New water-cooled turbogenerators in the 400-MVA plus power class

Highest possible availability and low maintenance were the development goals for a new series of turbogenerators with water-cooled stator and rotor windings which ABB Generation has now brought to the market. Water, like air, is a trouble-free and efficient coolant, and allows reliable and rugged generators to be built. The seals between the rotating and stationary parts are simpler than in the case of hydrogen-cooled generators. Also, fewer auxiliary systems are needed.

Power generation capacity in Sweden is divided almost equally between hydroelectric and nuclear power plants. Compared with these, fossil-fired plants generate only an insignificant amount of electricity.

Together, the Nordic countries have 16 nuclear power plants with a total of 25 turbine-driven generators in operation. The total installed capacity is about 12,000 MVA. Fourteen of these generators are cooled by water **1**.

On average, each of the water-cooled generators in Sweden produces 3 percent of the electrical energy produced in that country. This figure serves well to stress the importance the power industry attaches to the availability of these machines.

Statistics show that whereas the availability of nuclear power stations worldwide generally averages 72 percent, in the Nordic countries this figure is almost 90 percent. To achieve the highest values possible, operators of nuclear plants take a pro-active stance in their efforts to ensure maximum availability for all the plant subsystems. The generators are one of the focal points of these efforts.

Against this background, ABB Generation has further developed its water-cooled generators with the goals of highest availability and reduced maintenance.

Better availability with water-cooling

Mature designs and high quality, plus optimized maintenance and customer support programmes, underlie the extremely high statistical availability of water-cooled turbogenerators. Serious disturbances occur only seldom, largely because of certain specific characteristics of the machines:

- No risk of fire or explosion with water- and air-cooling.
- Seals between the rotating and fixed parts of the generator are of simple construction.
- Simple auxiliary systems.
- Low winding temperature, ie longer service life for the windings and insulation.
- Simple monitoring equipment (sensors are easily fitted and maintained).
- Easy access for visual inspections (no need to remove and then refill gas).
- Rugged design, straightforward operation and ease of maintenance, since the generator is under atmospheric pressure.
- Short, compact rotor, which is largely insensitive to vibration.

The statistics of the International Atomic Energy Association (IAEA) show that the average availability of water-cooled generators in nuclear power plants over the past 15 years has been 99.8 percent **2**.

