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Renewable Energy 30 (2005) 1091–1099

RENEWABLE ENERGY

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Case study of upgrading potential for a small hydro power station

Karin Thorburn*, Mats Leijon

Division for Electricity and Lightning Research, The Ångström Laboratory, Department of Engineering Sciences, Uppsala University, Box 534, SE-751 21 Uppsala, Sweden

Received 13 November 2003; accepted 8 August 2004
Available online 2 November 2004

Abstract

Schemes for upgrading hydro power are formed in many parts of the world. Small hydro power (<15 MW) constitutes a fraction of all hydro power, but upgrading can still be worthwhile. In this article, a small generating station in Sweden, with two generators, is simulated with new generators. The voltage is increased by introducing a cable wound stator, thereby the transformers can be excluded, and more efficient generators are introduced with a higher power factor. These improvements lead to an active power increase from 8.9 to 9.4 MW per generator, which means an increased total annual production by 4.2 GW h.

Keywords: Small hydro power; Powerformer; Upgrading potential; Renewable energy

1. Introduction

Hydro power stands for 17% of the EU electricity supply, see Paish [1], and for almost half of the energy production in Sweden. The hydro power assets are divided in Sweden: the largest rivers are found in the north while in the south, where most of the population live, the streams are limited. Therefore a large amount of hydro power generators can be considered small, i.e. less than 15 MW. The contribution from these generators is quite small, but should not be ignored as the acteurs on the deregulated electricity market need renewable energy in their portfolios.

* Corresponding author. Fax: +46 18 471 58 10.
E-mail address: karin.thorburn@angstrom.uu.se (K. Thorburn).

0960-1481/$ - see front matter
doi:10.1016/j.renene.2004.08.006

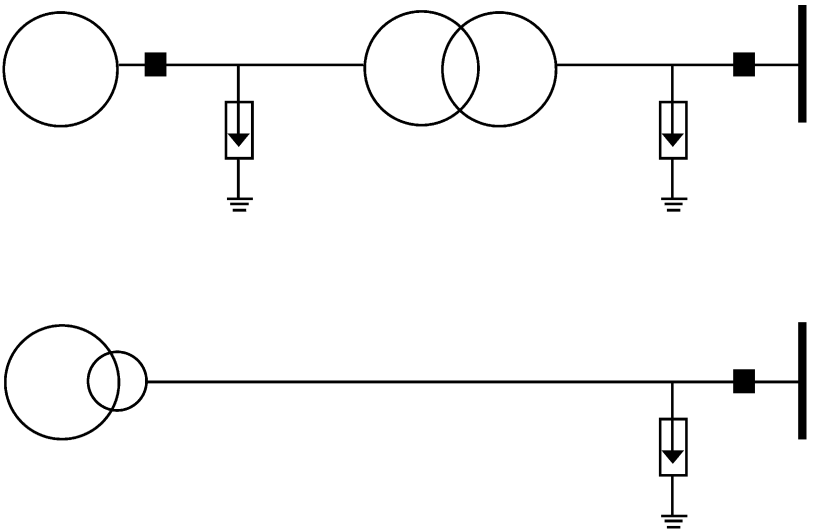

Fig. 1. Single line diagams, conventional (top) and Powerformer.

A Green Paper, issued by the EU Commission in 1996, summarizes the renewable energy situation in Europe. As a consequence, a law was enforced in Sweden on May 1, 2003 regarding electricity certificates. The aim is to increase the Swedish renewable electric energy production with 10 TW h by 2010. Similar plans are seen in several European countries.[1]

The generators found in most hydro power plants today are conventional synchronous machines in which the voltage level cannot exceed 25 kV due to insulation limits. This means that a high current, I, is needed in the stator windings to obtain a high output power. Since the resistive losses and mechanical forces are proportional to I^2, a lower current is desirable. A transformer is also a necessity, when a lower generator voltage is used, as transmission voltages can be of magnitude of several hundred kV. The transformer step also contributes to the losses.

It is possible to increase the voltage substantially by using a Powerformer™ generator, described by Leijon et al. in [2–4], due to the use of insulated cables in the stator windings, see Leijon et al. [5]. A number of transformers in a power system can thereby be removed completely, or be replaced by cheaper and more efficient autotransformers, whose function is described by Grainger and Stevenson [6]. Generator and transformer losses can be cut by several percent. In Fig. 1, a traditional single line diagram and a Powerformer diagram are presented.

