Options & Considerations for Generator Rewind Decisions

Presented by –

Edward Jenkins, Jr., P.E., PhD

Senior Engineering Advisor

Jenkins Electric Company

Charlotte, NC

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I Introduction

A. Background

Hydro generators operate in a weather controlled situation. By nature, the atmosphere is damp, and the buildings are cold in the winter. In addition, since river water flow is not guaranteed, the individual generators run intermittently. They often sit idle for weeks or months in a damp atmosphere. Then, the ultimate calamity: the plant floods.

Although a visitor to a hydro station can appreciate the idyllic surroundings, the generator winding may not be so appreciative. The moisture in the air can creep into the winding insulation if the surface seal on the insulation has cracked. Water with any mineral content will provide a conducting path to ground.

Intermittent operation of the generator means the winding temperature rises, and the conductors expand. Since the stator core iron has a different coefficient of expansion than the copper conductors, the ground wall insulation is subject to shear forces. Conversely, when the generator goes off line, the conductors cool and shrink. This again mechanically stresses the insulation. The field coils do not have the same shear stress against their core, but turn to turn forces do occur.

[The above comments assume stationary power producing coils in the generator frame and field coils attached to the rotor with field current supplied through slip rings. [This is not always the case, as will be illustrated later.]

Surges or lightning strikes are a further source of winding stress. Failure due to a line surge often occurs in the coils nearest the line connection.

These comments give background for visual inspection of a generator with suspected problems. In every case, fault finding should use most senses.

B. What we are going to talk about

This paper was titled “Rewind Decisions”, but we will consider many things involved in a productive hydro-generating system. Sometimes the generator has known problems and been left off-line for years, waiting for a cost driven decision. In other cases, the generator has been working until an operator has noted a fault and called for help. Our suggested procedure:

1. Review the generator’s history, if available
2. Talk to the operators

3. Measure insulation resistance and circuit continuity
4. Analyze the core and frame
5. Check the excitation circuit
6. Choose the method/ extent of repair or rewind
7. Repair/ rewind as decided, test
8. Verify working controls and line breaker
9. Address mechanical considerations
10. Return to service

II Analyzing the generator condition

A. General Comments

Burned insulation has a characteristic acrid phenolic smell. Cracks in the insulation can be seen and felt. Arcing faults to ground can be heard. Rotor to stator rubs have a characteristic noise or click if the generator is turning without load. The bumping from a stator rub or a runner rub can also be felt in the frame of the generator. Laminations can loosen and their insulation dust away. Instrumentation is used to supplement personal observation.

B. Initial Inspection - Windings

If the problem or location has been determined by the operator, many steps are eliminated. Assuming no operator information, the following procedure is suggested. These comments assume the generator is still all together and wired to an AC disconnect, **which is open and locked out. Safe working conditions and procedures are primary!** (18)

1. Record all nameplate data. (And all test data taken in the steps below).
2. Visually inspect the windings for signs of burning, flaking insulation, or arcing. Take pictures of any problem areas and the entire generator.
3. Shorted coils often show signs of excessive heat.
4. Measure the resistance to ground of the stator and field windings. Table 1 provides recommendations on test voltages.
5. If the neutral connection is available and can be opened, measure the resistance between phases.
6. Measure and compare the phase winding resistances.
7. Measure resistance of the field windings and compare this to the nameplate ratings. Remember that the field resistance will rise about 30% when it reaches operating temperature.

Table 1:

TABLE 15.3 Guidelines for DC Voltages to be Applied During IR/PI Test

Winding Rated Voltage (V)[a]	Insulation Resistance Test Direct Voltage (V)
<100	500
1000–2500	500–1000
2501–5000	1000–2500
5001–12,000	2500–5000
>12,000	5000–10,000

[a]Rated line-to-line voltage for three-phase AC machines, line-to-ground voltage for single-phase AC machines, and rated direct voltage for DC machines or rotor windings (from IEEE 43-2014).