Stellan Thorén
ABB Generation

Water-cooled stator and rotor windings

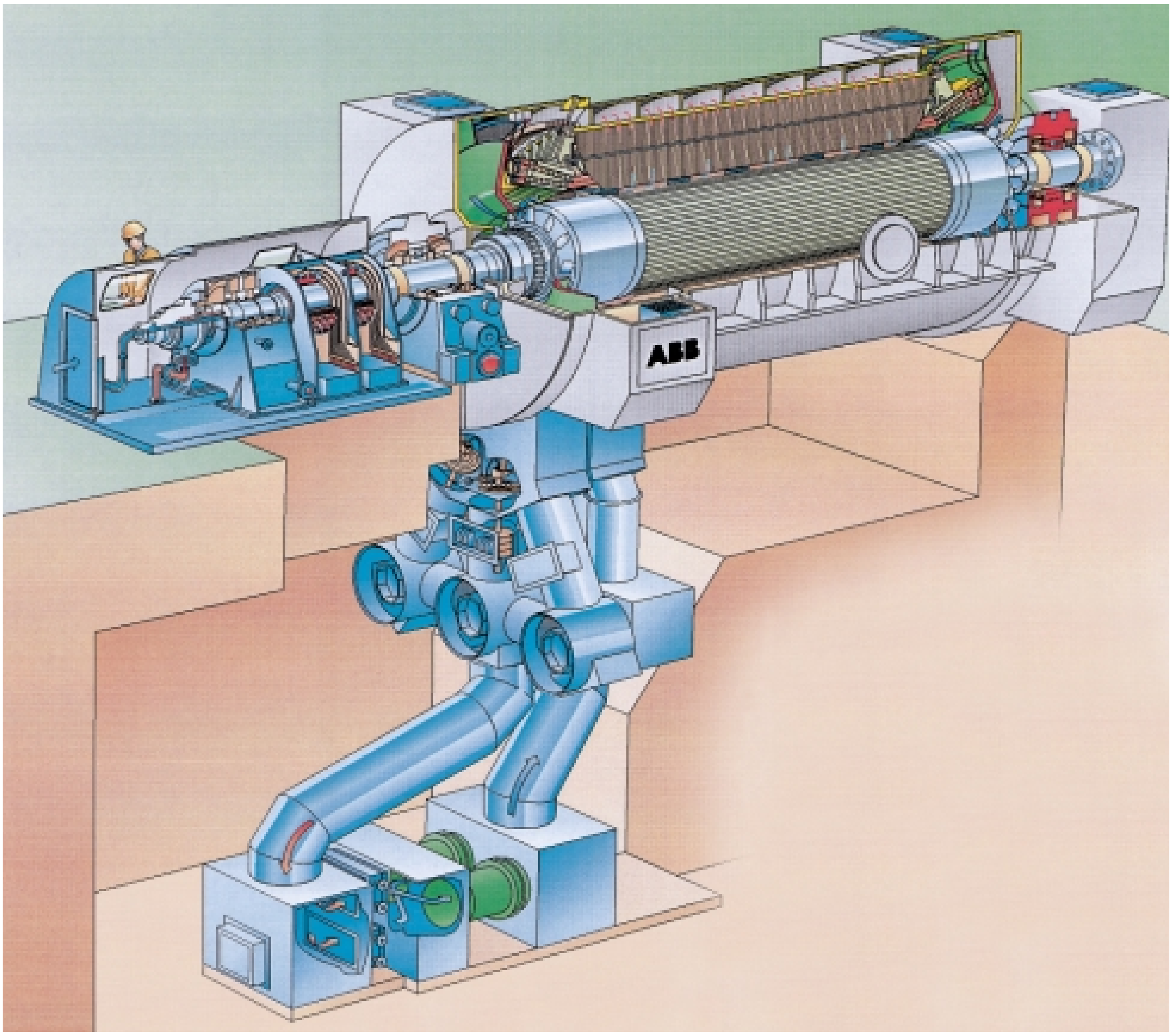
In water-cooled generators the stator and rotor windings are cooled directly by water, the other parts of the machine being cooled by air in the usual way. There is therefore no need for complicated auxiliary systems; the machines are generally of a simpler design, which significantly reduces the risk of disturbance or failure. The adoption of this cooling principle means that the generator is under atmospheric pressure, allowing simpler design solutions for the stator casing and seals as well as easier access to the internal parts of the machine.

Deionized water is used as coolant for the windings. Per unit of weight, this has a heat-absorption capability 3,300 times higher than that of air at atmospheric pressure. What is more, it is environmentally benign **3**.

Rugged rotor design

Direct water-cooled rotor winding

One of the advantages of water-cooled generators is the direct water-cooling of the rotor winding. This cooling method was developed by ABB more than 25 years ago. Technical advances since then have perfected the method and enhances its efficiency. Numerous generators with water-



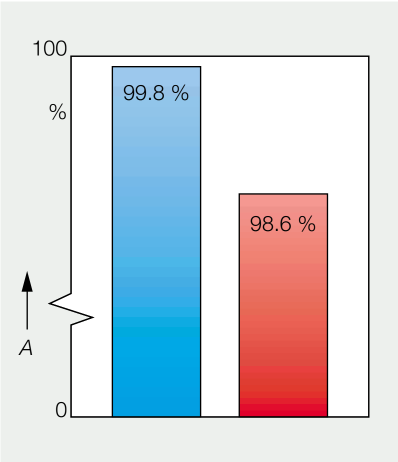
Two-pole, water-cooled ABB generator of advanced design. The machines in the new series are designed for power outputs of 400 MVA and more. **1**

cooled rotors have been in service for more than ten years and experience with them has been excellent.

