Adjustable Speed Hydro Machine Applied for Improved Utilisation of Power Networks

Roald Sporild
Jan Ove Gjerde

ABB Corporate Research
P.O. Box 90
N-1361 BILLINGSTAD
Norway
roald.sporild@nocrc.abb.no
jan.o.gjerde@nocrc.abb.no

Terje Gjengedal

Statkraft SF
P.O.Box 494
N-1322 HØVIK
Norway
terje.gjengedal@statkraft.no

Abstract - **This paper presents the Adjustable Speed Hydro (ASH) machine concept as an alternative for obtaining better utilisation of power networks. Transmission lines appearing as bottlenecks with respect to power demand may increase their transfer capacity as ASH machines are introduced in the network. This is achieved by a quick and precise regulation of rotor currents and thereby active and reactive power out of the machine. During faults in the network, these properties may be utilised to maintain near constant power production and torque equilibrium. This in turn gives less speed deviation and better ability to control the network behaviour. Hence, the ASH machine can give a considerable contribution to the network both during and after serious conditions in the power system.**

Keywords: Increased utilisation, Deregulated market, Dynamic stability.

I. INTRODUCTION

In established power networks, the tendency of increasing power consumption results in a need for new transmission corridors. This is normally not easily obtainable due to environmental and economical constraints. Therefore, the established network must often come into focus for alternative ways of increasing the power transmission capacity. At the same time, this must not violate the stability constraints associated with the network.

Optimised utilisation of power networks is partly the superior ambition of introducing privatisation, deregulation and competition in power markets worldwide. Competition has resulted in renewed utilisation of assets for generation, transmission and distribution with the aim of enhancing profitability and increasing owners value. This optimal utilisation can not be accepted without maintaining a secure operation of the network. Utilising the power system in a more optimal manner must also be followed by a strategy for maintaining the transient behaviour of the network in order to ensure that the stability is maintained within certain limits. Hence, efforts to improve control of existing transmission systems, as well as increasing the transmission network capacity and effectiveness, are becoming increasingly important. At the same time, the concerns for continued high levels of systems reliability, security and competitiveness will create uncertainties for system operators and planners. [1]

Also in the Norwegian power system, these constraints are being more apparent as the power consumption is increasing. From being an energy rated, regulated power system, it is now de-regulated and in the transition to be rated according to power demand. Increased power consumption in general combined with new HVDC interconnections being set into operation between Norway and Germany/Holland makes a paradigm shift with respect to the pattern of power flow within the Norwegian power system. This also puts more pressure on the transmission lines in accommodating the highly varying demand of power flow and on average, the main grid is loaded closer to its transmission capacity. As a result of these constraints appearing as bottlenecks in the power network, the Norwegian power system is now very often being separated into a number of local price areas.

The aim of this paper is to show how an Adjustable Speed Hydro (ASH) machine can be an alternative to ordinary overhead line implementation in order to increase the power transfer of transmission systems and still maintain a secure operation.

II. ASH MACHINE CONCEPT

In the last decade, considerable attention has evolved on new power electronics technology, announced under the common term FACTS (Flexible AC Transmission Systems) [2], [3], [4]. The dynamic components are based on their capability of forcing reactive or active power into certain points in the network, resulting in an improved power factor, less transmission losses and a more optimal utilisation of the power system. This is achieved by means of advanced regulation systems in order not to aggravate the network behaviour during transients.

Another possible technology is the ASH machine, which is capable of maintaining the quality, reliability and stability of the transmission system to face the issues mentioned above. Compared to conventional synchronous machines, the main advantages of the ASH machine are the improved efficiency and its use as a FACTS device both in generator and pump mode. It will increase the stability of the power system and makes a significant contribution in improving the frequency control.

Essentially, as observed from the network, the benefit of this concept is that the quick regulation of rotor currents de-couples the mechanical system (with its characteristic long time constants) and the electrical system with respect to speed /frequency. Therefore, the ASH machine is able to quickly compensate for transient frequency deviations between the mechanical and electrical system. In order to make these compensations, a precise, dedicated regulation system must be developed to operate the converter switches in the milliseconds range.

