Comparative Evaluations of Coil Insulation Systems in Hydrogenerator Uprates and Refurbishment

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Introduction

The design of hydrogenerator stator coils for a machine uprate requires a careful evaluation of various options for insulation systems. In an uprate, slot dimensions cannot change, so the volume formerly occupied by a coil's insulating materials is traded for greater space to accommodate a larger copper cross-section. Gains of one or two mils, painstakingly shaved from the insulation on individual wire strands and from the overall dimensions of turn insulation and ground insulation, provide a cumulative gain, but they also affect other uprate issues. With more copper available to carry the current, generator capacities can be increased by as much as 30 percent or more in some machines. However, different aspects of mechanical and electrical issues and of thermal and fluid dynamics must now be considered in the overall uprate design.

And in considering strictly coil design for an uprate, it is not just a matter of choosing which type of "insulation system" to use and manufacturing coils that fit the specified slot dimensions. Trade-offs also must be made between the physical characteristics of various insulating materials — thickness, durability and strength — and their dielectric properties, and of course, their cost. Although other factors, affecting various machine components also limit the generator's uprate potential, this paper will focus solely on providing information on coil insulation systems.

Strand Insulation

Until the 1890s, electric generators were predominately DC machines. Because of the disadvantages, such as the voltage drop in transmission, a shift eventually was made to AC generators, allowing the voltage to be changed with transformers. But with this change came other issues. The first large Westinghouse AC hydrogenerators in North America (3.7MW) were installed at Niagara Falls' Edward Dean Adams Power Plant prior to its commissioning in 1896. It is said that the first windings had solid, rather than stranded, turns and ran far hotter than the calculations had predicted.[1] Considerable study and testing showed a "new" source of losses, which were associated with large AC machines and had not been present with large DC machines. This extra loss was due to "skin effect" in the conductors, by which the current all tries to flow near the surface of the conductor, and the interior portion of the copper is not utilized.

The solution, which came very quickly after the problem was discovered, was to break the conductors, carrying the AC current, down into many smaller conductors, thus eliminating the possibility of skin effect. With the current always near the surface of a smaller conductor, uniform current distribution occurred, and conduction losses were reduced. The starting point in all stator winding upratings is to maximize the copper cross-section, while maintaining adequate insulation, at a competitive cost, and achieving the overall gains that justify this additional cost.

This brings us to the first type of insulation used in high voltage stator coils, strand insulation. Without insulation between them, small strands together would behave much the same as one large conductor. Typical strand insulation utilizes Dacron®-glass filaments wrapped on the wire (strand), in two layers in opposite directions, so that the copper strands are always separated from each other. The strand insulation usually has a polyester or epoxy resin over-coat, which also serves to bind the wires together into a solid bundle, over which ground insulation is applied. This bonding of the strand bundle is important in maintaining the shape of the coil, and it also provides a consistent "inside gage size," allowing the buildup of ground insulation to be uniform.

Since the strand-to-strand voltage is typically only a few volts, a buildup of 10 to 12 mils (.010" to .012") of Dacron®-glass on a wire is all that is needed. For up-ratings where space for copper is at a premium,

[1] *The author surveyed several ex-Westinghouse design engineers and found they had all heard this same story, but he could find no formal source to confirm it.*

some of the Dacron®-glass insulation can be exchanged for enamel or Kapton®. These materials are thinner, but have higher "per mil" dielectric strengths. However, their material cost is more, and their use presents more challenges in the coil manufacturing process.

Turn Insulation

The number of "turns" in a coil is a function of the machine's voltage, speed, number of slots, core length, number of winding parallels and some other parameters. A "turn" is made up of a strand bundle, comprised of one to about twenty wires for a typical high voltage machine. If there are just one or two strands in the turn, then the strand insulation may "double" as turn insulation. However, turn-to-turn voltage stress is higher than the strand-to-strand voltage, so additional insulation is required on the turn.

In a high voltage machine, the typical number of turns likely would be three to six, and the typical turn insulation would be one or two "half-lapped" layers of mica tape. Additional layers of turn tape would be used when the turn-to-turn voltage levels are higher.

One special case should be mentioned, the "one turn" coil. Although the one turn coil is more common in turbo-generators, a few hydros also have this type of coil. With one-turn coils there is no separate turn insulation, and that potential failure mechanism is eliminated. Also, the space vacated by turn insulation can be used for copper instead. If the winding is large enough to require direct water cooling, a one turn coil greatly simplifies the cooling design application.

Ground Insulation

Large "high voltage" machines (typically 6.6 kV to 26 kV, line to line, AC RMS) require ground wall insulation between the conductors and components, (such as the core), that are at ground potential or potentials which are different from that conductor (the other phases).

Ground insulation is normally made up of multiple half-lapped layers of "mica paper" or "mica splittings" tape. In a finished winding, the tapes are bonded together with polyester or epoxy resin. These resins can be "pre-loaded" into the tapes, before they are wrapped on the coil, creating what are known as B-staged tapes, or the resins can be injected after the tapes are applied to the coil by using vacuum-pressure-impregnation (VPI).

