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Development of synchronous generators for Swedish hydropower: A review

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Abstract

The development of large-scale hydropower in Sweden started around 1900 when the Swedish government considered replacing of steam engine power with power from water falls, especially for utilization in railway operation. The hydropower development extends more than hundred years. Most of the Swedish hydropower was built in 1950s and 1960s. Due to the advancing age of installations, Sweden is facing an extensive refurbishment work in the upcoming decades. A large variety of individual designs exist among hydroelectric generators. The generator design has constantly strived for more compact and cost-effective constructions and this has resulted in a constant increase in the unit size. This paper describes the evolution of hydropower generators in Sweden. The development of assembling, stator insulation, cooling and materials used are described.

Keywords: Hydropower; History; Synchronous generator

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1. Introduction

Hydropower is historically the most important electric energy source in Sweden. Most Swedish hydropower plants were built in 1950s and 1960s, about 40–50 years ago. Sweden is facing an extensive refurbishment and upgrading work. New techniques and modern computer-based design tools make it possible to increase the output and decrease the losses in existing hydropower plants [1–3]. The biggest potential is in turbines and generators. Most generators built before 1960 can be modified and uprated by at least 15% [4]. The areas where most advances have been made since the time of construction are stator coil insulation, cooling, thermal analysis and computational tools.

Among Swedish hydropower generators a large variety of designs exist. As one part of the potential upgrading of the hydropower in Sweden a better understanding and description of the old hydropower generators in service is needed. If valid guidelines for future investment plans are to be made, it is necessary to understand the old generators in detail and also how their behaviour depends on design.

In this paper a brief historical review of the hydropower development in Sweden, together with an extensive review of the hydropower generator development in Sweden, is presented.

2. Historical background of hydropower extension in Sweden

Hydropower has historically contributed to the bulk of the electricity production in Sweden for more than a century. The first hydropower plant delivering electricity in Sweden was commissioned in 1882. The power was extracted with a dynamo (DC generator). The consumption had to be relatively close to the power plant because the rated voltage was low and the transmission losses were relatively high.

At the end of the 1880s the Swedish engineer Jonas Wenström discovered the advantages of the three-phase system. About the same time he started to construct the first three-phase generator, the same year 1890 ASEA (ABB Generation 1988–1999 and Alstom Power Generation 1999-) was established in Västerås, in Sweden. Alternating current gave an opportunity to raise the voltage by using a step-up transformer and consequently reduce transmission losses, which permitted larger distances between consumption centers and the power plants.

The history of large-scale hydropower in Sweden started in the summer of 1900 when Professor S. Arrhenius (awarded the Nobel Prize in chemistry 1903) and Associate Professor A.D. Åström were asked by the Swedish government to investigate the possibilities to produce electric power from waterfalls, especially for the electrification of railways. They were sent to central Europe where the development of hydropower for electricity production purposes already had started a few years earlier. The purpose of the journey was to investigate hydropower as a source of electricity with respect to juridical, technical and economical aspects.

At that time the industry worked on steam engines using black coal as fuel. This fact favoured the countries with a good supply of black coal but disfavoured countries that had to import black coal such as the Scandinavian countries. In 1900 electricity from waterfalls was beginning to be considered as an alternative to steam engines, especially for railway operation.

Arrhenius and Åström studied, during their journey, different constructions for extracting power from water falls. Areas of special interest were hydraulic engineering, which types of turbines were used for different heads and flows, how the generators were constructed, and transmission line design. Advantages and disadvantages of hydropower and steam engines were unraveled on both technical and economic basis.

In February 1901 they handed over the final report to the Swedish government. The conclusions were that hydropower was a good alternative to steam engines for railway operation. With a large utilization time, the hydropower plants were far more economical than the steam engines [5]. This was the starting point of hydropower development in Sweden. The general opinion at that time was that hydropower potential was very large and exceeding much the demands for all future.