In this article, the design of a small Powerformer is presented. Background data were obtained from an existing generating station, containing two similar generators, in the south west part of Sweden. The Powerformer is then compared with the existing generator in Section 4 and in Section 5 the transformer issue is discussed further.

[1] Website accessed 2004-10-05: http://www.recs.org/

2. Reference hydro power system

Background data have been obtained for a small hydro power generating station in the south west part of Sweden. Two units, each consisting of one turbine, one generator with breaker, and one tap changing transformer with breaker, are connected to the same busbar.

The generators are designed for 11.5 MVA at 6.6 kV, and power factor cos $\varphi = 0.80$. Some further information is presented in Table 1.

There is also two tap changers, which are set to a fixed voltage at 51 kV. This means that they act as ordinary transformers. The transformer losses are approximately 70 kW, or 0.6% of the installed generator MVA.

A simple single line diagram of the existing system is shown in Fig. 2.

Running conditions sets the generator voltages to 6.2 ± 0.2 kV, even though the generators are designed for 6.6 kV.

Furthermore the head is 29.5 m and the average flow is 38 m^3/s. The turbine shaft power is 9.5 MW per turbine, which gives a station total of 19 MW, and the average annual power production is approximately 75 GW h.

There is a discrepancy between power levels: the turbines can deliver a maximum of 9.5 MW, while the generators are designed for 11.5 MVA at cos $\varphi = 0.80$. This means that the generators never work under design conditions, as the turbine power provides the total apparent power to the generator.

3. Powerformer simulations

The Powerformer calculations and simulations have been performed using a finite element method, FEM. A calculation tool provides a platform for the material in this

Table 1
Existing generator and new Powerformer data

Data	Existing generator	New Powerformer
Year	1963	Study 2003
Power (MVA)×cos ϕ	11.5×0.80	9.5×1.0
Voltage (kV)	6.6	51.0
Poles/slot, phase	7/2	7/2
Inner/outer stator diameter (mm)	4530/5000	4430/5200
Airgap (mm)	10	10
Gen. length (mm)	650	850
Load angle	Unknown	20.9°
Iron losses (kW)	51	69.4
Copper losses (kW)	148.5	34.9
Magn. losses (kW)	45.9	30.4
Theoretical el. efficiency	97.9%	98.6%
Active el. efficiency	97.3%	98.6%
Transf. losses (kW)	70	0
Tot. el. efficiency	96.6%	98.6%
Active output power (MW)	8.9	9.4
Active power increase (MW)		0.5
Annual production (GW h) (for two generators)	75	79.2

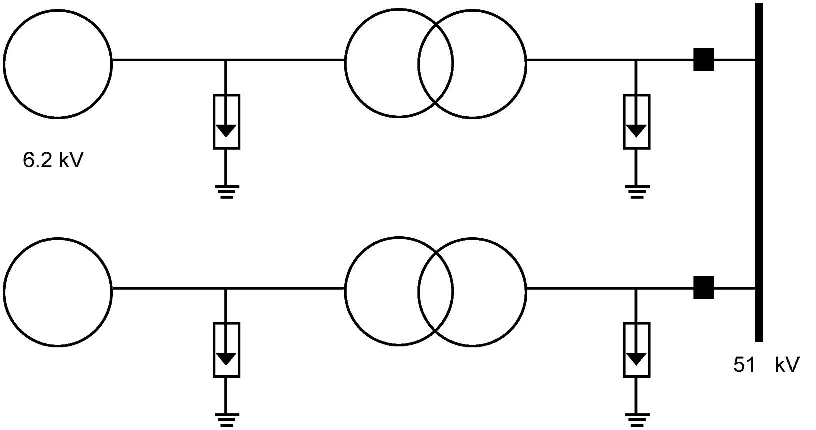

Fig. 2. Single line diagram reference power system.

paper. The program calculates magnetic and thermal fields, which are used as decision parameters for the design. A stationary and a quasistationary case have been studied in order to find a model that best utilizes the given conditions of the power station. The machine design is based on data from the existing generator.