III. PRINCIPLES OF THE ASH MACHINE CONCEPT

A synchronous machine, being operated either in pump or turbine mode, will have its dedicated, constant mechanical speed; the synchronous speed. The only way of changing the active power production is to change the mechanical torque delivered by the turbine.

In power stations with considerable variations in head and load as well as variable trickle of water, it is desirable to make a change in machine speed in order to operate in an optimal way and thereby increase the income for the owner. By varying the speed within a certain range around nominal speed, an ASH machine may obtain optimal efficiency for a number of combinations of head and water flow.

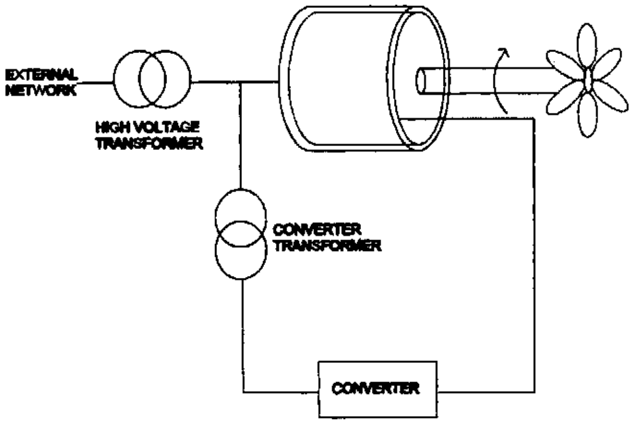


Fig. 1 General sketch of an ASH machine unit

By injecting definite currents with variable frequency into the rotor (ref. figure 1), the generation of active and reactive power from the ASH machine is controlled continuously and rapidly. The active power from the generator can be controlled independently from the turbine output both in pump and generator mode by means of the active part of the rotor current.

After large perturbations in the transmission grid, the frequency will normally oscillate with the speed of the synchronous generators. By changing the frequency of the rotor current, an ASH machine can keep the frequency of the current delivered to the transmission system at its reference value. Depending on the nature of the disturbance and the ASH machine's location in the network, it can either absorb or deliver active power to the network very quickly by transforming rotational energy to electric energy and vice versa.

These currents are fed from a converter into the doubly fed wound rotor over some dedicated slip rings. The stator frequency is maintained at 50Hz by means of the rotor currents, which are compensating for the difference between actual speed and nominal speed.

In a conventional hydro generator, the active power generated is controlled by the gate opening. This regulation has a time constant in the order of seconds, given by the shape of the production facility (penstock, turbine, regulation system etc.). For an ASH generator, both the active and reactive power production can be changed very rapidly, about the order from 10 to 30 ms. This is possible due to the ability to change the rotor current frequency very fast. By this, the active power supplied or drawn from the generator terminals may change quickly without affecting the network frequency. The instantaneous rating of the power variations depends on the possible speed variation; typically ±15%.

IV. MODEL DESCRIPTION

The ASH machine model is based on the standard equations for a two-axis reference system. For studies of transient stability, the converter model can be simplified. In this paper, the dynamics of the converter is neglected, assuming that the converter is able to control the rotor current to the reference values at all times.

The rotor current regulators of the ASH machine model are built up based on phasor domain analysis, where the active and reactive power delivered to the network are kept track of by means of the two rotor current phasors $IR\alpha$ and $IR\beta$. This orientation system is selected based on the alignment to the d-axis component of the stator flux (ref. figure 2).

The relatively large speed range of an ASH machine makes it necessary to use accurate models of the hydraulic system. Common turbine models is also linearised around the reference speed, and can not be used in this type of simulations. A non-linear model of the turbine assuming inelastic water column is suggested for transient stability studies in [5]. In [6] a more detailed model based on these recommendations is suggested.