In 1909 the Swedish State Power Board (later Vattenfall) was established. The purpose then was to handle the hydropower project Olidan in Trollhättan. This was the first large-scale hydropower project in Sweden and 13 aggregates were successively taken into commission between 1910 and 1921. The aggregates were rated 11 MVA, 11 kV, 25 Hz and 187 rpm, five times larger than those seen in Sweden before.

The development of hydropower in the southern part of Sweden continued during the first-third of the 20th century. At the end of 1930s the main part of the hydropower resources in the southern part of Sweden were exploited. The large hydropower resources situated in the northern part of Sweden were, at that time, practically unexploited. An exception was Porjus hydropower station on the river Lule älv, which was taken into commission in 1913. The aim of the power plant was to supply the railway between the iron mines in the northernpart of Sweden and the harbour in Narvik in Norway with electricity. Porjus is today the fourth largest hydropower station in Sweden with a rated power of 440 MW and has two full-scale aggregates available for education and research [6].

The large hydropower resources in Sweden are placed in the north while the main consumption is around 1000 km southwards, mainly the Stockholm area and the southern part of Sweden. This was a huge transmission distance at that time. The large distance between the centre of consumption and the north of Sweden, along with the lack of transmission capacity was the explanation why the resources in the north were practically unexploited until 1930s. In 1936 the first 220 kV line from the north to the south of Sweden was taken into commission. The extension of the hydropower rapidly increased and the transmission capacity soon became a bottleneck again. In 1952 the first 400 kV line in the world, 1000 km long, was taken into commission. The largest hydropower development in the history of Sweden now began and it peaked in 1950s and 1960s (see Fig. 1).

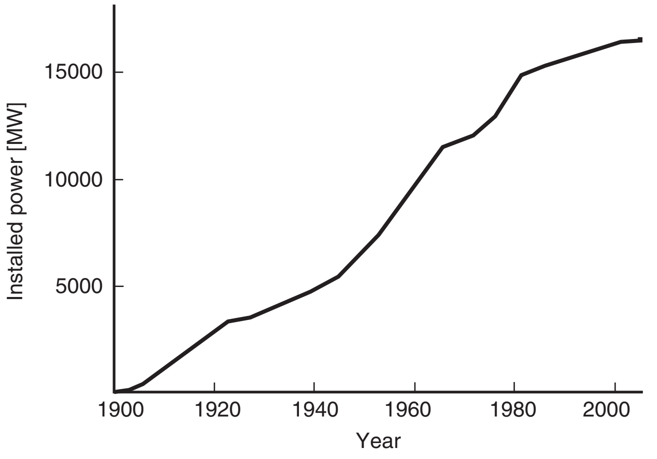

Fig. 1. Hydropower extension in Sweden during the 20th century [4].

At the end of 1960s development started to decrease mainly for three reasons:

- Nuclear power made its entry into Swedish electricity production and further development of hydropower was not considered to be necessary.
- Hydropower became strongly criticized from an environmental point of view.
- Further development became more costly due to increasingly difficult development conditions, and site access.

Today Sweden has 16.2 GW installed hydropower capacity, distributed on approximately 1900 hydropower plants, producing about 64 TWh a year with normal precipitation [7]. The construction of new hydro plants is virtually stopped in Sweden, on account of environmental and political considerations. Future activity is likely to be largely confined to modernization and refurbishment of existing installations. About 65–70% of the economical potential is utilized. Four relatively big rivers, representing about 17 TWh per year, Vindelälven, Kalix älv, Pite älv, and the Swedish section of Torne-Muonio älv, are unexploited (except a small hydropower plant in Pite älv) and are protected from future exploitation.