During the stationary, or snapshot, simulation the generator model is calculated from the indata. With this model a quasistationary simulation is performed, as a function of time. The machine is then running with a constant load at a constant speed and the magnetic fields are calculated at each time step. From the fields all other relevant parameters are produced.

3.1. Data

A selection of the most important indata to the simulation of the Powerformer contain the following: desired output power, generator voltage, stator outer diameter and stator cable dimensions.

Among the output parameters the following is found: currents, voltages and power over time, magnetic field distribution, heat distribution and load angle.

3.2. Assumptions

It has been allowed to make the Powerformer somewhat longer than the existing machine as the space in the generation station is believed to be available. The mechanical forces caused by a fault are proportional to the current squared, I^2, and as the current in a Powerformer is lower than in a traditional machine, the forces are substantially lower as well. This means that the supporting structure can be weaker. Hence, the diameter of the Powerformer can be larger than that of the existing machine and still fit in the enclosure. It has also been a prerequisite that both the rotor and the stator were ready for renovation, meaning that the stator inner diameter and the rotor dimensions could be varied in the optimization process. The efficiency of the turbine is assumed to be constant for the relevant power levels.

The results for the simulated Powerformer, compared with the existing machine, are presented in Section 4.

3.3. Optimization philosophies

During the optimization process several parameters were taken into account. The magnetic field, B, should not exceed 1.8 T globally due to saturation in the stator material. A field plot is presented in Fig. 3 for the simulated Powerformer. Dimensions of the stator and rotor were limited as stated in Section 3.2. A small load angle is a target, preferably less than 30°. In Fig. 3, the load angle is represented as the distortion of the field lines. For the simulated Powerformer a load angle just above 20° is obtained. The power factor is set to unity in order to maximize the active power production.

Another important parameter to keep in mind is the current density in the stator cables. This density should not exceed 2.0 A/mm^2 as this will cause damaging heat. The cable temperature is kept below 70 °C to ensure an overload capacity. Standard nominal XLPE cable design temperature is 90 °C, according to Sillars [7]. In Fig. 4, the temperature, as a function of radial distance, in a line through the stator cables in a stator slot is shown.

The two existing generators on the site were of the same size. It was found that they had been over-dimensioned relative the turbine powers, as described in Section 2. The new

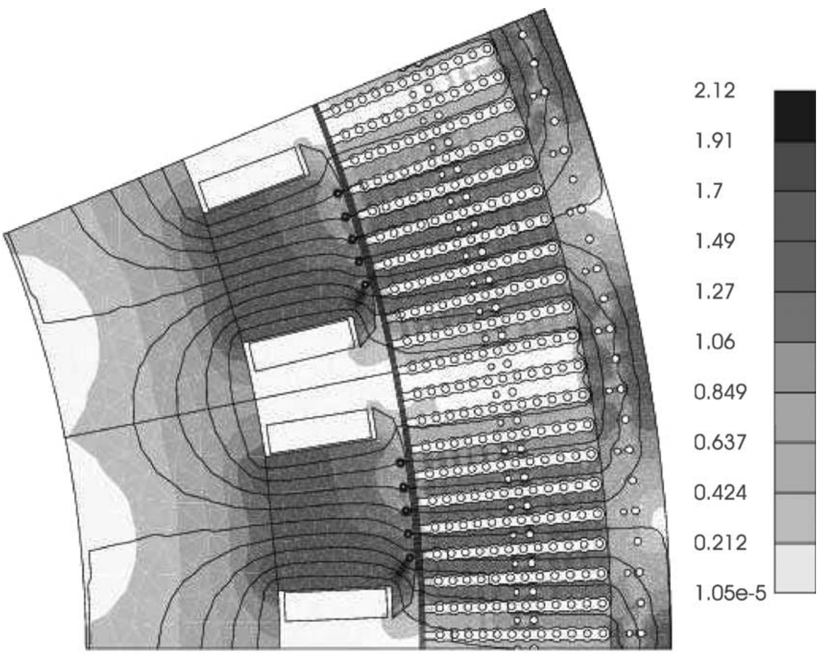

Fig. 3. Magnetic field, in [T], in rotor and stator.

