Trial and Error

Operating Experiences with the Siemens MICALASTIC® Insulation System for Stator Windings of Hydro-Electric Machines

The performance of a stator winding insulation system in hydroelectric machines is best documented through operational experience.

By H. Meyer and W.D. Blecken***

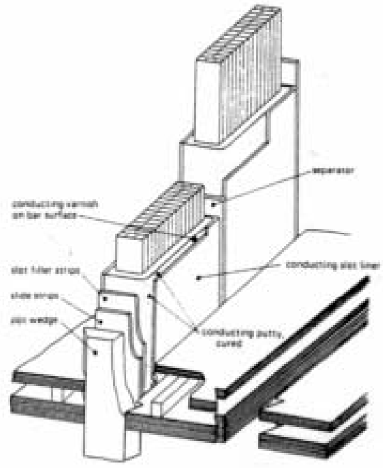

Fig.1 Fixing of stator winding bars in stator slots.

Operational experience is arguably the only true measure of the suitability of electrical insulation systems in power equipment. Short duration as well as accelerated life-time tests are more meaningful when judged in an operations context and it is on the basis of these fundamental assumptions that standards and guidelines have been established over the last two decades [1,2].

In 1984, a study was published which described the reliability over a ten year period of stator winding insulation in a large number of different hydroelectric applications. The machinery employed identical insulation systems and winding techniques but had a wide range of rated power, voltages, speeds and modes of operation.

Service experience reports for 56 out of the 69 units supplied between 1972 and 1982 were obtained from the operators [3]. Ten years later, in 1993/94, operational data were again assembled, this time covering a more extensive group of hydroelectric plants. Operating reports on 100 of the 136 machines supplied between 1972 and 1989, which have a special technique for fixing the winding bars in the slots and totalling up to 158 000 hrs operating time for individual generators and up to 18 000 load changes per machine, have been reviewed.

Fig.2 Inserting winding bars with a conductive slot liner and conductive resin putty

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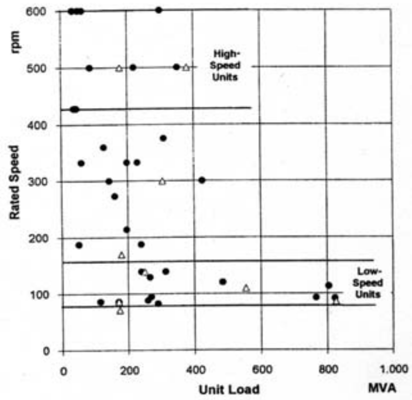

Fig.3 Unit MVA versus speed of 32 machine designs with operating reports 1993/94 (triangle represents machines under construction).

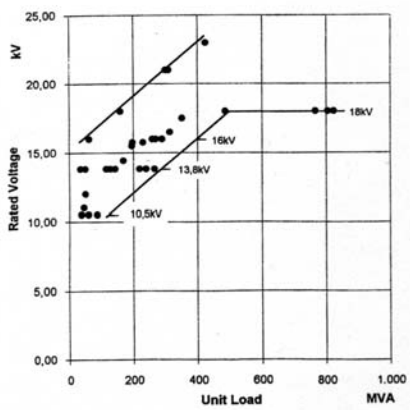

Fig.4 Unit MVA versus voltage of 32 machine designs with operating reports 1993/94.

1. Insulation and winding technique.

A feature of the winding technique is the use of MICALASTIC insulation on mica tape, impregnated with synthetic resin, using a vacuum pressure impregnation method and a thermal curing process. This insulation technique has been employed successfully for over 35 years for various applications, passing several development stages [4,5,6].

In 1957, the first machine - a 15kV synchronous motor for a rolling mill - was equipped with synthetic resin-impregnated, hardened insulation for the stator winding coils. This insulation technique was then also used for hydroelectric generators and synchronous condensers with hardened insulation bar windings. The bars can be inserted without problem whatever the diameter of the stator.

When, in 1965, the technique of impregnation by total immersion was developed to the point was where it could be used in production, the winding elements (coils or bars) with unimpregnated insulation were fitted in the stators in such a way that they could still be formed in the coil end section and then impregnated along with the stator cores as complete stators using a vacuum pressure process. From 1966 onwards, the MICALASTIC insulation therefore used for coil windings in machines with sizes limited only by the dimensions of the impregnation tank [4,5].

