

Service Life of Stator Winding Insulation as an Important Quality Feature of Large Hydro Generators

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As central components of hydroelectric power plants, generators are subjected to operating stresses which influence the long-term performance of the winding insulation. Failure of the insulation can lead to lengthy downtimes. The unsurpassed reliability of products such as MICALASTIC® insulation is therefore of great economic significance.

The capacity of a hydroelectric power plant is determined by the available water flow and head. Both of these parameters vary widely, and generators can be dimensioned for any rating between 10 kW and 800 MW. The head determines the turbine type as well as the speed, which can lie between 50 and 1500 rpm. Additional parameters include the generator voltage, the rotor's moment of inertia, the runaway speed of the turbine, the physical design of the generator (horizontal or vertical) and various requirements imposed by the grid. Hydroelectric generators are therefore always custom-designed.

Dimensions and weights can assume enormous proportions (Fig. 1): External diameters of up to nearly 23 meters are possible, and total weight can amount to as much as 3500 metric tons. Generators of this size cannot be assembled and tested at the factory. Nevertheless, the generators can be expected to operate well right after their initial installation at the power plant. It was once correctly stated that "the construction of a hydroelectric generator can be compared to making a tailor-made suit without trying it on".

To date, Siemens has manufactured more than 1200 large hydroelectric generators with a combined capacity in excess of 80,000 MVA. Of these, 360 generators (over 50,000 MVA) have MICALASTIC windings. These machines are characterized by their outstanding reliability, which can be attributed in large measure to their high-quality MICALASTIC insulation system.

The MICALASTIC Insulation

MICALASTIC is the registered trademark for Siemens insulation systems for high-voltage windings of rotating electrical machines. These systems use mica, a material capable of withstanding high electrical and thermal loads, together with curable, elastic epoxy resins as bonding material. Since the early days of electrical machine construction, the naturally occurring, inorganic mineral mica has been an indispensable constituent of high-voltage insulation systems. The most important criterion for the use of mica is its ability to durably withstand the partial electrical discharges which can occur inside the insulation due to high electrical stresses.



Fig. 1
Insertion of a rotor at the Itaipú hydroelectric power plant. Due to its diameter of 16 m and weight of 1960 t, assembly on site is the only practicable approach.

Manufacturing and Design

As early as 1957, Siemens-Dynamowerk in Berlin manufactured the first stator windings that made use of mica tape and a vacuum-pressure impregnation process. With this method, single coils and Roebel bars for hydroelectric generators are continuously wrapped with mica tape in the slot and end sections. The taped winding elements are then dried out and degassed in a vacuum impregnation tank, and flooded with low-viscosity, curable synthetic resin. High nitrogen pressure applied to the impregnating bath completely impregnates the mica tape. After being placed in accurately sized, portable pressing molds, the insulation is cured at high temperatures in large chamber ovens.

Continued development of this insulation technology ultimately led to the use of a film of ground mica on mechanically strong glass fabric as the carrier material with epoxy resin as the impregnant, which produced a very durable (electrically, thermally and mechanically), modern insulation system. Long-duration tests in a slot model were unnecessary, since the desired voltage endurance had already been achieved in the previous development stages (Fig. 2) using lower-quality carrier materials. Short-duration tests were performed, however, for verification.