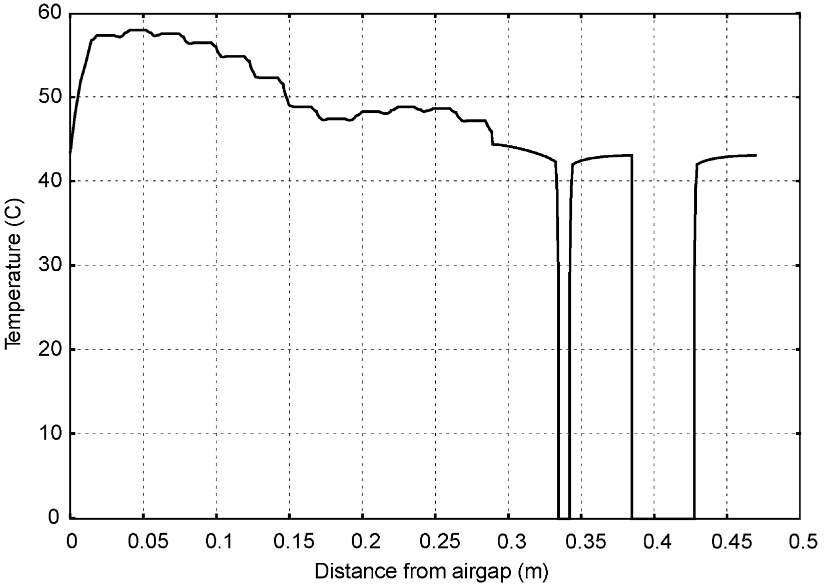

Fig. 4. Radial temperature in stator slot.

generator was designed with cos $\varphi = 1.0$ to match the turbine power level and to maximize the active power output.

Today the generator design voltage is 6.6 kV, and the nearby voltage level is 51 kV. Therefore the new Powerformer voltage was chosen to 51 kV.

4. Results

In this section, the results for the simulated Powerformer are presented. A comparison with the existing machine is presented in Table 1. In the table two electrical efficiencies are calculated for the existing generators from 1963. The first is the theoretical value, which refers to the generator design, 11.5 MVA. The maximum active power for the existing machines is $11.5\times0.8=9.2$ MW each under rated conditions. This is the base for the second efficiency in the table.

The main benefit to point out is the total electric efficiency at the bottom of the table. This value is based on the available power from the turbine for the existing units. A 0.5 MW, or more than 5%, overall increase in active power is achieved for each of the two generators.

The production increase can be divided into three main parts; transformer elimination (0.8%), more efficient generator (1.3%) and power factor increase (3.3%).

For the conventional station the utilization, α, defined by Leijon et al. [8], is approximately 46%, calculated with the equation $\alpha = E/(Ph)$, where E is the annual production and P is the maximum active power output. In this calculation, the total station active power, 2×8.9 MW is used. A 0.5 MW improvement per generator means that

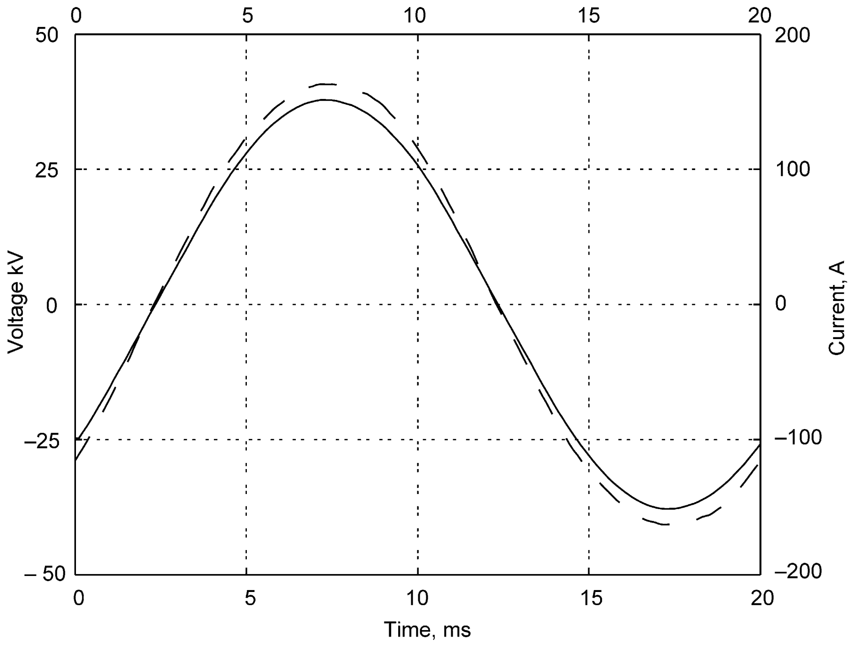

Fig. 5. Phase A voltage (dashed) and current (solid).

the energy output ideally increases by approximately 4.2 GW h in 1 year with a 48% utilization for the station.