C. If the stator winding has very low resistance to ground (less than 1 Megohm at room temperature).

1. Check moisture by reading the voltage between the winding and ground. A wet winding will show several millivolts between the coil leads and the frame. Moisture provides an electrolyte to produce this voltage. The insulation on a dry winding will produce much less than 1 millivolt. A grounded winding will not produce a voltage. This technique does not work for newer formed-coil, VPI/B-Stage insulation systems.

2. If moisture is detected, and the reading is not a hard ground, drying actions include running with no excitation to stir the air around the coils or hot air drying. If “wind-milling” for a day does not change the resistance reading, external heat may be applied. The winding areas must be enclosed by tarps or insulation boards and gas or electric heaters used to force warm air around the windings to dry out the winding insulation. This process can take days to weeks. A minimum of 10 Megohms is desired in a dried-out stator winding (resistance corrected to 40 C). Field windings may operate safely with lower resistance to ground.

3. If the winding resistance is less than 10,000 Ohms, a grounded coil (or coils) is likely. Sometimes there are visual indications of burning in the area of the ground. If the ground location is not obvious, a capacitor discharge can be tried. Using a DC Hi-pot, charge a capacitor to 7 to 10,000 volts. Connect one side of the capacitor to the generator frame and discharge the capacitor into the winding by touching a lead. A “Pop” or a “Flash” may indicate the source of the ground.

   When the ground source is not yet found, the winding must be split into sections and the ground location found by methodically checking the resistance to ground of each phase, and then of each group in a phase.

D. If the field windings are suspect

Field coils usually fail when the turn-to-turn insulation has deteriorated. They can also fail if the ground insulation and/or packing insulation has deteriorated and allowed the coil to move on the pole. Checking for grounds on field poles is easier, since the terminals for each coil are usually visible and accessible.

Checking for turn-to-turn failures can be done by recording voltage drops or current draw at a constant voltage. If the field pole inter-connections can be accessed, apply 120 VAC to each field pole and record the current draw. All field poles should draw the same current, +/- 10%. If DC testing is used on the entire field, every pole should have the same voltage drop, +/- 5%. An alternative quick check is to compare the voltage induced in an AC pickup coil from each field pole when 480 to 600 V AC is applied to the entire field circuit, or portions of the circuit.

E. Stator Core Laminations

Over time, laminations will rust and loosen as the generator starts and stops, warms, and cools, and moisture creeps in. Laminations can also be damaged if wear in the rotor shaft bearings has allowed the rotor to rub the stator. If the lamination stack is tight, and the wedge slot is not damaged, laminations do not need to be replaced. Modern steels have better core-plate (insulation between layers), lower losses, and higher permeability. However, for most hydro applications, these advantages do not out-weigh the cost of replacing a core that is still viable.

F. Excitation Circuit

The generator may have a rotating exciter or a solid-state exciter. The excitation current usually flows to the field circuit through slip rings. These rings occasionally need turning to restore a smooth, concentric surface. Similarly brushes, brush springs, and brush-holder insulation need to be inspected to insure reliable operation. Brush grade may have been changed and commutation or slip ring wear increased.

G. Protection Circuits

RTD's are often provided in the stator windings. Some of these are brought out to a monitoring circuit to detect overheating. The rest of the RTD's are left as spares. Occasionally, vibration monitoring is provided. The operators will usually know if there are problems in these circuits.

The neutral to ground connection may be left to float, hard wired, wired through a neutral grounding resistor, or connected through neutral grounding transformer. The neutral connection should be verified and the related circuits checked.

