New air-cooled turbogenerator in the 300-MVA class

Systematic improvement of the design and cooling principles of air-cooled turbogenerators has produced unit ratings that until just a few years ago were only possible with hydrogen-cooled machines. Proven features such as axial ventilation of the rotor and indirect cooling of the stator winding have been retained in the new units. The efficiency figures are excellent: for the described 300-MVA turbogenerator in the 50-Hz version just 0.1 to 0.2 percentage points below the value for a hydrogen-cooled unit, and for 60 Hz – due to the higher windage losses – 0.2 to 0.4 percentage points lower. A slight increase in losses with air cooling is compensated for in most cases by lower investment and maintenance costs, so that economic advantages can generally be expected when air-cooled generators are used.

Ever since the first turbogenerators appeared almost a century ago, their history has been marked by a steady rise in unit rating. At about the half-way stage, turbogenerator designers turned from air to hydrogen and even water for direct conductor cooling, since these media proved to be more efficient coolants. Development of the air-cooled generator has continued nevertheless, being stimulated from time to time by the rise in unit ratings of the gas turbine – the most common prime mover for this type of generator.

Although it is the simplest coolant there is and also the easiest one to handle, air has a relatively modest cooling capability: the thermal conductivity of hydrogen, for example, is seven times better than that of air, while for the same absolute pressure the density of hydrogen is only one tenth that of air when the volume-specific heat capacity is the same. On the other hand, hydrogen-cooled generators have a more complex design, since, unlike air-cooled generators, they require a pressure-resistant casing, a special sealing system and additional gas conditioning plant. This is where air-cooling offers its first advantage – lower first-time costs, despite the air-cooled unit being larger for the same installed rating. What is more, the maintenance of an air-cooled machine is easier, and thus more economical than for the H_2-cooled machines. This is due in part to the special training that is required to service the hydrogen-cooled generators. Another advantage of the air-cooled units is that because overhauls require less time, their availability is increased. In contrast, complicated procedures are needed to purge the hydrogen-cooled machines with carbon dioxide before opening, and afterwards when refilling with hydrogen. Taken over a unit's total service lifetime – and despite the lower efficiency – these benefits add up in most cases to better economy for the air-cooled turbogenerator.

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1 shows how the unit ratings of the air-cooled ABB turbogenerators have evolved over the last four decades. It can be seen that air-cooled generators rated at 90 MVA were already in operation at the beginning of the 1970s, also that a 188-MVA machine was commissioned in 1984 [1, 2], followed by a unit rated at 225 MVA in 1993.

Development of air-cooled turbogenerators at ABB Power Generation has been ongoing, the newest generator type surpassing even the 300 MVA mark. This goal was made possible by a recently concluded development project known as TOPAIR.

An increase in the maximum unit rating with air-cooling to more than 300 MVA could not be achieved simply by increasing the generator's overall dimensions. Further development of several key parts was also necessary, while the proven ABB cooling system had to be extended into new areas. In addition, tests and computer-aided investigations were carried out to optimize the cooling circuit. As a result of all this work, the field-tested axial rotor cooling and indirect cooling of the stator winding could be retained. Running tests with the 300-MVA prototype machine have since been successfully concluded.

The approach to higher-rated air-cooled generators

The apparent power S of an electrical machine can be expressed by:

$$S = k\,D^2\,L\,B\,A\,n$$

where

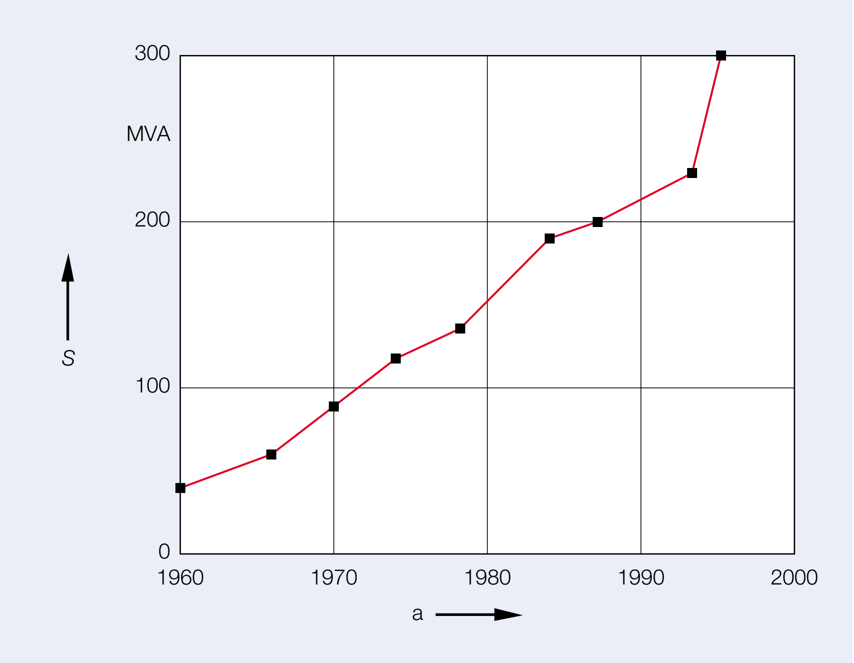
- k Constant
- D Rotor diameter
- L Active length
- B Air-gap induction
- A Linear current density
- n Rotational speed

An increase in the air-gap induction is hardly possible because of the existing limits to magnetic utilization. Similarly, a significant increase in the linear current density is not possible due to the limits imposed by air-cooling. Altering the dimensions, on the other hand, enables a notable increase in output to be achieved. For example, increasing both the rotor diameter and the active length by 10 percent, whereby the slenderness factor is retained, raises the output by approximately 33 percent providing the volume-specific utilization remains unchanged. Using the previous maximum rating of 225 MVA as reference, this alone would allow an increase to about 300 MVA.