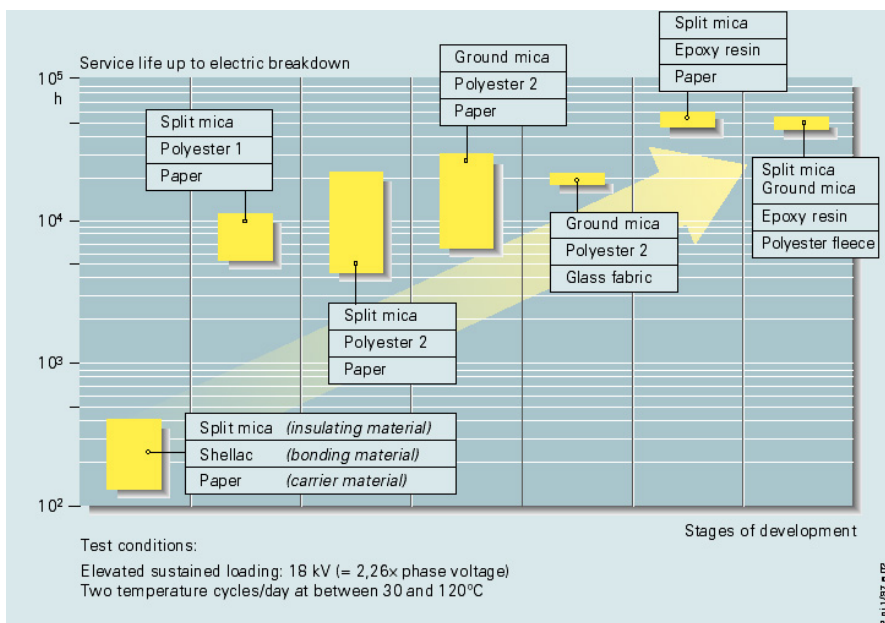


Fig. 2
Comparative functional testing using the stator slot model confirms the progress achieved in extending the service life of 13.8-kV insulation of varying compositions.

Fitting of Roebel Bars into Slots

Winding elements with cured MICALASTIC insulation are secured in the slots by filling up the tolerances between the slot wall and the conductive surface (coil-side corona shielding) of the bar insulation. Initially, Siemens used graphite-treated paper as filler material. Since about 1969,

however, a special bar fitting procedure has been used for hydroelectric generators.

The main features of this procedure are U-shaped slot liners made of polyester fleece impregnated with a conductive material, and a conductive, curable synthetic resin paste between the surface of the bar insulation and the slot liner (Fig. 3). Therefore, the insulation does not stick to the stator core, and the option of removing the bars, even though seldom required, is retained. In the radial direction, the slot portion of the winding elements is secured by means of various packing strips or ripple springs, and slot wedges. Bracing the end windings and jumpers by using glassfiber-reinforced spacers and epoxy-resin-impregnated cording makes the winding resistant to electro-dynamic forces during operation and to possible short-circuit faults. This resistance is also aided considerably by the mechanical stiffness of the MICALASTIC insulation, which is also cured within the end winding.

Thermal Stability

The MICALASTIC insulation system was developed strictly for a continuous load in accordance with temperature class F (155°C). Nevertheless, generator design engineers generally guarantee compliance with class B (130°C) temperature limits for nominal operating conditions, as is also required in most invitations to tender. In practice, the stator windings of hydroelectric generators are frequently dimensioned for even lower operating temperatures, because the stators will usually be optimized for good efficiency by adding electrically active material (winding copper and core lamination).

Particularly low operating temperatures can be expected in the case of stator windings with direct water cooling. With an appropriately dimensioned demineralized-water cooling

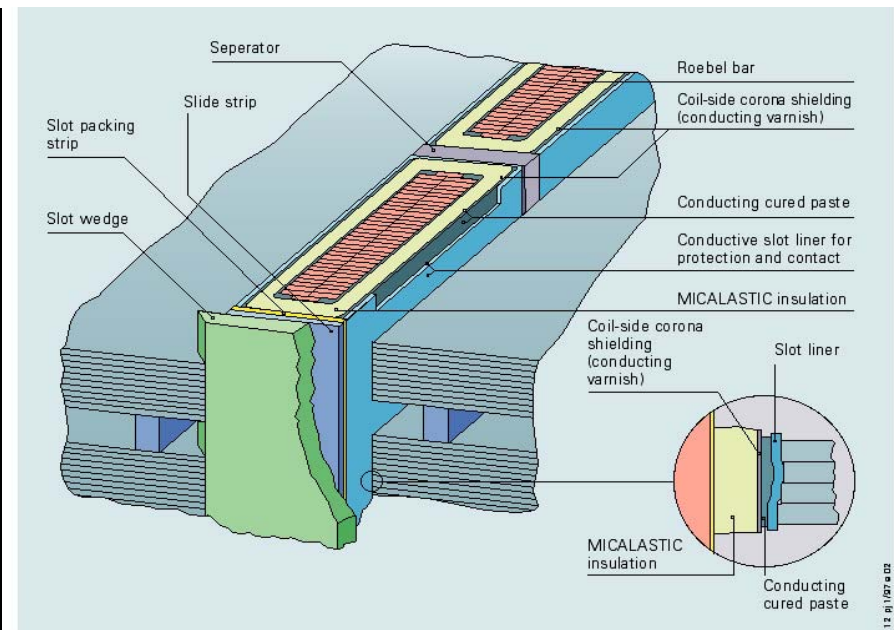


Fig. 3
Fixing Roebel bars in a stator core using Ushaped slot liners and conductive curable synthetic resin paste. This method ensures a particularly tight fit and rules out slot corona discharges.

system, the maximum winding temperature can be reduced to 70°C and lower. Thermal aging of the insulation is therefore essentially eliminated, and thermomechanical stresses are also substantially reduced. The resulting increase in operational reliability makes a real difference in the case of hydroelectric generators which are essential to safe grid operation.

