Large-scale Wind Power Integration and Voltage Stability Limits in Regional Networks

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Abstract – **When planning and developing large-scale wind power plants in areas distant from the main power transmission system, voltage control assessments and reactive power compensation are increasingly important. Voltage stability of the regional network may be a main limitation with respect to maximum rating and operation of the wind power plant. 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. In certain situations, however, local constraints regarding development of new transmission lines or upgrading of existing lines can make it interesting to utilise the existing lines to a level which in worst case may imply operation beyond the normal technical constraints of the system.**

In this work, challenges and opportunities arising from situations as described above are analysed, and viable measures to enable secure and acceptable operation of large wind farms in remote areas close to the thermal capacity and stability limits of the power system, are pointed out.

The paper presents results from computer analyses of a simplified, yet realistic, electrical power system with wind power integration, illustrating possible solutions to achieve this.

Index terms – **Wind power, voltage control, voltage stability, regional grids, thermal capacity, reactive compensation, SVC, reactive power control.**

I. INTRODUCTION

Voltage control assessments and reactive power compensation are increasingly important when large-scale wind power plants are planned and developed in areas distant from the main power transmission system. A main limitation with respect to maximum rating and integration of the wind power plant may be associated with voltage stability of the regional network.

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. In certain situations, however, local constraints regarding development of new transmission lines or upgrading of existing lines can necessitate a utilization of the existing lines, which in worst case may imply operation beyond the normal voltage stability constraints of the system.

For the system studied in the present work, preliminary analyses have shown that voltage stability problems will occur long before the thermal limits of the regional network are reached.

Voltage instability problems and collapse typically occur 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]. In the present work, however, the problems seem mainly to be connected to the characteristics of the wind turbine generators more than the ordinary loads in the system. On the other hand, generation can also be viewed as a complex load, but with a negative real part (representing production) in contrast to an "ordinary" load.

The voltage stability phenomenon covered by the present work may be classified as transient voltage stability, since the power output of the wind turbine generator normally varies significantly within a time frame of a few seconds, reflecting the incoming wind speed variations at the wind turbine.

The aim of this work is to analyse challenges and opportunities arising from situations as described above and 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.

This paper presents results from computer analyses of a simplified, yet realistic, transmission system with wind power integration, illustrating possible solutions that enable secure operation of large wind farms in remote areas under the above mentioned situations.

The paper is organised in three main sections. In Chapter II, the main objectives of the study are stated and thorough description of the model and procedures for the analysis are given. Chapter III presents results from the analysis, for a

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number of different cases. In Chapter IV, the results are discussed and commented. Additionally, data for the simulation model is given in Appendix.

II. APPROACH

A. Objectives

The main objectives, in the context of this paper, 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.

In this paper, limits for voltage stability at different wind power integration levels and grid alternatives are illustrated, for situations with and without extra stabilizing controls in the system (SVC) and for different characteristics for the wind turbine generators. In addition, the effects of choosing different locations for the SVCs are illustrated.

B. Need for reactive power support

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

Mechanically switched shunt capacitors (MSCs) represent in general a well-established solution to enhance the system voltage stability limit. In the present case, however, MSCs are not considered to be the best solution due to the high rate of switching for the capacitor breakers, which can be expected due to the relatively high variations normally occurring in the wind power production. If they are switched on too late, they will have little effect in preventing the voltage collapse. As more shunt capacitors are added, the sensitivity of the voltage to changes in power increase. It is assumed that this can represent a problem in practice when developing a control strategy for the MSCs.

In this work a Static Var Compensator (SVC) has been chosen as a source for reactive power support due to the ability of the SVC to provide continuously variable susceptance and the ability 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.

C. Model description

A large wind farm (rated power max 200 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 some other small generation. Due to environmental constraints, the rated voltage of the radial must be restricted to 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 turbine generators. (A real wind farm of this rating would consist of 100 – 200 wind turbines). 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.

