Field Tests And Modelling Of A Wind Farm With Doubly-Fed Induction Generators

Magne Meisingset and Trond M. Ohnstad
Statnett SF
Oslo, Norway

Kjetil Uhlen
Sintef Energy Research
Trondheim, Norway

Leif R. Strand
Hydro
Rjukan, Norway

Abstract— **Havøygavlen is Norway's second wind farm and started operation in 2002. Several new wind farms are currently under planning at various sites along the Norwegian west coast. The Norwegian System Operator (TSO) Statnett SF and Sintef Energy Research have jointly developed a dynamic simulation model for Havøygavlen in order to analyse the interaction between wind farms and the transmission grid. Full-scale field tests have been conducted to verify the model by comparing simulations to measurements. This paper presents results from the field tests, model validation work as well as operating experiences for Havøygavlen wind farm.**

Index Terms—**Doubly-fed induction generators, field tests, simulation model validation, wind farm**

I. INTRODUCTION

Statnett has as the TSO (Transmission System Operator) the responsibility for integration of new power generation into the Norwegian transmission grid. Installation of new generation has been marginal during the last decade, whereas the consumption has gradually increased. New and expansion of existing power intensive industry will significantly increase consumption. In addition, plans to build gas-fired power plants and HVDC-transmission links to neighbouring countries have been put on hold or terminated. As a result, there is a need to install new generation to improve both power and energy balance.

The first wind farm in Norway is situated on the island of Smøla and started operation in 2001. The 20 wind turbines have a combined installed capacity of 40 MW, generating 120 GWh per year. Havøygavlen was the second wind farm to start operation in 2002. The wind farm at Hitra (55 MW, 150 GWh) and the expansion of Smøla (110 MW, 330 GWh) are scheduled to start operation respectively in 2004 and 2005.

The Norwegian Government has a target of 3 TWh wind power by 2010 [1]. The regulatory body, the Norwegian Water Resources and Energy Directorate (NVE) has granted wind power licenses involving approx. 660 MW installed capacity [2]. Licenses and notifications of another 2000 MW wind power are presently under processing by the regulator.

This large-scale integration of wind power represents a challenge for Statnett due to its different characteristics with respect to grid connection, controllability and generator technology compared to conventional power plants. It is important to gain experience in the new technology and develop adequate models to investigate the interaction between wind farms and the transmission grid. This includes dynamic simulation models for various wind turbine concepts. Furthermore, it is necessary to use the knowledge gained through system studies to develop grid connection guidelines and requirements for new wind power.

This paper is organised by first introducing Havøygavlen wind farm including technical data, grid connection and experiences during the first year of operation. Then, the field test results are presented. The developed dynamic simulation model is thereafter presented and compared to field test measurements. Finally, the results are discussed with concluding remarks.

II. HAVØYGALVEN WIND FARM

Havøygavlen wind farm started operation in October 2002. It is the world's northernmost wind farm, located 180 km northeast of Hammerfest in the North Norway county of Finnmark. The wind farm is owned and built by Arctic Wind AS, a company jointly owned by Hydro and Nuon. The wind turbines were delivered and installed by wind turbine supplier Nordex Energy GmbH.

A. Technical data

The wind farm has a combined 40 MW power rating and an expected 120 GWh annual energy production.

The farm consists of 16 variable-speed wind turbines each with 80 m rotor diameter and 2500 kW rated power. The turbines are equipped with doubly-fed induction generators [3],[4] with a back-to-back voltage source converter (VSC) feeding the rotor. The 750 kVA VSC employs water-cooled, pulse width modulated IGBT semiconductor switching devices.

The turbines are pitch controlled and operates at wind speeds from 4 m/s at start-up to rated power above 15 m/s. The three blades can be pitched individually. Havøygavlen has good and stable wind conditions with an average wind speed of more than nine meters per second.

