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Large Electrical Machines

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By means of selected examples the state-of-the-art and the current developments of large generators, motors and special-purpose machines are surveyed. Details are given on the actual problems and measures in design, manufacture, testing and operation of large electrical machines. Especially, the practical requirements on the technical and scientific developments are highlighted.

Anhand ausgesuchter Beispiele wird eine Übersicht über den Stand der Technik und derzeitige Entwicklungen bei grossen Generatoren, Motoren und Sondermaschinen gegeben. Näher geschildert sind die aktuellen Aufgaben und Massnahmen beim Entwurf, Bau, Prüfen und Betrieb elektrischer Grossmaschinen. Besonders hervorgehoben werden die Anforderungen der Praxis an technische und wissenschaftliche Weiterentwicklungen.

Un survol de l'état de la technique et du développement moderne relatifs aux alternateurs, moteurs et machines spéciales de grande puissance est présenté à l'aide d'exemples actuels et adéquats. Les problèmes, objectifs et mesures liés à la conception, à la construction, aux tests et à l'exploitation des grosses machines électriques sont décrits plus précisément. Les exigences imposées par la pratique aux développements technico-scientifiques sont mises particulièrement en évidence.

This paper was presented by G. Neidhöfer as a survey lecture at the ICEM '84, International Conference on Electrical Machines, Lausanne, September 1984.

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1. Introduction

With a population of only 6½ millions, Switzerland is small amongst the industrial nations. Nevertheless it has made a significant contribution to the development, manufacture and application of electrical machines. This shall be illustrated with a few examples of hydrogenerators, turbogenerators and large special-purpose machines.

The geography of Switzerland and in particular the Alps and the Alpine foreland led to a very early exploitation of water power and to the develpment of the related electrical and other industries. A typical modern example is the hydro-electric scheme of Grimsel-Oberaar situated in the central Alps, which was recently supplemented with a pumped-storage facility. Figure 1 shows the underground machine hall with four sets of 100 MVA each comprising motor/generator, pump and hydraulic turbine rotating at 750 rpm. The electrical machines are also operated as synchronous condensers.

At the present time two major electrical companies – one Swiss and one German – are jointly engaged on the construction of the generators for the world's largest hydro-electric power station, which is being built on the River Paraná at Itaipu on the border between Brazil and Paraguay. The station will have a total of 18 generator sets each of 700 MW, half of them being rated at 766 MVA for 60 Hz and the others at 824 MVA at 50 Hz. These huge machines were developed by both consortial partners and are being built, for the most part, by their subsidiaries in Brazil. Figure 2 shows the rotor of one of the first machines being inserted into the stator on site. The rotor speed is just over 90 rpm, its diameter reaches almost 16 m and the complete rotor weighs around 2000 tons.

Back in Switzerland again, the latest nuclear station in the country is just going into service at Leibstadt. The site is in the northernmost part of Switzerland on the banks of the Rhine. The two-pole turbogenerator rotates at 3000 rpm and is rated at 1182 MVA/1014 MW. Figure 3 shows the generator on test in the manufacturer's works.

It would be wrong to depict the modern large electrical generator exclusively associated with maximum unit-ratings. In recent years medium and even small unit ratings have greatly increased in technical and commer-

Fig. 1 Underground machine hall of the pumped-storage plant Grimsel II East

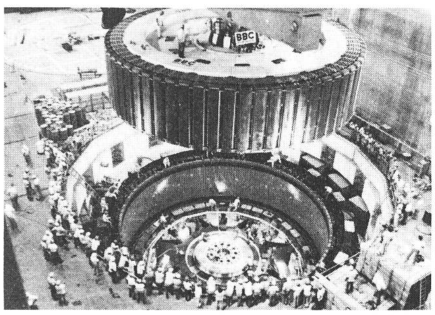

Fig. 2 Erection of one of the Itaipu hydrogenerators

International Conference on Electrical Machines ICEM '84

Lausanne, Switzerland, September 18–21, 1984

The International Conference on Electrical Machines (ICEM) was founded in 1972 to provide a forum for exchanging information on current problems, trends, designs, theories and application areas of electrical machines. It should allow engineers from Industries and Universities to meet, to deepen existing contacts and to build new ones.