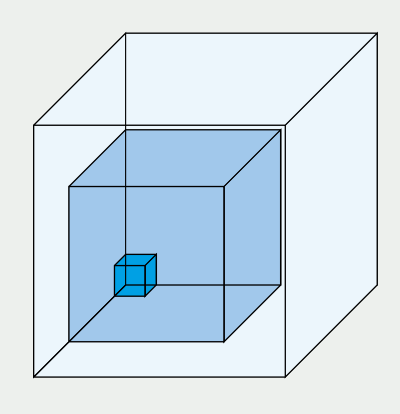
Two concentrically arranged tubes, located in the center of the shaft at the exciter end, carry the cooling water to and from the rotor. The water passes to the rotor through the inner pipe, and away from the rotor through the outer one.

Radial tubes direct the inlet water into two of the four sectors of an annular chamber. From this chamber, the water flows through insulated ducts into the parallel cooling circuits of the rotor winding **4**, **5**.

The winding terminals, which are made of insulated copper bars with cooling tubes of high-grade steel, are located in axially drilled holes in the rotor shaft. These holes lead into slots which have closed ends. The cool-

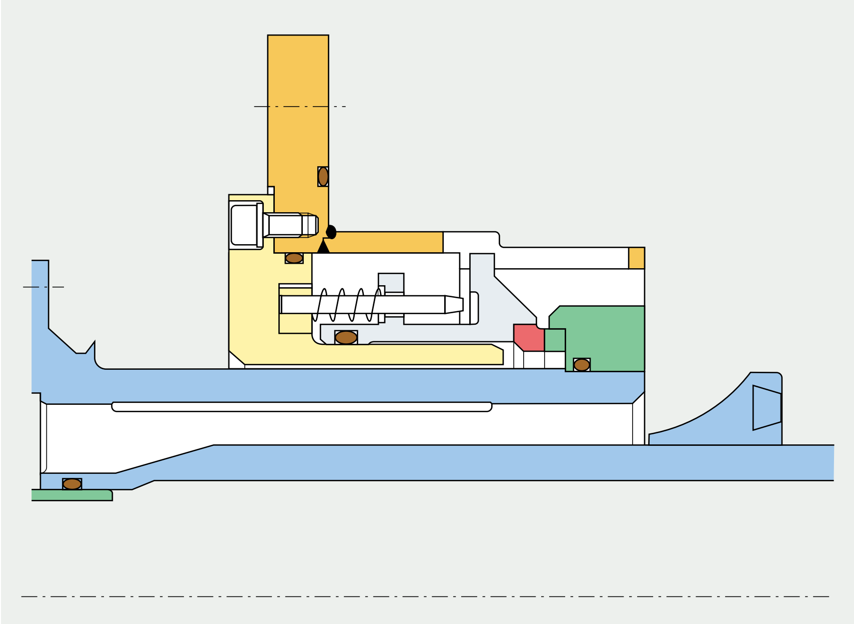


Availability (A) of generators in all the world's nuclear power plants (red), compared with the availability of water-cooled generators (blue) **2**
Source: IAEA



Relative effectiveness of different coolants **3**

Dark-blue *Water*
Medium-blue *Hydrogen*
Light-blue *Air*



Chamber for the rotor cooling-water inlet and outlet **4**

ing water passes from here to the drive end of the generator, where the cooling ducts are connected to the rotor winding. Thus, there is no need for radial bores for the winding terminals in the most highly stressed part of the rotor body; also eliminated are the flexible coupling elements needed to equalize the differences in rotor deformation. This simple and reliable solution is only possible with direct water-cooling **6**.

Safe, reliable operation

Water-cooling ensures safe and reliable operation of the generator for the following reasons:

- The winding temperature remains low, resulting in a longer service life for the insulation, etc.
- Local hot spots are avoided.
- Uniform cooling means that the rotor is insensitive to thermal instability.
- The low operating temperature and possibilities for support preclude creepage in the winding overhangs.

Compact design

Direct water-cooling enables the rotor to be kept short, therefore allowing a more compact generator. This reduces the specific mass and volume of the machine (typically by 20 percent), though without compromising the high mechanical stability of the generator, which was one of the main development goals **7**.