III Temporary Repair Options

A. Cut out stator coils

If the general condition of the winding is satisfactory and the circuits intact, one or more grounded or shorted coils can simply be removed from the circuit, and the end turns cut to avoid circulating currents. Once the fault(s) have been located, the winding must be analyzed to determine the effect of removing coil(s). If the generator neutral is not grounded, it can float enough to offset slight (<5%) unbalance in generated phase voltages. Figure 1 illustrates coil connections on a 3-wye, 12 pole winding. If the number of coils in each parallel path of one phase are equal, (but less than the number of coils per phase path in other phases), the neutral can shift to accommodate. Care must be taken to avoid serious unbalance in parallel paths. Cutting out a bad coil may require removing similarly placed good coils in parallel paths. There is no hard rule as to how many coils can be removed and still generate satisfactorily. Engineering judgment is required to consider the effects on the overall performance of fewer coils in a phase.

Figure 1. 12 Pole, 3-Wye connections

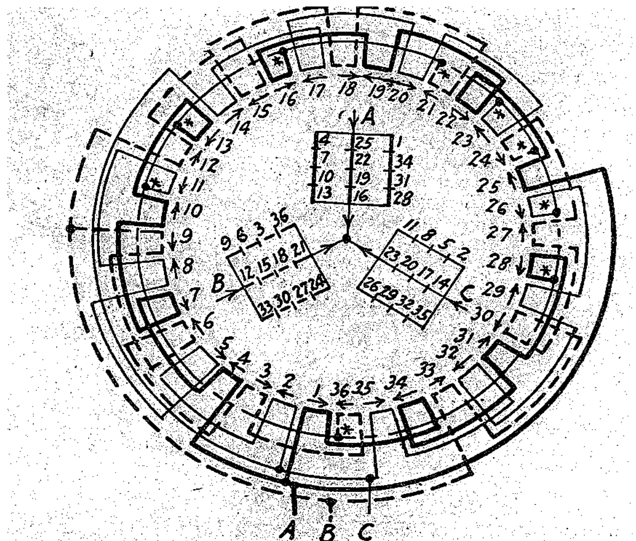


FIG. 249.—Twelve pole, three phase, three parallel star.

B. Rewind or Replace a Few Coils

In early years, all coils were made with flexible insulation and providing spare coils with a rewind was common practice. When a coil failed, the area could be warmed, coils lifted, and a “new” coil inserted. In other winding types, bar-type windings were used, and the slot section of the bar could be removed after the end connectors were taken off. Often these bars were wound with transposed conductors (roebel transposition). This type of bar is difficult to push out of a slot.

Newer insulation systems on coils are hard cured in the slot length, and have slightly flexible end turns. The end turns gradually harden in use. This type of coil is difficult to replace without damaging adjacent good coils.

C. Rewind One or More Field Coils

Individual field coils can be removed, repaired, rewound and replaced without disturbing adjacent coils. Lead position is important on a replacement coil to be sure it connects easily to adjacent poles. Coil shape is important, to be sure the replacement coil fits easily between adjacent poles.

D. Patch or Replace Leads

Generator leads usually pass through twists and turns on their path to load connection. Magnetic forces due to surges can cause the leads to move and fray or loosen the insulation and the tape at joints. In addition, the leads are closest to any incoming surge which can cause lead insulation to fail to ground.
Replacing, re-soldering, and reinsulating/ taping leads are cost effective repairs to an otherwise sound winding.

E. Clean and Paint Windings

Over the years, moisture, dust, fungus, and corrosion will attack the generator. Although complete insulation improvement on all surfaces is not possible in a re-condition effort, cleaning can help prolong life. Once the accumulated debris is removed from coils, laminations, and frame a coat of insulating varnish can be applied. Care must be taken to be sure the surface is dry and as clean as possible, so the paint does not trap contaminants in the coil area.

IV. Full rewinding and restacking

A. Armature (Stator) Re-wind

Winding layout/ connection, span, and number of coils should be checked before coil removal. Measurements are required of coil extension lengths and drop angle on end turns. Notes should be made of the blocking and ties between coil ends on the old winding. The span should be checked again after the lap is lifted.