The first conference was held at the City University, London 1974, followed by the Technical Universities of Vienna (1976), Leuven (1978), Athens (1980) and Budapest (1982). This year ICEM was organized by the Swiss Federal Institutes of Technology Lausanne (EPFL) and Zürich (ETHZ), Zürich being responsible for the technical programme and Lausanne for the local organization.

The conference was attended by some 410 participants from 39 countries. During the three days over 300 papers were presented and discussed in 10 parallel working sessions and two poster sessions. The main topics treated at the conference were: field theory and calculation methods, field calculation methods applied to electrical machines, theory of electrical machines, transformers, special machines, modelling and identification, computer-aided design and optimization, design problems related to cooling, noise, vibration and overvoltage, linear machines, brushless, permanent-magnet and d.c. machines, power electronics and d.c., synchronous and asynchronous machines, dynamics, stability and control of machines, synchronous and double-fed machines, superconducting machines and asynchronous machines. The wide material presented at the conference shows that the subject of electrical machines has still a very high development potential. Modern methods of engineering such as finite-element methods, identifiction and optimization procedures become increasingly significant. Progress in power electronics is changing the machine characteristics and requires special machine design. The availability of new material, such as rare-earth permanent magnets and superconducting materials improves machine characteristics and opens new areas of research and development.

All technical papers presented were published in the conference proceedings[1]). Following a decision of the International Steering Committee three survey lectures have been arranged. Their purpose was to inform on the state of the art, on modern trends and on actual problems in specific or forthcoming areas and to provide a common platform for discussions. Their topics: large machines, inverter-fed a.c. machines and small machines reflect the importance of large and small electrical machines in energy conversion processes. Almost 100% of the available electric energy is generated by electrical machines; on the users side some 60–80% is converted in electrical motors into mechanical energy. Our daily life is full of small motors. Power electronics have extended the application areas of electrical machines and allow optimization an energy savings.

The next ICEM will be held in Munich in September 1986. *K. Reichert, M. Jufer*

[1]) Surplus conference proceedings are available from Institut für Elektr. Maschinen, ETH-Zentrum, CH-8092 Zürich.

cial significance. As an example figure 4 shows part of a machine hall of the new gas turbine power station Riyadh 8 in Saudi Arabia which was delivered by a Swiss company as a turnkey project. The total output of 800 MW is obtained from 16 gas-turbine generators of 50 MW each.

As a first example of large special-purpose machines figure 5 shows a ring motor which represents a class of very low-speed machines. These cycloconverter-fed synchronous motors are used as gearless direct drives for cement tube mills. The rotor has a diameter of about 7.3 m and is rated at 5200 kW at its maximum speed, which is only $14\frac{1}{2}$ rpm corresponding to the highest electrical frequency of 4.83 Hz.

Large special-purpose machines are also used in rotating converter sets for supplying railway networks. An example is the converter station Seebach near Zurich which feeds power to and from the Swiss Federal Railways' system. Each group comprises a three-phase wound rotor induction motor for 60 MW at 50 Hz coupled to a single-phase synchronous generator of 80 MVA at $16\frac{2}{3}$ Hz. In both their design and size, these machines are also world leaders in their class.

2. Review of the Present Situation

The preceding few examples illustrate the «state of the art» in a very general way. Even the casual observer of the development of large machines in past years must have been impressed by the tremendously fast growth of unit ratings. This was achieved partly by "external growth", i.e. by increase in physical dimensions of the machines. For the engineer, however, the "internal growth", i.e. the increase in power density inside the machine, has presented equally

