage level for final in shop Hi/Pot testing of slot groundwall insulation:

$$V_{TAC} = (2.6 \cdot V_{l\text{-}l} + 4) \qquad [\text{kV}] \qquad (2)$$

where V_{TAC} = AC Hi/Pot testing voltage [kV] and $V_{l\text{-}l}$ = machine rated line to line voltage [kV].

For an 11 kV machine, the final in shop Hi/Pot test level is therefore 32.6 kV AC, as compared to the final winding test after installation of 23 kV AC. This allows

Table 7: Prescribed number of bars and coils to be routine tested relative to the machine size and number of poles (BSI, 1987a; 1999).

Number of poles	Rated output	Number of test samples
All polarities	< 5 MVA (MW)	10% of bars or coil sides with minimum of 20
2 and 4	≥ 50 MVA (MW)	All bars or coil sides
	< 50 MVA (MW) but not less than 5 MVA (MW)	At least 60 bars or 60 coil sides, and in addition 10% of all bars or coil sides
6 and more	≥ 5 MVA (MW)	

Figure 15: Strand-to-strand and strand continuity testing with automated test equipment.

for downward graduation of high potential testing during various stages of the winding installation.

The routine *Hi/Pot testing of the end windings* is not carried out.

The routine *surface resistivity measurement of slot section conductive corona protection layer* is carried out on all coils to ensure uniformity of surface resistivity, which should be between 0.5 and 40 kΩ/square maximum (internal TGE standard). In the author's experience, this maximum range of surface resistivity produces satisfactory grounding between coil/bar conductive surface and the stator core when used in conjunction with properly installed conductive slot side packing. The author is of the opinion that lower values of surface resistivity between 0.3 and 10 kΩ/square should be specified, which indeed seem to be the direction of modern practice. The simple square probe with an ohmmeter attached to two flat opposing copper edges is used for this purpose. The author is often asked the question: "kΩ per square what?" Referring to figure 16, and considering that the length and width of a square are the same, and given that measuring electrodes are on two opposing sides of a square, the answer is "it does not really matter as long as it is square, ie. square centimetre, square inch or square metre" (Nailen, 1980).

The routine *physical measurement of the slot section dimensions* is carried out with go-no-go gauges, to ensure compliance with the designed slot section dimensional tolerances. The *final routine visual inspection* is carried out to ensure that no surface defects or any other signs of inadequacy are present.

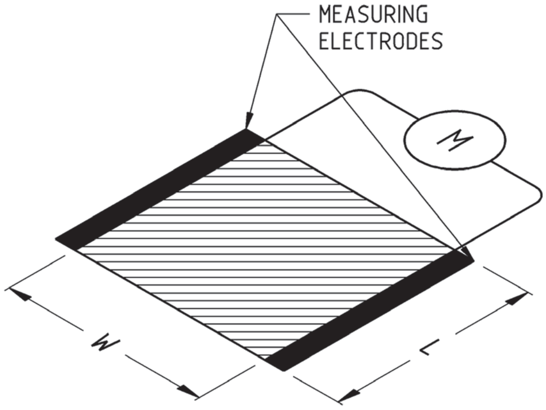

Figure 16: Method of surface resistance measurement of slot section conductive protection layer.

3 NEW WINDING TESTS DURING AND AT COMPLETION OF SITE INSTALLATION

The new stator winding site tests can be broadly divided into tests during site installation, tests to prove conformance with contractual specification, and baseline tests for future condition monitoring. The stator winding condition monitoring is another broad subject that may be covered in another future paper.

3.1 Winding tests during site installation

A brief chronological outline of HV winding site installation testing is presented below:

(i) *Stator core tests* – Before installation of the new winding, the condition of the stator core must be verified by either full Ring Flux Test (including measurements of losses at rated core flux density and core temperature rise), or low flux ELCID (Electromagnetic Core Imperfection Detector) test (Znidarich, 2008c; 2008d).

(ii) *Resistance between stator core and stator frame* – to ensure positive grounding of the stator frame via the stator core keybars. The resistance between stator core and the stator frame measured at about 100 points must be lower than 1 Ω.

(iii) *Resistance between installed coil/bar slot sections and stator core* – to ensure stator winding slot sections are side packed "tightly" and positively grounded in the stator core slots. The test is carried out using a specially prepared test probe about 150 mm long. Depending on the stator core length, two to five measurements may be taken and recorded for each top and bottom slot section. The maximum reading should not exceed 2000 Ω, but a more desirable reading is below 1000 Ω. Readings around or above 5 kΩ indicate a strong probability of slot discharges (Znidarich, 2008a; 2009e).