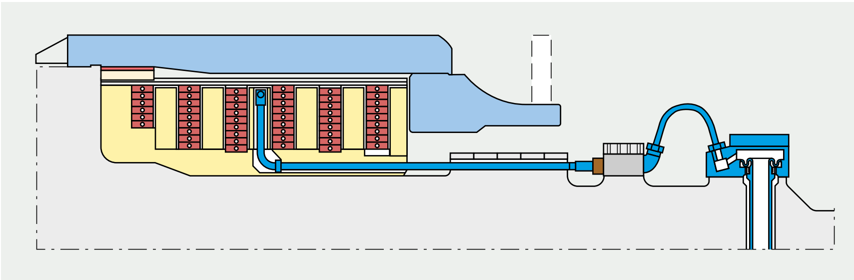
Rotor winding made of silver-copper alloy

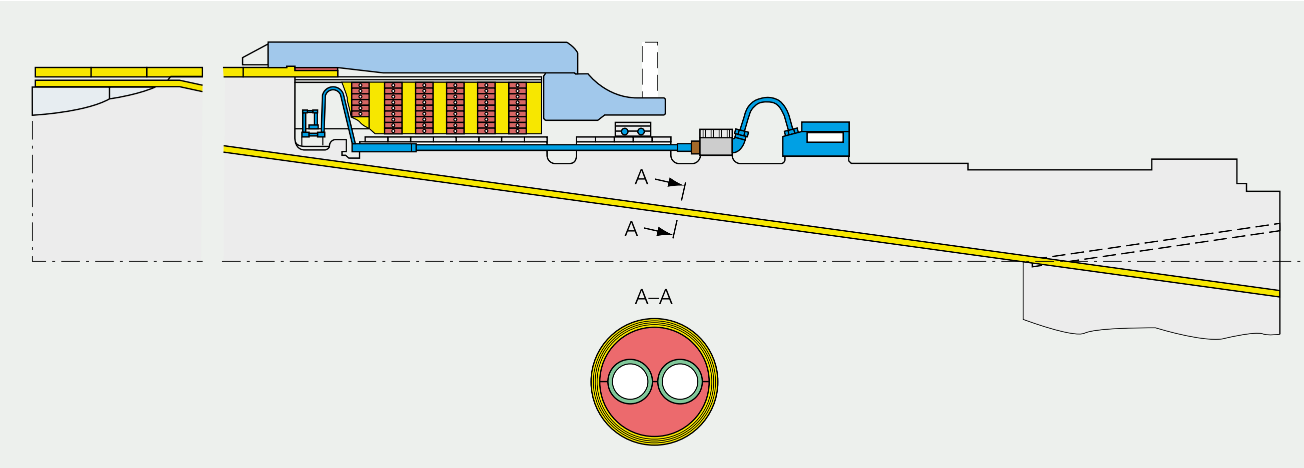
The rotor winding comprises conductors laid in pairs with a high-grade steel tube for the cooling water inserted between them. Centrifugal forces cause the rotor winding to be subjected to considerable loads in operation. In addition, the temperature rise during operation creates frictional forces that prevent axial expansion of the winding. A silver-copper alloy is used for the winding, as this has a higher yield point and exhibits better fatigue strength than other winding materials. Also, this alloy has excellent thermal properties, so the mechanical strength of the rotor winding is not diminished at operating temperature.

Special attention was given to the insulation of the winding overhang. All the insulating materials used belong to temperature class F. The design completely eliminates copper dusting in the rotor winding.

The centrifugal forces acting on the winding are taken up by the rotor slot wedges, which are made of a copper alloy specially developed for this application. The strength and conductivity of this material

Route of the cooling-water flowing to and from the rotor winding **5**





Special design of the rotor cooling-water connection **6**

remain high even at elevated temperatures. In addition, it is insensitive to stress corrosion and causes no contact fretting in the rotor body. The slot wedges and special rotor end-rings act as a damper winding. The main task of this winding is to improve the electrical and mechanical damping by providing well-defined conducting paths, and so reduce the loads acting on the body and other parts of the rotor **8**.

Rotor body

The mechanical dimensions of the rotor body were determined using both the classical theory of fatigue as well as analysis of its sensitivity to damage. These two methods complement each other in an ideal way.

The rotor body is a single piece, machined from a heat-treated, high-strength and highly permeable forging blank. The rotor half-couplings are part of the original blank and are adapted to the turbines. Dimensions have been chosen for the rotor body which ensure safe and reliable operation at clearly defined overspeeds with a satisfactory margin of safety. A good safety margin is also ensured under the shaft torque conditions existing during normal operation and short circuits.