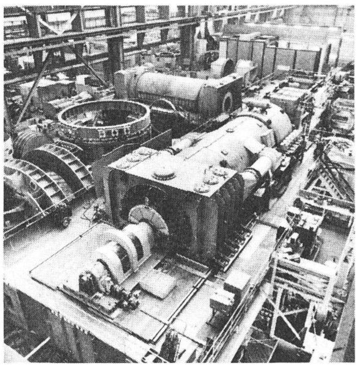

Fig. 3 The Leibstadt turbogenerator during test runs in the factory

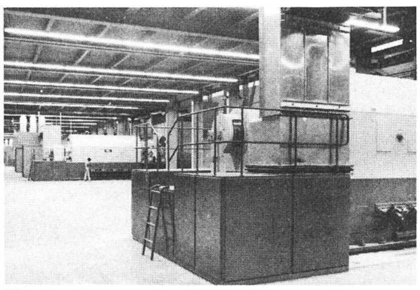

Fig. 4 One of the two machine halls of the gas turbine power plant Riyadh 8

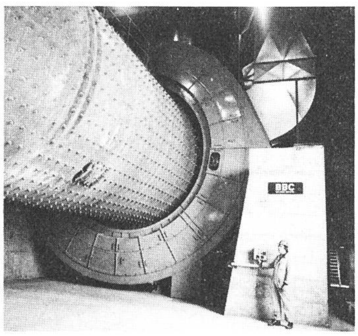

Fig. 5 Ring motor as gearless drive of a cement tube mill

Main Aereas of Activity in Large Machine Engineering Table I

Design	Dimensions, Power density Structure, Materials, Cooling Individual adaptation, Standardisation Optimisation, Rationalisation Calculation methods and facilities
Manufacture	Rationalisation, Automation Quality assurance
Testing	Development testing, Running tests Test facilities and procedures Measurement and evaluation systems
Operation	Normal and special operating conditions Reliability, Availability Protection, Monitoring, Process control Inspection, Diagnostics Maintenance, Retrofit

challenging problems and made at least as great a contribution to reach today's technology in both medium and high-rating machines. Particularly this "internal growth" is due in no small measure to the steadily improving accuracy and reliability with which one can determine electrical, mechanical and thermal stresses by calculation at the design stage.

It is from this era of impressive growth rates that the present development scenario is emerging—and emerging into a world of changing priorities, where growth is still the keyword but with a slightly shifted meaning! As ever, today's market sets today's goals, namely: new applications—better reliability—higher efficiency—lower costs—faster delivery times in manufacture. For the engineer the challenge is certainly greater than ever.

3. Present Development Problems

The majority of participants in the ICEM'84 conference are certainly coming from Universities and Technical Institutes and have predominant interests in scientific and technical problems, with the accent probably on the electrical disciplines. It will be useful here to list some of the main areas of activity—not only electrical ones—in large-machine engineering and to outline the most important problems which arise from the requirements of engineering practice (table I).

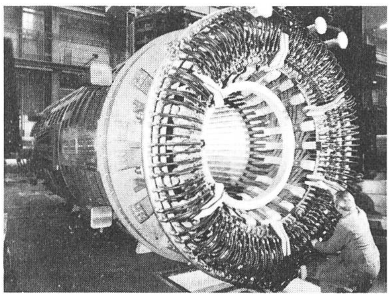

Fig. 6 A large turbogenerator stator during assembly

3.1 Design

The initial design steps, namely the determination of the leading *dimensions* and *power density* have already been suggested. They are closely associated with the choice of the *structure* and the design of the component parts, their *materials* and *cooling* methods. Several examples of modern design features can be seen in figure 6 on a turbogenerator stator. Special attention should be paid to the high-current winding, high-voltage insulation, intensive cooling, low-loss laminated core and to the soundly constructed pressure and support structures. Materials in modern machines include electrical conductors, special magnetic materials and steels, high-grade insulation systems and fibre-reinforced resin-bonded composites. Figure 7 illustrates the basic structure of a high-speed hydrogenerator. One can clearly see the electrical sheet core segments of the stator, the sheet steel punchings of the salient pole rotor, the pressure and support components and finally the stator and rotor windings.

Large-machine designs must often be adapted to *the specific application*. This restricts a full *standardization* to only a few machine types. Nevertheless great efforts are done to standar-

