Important Considerations for Specifying New Hydrogenerator Stator Windings or Rewinds

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Introduction

As a source of power from renewable resources, hydroelectric generators are viewed with favour by both the general public and power system operators. Their relative simplicity, low production cost, ease of operation and high degree of flexibility make hydro-power a very important piece of the overall generation bundle. Traditionally they have been very reliable and have established a reputation for durability.

Since retirement of hydro-electric power is quite rare, over the period of their life these units may have their stators rewound several times and, depending on circumstances, receive a new stator core on one or more occasions. In addition, many rewinds are planned and expected to deliver more energy from the same basic machine. Where site re-development opportunities warrant more than this, significant increases in ratings may be initiated through proposals for complete machine replacement. Regardless if it is a new machine, a simple rewind, or a major up-rating of the existing unit, competitive pressures force vendors of windings and new plant to use innovative production techniques, materials and installation methods to reduce costs while still meeting the intent of the Purchaser's specification. For most cases, these changes in design and manufacturing will still yield an expected life of 30 years or more. However, if the design, manufacturing or installation is not optimal windings may fail prematurely, or fail to live up to the expectations of a long, trouble-free life.

To reduce the risk of premature stator winding insulation failure, a specification for a new winding should require the manufacturer to do more than just meet the requirements of IEC 60034 Part 1. In essence, the only requirement of IEC 60034-1 that may impact winding insulation life are the 1-minute high potential test and the maximum temperature rise at full load. Thus it is sensible for the user to specify tests in addition to those in IEC 60034-1, as well as providing to the prospective Vendors a clear indication of expected life at the highest operating temperature.

This paper will cover some important considerations that should be examined when specifying stator windings for either new machines or replacing existing windings. While adherence to the suggestions here will not necessarily guarantee a long and problem free life, it should minimize the chances of early failure due to design or manufacturing problems.

1 Pre-Qualification

One of the mechanisms that can be made available to assist in the purchasing of either a new or replacement stator winding is to have available a list of pre-qualified Vendors. Since the process of specifying and obtaining a winding is generally measured in months, it is highly desirable to know that prospective Vendors are capable of providing windings with service proven designs and materials. It therefore makes sense to pre-qualify selected Vendors who will then be invited to bid on contracts. This is particularly true where multiple or regular purchases are anticipated so that that when bids are solicited they are restricted to these pre-qualified sources.

Generally, the pre-qualification of Vendors can be initiated without waiting for the need to purchase a winding. The validation process may be initiated and carried out by creation of a document or specification that outlines the qualification process. This specification will define the scope of the pre-qualification process and as a minimum should address such things as:

- Manufacturing capability
- Process and material evaluation
- Quality assurance program
- Proven service record of materials used
- Demonstrated service capability for winding installation
- Voltage endurance tests
- Thermal cycling tests
- Insulation resistance and polarization index
- Power factor tip-up or dissipation factor tip-up tests
- High potential
- Surge tests

and any other electrical tests deemed necessary for the intended application of the particular winding(s).

1.1 Advantages

There are several advantages of such a program to the Purchaser. Perhaps the most significant is that the prospective Vendors can be studied and evaluated without the pressures of delivering a winding at the same time. This avoids any tendencies to reduce standards or acceptance criteria due to pressures to obtain a winding and have it installed quickly. It also allows the Purchaser the opportunity to fully familiarize themselves with the Vendor's manufacturing capabilities, capacities and to observe in action, the full quality program of the Vendor and to see how it is applied to the processes to insure consistency and quality.