Stripping a generator stator in-situ is labor intensive. Care must be taken to avoid damage to the laminations. Old windings are usually tight in the slots, and slot insulation, if used, often sticks in the slot. After the lap coils are removed, several good sample coils should be carefully removed with as little distortion as possible.
One or more coils should be unwound to measure conductor size(s) and number of turns. Intact coils would be used with a replacement order, and saved to compare with the new replacement coils when they are received.

Once the core is cleaned, measurements should be made of slot width, depth, and length. Slot width is particularly critical. Measurements in several places should be taken to get a reliable measure of average width and minimum width.
All dimensional information is needed for the replacement coil order.

The following figure illustrate the effect on generated voltage waveforms from changing the coil layout/ design in a small generator.

Figure 2. Coil designs: Bar, Lap and Concentrated or “Overlap” (7)

Bar and Coil Windings.—Armature windings may be divided into two general classes according to the way in which the coils are placed in the slots, namely: bar windings and coil windings. In the former, insulated rectangular copper bars are laid in the

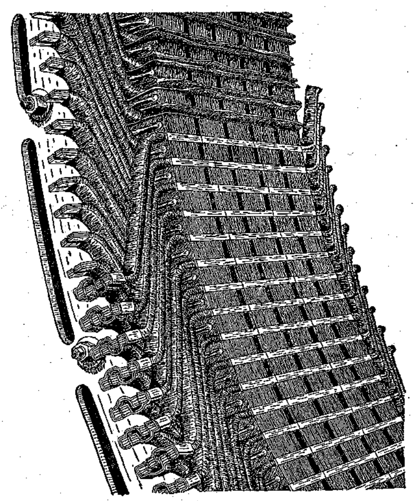


Fig. 18.

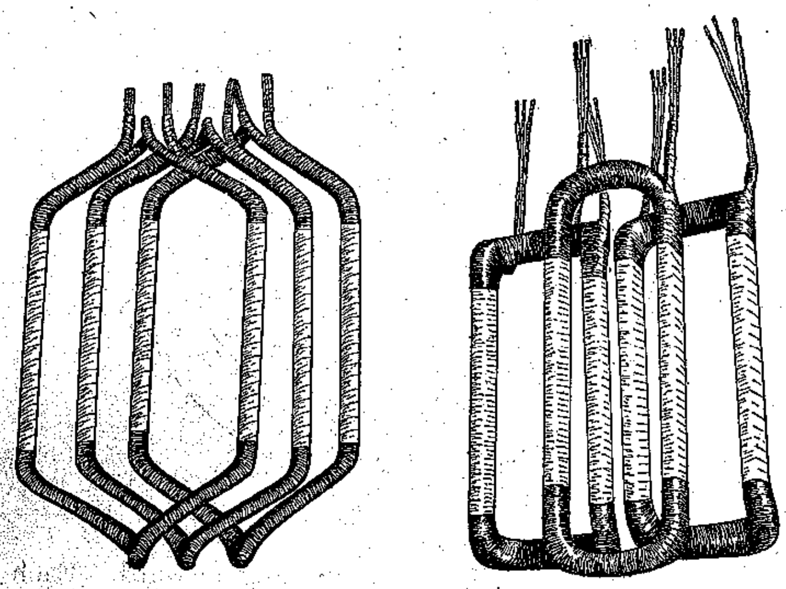
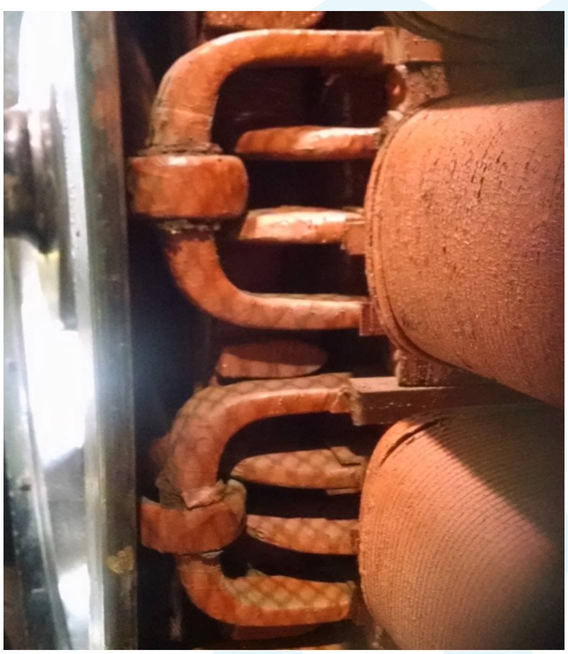