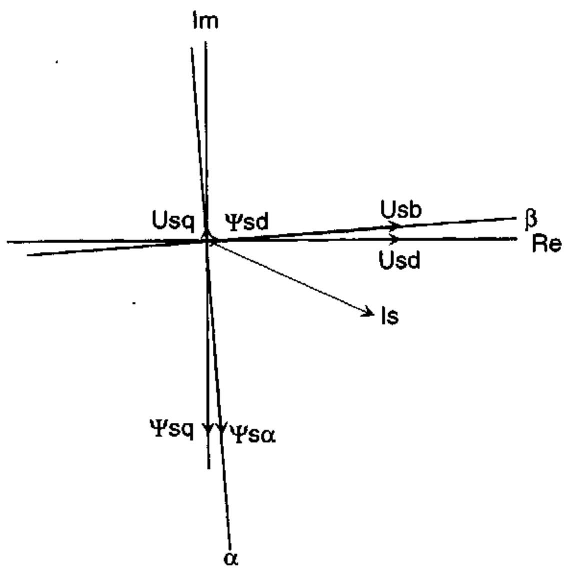


Fig. 2. Conversion from dq- to αβ-representation

In [7] and [8], two control strategies are presented. The model presented in our paper is implemented with the power master strategy, which allows the active power output to be controlled independently of mechanical speed. To control the speed, a common PID-controller with a first order filter is used. The speed control can not be so fast that it impairs the response of the active power output. This means that the gain, both proportional and integral, have to be set at low values to stabilise the system.

V. DESCRIPTION OF SIMULATION CASES

In the following, a possible application of an ASH machine will be discussed. This is done in order to visualise how it will contribute to an enhanced performance of power networks as related to conventional machines.

In general, the network models presented in this paper illustrate typical cases where one or more transmission lines represent bottlenecks in the power system. It is presumed that there are certain constraints with respect to the maximum power transferred and these restrictions are associated with a stability problem in the respective area.

The simulations described in the following have been carried out by means of the SIMPOW computer tool.

A fifth order synchronous machine model is used to represent the conventional generators applied in the network model. The synchronous machines are associated with a general conventional governor, which is measuring the speed deviation, while the ASH machine takes into account the deviation of power production related to the power reference.

The following simulations primarily concern with the first swing stability. No Power System Stabilisers (PSS) are used for the ASH machine or the synchronous machine.

VI. SIMULATION RESULTS

In the following, attention will be paid to some simulation cases where generator G2 in figure 3 below is represented by a synchronous machine or an ASH machine respectively. In the first case, the two types of machines are compared directly with each other to clearly indicate the different properties. This is followed by a case for comparison of the phase angle of generator G1 as related to that of generator G3 by using synchronous versus ASH machine for generator G2. This is done to illustrate the impact of the ASH machine with respect to the stability margin.

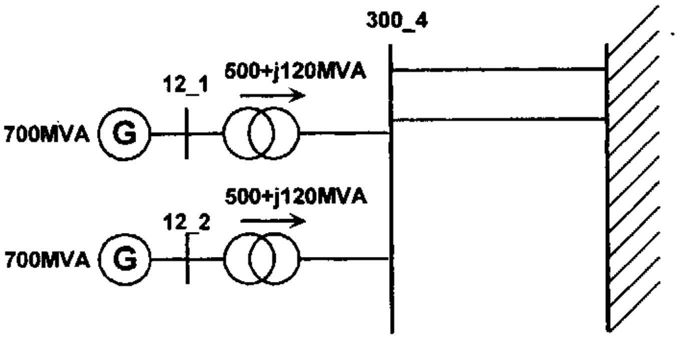


Fig. 3. Power system model

The network in figure 3 is used in the first case and it represents a general transmission system where power is transported from the two generators G1 and G2 (rated 700 MVA) to the stiff node behind the transmission lines. The two generators are producing 500 MW each. The relatively high load is selected intentionally to illustrate the impact of the ASH machine on the stability margins.