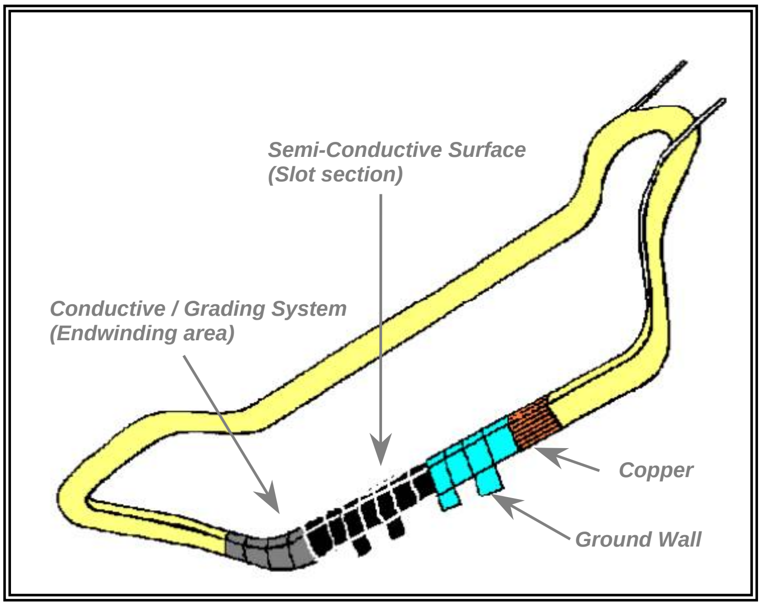
From the Vendor viewpoint there are also advantages. By submitting to a pre-qualifying exercise the prospective Vendor gets to know and understand his potential customer better. Again, it allows the ability to discuss, revise and possibly amend conditions, tests and expectations without the pressures of a winding being produced concurrently. The Purchaser may require some unusual or unique test or check for which the Vendor does not have statistical data to enable the proper evaluation of the risks of accepting such tests or checks. It also allows the Purchaser to perhaps be educated as to what may be realistic and what may be philosophically correct but of questionable validity as a quality measure. It also will permit the Vendor to illustrate the impact of individual specification requirements on the ultimate winding cost and therefore educate the customer such that there are no unrealistic or unrealized expectations.

1.2 Methodology

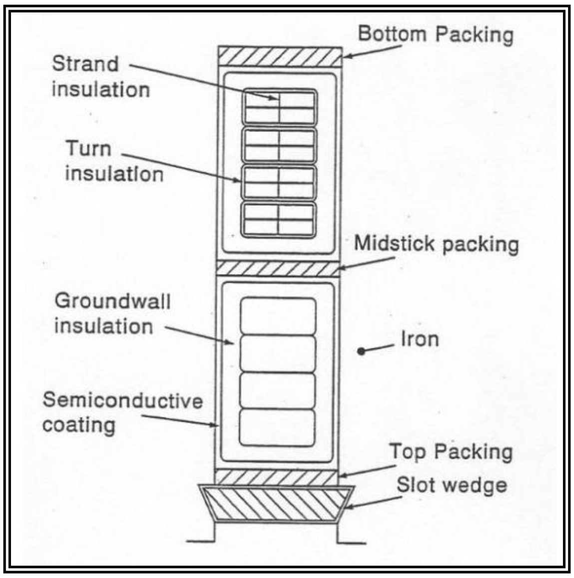
The best manner to achieve a realistic assessment of the production capability and quality of the Vendor is to arrange the pre-qualifying specification such that all tests and checks are carried out on normal production runs and not special coils or bars fabricated specifically for the qualification process. Stating that the qualifying tests are to be carried out on a random selection of coils or bars from a production run on a winding similar to that intended to be eventually purchased can facilitate this. Such a production run can be identified in consultations between Vendor and Purchaser and the appropriate number of extra coils or bars manufactured. A random selection of these would be made and these would then be subjected to the tests and checks stipulated in the pre-qualifying specification.

Should intended winding design be unique or new to a Vendor seeking pre-qualification, and thus there is no production run available, special bars or coils may be offered for testing and evaluation. In these cases it is difficult to insure that these would be "equivalent" to a production run and therefore the results may be subject to more uncertainty. However, if this must be carried out then it is strongly recommended that for qualification purposes full bars or coils be produced rather than straight test sections such that all aspects of the winding design can be evaluated, both physically as well as electrically.