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

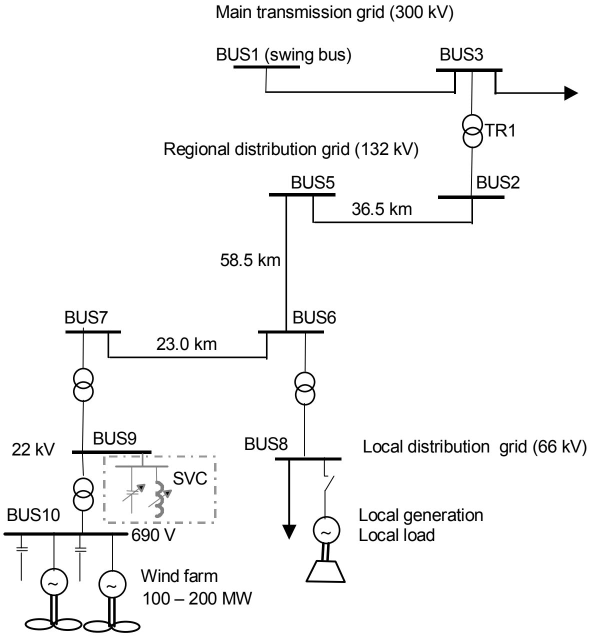

Fig. 1. A single-line diagram of the modelled system. SVC at BUS9.

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

Only one load situation has been analysed as well as only one grid configuration (see Figure 1).

For further details regarding the model, see Appendix.

D. Procedure for analysis and limitations

Both static (load flow) and dynamic simulations have been applied for analysing the problems encountered in this work. The load flow simulations have been applied to establish initial conditions for the dynamic simulations. The main parts of the results presented are based on dynamic simulations.

This paper does not deal with fault analysis, long-term dynamics (in the range of minutes) or switching transients. Detailed dynamic load modelling is not treated.

E. Simulation software

In this work the computer program SIMPOW® is used for all simulations and analyses.

The program covers different kinds of power system analyses, such as load flow analyses, transient stability analyses, machine dynamics and faults, etc. In addition, eigenvalue calculations and frequency-scan can be performed.

The basic modules of SIMPOW, which also have been used in the present work, are OPTPOW (load flow) and DYNPOW (dynamic simulation). The dynamic simulations performed cover phasor models only.

For further information, see [3].

III. RESULTS

A. General

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

- Base case, wind turbine generators represented by induction machines, local reactive compensation corresponding to no-load reactive consumption of the induction machines, no SVC.
- Same as base case, but with one SVC giving an illustrating example of how a SVC can raise the voltage stability limit.
- Case with fully compensated wind turbine generators, i.e. Q=±0 Mvar irrespective of production level. One SVC.
- Case with fully compensated wind turbine generators and two SVCs. Zero net exchange of reactive power between the regional network and the main transmission grid.
- Case with fully compensated wind turbine generators and two SVCs. Realistic wind power production variations. Zero net exchange of reactive power between the regional network and the main transmission grid.

B. The base case – no extra stabilizing controls

Wind farm consisting of traditional induction generators, without any extra reactive power production (apart from the no-load reactive power compensation), is considered a worst-case scenario in this context. To reveal the voltage stability limits, a linear increase of the produced active power in the wind farm is simulated. The power is increased in the dynamic module of the simulator from zero until the voltage stability limits are reached.

The curve "Without SVC" in Fig. 2 shows a power-voltage curve (ref. BUS7) for this case. The curve is constructed by plotting the time series for the node voltage (at BUS7) as a function of the time series for produced active windpower from the dynamic simulations. The voltage stability limit (with respect to produced active power) lies at approximately 75 MW (the tip-point of the curve). At this point only 40% of the thermal capacity of the radial is used. However, the practical limit for wind power production is below 70 MW, because voltages in parts of the system are very low so the wind farm can not be operated at this point. This means that in this case the maximum power production in practice is limited by the voltage restrictions.

No consideration has been given in this case to limit the net exchange of reactive power between the regional and main transmission grids.