Fig. 19.

Figure 3. Concentrated coil shapes and waveform (one coil side per slot)



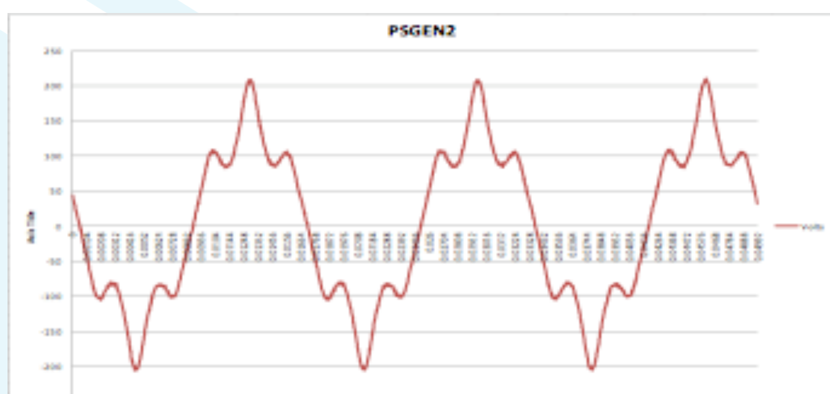


Figure 4. Lap winding and generated waveform (two coil sides per slot)

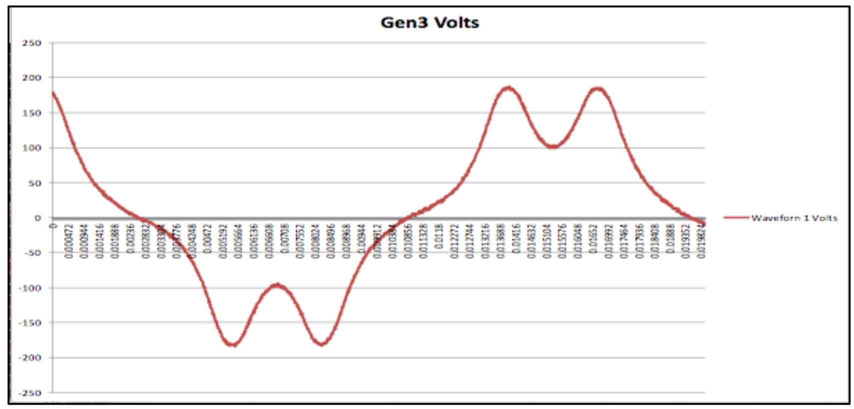
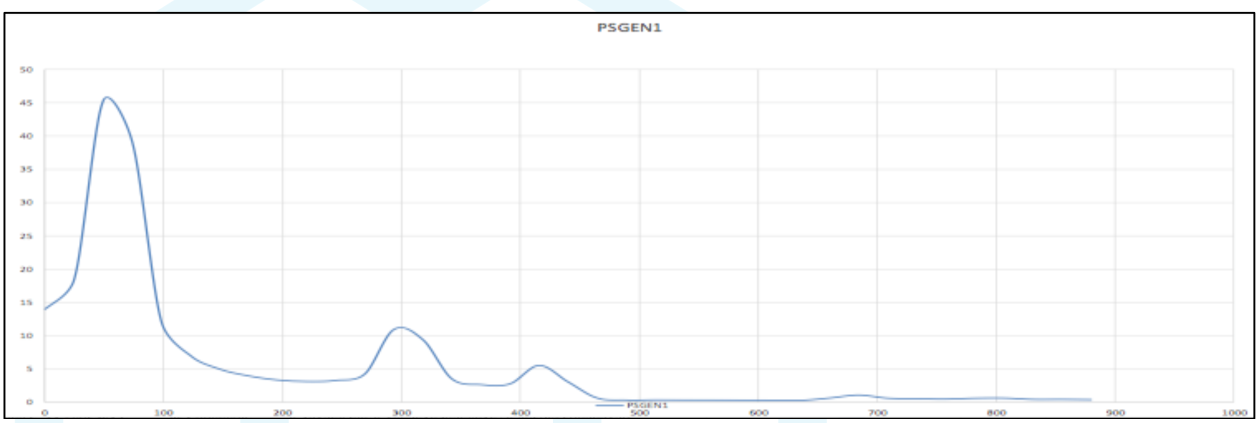