B. Grid connection

Each of the 16 windmills is connected to the grid via a medium-voltage transformer (660 volts / 22kV). Figure 1 shows that the wind farm is connected to the distribution grid at Havøysund by a 22/66 kV transformer at 40 MVA power rating. The 66 kV grid is connected to the 132 kV transmission grid at Skaidi and Lakselv transformer stations via Smørfjord. The transmission line between Smørfjord and Lakselv is normally out of operation (stand-by reserve).

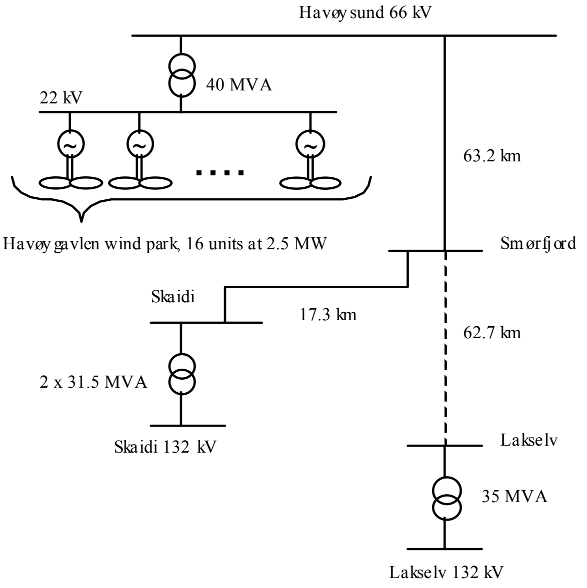

Figure 1. Grid connection for Havøygavlen wind farm.

C. *First Year Operational Experiences*

The wind farm is producing power at the level of the guaranteed power curve. During the first year of operation, the wind speed was below the predicted average, and hence so was the energy production.

The farm has not experienced any significant downtime due to disturbances in the main grid. At some few occasions, the wind farm was stopped for shorter periods caused by voltage fluctuations in the same grid. Arctic Wind has awarded the wind turbine supplier Nordex a 5-year operation and maintenance contract, which targets an availability requirement of 97.0 %.

Figure 2 shows duration curves for active and reactive power generation (10 minutes measurements) during the first seven months of operation (October 2002 to May 2003) by a single windmill at Havøygavlen. It is evident from the curves that marginal amounts of reactive power are being consumed independently of active power generation. This indicates that the doubly-fed induction generators control the power factor to unity.

On October 29th 2002, shortly after start-up of the wind farm, one windmill experienced a mechanical collapse caused by over-speed of rotor. The nacelle loosened from the steel tower due to excessive mechanical forces on the yaw bearing. The main reason for the collapse was a short-circuit in the slip rings. This course of events did not indicate any design errors. A new windmill is now in operation with the original steel tower and foundations reused.

The main challenge has been the wind turbulence at some locations at the wind farm. This has caused higher forces to the yaw system than predicted. Modifications have been implemented by reinforcing the yaw-gear. Software changes will also be necessary to adjust the yawing sequence.

Periods with strong wind, snow and low temperature have exposed the need for additional technical modifications. This includes reinforced nacelle locking system, battery-heating system and converter cooling system. Modifications of all transformer housings will also be necessary.

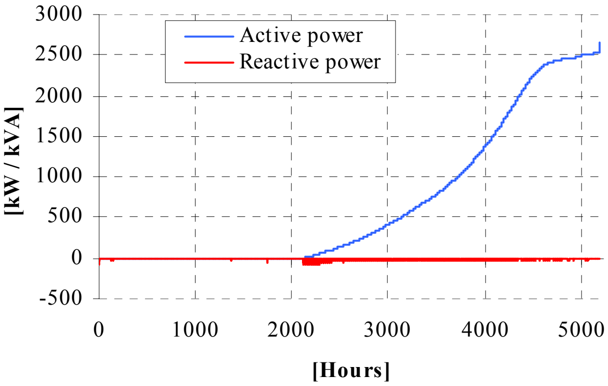

Figure 2. Active and reactive power generation from one windmill. The active power curve can be interpreted as the number of hours (on the x-axis) that the power output is below the given level (on the y-axis).