Who pays for the pre-qualifying tests? That can be a negotiated item. Factors such as confidence in obtaining future business may mean that the Vendor will absorb the cost as part of the cost of doing business. If not as certain, then costs may be negotiated and shared. At the other end of the spectrum, it may be that the prospective Purchaser has to pay the marginal costs to have extra coils/bars manufactured and tested. In some cases, specialized tests may be required to be carried out by a third party and this must enter into the overall consideration and specification.



Typical High Voltage Coil Insulation System Components (Courtesy vonRoll Isola)



Typical Slot Contents (Side packing not shown)

2 Installation

The impact of a Purchaser's specification details and vendor selection should not be overlooked when it comes to stator winding installation. Regardless of how well made a winding might be, today's materials are not very forgiving of haphazard or poor installation. Materials may be more exotic and perform far superior to older materials in a similar application. But they have generally been engineered to much closer tolerances and performance and therefore do not have the margins that older units had to mitigate the effects of poor machine design or poor installation practices or workmanship.

The specification for the installation phase of any rewind must be every bit as clear and detailed as the supply portion. It should always endeavor to clearly state or define who is to do what, how is it to be checked or tested, what is to be done if something is discovered that was not apparent at the tendering stage, who handles removed materials especially if they contain designated hazardous substances such as asbestos. A good installation specification should cover such points as:

- Vendor supplied facilities and services at site (This needs to address such things as Telephone/fax, internet, power, water, compressed air, crane(s) service and operator, scaffolding, storage, access to specialized plant tools, access and egress from plant, office, locker, lunchroom and sanitary facilities and so on.)
- Assignment of a Safety Officer
- Vendor or other contractor activities that might interfere with the winding installation schedule due to the need to access the turbine pit or to use the powerhouse crane
- Define the state of the machine disassembly / re-assembly at which point responsibilities change between Vendor and Purchaser
- What components (if any) are to be re-used. Any tests/inspections required to establish if components can be re-used
- Indicate any stator core testing to be done before, during or after the winding installation and clearly define what is acceptable, what is to be done if not acceptable and who is responsible for carrying out any corrective measures. Checks may include measures such as rotor - stator roundness and concentricity, air gap measurements, stator verticality, core tightness, full flux test and so on
- Measures to be carried out by the Purchaser to satisfy the need to confirm the winding is installed properly such as side-packing tolerances, contact resistance, wedge tightness, coil spacing and endwinding clearances, winding blocking and tying, and so on. All checks must clearly state go / no-go criteria, how these measures are to be made if more than one option is available and, where required or necessary, define how disputes are to be resolved.
- Tests to be performed during winding installation and after complete installation. These should include insulation resistance, polarization index, AC hipot, coil surge test before connection and a wedge tap to confirm winding tightness and acceptance criteria where appropriate.
- Commissioning tests after the generator is put back into service to confirm new operating parameters including stator winding temperatures.
- Specialized tooling used by the Vendor that are to be left with the Purchaser

3 Material Verification and Quality Assurance

To ensure that a new or rewound stator will perform reliably it is important to verify that the materials, components and workmanship used are of acceptable quality. The first step in the process to obtain this assurance is to have the Vendor produce a detailed Inspection and Test Plan (I&T Plan) that covers the following:

- Coil/bar manufacture and QA testing
- Stator core preparation and testing prior to winding
- Stator coil insertion and testing during winding
- Checks on slot wedge insertion and tightness after coil insertion
- Adequacy of endwinding radial bracing, inter coil blocking and inter-coil spacing
- Verification of winding jumper and circuit ring insulation and connections
- Final testing of completed winding and core insulation
- Commissioning tests after generator is placed in service

This document should also reference both Vendor and Purchaser specifications and procedures that apply to the activities and processes described in the I&T Plan which should be prepared by the Vendor and approved by the Purchaser. The I&T Plan should identify hold points at which the Purchaser’s representative may witness the progress of the winding/rewinding process. The Vendor should be responsible for providing adequate notice to the Purchaser of when the work will have progressed to a hold point. The Purchaser should appoint an Inspector to verify that the I&T Plan is being followed. This Inspector must be familiar with the manufacturing, testing and QA procedures used in the winding process. It is recommended that the following hold points be included in the I&T plan.

