Powerformer™ – a radically new rotating machine

ABB has developed a radically new electrical machine with innovative features that include stator slots in which windings, based on conventional HV power cables, lie in circular bores. Benefits of the new machine, such as higher efficiency (0.5–1.5 %), better availability, lower maintenance costs, and reduced environmental impact, add up to a considerable improvement in life cycle profit. A high-voltage generator based on this new concept can be connected directly to the transmission grid, ie without a step-up transformer or generator circuit-breaker. Since it incorporates the functionality of both the generator and the transformer, the new machine has been named Powerformer™. The world's first hydropower generator to feature the new concept has already been factory-tested and will be commissioned at the Porjus Hydropower Center, Sweden, during the spring of 1998.

The concept that led to the change in design was first considered in earnest in 1991. The issue was how to construct a generator that could work in the high-voltage range whilst guaranteeing uniform loading of its component materials. A preliminary look at generator design began with the simple question, 'Does it have to be the way it is now?' The answer evolved into a radically new and innovative design with major consequences for hydro-electric and thermal power plants as well as other electrical equipment.

Solid insulation, an innovative stator design with slots having cylindrical openings, and a unique winding arrangement are at the heart of this new concept [1, 2]. High-voltage cables are threaded through the slots. This design feature avoids the usual difficulty involved in making assumptions about the magnetic flux – no compromises need to be made. The cylindrical shapes used in the design allow Maxwell's equations to be applied in a straightforward way without approximations.

A new energy system

One of the goals of the development programme was to design a high-voltage rotating electric machine that could be connected directly to the grid, ie without a step-up transformer or generator circuit-breaker **1**. During the last century a number of attempts were made at developing such a machine [3]. However, although grid voltages can reach 800 kV or more, generators are presently constructed only for voltages of up to 30 kV. Powerformer has been designed with several unique features that allow it to exceed the 30-kV limit, including a winding consisting of power cables with solid insulation, on both sides of which there is a semiconducting layer[1)] **2**. The outer

Dr. Mats Leijon
ABB Corporate Research, Sweden

Background

The magnetic circuits in a generator normally consist of the laminated, sheet-steel core and its welded frame. Cooling and ventilation are provided by dividing the core into packets, with radial or axial ducts between them.

The steel laminations for the larger units are stamped out into segments and stacked inside the machine's frame. Wedges and press rings hold the laminated core in place. The circuit windings are laid in slots, usually rectangular in cross-section, around the core.

Multi-phase generators have either single- or double-layer windings. Normally, all large machines are fitted with double-layer windings and the coils all have the same size. Since every coil has one side in each layer, the coils cross each other in the coil-end region. This makes winding a complex job that has to be carried out by skilled workers.

Stators for rotating machines are normally manufactured for the voltage range of 3-30 kV. When connecting a synchronous machine to a power grid a step-up transformer has to be used because the grid voltage is considerably higher than the voltage rating of the electric machines. It is due to this that the generator and transformer are often installed in power stations as integrated systems.

Besides being a major cost item, the transformer also lowers the overall plant efficiency. Generators capable of much higher voltages which can be connected directly to the grid are obviously of immense interest to power utilities.

1) The word 'semiconductor' as used in this article describes a material with relatively high resistivity, in this case XLPE doped with carbon. Such a 'semiconductor' is therefore, more accurately, a resistive conductor.

semiconducting layer is connected to earth potential. Modern power cables, such as XLPE cables, have conductors that satisfy this requirement.

According to Maxwell, a circular conductor geometry provides the most evenly distributed electrical field. This means that a cable with circular cross-section should be chosen in order to minimize the electrical stresses in the insulation. Another advantage of such cables is that the laminated core can be designed with an optimum tooth and slot arrangement.

Since the potential along a winding increases with each turn, the demands made on the cable insulation increase accordingly. It is therefore possible to use thin insulation for the first turns and then increasingly thicker insulation for the subsequent turns – an arrangment called 'stepped insulation'. This enables the utilization of the volume of the laminated core to be optimized.

The cross-section of the winding cable is taken into account by the stator slot design. These slots consist of radially arranged cylindrical bores running axially through the stator and joined by narrow sub-slots **3**.

The cable conductor consists of uninsulated and insulated strands in order to reduce eddy-current losses.