III. FIELD TESTS

Full-scale field tests have been conducted to gain knowledge in the electrical performance of Havøygavlen wind farm and to verify the developed simulation model.

Two types of field tests were performed, single line-to-ground fault and transmission line tripping. The tests were conducted during October 28th and 29th 2003. The power generation in the wind farm during the tests varied from 5 to 20 MW due to weather conditions with light wind.

Measurements of voltages and currents were done by transient recorders (HIOKI) at Havøygavlen, in one single windmill (660 V) and at the 66 kV side of the transformer. In addition, voltages were measured by a digital fault recorder (BEN 5000) at the 66 kV station Skaidi.

A. *Single Line To Ground Faults*

The purpose of the tests was to measure the wind farm's response to grid faults. A single-phase to ground fault was applied three times at Lakselv on October 28th. Lakselv is situated about 130 km from Havøysund in electrical terms. The short-circuit was applied by connecting phase R at the end of the 66 kV transmission line Smørfjord – Lakselv to ground by a 60 cm fuse wire. Each fault was enabled by closing the circuit-breaker in Smørfjord towards Lakselv. The 66 kV grid is resonant-grounded and the short-circuit current should thus be limited properly by Petersen coils.

The short-circuit current did however not immediately burn off the fuse wire during the first test fault. Initially the fuse wire was glowing and a flame arc ignited after 7 seconds. The fault was manually removed after 15 seconds by disconnecting the circuit breaker at Smørfjord. This indicates that the Petersen coils in the 66 kV grid are not properly tuned. A proper tuning of the coils should normally remove the short circuit current arc within 1-2 seconds and maximum within 5 seconds. It is not known whether the grid was under- or over compensated. The latter is most common and implies an inductive fault current.

The short-circuit current quickly burned off the fuse wire and ignited a flame arc during the third test fault. A somewhat thinner fuse wire was employed in this test. The fault was manually disconnected after 4.3 seconds. The wind farm remained in operation during the occurrence of both faults. This is as expected since the main advantage of the resonant grounding is to maintain grid operation during sustained phase to ground faults.

Figure 3 shows the 66kV phase voltages at Havøysund during 6 cycles when the single line-to-ground fault was applied at Lakselv (the third test fault). It can be seen that the voltage in the faulted phase R is suppressed, whereas the steady-state voltages in healthy phases increase from phase voltage to eventually line-to-line voltage (not captured in the time frame presented in the graph).

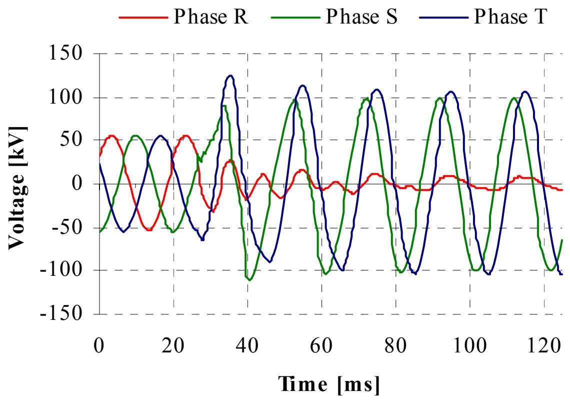

Figure 3. The 66 kV voltages at Havøysund during a single line fault.

The second test fault developed to a double line to ground fault, since a phase S to ground fault occurred between Skaidi and Lakselv 1.2 seconds after the initial phase R fault was applied at Lakselv. Figure 4 shows the 66kV phase voltages at Havøysund for 9 cycles when this double line-to-ground fault occurred. As may be seen from the graphs, the phase R voltage is initially suppressed due to the fault applied at Lakselv. Then, the phase S voltage is also suppressed when the additional fault between Smørfjord and Lakselv occurs.