(iv) *High potential tests during winding installation* – these tests are carried out at specific stages of winding installation to locate the coils/bars that may have been damaged in transport or during the installation process, so they can be removed and replaced with minimum cost and delay. For the single turn bar windings, these tests are carried out at least three times: following the installation and side packing of all bottom bars, following the installation and side packing of all top bars, and following wedging of stator slots before connecting. For the multi-turn coil windings, these tests are applied at least twice: following installation and side packing of all coils, and following wedging of the stator slots before connecting. Referring to section 1.5.3 of this paper, the author prefers to carry out these intermediate tests by using DC Hi/Pot to minimise insulation damage. Depending on the number of these intermediate tests, the voltage is gradually reduced from the final coil shop value (refer to equation (2)), to arrive with the last test at the value slightly above the final test voltage requirement of $(2V_{l\text{-}l} + 1)$ kV AC. Every Hi/Pot test is preceded by IR (Insulation Resistance) and PI (Polarisation Index) tests. Traditionally IR and PI tests indicate degree of winding contamination and moisture ingress, however, in the context of winding installation testing they are used as an indicator of whether windings can be safely Hi/Pot tested relative to the existence of possible winding installation damage.

(v) *Turn-to-turn surge test of installed coils* – this test is only applicable to the multi-turn coils to ensure no turn-to-turn insulation damage was incurred during the winding installation. Since a coil embedded into a stator core presents a much higher surge impedance, it is common to carry out this test out by using a surge tester, which has a much gentler increase slope of applied voltage when compared to an impulse tester.

(vi) *Final winding inspection* – before the winding is subjected to the final conformance testing, a detailed final inspection is carried out. The inspection usually includes thorough visual inspection, a survey of all winding clearances, quality and location of end winding bracing and blocking, and final slot wedge tightness mapping. The winding connections are checked and verified to be in accordance with the approved winding connection diagram. In some cases, end winding resonance testing (so called "bump test") may be carried out, particularly if a previously installed winding had a history of end winding vibration and fretting degradation.

3.2 Winding tests to prove conformance with the contractual specification

To establish conformance with the contractual specification, the following tests are usually carried out:

(i) *DC winding resistance tests* – the DC winding resistance of the stator winding is a guaranteed figure subject to the contractual liquidated damages imposed on the winding manufacturer in case of non-conformance, and must be confirmed by tests on completed winding. The measured figure corrected to a particular temperature (usually 25 or 75 ºC) may be used later on for determination of generator efficiency by summation of losses. In addition, this test also checks the rewinding quality, ensuring the absence of high resistance joints. The resistance is usually measured with double Kelvin bridge, which is normally capable of applying between 10 and 100 A DC through the windings for measurement purposes. Care must be taken to ensure applied measuring current is not too high to cause any thermal changes in the winding while the resistance readings are being taken. The winding temperature must be allowed to stabilise and must be recorded along with the winding resistances (usually obtained from the embedded winding temperature detectors). The winding resistance readings of each phase winding are considered satisfactory if they meet (equal or below) guaranteed values, and if they do not vary by more than 1-2% between the three phase windings.

(ii) *Final Hi/Pot test of completed winding* – This test is carried out with either a AC or DC test voltage equivalent to the well known test voltage level of $2V_{l\text{-}l} + 1$ kV AC. Each connected phase winding is tested individually with other two phase windings grounded.

(iii) *Stator winding temperature rise test* – is carried out as a part of a complete generator heat run test, to prove conformance with guaranteed values of stator winding temperature rise (Znidarich, 2008b). The stator winding operational temperature greatly influences the HV insulation rate of thermal degradation and its service life expectancy (Znidarich, 2008b). Similarly to the guaranteed values of the winding resistance, the predicted stator winding temperature rise is also guaranteed and tied to the contractual liquidated damages imposed on a non-conforming winding manufacturer. The advantage of in-situ testing of hydro generator is that the full load at rated power factor can be applied, with all machine supporting systems functional (cooling and ventilation, lubrication, etc.), so that the machine true thermal performance can be measured and confirmed. This is one of the most complex and resource-intensive tests, since up to 40-50 different temperature inputs are simultaneously measured and recorded. The essential temperature measurements are taken from permanently mounted temperature sensors of stator windings, rotor field winding, stator core, inlet and outlet cooling air, inlet and outlet cooling water, and bearings and lubrication oil. In addition, temporary (local) temperature sensors may be fitted to the points of interest or concern, such as stator coil end windings and connections, sliprings and slipring air enclosure, etc. The stator winding temperature is measured by embedded temperature detectors (ETDs). The generator should be shut down long enough before start of the heat run, so that all machine components and parts are normalised to the same temperature. All temperature sensors should be correctly wired, and connected by shielded conductors to eliminate errors in readings caused by stray fields. The generator is then started, synchronised with the power system and usually loaded at approximately quarter, half, three-quarters and full rated load at rated lagging power factor. The machine is kept at each step load until the temperatures are fully stabilised. The temperatures are considered stable when they are within ±2 ºC for three consecutive half hour intervals (IEEE, 1995). To obtain stable temperatures at all four temperature levels, the author has often carried heat run tests continuously for up to 24 hours.

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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.

Michael is a is a fellow of Engineers Australia and registered Chartered Professional Engineer in Australia.