C. Raising voltage stability limits by using a SVC – induction generators in wind farm

A SVC (rated at 185 Mvar) is connected to BUS9 (22 kV level in the wind farm), controlling the voltage on node BUS6. This control node for the SVC is chosen because it represents the PCC (point-of-common-coupling with respect to ordinary consumers). The simulated wind power production increase is the same as in Case 1.

The curve marked "With SVC" in Fig. 2 shows the power-voltage curve for this case.

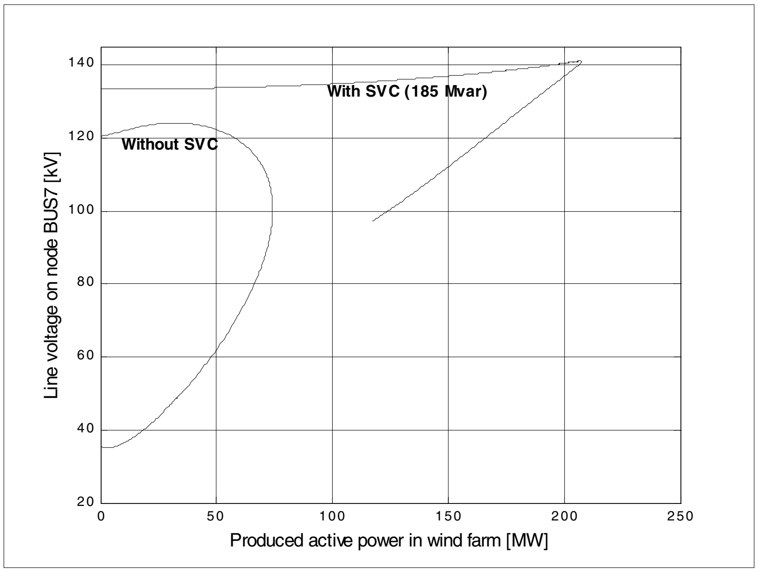

Fig. 2. Line voltage on node BUS7 in relation to produced active power in the wind farm. SVC placed at node BUS9.

By using a SVC as shown in this example, it is possible to produce and transmit more active power through the radial, thus utilising more of the available capacity of the radial. The SVC in the example is rated at 185 Mvar and it raises the voltage stability limit to over 200 MW. The practical limit (with respect to thermal limit of the radial) is approximately 195 MW. The voltage conditions are also significantly improved.

It should be noted, that the dynamic simulation model has not been equipped with regulators for the load-tap-changing (LTC) transformers. The reaction time for these, is normally in the time range of minutes. It is therefore believed that their dynamics will not have an influence on the results in this context.

As in the previous case, no consideration has been given to limit the net exchange of reactive power between the regional and main transmission grids.

D. Fully compensated wind turbine generators – one SVC

Modern wind turbine generators are capable of producing active power at a power factor cosφ=1.0 irrespective of active wind power production. Using fully compensated generators in the present system, the thermal limit of the radial is reached at approximately 200 MW production in the wind farm. To achieve this, still a SVC is needed at the wind farm (in this example located at node BUS9), but with a much smaller rating than in the corresponding case with induction generators in the wind farm (as described in section C). A SVC of 85 Mvar rated capacity shows to be satisfactory, compared with 185 Mvar in the previous case. (Note: In this case the local reactive compensation is taken care of by the SVC only; no capacitors as shown in Fig. 1 are installed).