3. Hydropower generator design evolution

The technical evolution of energy-converting equipment such as hydropower generators has been strongly influenced by capital-reducing actions. The development has strived towards highly utilized and efficient, and thus cost-effective machines [8]. A number of technical breakthroughs have contributed to the development towards highly utilized and efficient machines. The ability of optimization has constantly increased with development of powerful computational tools. Computers started to be a part of the construction process in the middle of the 1960s. This increased the ability to optimize the machines and save time-demanding calculations. In the 1970s the finite element method (FEM) was introduced as a tool to perform detailed analysis. FEM simulations at that time were very time demanding and only specific details could be analyzed within reasonable time at the design stage. With increasing computer capacity, detailed FEM simulations have become a useful tool in design and optimization process.

The evolution has been affected by costs of material and manufacturing as well as loss capitalization. The unit rating has constantly increased during the expansion period since large machines, to a certain limit, often have lower costs per installed kW than small machines.

3.1. Assembling

Methods of assembling the rotor and the stator have always been a key factor in increasing unit rating. Large generators often demand special assembling and erection methods, since they cannot be transported as a whole unit to the installation site. The first rotor rims assembled at site in Sweden were the rotors at Hölleforsen power station in the end of 1940s [9]. On site assembling of rotors was a necessary condition for increasing the generator size further.

In the beginning of the 1960s ASEA was granted an application for a patent for a new method to put the rotor rim together. The rotor rim was assembled directly in the generator pit with a simple fixture, without presence of the rotor spider. With the new method there was no need to lift the whole rotor rim and the crane capacity could be reduced. This method also permitted the turbine to be erected at the same time as the rotor rim, which shortened the installation time.

3.2. Stator and rotor material

Until the 1930s the rotor rims were made by cast steel. The poor quality of cast steel limited the peripheral velocity of the rotor and prevented increasing the rotor size and thus the increase in rating. In the 1930s bolted thick sheet metal segments replaced the cast steel construction. The rolled sheet metal had much better tensile strength properties than the cast iron. In the end of 1930s thin sheet steel segments replaced the thick sheet steel as a standard, because of its advantages in the manufacturing process.

A crucial factor in increasing unit rating is the centrifugal forces on the rotor. The rotor rim can be exposed to very large stresses in the case of runaway speeds. The centrifugal forces have always put an upper limit for the diameter of the rotor. Yield points of rotor materials have increased substantially in 1900s. Modern rotor steel has yield points up to about 650 N/mm^2 [10].

The stator frame was, as the rotor rim, made of cast steel until 1930s it was constructed of welded steel as standard. The stator core was in the beginning of the 1900s built by unalloyed laminated hot rolled sheet metal with a thickness of 0.5 mm. The sheets were insulated by a 0.3 mm layer of cellulose material. Silicon-alloyed steel was not frequently used at that time, so the losses were very large up to 4 W/kg at a magnetic flux density of 1.0 T. In 1940s the cellulose layer was replaced by a thin varnish coating, which gave a higher fill factor, lower losses, and a smaller required magnetization as a result. The losses were further reduced by introduction of nonmagnetic press plates. Modern stator steel is cold rolled and has excellent magnetic properties and the losses are very low, compared to the steel at the beginning of the 1900s, around 1 W/kg at 1.0 T [10,11].

3.3. Stator insulation

The stator winding insulation is one of the most important components of the generator, since it puts an upper limit on the rated voltage. The main component in high-voltage insulation has always been mica due to its high dielectric strength [12]. A disadvantage with mica is its mechanical weakness; the mica splitting requires a binding material. It is mainly the binding materials that have changed over the years. During the first decades of the 20th century the insulation often consisted of organic materials, cellulosic paper and mica splittings with a shellac bond [13]. This type of insulation can withstand temperatures up to 90 °C.

In the beginning of the 1940s the first generators with asphalt impregnation were taken into commission. Asphalt bonds have several advantages towards shellac bonds. The temperature class could be raised from 90 to 130 °C, which gave a better utilization of the machines. The asphalt products posses better insulation properties and lower dissipation factor. The new insulation permitted an increase of the voltage level.