- Sample inspection of the coils or bars after forming, but before ground insulation application
- Sample inspection of coils/bars after groundwall application, but before bonding resin curing.
- Review of results of strand/turn insulation, insulation resistance, hipot, power factor tip-up and any other specified tests at the coil manufacturing facility.
- Verification that the coils and other winding materials are adequately packaged for shipment and long term storage, if appropriate.
- Inspection of the condition of all coils/bars and other winding materials after arrival at the rewind site.
- Visual inspection of the stator core for defects and review of core test results prior to the commencement of stator coil/bar installation.
- Visual inspection of coils/bars and review of electrical tests after 1/3, 2/3 and all the coils/bars have been installed in the winding.
- Visual inspection after all endwinding bracing and slot wedging is in place. Also review and verification of wedge tightness map of completely wound stator.
- Visual inspection of all insulated coil jumper, circuit ring bus and main and neutral connections.
- Review of final core insulation test results.
- Witness final insulation resistance, polarization index, hipot and any other specified tests on completed stator winding.
- Witness commissioning tests on generator after it has been assembled and placed into operation.
- Verify that all documentation requested in the I&T Plan has been provided.

4 Tests for Vendor Qualification

As part of the process for selecting winding manufacturers, it is useful to have a few vendors perform certain tests on sample bars or coils that can demonstrate the capability of the insulation system and show the quality of their manufacturing process. All prospective vendors must perform tests or have recent data that shows acceptable thermal and voltage endurance performance using the same materials and processing methods that the user may be buy in a future winding. In addition, for hydrogenerators with a stator core longer than about 2 m that also are expected to experience a high number of load cycles, the thermal cycling test is appropriate. The latter test should also be required for qualifying pump-storage generator vendors.

4.1 Thermal Classification

Presently, virtually all commercial stator winding systems for hydrogenerators have a Class 155 (Class F) insulation system. Coil manufacturers (or their supplier of insulating materials) should have performed tests on their insulation system to ensure that it meets the requirements of the Class 155 system, or better. The thermal classification test method is well known, and described in IEC 60034 Part 18, Sections 1 and 31 and in IEEE 275. Note that the materials used in a Class 155 system will normally have an average life of 20,000 hours (about 2.3 years) when operated at 155 C [1]. Users need only confirm that the vendor has carried out such tests on their current system, and that they meet the requirements of a Class 155 system rather than requiring new tests.

4.2 Voltage Endurance

Winding manufacturers have been performing voltage endurance tests for 50 years as a method to design their insulation system. These tests are usually performed on small models of coils. In the past 25 years, and especially in North America, users have required voltage endurance tests on full size coils either for vendor qualification, or as a quality control test for a new machine or a rewind. In the voltage endurance test, 2 coils or 4 bars are energized to 3 to 4 times the rated operating voltage, and heated to the expected operating temperature of the winding (typically less than 120 C). To pass the test, the coils should not fail in less than 250 or 400 hours (depending on the voltage). The intent of the voltage endurance test is to show that:

- The copper cross-section is rectangular with no copper strands out of alignment
- The mica paper taping process is wrinkle-free
- The impregnation process with epoxy or polyester resin produces no significant air voids, and the resin itself has not been contaminated
- The semiconductive and stress grading coatings are uniform in electrical properties and well-applied
- The insulation groundwall thickness is sufficient.

The IEC voltage endurance test method (IEC 60034 Part 18, Section 32) is not a closely-defined test method and contains no realistic pass/fail criteria. Thus the only voltage endurance test standard that can be specified by users is IEEE 1553 – "Standard for Voltage Endurance Testing of Form Wound Bars and Coils for Hydrogenerators". This document details the exact test method, the test conditions and the acceptance criteria. Manufacturers who pass the test show that, in principle, their insulation system design and processing should yield a winding life exceeding 30 years, in the absence of any mechanical or contamination issues. It is usually acceptable for previously performed voltage endurance test results, on coils similar to those intended for the user's generators, to be used for vendor qualification, rather than a new test be done.

