The Swedish Development of Turbogenerators with directly water-cooled Rotors

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Abstract – **Large steam turbine-driven generators rated at a few hundred MW and higher constitute, in many respects, a big engineering challenge. The Swedish manufacturer of heavy electrical equipment, Asea was faced with this challenge in the late sixties, when the company started to develop such generators for nuclear power plants. Due to the company's background, it was necessary to choose new design concepts, and Asea decided on a very unique concept, turbogenerators with directly water-cooled rotors. The development led to difficult teething problems before the generators could be delivered and operate satisfactory; a process, which took around a decade to complete. Since then, the operation records have been very good. These turbogenerators constitute the only existing group with a significant number of two-pole, directly water-cooled rotors. The background, the development and results are summarized in this paper.**

I. THE START POSITION

Asea had, in the early 1960's, a position as one of the world's leading manufacturers of hydropower generators. An important reason for this was a large domestic market for such generators. The harnessing of the abundant energy from the Swedish waterfalls for electricity production started already in the late 19th century and the construction of new hydropower plants continued then for 70 – 80 years. During this long period, there was a stable growth in generator size and several Asea generators have been milestones also in the international development; some were the largest in the world at the time they were put into operation.

The situation for Asea as manufacturer of turbogenerators was very different, even if the company had delivered its first directly steam turbine-driven generator already in 1903. Steam turbines had been used for driving dynamos since the late 1880's, but the directly coupled turbo-generator with cylindrical rotor was first introduced around the turn of century. It had been invented by Charles E. L. Brown, who was one of the founders of Brown Boveri Co. (BBC). Some years later, in 1908, two Swedes, the brothers Birger and Fredrik Ljungström invented and developed a special type of steam turbine, the so-called double rotation, radial flow turbine. They established a company named Svenska Turbinfabriks AB Ljungström (STAL). The STAL-turbine was a reaction type turbine, in which the steam expands in radial direction from the steam inlet through two counter rotating disks Each disk was directly coupled to a generator rotor, so this concept implied that two identical generators shared the turbine power. For somewhat larger outputs, axial flow turbines were combined with the radial turbine as figure 1 shows. The advantages with the STAL-turbine were that they were very compact, had a good efficiency, and thus were cost-effective. This type of turbine proved to be very suitable for industrial backpressure applications and STAL manufactured large numbers of such units for installation all over the world. Usually, the industrial turbines were rated below 50 MW, consequently the two generators less than 25 MW each. Asea therefore became an important manufacturer of smaller turbogenerators. The delivery in 1965 of four 76.4 MVA, 3000 rpm generators for the Swedish State Power Board "Vattenfall" were the largest turbogenerators with which Asea had real experience when the rapid development of the much larger generators for the nuclear power plants started.

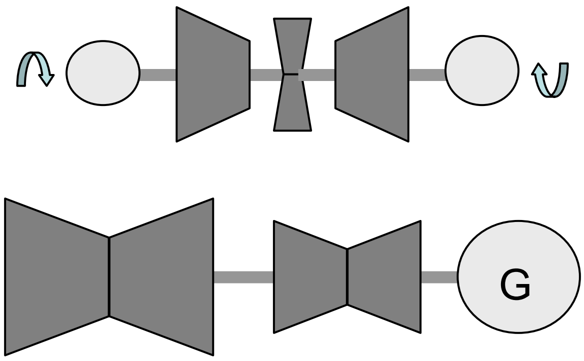

Figure 1. A radial flow high-pressure turbine combined with two axial flow low-pressure turbines requires two generators while a common axial flow turbine drives one generator

The diagram in figure 2 shows how the size of Asea's turbogenerators had developed until the mid 1960's. The corresponding international development has been included for comparison and also the hydropower generators. It is evident that Asea, at that time, had a pronounced profile as manufacturer of hydropower generators [1].

Turbogenerators were always delivered together with the steam turbines. All the large electrical companies built complete units consisting of both turbines and generators. There was hardly any separate market for turbogenerators and Asea had, in reality, only one customer for these generators, its own daughter company STAL.