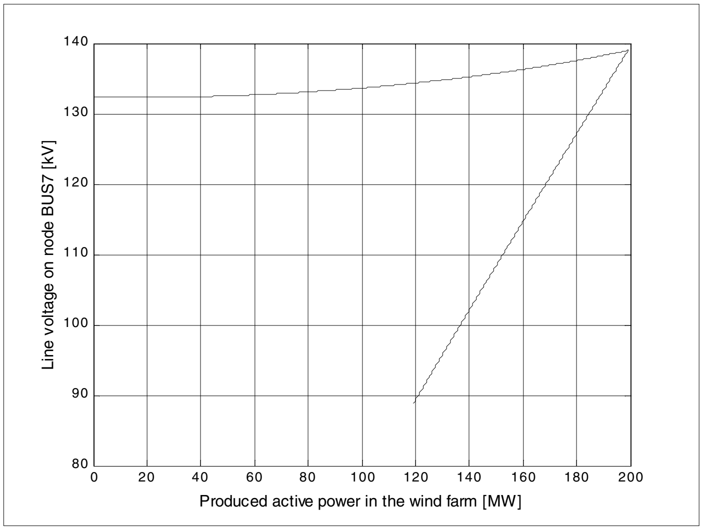

Fig. 3. Line voltage on node BUS7 in relation to produced active power in the wind farm. Fully compensated wind turbine generators. SVC placed at node BUS9. SVC rated at 85 Mvar, and controlling voltage at BUS6.

Fig. 3 shows the P-V curve for BUS7 for this case. The maximum active power production in the wind farm (200 MW) corresponds to the thermal capacity of the radial between BUS7 and BUS6.

E. Fully compensated wind turbine generators – two SVCs (located at different nodes). Zero reactive power net exchange with the main grid.

Two of the main objectives of this work, as described in chapter II, are to keep a stable voltage profile at the wind farm and keep net exchange of reactive power between the regional and main transmission grids at zero.

To fulfil these objectives a decoupling of the two control tasks is made. To meet the first requirement, a SVC is placed at node BUS7 at the wind farm (132 kV level). This SVC controls the voltage at node BUS7.

In this example, another SVC is placed on node BUS5 to meet the second objective. This latter SVC is equipped with a secondary controller, controlling the set-point value of the voltage controller. 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 SVC controllers, see Appendix.

Fig. 4 shows some results from simulating a linear increase of the produced active power in the wind farm. The active power production is in this case increased from zero to 200 MW in 50 s in the simulations.

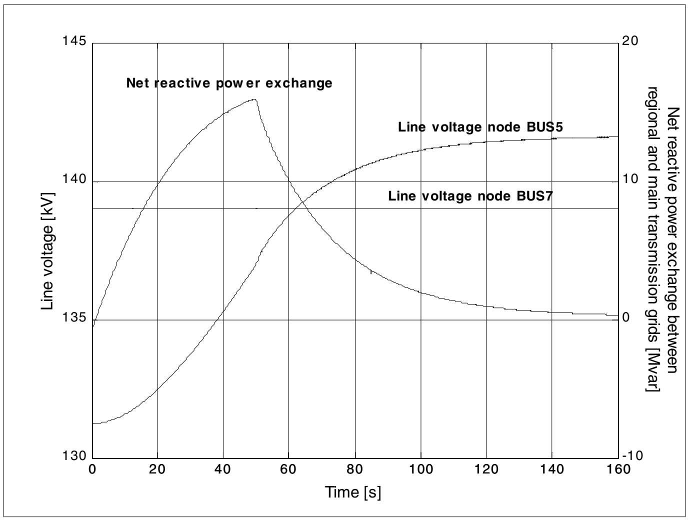

Fig. 4. Line voltage on nodes BUS7 (at the wind farm) and BUS5. Net reactive power exchange between the regional and main transmission grids (transf. TR1). One SVC placed on node BUS7 and another on node BUS5 with secondary controller. Linear ramping of wind power production (0 – 200 MW in 50 s). Fully compensated wind turbine generators.

To establish the initial conditions for this dynamic simulation, the voltages on selected nodes have been tuned manually to give both an acceptable overall voltage profile in the regional grid and to obtain zero net exchange of reactive power into transformer TR1 (ref. 300 kV side). This corresponds to the tertiary control normally performed by the system operator.

The SVC at node BUS7 keeps a very stable voltage level at the wind farm with this solution, and the secondary regulator of the SVC at node BUS5 achieves the objective of minimising the deviation (ref. flow of reactive power) between BUS2 and BUS3. This, however, comes at the cost of increased voltage on node BUS5.

F. Fully compensated wind turbine generators – two SVCs (located at different nodes). Realistic wind power production variations. Zero net exchange with the main grid.