The described features of Powerformer have several advantages:

- Stepped insulation ensures a practically constant tooth width, irrespective of the radial spread.
- The entire outer sheath of the cable can be connected to earth potential.
- The electric field outside the outer semiconducting layer is close to zero in the coil-end region. Since the outer sheath is at earth potential there is no need to control the electric field (in conventional technology the field has to be controlled at several locations per turn). This eliminates field concentrations in the core, in the coil-end regions, and in the transition between them.
- The winding is produced simply by threading the power cable through the cylindrical slots in the stator core **4**.

Important benefits for users

A rotating electrical machine based on this new concept offers users many advantages over machines making use conventional technology:

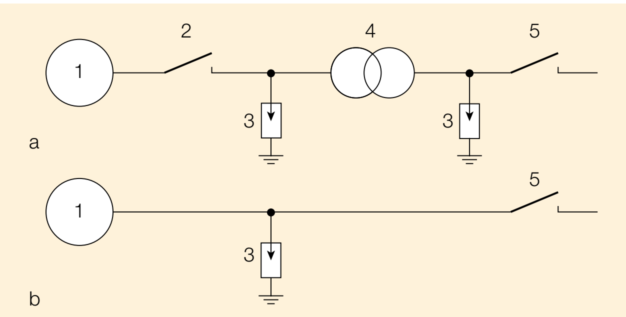
- The machine can be connected directly to power networks operated at all high voltages for which there are cables currently available.
- The surface of the winding is connected to earth potential.
- Oil-based transformers and the long busbars between the high-voltage circuit-breakers are dispensed with.
- Less space is required and foundations can be designed for smaller loads.
- Environmental impact is reduced due to increased efficiency achieved with systems using Powerformer.
- Maintenance is reduced and reliability is enhanced.

Direct connection to the grid

The innovations embodied in the Powerformer, especially the solid insulation, enable the winding to be arranged in a way that makes direct connection to the grid possible. Thus, no step-up transformer is required, not even for networks operating at 20 kV and above.

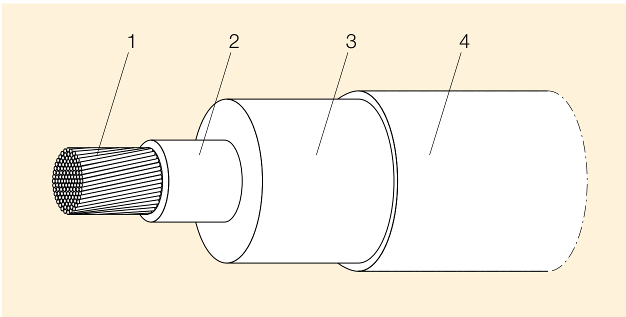
Schematic diagram of a conventional plant with step-up transformer (a), and the same plant when the new technology is used (b) **1**

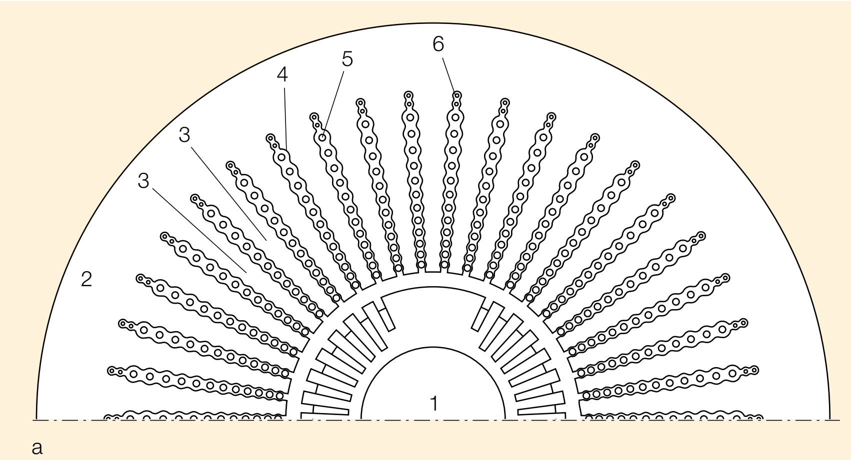
1 *Generator*
2 *Generator circuit-breaker*
3 *Surge arrester*
4 *Step-up transformer*
5 *Line circuit-breaker*

