Applying new technology in the upgrading or uprating of generators

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Properly designed and constructed hydro generators can run reliably for more than 50 years without major repairs or corrective work. However, as this article demonstrates, carefully planned and executed rehabilitation after only two or three decades can be more economical in the long term, even for generators with excellent reliability records.

The availability of new materials and greatly improved design methods for both hydro turbines and generators permit substantial increases in efficiency and output. The tremendous improvements in insulation materials alone in the last four decades, for example, allows for stator winding designs with higher performance characteristics.

Hydro turbines are subject to perpetual wear and tear. The effects of cavitation and abrasive erosion on runners and distributor components necessitate regular outage periods of several weeks for corrective work. Reliable hydro generators, in contrast, require far less attention. The replacement of parts subject to wear, such as slipring brushes, the changing of bearing oil or the replacement of filters can be done in less than a day.

It is therefore no surprise that utilities tend to concentrate on their mechanical equipment first when refurbishment is considered. Such upgrading or uprating activities require an extensive outage period with substantial loss of revenue. Therefore it is important to deal with the generator and associated electrical equipment during a scheduled turbine upgrading or uprating outage. This avoids an additional major, and perhaps unanticipated, outage associated with the generator at a later stage.

Siemens has long-term experience of refurbishing and uprating hydro generators, and this continues to be an important business area. The implementation of uprating measures is the least expensive and fastest way to provide additional capacity. Hydro generators built 30 years ago, based on technology of that era, can generally gain an increase in capacity of 20 to 30 per cent.

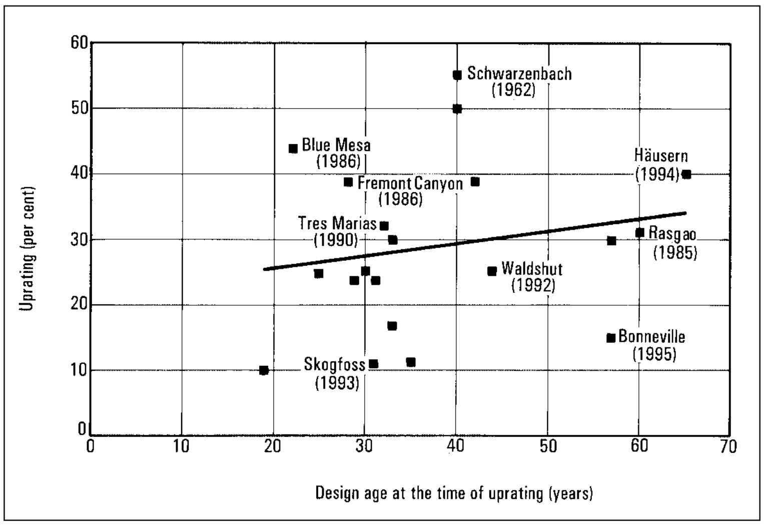


Fig. 1. Some examples to show a range of recent generator uprating projects, carried out by Siemens.

The life expectancy of a hydro generator mainly depends on its:

- service conditions (peaking, base load, and so on);
- mechanical, thermal and electrical stress levels;
- environmental conditions; and,
- maintenance standards.

The actual uprating potential of a project depends on:

- the age of the equipment;
- the generator design (which can vary considerably between different manufacturers);
- the respective turbine uprating capabilities; and,
- the possible power train limitations.

This explains the wide generator uprating range of actual projects shown in Fig. 1.

A generator uprating can cost as little as US$ 50 per uprated kVA. This is for conventional, low-speed, run-of-river units when only a stator winding replacement occurs, provided the original design permits a high uprating. However, an increase in efficiency is also paramount, especially for high-speed pumped-storage units. Such upratings usually include new stator windings and new stator cores and, in some cases, field poles as well. This can cost a multiple of the above figure; however, a considerable portion is justifiable with a high loss evaluation. Various European utilities have specified loss evaluation figures of up to US$ 5000 per kW in recent years.

1. Upgrading

Our definition of upgrading is the replacement or improvement of components which have been the cause of high maintenance and repair, or for which failure, due to age, is expected in the foreseeable future. Upgrading also includes the installation of additional components or devices to improve the equipment.

The main objective of upgrading is the modernization of existing generators to increase efficiency, increase life expectancy, improve availability and reduce labour-intensive maintenance. Therefore, a component-to-component examination is essential to obtain the best results.