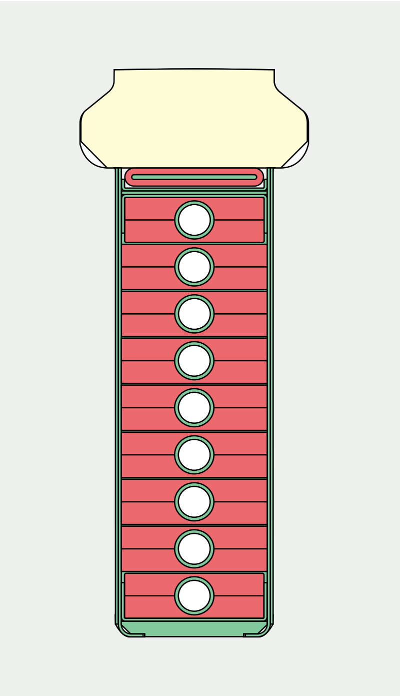
The compact design allows accurate calculation of the critical speed, thus ensuring low vibration loads for the rotor and bearing. It is interesting to note that ABB Generation carried out the first computer calculations of critical speed already in 1954, during trial operation of the first computer to be installed in Sweden.

Stator

MICADUR insulation for the stator winding

The advantages of the MICADUR insulation system, which was developed by ABB with the goals of maximum quality and reliability, come to the fore in the design of the stator.

Water-cooled 480-MVA generator in the Ringhals 2 nuclear power station, Sweden **7**



Cross-section through a water-cooled rotor winding **8**

Strict quality control measures are applied throughout the manufacturing process for the windings.

The stator coil sections consist of insulated copper conductors and cooling pipes made of high-grade steel. All the conductors are transposed by 540° using the Roebel method. The transposed section is located in the embedded part of the coil, the conductor assembly being transposed around the longitudinal axis of the slot. This results in low stray losses and allows simple and reliable connection of the conductors.

The insulation is made using VPI technology, ie under pressure and vacuum. This technology combines all the benefits of solid insulating materials and advanced synthetic resins. The MICADUR system was developed by ABB more than three decades ago and has been continually improved in the intervening years.

The main insulation is provided with corona shielding in the form of a low-ohm coating on the part of the coil section inside the slot and a semiconducting, voltage-sensitive coating on the part outside. Since the spacers in the end-winding assembly are not at earth potential, the insulation of the coil section is subjected to relatively low electrical stress.

The cooling water flows through steel tubes in the stator winding. This solution has been used for as long as ABB has been building generators and has proved to be completely trouble-free. Neither leakage nor blockages of the tubes have ever occurred.

Round packing ensures perfect adaptation to the slot

Use of ABB's Round Packing® System guarantees perfect fitting of the coil sections in the slot and reliable earthing of the slot corona shielding. This system, which allows adequate thermal expansion, consists of a double-folded, semiconducting tape, filled with a silicone compound. The tape is wound spirally around the parts of the coil sections laid in the slots, after which the silicone hardens. This method has the advantage that the coil sections can be removed from the slots without being damaged.