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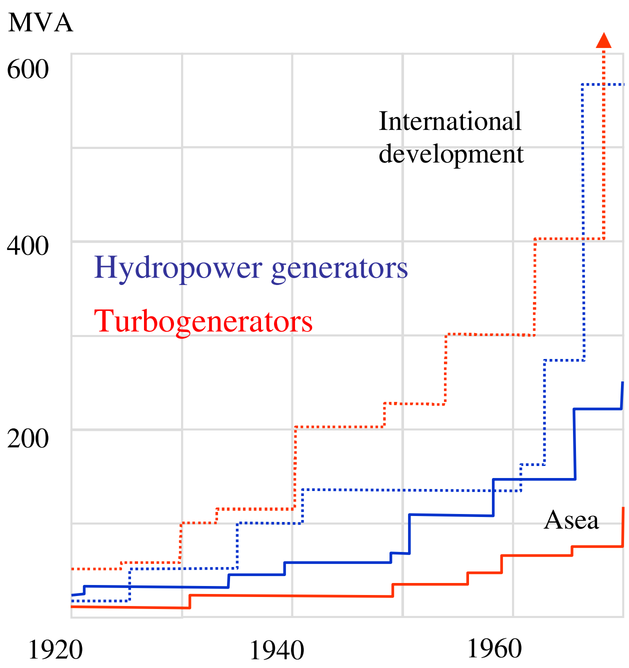

Figure 2. Increase in turbogenerator and hydro-power generator ratings for Asea and internationally

II. GENERATOR DESIGN

The rotor is usually the bottleneck in a turbogenerator, especially in two-pole machines, and the design of such rotors is very crucial. The rotor diameter is limited by the centrifugal stresses and the strength of the available materials. The active length is limited by rotor dynamic properties. If a rotor becomes too slim, it would be very difficult to avoid severe resonance vibrations induced at or near critical speeds. Furthermore, the total flux has to pass the rotor centre and it is important to avoid that this region becomes magnetically saturated. Cooling is always very essential for all types of electrical machines and it became more critical when the machine size increased. Air-cooling was clearly insufficient for large turbogenerators and the introduction of more effective cooling has been the main road towards higher ratings. The chosen cooling concepts have also had a big impact on the generator design in many other respects and were a factor, which differentiated the manufacturers from each other. The three main parts requiring cooling were the stator core, the stator winding and the rotor winding. In the early 1960's, most manufacturers used directly water-cooled stator windings for large turbogenerators and directly hydrogen-cooled rotor windings. Asea had introduced hydrogen for indirect cooling of turbogenerators above 50 MVA. The inner parts were in principle similar to those in the air-cooled generators with radial slot rotors, but they were contained in a tight pressure vessel.

Some different concepts were developed for direct hydrogen-cooling of the rotor windings and, in several respects, these concepts characterized the whole generator design. Two basic concepts could be identified, axial cooling and gap-pickup cooling, but both of these can then divided in a few variants. Many manufacturers used axial cooling (figure 3a). The rotor conductors are made from hollow copper and the hydrogen enters into these conductors through special openings at both end-regions and is discharged to the airgap through radial holes in the conductors and the slot wedges in the axially central part of the rotor. A variant of the axial cooling is the so-called sub-slot system, which also could be referred to as radial cooling (figure 3b).

A very different approach to provide the rotor winding with hydrogen for cooling is the gap-pickup principle. In this case, the slot wedges are provided with inlet and outlet holes so that gas could be taken from the airgap and forced through channels in the conductors before it is discharged back to the airgap (figure 3c).

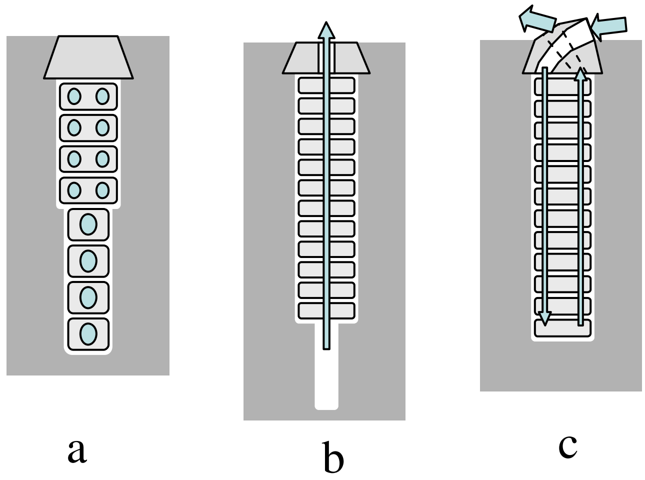

Figure 3. Cross section of hydrogen-cooled turbo-generator rotor slots with a) axial cooling, b) subslot cooling, and c) gap-pickup cooling

Common for all these rotor cooling concepts was a fairly complicated manufacturing process, but also the necessity to build the generators as pressure vessels with efficient sealings, and external systems for hydrogen supply and control, required much attention too.