The following are typical measures for a generator upgrading.

1.1 Installation of a new stator winding into an existing stator core

The new stator winding with a modern insulation system is based on a Vacuum Pressure Impregnation (VPI) process. Siemens has developed the Micalastic insulation system to comply with Class F insulation

(155°C). The Micalastic insulation system requires less ground wall insulation than previous methods, with a welcome side effect of improving heat transfer from the winding to the core. A depiction of improved slot space factor for an actual project is shown in Fig. 2. The resultant reduction in ohmic copper losses and winding temperatures permits modifications to the cooling air circuit, such as lower cooling air flow and windage losses. The extent of possible improvements can vary widely. Some individual case studies will be discussed in detail later.

The Micalastic system is currently in use at more than 360 large hydro generators. These machines have a combined output of more than 50 000 MVA. This includes well known projects such as Grand Coulee (unit rating 825.7 MVA), Itaipu (unit rating 823.6 MVA) and Guri (unit rating 805 MVA).

The cumulative operating time of Micalastic windings presently installed in hydro generators (as of September 1997) amounts to 4800 years. The highest number of single generator operating hours, to our knowledge, is close to 280 000 h, equivalent to 32 trouble-free operating years, despite the fact that the Micalastic winding concerned is an early production type (Class B with polyester resin as impregnant and paper as carrier material), being commissioned in 1963.

With more than 250 000 Roebel bars installed to date, there has been no reported damage to Micalastic insulation caused by electrical or thermal ageing under normal operating conditions [Meyer and Blecken, 1995[1]].

Excluding regular maintenance, the actual service life of a stator winding largely depends on the manufacturing quality of the respective winding elements and on a proven installation procedure. A unique Roebel bar installation method, that ensures a particularly tight fit in the slots and virtually eliminates slot discharge, supplements the hardware quality of the Micalastic system [Blecken and Meyer, 1997[2]].

In the 1960s and 1970s, North American utilities experienced problems with particular stator winding insulation systems, and many detailed articles have been published about these phenomena [Jackson and Wilson, 1982[3]; Evans et al., 1981[4]]. Looseness of coils or Roebel bars in stator slots caused problems with thermoset insulation systems. Loss of electrical contact between the conductive outer surface of the winding elements and the slot surface resulted in erosion of the ground wall insulation as a result of slot discharge and corona. This was followed by mechanical damage because of vibration and increased thermal ageing as a result of reduced heat transfer from the winding to the core.

The problem was addressed at two different levels:

- For early fault detection, partial discharge analysis equipment was developed and introduced for monitoring or periodic testing; and,
- New methods for insertion and fixing winding elements in stator slots were established.

At the same time, detailed research started on insulation reliability. Accelerated functional life tests and short time high voltage tests became essential criteria for new generators and for stator winding replacement programmes. As a result, various North American utilities specified considerably increased test voltage levels when procuring, with the objective of obtaining extra insulation safety margins.

Quality assurance problems in the stator winding manufacture and installation of a few vendors forced the entire industry to comply with new standards and specifications. These specifications required the increase of ground wall insulation thickness and the incorporation of extra measures for the potential grading. Most manufacturers had to modify their products, which were not in dispute, with the costs being absorbed by the utilities and consumers. An exchange of information between utilities about their actual stator winding service experience could reverse this trend.

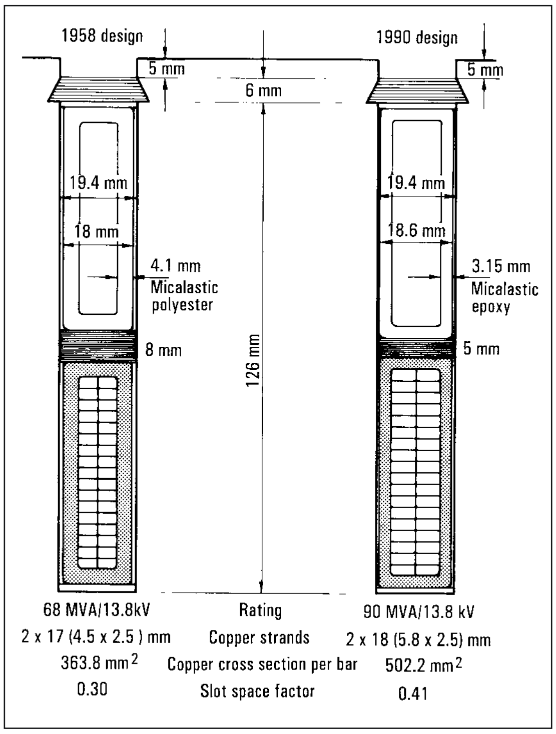


Fig. 2. Stator slot cross section of the Tres Marias uprating project.

