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A Study of Power Formers and Their Impact on Power System Reliability and Environment

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Abstract: Conventional high-voltage generators are designed with voltage levels rated to maximum of 30 kV. The power grids with voltages as high as 1,100 kV cannot be directly supplied from these generators, power step-up transformers are used to transform the generated voltage to high transmission voltage level suitable for the interface with the transmission grid. These transformers impose significant drawbacks on the power plant as a whole - reduction in efficiency, high maintenance costs, more space, less availability, and an increased environmental impact. During the last century, a number of attempts were made at developing a high-voltage generator, the Powerformer, that could be connected directly to the power grid, without step-up transformer.

When XLPE-insulated cables were introduced in the 1960s there were some initial problems with their reliability, caused by poor control of the manufacturing processes. These problems have since been overcome, and today's high-voltage XLPE-insulated cables have an impressive track record. Therefore, the development of the Powerformer is inherently linked to the reliability and the development of the XLPE insulated cables. The powerformer has opened a new technological chapter in the generation and transmission of electrical energy. The technological advantage offered by the powerformer was studied in good detail and their impact on reliability in particular and environment in general was highlighted.

Index Terms— Powerformers, high-voltage generators, power system reliability, power step-up transformers, conventional generator.

I. INTRODUCTION

Today, the three-phase synchronous generators are used in all power plants around the world. The output voltage of the synchronous generators is limited to a maximum of 30 kV due to insulation restrictions. Therefore in power plants, step-up transformers are necessary to increase the output voltage of the generator to the voltage of transmission lines. In 1998 for the first time a high-voltage generator called Powerformer was invented [1]. It could generate voltage at the level of transmission lines through an innovation in configuration of the armature winding of stator.

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With these new generators and by generating of high voltage in terminals of the generator, the step-up transformer can be removed in power plant .
Figure 1 illustrates the difference between conventional power plants and power plants Powerformer.[7]

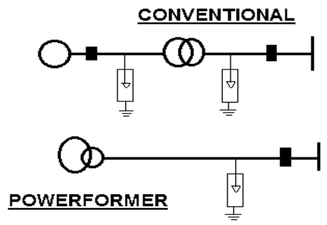

Fig.1. Single line diagrams, conventional (top) and Powerformer power-plants

In Powerformers, for armature winding, high voltage XLPE cables are used instead of the rectangular coil in conventional generators. Therefore, the restrictions that exist in conventional generators due to insulation have been removed by replacing rectangular coil with a round cable, and generation of high voltage at terminals of the generator was possible. Number of turns per phase has also been increased to increase the voltage. [8] Slots for conductors in powerformers are different than conventional slots in synchronous generators. The slots in Powerformer are deeper than the conventional generators, so that a greater number of turns in each slot could me placed. Also the cross section of slot is such that it encloses the cables.
Due to the increasing number of turns in each slot, the induced voltage is gradually increased in stator winding of powerformer from neutral point to line terminal. Therefore, the cables in the slot are subjected to different electrical voltage along the length of the winding. It is therefore possible to use different cables with different thicknesses in each slot. [8].
The step-up transformer is imposing great disadvantages in the power plant as a whole, from reducing the efficiency, high maintenance costs and more space, less availability and not to forget the increased pollution due to the plant. During the last century, have been a number of attempts to develop a high-voltage generator, which could be connected to the electricity grid, without going through the step-up transformer. But although voltages in grid can reach 800 kV or more, generators are currently being designed for voltages up to 30 kV only, as indicated above. ABB, in close cooperation with Vattenfall (the Swedish state-owned utility) has developed a new high-voltage generator with innovative features such that it can be directly connected to the transmission grid.[3] Its Output voltage can reach values of up to 400 kV, With the new technology, future transformer-less power stations can be built leading a new concept of energy systems.

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The new machine named "Powerformer" has its advantages such as higher efficiency, higher availability, lower maintenance costs and reduced environmental impact, which are simply consequences of the transformer-less power stations.

A. *Conventional generators*

The stator windings of the conventional generators consist of rectangular conductors, which are placed in the stator slot. The main objectives of the rectangular conductor shape selection are to maximize the load current and the filling factor.[8] According to Maxwell's equations, the shape of these conductors leads to an uneven electric field and a magnetic field distribution with values, established at each of the four corner slots, as shown. This intensification of the corner field dictates the use of insulating materials with extremely high dielectric strength (eg: mica sheet set in epoxy resin). The practical consequence of a rectangular conductor in an electric machine is that the insulation and the magnetic materials of the machine are highly stressed and loaded non-uniformly, and this leads to an inefficient use of the materials involved. A defect in the machine because of high electrical voltages of the insulating materials is also very likely.[7] Therefore complex measures have to be taken in the end winding region, in order to control the electric field, in order to avoid partial discharges and corona. In order to minimize the eddy current losses in the stator coils, the copper laminations constituting the conductors must be transposed along the winding according to an elaborate scheme.