Figure 5. Harmonic content of windings in Figures 3 and 4



Some customers want scrap copper back, but in the usual rewind, the rewind company gets the scrap copper. This is subject to negotiation in the repair agreement.

B. Field Coils

Field coils should be removed carefully with collars and packing/ tightening material intact. Sometimes the coils are held in place by steel springs or glass fiber ripple washers. Record the method used to be sure the coils are replaced tightly on the rotor. Original coil shape and height should be recorded. Sometimes the coils are wound with fewer turn layers near the shaft, spreading out nearer the top cap. In addition, spacer v-shaped wedges positioned between coils are often used to hold turns in place.

Coils should be marked with a number corresponding to their position on the rotor spider and weighed individually. Weight distribution is important to know when the generator is placed back in service and balance is required. A similar record is needed of the finished coils.

The wire size or sizes should be recorded along with the number of turns. On larger field poles with accordion winding, there is only one rectangular conductor wound on edge. The position of start and finish leads is important to allow easy re-installation. Usually half of the poles have lead position reversed so finish leads and start leads are adjacent on alternate coils. The coils are all wound in the same direction.

Once original data have been obtained, replacements must be designed. For large field poles with accordion winding, reinsulating the existing copper turns is most economical. Specialized coil manufacturing firms can also supply new coils of this type, if the conductors are not re-usable. Field poles on smaller generators are layer wound with rectangular wire and then vacuum-pressure-impregnated (VPI) with an epoxy varnish. A preferred wire insulation is Double Dacron-Glass over film (DDG-HAPT). Copper conductors are universally used.

C. Laminations

The core steel (laminations) need to be examined before rewind.

Cleaning old insulation out of the slots gives time to examine the condition of the core. The core lamination stack needs to be tight. One reference (4) describes a knife test for tightness. If a winder's knife blade with a maximum thickness of 0.25 mm can be inserted between laminations in several places to a depth over 5 mm, the core is loose. The looseness can be due to age, loosening of clamp bolts, or deterioration of the lamination steel due to vibration. If the loose laminations show rust, dusting of the interlaminar insulation, hot spots, broken or cracked teeth, fretting at the segmented core support bars, or the wedge slot is not clearly defined, new laminations are recommended. An old core can be restacked to spread problem laminations. Modern laser cut laminations are now cost competitive with the time taken to re-condition old cores. Cleaning, straightening, and reinsulating old laminations is labor intensive.

If the core's mechanical integrity is satisfactory, a core loss test is suggested to find any hot spots. This involves exciting the core with current fed through loops around the back iron. See IEEE Reference (13) and Reference (5), Page 5-34. Once the core is excited, thermal imaging will indicate areas which are more than 5 C hotter than the main core. These areas should be examined for laminations which may be stuck or welded together. Rotor rubbing or previous coil failure can damage the insulation (core-plate) on the laminations. Older laminations with organic surface insulation deteriorate over time, and can show more hot spots. Newer insulations have inorganic insulation with longer life. On larger machines, El-Cid testing provides good definition of core integrity.