1.2 Re-insulation of field coils

Re-insulation of field coils is sometimes a prerequisite if rotating DC machinery is being replaced by static excitation equipment. The latter generates steep voltage gradients that can over-stress the inter-turn insulation of the entrance and end field coils.

Re-insulation of field coils with state-of-the-art Class F insulation has the beneficial side-effect of removing asbestos.

1.3 Installation of static exciter equipment

Replacement of rotating DC exciters (the main shaft mounted three-phase auxiliary generators and their rotating converter sets, if applicable) with static exciter equipment improves service reliability. This not only considerably reduces maintenance costs (frequent replacement of brushes, cleaning, care of commutators, and so on), but also reduces excitation equipment and windage losses. Improvements in the vibration characteristics of the rotating element are possible since removal of excitation machines reduces the rotating mass at the unit shaft end.

1.4 Improving the cooling air circuit

Alterations to shaft fans and air coolers can also improve hydro generators. Cooling circuit alterations are necessary if the generator temperatures are undesirably high. If temperatures are unnecessarily low, reducing the angle of the fan blades will decrease cooling air flow and fan losses. Replacement of inefficient fans or installation of auxiliary fans can also improve the air flow. The effectiveness of auxiliary fans can be controlled either by generator load or winding temperature.

Significant savings on cooling water can be achieved by installing new, more efficient, air coolers and a load-dependent cooling water control system.

1.5 Replacement of stator winding shrouds

Replacement of steel stator winding shrouds with fibreglass segments can reduce stray losses.

1.6 Improving the field pole area and rotor surface

To reduce windage losses and field winding temperatures the inter-pole space configuration should be examined with the possibility of installing displacement fillets.

Rotating covers improve the rotor surface quality for lower windage losses.

1.7 Installation of PTFE bearing pads

Existing white metal journal and thrust bearing segments can be replaced with PTFE coated pads. Permissible thrust bearing specific loads increase greatly, resulting in lower thrust bearing losses. Catastrophic bearing failures (such as wiping of white metal) are unlikely, because of the lower frictional coefficient and material thermal properties of PTFE. No high pressure oil injection between the bearing pads and thrust runner is necessary. Combining PTFE thrust and journal pads makes it possible to ensure complete electrical insulation of the NDE bearing arrangement. Further shaft current protection is unnecessary. Brake actuation speed can be less than 10 per cent rated speed, which reduces stator winding contamination.

1.8 Installation of electronic turbine controllers

Governor permanent magnet generators can be removed and conventional governors can be replaced with electronic turbine controllers. Adding an electronic turbine controller to the existing station automation will permit power control operation.

1.9 Installation of new control equipment

Replacing existing monitoring devices with higher quality electronic instruments offers the advantages of digital operation. Replacing mercury spring remote thermometers with contacting Pt 100 resistance temperature detectors is one method. Installation of devices with expanded functional applications such as air gap monitoring and partial discharge analysis are other methods. All newly installed devices should allow for the provision of digital control.

1.10 Installation of other equipment

The installation of on-line monitoring equipment, for early fault recognition, also permits a transition from periodic to condition-based inspection intervals. Trending analysis of critical parameters, reduction of the maintenance work force, installation of a true supervisory expert system and remote control of the power station all become possible.

1.11 Miscellaneous

Many hydro generators are plagued with permanent deficiencies which, on their own, only impair operation a little. Most of these imperfections are nevertheless annoying to the plant operators and require regular and costly maintenance.

A few examples of such deficiencies are:

- oil vapour in the generator ventilating air which originates from the bearing oil reservoirs;
- extensive wear of slipring brushes with subsequent carbon dust contamination; and,
- instruments and devices which require frequent calibration or are prone to failure.

The replacement of components or modification measures applied during an upgrading outage can eliminate such imperfections.

Hot spots in generator components can easily be removed by installation of suitable material or by application of forced cooling.