B. *Going against convention*

The powerformer, although a new machine is a three phase synchronous generator with a rotor of a conventional type. The fundamental difference, compared with the conventional generator, is located in the Stator windings. In Powerformers, the stator winding is made of high-voltage cables instead of the conventional rectangular cross-section windings. To increase the output power of an electric machine, either the output voltage level or the current in stator windings must be increased. Insulation technologies limited output generated voltage, so the solution now was to increase the current in the stator, instead of the output voltage. However, in Powerformers, the output power is increased by increasing the output voltage by using XLPE cable in the stator winding.[13]

C. *Advantages of Powerformer*

In contrast to conventional generators, the windings of Powerformer have cylindrical conductors. As can be deduced from Maxwell's equations, there is an even electric and magnetic field distribution in cylindrical conductor, which is a prerequisite for a high voltage electrical machine. As already mentioned, there is a stator winding of high voltage cables in the powerformer. Consequently, the output voltage of the Powerformers is limited by the state-of-the-art high voltage cable technology.[8] Recently, insulation materials and production techniques provide reliable cables at operating temperatures gradients in the order of 10 kV / mm and more. Such a high electric field is not suitable for conventional mica / epoxy based coil insulation. Circular cross-section of cable solves the two main problems arising from the use of conventional rectangular stator windings:

- First, within the stator slots, insulation performance and the voltage rating of the cable is maximized by the uniform electric field in the insulator.
- Second, by bending a cable with circular cross-section there are no kinks and sharp edges that arise when using a rectangular cable. Thus, even in the end regions where the cable is bent to make transition from one slot to the next slot, the electric field inside the insulator is free from singularities. Even at the end regions of Powerformer, the electric field is confined within the cable. Hence the need to control an external electric field, as in a conventional machine, is eliminated in the Powerformer.

II. POWER FORMER CONCEPT

Powerformer, although a new machine, it is a 3-phase AC generator with a rotor of a conventional design.[14] The difference in comparison with conventional generator is located in the stator windings. In Powerformer, stator winding consists of high-voltage cable instead of square cross-section windings used in conventional generators. By the use of high-voltage cables as a generator stator winding, it is possible to highly increase the generated voltage. The crucial difference between this design and modern technology is that Powerformer allows direct connection to the high voltage network.[14] This is illustrated in Figure (2).

1. Generator
2. Generator circuit breaker
3. Surge arrester
4. Step-up transformer
5. Line circuit breaker

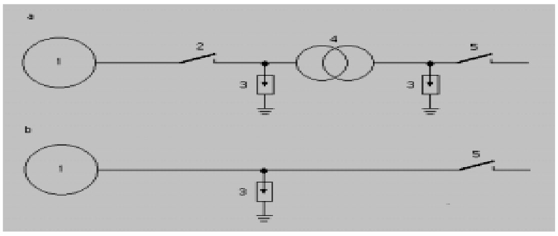

Fig.2 Schematic diagram of a conventional plant with step-up transformer (a), and the same plant when the new technology is used (b).

This design results in the omission of generator circuit breaker, the high power bus and the step-up transformer from the power plant, because Powerformer includes the features of both the generator and step-up transformer as shown in Figure (2). As a consequence there is an increase of up to 1.5% of the total electrical power efficiency in comparison with the today's best designs, without using superconductive materials. Reactive power output and overload capability are also improved in powerformer. There are also major changes in design, engineering, manufacturing and production of the complete plant. These give a total reduction in size and weight, which has a lesser impact on the environment. The technological basis of the new machine gives a promising future possibility for both water-and thermo-power stations and other electrical devices.

III. INNOVATIVE DESIGN PARAMETERS

Powerformer is designed with several unique features that allow it to exceed the limit of 30 kV, including a winding consisting power cables and innovative stator design.

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A. Powerformer windings

Powerformer's magnetic circuit makes certain demands on the winding. The winding consists a power cable with solid insulation and two semiconducting layers, one surrounding the conductor and the other outside of the insulation used, the semi-conducting layers serve as equipotential surface, which forces the electric field to distribute uniformly around the circumference (see Figure (3)).

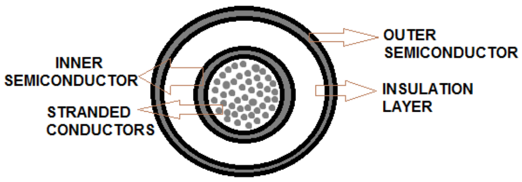

Figure 3. A cross section of the power cable used in the stator winding of Powerformer.