4.3 Thermal Cycling Test

The thermal cycling (or load cycling) test is only used for vendor qualification if the purchaser has machines that are pump storage units or large, peaking hydrogenerators that have a stator core length of 2 m or more. This test evaluates the ability of the insulation to resist delamination of the groundwall insulation when rapid load cycling occurs [1]. When a winding goes from no load to full load in just a minute or so, the copper expands due the rapid heating of the copper due to I^2R losses. Since it takes 10 to 15 minutes for the insulation to heat up, the insulation does not expand as quickly. The result is a shear stress between the copper and the groundwall insulation that, after many load cycles, may delaminate the insulation, leading to failure because of the resulting partial discharges.

The test method is described in IEC 60034, Part 18, Section 34 and in IEEE 1310. Essentially, the bars are heated by current and then force-cooled to cycle the bars between say 40°C and 155°C, once per hour or so, for 500 cycles. The user must identify a pass/fail criterion. A common criteria is that the dissipation factor tip-up or the PD magnitude must not increase by more than 2 times when tested before cycling, and when tested after 500 thermal cycles. This test is expensive to perform, so should only be required when large, peaking generators are to be bought or rewound.

5 Tests for Quality Control of Manufactured Coils

To ensure that all the coils for a new stator or a rewind are of good quality, there are several quality control tests that should be specified by the user. Most vendors perform a variety of electrical and dimensional checks on some or all of the coils. Dimensional checks are very important, since these ensure that the coils are just able to fit ion the slots, and the there will be at least 1 cm of space (for 11-13.8 kV stators) between adjacent coils in the endwinding, in order to prevent endwinding partial discharges. The electrical tests include:

- Strand insulation check
- Surge test for the turn insulation
- Dissipation factor tip-up test for groundwall impregnation
- Partial discharge (PD) test for impregnation and stress control coating evaluation
- Hipot test for the groundwall insulation integrity.

The surge test is not required for Roebel bars (also called half turn coils). The partial discharge test is sometimes not performed if the tip-up test is done, and the tip-up readings are acceptable.

5.1 Strand Insulation Test

This is a simple test where one copper strand in a coil is energized to say 120-240 Vac, with all other strands in a coil or bar grounded. There must be no short to ground. The test must be done prior to soldering all the strands together at the ends of a coil or bar.

5.2 Surge Voltage Test

When a lightning strike occurs close to a plant, or a generator is not synchronized exactly in phase, a fast rise-time voltage surge may be applied to the stator winding. The high frequency components of the voltage surge can apply a very high voltage across the turn insulation in the fist coil, that may break down the turn insulation [1]. Punctured turn insulation will result in a very high current in the coil- which will rapidly melt the copper conductors, leading to a ground fault. The surge test is performed on every coil to ensure that the turn insulation can withstand such transients. The surge test applies a 200 ns rise-time voltage impulse that is 3.5 times the rated peak line-to-ground voltage of the stator between the two leads of the coil. If breakdown under this high voltage occurs, then the coil is rejected. The test should be performed on every coil. The test method and pass/fail criteria are in IEC 60034 Part 15 or IEEE 522. In general, the IEC version of this test is easier to pass than the IEEE version.

5.3 Dissipation Factor Tip-Up Test

The dissipation factor (very similar to power factor or tan δ) tip-up test indicates if the polyester or epoxy bonding resin has been contaminated or has not filled all the spaces between the mica paper tape layers. The dissipation factor measures the power loss (heating) of the insulation caused by the 50/60 Hz voltage. Ideally the insulation should have a zero loss, but common insulations such as epoxy mica typically have a loss or dissipation factor of about 1% of the capacitive volt-amps. If the dissipation factor (measured at a low voltage) is higher than coils made in the past with the same process and materials, then it may mean that the resin is different, has aged and/or been contaminated with say water or dirt. Thus the user should specify that the dissipation factor be the same as in the past, and the vendor identifies what is an acceptable dissipation factor for their process.