The system described in section E has been further analysed by applying a measured wind power production time series in the dynamic simulations, to investigate power quality and control aspects in the given system. This time series represents real-life behaviour of a modern wind turbine generator (Vestas V80) [5]. The resolution of the time series is 1 s.

The cut-out of the received time series used as an input to the simulations is shown in Fig. 5. It is assumed in the case study that all of the wind turbine generators (100 in this case) follow the same production pattern. This represents an absolute worst-case situation regarding power fluctuations from the wind farm.

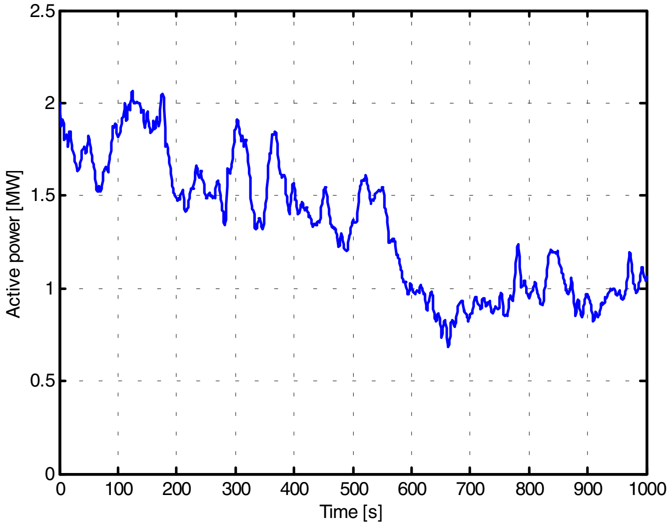

Fig. 5. The applied active wind power production time series for one wind turbine generator [5]. Same profile applied for all wind turbines.

Fig. 6 shows results from the simulations regarding the reactive power flowing into transformer TR1 (ref. 300 kV side) with and without a secondary controller applied for the SVC on node BUS5. The results indicate that the chosen control strategy (secondary controller) meets the requirements regarding net reactive power exchange with the main transmission grid.

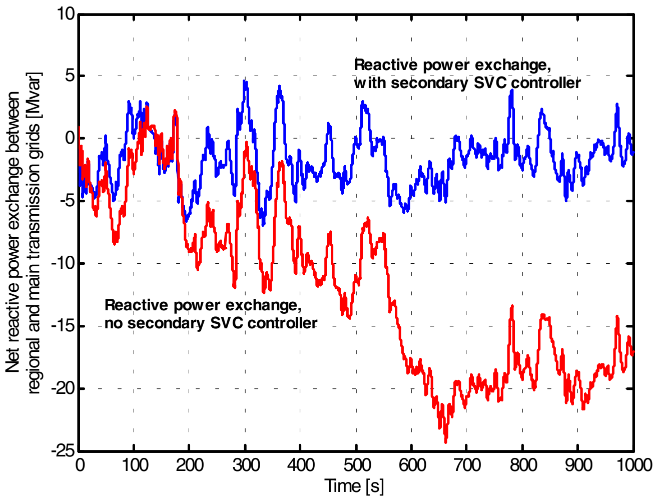

Fig. 6. Net reactive power flow between the regional and main transmission grids. One SVC placed on node BUS7 and another on node BUS5 with and without secondary controller.

Fig. 7 shows results from the simulations regarding the voltage on node BUS5, i.e. the bus where the SVC with the secondary controller is located.

The resulting time series for voltage at BUS5 has been analysed by means of a software version of the flickermeter described in IEC 61000-4-15 [6]. The results show that no flicker occurs at this bus for the voltage variations in question.