The insulation material used here is cross-linked polyethylene (XLPE), a material successfully being used in high-voltage power lines since the 1960s. The cables are threaded through the stator slots, forming a winding which produces the desired high voltage. [9] The use of high-voltage cables in Powerformer windings offers significant advantages over conventional designs. Firstly, in conventional generators to favor maximizing the current loading in the machine, rectangular conductors are used in order to obtain a maximum packing density of copper for the stator windings. These conductor shapes, however, result in a non-uniform field distribution with high field concentrations at the corners of the circuit, as shown in Fig(4).

As previously indicated, the winding of the Powerformer consists of insulated high voltage power cables, that is similar to the commercial and standard power cables in power distribution system used. However, the cables in Powerformer neither have a metallic sheath nor a screen.

The Powerformer Winding cable consists of stranded conductors, inner semi-conductive layer, a solid dielectric (usually XLPE), and an outer semi-conductive layer. The purpose of the inner semi-conductive layer is to create a uniform electric field on the inner surface of the insulating layer while the outer semiconducting layer acts to limit the electric field within the insulator.

The word "semiconductor" refers to a material having a relatively high resistivity,in this case which is XLPE doped with carbon. Such a semiconductor is, more specifically, a resistive conductor.

In general, in stranded conductors there is a central wire surrounded by concentric layers of 12, 18, 24, 30, 36 and 42 wires. This is commonly called "concentric-lay" conductor. Each layer is applied with alternate directions of lay. The wire cross-section is to be dimensioned in relation to the prevailing system voltage and the maximum power of the generating unit. A conductor inserted into an electric machine is subjected to a higher magnetic flux leakage than a conductor in a transmission or distribution systems.

In order to minimize the additional losses due to the magnetic leakage flux in the Powerformer conductors, it is necessary to divide the conductor into mutually insulated strands. The majority of the strands may be insulated, but to ensure a common electrical potential of the strands and the inner semi-conductive layer, one or more of the strands in the outermost layer may be non-insulated. The voltage induced in stator windings of Powerformer is gradually increased from the neutral point to the line terminal. Therefore, the cable used for the stator winding is exposed to various electrical stresses along the length of the winding. It is therefore possible, in a powerformer, a thinner insulation for the first turns of the winding, and thereafter increasing the thickness of the insulation used. This is known as "stepped insulation".

A method of obtaining this is by using a predetermined number of different dimensions of cables per phase (i.e. a gradual increase of the insulation thickness). This type of insulation allows better optimization of the volume of laminated stator core. Also stepped insulation's effect is to ensure that the tooth width is effectively constant along its length, and independent of the radial expansion, keeping the flux density constant.[9]

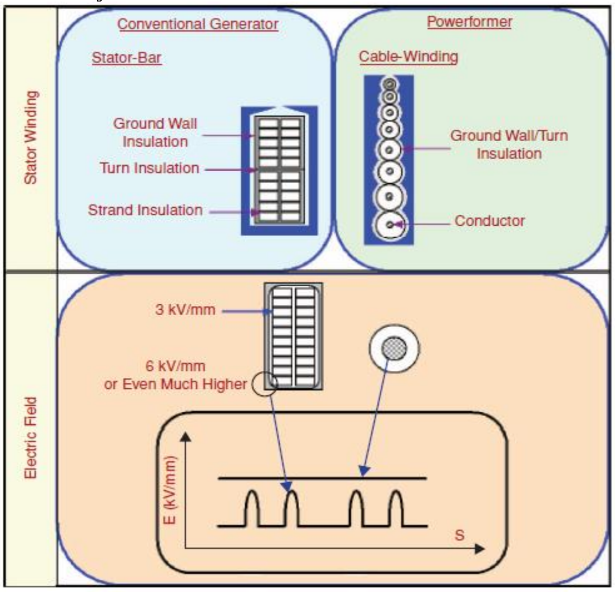

Fig. 4 Stator bar of the conventional generator and stator cable winding of the Powerformer

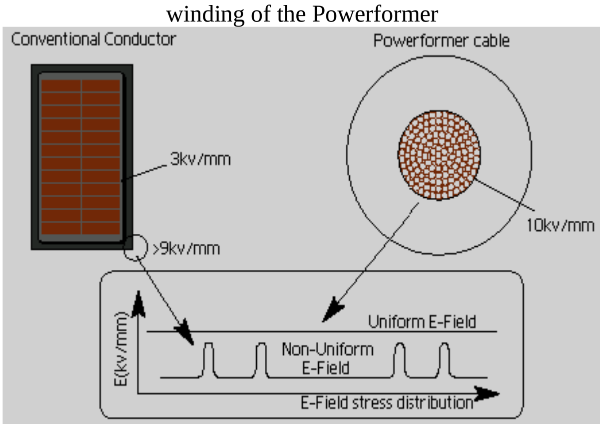

Fig. 5 Powerformer cable in comparison with conventional rectangular conductors.