A selection of graphs from the simulations are found in Figs. 3–5. The graphs show results from the FEM calculations, where the generator is running at a constant speed.

In Fig. 3, the magnetic field distribution in the generator is shown. The radial temperature in a line through the cables in a stator slot is presented in Fig. 4. Fig. 5 illustrates the phase A current and voltage. The phase voltage harmonics are calculated and presented in Table 2. It is noted that the voltage harmonics are low, the third harmonic is less than 2%.

Table 2
Phase voltage harmonics, percentage of fundamental

Harmonics	Percentage
3rd	1.905
5th	0.391
7th	0.196
9th	0.340
11th	0.005

5. Discussion

In this article, the active power production is in focus, but there are several other benefits with a Powerformer installation that should be mentioned. As one system component, the transformer, is eliminated, one generator circuit breaker can also be eliminated. Positive environmental and safety effects are a consequence as old transformers contain oil. Operation and Maintenance costs are also reduced with the exclusion of transformers and breakers.

The generators in the reference hydro power station were installed in 1963, which is quite recently compared with other installations in Sweden. Some stations were started in the early 1900s, and has had only minor revisions since then. Major upgradings are planned for a large number of stations in a near future, but which kind of revision is not decided. Powerformer is an option mainly for those connected to higher voltages than 20 kV.

It is not only possible to upgrade small hydro power stations with the Powerformer technology, it is even better when applied to large stations with high voltage transmission lines nearby. A 400 kV Powerformer is theoretically possible to produce. The highest Powerformer generation voltage today is 155 kV, in the Porsi station in northern Sweden. An installation that resembles the generators simulated in this article has been running since 1998. It is the Porjus U9 Powerformer, which operates at 45 kV and is rated at 11 MVA. Some test results from this machine are presented by Johansson and Larsson [9].

It can also be noted that the transformers associated with the old conventional generators were installed at the same time as the generators. This makes them quite aged. A replacement or revision is unnecessary with a Powerformer installation.

As the examined generation station contains two similar generators it might be a better option to optimize the generation station by replacing both machines by one large Powerformer. Load variations would then require a generator with a wide optimum operation interval. The water paths would also need revision and the operation would increase dramatically in size.

For economical calculations the formula for capitalized value is used,

$$V = \alpha H p \frac{1-(1+r)^{-n}}{r},$$

where V is the value of one installed kW, α is the utilization factor, H is the number of hours in one year, p is the price per kW h, r is interest rate, and n the number of years for the investment.

Each new kW (assuming utility $\alpha = 48\%$) can allow an investment of up to 2400 €, with a pay back time of 20 years ($r = 6\%$ interest and an energy price $p = 0.05$ € per kW h). This implies great possibilities for the many upgrading schemes that are found all over the world, see Bartle [10].

The allowed investment cost of the additional 1 MW would then be 2.4 M€.

6. Conclusions

It has been shown that a small hydro power plant can be upgraded with Powerformer generators yielding an increase in active power by 1 MW. There are three main reasons why this is possible.

First, the transformer is eliminated, which adds 0.8% to the output power. This is possible as the Powerformer generates at a higher voltage level.

Secondly, the turbine power is fully used and the generator is more efficient. This adds 1.3%.

Finally, the power factor is set to unity, to maximize the active power production. This is the main contribution, and brings another 3.3% to the output power.

These three improvements can result in an increase in active generator power from 8.9 to 9.4 MW. With an annual utilization of 48% the station production is increased by 4.2 GW h, from 75 to 79.2 GW h.

Acknowledgements

The work presented here is a part of a larger survey of the Swedish hydro power, performed in cooperation with Luleå University of Technology. Project coordinator Stefan Nilsson, project leader Prof. Håkan Gustavsson, and the Elforsk companies are gratefully acknowledged. The project is financed by the Swedish Energy Agency and the authors wish to thank for this support.

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