The advantage of coils inserted in the slots with 'soft', unimpregnated insulation is that they fit well. This is because the insulation is adapted to the contours of the slot and is braced with the ventilation slots by a fraction of a millimetre. Therefore, a second feature of the technique applied by Siemens, is the mechanical bracing of bars with impregnated and cured insulation in the slots of hydroelectric generators built since 1970.

Winding bars which have already been impregnated and cured are inserted in the stator slots. The gap between the bar and the slot is filled by a combination of a thin U-shaped slot liner (bar wrapper) made of conductive polyester fleece and a conductive curable putty (see Fig.1 and 2).

The winding bars surrounded by the slot liner are pressed into the stator slots. The viscous conductive putty previously placed between the liner and the cured insulation of the winding bar then spreads out, filling the dimensional tolerance in the slot teeth area. In this way, the pre-determined amount of excess resin putty is displaced into the core's ventilation slots. Transverse vibrations of the winding bars in the slot cross field and displacements within the slot are practically eliminated as a possible cause of ageing during operation. Additionally, heat transfer from the winding to the core is substantially improved. This method of insertion for each winding element, coupled with the application of putty-tight U-shaped slot liners, prevents direct bonding of the insulation with the wall of the slot. In the rare event that a winding element - bar or half coil - has to be replaced and for purposes of insertion of spare parts, removal is possible without damaging the ground wall insulation.

2. Operating experiences with windings using conventional insertion techniques.

One example of the high reliability of the MICALASTIC insulation system - even without the mechanical bar fixing method described above - is provided by the operating data of 11 generator-motors installed in two pumped storage plants with horizontal axes of rotation. Here, the unilateral axial displacement of winding elements due to gravity was of no significance and the winding bars were inserted in the slots with optimum slot filling using a conductive slot liner of fibre materials (paper, polyester fleece).

On the older machines, with winding bars impregnated with polyester resin, bracing of the slot contours occurred because of a certain expansion of the insulation, an additional effect which does not occur with epoxy resin impregnation used nowadays. On four of the pumped storage units put into operation between 1958 and 1965, with ratings of 44MVA, 10.5kV and 375rpm, the range of experience is between 41 000 and 56 000 operating hours per machine with 19 000 to

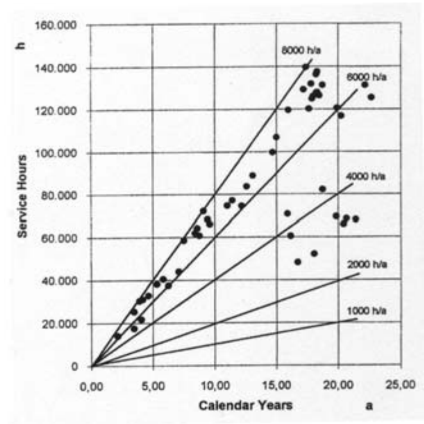

Fig.5 Operating hours of 51 hydro-electric machines between 115 and 823MVA/13.8 and 18kV/82 and 158rpm (low-speed units).

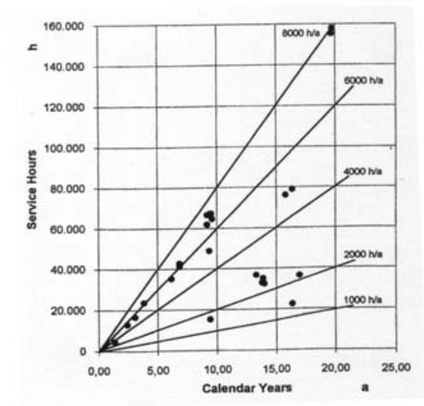

Fig.6 Operating hours of 26 hydro-electric machines between 50 and 425MVA/10.5 and 23kV/187 and 375rpm (medium-speed units).

24 000 starts.