Such field concentrations generates material stress and prevents the output voltage of the generator to be higher than 30 kV. Powerformer windings on the other hand form uniform electric field. This means that the insulating material is evenly loaded and used in an optimal way. Secondly Powerformer cable for an electric field strength of 10 kV / mm, which should be compared with the 3kV/mm is designed to be able to manage today's generator windings (Figure (5)).

These characteristics in combination greatly increase the voltage generated.

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With high voltage cable generator windings fully insolated, be an arrangement that minimizes the risk of partial discharges and internal two and three-phase fault. The stator current in Powerformer is much lower than with conventional generators -. With equal rating due to the high voltage generated, mechanical forces acting on the end winding are low.

This allows the bracing system for the end winding as compared to the conventional generators can be simplified. Using high-voltage cable has a positive effect in terms of the reliability of the generator. In a comparison of the number of defects in high-voltage cables statistics show that high-voltage lines have fewer faults. Powerformer itself is expected to have fewer errors than conventional generators. Since the potential along a winding increases with every revolution (Maxwell's equations), the cable insulation which needs to be increased accordingly. It is therefore possible to use thin insulation for the first turn, and then increasingly thicker insulation for subsequent turns an arrangement called "graded insulation", allows the optimum utilization of the volume of the laminated core and the solid insulating. The entire cable sheath (outer semiconductive layer) is connected to ground potential, so the electric field outside the cable (in the coil-end region) is close to zero.[8] Since the outer shell is at ground potential, there is no need for the further control of the electric field. Thus field concentrations in the core are removed, in the coil-shaped end portions and in the transition region between them. The field of conventional generators have to be controlled at several points per turn. [9] To optimize the cost of cable and to have ability of several output level in terminals, three types of standard XLPE cable used 11.33 and 63 kV in the stator slots Powerformer. In each slot, there are 12 XLPE cables in such a way that two of the first cables near rotor surface 11 kV cable and the next four 33kV cables are behind them and the last six cables are 63 kV.

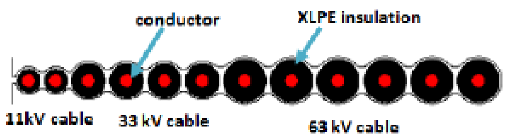

Fig.6 - The proposed slot of Powerformer and the cables inside.

In combination, it is clear that the neutral point of first conductors near the slots (near rotor surface) and the terminals of the generator are in the vicinity of the cable at the end of the slot.[9]

B. Non conventional stator design

The Powerformer is equipped with a conventional rotor. The Powerformer stator is constructed from a laminated core, built from electric plates. Teeth point in the outer portion inwardly towards the rotor (in the middle). The winding is located in the slots between teeth.[9] The cross section of the slots in the direction of the rotor decreases, since each winding turn requires less cable insulation closer to the rotor. The cross-section of the winding cable is accounted by the stator slot design. Each slot having circular bores at intervals to form narrow waist between the winding layers. The slots should surround the housing of the coil as close as possible. Simultaneously, the teeth should be as wide as possible at each radial plane. This will reduce the losses in the machine and also the required excitation current. The stator teeth can be formed so that the radial width of the slot is substantially constant over its entire length. This balances the loading of the stator tooth.[10] The winding can be described as a multilayer concentric winding, which means that the number of coil ends crossing each other is minimized. This feature allows simpler and faster threading of the stator winding. Figure 7 (a) and (b) shows a sectional view of the powerformer stator, the temperature distribution to a stator slot.

As a result of using a high-voltage cable in the stator winding corresponding to an increase of the output voltage to a decrease in the charging current in the machine for a given input power. Therefore, a lower current density leads to lower resistive losses in the machine.[9] The outer semiconductive layer is connected to the earth cable. Thus the electric field outside the outer semiconducting layer in the vicinity of the coil end portion is zero. Consequently there is no need for controlling the electric field in the coil-end region, as in the conventional generator. In the conventional generators, the field is to be controlled at several points per revolution. This eliminates field Concentrations in the core, the coil end portions, and the transition between them. There is no risk for either partial or corona discharges in each region of the coil. Moreover, the personal safety is increased substantially as the endwinding region is at ground potential. Because of the lower currents and current densities, the current forces in Powerformers are considerably smaller than for conventional generators. As a result, the support for the winding heads will be easier in the power conditioner. Another important aspect in the construction of a powerformer is to minimize vibration of the cable. To achieve this goal, and to ensure a good electrical contact between the cable and the laminated core, the cable is fixed in the slot. It is mounted on a triangular shaped silicon rubber tube, which is inserted between the cable and slot wall as the figure 7 shows. [10].