Increasing the main dimensions linearly also enlarges the slot volume, enabling more winding copper to be accommodated. However, a corresponding rise in linear current density is limited by the temperature rise. Also, an increase in the overall dimensions beyond those of today's highest-rated machines leads to higher voltages and consequently thicker stator winding insulation, which has an adverse effect on the indirect cooling of the winding bars.

A larger rotor diameter greatly increases the windage loss. For instance, the surface friction loss, which represents a significant portion of the windage and therefore the total losses, rises as the fourth power of the rotor diameter and linearly with an increasing active length. Thus, to achieve the maximum possible unit rating further measures had to be taken to reduce the losses and improve the cooling.

An increase in the rotor diameter also greatly increases the mechanical stresses: stronger centrifugal forces in the rotor cause an increase in the mechanical forces in the teeth, winding and end-bells, while in the stator the magnetic forces that act on the laminated core and winding overhangs become stronger. The combination of measures taken to overcome these problems created the springboard for the jump in unit ratings that ABB had targeted for the air-cooled turbogenerators.



Evolution of the unit ratings of air-cooled ABB turbogenerators **1**

S *Power output*
a *Year commissioned*

Some design problems and their solutions

To explain the problems that arise when designing for an increasing unit rating and higher level of utilization, it is necessary to look closely at the additional electrical losses, the interaction of the mechanical forces, the thermal efficiency of the ventilation and the windage losses.

Additional electrical losses

Stator pressplates

A drawback of high electrical utilization is that it is the cause of considerable stray losses, particularly in the stator end regions. For its lower-rated turbogenerators – air-cooled as well as indirect hydrogen-cooled – ABB has used solid aluminium pressplates for a long time, laminated pressplates being used for the higher-rated units with water-cooled stator windings. **2** shows the magnetic field in the end region of a generator with an aluminium pressplate. The good screening provided by the highly conductive aluminium can be clearly seen. Extensive calculations have shown that this is also the optimum solution for an air-cooled machine in the power class discussed here. The temperatures measured on the pressplate during running tests with a sustained short circuit and a current equivalent to Class F thermal utilization (corresponding to 340 MVA) were less than 30 K higher than the temperature of the cooling air flowing over it. Since a temperature rise of the same order may be expected during full-load operation, the pressplate does not represent a real limiting factor for generator operation in the underexcited range.

Pressure fingers and stator end region

The magnetic field in the region of the pressure fingers at the front of the stator teeth cannot be screened as for the pressplate **2**. Due to this, a non-ferromagnetic material (high-grade 18/8 steel) exhibiting a high specific electrical resistance is used. This reduces local losses, and thus the temperature rise, to a minimum. Running tests with a sustained three-phase short circuit and a current equivalent to Class F thermal utilization showed the temperature rise on the pressure fingers to be less than 25 K.

In addition, the core end zones were studied in depth to determine the optimum stepping and whether it was necessary to slot the teeth. High eddy-current losses can arise in the end zones of the teeth due to the axial component of the magnetic field. The results of comprehensive field calculations showed from which tooth width slotting is necessary to keep local temperature rises low.

Stator winding

The stator winding is a two-layer Roebel bar design. When indirect air-cooling is used, relatively high bars are required. Besides optimizing the number and thickness of the strands, it was necessary to determine precisely what kind of special transpositioning would be necessary. Investigations were therefore carried out with several different kinds of transpositioning to find a viable solution that combines economic production with lower losses [3].

Mechanical forces and noise

Stator winding overhang

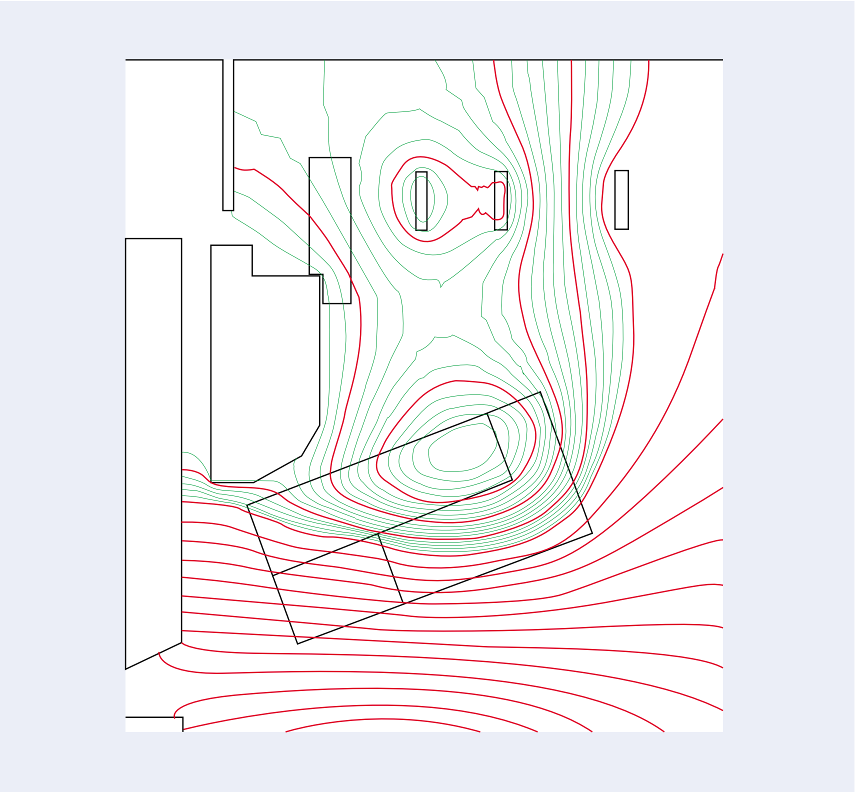
Increasing the diameter while retaining the same design for the winding overhangs reduces the natural frequency of the four-node vibration mode, which could move very close to the exciting double system frequency. On the other hand, the electrodynamic forces rise considerably under fault conditions (eg, sudden short circuits). Thus, what was needed was a stiffer stator winding overhang support system which can also be retightened later **3**. The solution is well-proven, having been used successfully for many years on large turbogenerators with water-cooled stator windings. Retensioning elements incorporating a double-bevel wedge are located between the angular supports around the circumference and the end windings. The angular supports themselves are fixed by two outer rings. Retensioning causes the entire winding structure to be pressed inwards against an inner ring, thereby bracing the whole system. Spacers are located between the bars. Sets of springs, arranged between the stator core and winding overhang, prevent an axial shift.