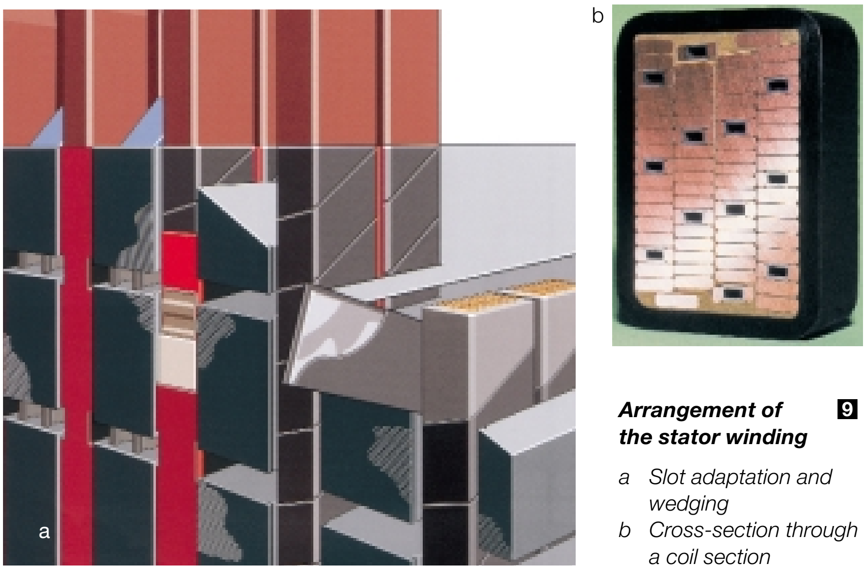
The coil sections are held firmly in place by wedges made of glass laminate. Resilient, corrugated laminates in the slots ensure that the coil sections remain in their fixed positions even after a long period of operation. The laminate design also makes sure that a constant pressure is exerted over the full embedded length. More than two decades of field experience with this method have proved its worth **9**.

Winding overhang support

To minimize the vibrations in the windings and in the end connections, ABB has developed a special end-winding support system. It ensures a sufficiently high flexibility, while also providing space for thermal expansion, especially in the axial direction.

The support system must be strong enough to withstand the effect of the electrodynamic forces in normal operation as well as when disturbances occur in the power network. It is especially important that the end windings do not exhibit resonance at frequencies of 100/120 and 50/60 Hz. The resonant frequencies are avoided by appropriate dimensioning of the end-winding support **10**.

The bottom and top winding overhangs at each end of the generator are joined together to form the end-winding assembly. This homogeneous ring results in precisely defined natural frequencies for the winding overhang as a whole. The end-winding assemblies have an additional tangential support which absorbs the resulting forces, eg when short circuits occur.



Arrangement of the stator winding **9**

a Slot adaptation and wedging
b Cross-section through a coil section

The end-winding assembly also provides sufficient clearance for axial displacement due to temperature rise. Field experience with this support system has been good.

Stator core

The stator core, as one of the most important parts of the magnetic circuit, is designed to meet the power and lifetime requirements with a large margin of safety. The core and the laminated press rings have radial cooling slits and are cooled exclusively by air **11**.

Low-loss electrical sheet steel is used for the stator core. The laminations are stacked in the stator casing, the segments being laid with a 50% overlap. Intermediate core pressing is carried out approximately five times during stacking, the core being shaken and heated at the same time. This method ensures compactness and practically excludes displacement over the lifetime of the core.

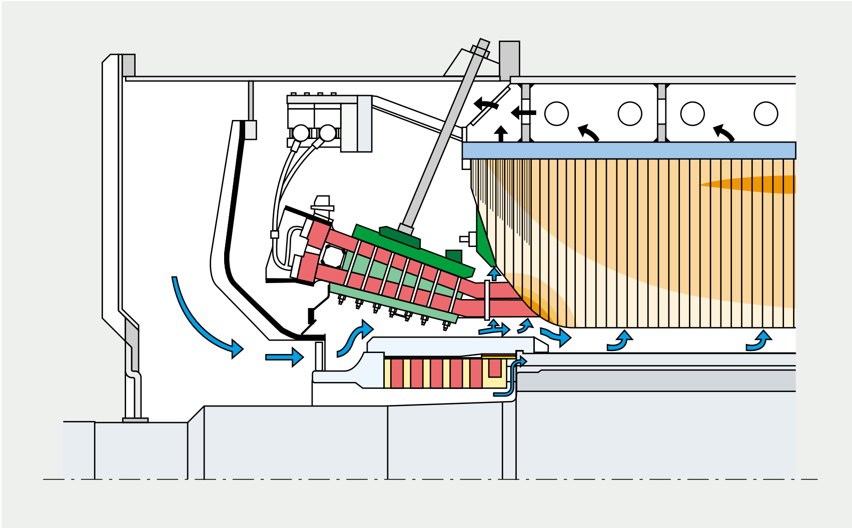
The press rings are constructed separately with electrical sheet steel segments, glued together using the VPI method to form a hardened, rigid ring. Stacking the laminations in steps reduces the stray flux in the end regions, thereby lowering the losses and ensuring a low operating temperature.