The shape of the cross section of the rubber tube is adapted to necessary elastic deformation, allowing the fixation forces to be kept within certain limits. This limits the maximum force, reducing the viscoelastic deformation of the cable cross-section. A minimum Force must be kept at low temperatures, to avoid the loss of contact between the cable and slot wall. However to avoid local deformation of the cable at the end-winding region due to vibrations and tension forces, the cables are separated by a rubber spacer.[10]

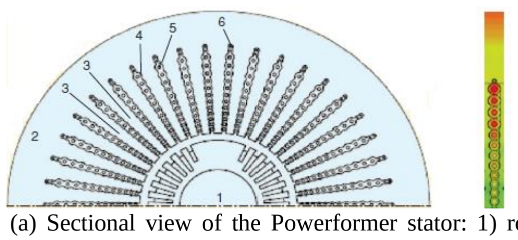

Fig. 7 (a) Sectional view of the Powerformer stator: 1) rotor, 2) section of stator, 3) teeth, 4) slots, 5) main winding cable, and 6) auxiliary winding , (b)temperature distribution around a stator slot

Each slot has circular holes at intervals to form narrow waists between the winding layers, as shown in Figure (8) below.

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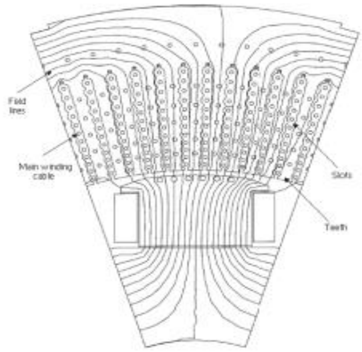

Fig.8 Section of the stator in Powerformer.

From the analysis and synthesis it was found that the principal losses in Powerformer are associated with the laminated iron core. Therefore, the stator core in Powerformer (Figure (4)). is axially cooled by water pipes of XLPE. The water cooling is done at zero potential (in the core) and is completely separate from all E-fields.

IV. EFFICIENCY

In general, a power plant with Powerformer 0.5-1.5% has higher efficiency than conventional power plants (Powerformer plants 0.5-1.5% suffer less active losses than conventional plants losses). For a 120-MW power plant, the figure is around 1.5%. This means that a system with Powerformer produce 1.8 MW more power than a conventional system. This additional power, of course, improves the efficiency of the entire system.

V. ECONOMY

Using the Powerformer in a given power system has a significant effect on the total plant cost. The cost reduction is due to high efficiency, less waste and low environmental impact. A study was conducted to show how a Powerformer may affect the economy in hydropower project. The aim of the study was to use the existing hydroelectric power plant in India compared with a hypothetical plant with a poweformer. The annual electricity production is 3,200 gigawatt hours.

There are four turbines, four generators and 13 single-phase transformers. Four Powerformers are used to replace the four generators and the 13 single-phase step-up transformers. The total cost savings associated with Powerformers due to lower construction and maintenance costs were estimated at 24% in addition to the increase in power generation of 17 GWh (0.56%).

VI. REACTIVE POWER CAPABILITY

The generation of reactive power is needed to compensate for the reactive power losses in the transmission networks. In a Powerformer, the reactive power losses are eliminated in the step-up transformer. With more reactive power capability Powerformer will be a competitive alternative to traditional reactive power compensators (RPC) because Powerformer, in contrast to traditional RPCs can be overloaded over quite a long time, due to its rugged construction. This function is required when disturbances in high-voltage transmission networks are observed. For example, neither the copper windings nor the laminated core can be influenced by any rapid temperatures in Powerformer, which reduces the risk of damage to the generator insulation.

VII. MAINTENANCE AND AVAILABILITY

Powerformer based plants are easier to operate with substantially smaller number of components than conventional units, a realistic situation is provided (9) below.

1 Generator hall 3 Bus-bars system
2 Generator 4 Tunnel system
5 Transformer bay

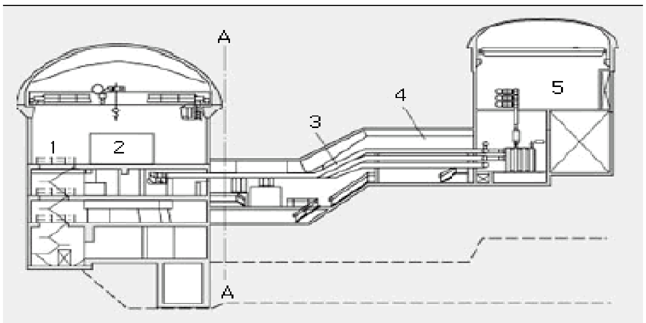

Fig. 9 Section through a conventional power plant. With the new technology, anything right of the plane AA are eliminated.

With Powerformer everything can be eliminated right from the plane A-A in Figure (9). Thus leading to power plants with fewer components. For example Powerformer technology eliminates the step-up transformer, the use of oils, generator circuit breaker and part of the bus-bar system. Fewer components means fewer sources of potential errors and significantly lower maintenance and repair costs.

With the Powerformer, availability of the power plant is improved because fewer components mean fewer errors and greater availability. Powerformer works with high voltage and low current, thus the heat developed in its stator windings is lower than with conventional generator stator with the same rating.