Selected References

Since 1984, the world's largest hydroelectric power plant Itaipú on the Brazil/Paraguay border has given problem-free operation using MICALASTIC windings with direct water cooling in nine generators with a combined capacity of nearly 7200 MVA. Another fifteen MICALASTIC stator windings with water cooling have yielded excellent results in pumped-storage and peak-load machines with a combined capacity of 4800 MVA. The demineralized-water cooling systems with built-in redundancy are easy to maintain. Siemens' experience in more than 150 years of operation has shown that the reliability of generators with direct water cooling, as opposed to air cooling, is not affected in the slightest by these plant components. In fact, when life-limiting effects are

are minimized in this way a longer service life is anticipated for the respective ground wall insulation.

The MICALASTIC stator windings installed at the Grand Coulee hydroelectric plant in the U.S. (see article on page 40) represent a highlight in terms of the development and fabrication of Roebel bars with direct water cooling. Due to negative experience with the originally installed windings, the new request for proposals issued by the power plant operator, the United States Bureau of Reclamation, included strict quality requirements that are likely unprecedented. The Roebel bars developed and fabricated for these generators have set new standards in terms of the quality and reliability of stator windings with direct water cooling (Fig. 4).

Rated Voltage Level

MICALASTIC-insulated stator windings can be manufactured with a rated voltage of up to 40 kV for large turbogenerators operating in a hydrogen atmosphere. Hydroelectric generators, on the other hand,

always operate in air, which is why the ionization processes caused by the high electrical field strengths are of higher significance. To obtain an optimum generator design, the design engineer should be given the latitude to select the best rated voltage-particularly with respect to slot ampere-turn limits. At power output levels above about 400 MVA, however, 18 kV has proven to be a good compromise between the costs of the generator and the bus ducts. The world's highest voltage rating for hydroelectric applications is 23 kV, at which the pumped-storage units at Raccoon Mountain in the U.S. have been operating since 1978.

Operating Stresses

During operation, the insulation is subjected to electrical stresses due to field strength, and to thermal stresses due to the temperature of the winding copper and core teeth (slot walls). As a result of differences in temperature and coefficients of thermal expansion, forces develop within the winding elements which are superimposed on the electrodynamic stresses caused by the live Roebel bars.

Added to the electrical and thermal stresses-which occur similarly in the stator windings of turbogenerators and hydroelectric generators-is a thermomechanical stress element which occurs in hydroelectric generators, particularly in peak-load generators and even more in pumped-storage units. Although the operating times in this case lie within a range of only 1500 to 5000 hours per year, up to 80 load cycles per day can occur in extreme circumstances. It often takes only ten seconds to go from a no-load, synchronous condenser mode to full-load operation, and the load service duration can range from one minute to several hours. The stator windings in particular are subjected to extreme mechanical stresses imposed by load cycles of this kind. This factor is taken into consideration in the abovementioned fitting procedure,