2. Upgrading study

If design documentation, detailed drawings, test reports and commissioning data are available, it is possible to design a customized upgrading package, using new materials, techniques and devices. This requires an evaluation, as a first step, to document the present condition of the machine and the system. The evaluation should provide a summary of the relevant potential improvements, outlining the improved performance along with related costs. It would require:

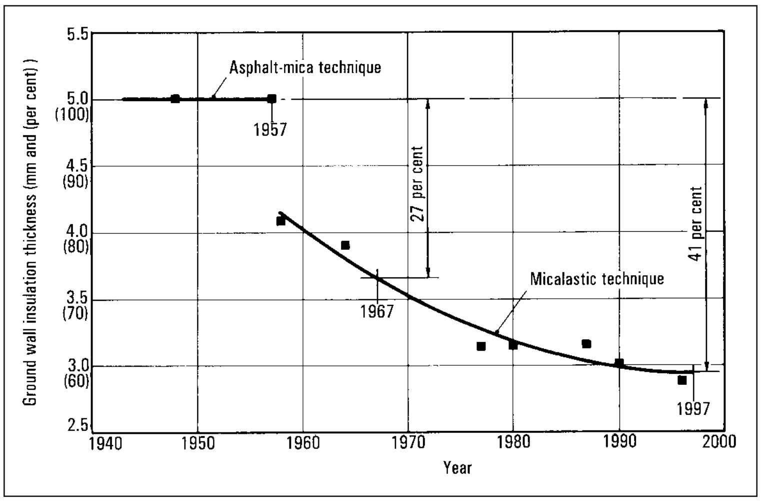
- a thorough inspection of the generator;
- a review of all the available operating and maintenance reports; and,
- questioning of power station personnel about their operating experience with all similar generators.

The detailed generator upgrading study deals with all components between the turbine coupling flange and the generator terminals. This includes protective relays, excitation equipment, control equipment and any auxiliary equipment required for operation of the generator. The evaluation should describe the present conditions, the history since commissioning and a procedure listing all the upgrading measures. The costs for the modifications need to be listed individually. On this basis, a cost-benefit calculation can be established. The study can be subsequently used as a basis for the preparation of a bid specification.

3. Uprating

The definition of uprating is the replacement or improvement of components required to increase the unit kVA output.

Fig. 3. Development of ground wall insulation thickness for 13.8 kV stator windings of actual projects.



Before implementing an uprating project, all components between the generator terminals and the unit transformer high-voltage bushings, and also including the HV switchyard, should be investigated. However, the ratings of the current transformers, bus ducts, unit transformers, switchgear and so on, needs consideration at the same time.

Prior to a generator uprating evaluation, it is necessary to determine whether or not the turbine rating can be increased with changed hydraulic conditions and improved design. This may require either a rebuilt or a replacement turbine runner. A replacement runner often has the additional benefit of improving machine performance beyond the upgrading or uprating objective. This is the case if it resolves other problems that may have developed during the operation of the unit.

When a turbine manufacturer specifies the possible uprating potential for the turbine, the generator supplier then has to evaluate whether a likely increase in hydraulic thrust and runaway speed can be tolerated. However, in most cases one can assume that the rotor of the hydro generator is not the limiting factor since, in the past, rotor and bearing designs have been very conservative.

Fig. 1 demonstrates that actual uprating projects virtually start at a design age of 20 years, with a certain peak for hydro generators with an average age of about 30 years. This fact is self-explanatory, as shown in Fig. 3. The reduction of ground wall insulation for the 1957 to 1967 decade alone (starting with an asphalt-mica thickness level of 5 mm = 100 per cent in 1957, when this insulation system has been replaced by the Micalastic insulation) amounts to 27 per cent. The total reduction, to date, is 41 per cent.

It therefore is advantageous nowadays to uprate projects with hydro generators of 30 years or older, since the VPI insulation technique has reached maturity. Any future reduction of ground wall insulation will be limited.

Before evaluating a project or unit for increased output, present site characteristics should be compared with the original conditions specified decades ago. It is advisable to redefine present operating conditions to establish the following:

- Do original hydraulic conditions (planned water flow and/or storage and head applicable to a base year), coincide with present day conditions?
- Have system requirements changed, and is a conversion from low value off-peak energy generation to high value peak energy generation possible?
- Can peak loads be generated without exceeding permissable flood and/or discharge fluctuations?
- Do current penstocks and draft tubes or tailrace tunnels allow for increased flow?
- Is it possible, or even necessary, to increase the impounding height to improve flood protection for an increase in turbine output?
- Have system requirements changed to allow for revisions in generator design (such as power factor, short-circuit ratio, reactances, and so on) for the most economical overall layout?

