DYNAMIC STABILITY OF AN ELECTRICITY GENERATION SYSTEM BASED ON RENEWABLE ENERGY

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ABSTRACT

Renewable energy must be stored in order to make it reliable. Flywheels are capable of storing high amounts of energy and can also be used as power buffers, due to their high power densities. This paper investigates a way to smooth the power output from renewable energy converters (wave, wind and marine current) by adding a double-wound flywheel energy storage to the system. Simulations show that a ramp-controlled flywheel energy storage would drastically smooth the short time power from a wave energy converter but not be that appropriate for longer term energy storage. The power quality enhancement produced by the addition of the flywheel to the system is also simulated and discussed.

INTRODUCTION

During recent years there has been an increase of electric power production from intermittent renewable energy sources. The fluctuation in power production from these sources can have a negative impact on the efficiency of the electrical conversion system as well as on the power quality, but it may also affect the attractiveness of these resources as base-load providers as well as the dimensioning of grid connections. Therefore, it is important to study to which extent these fluctuations can be reduced.

If the energy converter devices in a limited geographical area are connected into farms, the power fluctuations are decreased by stochastic smoothening – it is not likely that the peak power occur in all energy converters at the same time. An energy storage device can be utilized to even out power fluctuations even more. This will allow wind energy, for example, in the not too distant future to supply up to about 80 percent of total electricity demand [1].

Among different types of energy storage systems, flywheels combine high power and energy densities, have no capacity of degradation (their life time is independent of the number of charge/discharge cycles) and they are able to store a large amount of energy; several hundreds of kWh per unit [2].

This paper describes a way to smooth the power output on an intermediate time-scale by adding a double-wound flywheel energy storage to the system. Three energy conversion systems, shown in figure 1, are investigated converting the energy in wind, ocean waves and marine currents into electric power. Also the possibility of enhancing the quality of the output power is discussed.

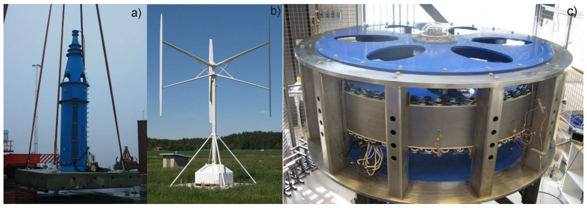

Figure 1. Photos of the concerned generators. a) One of the wave energy converters installed at the Lysekil research site. b) A 12 kW vertical axis wind turbine installed in Marsta outside Uppsala. c) Laboratory marine current generator.

A system overview is given in the first section. The simulated energy conversion techniques are discussed, as well as the proposed flywheel. The method used to simulate the complete system is described in the next section, followed by a presentation of the results of the simulations. A discussion about the effects of the flywheel considering the frequency and amplitude of its output voltage is finally presented in the last section.

SYSTEM OVERVIEW

Energy conversion techniques

Wave power

There are numerous ways to convert the energy in ocean waves to electricity (for an overview, see [3]). The wave energy converter used in these simulations (Lysekil test site [4]) has two main components; a linear generator placed on the seabed and a buoy on the ocean surface acting as a power take-off device. This wave energy converter gives a power output that fluctuates with each wave, that is, output voltage will vary in frequency and amplitude even on a small time scale. The individual power contributions cause heavy power fluctuations, which have to be mitigated in some way. In [5], five direct-driven wave energy converters, each oscillating with a phase shift of one fifth of the wave period and with individual rectification and successive interconnection in parallel, were simulated. Results show considerable smoothing compared to single unit operation. Later, the same model was tested for ten generators showing similar results [6]. It has also been shown how aggregation of power from individual converters in arrays can reduce the need for energy storage capability [7]. Simulations of the aggregation of power from the so-called SEAREV wave energy converter show decreasing standard deviation of power for up to 30 wave energy converters [8].

Wind and current power

The wind and current energy converters studied at Uppsala university [9, 10] both utilize a vertical axis turbine and a directly driven generator. As the turbines in both systems have fixed blade pitch, the generators will be run at different rotational speeds for different wind or current velocities. The resulting output voltage from a generator could be sinusoidal with little harmonic distortion but still varying in frequency and amplitude as the wind or current speed changes. Current energy converters may be adapted to the bathymetry and local current speeds of a particular site. In parks, each converter is likely to comprise a rectifier, but consequent system components may be for several units within the park. As for wind power, the power in a water stream is proportional to the cube of the velocity, resulting in significant variations in input power.