Manufacturing of large turbogenerators was an important and also prestigious industrial activity during the sixties and seventies. In those years, there were around 20 companies, most of them in Europe, which more or less independently developed such large generators. Most industrialized countries had been much more dependent on fossil fuels for electric power production than Sweden. Oil and coal fired power plants generated most of the worlds electricity and the power plants had become bigger and bigger. To have fewer, but larger units in each plant was cost-effective and therefore, it had been a pressure on development of very large steam turbines and turbogenerators. Asea had not been subject to this and was clearly behind its important competitors in this field.

Direct water-cooling of stator windings represented state of the art in the late 1950's and had received general acceptance as a very efficient solution. Therefore, it was a natural question whether it would be advantageous to also use this method for cooling rotor windings. It was easy to figure out that theoretically water-cooling was superior to all other cooling methods, but the practical problems in providing rotating parts with cooling water caused hesitation. Nevertheless, several manufacturers started studies, including experiments, regarding water-cooled rotor windings. GE reports it had such a program from 1957 until 1963, but abandoned it in order to focus on development of gap-pickup cooling. Other companies pursued the water-cooling much further, notably BBC and Siemens but also the USSR manufacturer Electrosila, even if directly hydrogen-cooled rotors remained their main concept. The first turbogenerator with water-cooled rotor was installed for regular operation in USSR in 1959.

III. THE NUCLEAR POWER PROGRAM

The electric power supply in Sweden was almost entirely based on hydropower until the mid 1960's. The power consumption had shown a steady increase, since the end of World War II, and it was projected to continue to rise. Many waterfalls had been harnessed and it had become evident that the remaining hydropower resources would be insufficient for the future demand of electricity. In addition, environmentalists had begun campaigning for the preservation of the remaining rivers. It was hence necessary to start developing other power sources. Sweden didn't have any fossil fuels and it was therefore natural that the Swedish government initiated research aiming at the development of nuclear power. The initial concept was a heavy water moderated reactor with natural uranium as fuel. The government had given preference to this concept because of Sweden's own uranium resources.

In parallel with the government's efforts, some private and municipal Swedish power companies formed a consortium, OKG, for building a nuclear power plant, preferably with a light-water reactor. In July 1965, OKG placed a turnkey order with Asea for a 440 MWe nuclear power plant with a BWR reactor. Many alternatives had been studied before this decision was reached, and Asea had even negotiated a licence agreement with GE, but this was never signed. Asea decided instead to develop its own light-water reactor, which must be considered as a very brave and visionary step. Asea happened to be the only company in the world that developed light water reactors without licence from GE or Westinghouse. The steam turbine was ordered from STAL. It was a double rotation radial/axial turbine of the company's traditional type, but much larger than earlier units. The two generators were rated 271 MVA each, by far the largest turbogenerators Asea had received order for at that time. It was decided to use the hydrogen-cooled design for these generators, but with directly water-cooled stator windings. The rotor windings were indirectly hydrogen-cooled.