In general, the measures for upgrading described previously are also applicable to uprating. However, since an uprating provides for increased generator output, it is necessary to review generator characteristics and their effect on the system. This includes such items as higher excitation requirements, ventilation air flow, air cooling system, and so on.

There are two uprating measures to be considered beyond those already discussed. These are installation of a new stator core and installation of new field coils.

3.1 Installation of a new stator core

Stator cores designed decades ago had layers of 50 to 70 mm, separated by 10 mm-wide ventilation ducts. Contemporary designs have layers of 30 to 40 mm with ventilation ducts of 6 to 8 mm for improved cooling. Re-torquing for modern cores is eliminated, since compression is maintained with spring elements. Core buckling can also be eliminated with new torquing and core stacking techniques, and by using double dovetail positioning bars for the core-to-stator frame attachment, and PTFE-coated radial keys for attaching the stator frame to the sole plates. Both measures allow for unhindered thermal expansion.

The advantages of installing a new stator core are:

- The reduction of core losses through the use of low-loss core steel, with the additional benefit of Class F epoxy varnish (instead of paper or shellac). This results in better lamination smoothness and improved core space factor.
- The latitude given to the designer in selecting the optimum combination of stator core and stator winding. The number of core slots, slot size and other design characteristics can be optimized.
- Construction of the new stator can be done in the existing assembly bay of the powerhouse. This allows for application of the “continuous-core-stacking” method. Stator joints, which require regular inspection and maintenance, are thus eliminated, considerably improving the mechanical stability of the stator core.
- The replacement of a complete stator permits the application of the “build-and-exchange” method, which results in a dramatic reduction of outage time.

3.2 Installation of new field coils

Installing new field coils with larger cross sections improves efficiency and reduces excitation power requirements. Altering the number of field turns may allow for the excitation equipment (of different generator types with similar output) to be standardized.

While other measures have already been described, individual modifications must be thoroughly discussed because uprating increases the machine output. The stress level of all stator and rotor keys needs consideration because of increased torque. The shaft design in most cases is of little concern to the generator designer, since shaft diameter, coupling flange dimensions and material specification were provided by the turbine manufacturer at the time of original construction. If the turbine designer today determines a certain uprating potential, the present shaft configuration should have been included in the respective evaluation already.

In the past it was quite common to design all rotor components with a 2/3 yield strength, possibly with a margin, for runaway speed conditions. Today, a limited overspeed increase, resulting from the turbine uprating, may be acceptable if, after careful evaluation, both the customer and generator manufacturer or refurbisher agree to increase permissible yield strength percentages by a few points.

4. Economy of uprating

None of the generator uprating measures require structural alterations to the powerplant (powerhouse, dam, and so on). Increased output can thus be achieved for a fraction of the cost of building a new powerplant.

The following figures show how the cost for uprating an existing storage-type hydropower plant with a total output of 750 MVA by 30 per cent to 975 MVA

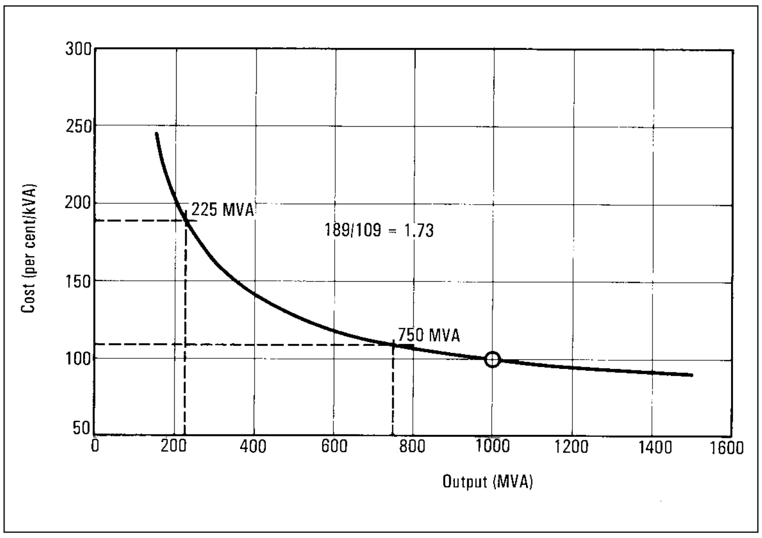


Fig. 4. Average electrical components cost curve for a number of hydro projects.

compares with the costs of constructing a new plant to provide the equivalent 30 per cent (that is, 225 MVA).