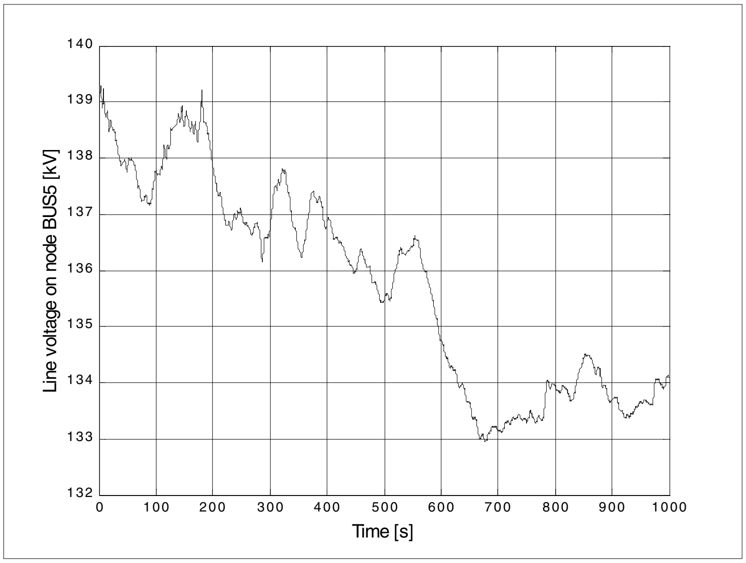

Fig. 7. The node voltage on node BUS5. SVC at BUS5 equipped with secondary controller.

The voltage at BUS7 shows very small variations for the same time period compared with BUS5, and accordingly no flicker will be experienced at this bus.

IV. DISCUSSION

This work shows analyses of the consequences of large-scale integration of wind power into a given regional network, when applying induction generators in the wind power plants. An objective has been to determine the network's need for additional reactive power production when the lines of the radial in question are operated at their thermal limits (corresponding to approx. 190 MVA, referred to 132 kV), for different locations of this reactive production.

Due to the strongly increasing demand for reactive power in the wind farm at increasing active power production, the maximum possible power production is limited at approximately 75 MW for the given network, when no extra reactive power support is included. The losses in the radial are approximately 7 MW, but the voltage level is not acceptable in parts of the network for this situation (as low as approximately 20% below nominal value).

The main objectives for this study are met by locating a SVC at node BUS7 and controlling the voltage on node BUS7 and a second SVC at BUS5 equipped with a secondary controller for minimising the reactive power exchange with the main transmission grid. By this solution it is possible to produce as much as approximately 200 MW without exceeding the thermal limits (I_{th} = 832 A) of the radial in question (between BUS7 and BUS6).

In this work 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, i.e. a SVC, has been applied. This solution though is cost intensive, but the economic aspect is beyond the scope of this work.

Voltage security or production margin are important keywords in connection with the operation of the present system. The production margin to voltage collapse for a given operating point can in this context be defined as the amount of additional production that would cause a voltage collapse. The most influencing factor in this context is assumed to be the normally expected variations in the wind power production at rated production. This will depend on type of wind turbine, manufacturer etc.

New developments in wind turbine generator 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 SVC treated in this work. Such a “modern” solution may represent an interesting alternative to the wind turbine generator / 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.

Whether it is viable or not to operate the given system for longer periods beyond the voltage stability limit is of course an important question, which should be analysed in detail before possible implementation. Design of proper protection equipment will represent a challenge in this context.

How to implement a solution where the SVC measurement-node/control node is located far from the SVC’s main node represents an interesting and challenging question which is beyond the scope of this work.

Detailed fault analyses will have to be conducted to clarify if the wind farm will have to be disconnected (completely) from the grid during faults or not.

V. CONCLUSION

The consequences of large-scale integration of wind power into a weak regional network, when applying different types of wind turbine generators in the wind power plants has been studied. The main objective has been to fully exploit the thermal capacity of the actual regional system, i.e. operate the system as close as possible to it’s thermal limits. In addition, acceptable power quality must be maintained at nodes with ordinary consumers. To be able to operate the actual system in this way, remedial measures are necessary to enhance the system’s voltage stability limit, and prevent a voltage collapse. The work puts emphasis on application of SVCs for these purposes. The work also illustrates how a secondary controller for a SVC can be implemented in this context.

The results show that it can be technically possible to operate the given system beyond the traditional voltage stability limits, and up to it’s thermal limits.

