Control Concepts to Enable Increased Wind Power Penetration

Magni Þ. Pálsson, Trond Toftevaag, *Member IEEE*, Kjetil Uhlen, *Member IEEE*, John Olav Giæver Tande

***Abstract* – This paper addresses problems encountered in planning and operation of wind farms in areas with favourable wind conditions, but long distances to load centres and relatively weak transmission systems.**

The paper presents an overview of several control problems and challenges to be considered in order to enable increased wind power penetration. This includes control objectives related to voltage/reactive power control and active power control, including management of network constraints. Realistic examples are provided to illustrate proposed solutions with respect to coordinated control of wind farms and their interactions with the existing transmission and generation system.

Results from computer analyses of a simplified, yet realistic, electrical power system model are used to illustrate two possible control concepts to achieve increased wind power integration. These are reactive power control and coordinated generation control.

***Index terms* – Wind power, voltage control, stability, regional grids, congestion management, SVC, reactive power control, automatic generation control.**

I. INTRODUCTION

Stability assessments and dynamic control are increasingly important when planning and developing large-scale wind farms in areas distant from load centres and with limited power transmission capacity. Technical constraints in relation to wind power integration in weak grids may in general be associated with limited thermal capacity in parts of the grid and/or the adverse effect wind power can have on voltage quality and stability. Further, in certain situations, local constraints regarding development of new transmission lines or upgrading of existing lines can make it interesting to utilize the existing lines to a level which in worst case may imply operation beyond the normal technical constraints of the system.

This work describes potential control problems and challenges arising from such conditions, and suggests viable measures to enable secure and acceptable operation of large wind farms in remote areas.

The paper presents results from computer analyses of a simplified, yet realistic, transmission system with wind power integration, illustrating possible control concepts that enable secure operation of large wind farms in remote areas close to the thermal capacity and stability limits of the regional distribution grid.

The paper is organized as follows: In Section II, the main control problems and challenges regarding wind power integration in weak grids are stated. The main objectives of the case studies and a description of the system model and procedures for the analysis are given in Section III. Section IV describes the chosen approach to modelling of wind farms and controls. Main results from the analysis, for a number of different cases are presented in Section V, and in Section VI, the results are further discussed and commented. Additionally, data for the simulation model is given in Appendix.

II. CONTROL PROBLEMS AND CHALLENGES

A main background for this paper is derived from problems encountered in planning and operation of wind farms in Northern Norway. This is an area with favourable wind conditions, but long distances to load centres and a relatively weak transmission system represent main challenges in exploiting this potential.

An overview of several control problems and challenges to be considered in order to enable increased wind power penetration are presented in this section. The term *wind power penetration* is here defined as the amount of energy from wind farms that can be integrated in the system. The overall objective is thus to increase the energy from wind, but the main challenges, as shown in this paper, are often related to transmission capacity problems.

A. Voltage control – reactive power compensation

Assessments regarding voltage control become increasingly important when large-scale wind farms are planned and developed in areas distant from the main power transmission system. A main challenge related to voltage control is to maintain acceptable steady state voltage levels and voltage profiles in all operating conditions, ranging from minimum load and maximum wind power production

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minimum load and maximum wind power production to maximum load and zero wind power. Capacitor banks and transformer tap changers represent the most common means to control voltage profiles. Another challenge in this context is related to the control (or limitation) of the exchange of reactive power between the main transmission grid and the regional distribution grid.

B. *Voltage stability*

Voltage instability may be a main limitation with respect to maximum rating and integration of the wind farms. Voltage instability or voltage collapse typically occurs on power systems that are not able to meet the demand for reactive power, are heavily loaded and/or faulted. Voltage stability is sometimes called load stability [1] – [3]. Related to wind power, voltage stability problems seem mainly to be connected to the characteristics of the wind turbines more than the ordinary loads in the system. Thus, the problem may be classified as short-term voltage instability, since the power output of the wind turbine normally varies significantly within a time frame of a few seconds, reflecting the incoming wind speed variations at the wind turbine. Sufficient and fast control of reactive compensation is required to reduce voltage stability constraints, which can be provided through the use of wind turbines with active voltage control, or by using external compensators, such as static var compensators (SVCs).