As part of a power plant inspection, the stator slots of the then 25 to 34 year old 44MVA generator-motors were re-wedged and the loose parts of the end winding reinforcement refastened. Non-destructive measurements of dielectric characteristics during subsequent years of operation revealed practically no changes. On seven other pumped storage units brought on line between 1962 and 1964, the rated data are:

P_N = 115MVA,
U_N = 13.8kV and
n_N = 429rpm

The current operating hours of the individual machines are between 125 000 and 145 000hrs with 38 000 to 48 000 pump respectively turbine starts per machine. After 30 to 32 years of operation, these 115MVA generator-motors have accumulated the highest number of starts and operating hours of all pumped storage units in service with the MICALASTIC insulation. The original windings are still in operation without sustaining a single fault.

The maximum number of operating hours of one individual run-of-river hydrogenerator with MICALASTIC windings to the authors' knowledge amounts to over 259 000hrs (29.5 operating years).

3. Obtaining data with a questionnaire.

Questionnaires were sent to operators of hydroelectric machines supplied since 1972 with a request to provide the following data:

a) Operating hours, number of starts or change of operating modes and power generation since commissioning;

b) Maximum output during operation and winding temperature at rated road;

c) Date, frequency and results of inspections. Special data from visual inspection, rigidity of the end winding, reinforcement of the slot wedges and the axial securement of the winding bars in the slots.

Also included, were data on the condition of the surfaces with electrical potential grading (outside/end corona shielding) and signs of electrical discharges outside the slots and in the end winding, data on the condition of the stator core, relating to any damage during operation or during tests and the removal or replacement of winding bars.

Responses were elicited for 100 generator units, representing 73.5% of the 136 units supplied between 1972 and 1989 using the winding insertion technique described above. These responses represented operational experience of up to 23 years.

4. Generators and operating data.

4.1 Rated power, voltage and speed of the machines with operating reports.

The operating reports available for evaluation include the entire range of rated power, voltage and speed for machines using the insertion and insulation technique described above for the past 23 years. The power values range from 35 to 823MVA, rated speed from 82 to 600rpm (see Fig. 3) and the rated voltage from 10.5 to 23kV (see Fig. 4).

4.2 Operating times and modes of operation.

Start-up information has been analysed from all the 100 machines for which operating reports were received. For the three groups of machine types categorised by speed ranges in Fig. 3, the operating hours achieved by 1993/94 since commissioning are shown in Figs. 5-7 against the number of calendar years since commissioning.

• The majority of the low-speed units (82 to 158rpm) achieved between 6 000 and 8 000hrs/calender year. The highest number of operating hours for one generator was 139 612hrs after 17.4 calendar years. The lowest annual operating time for one generator design amounted to an average of approximately 3 000hrs over a period of 16 to 22 calendar years (see Fig. 5). These particular generators are used

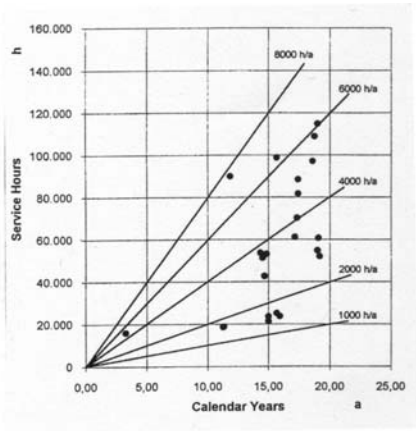

Fig.7 Operating hours of 23 hydro-electric machines between 35 and 352MVA/10.5 and 21kV/428 and 600rpm (high-speed units).

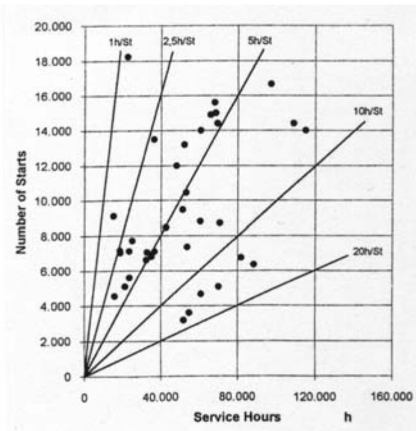

Fig.8 Type of operation of 36 machines for pumped storage and peak-load service.

as peak-generating units with two starts daily.

• The medium speed range group of 187 to 375rpm includes a sub-group of seven pumped storage generator-motors used for peak load only. These machines can be identified in Fig. 6 by the relatively low annual operating time of 1400 to 2 800hrs. The remaining 19 generators ran with average operating times per calendar year of 5 000 to 8 000hrs. Two machines have reached 155 000 and 158 000 total operating hours over 20 calendar years.