The evolution towards higher rated power and higher rated voltage required insulation with improved electrical and thermal properties. In 1963 a synthetic resin, Micapact, as a binder was tested for the first time. It consisted of glass/mica paper tape with epoxy as a binder [14,15]. The temperature class of Micapact was 155 °C. The Micapact system was improved about 15 years later [16–19]. The new insulation system named Micapact II had better electrical and thermal properties than its predecessor. Micapact II was tested first time in a Swedish hydropower generator in 1978. Fig. 2 shows the evolution of mica-based insulation systems in terms of average electric field strength.

3.4. Cooling system

In the beginning of the 1900s no special actions were taken to cool the generators. The air circulation produced by the rotor provided a sufficient cooling effect. When the

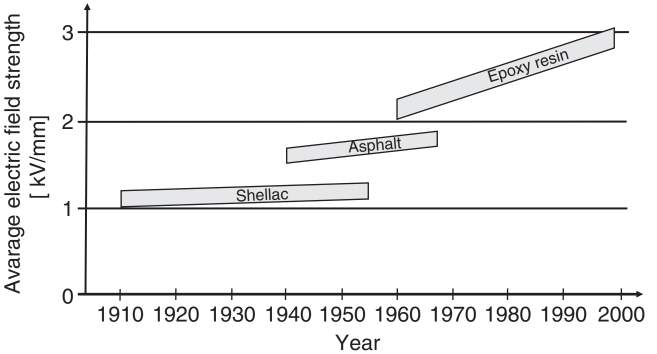

Fig. 2. The development of mica-based insulation materials.

machines increased in rating this solution was not enough. In the 1920s the generators started to be equipped with radial fan vanes mounted on the rotor. The fan vane solution was improved in the middle of the 1930s when the radial fans were exchanged by axial fans mounted on the upper and lower side of the rotor. The maintenance was reduced and the reliability increased in the beginning of the 1940s when closed cooling systems became the standard design. In the late 1970s the air-cooled design was further improved. The cooling air is forced through radial ducts in the rotor rim. This design provides a more efficient cooling than the earlier solutions, especially in axially long machines.

The cooling system of the generator plays a crucial role in the evolution towards highly utilized and efficient machines. The complexity of calculating the airflow pattern and cooling effect of the circulating air through the machine has often resulted in conservative solutions, with high losses as a result. Trimming the ventilation system is often the main object in improving efficiency. Today a long time experience of similar machines and development of computational fluid dynamics (CFD) provides better conditions to determine the airflow pattern [20,21]. Still there is substantial progress to be made in this area.

Water cooling has only been tested a few times in Swedish hydropower generators. Water has a superior cooling effect compared to air, which allow water-cooled generators to have a higher loss density and thus be more utilized. The first water-cooled generator in Sweden was at the Seitevare power plant, with a rated power of 225 MVA, taken in commission 1967 [22]. The generator in Seitevare was totally water cooled, both rotor and stator. The stator winding contained water ducts of stainless steel embedded in the coils. The rotor cooling was provided by cooling tubes inserted in every third turn of the field winding. The stator core contained blocks of aluminum alloy with a radial stainless steel tube inserted arranged in a ring around the stator core circumference. This cooling solution was estimated to reduce the dimensions and weights of the active parts of the generator with 25% compared to an air-cooled generator. The water-cooled generator in Seitevare is today replaced by a air-cooled generator because of failure in the cooling system. Water cooling was tested once more in Juktan pumped storage plant in 1976 and this machine was also replaced by an air-cooled type. The water-cooling system was considered too complicated and only feasible for very large machines and has never been tested anymore in conventional generators in Sweden since Juktan.

3.5. Unit rating

A consequence of the capital-reducing development is the constant increase in unit rating, even if the unit size depends on other aspects such as turbine and water engineering skills, since the cost per generated kWh often becomes lesser for big machines. The increase in unit size was exceptional in 1950s and continued in 1960s and 1970s (see Fig. 3).