C. *Transient stability*

Traditionally, the protection systems of wind turbines have been designed to disconnect and stop the units whenever a grid fault (temporary or permanent) is detected. With increasing integration of wind power there are and will be system requirements implying that wind turbines must be able to “ride through” temporary faults, and contribute to the provision of important system services, such as momentary reserves and short circuit capacity. This puts emphasis on transient stability performance, power oscillations and system damping. Control equipment within wind farms enabling both power and voltage control becomes increasingly important in this context.

D. *Thermal transmission capacity constraints*

Thermal transmission capacity problems associated with wind power integration may typically be of concern in only a small fraction of the total operating time. Applying control systems to limit the wind power generation during critical hours may then be the optimal solution. Or, as shown below, this problem can be solved by coordinated automatic generation control (AGC) if other controllable power plants are available within the congested area.

E. *Power fluctuations – frequency control*

Wind energy is by nature a fluctuating source of power. In a system where a significant part of the power generation comes from wind, system operational issues, such as frequency regulation and congestion management become a challenge due to the normal variations in the available wind power. This problem asks for flexible and improved solutions with respect to secondary generation control.

F. *Adverse impact from interaction of power electronic converters*

Modern wind turbines utilizing power electronic converters provide enhanced performance and controllability compared to traditional fixed speed solutions. With increasing use of power electronics, however, there may be uncertainties with respect to possible adverse control interactions within the wind farm itself. Converter modulation principles and filter design are important issues that must be addressed and analysed as part of the wind farm design and installation.

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In summary, most of the problems described above may result in operational conditions that adversely affect the quality of the voltage and power supplied to customers. Additionally, there may be system operational problems, such as congestion management and secondary control that not only affect the wind farm in question but the entire network.

Thus, the problems suggest coordinated control solutions that maintain secure operation of the network, and at the same time allow for maximized and profitable integration of wind power.

III. CASE STUDY SPECIFICATION

The aim of the case study is to analyse and propose solutions to deal with the control problems, as described in the previous Section, and to point out viable measures to enable secure operation of the system close to the thermal capacity and stability limits, yet keeping the voltage quality and stability within acceptable limits for all parts of the system in question.

The case study includes control concepts and objectives related to voltage/reactive power control and active power control, including management of network constraints. Examples are provided to illustrate proposed solutions with respect to coordinated control of wind farms and their interactions with the existing transmission system and hydropower generation.

A. *System model description*

A large wind farm (rated power max 150 MW) is connected to the main transmission grid via a long existing 132 kV radial with limited transfer capability. The same radial also feeds local distribution grids and connects other generation, in this case hydropower unit equipped with a synchronous generator. Due to environmental constraints, an upgrading of the radial is not possible, and therefore the rated voltage of the radial has to be kept at 132 kV.

A single-line schematic diagram of the modelled system is shown in Figure 1.

For the purpose of the analyses presented in this paper, the wind farm is modelled as two aggregated wind turbines. (A real wind farm of this rating would consist of 100 – 200 wind turbines). For details regarding wind turbine modelling, see Chapter IV and comments in Appendix. When induction machines represent the wind turbine generators, reactive power compensation is included at the 690 V level in the wind farm. This reactive power compensation is approximately equal to the no-load reactive power consumption of the induction machines.

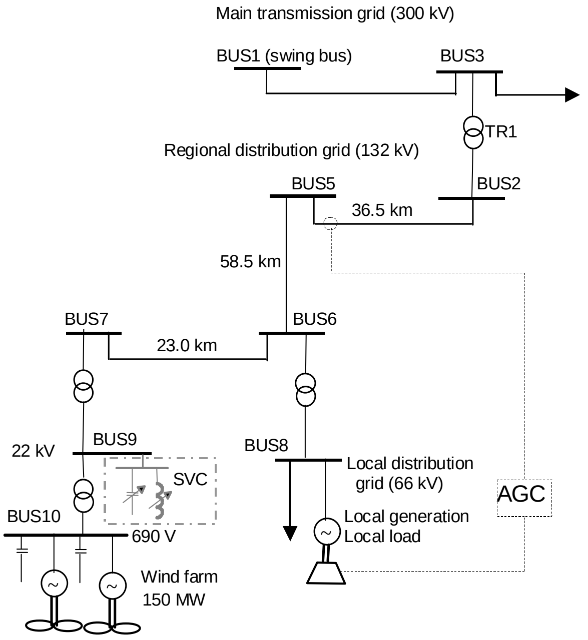

Fig. 1. A single-line diagram of the modelled system. SVC at BUS9.