The stator is thus operated at lower temperatures, so that the materials from which it is made are less stressed which further leads to lesser faults, and higher availability. By comparing statistical availability figures for conventional power plants with the expected availability of a system based on Powerformer adoption of a nominal operating time of 7000 hours per year. It was found that a plant with Powerformer has 1.0% higher availability, i.e. 70 hour operation, in which a Powerformer based plant shall produce power and income, while a conventional unit is out of operation (unavailable).

VIII. ENVIRONMENTAL IMPACT

A Life-Cycle Assessment (LCA) is a tool to create a complete picture of the environmental impact of a product or system, throughout their life from raw material extraction, production, use, recycling, and finally give up for disposal. [11]. LCA is carried out on two systems, both connected to a 130-kV grid. A 150 MVA Powerformer compared to a conventional 136 MVA generator, transformer and circuit breaker system. A lifetime of 30 years was assumed, the environmental impact expressed as Environmental Load Unit (ELU), a high impact on the environment is expressed as a high ELU number. The results are shown in Figure (10), so that the Powerformer system has less environmental impact than a traditional system, in all its life stages, this is mainly because Powerformer has less energy loss.[11]

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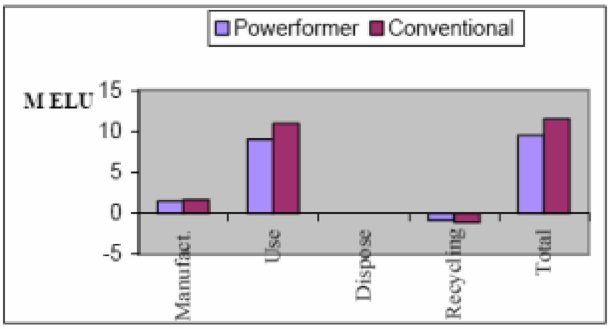

Fig. 10 Results from a comparative LCA study on Powerformer system and a conventional generator system

Powerformer is clean and safe, a conventional step-up transformer has several tones of oil. The handling of the oil-based insulation and cooling systems with the associated fire and leakage risks can be avoided, which gives a clean and safe power plant. Powerformer fully insulated winding minimizes the risk of PD, thus less danger of ozone production and environmentally friendly power plants.[11] Finally, a majority of the material used in Powerformer be easily recycled after the dismantling of the machine. A matter that has been considered with concern in the design of Powerformer and in the material used.

IX. TABULAR COMPARISIONS

Table (1) compares the data of a conventional generator with a Powerformer.

Table 1**.** Conventional generator versus Powerformer

Conventional generator	**Powerformer**
Low voltage (<30kV)	High voltage (>>30kV)
High current	Low current
High temperature	Low temperature
Short teeth	Long teeth
Weight = 1	Weight = 1.2-4
PD accepted	PD minimized

PD: Partial Discharge.

The total plant comparison, which is more realistic since Powerformer also comprises a Transformer function is shown in Table (2) below.

Table 2. Comparison between a conventional system and a Powerformer system.

Conventional	**Powerformer**
Transformer	None
MV bus-bar	None
Generator switches	None
Space & volume = 1	Space & volume < 1
Many parts	Few parts
Weight = 1	Weight < 1
Overload capability = 1	Overload capability > 1

The above tabular comparisons clearly show the superiority of Powerformer based-plans over conventional plants.

X. FIRST POWERTRANSFORMER INSTALLATION

The world's first high-voltage generator based on the new technology, a hydro-electric machine is rated at 11 MVA, 45 kV and 600 rpm. The machine is tested at the factory and installed on the Porjus hydropower Center on the Lule River in northern Sweden [1]. The machine is directly connected to the 45 kV power grids, the stator shown in figure (11).

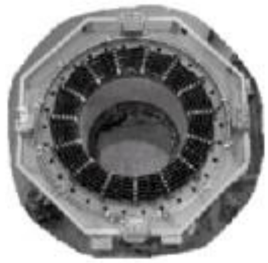

Fig. 9: Stator view of the first Powerformer**.**

Today (April 1999), the machine is being tested under realistic conditions to assess their influence on the transmission network. According to ABB, since the start-up of audits at Porjus last summer (1998), the machine has been operating without any troubles or disturbances on the network. Earlier (early 1997) a different unit (a traditional system with the generator, transformer, etc.) has been in service at Porjus [1]. A comparison between the parameters of the conventional system and the installed Powerformer are shown in Table (3) given below.

Table 3. The data from the two units installed at Porjus, a conventional generator versus a Powerformer.

Compared parameters	**Generator**	Powerformer
App.power (MVA)	11	11
Voltage (kV)	10	45
Current (A)	635	141
Speed (rpm)	429	600
Length (mm)	750	1450
Stator outer dia. (mm)	3100	3050
No of cables per slot	-	12
Weight of stator (ton)	11.5	34.5
Weight of rotor (ton)	23.0	22.8
Efficiency	97.2%	97.6%

*Efficiency considers the transformer in conventional system.

