Abstract — The synchronous machine has long been the most important of the electromechanical power-conversion devices, playing a key role both in the production of electricity and in certain special drive applications. This paper describes the synchronous generator achievements chronologically from the beginning up to now in separate decades. An outlook into a dynamic future is presented in the last section.

Index Terms — Synchronous Generator, Insulation System, Cooling System, Powerformer

I. INTRODUCTION

The synchronous machine has long been the most important of the electromechanical power-conversion devices, playing a key role both in the production of electricity and in certain special drive applications. Its beginnings are found in the closing decades of the 1800s, when innovatory engineers in several different countries showed courage, conviction and far-sightedness as they worked on its early development.

Later on, several attempts were done in order to solve the problems against the rating MVA and voltage increase. The most important problem against the rating MVA increase was the low performance of electrical insulation and cooling systems. Utilizing various combinations of synthetic insulators and optimizing the air-cooling systems have resulted in outstanding improvements [1,2]. Invention of powerformers in the closing years of the 20th century has increased the rating voltage to transmission level. Even some researchers believe that there will be no need of power plant transformers in future years. Nowadays cutting-edge technology of superconducting synchronous generators is highly noticeable. Achievement of higher MVA ratings in lower volumes is expected by this technology.

This paper describes the synchronous generator achievements chronologically from the beginning up to now in separate decades. An outlook into a dynamic future is presented in the last section.

II. THE BEGINNING

Synchronous generator has a history of more than a hundred years. The real beginning was in the 1880s. At first, stationary poles were used, with the poles surrounding a rotating ring armature. This was known as the external-pole type. An important milestone was the ‘three-phase dynamo’ derived from the direct-current machine with the Thomson-Houston armature. The three armature coils with their common internal neutral point were no longer carried on a three-segment commutator, but on three slip-rings. The reverse of this structure, namely the internal-pole type with a rotating field and stationary armature, was also recognized as a possible form and subsequently worked on. It was soon seen that the optimum was to be found by combining three phase-shifted alternating-current systems to form the so-called ‘rotary-current system’. The machines were provided with ‘triple coil pairs’ in the armature, with their inner ends star-connected and their outer ends simply connected to three ‘long-distance’ transmission wires. Haselwander is credited with recognizing the function of the rotary current in synchronous machines, and he was the first to try it out in practice. In 1887 he built the first three-phase synchronous generator shown in Fig. 1, which produced about 2.8 kW at 960 rev/min, corresponding to a frequency of 32 cycles per second, today known as Hertz, or Hz. The machine had a stationary, ring-shaped, three-phase armature and a rotating ‘internal-pole magnet’ with four wound salient poles, which provided the revolving field. 1891 was the year in which the three-phase synchronous machine passed its first big test and made its actual breakthrough. The scene was the Frankfurt Exposition, the event the great experiment whereby 300 hp was transmitted from the hydroelectric power plant at Lauffen...
am Neckar, 175kms away, via three-phase current transmission. It was an event that drew worldwide attention and acclaim. The appearance of powerful steam turbines at about the beginning of the 20th century meant that high-speed turbine-generators were needed. In 1901 the first actual turbogenerator was built by Charles E. Brown [1].

The first insulation systems used materials that were then common in industry for other uses. These included natural fibers of cellulose, silk, flax, cotton, wool, and later asbestos. The history of synthetic products for insulation started with the work of Dr. L. H. Baekeland in 1908. This led to the development of a workable and reproducible process for the production of phenol-formaldehyde resins, which were used to make many types of electrical products. During World War I, asphaltic resins (also called bitumen) were combined with mica splittings for the first time to make improved groundwall insulation for turbine generator stator coils shown in Fig. 2. Not long after the end of World War II, Westinghouse Electric Corporation engineers began the laboratory work to turn the new polyester chemistry into a workable generator and motor coil high voltage insulation system. The system they developed was trade named “Thermalastic”. Variations of the same basic system have been licensed by the Corporation to several other rotating machine manufacturers and also duplicated by others as the 1950s era covering patents expired [3].

The first cooling systems were air cooled, with much time spent refining these designs before their capability was exceeded. Maximum rating reached by using air-cooling was a 200 MVA generator at 1800 rpm installed in Brooklyn in 1932 [4]. The idea of using hydrogen to cool electrical machines was proposed as early as 1915 by Max Schuler, who was granted the initial German and American patents in this field. We have to thank the Americans, both individuals and companies, for building the first hydrogen-cooled machines. They started in 1928 with a synchronous compensator, and in 1936 they put the first 3600 rev/min hydrogen-cooled turbogenerator into commercial operation [1]. The first hydrogen-cooled turbine generator developed by the GE Company went into service in 1937, and hydrogen-cooled machines were able to satisfy the power output needs for many years before another step (direct cooling of the machine windings) was required. Between 1950 and 1960, manufacturers developed a broad range of direct cooling methods, including air gap pick-up rotor windings, direct gas-cooled stator windings, oil-cooled stator windings and, finally, water-cooled stator windings. Since the introduction of these technologies in the mid-1950s, further refinements have led to a quadrupling or more of the generator output rating, with maximum ratings of 1,500 MVA or greater [4].