The SVC is modelled as a variable susceptance with maximum and minimum limits on the reactive power output.

Modelling the wind farm with induction generators is obviously a worst-case situation with respect to reactive power consumption and control.

Only one load situation has been analysed as well as only one grid configuration (see Figure 1). For further details regarding the system model, see Appendix.

B. Voltage control and stability

The first case study is shown to illustrate coordinated voltage control to maintain voltage quality requirements and overall limitations on reactive power exchange between a regional distribution grid and a main transmission network. This problem is relevant when the local hydropower plant is not operating.

For the system studied in the present work, previous analyses [5] have shown that voltage stability problems will occur long before the thermal limits of the regional network are reached. Without any extra reactive power production (apart from the no-load reactive power compensation for the induction generators) the voltage stability limit (with respect to produced active power in the wind farm) lies at approximately 75 MW. This represents only 40% of the thermal capacity of the radial. To be able to fully exploit the thermal capacity, additional reactive compensation is needed.

For this case study, the main objectives can be described as follows:

- Exploit existing lines up to thermal limit, I_{th}, at full wind power production.
- Integrate as much active wind power production as possible.
- Keep the voltage profile at the wind farm within ±5% of rated voltage, U_N (ref. to 22 kV level).
- No net exchange of reactive power between the regional network and the main transmission grid.
- Keep acceptable power quality at all buses where ordinary consumers are connected, for all levels of wind power production.
- Minimize electrical losses.

Since this implies that the system occasionally will be operated beyond it’s conventional voltage stability limits, additional equipment and control measures and/or special protection systems become necessary. Investment costs are obviously important, but such considerations are beyond the scope of this paper.

To be able to operate the actual regional distribution network close to it’s thermal limits, remedial measures have to be designed to enhance the system’s voltage stability limit, and prevent a voltage collapse.

In this work a Static Var Compensator (SVC) has been chosen as a source for reactive power support in the furthermost part of the regional distribution grid due to the ability of the SVC to provide continuous control and to react fast. The SVC can either control the voltage at a local node, i.e. the node where the SVC is connected to the system, or at a remote node. It is believed that by using modern wind turbines, i.e. wind turbines with reactive power generation capability, the SVC can be left out in this context.

Switched capacitors are connected to BUS5 in the model, in order to provide necessary reactive power support to this part of the distribution grid. No reactive power import is allowed to the regional distribution grid from the main transmission grid, for any production scenario (wind only, hydro only, wind/hydro); this requirement is to be handled by the capacitor-bank on BUS5. For further details, see Section V.B.

C. Coordinated generation control

The second case study is a technical assessment of the performance of coordinated active power generation control. In a system with both wind and hydropower generation, there is an additional control flexibility in utilizing the hydro storage capacity. It is demonstrated via two examples how AGC equipment can be utilized for load following control purposes in order to meet two different (and independent) objectives. One objective is to avoid grid congestions on demand from grid operators. The second objective is to fulfil market obligations with respect to maintaining generation plans. The economical and administrative issues regarding the utilisation of hydro storage are not part of this study.

IV. Wind Turbine Modelling Approach

The power system simulation tool SIMPOW is applied in this study. The tool includes built-in models of generators, network components, various control loops etc to facilitate phasor simulations of power systems. A wind farm user model has been implemented to facilitate the analysis presented in this paper. The model is described and verified in [4]. A brief description will be given in this section. Fig. 2 shows the main components of the model.

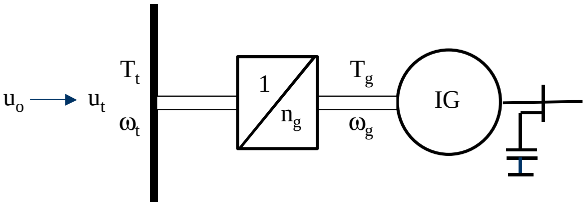

Fig. 2. Main components of fixed speed, stall controlled wind turbine model.