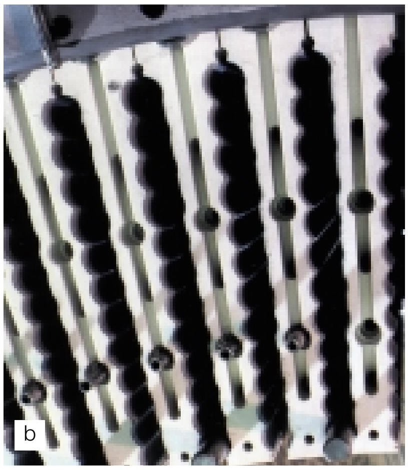


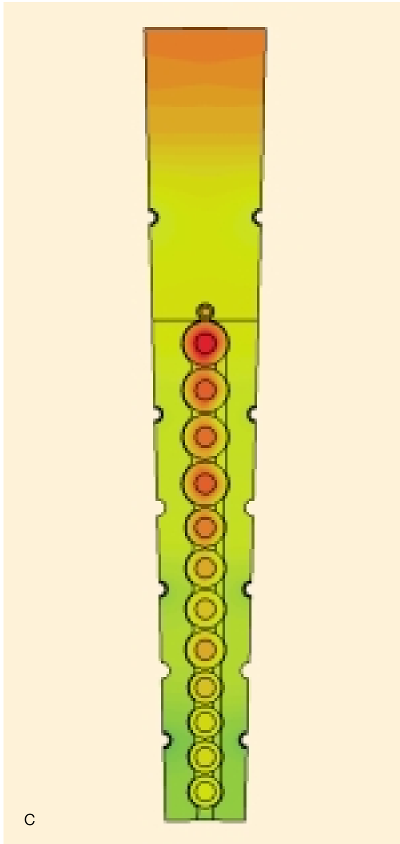
Power cable used in the stator winding of Powerformer **2**

1 *Cable strands*
2 *Semiconducting layer*
3 *Solid insulation*
4 *Semiconducting layer*









Section of the stator in Powerformer (a), a detail of the stator without cable (photo, b), and the calculated temperature distribution around a stator slot (c) **3**

1 *Rotor*
2 *Section of stator*
3 *Teeth*
4 *Slots*
5 *Main winding cable*
6 *Cable for standby power*

The new technology makes a non-issue out of the space taken up by the step-up transformer, eg in a hydro-electric power plant which is often in a cavern cut out of rock. Also, safety is greatly improved – no oil-insulated transformer means no fire hazard.

In plants where the transformer is located above ground, the new technology reduces busbar lengths and simplifies their handling. Since currents of the order of 10-20 kA often flow in these busbars, power losses are also reduced by the simpler, more straightforward connection.

Several major benefits arise from the direct connection to the grid:

- Losses in the windings are lower due to the higher voltage.
- The risk of two- or three-phase faults is much lower with high-voltage cables.
- Fewer electrical components are needed, allowing a reduction in the necessary protective measures.
- There are more opportunities for connection to different voltage levels. For example, the plant auxiliary power supply can be integrated in Powerformer.

Together, these features can radically improve the overall economy of a power station. The higher efficiency alone means that operating costs are lowered by up to 1.5 %. Less maintenance is also expected, and the higher reliability resulting from the fewer components also reduces the operating costs.

New cable is based on standard power cables

The magnetic circuit of the new machine makes certain demands on the winding. The winding consists of a cable with solid insulation and at least two semiconducting layers, one at the conductor and the other outside the insulation **2**. Standard, commercially available power cables have these characteristics.

The inner conductor of the standard power cable is made up of uninsulated strands, around which there is a layer of semiconducting material. Outside this layer is a layer of solid insulation, surrounded by another semiconducting layer. The outermost layer consists of a metallic screen and a sheath.

ABB has further developed this type of cable to produce a new design with a conductor embodying both uninsulated and insulated strands.

Porjus stator under construction. Here, the cable is being threaded through the bores. **4**

Around this conductor there is a semiconducting sheath surrounded by a layer of solid insulation. This is surrounded by a semiconducting layer, as in the standard cable. Here the similarities end; the new cable has neither a metallic screen nor a sheath.