A. Case 1: General Comparison

The actual case simulated is a three-phase short circuit initiated at the node 300_4 at the point of time 0.1s. The fault duration time is set to 210 ms.

The resulting curves developed are given in figures 4 through 6 on next page. Here, the most relevant parameters are compared to each other in the respective diagrams.

The most conspicuous difference between these two types of machines is how they handle the active power production. The synchronous machine loses much of its production due to the instantaneous voltage drop. This makes a difference between the electrical and the mechanical torque and the speed increases. As this happens, the pole angle increases and the electrical torque becomes higher than the mechanical one and the machine retards. As the fault is disconnected, the voltage gets its nominal value and the electrical power and torque increase considerably. The machine finds its new stationary state by means of low frequency, poorly damped oscillations as given by time constants in the mechanical system.

For the ASH machine, the rotor currents are controlled by the converter in order to produce the specified active power according to a reference value. As can be clearly observed by the curves, this also applies during fault situations. Even though the stator voltage is significantly reduced due to the fault current, the production is maintained. This is obtained by means of reference values which takes into account the actual value of the terminal voltage. By generating these compensated rotor currents, energy is extracted from the rotor and forced into the network. This creates near equilibrium between the electrically developed torque and the mechanical torque. Consequently the speed deviation during the fault is considerably reduced compared to the synchronous machine.

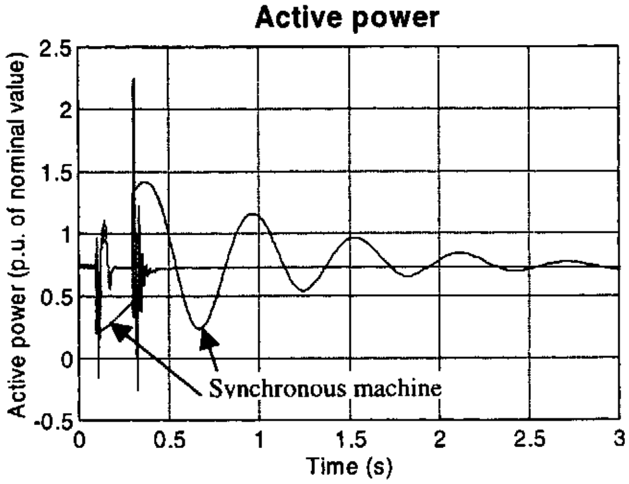


Fig. 4. Active power of the ASH machine and conventional machine, respectively

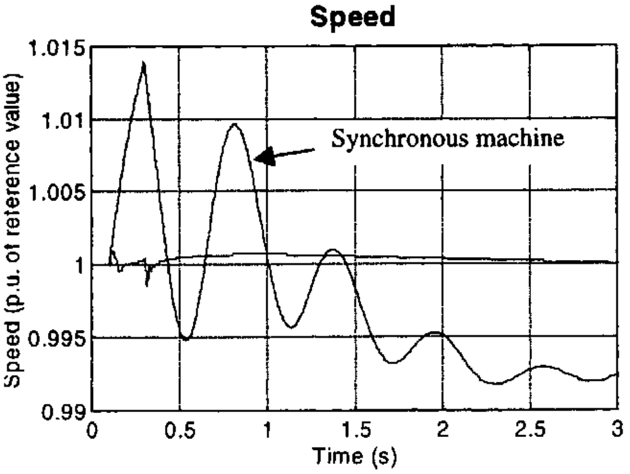


Fig. 5. Speed of the ASH machine and conventional machine, respectively

On the other hand, the ASH machine is able to maintain a constant active power during the fault only with the presence of a certain voltage level at the fault location. The machine must be able to get the power transported through the network. Below a particular voltage limit, the ASH machine must correspondingly reduce the electrical torque in the same manner as conventional machines.