The State Power Board, Vattenfall had, during a few years, looked into the possibilities to build a nuclear power plant with a light-water reactor. The private power company OKG's decision to build Oskarshamn 1, pushed the government and Vattenfall to go ahead and plan a large nuclear power plant at Ringhals at the Swedish west coast. Orders for two units were placed in July 1968. Each unit should consist of one reactor and two parallel turbine/generator sets. Asea received an order for a 750 MWe BWR for Ringhals 1, while the turbines and generators should be supplied by English Electric. Westinghouse received the order for an 800 MWe PWR for Ringhals 2. STAL was chosen as supplier of the two turbines with generators from Asea. These generators were rated 504 MVA each. Less than a year later, Sydkraft, which was the leading partner in OKG, placed an order for a 600 MW unit with generator from Asea. Asea had thus, in addition to the Ringhals generators, an order for a 710 MVA turbogenerator, an enormous challenge taking into account that experiences from operation were still limited to turbogenerators below 75MVA. In 1971, Asea received firm orders from Vattenfall for four 577 MVA generators and options for another four. Even Finland needed more electricity and had also decided on using nuclear power. The private Finnish power company, Teollisuuden Voima Oy (TVO), planned a power plant located in Olkiluoto at the Finnish west coast. The contract for TVO 1 was signed in 1973 and for TVO 2 in 1974. [42] STAL was chosen as the turbine supplier including generators from Asea. The generators should be rated 825 MVA each, thus the largest ever designed and built by Asea. [1]

IV. STRATEGIC DECISIONS

STAL's old turbine concept had reached the end of the road. The combined radial-axial flow turbines could not handle the large steam flow from really big nuclear reactors; in addition, the experience from the thermal power plant in Stenungsund was discouraging. Therefore, the company had started to design its own axial turbine. The order from Vattenfall for Ringhals 2 in July 1968 was, in principle, based on this new design, but the matter was not finally settled. In view of the problems in Stenungsund, Vattenfall required that Stal-Laval should acquire a licence on an existing design. Therefore, a licence agreement was signed with BBC in April 1969 for steam turbines larger than 200 MW.

A very important question is now: "Why didn't Asea also take a licence for the corresponding generators?" The increase in size was the same. The generators also required new design concepts. The company had no experience with really large turbogenerators. Looking from the outside, it seemed like the prerequisites were more or less the same for the generators as for the steam turbines. Asea had a reputation as a successful supplier of generators, let be mainly for hydropower, but was confident that it was also capable of developing large turbogenerators. Electrical machines of all kinds were core business for the company and acquiring licences had never been part of the strategy. Therefore, according to well-informed sources, the alternative to take a licence also for the generators was never investigated or seriously considered. Looking at Asea's history, it is evident that the company had a long tradition of developing the necessary technology in-house.

The single most important technical decision for the development of the large turbogenerators was to use direct water-cooling not only in the stator windings but also in the rotors. This was different from what other manufacturers used to do and it had a profound impact on the entire concept and the course of events that followed.

Direct water-cooling results in lighter and more compact machines, which also are potentially more cost effective. The drawback is that it is complicated to have the water circulating directly through the windings and other active parts of a machine. This cooling principle is therefore only used when necessary, mainly for very large machines. As mentioned earlier, in case of large turbogenerators, the common solution was to have the stator winding directly water-cooled while the stator core, the rotor winding and other parts were cooled by hydrogen. Asea decided to avoid the hydrogen and apply direct water-cooling even in the rotor. A cross section of the rotor slot is shown in figure 4.

Figure 4. Cross section of water-cooled turbo-generator rotor slot with stainless steel cooling tubes.

In 1964, Asea had received orders for two completely water-cooled machines from Vattenfall, a 125 MVAr synchronous condenser and a 225 MVA hydropower generator.[2] The turbogenerators ordered in 1965 for OKG had only water-cooled stator windings, but the intentions from the management were clear according to the following short quote from a meeting in December 1966: "*All efforts shall be made to receive an order as soon as possible for a water-cooled turbogenerator, preferably for a peak power plant or a large gas turbine.*" The second part of the sentence indicates that the risk to go directly for a nuclear power application was considered too great. Asea's next completely water-cooled machine was, in spite of what has been said above, also a salient pole machine; a 345 MVA, 900 rpm synchronous condenser ordered by American Electric Power Company (AEP) for a transformer station in Dumont, Indiana [3].

Asea was not the only manufacturer working with directly water-cooled rotors. Some others also developed and built a few with water-cooled rotors. Manufacturers already mentioned were BBC, KWU (Siemens + AEG) and Electrosila. During the period of interest, the second half of the 1960's, BBC and KWU built one 2-pole generator each, and Electrosila also built a few 2-pole generators with this type of cooling. Later, during the 1970's, both BBC and KWU also built some very large 4-pole generators with water-cooled rotors.