Cost split for the hydro plant

Civil works portion:	70 per cent
Mechanical components portion:	15 per cent
Electrical components portion:	15 per cent

Cost split for the electrical components portion

Generator:	35 per cent
Unit transformer:	10 per cent
Other components to be uprated:	10 per cent
Remaining components:	45 per cent

The next group of figures are based on the following assumptions:

• 40 per cent of the generator components have to be replaced (complete new stator plus re-insulation of the field winding).
• Extra costs for dismantling and reassembly will account for 25 per cent of order volume.
• The prices of the unit transformer and other components to be uprated follow the square root of the respective output increase. Dismantling and reassembly are assumed to be 10 per cent of the order volume.

Costs for the electrical components portion at 30 per cent output increase

Generator
35 per cent × 0.40 × 1.25 = 17.5 per cent
Unit transformer
10 per cent × $\sqrt{1.3}$ × 1.10 = 12.5 per cent
Other components to be uprated
10 per cent × $\sqrt{1.3}$ × 1.10 = 12.5 per cent
Remaining components unchanged = 0 per cent

≈ 42.5 per cent

Case A: Uprating of an existing hydro plant by 30 per cent

Civil works portion
unchanged = 0 per cent
Mechanical components portion
15 per cent × 0.40 = 6.0 per cent
Electrical components portion
15 per cent × 0.425 = 6.4 per cent

≈ 12.4 per cent

The price factor of 0.40 for the mechanical components portion includes modifications required in the distributor section of the turbine and a new runner.

Case B: Building a new hydro plant (225 MVA) next to the existing one

For the civil portion it has been assumed that the upper reservoir can be used for the new powerplant and that this represents a saving of 20 per cent. The factor of 1.73 takes into account the cost per kVA increase for decreasing plant capacity with a base output of 750 MVA. Fig. 4 shows the cost per kVA for the electrical components portion over the plant capacity with 100 per cent cost for a typical 1000 MVA hydro plant (For easier handling it has been assumed that for the civil portion and mechanical components portion similar conditions exist.)

Civil works portion
50 per cent × 0.30 × 1.73 = 26.0 per cent
Mechanical components portion
15 per cent × 0.30 × 1.73 = 7.8 per cent
Electrical components portion
15 per cent × 0.30 × 1.73 = 7.8 per cent

≈ 41.6 per cent

By comparison, it is obvious that for this specific project a new powerplant would cost at least three times more than uprating the existing one. For plants with smaller outputs, the cost-ratio can easily approach a figure of 5 or more. This does not include the loss of revenue and costs attributable to delays caused by the construction activities. Assuming an energy price of US$ 0.05 per kWh and an average plant factor of only 50 per cent, the loss of revenue for a 100 MW unit amounts to US$ 60 000 each day.

The alternative of building a new plant is somewhat theoretical, since obtaining a new operating licence can be extremely difficult

The effort required to produce an uprating study is greater than for an upgrading because of the additional investigations illustrated above.

5. Practical implementation

It is essential to appoint appropriately qualified experts to conduct upgrading or uprating studies. Specialists with long experience in the design and commissioning of hydro generators should inspect and document the present conditions, and have access to operating and maintenance reports for assessing the history of problems. Operating personnel are needed to answer questions. When uprating studies are considered, turbine and generator specialists should carry out joint inspections.

Usually, it is recommended at this stage that non-destructive diagnostic measurements are made to reach a sound judgement on the condition of the stator and rotor windings. Such an evaluation mainly consists of, but is not limited to: DC insulation current, dielectric loss factor and partial discharge measurements (stator winding), and impulse/surge and impedance measurements (field winding). For various reasons it is impossible to determine with sufficient accuracy the remaining life expectancy of a stator winding insulation. This is the case even if detailed test results are available. The stator related measurements permit experienced specialists to some extent, by comparison with previous test results, only to evaluate the dielectric ageing originating from electrical and thermal stress. With a certain probability, a statement can be given that the insulation may survive one more inspection period. However, these measurements can be avoided if economic reasons alone dictate a stator winding replacement.