The dissipation factor tip-up test is a variant of the dissipation factor test. The dissipation factor is measured at low voltage and (at least) rated line-to-ground voltage. If the insulation has no voids (that is it has been perfectly impregnated by the resin) then the dissipation factor should be the same when it is measured at low voltage and at rated voltage. However if voids are present, when the coil or winding is energized to rated voltage, PD will occur at the rated voltage. Since PD creates heat, light and sound – they require energy, and contribute to an increase (or 'tip-up') in the dissipation factor. As an example of the tip-up test, the power factor for an 11 kV stator is measured at 1.3 kV and 6.5 kV. The tip-up is the difference in percent power factor measured at the two different voltages. The higher the tip-up, the greater is the PD, which normally means the more poorly impregnated the coil is, and the more likely it will fail in service due to partial discharge.

The test procedure for this test on individual coils is given in IEC 60894 and IEEE 286. All coils should be tested. Many utilities require the tip-up to be less than 0.5%.

5.4 Partial Discharge Test

Many coil manufacturers also perform a partial discharge test, at least on a few of the coils in each production run. The PD test on a coil measures the magnitudes of the individual discharges, and provides much the same information as the tip-up test. However, by interpreting the PD pattern, it is possible to identify the cause of any PD, unlike the tip-up test [1]. Thus one can distinguish poor impregnation from poorly made or poorly applied stress control coatings. The test methods for individual coils can be found in IEC 60270, and the soon to be published IEC 60034 - Part 27, which is specifically written for stator windings. No pass/fail criteria are standardized as yet.

5.5 AC Hipot Test

The hipot test is an overvoltage test that is applied to a complete winding to prove that the groundwall insulation has not been cracked or damaged during winding installation. According to IEC 60034

Part1 (or NEMA MG 1), the complete winding will be tested to twice rated phase-to-phase voltage plus 1 kV. Thus, for an 11 kV stator for example, the complete winding is energized to 23 kVac rms,. Although the standards allow a DC hipot as an alternative, this should not be permitted in a purchase specification, since the DC hipot is not as sensitive to insulation problems in a modern winding as an AC hipot test [2].

Although not required by any standard, most winding manufacturers perform a hipot test on every coil or bar after coil manufacture. Most use a coil hipot voltage that is usually at least 30% higher than the final winding hipot [2]. Users should require that that each coil or bar be hipot tested to at least twice rated voltage plus 1 kV. Before each coil is hipot tested, the insulation resistance measured according to IEEE 43 (IEC has no equivalent document) should be a minimum of 100 Mohms after 1 minute, corrected to 40ºC.

5.6 Voltage Endurance and Thermal Cycling Test

In North America, it is common for large utilities to require a voltage endurance test (see previous section) on two coils (or 4 bars) that are randomly selected from the entire production batch for a rewind or a new machine. Since the voltage endurance test destroys the coil or bar, extra coils or bars need to be made for the winding. The purpose is to ensure that the bars or coils made for the winding receive the same process and manufacturing care as the coils tested as part of vendor qualification. Thus in this application, the voltage endurance test is essentially a quality control test on the complete coil manufacturing process.

Far less frequently, the thermal cycling test has been used as a quality control test during the production of a set of bars. However, this should only happen for the most critical machines, since the test is very expensive, and takes a few months to perform.

6 Conclusion

Long and problem free operation of new hydrogenerator stator windings can be a realistic expectation to maintain the outstanding reputation that these machines have established for reliability and availability. However, in order to do so, greater attention to detail in the manufacture and installation of these windings is essential since competitive pressures have forced both Vendors and Purchasers to seek new and innovative ways to produce these windings. A comprehensive plan involving supplier qualification, capability and quality assurance testing is essential to maximize the probability of a long service life.

References

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