Both the ASH machine and the synchronous generator react in the same manner with respect to the voltage drop. They instantaneously feed reactive power into the network in order to support the voltage (figure 6). The amount of reactive power produced is primarily given by the gain of the voltage regulator.

B. Case 2: Comparison of Power Transfer Capability

How could these properties of the ASH machine be utilised in ordinary transmission networks? In order to illustrate this, investigations have been carried out on the same type of fault as applied in the previous example.

In this case, the network in figure 7 on next page has been used in the simulations. There is one large load in the network (7000 + j1000 MVA), located at node 300_5. Generator G3 represents the auxiliary strong network as seen from the load point. This network can very well represent one of the main generation areas in the southern part of Norway and the connection to more heavily populated areas around the capital.

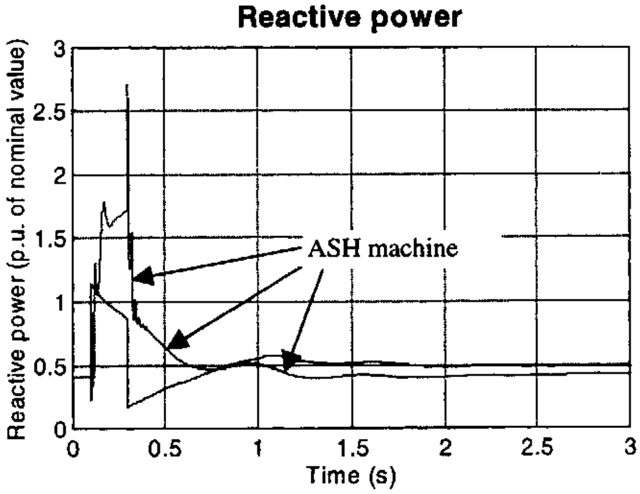


Fig. 6. Reactive power of the ASH machine and conventional machine, respectively

While using synchronous machines for all generators, the fault period is successively increased until the network gets out of synchronism. This is obtained for a fault period equal to 390 ms. The simulation results presented below apply to a fault period marginally less than the limit found (i.e. 380 ms). A corresponding