The electric power consumption in Sweden increased year after year during the 1960's at a rate of 5 – 10 % annually. Prognoses made indicated a need for around 20 large nuclear reactors towards the end of the 1980's. The generator size had also grown and there were no reasons to believe that it would stop growing. Turbogenerators in the 1000 – 2000 MVA size were anticipated. For such large generators direct water-cooling of both stator and rotor was considered a necessity, at least within Asea. Therefore, Asea was of the opinion that by developing generators with water-cooled rotors, the intermediate step with directly hydrogen-cooled rotors could be omitted. This was probably the most relevant and also most important reason for the decision.

Managers at both executive and operative levels did not question the direct water-cooling. On the contrary, it was almost a policy to prioritize concepts, which would put Asea in the technical forefront. As a conclusion, the following reasons for choosing directly water-cooled rotors have been identified:

- Water is the most efficient cooling medium resulting in more compact and, for larger units, more cost effective machines.
- Water-cooling is also applicable for very large generators expected in the future when hydrogen-cooling would be insufficient.
- The company had started to use water-cooled rotors for salient pole machines, so this technology was already familiar to the organization and several synergies could be expected.
- Hydrogen-cooling is not a realistic option for hydropower generators, so by choosing direct water-cooling, it would be enough to develop only one technology.
- A few other leading manufacturers were also developing generators with this type of cooling.
- It was possible to avoid costly development of an intermediate step with direct hydrogen cooling.
- It was an advantage to avoid hydrogen due to the explosion risk, especially in nuclear plants with sophisticated ventilation systems.
- The stator housing did not have to be a pressure vessel with hydrogen sealings around shaft ends, terminals etc.
- No external hydrogen system was required.
- The concept represented state-of-art, which emphasized Asea's high-tech profile and this was preferred by the management.

V. TWO GENERATIONS OF GENERATORS

Asea built, during the 1970's, 15 turbogenerators with directly water-cooled stators and rotors (table 1). They can be divided in two generations, notwithstanding the fact that they all were subject for continuous development and had different ratings. The design of the first generation of represented a radical step in turbogenerator development and it is not surprising that there was room for improvements. There was first an almost fundamentalistic approach to the use of water-cooling for all components, even when this was neither technically nor economically the best alternative.

Table 1. Asea's originally delivered directly water-cooled turbogenerators.

Plant	No. of units	Delivery years	Power [MVA]	Voltage [kV]	Exciter
Aroskraft	1	1973	294	17.5	Static
Ringhals	2	1974	506.5	19.5	Static
Barsebäck	2	1975 - 77	710	17.5	Static
Ringhals 3 and 4	4	1977 - 79	577	21.5	Brushless
Forsmark 1 and 2	4	1978 - 80	577	21.5	Brushless
Olkiluoto, Finland	2	1978 - 80	825	20	Brushless

Some parts could preferably be air-cooled in a more traditional way. In addition, a number of faults had occurred during manufacturing, testing and operation of the first generators. All this led to development and implementation of many new solutions in later generators and they became therefore considered a second generation. The most obvious differences between the first and the second generation were the stator core cooling, the cooling circuits in the rotor and the excitation system. Figure 5 shows a sketch of a generator belonging to the first generation.