It was necessary at every stage to find a compromise that would ensure the required mechanical strength and satisfy the cooling requirements. If the outer rings had been too big they would have hindered the cooling air passing through the overhang; if they had been too small they would not have given the mechanical support that was necessary.

During the design of the winding overhang support extensive calculations were carried out to determine the mechanical stresses occurring under fault conditions. Further, it was necessary to forecast as accurately as possible the natural frequency of the four-node vibration in the winding overhangs. **4** shows one of the calculated mode shapes. The detailed design work could be defined on the basis of these results.

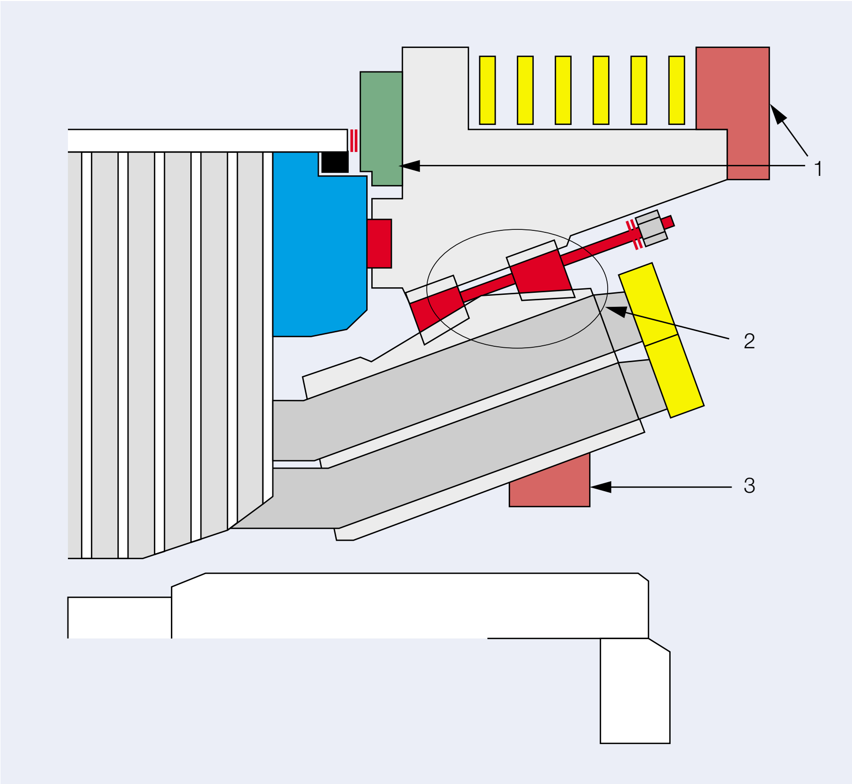
Experimental modal analysis was used to determine the natural frequencies and mode shapes. The location of the resonances and their related frequencies was

Magnetic field in the stator end region. The screening effect of the highly conductive aluminium pressplate can be clearly seen. **2**



Stator winding overhang support, allowing retensioning of the end windings **3**

1 *Outer rings*
2 *Retensioning device*
3 *Inner ring*



verified during run-up and coast-down of the generator in the test bay, in each case in the open-circuited excited state and with a sustained electrical short circuit. As had been intended, the natural frequencies proved to be sufficiently far away from the double system frequency. The final inspection of the generator, performed after the sudden short-circuit tests had been concluded, showed that this had had no adverse effects on the winding overhang bracing system or any other load-bearing components.