III. THE 1970s MILESTONES

Insulation system improvement was one of the great milestones in 1970s. Prior to 1975, most laminates were made using adhesive resins dissolved in solvents. The substrates were coated and the solvents were driven off into the atmosphere in drying ovens. With the energy crisis of the early 1970s plus the beginnings of health, safety, and environmental regulation, coating operations began to shift to high solids adhesives or solvent emission capturing equipment. The captured solvents were recovered for re-use or were incinerated to capture the heat benefit and reduce emissions. Today, high solids and solvent-free resins are becoming the norm [5].

Another milestone of the 1970s was the appearance of superconducting (SC) synchronous generator technology (Fig. 3). The Westinghouse Company carried out design studies on
large SC ac generators and built a prototype two-pole “utility-type” generator during the early 1970s using low temperature superconducting (LTS) wires. A 5-MVA generator was developed and successfully tested in 1972. The GE Company carried out design studies on large SC generators and built prototype generators during the 1970s using LTS wires. The purpose of these activities was to assess the technical feasibility of SC generators for long-term reliable operation on electric power systems. A 20MVA two-pole 3600r/min turbine generator for utility applications was designed, built, and load tested. This machine followed the air-core SC generator design approach. At that time (1979), this was the largest SC generator to be fully load tested. During the 1970s, multifilament LTS wires were being developed at the Laboratoires de Marcoussis in France. This LTS conductor technology was used in the design of an SC rotor for a synchronous turbo-generator. The design effort was subsequently transferred to Alsthom Atlantique’s (now ALSTOM) manufacturing plant in Belfort, France, where the design was finalized and a prototype rotor was manufactured. This rotor was essentially designed as a 250MW machine with an active length of 2m and an overall length of 3 m, but used a larger diameter of a 1200-MW machine (1.06 m) [6].

As the cooling system plays an important role in the proper performance of the SC generators, SC generator evolution has always been driving the cooling system development. In 1979 T. E. Laskaris presented a two-phase cooling system for rotors of superconducting generators. The system employed a two-phase, irreversible flow process to deliver the helium to the superconducting winding such that the liquid was separated from the vapor by the rotation and formed a pool. The free surface of the pool was maintained at subatmospheric pressure, and the winding, which was partially immersed in the liquid, was cooled by pool boiling at temperatures below 4.2 K [7].

IV. THE 1980S MILESTONES

Like the previous decade, the insulation system was one the main research areas in 1980s. During the 1980s, GEC ALSTHOM designed a brand new resin rich based insulating system named Duritenax®. The system uses a unique fast curing F class solventless epoxy formulation, impregnated in a combination of glass fabric and specific mica paper. Duritenax® had improved mechanical properties, dielectric strength and fewer losses as well as thermal resistance than the previous systems [8].

The superconducting generator and materials program (SuperGM), a 12-year national project was initiated in 1988 in Japan by the New Energy and Industrial Technology Development Organization (NEDO) as a part of the New Sunshine Program of the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry (MITI). The research and development activity was focused on the applications of SC technology to electric power apparatus. The research yielded a great number of promising results in next decades [6].

As an evolutionary step in cooling system, Japan Atomic Energy Research Institute (JAERI) propelled cryogenic technology development to aim at realization of superconducting coil system in 1985. An advanced heat exchanger combined with a 350 lit/h helium liquefier/refrigerator was the outstanding characteristic of this system [9].

V. THE 1990S MILESTONES

Insulation systems achieved great milestones during 1990s. Westinghouse Electric Company developed a new Class F rotor turn insulation system that met most of the functional requirements. The system consisted of a rigid epoxy glass laminate bonded to the copper with a polyamide epoxy film adhesive. The system was verified by factory trials and used in several turbine generator rotors since early 1991 [10]. In 1998 Nanjing Turbine & Electric Machinery Group Co. presented a new rotor winding insulation system which consisted of Nomex 411 paper impregnated with adhesive varnish. The system had the advantages of higher flexibility and higher ability of being impregnated by varnish than the previous systems. Also it was withstanding against moisture absorption and could be easily cleaned [11].

Along with great improvements of computers in this decade, powerful softwares were developed to design and analyze the synchronous generators. In 1995 K.W. Cowan presented advanced computational techniques involving computational fluid dynamics (CFD) and electromagnetic and thermal finite element analyses to predict the thermal performance of prototype hydrogen cooled generator shown in Fig. 4. The project was achieved by using the CFD software of the Rolls Royce Aerospace Division in the University of Newcastle [12].

During the last years of 1990s, the SuperGM project, which was launched by the Japan New Energy and Industrial Technology Development Organization in 1988, resulted in three models of superconducting rotors and a conventional stator. The first model machine (type-A machine), tested between April and December 1997 achieved the highest
output of 79 MW, which was a world record. Leading power factor operation was also demonstrated at approximately rated capacity of 82MVAR. The second model machine (type-B machine) was tested between March and September 1998. The type-B machine also achieved a record output (79.7MW) and demonstrated the longest continuous operation of 1500h. The third model, equipped with a quick-response excitation system, was tested between October 1998 and June 1999. This model machine was connected to a commercial power grid for the first time in the world to study basic performance in an actual electric power system. Application of high temperature superconducting (HTS) materials in synchronous generators was a great milestone in this technology. In the mid–1990s, GE conducted design studies on HTS generators and built and tested an HTS prototype coil [6].