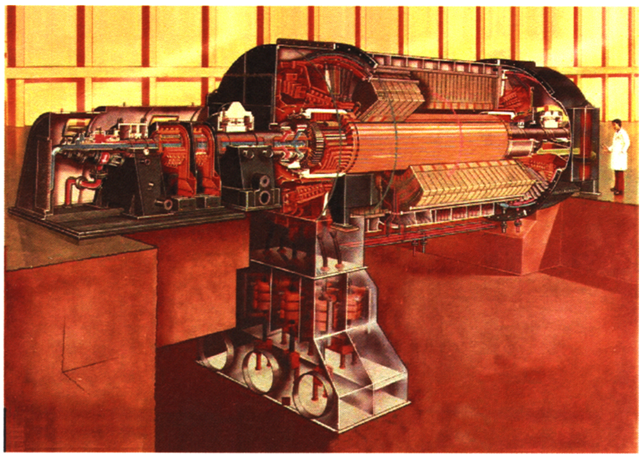

Figure 5. Directly water-cooled turbogenerator rated 710 MVA, 3000 rpm

VI. COOPERATION

During the most critical development period, the end of the 1960's and the first couple of years in the 70's, Asea's engineers had hardly any direct contacts with external experts and competitors. The only forum for communication with colleagues from leading competitor companies was Cigré's study committee for rotating machines. It can be concluded that the input of external knowledge was limited. This was probably not due to an underestimation of the need, at least not from the engineers concerned, but a lack of tradition. These engineers turned to specialists in Asea's Central Laboratory for help with certain problems as they had usually done. Two important factors could be part of the explanation why there was so little input of external know-how. One was that the organization was overloaded with all the large orders and simply did not have time for any outlook. Another was that Asea did not have sufficient experience from building large turbogenerators to be able to approach the leading manufacturers. You must have interesting information to trade if you expect to obtain any.

VII. MAJOR PROBLEMS

The manufacturing of the first water-cooled turbo-generators was problematic. The machines were complicated. The workshop faced a lot of difficulties and the operations took much longer than expected. The costs became very high. The risk for water leakages had been discussed as a possibility; therefore it was no surprise when the first leakage was detected in the autumn of 1972. This was the first in a long series of leakages, which led to a number of design modifications. Except for problems like these, the results from the performance tests of the first generators showed good agreement with predicted values, and losses as well as temperature rises met the guarantees.

The development, manufacturing and operation of the GTD generators initially created many problems, both technical and commercial. Many could probably have been avoided through a slower development pace and more comprehensive prototype tests, but several problems were shared with other, even larger manufacturers. The 1960's and 70's constituted a learning period for the generator industry and the knowledge increased partly through some generic failures, some of them very spectacular.

7.1 Water leakages in cooling tubes

The first water-cooled rotors suffered repeatedly from water leakages, first in insulating hoses, but most of them from small cracks in the cooling tubes in the end section of the rotors. Analyses of different cracks showed that they were usually caused by mechanical fatigue. The tubes were subject to both rotational speed and start-stop frequent deflections that initiated and propagated cracks. Asea modified the design of these cooling tubes in a number of steps increasing the flexibility and reducing the dynamic stresses to a safe level. The photo in figure 6 shows such flexible water inlets in rotor coils.

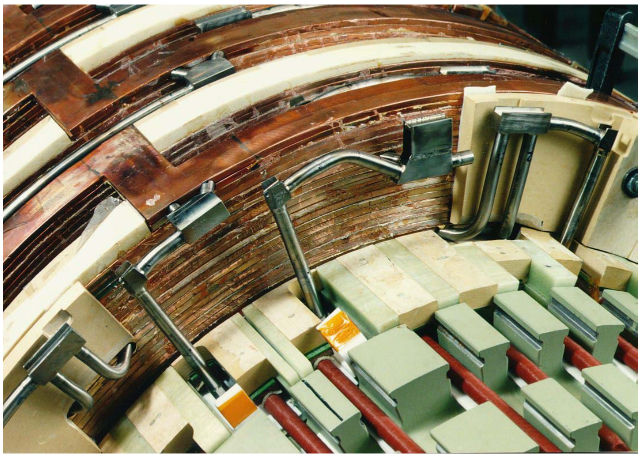

Figure 6. Flexible water inlets in rotor coils.

7.2 Stress corrosion in retaining rings

One of the units in Barsebäck was running with full load in the morning hours on Good Friday April 13, 1979. The operators on duty had, during 15 minutes, noticed a slight increase of the vibration level on the slipring side generator bearing, when the vibrations suddenly increased drastically. The unit tripped and a fire alarm was received from the turbine hall. An inspection could soon verify what had happened. It was a matter of a retaining ring explosion. The slipring-side retaining ring had broken into three pieces, which were thrown out through the stator end-winding and the generator end-cover. One of the heavy pieces hit the pedestal bearing so lubrication oil was sprayed around. The short-circuit of the winding caused arcing that ignited the oil and created the fire. The investigations would very soon focus on the reasons for the retaining ring failure. Figure 7 shows the machine hall with the destroyed generator.