To determine the necessary production margin (ref. point of voltage collapse) in this context will be an important task when planning such an untraditional form of network operation. The most influencing factor in this context is assumed to be the normally expected variations in the wind power production at rated production.

Wind turbine generator design including power electronic converters between the generator and the grid may represent an interesting alternative to the wind turbine generator / SVC combinations presented in this work.

Whether it is viable or not to operate the given system at a degree of loading which may give losses up to 10% and for longer periods beyond the voltage stability limit is of course an important question, which should be analysed in detail before possible implementation. Also detailed fault analyses and development of proper protection schemes have to be conducted.

VI. APPENDIX

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

TABLE I

Data for induction generators aggregated model [1)]

Parameter	Description/value
Type of model	SIMPOW Type 1A (transient model without saturation)
Rated power, S_N	80 MVA
Rated voltage, U_N	0.69 kV
Inertia constant, H	6.3 MWs/MVA
Stator resistance, R1	0.00619 pu
Stator leakage reactance, X1S	0.135952 pu
Rotor leakage reactance, X2S	0.112143 pu
Magnetizing reactance, XM	3.904762 pu
Magnetizing resistance, RM	0.088095 pu
Rotor resistance as a function of slip, R(s)	0.02 pu

[1)] pu values refer to rated power of generator

TABLE II

Transformer data[1)]

	Between nodes…			
	BUS2 BUS3	BUS8 BUS6	BUS10 BUS9	BUS9 BUS7
S_N [MVA]	250	70	160	160
U_{N1} [kV]	132	66	0.69	22
U_{N2} [kV]	300	132	22	132
e_r [pu]	0.005	0.00633	0.009	0.0075
e_x [pu]	0.1462	0.24787	0.055	0.100
Tap size [%]	1.67	1.67	1.67	1.67
+ steps	7	7	7	7
- steps	7	8	8	8

[1)] pu values refer to rated power of transformer

TABLE III

Line data

	Between nodes…		
	BUS7 BUS6	BUS6 BUS5	BUS5 BUS2
Length [km]	23.0	58.5	36.5
Resistance [Ω/km]	0.098	0.098	0.098
Reactance [Ω/km]	0.398	0.398	0.398
Susceptance [S/km]	2.89e-6	2.89e-6	2.89e-6
Thermal limit [A]	832[1)]	832[1)]	832[1)]

[1)] Corresponds to 190 MVA at 132 kV

The transmission line between nodes BUS1 and BUS3 (300 kV) is modelled with the following parameters:

Resistance [pu]	0.0047
Reactance [pu]	0.05884
Susceptance [pu]	0.086543

Line base = system base, S_{base} = 100 MVA.

SVC regulator

The SVC primary regulator is modelled as shown in Figure 8. This is a SIMPOW Type SVS regulator (symmetrical SVC) with a lead-lag network (RTYP 3 in SIMPOW).

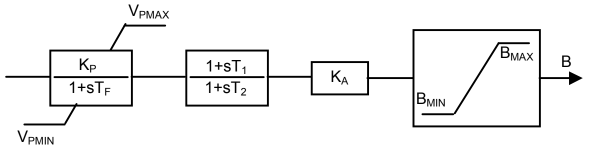

Fig. 8. SVC primary regulator.

The model of the secondary regulator for the SVC, used for minimising the net reactive power exchange between the regional and main transmission networks, is shown in Fig. 9.

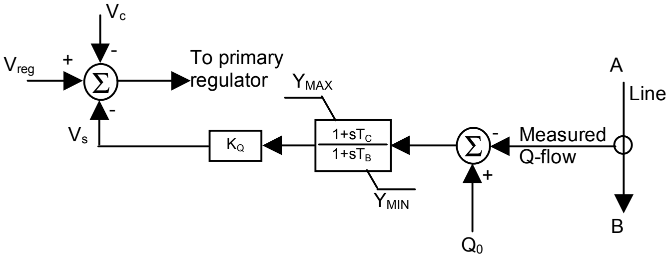

Fig. 9. SVC secondary regulator.