In 1999, the Siemens Westinghouse Corporation developed an air-cooling system for large generators, combining with thinner, higher temperature capability, high voltage stator insulation, improved ventilation analysis such as CFD, and high efficiency filters led to economics favoring large air cooled generators over hydrogen for many applications. This was a beginning for air-cooling systems to be preferred rather than hydrogen cooling ones [13].

Last years of 1990s encountered the appearance of the powerformer technology. The idea of electrical generation in high voltages was proposed in the beginning of 1998 by Dr Mats Leijon from the ABB Corporate Research in Sweden. In the conventional generator, the stator windings are made up of rectangular insulated conductor bars shown in Fig. 5 and the operating field is 2.5 kVrms/mm. As shown in Fig. 5, the shape of the conventional rectangular stator-bars results in an uneven electric field distribution along the conductor surface with high electric fields at the corners. This design philosophy of the conventional generator has prevented the output voltage from exceeding about 30-35 kV. In contrast, the voltage for power transmission has reached levels of 800 kV and even higher. A power plant based on a conventional generator very often requires a step-up transformer. In contrast to conventional generators, the windings of powerformer shown in Fig. 6 were made of extruded cross-link polyethylene XLPE cables (Fig. 7), and field non-uniformities in conventional insulation structures could be avoided. Cylindrical conductors in the cable-winding yielded an even electric field distribution along the conductor surface, and the stator slot was shaped to be suited for application of the cable-windings with graded insulation. The operating field in XLPE insulation for these applications could be up to 15 kVrms/mm. Therefore, the new type of generator offered a possibility to build high voltage generators, which could be directly connected to the power transmission systems without any step-up transformer. In 1998 the fist powerformer was installed in the Porjus power plant in the north of Sweden with the rating voltage of 45kV and the rating power of 11MVA [14].

VI. 2000 UP TO NOW

Due to the appearance of HTS materials in the last years of the 1990s, the superconducting generator technology has had great experiences in the 21st century. In 2002 GE initiated a development program to build and test a 100MVA class HTS generator shown in Fig. 8. This program is supported by the DOE through the Superconducting Partnership Initiative and targets the development of a commercial-grade HTS prototype generator. The project team includes GE Global Research, GE Energy, American Electric Power, and the Oak Ridge and Los Alamos National Laboratories. This HTS project is expected to achieve major improvements in the efficiency of new generators and to allow retrofitting existing generators with HTS rotors. Upon successful completion of this initial program, it is anticipated that the HTS technology will be scaled up to larger generator ratings for combined-cycle gas-turbine power plant applications [6].

Wide activities have been done to build commercial powerformers since 2000. The following is a list of powerformers and their characteristics connected to commercial power grids.

1) The powerformer of Eskilstuna power plant in Sweden, 136kV, 42MVA.
2) The powerformer of Porsi power plant in Sweden, 155kV, 75MVA.
3) The powerformer of Holjebro power plant in Sweden, 78kV, 25MVA.
4) The powerformer of Miller Greek power plant in Canada, 25kV, 32.8MVA.
5) The powerformer of Katsurazawa power plant in Japan, 66kV, 9MVA.
VII. OUTLOOK

Air-cooling in general will continue to supersede hydrogen, while a further approach to hydrogen-cooling efficiency can be achieved with customer interest.

HTS generators will have a great share of research and industrial milestones. Future power generators of higher ratings might require the following improved features:

1) Higher current capability than achievable with a single HTS tape, thus requiring stranded conductors.

2) Three-dimensional windings in the rotor end region, which are presently difficult due to limited bending capability of today’s tapes.

3) Layer-wound coils (instead of pancakes) to minimize the number of intercoil connections, provided the HTS material become available in significantly larger piece lengths.

The powerformer has been introduced to the market and will become an accepted technology.

Trend to further improve the stator bar ground wall insulation, driven by indirectly cooling is predictable. Polymer insulation systems with improved properties might supersede the established mica glass tape.

Today’s progress in generator technology and the potential risks bring about a considerable in-house development capacity, which cares for the present technology and projects
future concepts. This is mirrored in a narrowing field of independent designers shown in Fig. 9.

VIII. CONCLUSION

A chronological description of the synchronous generator achievements was presented from the beginning up to now in separate decades. In addition, an outlook into a dynamic future was presented in the last section.

In sum, the history of the synchronous machine is now more than 100 years old. Within this span of time its power capacity has grown enormously, and it has established itself as a major player in the conversion of energy. The most significant determinative technologies are still insulation systems and cooling systems.

Nowadays, the plant is no longer a site for assembling the parts under lab conditions. Shortest lead-time and harsh conditions on site require package solutions.

No gift of prophecy is needed to predict that the synchronous machine will continue to evolve and grow in importance in the same impressive way as it has in the past.

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REFERENCES


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