Another Powerformer, with the ability to feed at 155 kV directly to the power supply is planned on Porsi hydro power plant in Lapland (Sweden). The new unit will add an installed capacity of 75 MW.

XI. IMPACT ON POWER SYSTEM RELIABILITY

Modern energy markets are characterized by their intense price competition, new challenges for security, environmental protection and competitiveness of non-conventional suppliers. In a competitive and open market, the generation companies revenues are associated with competition in a market filled with risks and uncertainties. The whole phenomenon makes utilities under conflicting pressure for higher standards of reliability at competitive prices drop.

In such a system the reliability of restructured power supply strongly influences customer purchase decision because customers are more concerned with their individual load point reliability than with reliability of the whole system [15].

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Thus, the major challenges now for utilities are to increasethe market value of services with the right level of reliability and reduce the cost of their operation, maintenance and construction.

Reliability is necessarily interdependent with business and higher investment in order to achieve a higher reliability or even to maintain the reliability of current and acceptable levels [16]. Currently, the only approach to improve the reliability of systems without additional new capacity, either by reducing downtime by hiring additional personnel for repairs, or to extend up time by more sophisticated monitoring and maintenance techniques. These alternatives are now more likely than the Combination of capital scarcity and uncertainty in demand and fuel costs are higher for the new equipment [17]. In this context, in this section the effect of a new high-voltage generator is examined.

This high voltage machine directly controls the high voltage side of the grid and has some additional features such as higher availability, more reactive power margin and additional short-term overload capacity [18, 19]. Several studies on the effects on the system dynamic behavior have in the recent past was made at the University of Queensland. Studies [20] have confirmed that they delay the system voltage sag by several seconds. They have also found the design to be able perceptible changes in the case of malpractice system [21].

A. PowerformerTM Reliability Parameters

Since the PowerformerTM is a new innovation is its reliability evaluation in the long term were carried out by the available data and power cables from some experiments by the manufacturers.

B. Stator winding reliability

The evaluation of reliability and failure rate of the stator winding with failure data from the old and conventional three-phase lines that were installed during 10 to 30 years in the transmission and distribution networks will be carried out. Based on the information in reference [22], failure rate for the stator and associated joints are as follows:

Failure Rate for Stator = (0.02 * No. of faults) / (100three phase circuit-km-years)

Failure Rate for Joint = (0.05 * No. of faults) / (100 joint-years)

The calculated failure rate for high-voltage stator winding is equal to 0.53 faults / (100 Alternator years). So the amount of the mean time to failure (MTTF) is calculated as follows:

$$\lambda_{stator} = 0.0053 \frac{\text{faults}}{\text{years}},$$

$$\text{MTTF} = \frac{1}{0.0053} = 190 \text{ years.}$$

If the error is within the stator core and a severe disturbance occurs, the stator laminations are to be completely replaced. In this situation, the mean time to repair (MTTR) estimated to be about 13 days. The non-availability of the high voltage generator in this stator winding is as low as 0.019%. Thus, according to the analysis performed, the conclusion can be drawn that the PowerformerTM failure rate is significantly lower than the recorded failure rate of the conventional generator of hydropower plants

C. Step-up transformer and substation equipment

Electrical substations are the main source of errors and failures in the power networks. Failures of station equipment, such as circuit breakers, transformers and buses have significant impact on the power system reliability. This enables the system to be more reliable, by removing some of the components that can fail, such as the transformer and the circuit breaker. This can be done by powerformersTM.

D. Rotor reliability

There is no difference between rotor and powerformersTM conventional generators. So all the different excitation systems, that can be used in conventional generators are used in powerformersTM.

Therefore, it is reasonable to assume that the failure rates of conventional rotors and the rotors in powerformersTM are equal.

Table 4: shows the forced outage rate (FOR) for various power plants in two generators used in this study (conventional generators and powerformersTM).

Power Plant / Machine	Hydro Unit 2×50MW in bus 1	Thermal Unit 1×100MW in bus 2
Conventional Generator	0.025	0.05
Powerformer^{TM}	0.004	0.02

XII. NEW HIGH VOLTAGE GENERATOR INSTALLATIONS

A. The High Voltage Generator In Porsi Sweden

The High Voltage Generator In Porsi, Sweden In 2000, a 75 MVA high voltage generator was commissioned at Porsi hydroelectric plant. The rated voltage of 155 kV is the highest voltage generated directly, in the world.[4] The high voltage generator in Porsi replaced an old generator and had to fit in the same generator pit. In February 2002, the unit could be put into commercial operation. The single-line diagram in Figure (12) shows the situation of grid at Porsi hydroelectric plant. G1, the high voltage generator is connected directly to the 130-kV grid. G2 and G3 are conventional generators connected with the 130-kV grid via a transformer T23. A 20-kV network is connected to the 130 kV grid via transformers T4 and T5. The high voltage generator in Porsi has a propeller turbine as prime mover. This type of turbine has a very sharp efficiency curve and operates in a very narrow field of operation. Therefore, the generator will operate only when the current is large enough. This contributes to a relatively low operating time for the high-voltage unit. [4]

Total energy produced from the high-voltage generator in the period from February 2002 to October 2005 was 1364 GWh. The total operation time is close to 20 000 hours. The diagram in Fig. 13 shows the average power production per month and the accumulated operating time.