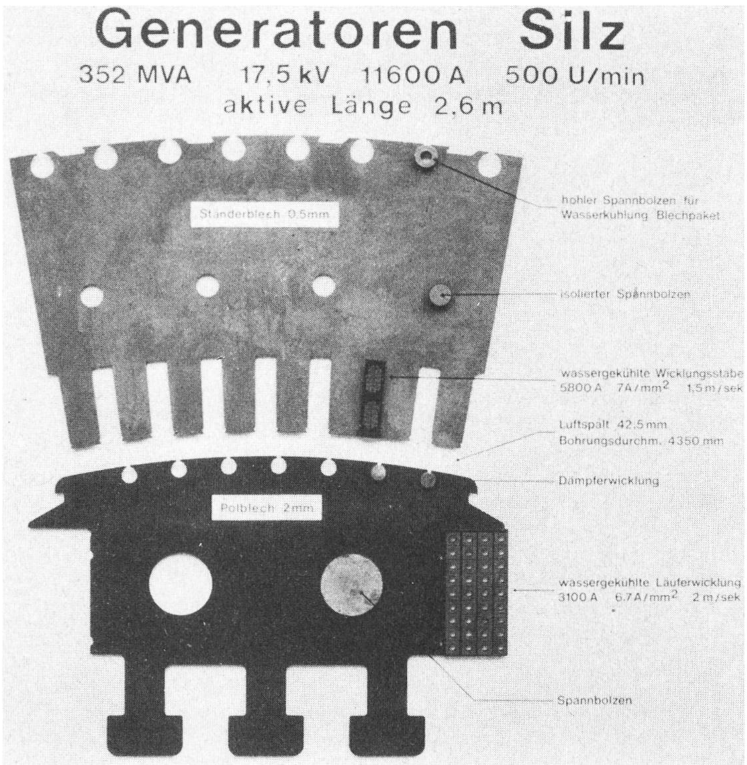

Fig. 7 Sectional view of the Silz hydrogenerators with part details

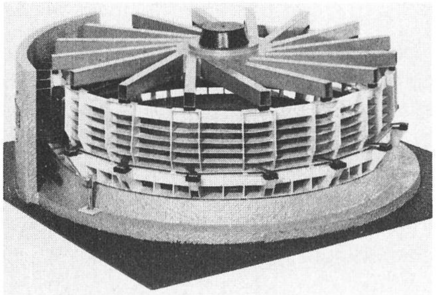

Fig. 8 Model of the stator frame and upper bearing bracket with skew arms for large low-speed hydrogenerators

dize as many components as possible. A most important aspect is the design *optimization*, i.e. finding design solutions which best meet operational requirements and also offer lowest costs. A key factor in attaining such optimum designs is *rationalization* which is aimed at reducing production costs, shortening delivery and commissioning times while improving operating economics by offering higher efficiency, reliability and durability. In other words: highest quality at lowest total costs — two traditionally conflicting goals, which with rationalized procedures and standardized design features can actually be brought into harmony!

The design process itself is a matter of continual improvement in both method and accuracy. This particularly concerns the increasing use of *calculation methods* and *facilities* such as finite elements and interactive computer applications and computer-aided design (CAD).

The following example of finite-element analysis on a large mechanical structure is related to a hydrogenerator stator (fig. 8). In this stator the upper and lower bearing brackets are connected to the outer frame by skew arms. This configuration prevents large tensile and compressive forces being transmitted to the foundation, it keeps down stresses in the structure itself and maintains a concentric airgap under varying operating conditions. In the finite-element calculation model the structure is subdivided into many discrete elements (fig. 9a). Static and dynamic deformations on normal operation and due to faults can be studied in detail with this model. As an example of the results, figure 9b shows the deformation of the lower bearing bracket while going from cold to normal operating temperature.

An important aid in mechanical modelling is provided by experimental modal analysis, which consists in analysing the frequency response of an object to an applied impulse or vibration in order to identify modal parameters such as natural frequencies, deflection forms or the dynamic elasticity of, for example, bearing supports. Such experimentally determined results serve to support the calculation methods which can never be more accurate than their parameters and assumptions.

This statement also applies, of course, to electrical problems. For example magnetic saturation affects many machine parameters. For this reason, for instance, we discriminate between unsaturated and saturated reactance values. There are also other analogous effects. For instance we may speak of a "cold" or a "warm" synchronous reactance, a difference which can arise in large hydrogenerators due to a change in airgap resulting from the radial thermal expansions of rotor and stator - and it can be quite noticeable.