Stator core suspension

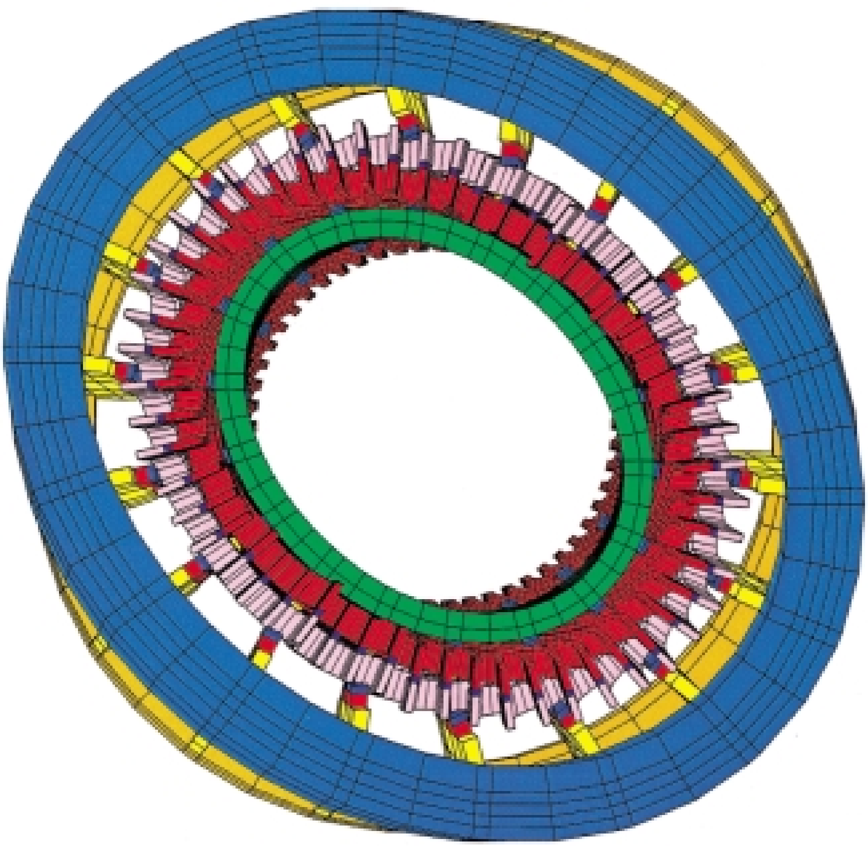
If the core yoke diameter is made larger, the natural frequency of the four-node vibration will decrease even when the yoke height increases linearly. As a result, the stronger core vibration would emit a higher level of structure-borne noise via the stator housing.

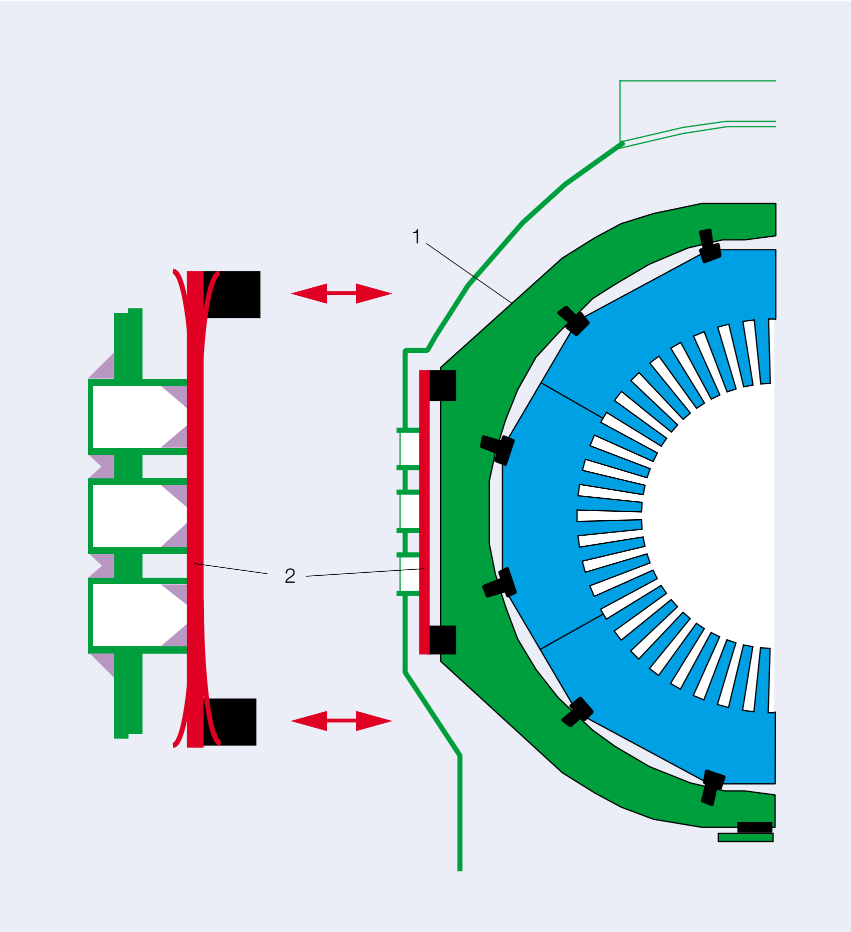
A special suspension system is used to decouple the core mechanically from the housing. **5** shows the solution employed for this type of generator. The rings welded to the core's periphery have a fastening plate on each side which acts as a leaf spring. After the core has been lowered into the bottom half of the housing the leaf springs are connected to it by means of short lengths of tube, the ends of which are welded in place one after the other. The welding can be performed from outside the structure, thus minimizing the risk of contamination during assembly. The housing is very rigid despite being a split structure.