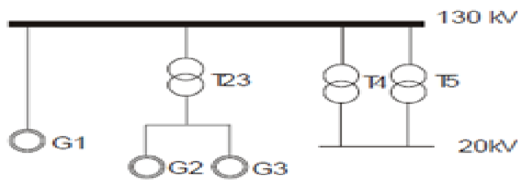

Fig.12 Single line diagram of Porsi hydropower plant. G1 is a high voltage generator, G1 and G3 are conventional generators. T23, T4 and T5 are transformers

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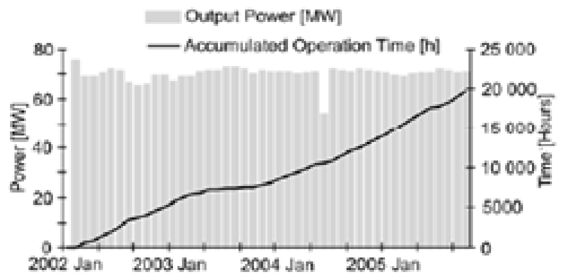

Fig.13 Power production and operation time for Porsi hydro power plant. From February 2002 to October 2005.

B. New High-Voltage Generator Put into Service for the First Time in Japan

The J-POWER-owned Katsurazawa Hydroelectric Power Station (commissioned in September 1957; licensed output: 15,000kW (Rated generator output: 9,000kVA 2 units) in Mikasa City, Hokkaido, has now been in operation for 45 years since it was first put into service in 1957, and time has taken its toll in the form of serious deterioration affecting all major equipment and necessitating large-scale modification work. The No. 2 Unit (Rated generator output: 9,000kVA) was put first on the repair schedule and a thorough search and assessment of the new technological trends in the field has led to the decision to install a new type of generator for the first time in Japan. This is a new high voltage generator built by Alstom Power Sweden AB. Even abroad there are only four of this novel type generator in service in Sweden and one in Canada.

The new high voltage generator that can thus be used to generate the high output voltages tolerated by the insulation was developed in Sweden and has already established a record of successful operation on a commercial basis in Sweden.

C. Merits of the New High Voltage Generator

- Savings in material costs as no mains transformer and no and low-voltage make / break switches are required.
- Savings in maintenance costs because no main transformer and no busbar cubicle and low-voltage make / break switch are required.
- Improving generator efficiency (equivalent to a 2% increase in efficiency in the Katsurazawa Powerplant (Higher efficiency is the result of lower power loss due to the lower rated current value and reduced losses in the main transformer.)
- Improved reliability, since no main transformer and low-voltage make / break switch and busbas cubicles are required.

Moreover, as the capacity of the generator increases, thus increasing their output power. As a result of the merits of the improved efficiency of the new high-voltage generator will be higher, the higher is the output voltage, and the higher is its capacity.

D. Future Deployment of the New High-Voltage Generator

The new high-voltage generator to be istalled at J-POWER Katsurazawa Power Plant is a relatively small unit with a rated output of only 9,000 kVA (table:5-comparison). Since it will be the first of its kind in operation in Japan, the cost of installation will be relatively higher than that of a conventional generator.
J-POWER is therefore considering the replacement of high-voltage, large-capacity generators in large hydroelectric plants with a lifespan of 40 years or more with the new high-voltage generator.
The advantages of the new high-voltage generator also benefit the new small and medium hydropower development projects, which are seen to contribute as a promising potential as a natural source of energy and its progress.

TABLE: 5

	ExistingGenerator @Katsuraza-wa Power Plant	Powerformer @Katsurazawa Power Plant	Overseas Example (Max.)
Output	9000kVA	9000kVA	75000kVA
PF	0.85	0.85	1.0
Voltag e	6600V	66000V	155000V
Current	787A	79A	--

XIII. CONCLUSION

The Powerformer was studied, and its effects on system's reliability in particular and environmental in general were highlighted. The study illustrated that Powerformer offers great advantage to the plant owner economically, as it improves the system reliability, availability a LCA of the system. It has an excellent overload handling capacity without any damage what-so-ever. Also, it has a proven successful record in hydropower plants across various parts of the world. So, Powerformer™ has immense potential to fully replace/succeed conventional generator plus transformer systems in the date to come offering numerous advantages.

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