If the laminations are tight and have no hot spots, they need to be checked for concentricity and firmness of support. Clamp bolts may shift or the support frame structure may have warped.

D. Rewinding the Generator Stator

The core has been prepared, the coils ordered and received, and an area cleared to store the coils and winding supplies and tools. The design of the coils has been chosen in conjunction with the coil manufacturer and their recommended installation procedures have been received. Trained technicians are needed to re-wind hydro-generators, following the coil manufacturer's procedure. A representative of the coil manufacturer may be on-site for the beginning to supervise coil installation and at the end of the winding process to supervise final testing. This supervisor may be necessary to validate the coil warranty.

The first coils are inserted to test slot fit, end turn location and angle, and clearance between coil sides in the end turns. Once a section covering two pole widths is inserted and one pole section is wedged, all coil leads are electrically connected and ground tested with AC or DC test voltage. The recommended AC test voltage is 1000 V plus twice the rated voltage. The recommended DC test voltage is 1.7 times the AC test voltage. Following a DC ground test, the leads must be grounded to dissipate the stored charge. Following the final test with DC applied to all coils in the winding, the winding should be grounded for several hours (MG-1, 22.52.2, Ref 8).

During the winding process, RTD's are often inserted at multiple places in the slots. These are brought out to a terminal block with RTD wire leads.

Usually, some RTD's are connected to the monitoring system, and others remain unconnected to be used as required for spares. Copper (10 Ohm) or Platinum (100 Ohm) are the usual RTD designs.

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Modern coils are generally made to fit tightly in the slot with semi-conducting surface paint extending about 25 mm past the laminations. Once all coils are inserted and wedged tightly in the slots, the connection should be made in a uniform manner, with ties and blocking added as connections are completed.   B-Stage tie material can be used and allowed to cure in service.

V - Verifying the Unit is Ready to Return to Generation

A. Acceptance Testing on Windings

Insulation resistance testing on a new winding is done at a DC voltage higher than the usual maintenance testing. As stated above, a 13.2 kV winding should be tested for one minute at [(2 x 13,200 + 1000) x 1.7 = 46,600 Volts, DC]. This final test should not be repeated if the generator winding to ground resistance exceeds 100 Meg-ohms corrected to 40 C. Achieving this resistance level in warm, humid conditions may not be possible. The field circuit should be tested in a similar manner to be sure the ground insulation on the field poles is satisfactory. The test voltage on the brush rigging and slip rings can be done at a voltage related to the exciter potential.

The phase circuit resistances should be compared on the new winding. No standard exists, but the variation should be less than 5%. The owner may require other tests, such as surge tests, before acceptance. IEEE 522 (16) recommends a peak surge test of 3.5 pu or 2.86 times the line voltage of the generator. This test is done while the core is grounded. Polarization Index testing does not give meaningful results on modern, factory insulated coils.

B. Operating Voltage Tests

There is a lot of activity required between completion of winding acceptance and running the generator. Normally most testing is done prior to the rotor being installed and the generator shaft connected to the water-wheel. Obviously, care is required to be sure the windings are not mechanically damaged during this assembly process.

The neutral connection to ground, however made, should be verified and the auxiliary controls checked.

Similarly, the stator and bearing RTD's should be checked for cold resistance.

The exciter circuit operation and synchronizer should have been checked previously, and the turbine and bearings repaired as required. The generator should be rotated at a speed near rated rpm, and the mechanical balance checked and adjusted. Once this mechanical operation is verified, excitation voltage can be applied to bring the generator up to rated line voltage. The phase voltages should balance within 1%, and the phase rotation should match the required line connection. The voltage waveforms should be observed and compared to those of similar generators in the plant. Harmonic content is likely in most smaller generators, and will not interfere with load bearing.