Noise reduction

The elastic core suspension is remarkable for the way it reduces the structure-

Computed mode shape of the four-node vibration in the stator winding overhang **4**



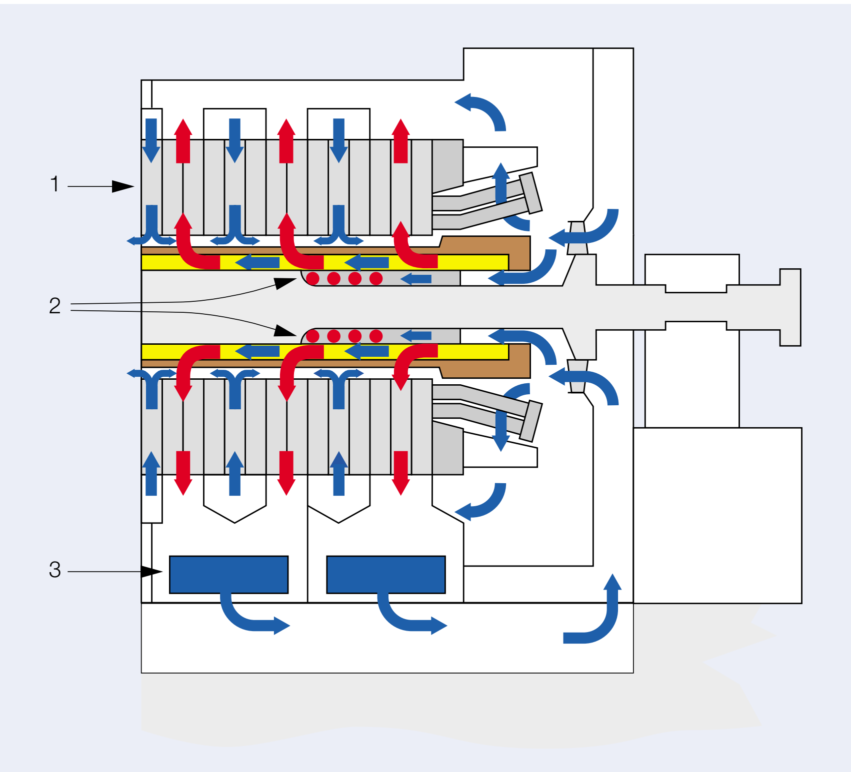


Elastic suspension of the stator core in its housing. On each side of the rings (1) welded to the core is a fastening plate (2) which acts as a leaf spring. **5**

borne noise. For instance, a 50 percent reduction in vibration amplitude results in a noise reduction of 6 dB.

The greater part of the machine noise is air-borne [4], the dominant sources being the fans and the self-ventilating rotor. Due to the larger diameters, the new generator type would produce very pronounced aerodynamic noise if no counter-measures were taken. Special soundproofing was therefore provided in the stator housing end regions to absorb the air-borne noise and reduce emissions to the surroundings. Small openings and gaps have to be avoided as they allow noise to pass unhindered to the environment. Measures were therefore also taken to ensure that the housing enclosure is as soundproof as possible.

The effectiveness of all these measures was verified during running tests with the prototype. The noise level, measured at rated speed and rated voltage in accordance with DIN 45635, was 94 dB(A). This value corresponded almost exactly to the value obtained during mechanical running only. It can be considered as ultimate verification that the core vibration is almost entirely isolated from the housing.