The user provides a time-series of wind speed, $u_o(t)$, as input to the model. This may be a measured or generated wind speed time-series representing the wind speed at hub-height and perpendicular to the rotor plane. The wind turbine is however affected by the wind speed variations over the rotor plane. These variations cause enhanced turbine torque T_t fluctuations around three times the rotor frequency (3p) and harmonics thereof, whereas the other higher frequency variations are damped. To achieve these characteristic turbine torque variations we hence transfer u_o to u_t by application of filters so that u_t approximates the weighted average wind speed over the three rotating blades. The turbine torque is then found applying the quasi-steady state relation:

$$T_t = 0.5\rho A u_t^3 C_p \omega_t^{-1} \tag{1}$$

The turbine efficiency C_p is in general a function of the tip-speed ratio, λ, and pitch angle. However, for a fixed speed, stall controlled wind turbine, C_p becomes a function of the wind speed only. Hence, for the wind turbine model presented in this paper, C_p is simply specified as function of the wind speed according to given data.

The turbine torque is transferred through the main shaft and gearbox to the generator shaft. This is represented by a two mass model, i.e. the turbine and generator inertia with a shaft and an ideal gearbox between them. Commonly the turbine inertia is fairly large compared to the generator inertia, whereas the shaft seen from generator appears to be rather soft.

The induction generator and capacitors are presented using the built-in models of the applied software tool. A third order induction generator model (assuming no saturation) is applied, and the capacitors are modelled assuming their steady-state representation only, i.e. consistent with the phasor model simulation applied in this study.

The wind turbine model has been verified against measurements on a 500 kW stall regulated, fixed speed wind turbine. As can be seen from Fig. 3, the model closely approximates the measured power fluctuations.

A detailed wind farm model may include the following components:

- A wind field model describing $u_o(t)$ for each of the wind turbines of the wind farm.
- A wind turbine model as just outlined for each of the wind turbines of the wind farm.
- A model of the internal grid of the wind farm with lines, transformers and possible ancillary equipment.

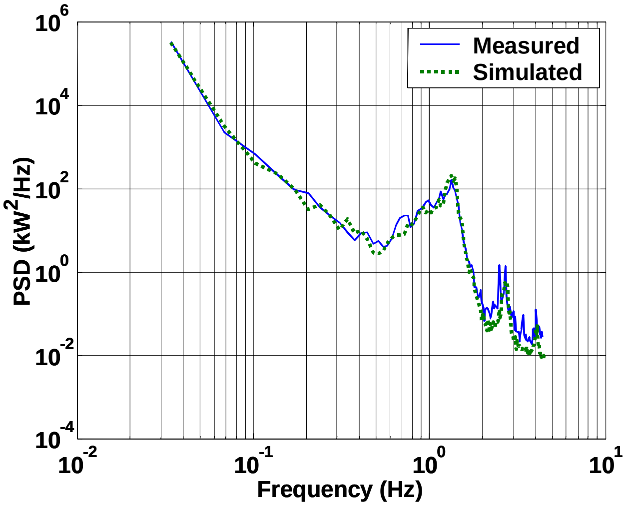

Fig. 3. Power Spectral Density (PSD) of measured (solid line) and simulated (dotted line) wind turbine output power.

Applying this detailed wind farm model in conjunction with a model of the external grid, comprehensive studies may be undertaken to assess the operational implications of the wind farm. However, for the scope of this paper, an aggregated representation is sufficient letting the single wind turbine model to present the wind farm. This is done straight forward keeping the pu values of the wind turbine model, and including a modification of u_t to reflect that the fast power fluctuations from wind turbines in a wind farm are uncorrelated.

V. ANALYSES AND RESULTS

A. *General*

This section presents the main results of this work. The following cases are treated:

- Control of voltage and reactive power exchange between the regional distribution grid and the transmission network during increasing wind power production. Worst case represented by the absence of the hydropower unit connected at BUS8.
- Coordinated generation control showing how the additional control flexibility of a hydropower unit can be utilized in systems with both wind and hydropower generation. This is illustrated with two examples:
  - Avoiding grid congestions on demand from grid operators during periods of high wind power production by using the additional control flexibility of a hydropower unit.
  - Fulfilling market obligations with respect to maintaining generation plans subject to the unpredictable variations in wind power.

B. Case 1: Voltage control and reactive power

It is important to keep an acceptable voltage quality for all consumers at all levels of wind power production. Additionally, an extra criterion in the example presented is to keep a zero net exchange of reactive power between the regional and main transmission grids. The voltage level at the wind farm must also be kept within limits given by the manufacturer.

In the example presented here, (increasing wind power production during a 10 minutes period), the reactive power exchange with the main grid is controlled by a switched capacitor bank located at node BUS5. To keep a steady voltage level at the wind farm, a SVC is placed at node BUS9 at the wind farm (22 kV level), controlling the voltage at node BUS7.