6. Case studies

6.1 Waldshut, Germany

The Waldshut pumped-storage plant had four 44 MVA units. Two motor-generators were designed by Siemens in 1948, and these were uprated from 44 MVA to 55 MVA in 1992, when an order was placed for completely new stators and sets of field poles. Siemens optimized the stator winding design by reducing the number of slots (from 342 to 288) and by changing the type of winding from lap to wave. The original 72 jumpers could be completely eliminated, considerably simplifying the stator winding. Even more important was the fact that the full-load efficiency increased from 97.33 per cent (44 MVA) to 98.16 per cent (55 MVA).

The efficiency improvement was not only achieved by redesigning the stator winding, but by the use of low-loss stator laminations for the new stator core and by increasing the copper cross section of the field winding, with removal of the former asbestos insulation. The rotating excitation equipment was replaced with a static excitation system and new air-to-water coolers were installed. The temperature rise of the new field winding is slightly above 40°K, and the temperature rise of the stator winding has been determined to be as low as 33°K (both at 55 MVA). Thermal ageing of the Class F Micalastic insulation can therefore be neglected, which also proves that the available uprating potential of this design has not been fully exploited.

With all the other modernization measures, this powerplant can now be regarded as being in an as-new condition with considerably improved reliability and maintainability standards.

6.2 Häusern, Germany

This pumped-storage plant was commissioned in 1931 with four vertical units, of 32 MVA each. The stators were replaced in 1954/57 with a modest uprating to 35 MVA. Nearly 40 years later, the utility decided to modernize the complete plant to state-of-the-art conditions. In 1995 the first unit received a completely new 45 MVA stator and new field poles. The jumper-free design of the new stator winding and the spring elements of the stator core are clearly visible in Photo 1.

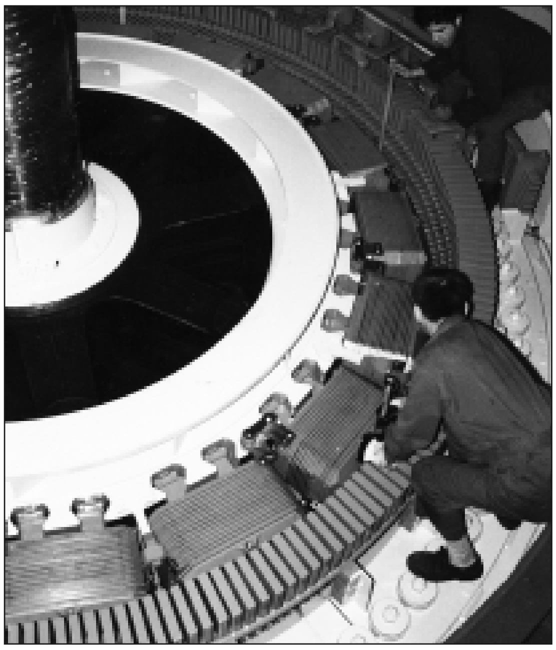


Photo 1. Rotor assembly of the uprated Häusern unit.

Despite an uprating of 40 per cent, the total losses at rated load have been reduced by 275 kW. This resulted in an efficiency increase from 96.36 per cent (32 MVA) to 98.44 per cent (45 MVA).

Since both projects belong to the same utility and the uprating measures of the Waldshut machines were a complete success, most of the design features have been repeated on the Häusern unit. There is one exception: the utility agreed to the designer's suggestion to have the stator core made of grain-oriented silicon steel laminations. The decrease in iron losses was beyond expectations and valuable experience has been gained for future rehabilitation projects.

6.3 Tres Marias, Brazil

The original design of this plant dates back to 1958 when the 68 MVA run-of-river units were ordered. In 1990, an uprating programme was initiated and new stators were delivered. The number of slots and slot dimensions remained unchanged. Improvements in the insulation technique permitted an increase of slot space factor from 30 per cent to 41 per cent (Fig. 2). The rated load was increased to 80 MVA with a permissible continuous overload of 90 MVA. The new stators were designed by incorporating various modern features. The lack of core joints considerably improves the mechanical stability of the new stator.

6.4 Grand Coulee, USA

Siemens also conducts upgrading and uprating of generators supplied by other manufacturers, such as at the U.S. Bureau of Reclamation's Grand Coulee plant in the USA. The machines were direct water cooled generators [Treichel, et al., 1993[5]]. Originally, the customer only planned to replace the troublesome stator windings on these generators (which now have the largest output in the world). The USBR maintenance schedule of the original direct water cooled stator windings called for water leakage related inspection outages at 90 day intervals. Subsequent repair activities, however, eventually required forced outages every 5 to 6 weeks, which resulted in a very poor availability record and a considerable loss of revenue.