The flywheel

The proposed flywheel has its novelty based on the two sets of windings, electrically separated from each other, which divide the system in two voltage levels. That allows the flywheel to handle input and output power completely independently. The flywheel automatically adjusts the output power so that the speed of the flywheel – and therefore also the frequency and the voltage – will be varying around a certain value that is the nominal speed of the flywheel. The flywheel model used is based on an existent flywheel prototype [11] with a reference speed of 5 000 rpm and an inertia of 0.364 kgm^2. The stator of the flywheel machine has two sets of three phase windings with a different number of turns, working as a transformer. In this way the energy storage system creates a galvanic insulation between the primary energy source and load increasing the overall passive safety [12].

Complete system

Figure 2 shows a circuit diagram of a wave power system in which the flywheel has been inserted. A set of linear generators is connected to the same DC bus. From this point, the signal is then inverted and fed to the low voltage side of the flywheel, in a voltage level of around 100V. The flywheel produces a 600 V voltage on the second set of windings with a much smoother output power, which is then rectified and inverted before being delivered to the grid.

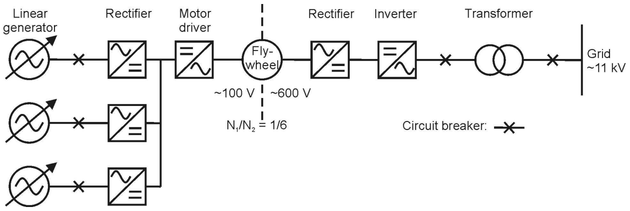

Figure 2. Circuit diagram of the proposed system applied on linear wave energy converters.

METHOD

All simulations have been made in Matlab Simulink. For the wave power simulations, data from the Lysekil test site, Sweden, July 16th 2009 21.30-22.00 is used. The data is given with a sampling frequency of 256 Hz as current and voltage through a dump load with the resistance of 12 Ω connected in delta. To facilitate the simulations the input data has been reduced by a factor of ten (the mean value of ten consecutive data points is calculated and used as input to the simulations), giving a sample frequency of 25.6 Hz. The predominant wave period of the data set is 5.70 s. The significant wave height during the period is 1.56 m and the mean power content of the waves is 6.43 kW/m.

For the wind power simulations, data from Marsta test site outside Uppsala, Sweden, is used (see figure 1). Data is sampled every ten minutes for a period of 56 days.

For the current power simulations, data from the Söderfors test site in Sweden in used [9]. The system is applied to a site with current velocities from below 1 m/s to almost 2 m/s, resulting in input powers of below 0.5 kW/m^2 to almost 4 kW/m^2. Data is sampled as one hour mean values over five consecutive years.

Different energy storage capacities of the flywheel are simulated to see how the power output is affected. Note that the flywheel energy storage capacity can be varied by changing the operating speed, but also the physical shape and size. Here only the size is changed. No losses are assumed in the flywheel since they would not add to the principal understanding of the system. For a real application though losses are important to consider.

Control of flywheel

In the simulations for this paper the flywheel is controlled by a ramped control algorithm where the output power is directly proportional to the energy content of the flywheel. The flywheel has an operating window between a minimum speed and a maximum speed at the relation 1:2. As the energy storage in the flywheel is proportional to the square of the speed, this means that the energy stored in the flywheel varies between a lowest value E_{min} and a highest value $E_{max}=4E_{min}$. The output power varies between $P_{min}=0$ and a maximum value P_{max} in relation to the energy stored in the flywheel. In this way the power output is varying but in a smooth way. For example; if the flywheel rotating at a nominal speed of 5 000 rpm, corresponding to an energy level of $E_{nom} = \frac{E_{\max} + E_{\min}}{2} = 2.5E_{\min} = \frac{5}{8}E_{\max}$, the power output is $P = 0.5P_{\max}$. If the flywheel speed is high, say corresponding to $3.4E_{\min}$, the power output is $P = \frac{3.4-1}{4-1}P_{\max} = \frac{2.4}{3}P_{\max} = 0.8P_{\max}$. The effective energy storage capacity is $E_{cap} = E_{\max} - E_{\min} = 1.2E_{nom}$.

SIMULATION RESULTS

The three energy conversion systems are simulated in different time scales to reflect the different properties of the energy sources but also to show the abilities of the flywheel in different energy storage situations. See table 1.

Table 1. Energy storage properties.

	Time scale	Energy source
Quality enhancement	<second	Wave
Power smoothing	second, minute	Wave, wind
Energy storage	hour, day, month	Wind, current

Power smoothing – Wave and wind power

Simulation results for a 30 minute period of time show that a ramp-controlled flywheel energy storage would drastically smooth the power from the wave energy converter. This is shown in figure 3 and 4 where the blue line shows the power from one wave energy converter sent in to a flywheel and the red and black lines show the power out from the flywheel with flywheel energy storage capacities of 50 kJ and 500 kJ respectively. The mean power in to the flywheel from the wave energy converter is shown by the dashed blue straight line. The maximum power is decreased from 20 kW by around a factor of ten, depending on the size of the flywheel.