The examination of the fractured surfaces revealed a primary crack caused by stress corrosion and secondary ductile fractures due to sudden overload. The retaining rings were made of a special, high strength, non-magnetic, austenitic steel and it was known that it could be sensitive to stress corrosion if it was exposed to water in combination with high stresses. The generator had been in continuous operation for almost one year when the failure occurred. No water leakages had been detected, but were nevertheless a matter for further investigations. The metallographic analyses indicated that the stress corrosion crack had grown over 6 – 9 months and the area where the crack started, on the inside of the ring, was not ventilated. A non-detectable micro leakage could have moistened the insulation material in contact with the ring.

Figure 7. Barsebäck generator hall after retaining ring fracture in April 1979.

Many manufacturers of large turbogenerators used the same retaining ring material and Asea was not the only turbogenerator manufacturer which experienced a retaining ring failure.

A study presented at an EPRI workshop on “generator retaining rings” in October of 1982 reported 38 fractured rings [4]. The matter of cracked retaining rings had, up till the Barsebäck accident, not received much public attention in the industry. The manufacturers tended to keep most information to themselves. Since then, a replacement material has been developed, which is stress corrosion resistant in water and humid atmosphere.

7.3 Cracks in rotor bodies

Cracks in electrical machine rotors can be disastrous, especially in the case of large machines and high-speed machines. Asea experienced some serious rotor body cracks in the generators supplied to TVO in Finland, a situation which required very special measures before it was solved. The solution involved the use of advanced and partly new theoretical tools as well as methods for monitoring and inspection.

In connection with a minor repair, inspections revealed cracks located at the bottom of winding slots right at the end of a rotor, as shown in figure 8. A method was quickly developed for ultrasonic crack inspection from the rotor surface. The inspections showed similar cracks in the rest of the teeth and also at a rotor still in use in the power plant. Both rotors had been in operation for a few thousands hours and had been subject to more than 100 start-stop cycles. It was decided to repair the faulty rotors simply by removing the cracked zone through machining and modifying the design to get rid of all stress-rising notches etc. This shortened the active length by less than three percent and would not reduce the generator performance. The repairs were quite time-consuming. In the mean time, one of the TVO units could be kept in operation with a third rotor. The same type of cracks could, however, be expected to occur in this rotor and it was therefore important to carry out ultrasonic inspections at regular intervals, and to carefully monitor the rotor vibrations.

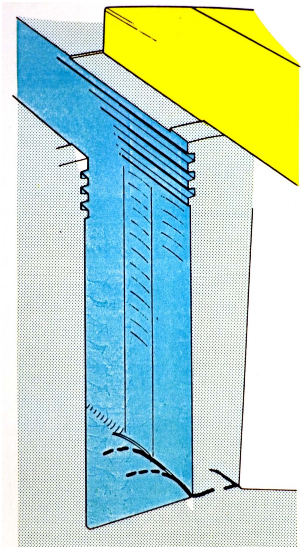

Figure 8. Fatigue cracks initiated at the slot bottom at the rotor end. The cracks propagated slowly and turned radially inwards to the rotor centre.

Why had the cracks in the TVO rotors occurred? It was obvious that they had started in a sharp notch, but no tensile stresses had been anticipated right there. Theoretical and experimental investigations revealed that this was wrong. A combination of low and high frequent dynamic stresses had caused the cracks. Fracture mechanics was used to calculate the threshold crack depth, the propagation growth rate, and the critical, instable crack size. The stress pattern was complicated but the analysis indicated that it would take in the order of 10 months for a crack to propagate to critical size, and this size was slightly more than half of the rotor cross section. The rotor stiffness would change significantly, long before a crack could become critical, so accurate vibration monitoring should prevent a dangerous situation from occurring as long as the old rotors were used [5].

The turbogenerators in Olkiluoto were not the first that had this kind of problem. Both British and French turbogenerators had been subject to similar or even more severe rotor cracks. However, comprehensive investigations were started in order to find a correct explanation for the initiation and propagation of the discovered cracks. Extensive know-how was built up, the rotor designs were improved and new methods for inspections and monitoring were developed. It can be argued that Asea had been too ignorant before, but it seems as if other manufacturers had acted in similar ways.

The vibration monitoring, introduced at TVO during this critical period, has later become a standard praxis for large power plant turbines and generators. It is of importance to note that the new rotors, which were installed later in 1981, have performed without any problems. The design was improved at a number of points resulting in much higher safety factors with respect to all types of fatigue stresses. The cracks in the original rotors had practically nothing to do with the water-cooling of the rotors, but rather with traditional extrapolation difficulties.