Siemens made an intensive study of the generators and was able to show that by changing the design and increasing the slot number, losses could be reduced considerably. The new design included a number of other innovations and it was shown that, with efficient logistics, the installation outage time for each generator could be reduced from about one year to only 70 days. This idea, on its own, represented multi-million dollar savings in revenue for each generator [Light and White, 1997[6]]

In addition, the previous 700 MW rating has been increased to a continuous output of 805 MW, which represents an uprating of 15 per cent [Clark, 1996[7]]. The customer applied for unscheduled funds and ultimately purchased the entire proposal.

USBR's specification demanded an exceptionally stringent Roebel bar test programme. Voltage endurance tests, thermal cycling tests and vibration tests were carried out on single prototype bars. Similar tests were done on a mock core with real laminations and an installed winding section consisting of 20 Roebel bars. All prototype tests have been carried out to the satisfaction of the customer [Bethge, et al., 1996[8]].

Photo 2. Refurbished stator of Grand Coulee unit G-24 being lowered into the pit.

The first generator (unit G-22) was re-commissioned on time in December 1995; the second (unit G-24) came on line a year later, just in time to serve the then cold-stricken Pacific Northwest. The third unit, G-23, will be recommissioned in December 1997.

Photo 2 shows the second stator when it was being lowered into unit G-24 generator pit. The custom-built lifting device, 23 m in diameter and weighing 115 metric tons, is attached to the existing gantry crane at four points. The lifting device consists of two main beams and 12 arms, clearly visible in the photograph. Each lifting arm is connected to the stator frame with two studs, each 82.5 mm in diameter [Light and White, 1997[9]].

After trouble-free operation, unit G-22 was shut down in June 1996 for the first contractual inspection. The inspection did not reveal any need for corrective work. No problems originating from vibration, overheating, leakage or mechanical failure were detected.

After successfully completing the inspection, all guarantee measurements were obtained. These measurements consisted of:

- segregated and full-load losses, determined with the water-calorimetric method, including a full-load heat-run test; and,
- vibration tests at all loads for determination of natural frequencies, including amplitude and direction of bar end turns and supporting brackets.

All guaranteed objectives have been fully met or exceeded. The total losses, after stator replacement, are more than 900 kW below previous data. The guaranteed total losses of 10 863 kW have been undercut by 500 kW, resulting in a full-load efficiency of 98.73 per cent (previously 98.62 per cent).

The averaged temperatures at a full-load of 825.7 MVA were determined as follows:

• Stator core (centre):	70°C
• Stator winding cooling water outlets:	69°C
• Stator winding RTDs:	65°C

Because of the very low temperature levels, thermal ageing of the Micalastic insulation can be ruled out and expansion-related stress between the stator winding and core is negligible.

The maximum output achieved since recommissioning has been 836 MW.

Preliminary investigations on unit G-24, with an air gap monitoring system, revealed that the rotor rim was loose. The rim consists of two layers separated by a centre air duct. The investigations indicated that both layers distorted elliptically with the top layer ellipse at 90° to the bottom layer ellipse.

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The USBR directed Siemens Power Corporation to retighten the rotor by: heating the rim to a temperature at which it was free of the spider arms; and, installing hardened spacers at the ends of each spider arm.

Varying the spacer thickness improved the overall rotor rim roundness. Extra thickness ensured a tight fit and allowed the USBR to avoid the expense of replacing the torque keys and rim clamping bolts.

7. Conclusion

Considerable improvements in output, efficiency, reliability and availability are convincing factors for an upgrading or uprating project, although a lack of funds or budget constraints are obstacles to short-term implementation. The financial hurdle can be overcome, however. Instead of prolonged operation of ageing equipment with the associated high maintenance costs, the funding which such maintenance would require over several years can instead be allocated to performing a major overhaul at an earlier time. This approach offers the additional advantage that subsequent maintenance costs are sharply reduced and reliability is increased considerably.

If a refurbishment project includes an uprating, this will usually lead to increased output revenue, and if the payback period is short, the rehabilitation should be initiated at the earliest opportunity. This applies even to generators with good reliability records. ◊

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