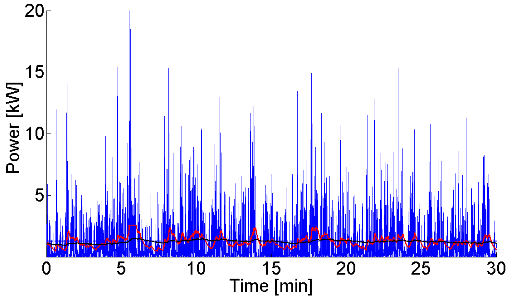

Figure 3. Wave power in to a flywheel (blue) and the power out from the flywheel with flywheel energy storage capacities of 50 kJ (red) and 500 kJ (black) respectively.

The minimum size of the flywheel, for this series of data and for this flywheel control, is 104 kJ (see the red line in figure 5). It means that below this size, the flywheel reaches its power handling limit so that its output power control is lost. In this region the energy storage is not regulated by the power outtake from the flywheel but by its speed, which is not desirable. The minimum size of the flywheel is around 4.5% of the total energy flux in to the flywheel (see table 2). The same reasoning of power smoothing is valid for other stochastic energy sources like wind and sun.

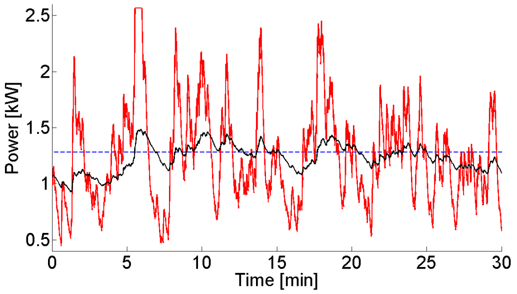

Figure 4. Part of figure 3 which shows in detail the power out from the flywheel with flywheel energy storage capacities of 50 kJ (red) and 500 kJ (black) respectively.

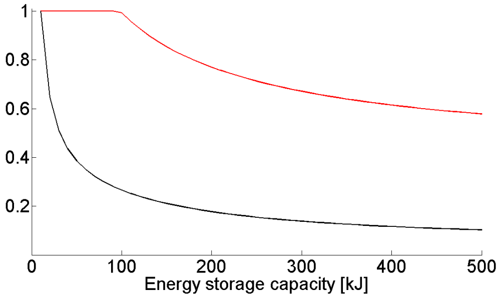

Figure 5. Normalized standard deviation of output power from flywheel with one wave power generator (black) and normalized maximum power out from the flywheel (red) as a function of the flywheel energy storage capacity.

Energy storage – Wind and current power

For long time energy storage the size of the flywheel would have to be significant compared to the total energy input to the flywheel, around a fourth for both the wind and current power data studied. See table 2 and figure 6 and 7 (the mean power in to the flywheel is marked by the dashed blue line).

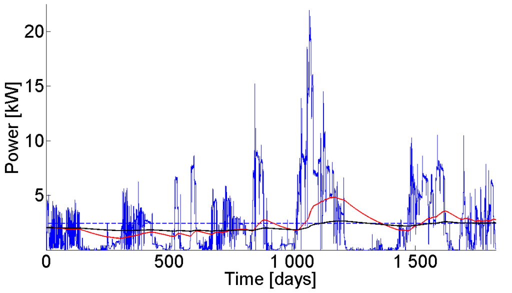

Figure 6. Power from a current energy converter sent in to a flywheel (blue) and the power out from the flywheel with flywheel energy storage capacities of 100 GJ (red) and 500 GJ (black) respectively.

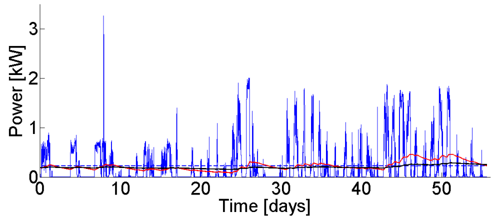

Figure 7. Power from a wind energy converter sent into a flywheel (blue) and the power out from the flywheel with flywheel energy storage capacities of 200 MJ (red) and 1 GJ (black) respectively.

Table 2. Smallest possible size of flywheel compared to total energy flux in to the flywheel.