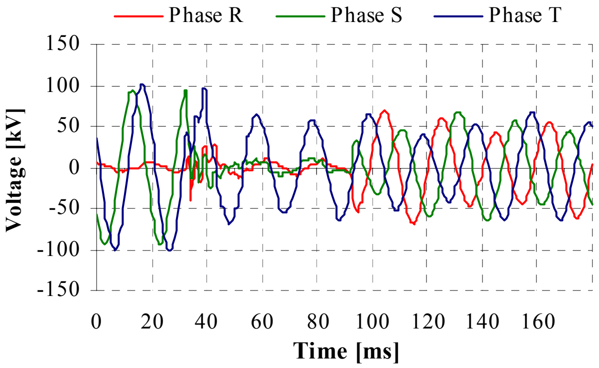

Figure 4. The 66 kV voltages at Havøysund during a double line fault.

The protection in Smørfjord disconnected the Smørfjord – Lakselv transmission line (and both faults) approx. 60 ms (i.e. 3 cycles) after the phase S to ground fault occurred. The power generation in the wind farm during the second test fault was 5 MW. The individual protection systems immediately disconnected all wind turbines from the grid and the entire wind park stopped operation. The wind turbines were manually re-started by maintenance personnel, who were working at Havøygavlen during the field tests.

B. Transmission Line Tripping

The purpose of the tests was to measure the wind farm's response to the tripping and re-closing of the 66 kV line Smørfjord – Skaidi between the wind farm and the transmission grid. The breakers were manually tripped in Smørfjord. The parallel 66 kV transmission line Smørfjord – Lakselv was in operation during these tests.

Unfortunately, the production in the wind farm and the general load flow in the grid were low during the line tripping, which was repeated 3 times (3 times tripped, 3 times re-closed). The line tripping caused only smaller disturbances in the 66 kV voltage recordings. It could be seen that the voltage at Havøysund increased when the Smørfjord-Skaidi line was tripped. This is expected since the impedance becomes larger between Havøysund and the 132 kV transmission grid. It can also be seen from the results that the voltage decreased when the transmission line was re-closed. The wind farm's line voltage response to the tripping and re-closing is shown in Figure 6. The response in active and reactive power is shown in Figure 5.

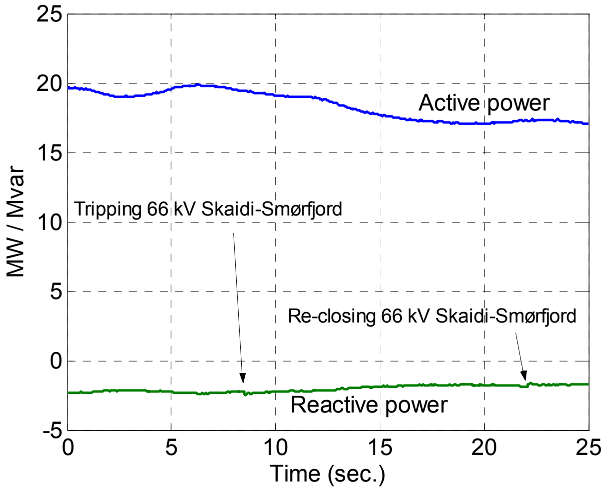

Figure 5. Total active and reactive power from wind farm when tripping and re-closing the 66 kV line Smørfjord-Skaidi.

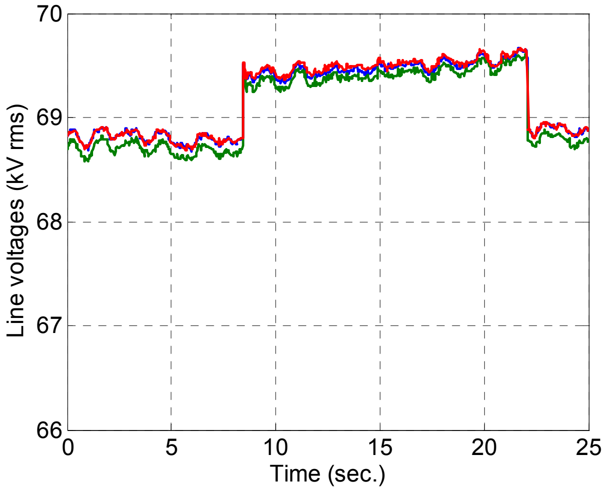

Figure 6. Line voltages as 66 kV Havøygavlen (rms) when tripping and re-closing the 66 kV line Smørfjord-Skaidi.