The first point of common coupling, PCC, (i.e. where other consumers are connected) is node BUS6.

The capacitor bank on BUS5 is equipped with a secondary controller, controlling the set-point value of the capacitor bank's voltage controller (controlling the voltage on BUS5). The secondary controller measures the reactive power flowing into the 300 kV side of transformer TR1 (between BUS2 (132 kV) and BUS3 (300 kV), see Fig. 1) and changes the set-point value to minimise the reactive power flow into TR1. For further details regarding the secondary controller, see [5].

Fig. 6 shows results from the simulations regarding the reactive power flowing into transformer TR1 (ref. 300 kV side) with a secondary controller applied for the capacitor bank on node BUS5. For reasons of comparison, the simulation results with an ordinary SVC (with and without secondary controller) are included in the figure.

The results indicate that the chosen control strategy (secondary controller) meets the requirements regarding zero net reactive power exchange with the main transmission grid.

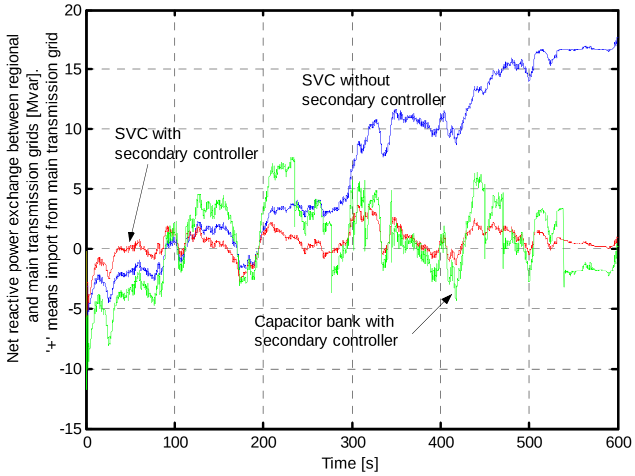

Fig. 4. Net reactive power flow between the regional and main transmission grids. One SVC placed on node BUS9. Capacitor bank on node BUS5 with secondary controller. Results with SVC (with and without secondary controller) also included.

It is interesting to note that the switched capacitors (with a secondary controller) is capable of keeping the net exchange of reactive power at a similar level as the SVC with a secondary controller.

No attempt has been made to optimise the step size of the capacitor bank, nor the controller parameters.

The voltage on BUS6 (first PCC) is shown in Fig. 5.

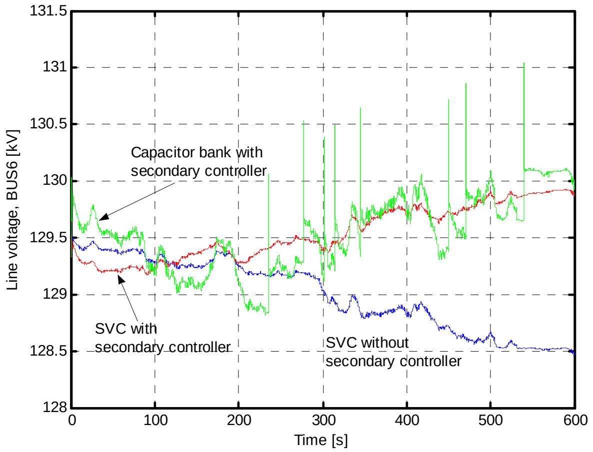

Fig. 5. Voltage on BUS6 for different reactive power supply solutions at BUS5.

The curve for the voltage when using the capacitor bank, shows spikes when switching on new capacitors. These are assumed to be caused by numerical imperfections in the simulation program. However, frequent switching of capacitors is a practical problem that needs to be assessed.

C. Case 2: Coordinated generation control

The aim of this case study is to illustrate how the additional control flexibility of a hydropower unit can be utilized in systems with both wind and hydropower generation. This is illustrated with two examples, using an automatic generation control (AGC) equipment to meet two different objectives.

<u>Avoiding grid congestions on demand from grid operators</u>: In this example the power transfer limit of the 132 kV lines in the regional distribution grid is 200 MW (thermal capacity of the lines). To avoid critical lines being overloaded during periods of high wind power production, a special system protection controller based on AGC technology is proposed. The controller performs secondary power control of the hydropower unit, and the aim is to reduce the generation from this unit when the total transmitted power exceeds 200 MW. This is illustrated in Fig. 6.