Mica Splittings vs. Mica Paper Tapes

The mineral mica naturally occurs in splittings, which are clear, thin and laminated. Supported by a thin backing of woven fiberglass strands, these splittings can be made into tapes. Overlapping the splittings in multiple layers accommodates their irregular shapes, while creating an even distribution of the splittings over the surface of the coil and providing mica coverage that reaches the desired average value for dielectric strength.

Mica paper tape is made with pulverized mica. The small particles lose some of the advantages of the larger flakes, but the product is more uniform in mica distribution, and it is typically less expensive to manufacture than the mica splittings tape. The author's company uses both mica splittings and mica paper tapes depending upon the coil design requirements.

Polyester vs. Epoxy Resin

The first synthetic resin stator coil insulation was developed in the late 1950s and quickly replaced the older "asphaltum" insulation during the 1960s. Polyester resins were the first types to be widely used (Westinghouse's "Thermalastic®" and National Electric Coil's "Neccobond®" were typical polyester systems in the 1960s and 1970s.) The early polyester systems were easy to use: Simply impregnate the tapes and bake the coils to cure them. The resultant insulation had an excellent track record over the years, and one of its advantages was a "forgiving flexibility." The coils could be distorted during installation without easily breaking or cracking the ground-wall.

Epoxy resins were developed, which had higher dielectric strength than the polyester resins, and as a result, insulation could be thinner and more of the insulation space could be traded for copper. Epoxy resin is more expensive than polyester and it requires closer control in its application to the coils.

At this point in time, there are still advantages and disadvantages to both the polyester and epoxy systems, and the author's company continues to use both systems depending on customers' preferences and their budgets.

B-Staged Tapes vs. Vacuum Pressure Impregnation

B-staged tapes are pre-loaded with polyester or epoxy resin that is dry to the touch, but will flow and bond when pressure and heat are applied. For very high voltages (24 to 26 kV), in which the thickness of the ground insulation is substantial, having the resin already in the tapes is a plus. Those are some disadvantages. When pre-loaded tapes age prior to installation, especially if they are not refrigerated, the resins do not flow as well, and the resultant product may be inferior. Also, the possibility of voids between tape layers can be more of a concern with B-staged coils. Since the quantity of resin is "fixed," the amount of tape applied and the curing cavity size becomes extremely critical.

With the vacuum-pressure-impregnation (VPI) system, the tapes are applied to the coils in a completely dry form. After taping, the coils are placed in a sealed steel tank, impure gasses are extracted by vacuum, resin is introduced and nitrogen pressure is applied to force the resin between the layers of tape. When the coils are removed from the VPI tank they are cured in heated steel dies, to the proper size. The advantage of this system is that there is always enough resin to fill the voids, and during the curing process a flow occurs, eliminating any excess, which is not needed. The disadvantage is that VPI requires expensive equipment, so not every manufacturer can provide this system.

Insulation Stress Levels for Uprating Windings

"Volts per Mil" Definition

The insulation stress levels of high voltage coils is calculated as the ratio of the line to ground voltage of the machine to the mils of insulation thickness between the copper conductor and the core. Since the stator winding voltage is always rated "line-to-line," it must be divided by $\sqrt{3}$ to obtain the line to ground value.

One "mil" is 1/1000th of an inch. Thus, if the strand insulation builds up .012", turn insulation .040", and ground insulation .238", the total "double wall" buildup is .290", or 290 mils. The single wall thickness would be 145 mils.

Sample Calculation

If the machine is rated 13,800 volts (line to line), then the line to ground voltage is $13{,}800 \div \sqrt{3} = 7967$ volts. Dividing 7967 by 145 gives the volts per mil as 55. In an uprating the goal might be to apply thinner insulations with improved dielectric strength, bringing the volts per mil up to 60 to 65.

Coil Insulation System — Typical Build-Up

In an actual uprate for the US Army Corps of Engineers, NEC engineers estimated values for the original winding as shown below in ***Table 1***. The goal was to increase the copper cross section and reduce the slot space occupied by insulation and other materials. Specifications for the new coils also are shown in Table 1. The result is that the machine's insulation stress level could be increased from 55 v/mil to 61 v/mil.

Table 1: Comparison of Insulation Build Up

Components	**Est. Original**		**Uprated**	
	Horiz.	Vert.	Horiz.	Vert.
Bare Wire	.246	.071	.260	.074
Strand Insul.	.012	.012	.010	.012
Wires per Turn	2	5	2	5
Turn Tape	.040	.040	.034	.034
Turns per Coil	1	6	1	6
Stiffeners	-	-	-	.010
Binder	-	-	.005	.005
G'ndwall Insul.	.210	.209	.196	.196
Armor Insulation	.028	.028	.016	.016
Corona Paint	.005	.005	.005	.005
Final Cell Size	.798	2.792	.796	3.016

Summary & Conclusion

Each of the insulation components presented is critical to the successful up-rating of a hydro stator winding: strand insulation, turn insulation and ground insulation. Presenting these key elements in overview, might lead some to conclude that the above-mentioned issues are "simple." In fact, none of these topics is simple. Each has filled volumes with research and development over the past 100 years, and the author's company, like all major manufacturers of electrical equipment components, continues to seek improvements in the materials and performance.

References

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