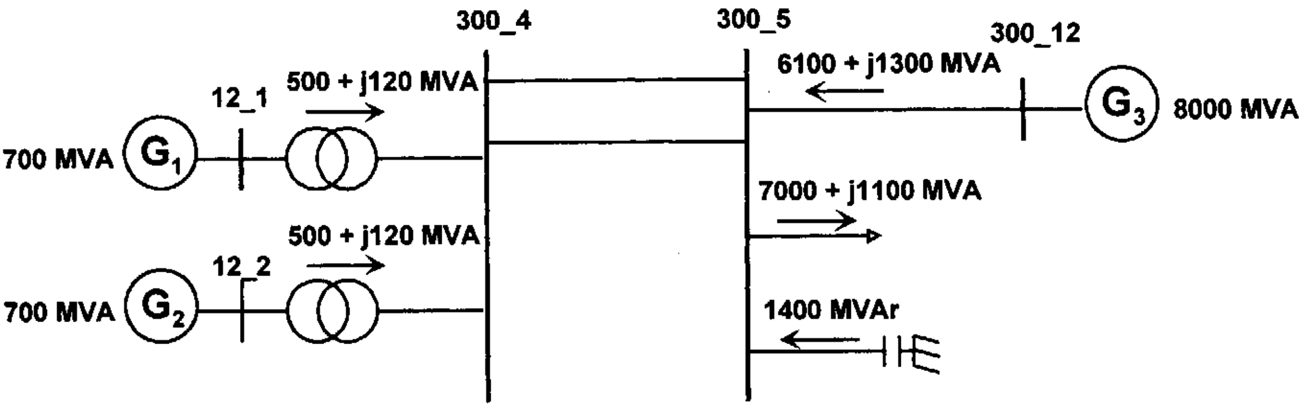
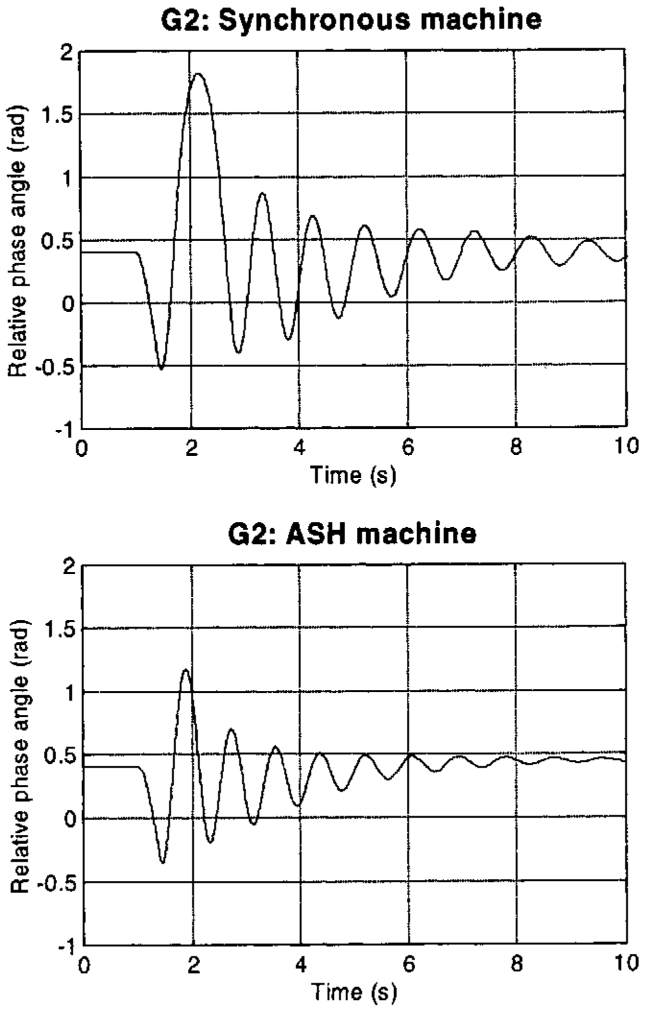


Fig. 7. Power system model

simulation is arranged for generator G2 being an ASH machine.

In figure 8, the phase angle difference between the generators G1 and G3 is shown for generator G2 being a synchronous machine and an ASH machine, respectively. This selection is made due to the fact that G1 is the first generator to get out of phase as related to G3.


G2: Synchronous machine

G2: ASH machine

Fig. 8. Difference in pole angle between generators G1 and G3 with generator G2 being a conventional machine (upper curve) and an ASH machine (lower curve).

With only conventional machines included in the network, the difference in pole angle increases continuously within the fault period (380 ms). When the fault is removed, the angle difference is –0.40 radians, increasing to –0.53 radians before the angle difference turns in positive direction. At this point of time, the most critical amplitude occurs, being equal to +1.8 radians. A further increase of the fault period results in a situation with no more braking torque left and the machine gets out of phase.

By introducing the ASH machine for generator G2, the maximum angle difference reduces to 1.2 radians and the following oscillations are more effectively damped in this case.

These results indicate that the ASH machine increases the stability margin and that more active power could be transferred without coming out of phase in serious fault situations.

C. Case 3: Maximum Power Transfer Capability with ASH Machine

The results from the previous section have been used to increase the transfer of active power through the transmission lines. The ASH machine is held at a fixed rating with a constant production as a single event implementation of this technology in the respective area. The rating of the synchronous machine G1 is also fixed, but its production is successively increased as to find the corresponding increase of active power that possibly can be transferred, still maintaining the same maximum fault time. With a generator production equal to 630 MW (26% increase) the maximum fault time is still 380 ms. The respective curve for the difference angle between generators G1 and G3 is shown in figure 9 on next page. Also in this case, the most critical amplitude occurs in the first swing, being effectively damped in the following oscillations.