Initially (i.e. at time t=0) the transmission line is loaded slightly below the thermal limit (which is approx. 200 MW). The wind speed time series has an increasing trend, thus the wind farm power production is increasing. To fully utilize the potential of the wind power, and at the same time maintain the power transmission within the thermal limit of the transmission line, the secondary controller (AGC) of the hydropower unit issues signals to the unit's governor to reduce production.

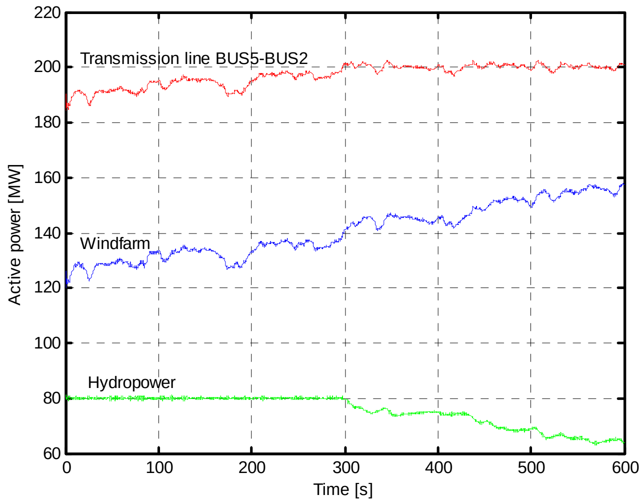

Fig. 6. Example showing how grid congestions can be avoided by using an AGC to utilize the hydropower storage.

Fulfilling market obligations with respect to maintaining generation plans: The unpredictable variations in wind power create challenges for production unit owners with respect to generation planning and market bidding. Furthermore, the stochastic nature of the wind may make it difficult to fulfil market obligations, that is, to control generation according to plan from hour to hour. For some power companies who own both wind power and hydropower generation in the same geographical area, the controllability of the hydropower can be exploited to develop coordinated controls. In this example a load following controller has been implemented based on the AGC of the hydropower unit.

Fig. 7 illustrates how this controller can be used to deliver a given total generation (wind power + hydropower) according to plan. The simulation shows the transition from one hour to the next where the generation is ramped from 100 MW (scheduled generation in the first hour) up to 200 MW, which is the plan for the second hour.

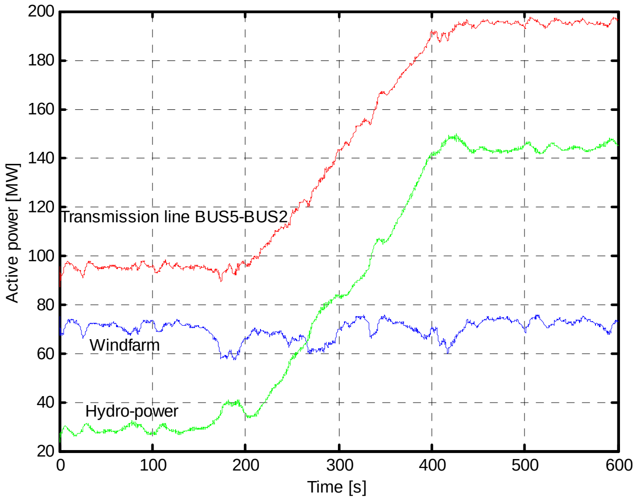

Fig. 7. Production of the hydropower unit following an increase in planned generation.

By using this approach, the wind power potential is fully utilized at the same time as market obligations with respect to planned generation are fulfilled.

VI. DISCUSSION AND CONCLUSION

This work presents results from a simulation study aimed at highlighting some possible consequences of large-scale integration of wind power into a given regional network, when applying induction generators in the wind power plants.

It has been shown that it can be technically possible to operate an electric power system beyond the traditional voltage stability limits. To raise these limits, extra reactive power compensation has been applied.

The results indicate that the chosen control strategy (voltage controller with a secondary controller) meets the requirements regarding zero net reactive power exchange with the main transmission grid. The results also show that the switched capacitors (with a secondary controller) are capable of keeping the net exchange of reactive power at a similar level as a SVC with a secondary controller.