Finally, insulated through-bolts are used to pretension the laminated core and the press rings.

Stator frame

The stator frame has been dimensioned to withstand all the static and dynamic loads that can occur under normal and fault conditions. In addition, the design of the frame and core ensures that these parts do not transmit excessive forces to the foundations.

Instead of clamping the stator rigidly in place, the foundation bolts are located inside spacer sleeves to provide relief from the pretensioning. Only a small clearance is provided between the sleeves and the baseplates of the stator. In the event of extreme loads, eg due to short circuits, the bolts and the spacer sleeves act together in absorbing the lifting force exerted by the stator.



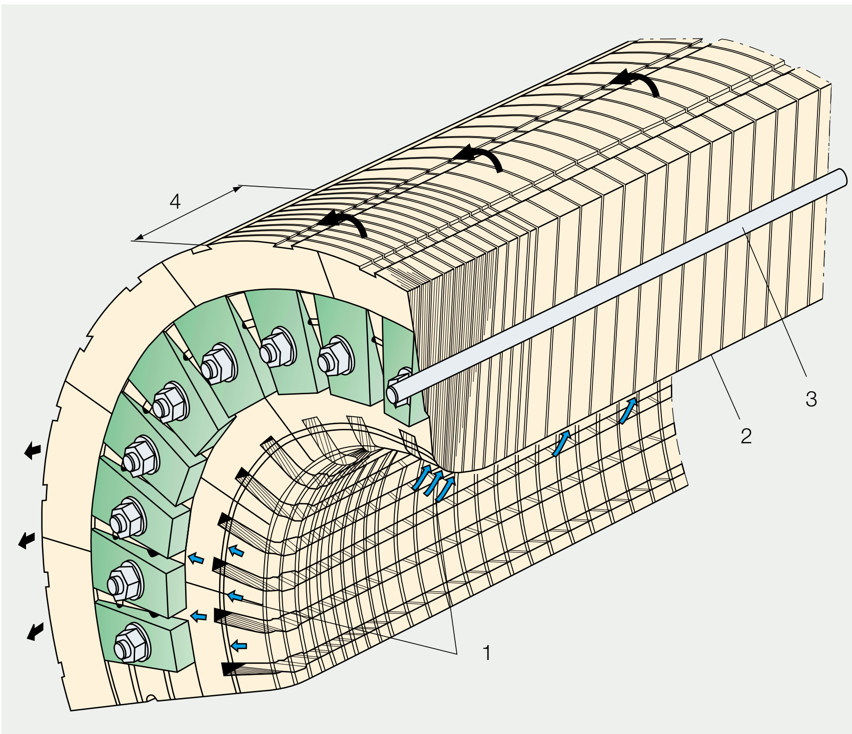
Construction of the winding overhang support for large generators **10**