• The high speed units (see Fig. 7), at 428 to 600rpm, are mostly used for pumped storage applications or as peak load generators. These machines achieve annual operating times of 1 500 to 6 000hrs. The highest total time of 115 000hrs, was achieved by a pumped storage generator-motor over a period of 19 calendar years. One generator, however, achieved around 7 600 operating hours per year with an average operating time per start of 390hrs.

5. Operating conditions and service life.

For the evaluation of damage-free operating times as the proven service life of a winding insulation, it is of special interest to know under what operating conditions these service life values were achieved. Electrical, thermal and thermomechanical stress and external environmental influences such as humidity and contamination determine the service life of the insulation. The experience reports contain information about the operating temperature, the magnitude of the power output of the machines and the mode of operation.

5.1 Electrical and thermal stress.

The laws governing the service life of the winding insulation of electrical machines under thermal and electrical stress are known. Their verification for certain insulation systems is, for example, dealt with in the IEC Standard 34-18-1, "Functional evaluation of insulation systems for rotating electrical machines". Relevant experimental data for the MICALASTIC insulation system has already been given in previous publications [4,5,7].

The electrical and thermal design of the machines and their insulation has been made so conservative that electrical and thermal loadings do not determine service life in normal operation. Accidents due to excessive loading which might impair the service life did not occur according to the operating reports provided.

5.2 Mechanical stress.

The insulation of stator windings is exposed to many types of mechanical stress during operation. Mechanical stress occurs between stator iron, winding copper and insulation because of different temperatures and different thermal expansion coefficients. Moreover, electromagnetic forces act between adjacent current-carrying parts of the winding and between these parts of the winding and the stator iron. These types of stresses are particularly pronounced during operation with frequent load change. Fig. 8 characterises this group of machines by their operating times of between 1 and 20 hours per start.

Fig. 9 shows the data for machines with continuous load operation of approximately 25hrs to well over 1 000hrs per start. The generator with the highest number documented achieved 1 867hrs per start over 16 calendar years.

In the range of experience characterised by the operating hours and number of load changes, no limitation to the service life of windings of either group of machines has so far occurred or become evident. The particularly tight fit of the winding bars in the slots achieved with the insertion method described above prevents destructive movement in the slot area even with very high numbers of load changes and in machines with a high number of ampere-turns per slot. Loosening of slot wedges (without loosening of the winding) were remedied during the course of normal inspections.

The reinforcement technique in the area of the end windings and the circuit connections is dimensioned in accordance with the number of reinforcement elements and the type of lashing as specified in the machine data. Rated voltage-dependent

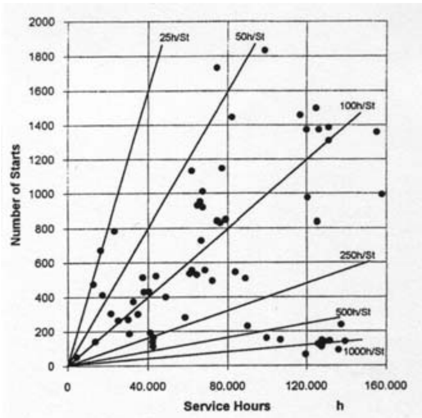

Fig.9 Type of operation of 64 generators for continous-load service.

conductor spacing, copper cross-sections determined by the rated current, end winding dimensions determined by the pole pitch etc., give rise to great variation in possible reinforcement arrangements. An absolutely motion-free end winding, however, is technically impossible. Loosening of reinforcement arrangements cannot therefore be prevented entirely during operation. If necessary, this is detected and remedied during the course of scheduled inspections.

6. Service life, inspection and maintenance.

Scheduled inspections serve to reveal any changes in the insulation system, its components and the effect of external operating conditions that influence the service life of the insulation. Maintenance and inspection schedules for stator windings with MICALASTIC insulation provide for an initial inspection after 4.000hrs of operation or after 1.000 start-ups or shutdowns, at the latest, however, after one calendar year. With continuous operation, the recommendation is to conduct an inspection after 16 000 operating hours or no later than two calendar years. Subsequent inspections are recommended every 8 000hrs of intermittent or 16 000hrs continuous operation, but no later than every two calendar years.