C. Connecting to the Grid

The line breaker and synchronizer (3) have been checked previously. Connect to the line in the usual manner and verify that voltage, frequency, and power factor settings are maintained. The owner may want to see the generator loaded to its rated kVA, though it probably will not be run that way continuously.

Some generating stations are set up for remote start-stop. The operation of the required communication links should also be verified.

VI – Final Review

A. Document Work Done

Record keeping is important for reliable operation and informed maintenance. The coil data, winding connection, and slot and frame measurements should be recorded for plant use. Some plants like to store a sample stator coil. Similarly, all insulation test results should be provided so the owner can trend data.
Providing too much information about a repair/ rewind is rarely seen as a problem by the owner/ operator.

B. Discuss with the Owner/ Operator and Describe Warranties

During the repair/rewind process the operator usually has technicians on-site to observe and help. Each stage of the repair should be explained and recorded for plant use. Standard Warranty on electrical windings is one year from date of installation. However, some manufacturers of motors give five year warranties if the machine has been properly maintained and lubricated.

Generator windings that are kept clean and dry are expected to last for 20 years in "normal" operation. The warranty given on any rewind should be stated before beginning the repair process.

C. Suggested Maintenance

As mentioned above, maintenance is required for reliability. References have been listed for suggested cleaning, testing, and reporting on a regular basis: (2, 5, 9, 11, 13, 15). Insulation resistance to ground or surge testing is done at lower voltages than acceptance testing (1000 V DC from a "megger", twice rated voltage + 1000V using a DC hi-pot, or up to 65% of the high potential acceptance test of a new winding). High test voltages can degrade insulation which is still serviceable. A 1000 V megohm test is not likely to cause damage. However, Reference (17) notes that a "Megger" test will not reveal complete, but clean ruptures in the ground wall insulation. Whatever test voltage is chosen, the results should be recorded for trending on a semi-annual or annual basis.

Annual Partial Discharge testing is useful as the winding ages to determine the likelihood of insulation failure. This test was usually performed on each stator coil during the manufacturing process.

Clean and dry are always watchwords for electrical machinery. Mechanical observations are needed to be sure of lubrication, balance, and concentric rotation. Rotor rubbing the stator core is always a danger.

Similarly, generating records should be maintained of excitation level, operating time, line voltage and current, frame temperature, and ambient temperature.

If a rotating exciter is used, commutator color, sparking, and brush wear on the armature and on the slip rings need to be checked. Occasionally, the commutator and slip rings will need to be taken out and turned true.

Eventually, cleaning of the windings may be desired. Steam cleaning will mean that a drying process is required. Dry ice blasting is useful to limit the need for drying the windings after cleaning.

D. Review with Operators

Too often, machine repair and maintenance records are not made available to the generating station operators. Similarly, operating anomalies noted by the operators do not get documented and passed on to the owners. Any effort to improve these communications is worthwhile. Therefore, a final and complete explanation should be made to the operating crew of the work done, the test results, and maintenance suggestions at the end of the repair process.

Appendix – Other Considerations

A. Drive shaft and bearings

Reliable generator operation depends on proper operation of drive shaft and turbine bearings. These items are usually continually exposed to water, torque oscillation, and friction. Shafts can be welded up, sleeved, or replaced. The guide bearings and Kingsbury bearings can be rebuilt, and re-babbitted. Lignum vitae turbine bearings are often replaced with modern polymers.

B. Wicket gates and dam inlet gates

The face of the dam or inlet channel has a lift gate to keep the water from reaching the turbine/ runner. These gates are vital for servicing the unit. The motors operating these gates are exposed to the weather, and their condition should be monitored. Wicket gates are used to control the flow of water through the turbine, but they do not seal. They are subject to surface and shaft corrosion.

C. Insulation Testing References

References listed below (1,2,8,9,10,11,12,13, and 15) all relate to insulation testing and maintenance procedures.

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