It has been seen that the realistic modelling of electrical machines and the identification of their parameters are subjects of increasing importance. The treatment of certain problems, where fast transient effects are important, can now be improved by introducing sub-subtransient reactances and time constants of the synchronous machine. Complete system analysis will include grid-values, turbine-generator shaft-line parameters and regulator characteristics. Typical problems being tackled by simulation methods include for instance: dynamic machine behaviour, torsional interaction, subsynchronous resonance and shaft stresses due to system faults.

Figure 10 shows the torque as a function of time in a turbine-generator shaft, following a three-phase short-circuit on one of the station's high-voltage lines. When the fault is cleared, the full grid voltage suddenly returns and applies a second torque impulse to the oscillating shaft. This can lead to very high shaft torques and stresses

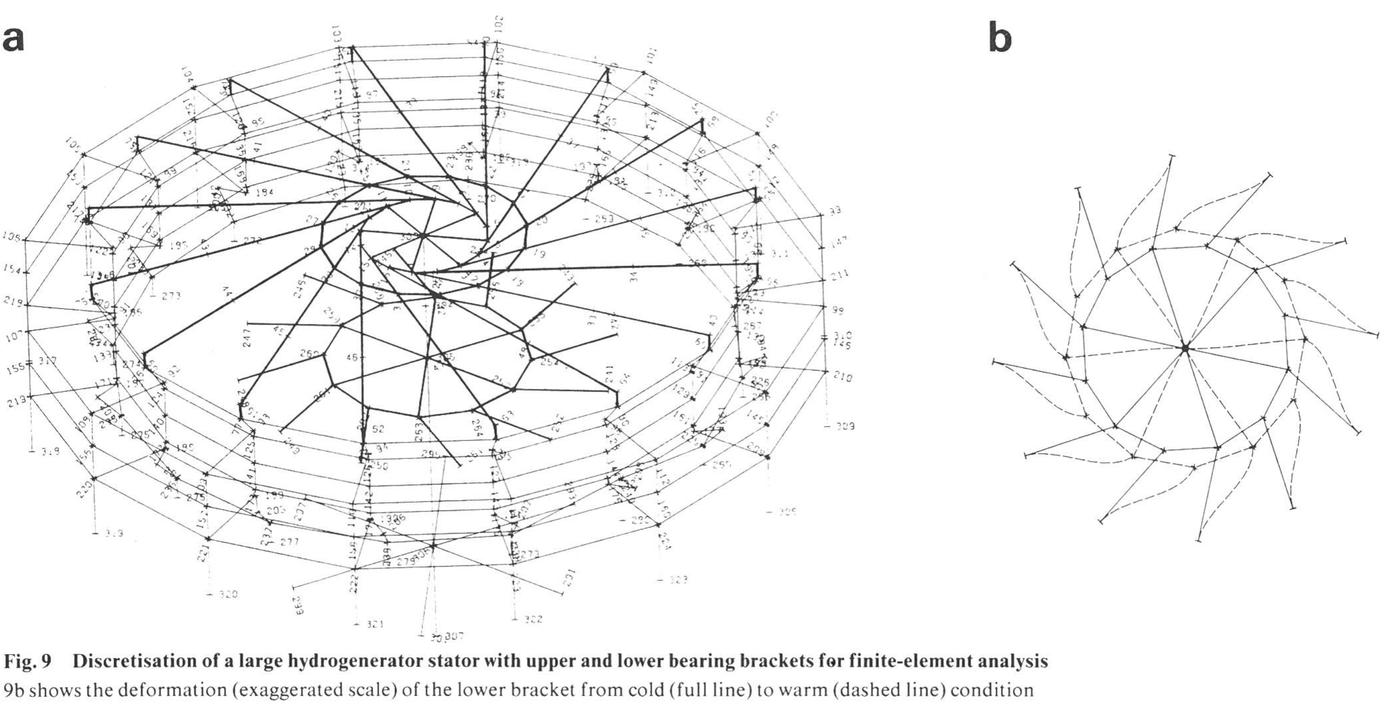

Fig. 9 Discretisation of a large hydrogenerator stator with upper and lower bearing brackets for finite-element analysis

9b shows the deformation (exaggerated scale) of the lower bracket from cold (full line) to warm (dashed line) condition