Cooling air distribution in the new turbogenerator **6**

1 *Ventilation chambers in stator*
2 *Sub-slots in rotor*
3 *Coolers*

Blue arrows *Cold air*
Red arrows *Heated air*

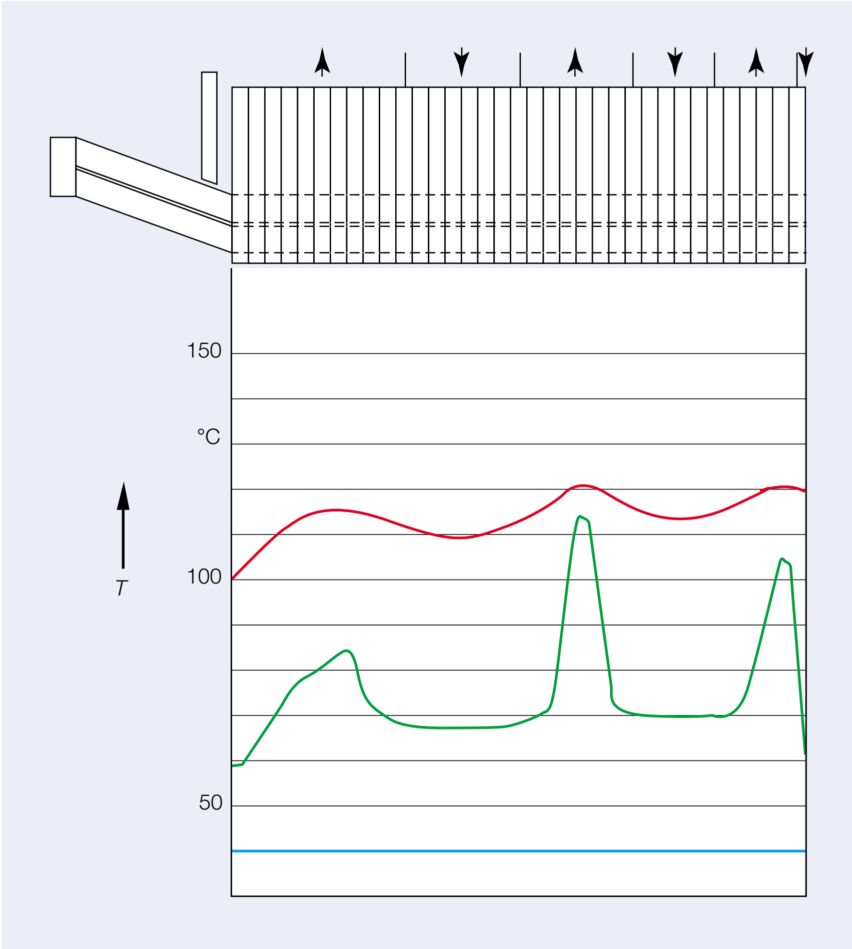
Ventilation and cooling

The new-generation machines are largely the outcome of further development of the proven cooling system and a programme of systematic optimization. This work was preceded by in-depth investigations, both theoretical and experimental, in the fluid flow laboratory. One of the development goals was to reduce the windage losses [5], another being to achieve a favourable flow configuration for the cooling circuit and improved ventilation of the loss-producing generator **6** shows a schematic of the air flow that was chosen for the new machine.

Cooling system and temperature rise

The conductors used for the rotor field winding are hollow and cooled axially. After leaving the fans, the cooling air passes under the end bells, part of the flow entering the overhang region and, after passing through the hollow end-winding conductors, exiting the rotor through slits at the beginning of the body. Unlike the active part of the earlier air-cooled generators, the field winding of the new generator type has two cooling sections per machine half. In the first section the cooling air flows under the end bell directly into the hollow conductors and exits the rotor after a certain flow length. The second section is supplied with cold air via a sub-slot located under the winding, this flow of air leaving the rotor mid-way down the machine. The distances have been optimized for a balanced temperature distribution in the winding. The concept has already been used successfully for a hydrogen-cooled turbogenerator of high rating.

The stator core is divided into packets separated by spacers that create radial cooling ducts for the ventilation and cooling. The cooling air flows alternately radially inwards and outwards from and to the ventilation chambers. The cooling system has been optimized to provide more ventilation chambers than in the earlier, shorter machines. This optimization and the fact that there are many exits for the rotor cooling air ensures a uniform temperature distribution in the stator winding and core **7**. The temperatures measured during the running tests have confirmed the calculated data.



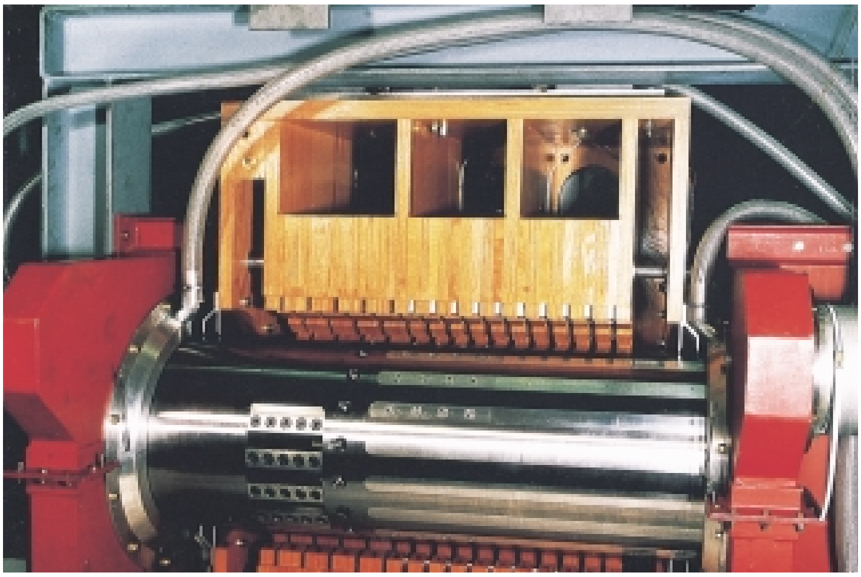
Computed temperature distribution in the stator **7**

Blue *Cold air*
Green *Cooling air in air-gap*
Red *Stator winding*

Special tests in the fluid flow laboratory

A characteristic of air-cooled turbogenerators is that the windage losses represent a not insignificant proportion of the total losses. This made it necessary in the case of the generator under discussion to take certain measures to reduce the volumetric air flow to the required minimum and ensure that the main pressure drops are concentrated in those sections that have to be cooled. Aerodynamic design of the air paths allowed a further reduction in the windage losses.

Increasingly, the cooling circuits in electrical machines are being designed with the help of equivalent flow networks. Using the results of the flow calculations, the design engineer can determine the expected temperature of the parts where the losses originate. However, these