The secondary regulator operates by comparing the measured reactive power flow in a selected branch of the network with a set-point, Q_0. The error is put through a lead-lag filter and the resulting signal is input to a gain block resulting in a input signal to the primary regulator changing the set-point value of the control voltage for the SVC.

TABLE IV
Parameters for the regulator for the SVC (only primary regulator)

Parameter name	
Max. value for susceptance, B_{MAX} [pu]	1.2
Min. value for susceptance, B_{MIN} [pu]	0.0
Proportional gain, KP [pu]	100
Filter time constant, TF [s]	0.01
Max. value of V_P, V_{PMAX} [pu]	12
Min. value of V_P, V_{PMIN} [pu]	-12
Adaption gain, KA [pu]	15.0
Lead time constant, T_1 [s]	1.0
Lag time constant, T_2 [s]	10.0

TABLE V
Parameters for the regulator for the SVC
(both primary and secondary regulators)

Parameter name	
Primary regulator	
Max. value for susceptance, B_{MAX} [pu]	1.2
Min. value for susceptance, B_{MIN} [pu]	0.0
Proportional gain, KP [pu]	10
Filter time constant, TF [s]	0.01
Max. value of V_P, V_{PMAX} [pu]	12
Min. value of V_P, V_{PMIN} [pu]	-12
Adaption gain, KA [pu]	5.0
Lead time constant, T_1 [s]	1.0
Lag time constant, T_2 [s]	10.0
Secondary regulator	
Gain, KQ	10
Lead time constant, TC	1.0
Lag time constant, TB	100
YMAX	0.5
YMIN	-0.5

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VIII. BIOGRAPHIES

Magni Þ. Pálsson was born in Siglufjörður, Iceland, on July 16, 1966. He graduated from the University of Iceland, Reykjavík in 1990 and recieved his dr. ing. degree from the Norwegian University of Science and Technology in 1999. He was with the Icelandic State Electrical Inspectorate from 1990 – 1994. He has been employed as a research scientist with SINTEF Energy Research in Trondheim since 1999. His main research interests are power system dynamics, modelling and simulation of electrical power systems, and wind power integration.

Trond Toftevaag (M 1999) was born in Bergen, Norway, on January 6, 1949. In 1972 he received the Sivilingeniør degree from the Norwegian Institute of Technology (NTH), Department of Electrical Power Engineering. He was with Kristian Gerhard Jebsen Shipping Company, Bergen, Norway, from 1973 – 1975, and with Ove Drangsholt A/S, Trondheim, Norway, working as an electrotechnical consultant from 1975 – 1979. Since 1979 he has been employed as a research scientist at SINTEF Energy Research (former EFI) in Trondheim. In 1995 he was part-time lecturer at NTH, Faculty of Electrical Engineering and Computer Science, Dep. of Electrical Power Engineering, Group of Power Electronics and Electrical Machines His main technical interests are electrical machines, power system dynamics, and modelling and simulation of electrical power systems.

Kjetil Uhlen (M 1995) was born in Lillehammer, Norway, on May 4, 1961. In 1986 he received the Sivilingeniør degree from the Norwegian Institute of Technology, Department of Engineering Cybernetics. He received his dr. ing. degree in control engineering from the same institute in 1994. Since1987 he has been employed as a research scientist at SINTEF Energy Research in Trondheim. His main technical interests are operation and control of electrical power systems.

John Olav Giæver Tande was born in Trondheim, on March 23, 1962. He received his M.Sc. in electrical engineering from the Norwegian Institute of Science and Technology (NTH) in 1988. After graduating he worked as a research scientist first at The Norwegian Electric Power Research Institute (EFI), then at Risø National Laboratory in Denmark from 1990 to 1997. He then returned to SINTEF Energy Research where he is currently employed. Throughout his career his research has been focused on electrical engineering aspects of wind power. He has participated in several international studies, including convening an IEC working group on preparing an international standard on measurement and assessment of power quality characteristics of grid connected wind turbines.

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