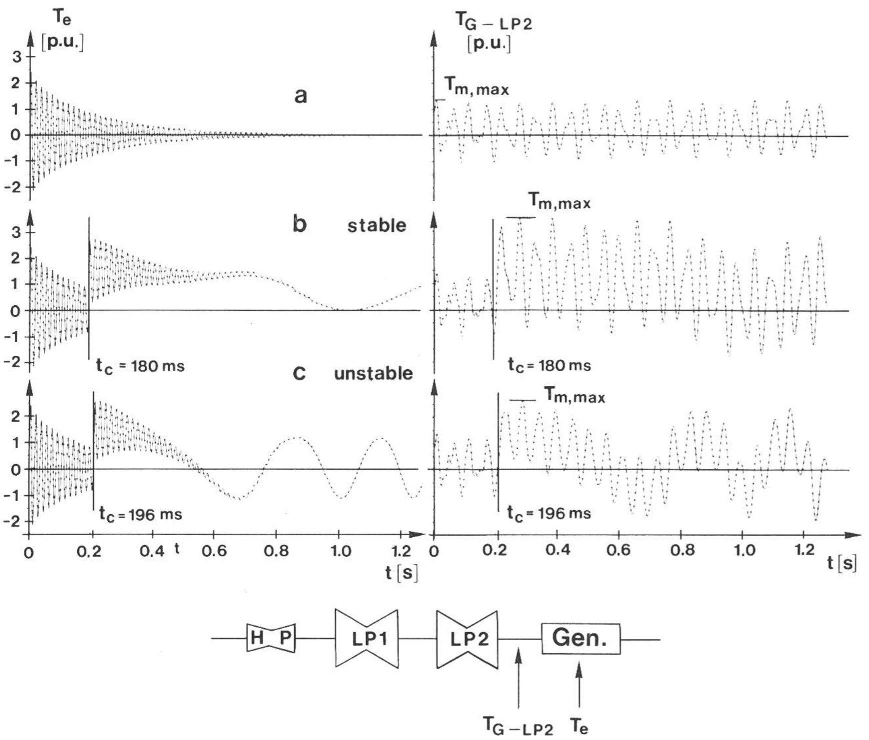

Fig. 10 Electrical and mechanical torques T_e and T_m in a turbine-generator shaft

a during L-L-L grid short-circuit
b, c ditto with fault-clearing after t_c

which in this example are actually higher in the stable case (b) than in the case (c) where synchronism is lost. In general, the increasing per-unit rating of today's networks leads to higher reactions on the generators as well as to stronger interactions between the grid and the power-station machine sets.

It must be emphasized that simulations in this class are very complex and costly, so that they require reliable assumptions and accurate system parameters. These two examples were also intended to show the increasing importance of electrical and mechanical analysis of the machine and its related system. It is clear that the results of such investigations have to be taken into account in the primary design stage.

3.2 Manufacture

Today the main effort in manufacturing is directed towards *rationalization* and *automation* with the clear goals of reducing costs and shortening delivery times. Product quality is of prime importance and a broad-based *quality-assurance* system is indispensable in the modern large-machine production process.

At this point, and with an eye on the following topic (testing), it may be mentioned that the final manufacturing stages of large hydrogenerators are usually carried out on site, in the power station. It is at this final stage that stator core and windings, and rotor spider and laminated rim are assembled.

3.3 Testing

Tests on large machines are carried out during manufacture, on the test bed and on site in the station. They include both tests on individual components and subassemblies and tests on the complete machine.

Special test rigs are built, if necessary, for *development testing* of new components or techniques. As a first example, figure 11 shows a stator-slot model for testing the long-term performance of stator-winding bars under electrodynamic and thermal loads.

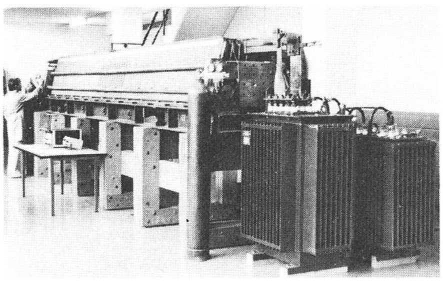

Fig. 11 Stator slot model with winding bars for long-term testing

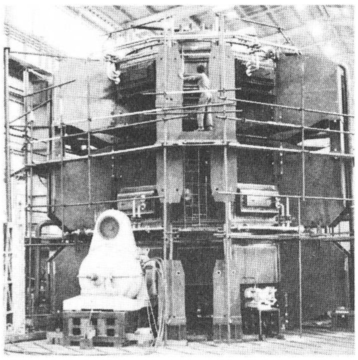

Fig. 12 Test rig of a thrust bearing assembled from original components of a large low-speed hydrogenerator