New stator

The design of the slots and teeth in the magnetic circuit plays a decisive role in the optimization of a rotating electrical machine.

The slots should enclose the casing of the coil as closely as possible. At the same time, the teeth should be as broad as possible at each radial level. This reduces the losses in the machine and also the need for excitation.

The stator **3a** consists of a laminated core, built up from electrical sheet. Teeth in the outer section point inwards towards the rotor (at the center). The winding is located in the slots formed by the teeth. The cross-section of the slots decreases towards the rotor since, as already mentioned, each winding turn requires less cable insulation the closer it is to the rotor. Each slot has circular bores at intervals, forming narrow waists between the winding layers. The resulting shape is not unlike that of a bicycle chain **3b**.

The large number of winding layers raises the question of cable dimensions. In the example shown, cables of three different sizes are used. The stator teeth can also be designed such that the radial width of the slot is largely constant over its entire length. This evens out the loading on the stator tooth.

The winding can be described as a multi-layer concentric winding, which means that the number of coil ends crossing each other is minimized. This feature allows simpler and faster threading of the stator winding.

Power plant with Powerformer under construction

The first generator POWERFORMER based on the new technology has already been successfully tested in the factory **5b**. Rated at 11 MVA, 45 kV and 600 rev/min, the generator is due to be commissioned in the spring of 1998 at the Porjus Hydropower Center in northern Sweden.

Key advantages of the new design

With the new system, different aspects of the construction, such as the thermal and electrical design, may be treated independently, giving designers far more freedom in optimizing the machine. This independent treatment is made possible on the one hand by the circular conductors, which result in a smooth field distribution thus minimizing the stressing of the insulation material, and on the other hand by the semiconducting layers on each side of the solid insulation which confine the electric field to the winding. By ensuring that the thermal expansion coefficients of the insulation and the semiconducting layers are almost identical, the risk of damage or fracture due to thermal expansion of the windings can be eliminated.

Further technical innovations

The winding cables are flexible and easy to bend, which simplifies handling and assembly. It should also be pointed out that the new stator can be designed for both horizontal- and vertical-shaft generators. The decisive difference between the new design and present-day technology is that this new design allows direct connection of the generator to networks rated, at present, from 20 to 400 kV. Connection to grids at higher voltages will be possible as soon as the higher-rated cable becomes available.

Joints for the grid connection

A standard feature of the new design is that the cable is threaded through slots, either at the factory or on site. The voltage level of the winding segment determines the type of joint used to connect the different cable sections and also to connect the generator to the grid. Prefabricated, vulcanized and taped joints can all be used.

Advantages for power plant construction

Generators used in hydropower plants are multi-pole, low-speed machines driven by water turbines. The same conventionally designed turbines are used with new Powerformer generators **5a**.

The stator winding is formed by the newly developed cable. This cable, which is unscreened, is jointed to the screened power cable by means of, eg, a fabricated joint. A hydropower generator like the one shown can generate extremely high voltages.

Thermal power plants, eg fossil-fired, district heating and nuclear power stations, use fuels as varied as natural gas, oil and coal, biofuel and fissionable materials. These fuels produce high-temperature gas, eg through combustion, or indirectly heated steam. The thermal energy contained in the steam or gas has to be converted into kinetic energy either by a gas- or a steam-driven turbine.

One or more generators, mounted directly on the shaft or driven via gearing, converts the kinetic energy into electric energy at a voltage of usually between 10–20 kV. A step-up transformer is therefore required for connection to the grid.