Some of these generators in Fig. 3 are worth some attention. The three generators installed in Harsprånget in 1951 with a rating of 105 MVA were almost a world high, at the time, (108 MVA) [23]. The three generators in operation in Stornorrfors (installed in 1958) were the largest in the world at that time [24]. The combined motor/generator in the pumped storage plant at Juktan was the largest hydropower generator in Europe at the time of commission in 1976 [25]. The fifth unit at Harsprånget installed in 1980 is the largest generator in Sweden and was the largest in Europe at that time [26].

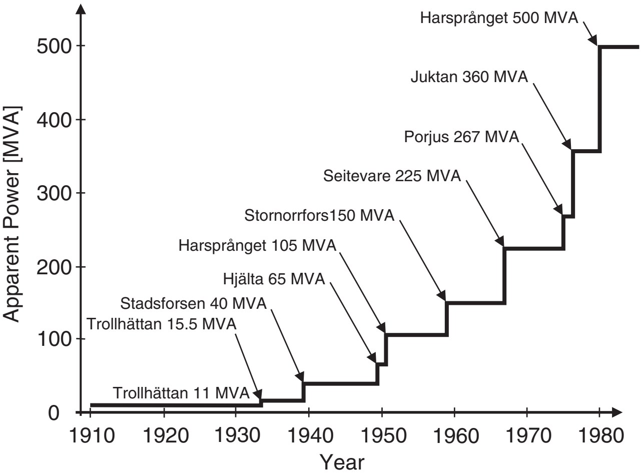

Fig. 3. The increase unit rating.

Table 1
Hydro Powerformers in operation in Sweden until now

Station name	Year in service	Rated voltage (kV)	Rated power (MVA)
Porjus	1998	45	11
Porsi	2000	155	75
Höljebro	2001	78	25

3.6. Powerformer

Until 1998 the rated voltage had been limited to about 20–30 kV. Then, ABB presented a new high voltage generator, the Powerformer [27,28]. It has some new features that make it possible to directly generate, without the use of a step-up transformer, at transmission voltage levels of hundreds of kV. The main difference compared to a conventional generator is the stator design. The stator winding consists of slightly modified high-voltage cross-linked polyethylene (XLPE) cables. The circular-shaped cables with XLPE insulation are able to withstand very high electrical field strengths. Powerformer has been designed for electrical field strengths of 10 kV/mm at the outer semi-conducting layer and 15 kV/mm at the inner semi-conducting layer [29]. In conventional mica-based insulation the field strength is usually limited to about 2–3 kV/mm. In Sweden there are three hydro Powerformers in operation so far (see Table 1).

Besides the generators shown in Table 1 there also exist two hydro Powerformers outside Sweden in Canada (Miller creek) and in Japan (Katsurazawa).

Along with the Powerformer concept a new water-cooling method of the stator was presented. The stator contains axial cooling ducts of a XLPE material in the yoke and the teeth. This system has worked out well without any major complications.

4. Summary

In this paper a brief review of the history of hydropower in Sweden and a more detailed review of the synchronous generator has been presented. The history of hydropower in Sweden started in the early 1900s and has, since then, been invaluable for the industrialization and welfare of the Swedish society. About 65–70% of the economic potential, corresponding to about 64 TWh per year, is developed and further development is unlikely, mainly due to political and environmental reasons.

The synchronous generator is an important part of the hydropower plant and many technical innovations have been made since the first generators were installed in the beginning of the 1900s. The most important progresses made to achieve more compact and cost-effective machines can be summarized as

- higher mechanical strength, especially in rotor materials,
- better electrical and thermal properties of the stator insulation,
- better magnetic properties of the electro steel,
- more efficient cooling methods,
- better optimization ability, mainly due better computer technology,
- better assembling methods.

Characterization of different types of constructions appearing during different periods of time can be useful to facilitate the development of guidelines concerning future investment plans and refurbishment.

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