	Energy in	**Mean power in**	**FW size, E_{cap}**	**FW size / Energy in**
Wave	2.31 MJ	1.28 kW	104 kJ	4.5%
Wind	1.09 GJ	228 W	246 MJ	23%
Current	386 GJ	2.44 kW	101 GJ	26%

Power quality enhancement – Wave power

A detailed simulation of the proposed system (see figure 2) has been made, using the rectified no-load voltage from the Lysekil linear wave energy converter as input to drive the low voltage side of the flywheel machine. The output voltage from the flywheel high voltage windings depends on the machine construction parameters.

Frequency and amplitude of the input voltage are varying, but the output signal is almost constant both in amplitude and frequency as it can be seen in figure 8. This non-variation of the output signals happens in consequence to the rotational speed of the flywheel, which varies very little thanks to the high inertia of the machine.

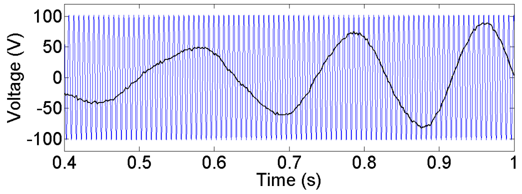

Figure 8. One phase output voltage from wave energy converter (black) and flywheel machine (blue).

CONCLUSIONS AND DISCUSSION

A flywheel could greatly improve the smoothness of the power output from a renewable and intermittent energy source. Though one has to consider the trade-off between the size – and with that the cost – for the flywheel compared to the declining marginal utility it brings to the smoothness of the output power.

For energy storage for longer periods, days and more, the flywheel does not give the same advantages due to the large amounts of energy to be stored.

On a short time scale the power quality from the linear wave energy converter is greatly increased by a flywheel. However for wind and marine current converters the enhancement of the power quality would not be significant since they already generate a sinusoidal shaped voltage.

REFERENCES

[1] A. J., Cavallo, 2001, “Energy storage technologies for utility scale intermittent renewable energy systems”, Transactions of the ASME, *Journal of Solar Energy Engineering*, vol. 123, no. 4, 387-389.

[2] B. Bolund, H. Bernhoff, M. Leijon, 2005, “Flywheel energy and power storage systems”, *Renewable & Sustainable Energy Reviews*, vol. 11, no. 2, 235-238.

[3] A.F. de O. Falcao, 2009, “Wave energy utilization: A review of the technologies”, *Renewable and Sustainable Energy Reviews.*

[4] M. Leijon, C. Boström, O. Danielsson, S. Gustafsson, K. Haikonen, O. Langhamer, E. Strömstedt, M. Stålberg, J. Sundberg, O. Svensson, S. Tyrberg, R. Waters, 2008, "Wave Energy from the North Sea: Experiences from the Lysekil Research Site", *Surveys in Geophysics*, vol. 29, 221-240.

[5] K. Thorburn, M. Leijon, 2006, “Analytical and Circuit Simulations of Linear Generators in Farm”, *IEEE Transmission and Distribution Conference and Exhibition*, 495-500.

[6] K. Thorburn, M. Leijon, 2007, “Farm size comparison with analytical model of linear generator wave energy converters”, *Ocean Engineering*, vol. 34, 908–916.

[7] M. Molinas, O. Skjervheim, B. Sørby, P. Andreasen, S. Lundberg, T. Undeland, 2007, “Power Smoothing by Aggregation of Wave Energy Converters for Minimizing Electrical Energy Storage Requirements”, *Proceedings of the 7th European Wave and Tidal Energy Conference (EWTEC), 11-13 September 2007.*

[8] J. Tissandier, A. Babarit, A. H. Clément, 2008,”Study of the smoothing effect on the power production in an array of SEAREV wave energy converters”, *Proceedings of the 18th annual conference of the International Society of Offshore and Polar Engineers 2008 (ISOPE’08), 6-11 July*, vol. 1, 374-381.

[9] M. Grabbe, K. Yuen, A. Goude, E. Lalander, M. Leijon, 2008, "Design of experimental setup for hydro-kinetic energy conversion.", *Hydropower and dams*, vol. 5, 112–116.

[10] J. Kjellin, 2010, *Experimental Vertical Axis Wind Turbine System***,** UURIE 318-10L, Uppsala, Sweden.

[11] J. Abrahamsson, J. Santiago, J. G. Oliveira, J. Lundin, H. Bernhoff, 2010, “Prototype of electric driveline with magnetically levitated double wound motor”, *Proceedings of the International Conference on Electrical Machines (ICEM XIX).*

[12] J. Santiago, A. Larsson, H. Bernhoff, “Dual Voltage Driveline for Vehicle Applications”, *International Journal of Emerging Electric Power Systems*, vol. 11, no. 3, article 1.