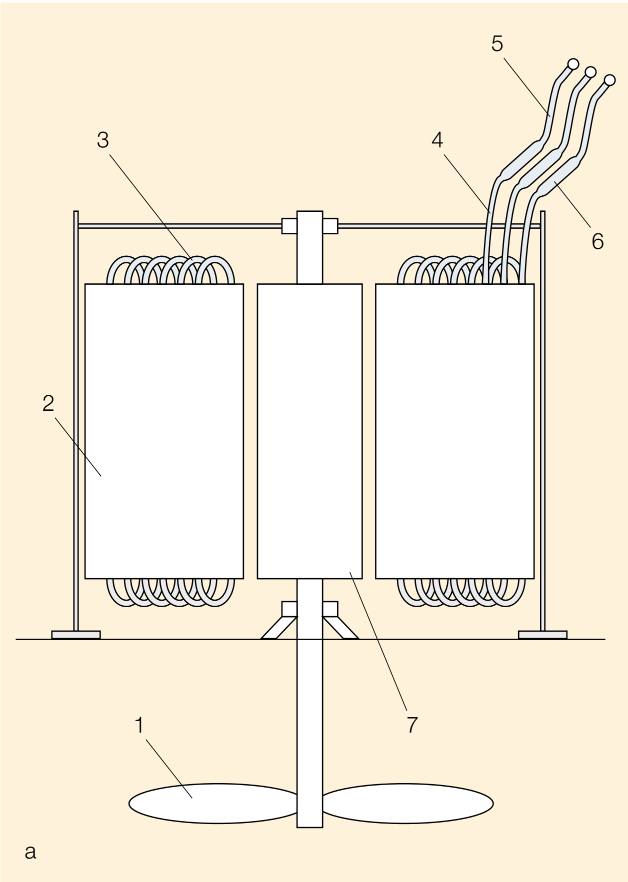
With the new technology, the step-up transformer is replaced functionally by a high-voltage circuit breaker and the busbars by screened high-voltage cable.

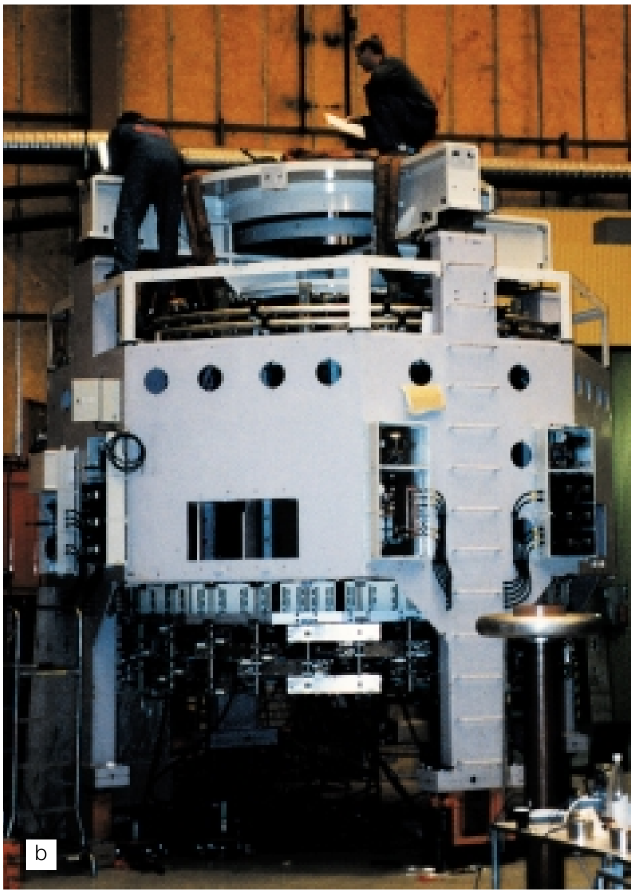
6 shows the basic circuit for a turbo Powerformer, in this case driven by a gas turbine.

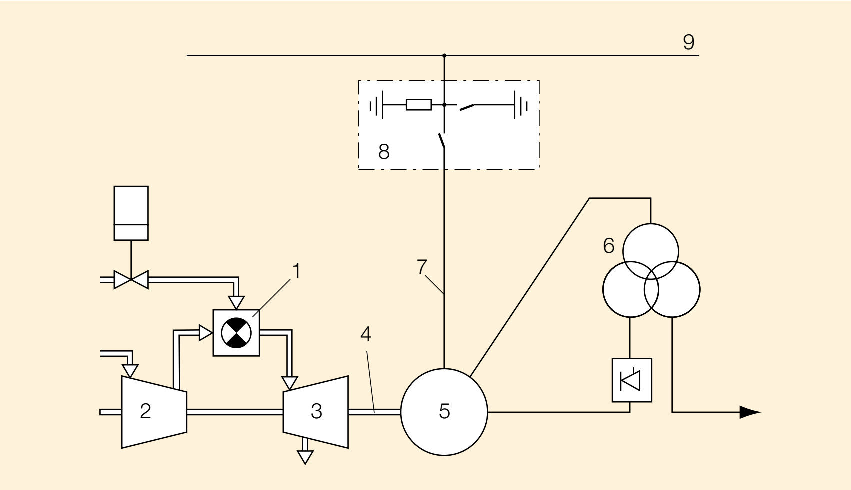
The various advantages of the new design concept are presented in a dramatic way by **7**, which shows a conventional hydropower plant with the transformer bay situated at a distance from the generator bay, which is cut out of solid rock.