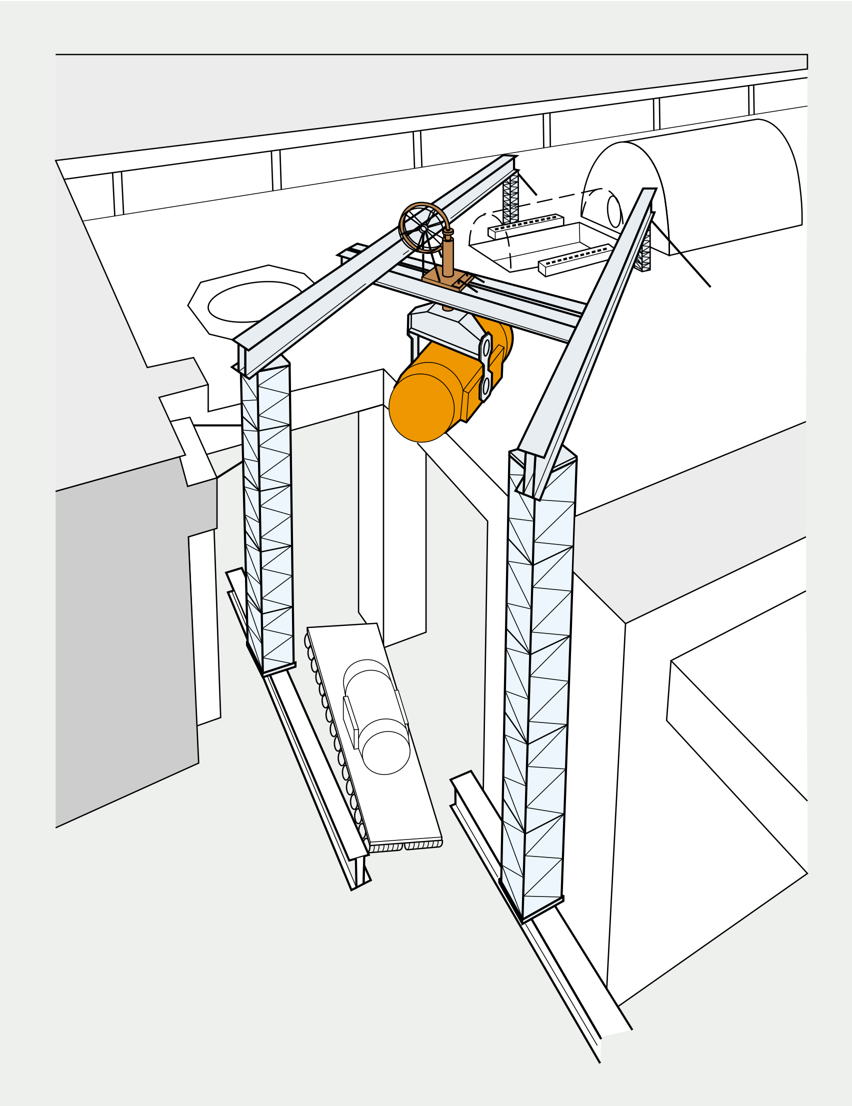
25 years of operating experience

ABB's field experience with water-cooled turbogenerators goes back at least 25 years. Over this period, know-how has been accumulated which today benefits both new installations and retrofit projects.

Section through a stator core for large generators **11**

1 *Cooling-air* 2 *Cooling duct* 3 *Clamping bolt* 4 *End region*





Special gantry system used to replace the generator in the Ringhals 2 nuclear power plant, Sweden. Replacements undertaken with this method at TVO in Finland and Forsmark in Sweden took just 18 days. **12**

Many of the older generators in service require only an overhaul. For such machines, ABB can perform analyses that include a calculation of the likely costs over the lifetime of the machine and proposed overhaul scenarios.

Due to their compact design, water-cooled generators with much higher power ratings than the original machines can be installed on the existing foundations. A new water-cooled rotor, a new stator winding or replacement of the complete generator will often result in a 10 to 20 percent increase in power.

If the downtime has to be kept short, a replacement of the complete generator is to be recommended. The combination of fast on-site installation, an increased power output and higher availability translates into quick payback, especially in the case of base-load plants.

Fast replacement of turbogenerators

In 1991, Swedish and Finnish operators of nuclear plants contracted ABB Generation to develop a method for replacing turbogenerators which was faster than the one in use at that time [1]. Both countries saw a need to be able to replace generators during the scheduled annual outage for routine refuelling and inspection of the installation, which normally took less than three weeks.

The method that was devised is based on a mobile lifting gantry fitted with special hoisting gear **12**.

The gantry can be adapted to the actual physical conditions in the plant and is suitable for most nuclear power stations. Suspending the generator from a single point provides high flexibility during lowering, whatever the design of the building.

Using this method, a generator can be installed in a much shorter time and at a significantly lower cost than with other methods. Only 18 days are needed to replace a complete machine. This time represents the total outage time, ie the time during which no electricity is produced, and includes the shut-down and start-up of the turbine as well as the commissioning tests.

The replacement of the rotor alone takes 5 days. This was the time needed, for example, in the Forsmark nuclear power station in Sweden.

ABB Generation has a product support team for such replacement work. Based in Västeras, Sweden, it consists of experienced engineers and assembly foremen, who supervise the work in the stations. Skilled workers are also recruited locally.

Reference

[1] T. Torsteinsrud: Faster replacement of generator stators in nuclear power plants. ABB Review 2/94, 8–12.

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