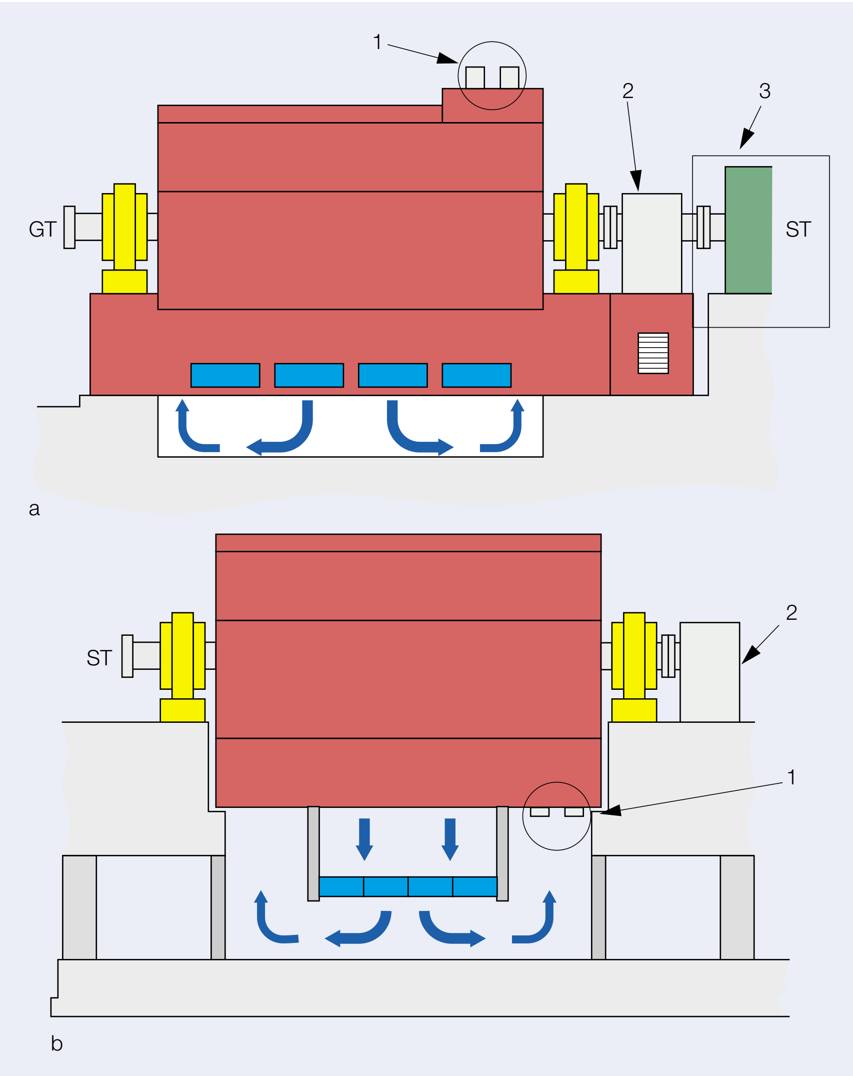
Rotor/stator model for flow tests **8**

results are only as accurate as the parameters of the numerical model. When the ventilation system has multiple stator chambers and rotor exit zones, it is extremely difficult to define the machine's air-gap for the flow model because Mach numbers of up to 0.7 are involved. To obtain a more precise basis for the calculation a rotor/stator model **8** was constructed in the factory and experimental investigations were carried out in the laboratory. The model was designed such that the Reynolds and Mach similarity in the air-gap (annulus) could be maintained, albeit for another radius of curvature. The rotor had a diameter of 400 mm and was rotated at up to 10,500 rev/min.

The model enables all the flow situations arising in the air-gap to be simulated. For example, it is possible to reproduce the exit where the cooling air leaves the rotor end-windings at the ends of the rotor body, likewise the air-flow exits in the active portion of the rotor. During the tests, the sub-flows were also determined experimentally for the individual paths. Using the measured pressure drops as basis, it was possible to specify the flow resistance coefficient functions for flow network modelling.

Other special design features

Several other special design features were included in the development project, either specifically for the new generator type or as part of the general development programme. For example, due



Different arrangements for the generator **9**

GT *Gas turbine*
ST *Steam turbine*

1 *Terminals*
2 *Slipring assembly*
3 *Coupling for double-ended drive in combined cycle mode (option)*

to the high centrifugal forces, and unlike air-cooled designs hitherto, the rotor conductors have twin cooling holes – a technique which has proved highly successful in the large hydrogen-cooled rotors. Another example is the new slot wedging system for the stator: a special type of double bevel wedge ensures the required pretensioning of the conductor assembly in the slot. Since the wedge can be retightened, maintenance is faster and longer intervals between overhauls are possible.

Table 1:
Technical specifications of the new air-cooled turbogenerators

Series	WX23Z/WY23Z
Output	200–310 MVA/Class B 200–350 MVA/Class F 50 Hz, $\cos\varphi$ = 0.8 200–280 MVA/Class B 200–340 MVA/Class F 60 Hz, $\cos\varphi$ = 0.85
Voltage	15.75–21 kV, depending on power and frequency
Rotational speed	3,000 rev/min at 50 Hz 3,600 rev/min at 60 Hz
Excitation	Static
Standards	IEC (normal design, 50 Hz) ANSI (normal design, 60 Hz)

Power data valid for a cooling-air inlet temperature of 40°C

The new turbogenerator series

The new-generation WX/WY23 air-cooled turbogenerators (*Table 1*) for ratings from 200 to 350 MVA complement the successful Type 21 series. They are designed for use with the new GT24 and GT26 gas turbines as well as with steam turbines as prime movers. The new turbogenerators, for which orders have already been received, can be installed in either of the two configurations (a and b) shown in **9**.