New developments in wind turbine design include power electronic converters between the generator and the grid. Such solutions are capable of offering continuous reactive power control in the same way as the extra reactive power compensation treated in this work. Such a “modern” solution may represent an interesting alternative to the wind turbine / SVC combinations presented in this work. The results in this paper may give input to the design of this solution regarding apparent power rating of the equipment.

It has also been shown how grid congestions on demand from grid operators can be avoided and market obligations with respect to maintaining generation plans can be fulfilled by use of coordinated generation control in a system with both wind and hydropower generation. This can be an effective means to enable increased wind power penetration.

VII. APPENDIX

A detailed description of input data to the simulation model is given in this Appendix.

A. *Wind turbine model*

TABLE I
ASSUMED DATA FOR WT500 1)

Nominal power, P_n (MW)	0.5
Nominal voltage, U_n (kV)	0.69
Nominal apparent power, S_n (Mvar)	0.557
Nominal frequency, f_n (Hz)	50
Number of pole pairs, p	2
Stator resistance, R_1 (pu)	0.0098
Stator leakage reactance, X_{1S} (pu)	0.1168
Rotor leakage reactance, X_{2S} (pu)	0.1691
Magnetizing reactance, X_M (pu)	3.9568
Magnetizing resistance, R_M (pu) (in series with X_m)	0.0999
Rotor resistance, R_{2S} (pu)	0.0096
Shunt-capacitor, Q_c (Mvar)	0.125
Generator inertia, H_g (s)	0.33

Turbine inertia, H_t (s)	2.99
Shaft stiffness, k (pu torque/el. rad.)	0.61
Mutual damping, d_m (pu torque/pu speed)	0.0017
Gearbox ratio, n_g	55.814
Turbine radius (m)	20.5
Hub-height (m)	36.0

$^{1)}$ pu values refer to rated power of generator

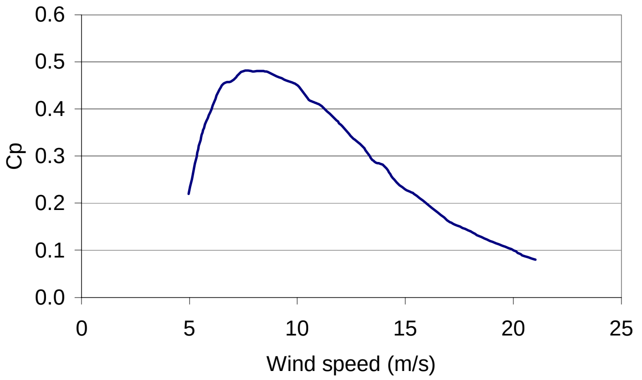

Fig. 8. Assumed WT500 efficiency (C_p) as a function of the wind speed.

B. *Wind farm model*

The wind farm is modelled as two units each rated at 80 MVA, and each applying the p.u. data for WT500, but the wind speed input has been modified to reflect that the fast power fluctuations from the wind turbines in the wind farm are uncorrelated.

C. *System model*

For information regarding network data (lines, transformers, etc.) and SVC regulators (primary and secondary), see [5].

A schematic diagram of the AGC-principle is shown in Fig. 9.

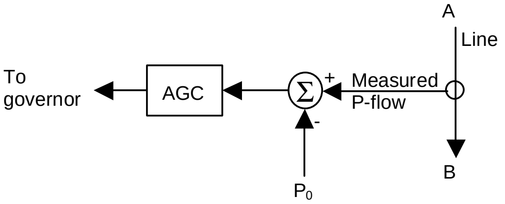

Fig. 9. A schematic diagram of the automatic generation controller (AGC).

REFERENCES

[1] P. Kundur, *Power system stability and control*, McGraw-Hill, 1994, ISBN 0-07-035958-X

[2] C. W. Taylor, *Power system voltage stability*, McGraw-Hill, 1994, ISBN 0-07-063184-0

[3] C. Canizares (ed.), “Voltage stability assessment, procedures and guides”, *IEEE/PES Power system stability subcommittee special publication*, Final draft, January 2001, http://www.power.uwaterloo.ca

[4] J. O. G. Tande, “Wind Farm Models for Power System Studies”, issued for publication in IEEE Trans. Energy Conversion, 10 October 2002.

[5] M.T.Palsson, T.Toftevaag, K.Uhlen, J.O.G.Tande, “Large-scale Wind Power Integration and Voltage Stability Limits in Regional Networks”, 2002 IEEE-PES Summer Meeting, Proceedings.

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