One of the aims of the test series was to prove the operating safety and durability of the winding fixation, including the slot wedging. The second example concerns a test stand for the large thrust bearing of a vertical hydrogenerator, as shown in figure 12. It was built to check a new, extremely high-load bearing design under realistic conditions and to provide measurements of important parameters such as bearing-segment deformations as well as the pressure and temperature of the oil film in the bearing.

As an example of a *running test* on a complete generator, figure 3 shows a fully assembled turbogenerator and part of the measuring equipment, set up in the manufacturer's *testing facility*. Running tests are usually conducted as type tests, and both normal design-check tests and special development tests are incorporated into the test programme.

The tests employ the most modern *measurement techniques* and facilities—for example a minicomputer for automatic recording and *evaluation*. Activity in this branch, particularly in both hard- and software development, is quite intense. A typical example is the on-line evaluation of sudden-short-circuit tests to give immediate results of reactance and time constant values during the tests.

Factory running tests on large machines are exceedingly expensive and on site-assembled machines, of course, not even possible. These reasons have motivated the search for special measuring procedures to be carried out, if possible, at standstill. A topical example is the frequency-response measurement of electrical machine parameters. Since such contrived measurement and identification procedures are made under special conditions, considerable ground work has to be done for the reliable transfer of parameters and characteristics into the real operating conditions.

3.4 Operation

The operation of large machines is usually beset with special requirements which need consideration at the design stage as well as during actual operation. Every machine has to meet a set of *normal operating conditions* and also some degree of *abnormal conditions*. At the same time it must offer a high standard of reliability. Special operating conditions include for example electrical self-starting of synchronous motors or motor/generators and running at variable speed. Abnormal operating conditions are for instance short-time overload, negative-sequence load, underexcited and asynchronous operation. Examples of exceptional operating conditions are operator errors and faults, such as synchronizing out-of-phase or short circuits and even natural disturbances such as earthquakes.

What are the operational precautions to be taken for high *reliability* and *availability?* In the first instance it is normal practice to install *protection* equipment which will guard against operator error and overstressing. In a second stage individual physical quantities are monitored and analysed on-line by a microprocessor or minicomputer. For instance the shaft vibration of a turbine generator set is measured and the vibration data are analysed, stored and prepared for display to station staff (fig. 13) as required. In addition, by comparison with previous stored data, trend analysis is available. Installations of this type could form part of a total *monitoring* and operations-control system. Such a system provides confirmation of correct operational procedure and can give early warning of impending faults. The trend is towards complete systems of operation or *process control* including monitoring, of course with minicomputer handling.

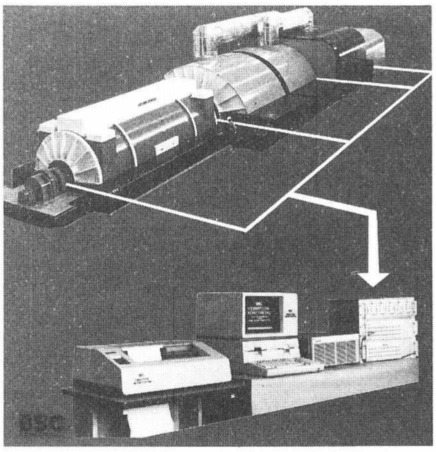

Fig. 13 Shaft vibration monitoring of a turbine-generator set

The early warning of impending faults is a long-standing objective which is now receiving more intensive attention. Apart from the computer-based monitoring, available procedures include *inspections* after severe faults and during overhauls, as well as *diagnostic* check-ups, based upon inspections and various non-destructive tests. The result is the timely provision of replacement material and personnel, to exchange critical components during a planned outage.

A new field of activity is the so-called *retrofit*. This means the renovation or partial rebuilding of older machines. Components, which have reached the end of their useful lifetime, are restored or replaced by modern counterparts. This kind of work often raises unusual and challenging problems for the engineer, because his design freedom is limited by the given machine structure and its interfaces.