Successful prototype test runs

A first generator from the new series was set up in the test bay in the summer of 1995 and put through exhaustive development and type tests **10**. These tests concentrated mainly on the following:

- Measurement of the open-circuit and short-circuit characteristics
- Determination of the temperature rise in the windings and of the losses
- Determination of reactances and time constants (including those for the quadrature axis) and verification of the short-circuit strength, each by means of sudden short circuits starting from no-load and preload conditions
- Determination of negative-sequence reactance and resistance by means of a sustained two-phase short circuit
- Standstill tests in order to determine the subtransient reactances in the direct and quadrature axes
- Additional temperature measurements on the pressplate and press fingers, on clamps and end connections of the stator winding as well as measurements of the cooling-air temperature at different locations in the generator
- Pressure measurements to verify the distribution of the cooling air
- Measurement of the mechanical vibration in the shaft and bearing pedestals, stator core and housing, and the winding overhangs
- Noise measurements to determine the sound level

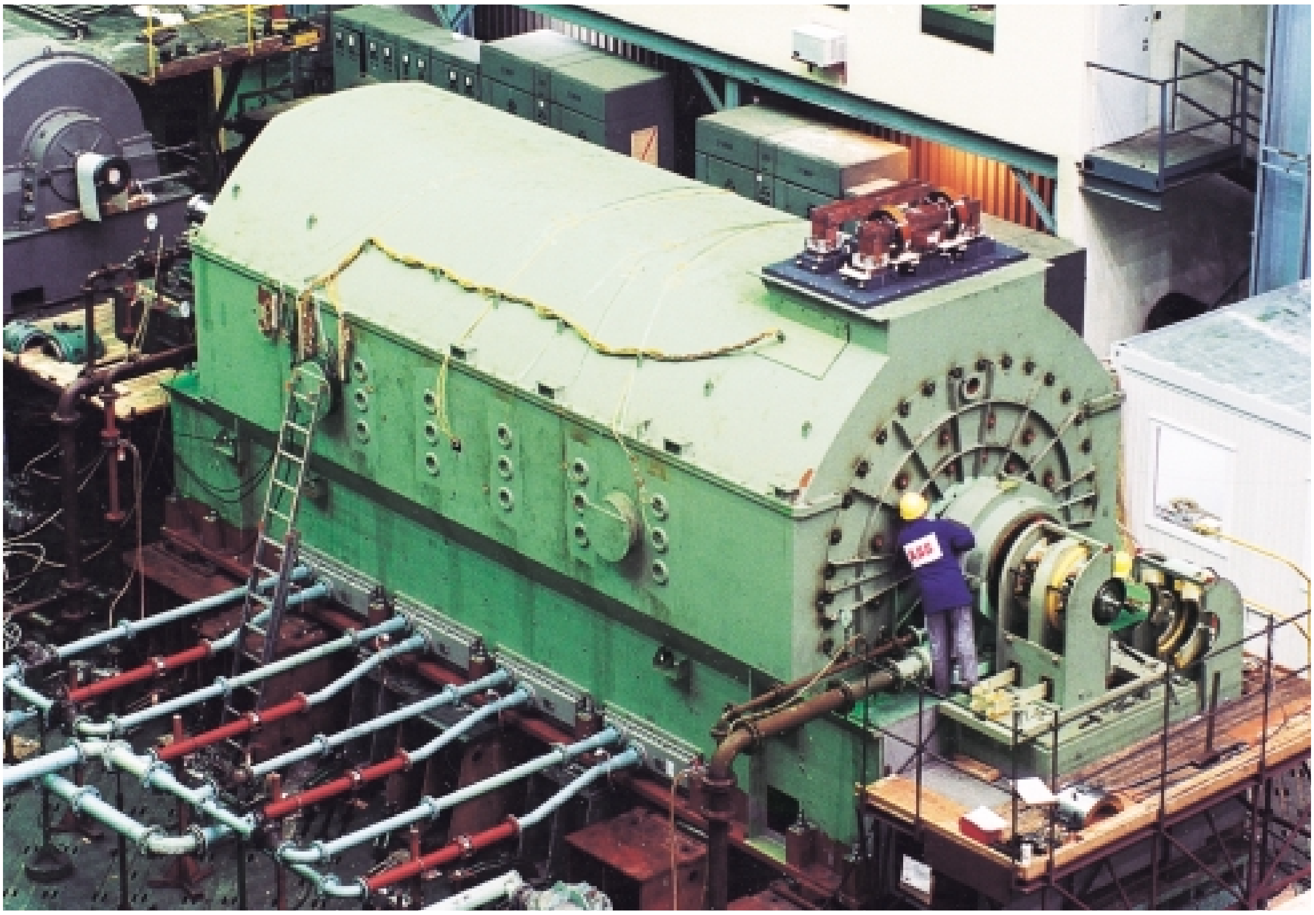
A total of approximately 70 vibration pick-ups, 80 pressure and 200 temperature measuring probes were used for the tests. The results of the test runs will be looked at in detail in a future article.

The prototype fulfilled the requirements – covering the running quality and

Table 2:
The prototype's technical data

Rated output	MVA	300/Class B [1]
Voltage	kV	19
Frequency	Hz	50
Power factor/overexcited		0.8
Efficiency [2]		
100% load	%	98.75
75% load	%	98.57
Short-circuit ratio [2]		0.51
Transient reactance x'_d [3]	p.u.	0.21
Subtransient reactance x''_d [3]	p.u.	0.17

[1] Cold-air temperature 40 °C (IEC)
[2] Measured, efficiency based on loss-summation method
[3] Measured values in unsaturated state



300-MVA prototype in the test bay **10**

vibration as well as temperature rises and losses – in every respect, even exceeding the high expectations in certain areas. *Table 2* gives the rated data of the prototype together with some of the more important measured values. Special mention has to be made of the excellent efficiency, which lies only marginally below that of the hydrogen-cooled generators. Based on the partial temperature rises measured under open-circuit and short-circuit conditions, the temperature rise during full-load operation at 300 MVA will lie below the limit for temperature class B by a sufficient margin of safety.

Given the information available today and looking to the future and further innovations (eg, in the stator winding insulation [6]), it is evident that air-cooled generators are potentially capable of another increase in output.

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