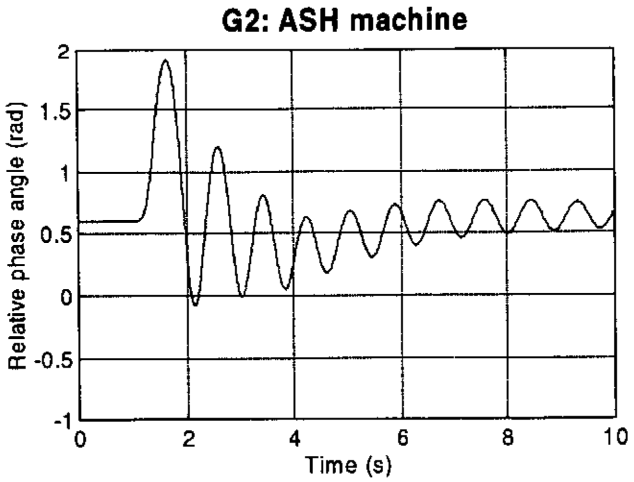


Fig. 9. Difference in pole angle between generators G1 and G3. Generator G2 is an ASH machine and the production of G1 is increased by 26% (630 MW). Fault period is 380 ms.

VII. CONCLUSION

In this paper, a direct comparison has been done between an ASH machine and a conventional synchronous machine. The simulation results show that the ASH machine is able to maintain the torque equilibrium even during serious failures. Using a fixed active power reference, the rotor current controller fine-tunes the current to give the correct power output from the machine. In transient situations, this is obtained by extracting power from the rotor (rotating energy).

The simulations have shown that by replacing conventional machines with ASH machines, an improved utilisation of the transmission system may be obtained. Restrictions to power transfer due to stability problems in the network may be circumvented by installing this promising technology.

VIII. REFERENCES

[1] T. Gjengedal, J.O. Gjerde, R. Flølo, *"Ancillary Services and Transmission in a Deregulated Market"*, ICEE '96, Beijing 1996

[2] N.G. Hingorani, *"Flexible AC transmission"*, IEEE Spectrum Vol. 30, April 1993, pp. 40 - 45.

[3] E.V. Larsen, J.J. Sanchez-Gasca, J.H. Chow, *"Concepts for design of FACTS controllers to damp power swings"*, Paper 94 SM 532-2 PWRS, presented at the 1994 IEEE/PES Summer Meeting, San Francisco, 1994.

[4] R. Flølo, J. O. Gjerde, T. Gjengedal, *"Selection of optimal TCSC damping control parameters and placement by use of eigenvalue and sensitivity analysis methods"*, Technical note, Norwegian University of Science and Technology, Trondheim, 1995.

[5] Kundur, *"Power System Stability and Control"*, McGraw-Hill, 1993, pp.387-393.

[6] B.H. Bakken, *"Technical and Economic Aspects of Operation of Thermal and Hydro Power Systems"*, Dr.ing.thesis, Norwegian University of Science and Technology, Trondheim, 1997.

[7] T.Kuwabara, A.Shibuya, H. Furuta, E.Kita, K.Mitsuhashi, *"Design and Dynamic Response Characteristics of 400MW Adjustable Speed Pumped Storage Unit for Ohkawachi Power Station"*, IEEE Transactions on Energy Conversion, Vol. 11, No. 2, June 1996.

[8] Goto, Shibuya, Inoue, Ishizaki, Tezuka, *"Power System Stabilising Control by Adjustable Speed Pumped Storage Power Station using Stabilising Signals"*, Cigre Symposium Tokyo 1995, Paper No. 510-01.

[9] J.O.Gjerde, R.Sporild, T.Gjengedal, R.Flølo, A.Elstrøm, *"Enhancement of Power System Stability in a Deregulated Environment - ASD-Machines a Promising Alternative"*, PowerCon'98 Proceedings pp. 1393-1397, Beijing, August 1998.