Schematic diagram of a hydro-electric generator (a) and view of the complete stator in Porjus (photo, b) **5**

1 *Water turbine*
2 *Stator*
3 *Stator windings*
4 *Unscreened cable*
5 *Screened power cable*
6 *Prefabricated joint*
7 *Rotor*







Schematic diagram of a turbo Powerformer system **6**

1 *Combustion chamber*
2 *Compressor*
3 *Gas turbine*
4 *Common shaft*
5 *Generator*
6 *Transformer for excitation supply and auxiliary power*
7 *Screened power cable*
8 *Circuit-breaker*
9 *Transmission grid*

The generator is connected to the transformer by a busbar system that runs in a tunnel several hundred meters long.

A hydropower plant based on the new technology does not need any of the equipment or civil works to the right of plane A – A **7**, while the floor space in the generator bay, etc, remains unchanged.

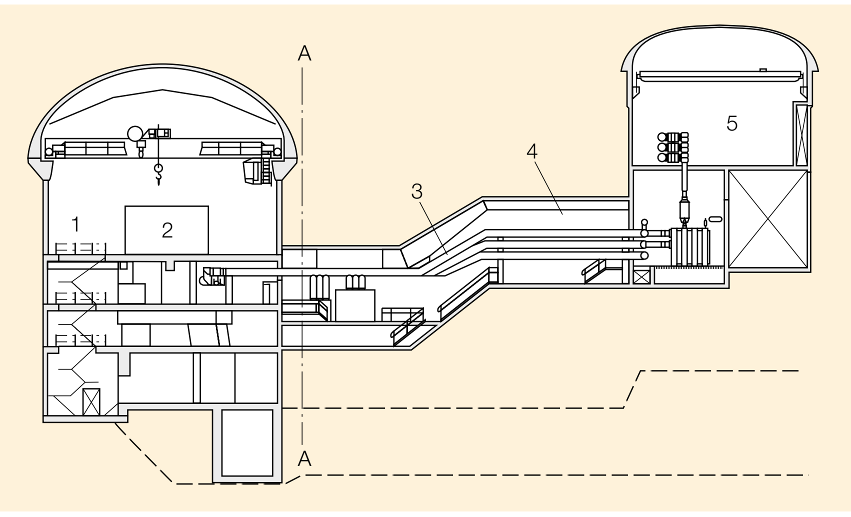
Even in a hydropower plant with a conventional generator and the step-up transformer and its auxiliary systems located in the generator bay instead of, as here, in a separate hall, the generator bay is still considerably smaller with the new technology.

Eliminating the step-up transformer and circuit-breaker further reduces installation and maintenance costs, thereby improving availability and reliability.

The advantages of the new technology point to a significance that goes well beyond the usual 'progress through development'. The Powerformer, by revolutionizing a century-old power generation convention, represents a quantum leap in electrical engineering and has far-reaching consequences for the power engineering industry.

Section through a conventional hydro-electric power station. With the new technology, everything to the right of plane A-A can be eliminated. **7**

1 *Generator hall*
2 *Generator*
3 *Busbar system*
4 *Tunnel system*
5 *Transformer bay*



References

[1] M. Leijon: Rotating electrical machines with magnetic circuit for high voltages and method for manufacturing same. Patent no. WO 97/45919.

[2] M. Leijon: Transformer and reactor. Patent no. WO 97/45847.

[3] M. Leijon, et al.: Breaking conventions in electric power plants. CIGRE 1998, paper 11/37.

Author's address

Dr. Mats Leijon
ABB Corporate Research
S-721 78 Västerås
Sweden
Telefax: +46 21 137 665
E-mail:
mats.leijon@secrc.mail.abb.com