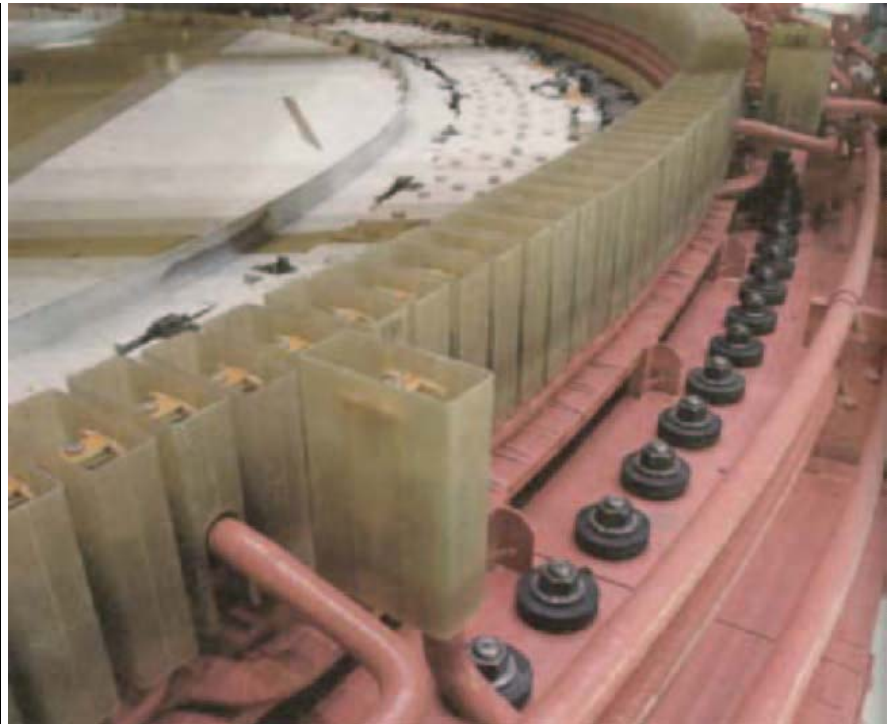


Fig. 4
End-winding section of the Grand Coulee stator winding with its characteristic insulating caps.

which guarantees a particularly tight fit of the Roebel bars in the slots.

And finally, the effects of the operating environment must be taken into consideration. Air quality is a function of the geographical location and the design of the power plant, and plant elevation and relative humidity are the most important natural parameters. Oil vapor escaping from bearings within the generator enclosure is extremely damaging too. The oil vapor precipitates out on the stator winding, among other components, and in combination with brake dust forms a deposit which can lead to corona damage.

Operating Experience

A comprehensive series of comparative functional tests is required in order to assess the expected service life of new or redesigned insulation systems before they are used in practice. In order to evaluate MICALASTIC insulation at its various development stages, operating conditions were simulated using slot models, and

accelerated tests were performed by applying increased stress levels.

The actual performance capability of an insulation system can only be measured in terms of its service life under true operating conditions. For that reason, Siemens sent questionnaires to plant operators in 1984 and 1994 to obtain data on their operating experience. Both questionnaires pertained to stator windings with MICALASTIC insulation which had been applied using the fitting procedure introduced in 1969. Generator output ranges from 35 to 823 MVA, and rated voltage lies between 10.5 and 23 kV [1,2].

The first hydroelectric generators with MICALASTIC insulation were commissioned in 1958, and are still in operation today. At present (as of March 1997), the 360 generators with MICALASTIC windings have amassed a total of 4700 years of on-line operating time. Of these, 39 generators have fed power into the grid for more than 25 years.

The individual service life record is 31.5 years.

Not a single operator of a hydro-electric generator equipped with MICALASTIC stator windings (with a total of more than a quarter of a million Roebel bars installed) reported winding damage or evidence of electrical or thermal aging. None of the MICALASTIC stator windings showed evidence of slot discharges. Some incidents of damage were reported, however these were without exception attributable to foreign particles, loose core tooth lamination or inadequate maintenance.

Regular inspections and a good maintenance program are important factors in getting a high reliability from an insulation system and achieving a practically unlimited service life. The use of sophisticated Siemens monitoring systems (see article on page 26) allows step-by-step transition from periodical to condition-oriented inspection intervals, which significantly decreases maintenance effort and expense.

Outlook

Due to its practically unlimited service life as well as its outstanding insulating properties, the MICALASTIC insulation system can be regarded as the standard for the reliability of rotating electrical machines. Despite its already high operational reliability, development of the MICALASTIC insulation system continues step by step. Reduction of the ground wall insulation thickness is still possible in small increments and can increase the utilization of electrical machines.

Although curable synthetic resins with a much higher long-term resistance to high temperatures are available for vacuum pressure impregnation, their use in standard hydroelectric generators would have no technical or economic benefit due to their conservative thermal design.

Limit-rating machines or units requiring high utilization factors (e.g., high-speed pumped storage sets) are natural design candidates for the application of proven direct water cooling with its low operating temperatures.

References

[1] H. Meyer, W. Schmatloch: Reliability of Stator Winding Insulation in Hydro Generators. Water Power and Dam Construction, Dec. 1984, pp. 40-43

[2] H. Meyer, W.-D. Blecken: Trial and Error. Water Power and Dam Construction, Feb. 1995, pp. 35-39



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