VIII. OPERATION RECORDS

It is evident, from what has been written that the first generators as well as those in Olkiluoto had a difficult time with serious teething problems. The second generation, which comprises the eight machines for Ringhals 3 and 4 and for Forsmark 1 and 2, has performed reliably from the very beginning. The others have done so after they have been modified or provided with new rotors. This means that the operation records from the early 1980's up until now have been very good. This is proved by statistics but perhaps more important by the fact that the power companies have chosen the same technology and supplier also in the case of new, machines upgraded to higher outputs. The diagram in figure 9a shows how the unavailability for the water-cooled GTD generators has varied over the years. The result has become very good, also in comparison with other large turbogenerators as shown in the availability diagram in figure 9b.

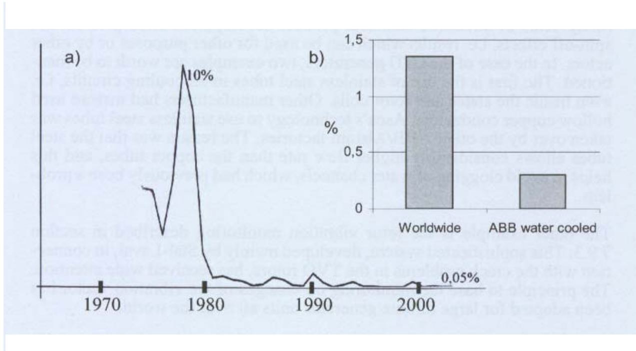

Figure 9. a) Unavailability for Asea/ABB's water-cooled turbogenerators, b) accumulated generator unavailability in nuclear power plants during 1980 – 2000.

IX. CONCLUSIONS

The development of the water-cooled generators must be considered as a major technical achievement for a country like Sweden. The concept was at the beginning seen as daring and pioneering. It was different from what was usual in the industry and some viewed it as too risky. Many problems occurred and the these generators were, for a number of years, not only questioned but even regarded as a serious failure. Extensive development efforts solved the problems and the generators have for decades had a very good reputation. They have during the last 25 years generated around 30 percent of Sweden's electric power. A corresponding figure for Finland is 20 percent. The concept has been maintained and the technology is in no respect obsolete.

Some explicit conclusions are:

- Asea chose the fully water-cooled concept:
  - to avoid development of directly hydrogen-cooled rotors as an intermediate step,
  - because it was the most efficient cooling method,
  - and also due to synergies with large salient pole synchronous machines.
- Asea's immediate challenge Asea became too large due to the drastic increase in machine size in combination with simultaneous orders for generators with different ratings.
- Asea underestimated the difficulties when they decided to make most of the development on customer orders. Manufacturing and testing of a full-size prototype as basis for the order design had eliminated several problems and saved a lot of costs.
- Mutual exchange of technical know-how with other manufacturers increased substantially, as expected, when Asea had gained certain experience

No generators of this particular design have been built for other countries than Sweden and Finland. Very little of the technology has been taken over by others. This could indicate that the concept is not competitive enough, but on the other hand, it has been preferred in open competition for recently upgraded units. The cost-effectiveness is therefore probably not much different from other designs of large 2-pole turbogenerators. Each manufacturer tends to hold on to their existing designs. The explanation is more likely to be found in the market and industry structure. The market for large steam turbines and generators had just started to shrink when Asea had solved the technical problems. There were simply no possibilities for Asea to sell large turbogenerators when the international situation was characterized by large overcapacity. The conditions became different when Asea became part of ABB. This company had access to the global market and could have decided to include the completely water-cooled generators in deliveries of large steam power units, if advantageous. This has not been done, the concept with directly hydrogen-cooled rotors, emanating from BBC, has instead been chosen. Why, is it better? This question is difficult to answer. The uniqueness of the Asea generators is the water-cooled rotors and absence of hydrogen. The management of ABB's, and later Alstom's, turbogenerator operations located in Switzerland, has obviously come to the conclusion that the customers prefer more conventional, hydrogen-cooled generators and the possible incentive for a shift of concept will not outweigh the risks. It is, of course, difficult to motivate radical design changes when the market for really large turbogenerators has become limited.

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