4. Some new Development Trends and Areas

One main feature is the increasing significance of calculation techniques and computer applications in both the development and operation of large electrical machines. In other words: the electrical machine is to be found in an increasingly electronic environment. This is particularly true in connection with power electronics.

4.1 Power Electronics

The excitation of synchronous machines using semi-conductor rectifiers is now a well-established technique either associated with rotating diodes or with stationary diodes or thyristors.

Induction motors with sub- or super-synchronous converter cascades find application in special-purpose variable-speed drives in the upper rating ranges. Figure 14 shows two such motors and the related converter in a test-bed arrangement for a load test. This type of drive is also used in modern network-coupling converters. Large synchronous motors for low and variable speed are fed by direct converters, for example the ring motor in figure 5. Higher-speed motors are used together with intermediate circuit converters. This kind of supply finds application for running up synchronous condensers, gas turbines and motor-generators in pumped storage plants. Another example concerns the connexion of large power station generators on to high voltage d-c transmission. The alternating current supplied by the synchronous generators is converted to direct current by rectifier blocks, which is not without reaction effects on the generator.

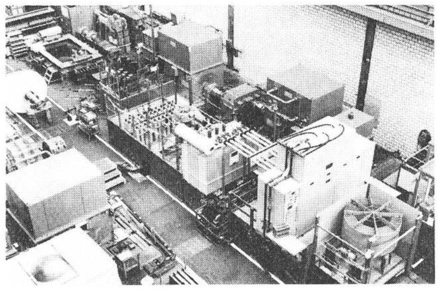

Fig. 14 Induction motors with subsynchronous converter cascade during a load run in the test bay

The preceding examples are intended to show that power electronics is opening up new fields also for large machines. It is obvious that operation in combination with inverters introduces new effects and imposes extra loading on the machine. These are factors which must be accounted in the design. Finally the simulation of the combined system machine/inverter raises particularly demanding problems for the engineer.

4.2 Turbogenerators with superconducting field winding

The development of large electrical machines has always been closely associated with innovations in machine cooling methods. Even with the simplest cooling medium, namely air, it has been possible, largely by improvements in cooling design, to achieve a steady increase in volume-specific power output and thereby in unit rating. The present high specific outputs are closely linked to the use of direct cooling. Using superior cooling media, such as hydrogen or water, it is relatively easy to reach the highest unit ratings currently demanded by the market, with a well-proven and reliable technology. The exact cooling methods to be used are determined, like other design aspects already discussed, by both the technical requirements and cost considerations.

It is against this background that the development of turbogenerators with superconducting field winding has to be considered. This development aims to exploit the possibility of building high unit-rating generators with operating characteristics superior in some respects to conventional machines as well as with lower manufacturing costs. The basic configuration is generally accepted: It comprises a helium cooled superconducting rotor winding mounted on an inner rotor, a damper cylinder as outer rotor and a normally conducting water-cooled airgap stator winding inside a slotless laminated stator core. The main advantage lies in the absence of excitation losses, so that the total loss is about halved with a corresponding improvement of efficiency. There is also a reduction in size and weight. Machine manufacturers and Research Centers around the world are engaged in the building and testing of components and prototypes. The running of larger test machines, scheduled for the second half of this decade, should establish the operational viability of these novel machines. The highest challenge they face is to reach the standards of reliability established by conventional turbogenerators.

5. Concluding Remarks

In this review presentation it is not possible to include all types of large special-purpose machines such as synchronous condensers, single-phase generators, short-circuit generators, diesel generators, bulb-turbine generators, motor/generators with two synchronous speeds. Furthermore, no attempt has been made to list problems and physical phenomena as a whole or in detail. Nevertheless, it can be observed that there are today very few isolated problems which can be separated out and treated on their own. In practice one has to deal increasingly with groups of interrelated effects. As a simple example, field calculations do not stand in isolation; they are rather the basis for particular effects such as forces, eddy currents, losses and heating. Likewise the simulation of components and systems is now increasingly involving the interplay of multiple technical disciplines especially in the electrical, mechanical and thermal areas.