The aim of inspection and maintenance is to make full use of the high life expectancy of the windings while maintaining the highest possible degree of reliability of the winding insulation. For this reason, observance of the permissible operating conditions is emphasised. One important part of the experience reports is therefore the documentation on the results of inspections of the stator windings and their insulation.

Approximately 30% of the available operating experience reports mention the inspection intervals. Scheduled intervals of 1 to 3 years are preferred but intervals of 3 to 5 years are also mentioned. As required, e.g. after maintenance work, inspections are also performed after shorter intervals. Maintenance work not only includes cleaning but usually also concerns three peripheral components of the insulation system, i.e.:

- Loose slot wedges.
- Voltage-controlling corona protection coatings on bar insulation surface between slot portion and end winding.
- Specific parts of the end winding reinforcement and fastening.

The machine groups, distinguished by their speed ranges, are affected in different ways:

- Corona protection maintenance is relatively more frequent for the group of low-speed units with continuous operation than for the other groups. The transition area from the so-called outside to the end corona protection is mainly affected while destruction of the outside corona protection within the slot by so-called "slot discharge" is completely unknown for the stator windings of the hydro-electric generators dealt with here.
- Slot wedge loosening affects all speed groups equally, whereas,
- Loose end winding reinforcements have almost only been found during servicing of high-speed units with frequent load changes.

7. Electrical tests of the insulation.

Some operating reports also contained data about electrical tests that were performed during inspection.

- Non-destructive AC high-voltage tests, usually with $Up = 1.5U_N$ or an equivalent DC voltage are used to verify and remove weak points. The occurrence of such weak points without any recognisable external (mechanical) cause would suggest ageing. The available operating reports contain only a few cases of damage, without exception due to mechanical damage caused by foreign bodies, by loose stator laminations or inflicted during maintenance work.
- Measurements of the insulation resistance and of the dielectric loss factor as well as partial discharge measurements can be used for comparative evaluation of periodically repeated tests in order to reveal tendencies towards change.

- A third way of assessing the state of the insulation is the destructive testing of the insulation of individual winding bars which are removed from the stators and replaced by spare bars. This method was used to study the insulation of 13 winding bars removed from various machines after long operating times. The rated voltages of the machines ranged from 10.5 to 15.75kV. The total operating times of the machines were between 23 000 and 125 000hrs.The electrical strength U_B/d of the insulation was determined with a voltage rise of $\Delta U/\Delta t$ = 1kV/s to AC values of up to 16.8 to 25.1kV/mm (U_B = breakdown voltage, d = thickness of the insulation).

The characteristic values U_B/U_N, i.e., the breakdown voltage over the rated voltage, ranged from 4.8 to 8.4. Even the lowest values for U_B/U_N measured on the insulation of a machine with an operational thermal stress (due to special circumstances, not design-related to the stator itself) of up to approx. 160°C, i.e. above limit temperature of class F, still met the minimum requirement for new stator insulation to IEC 34-15 with random sampling tests according to the formula $U_B > 2\ (2U_N + 1kV)$.

8. Prospects.

The analysis of operating experiences with a special insertion technique for stator windings with MICALASTIC insulation in hydro- electric machines is documented by more than 20 years of successful use.
Failures due to ageing did not occur during operation. Regular inspections and service ensure almost unlimited insulation life if normal operating conditions are observed. The excellent operating experiences with the MICALASTIC insulation system can be traced back to 1958 and now also include the application of the insulation system for synchronous condensers, turbo-generators, high-voltage motors, diesel generators, large DC drives and traction motors.

Because of its high life expectancy, its adaptability to various manufacturing processes and the excellent insulation values, the MICALASTIC insulation system will continue to provide a reference for the reliability of the insulation of rotating electrical machines. The use of MICALASTIC insulation systems has been adopted in large rewinding and power enhancing programs for North American hydroplants with the aim of improving operational reliability and lengthening service life [8,9].

Continuing development work will ensure in the future, as it has done in the past, the application of the best available materials and manufacturing methods for the MICALASTIC insulation system.

Fig.10 End winding reinforcement and circuit connections.

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