Even though the line tripping events did not create significant system disturbances, the general observations from the measurements provided valuable information about the wind farm behaviour. The main observations are summarised as follows:

- From measurements at different and varying wind power output it can be concluded that the wind farm is able to keep reactive power output very close to zero. The measured responses indicate a time constant in order of one second in the control of reactive power.
- By comparing power output from one wind turbine to the total power output from the wind farm, the preliminary observations indicate that the power-smoothing effect by the wind farm is considerable. As shown in Figure 5 the wind farm has relatively slow and limited power variations, whereas the output from one wind turbine (not shown) can vary considerably during 25 seconds.
- No statistical analysis is performed yet, but from the available wind farm measurements, there are hardly any characteristic “3P” power fluctuations to be seen. This indicates that the power control takes advantage of the variable speed operation to effectively damp these oscillations.

The voltage measurements at the wind farm also indicate that voltage quality is acceptable, and that harmonic distortions from the power converters are small at the 66 kV level. However, from the attempts to measure voltages and currents at one wind turbine (660 volts), there are still uncertainties regarding the harmonics contents at this level.

IV. MODELLING AND SIMULATION STUDY

A. Models

A main purpose of the field tests and the measurements described in the previous section was to obtain system responses and recordings in order to validate and tune dynamic wind farm models that are being developed for use within the power system simulator PSS/E. Dynamic power plant models in PSS/E are built by selecting one or more dynamic components models (generator, turbine/governor, excitation systems, etc). Presently, PSS/E does not offer wind turbine models as part of the standard component library. This also includes doubly fed induction generator models. Therefore, in order to model the Havøygavlen wind farm there was a need to establish a turbine model and a generator model.

The doubly fed induction generator model with converters and control system is described in full detail by a parallel paper [5].

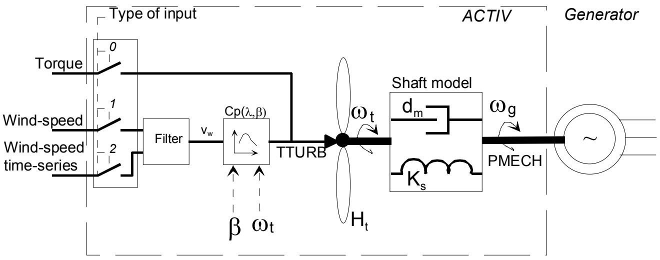

Figure 7. Wind turbine, mechanical and aero-dynamical model.

The turbine model is illustrated in Figure 7 and includes the following main features:

- The model takes constant mechanical torque, constant mean wind speed with turbulence or a wind speed time series as input.
- A special filter is designed to represent the spatial distribution of wind speeds over the rotor plane.
- The conversion to mechanical power (shaft torque) is computed using the steady-state efficiency characteristic of the wind turbine. The efficiency C_p is modeled as a function of tip-speed ratio, $\lambda = \omega/r$, and pitch angle, β.
- The mechanical drive train is modeled as a two-mass system taking into account the inertia of the turbine and generator and the stiffness and damping of the gear and couplings between the high speed and low speed shafts.

For the purpose of studying dynamic system responses and transient phenomena it is usually sufficient to apply a constant mechanical torque. This is done in the simulations described below.

B. Model Validation and Simulation Results

Various simulations in order to demonstrate and test the models are shown in [5]. The purpose of this section is to compare simulations with two of the field tests described above.

Results from the first case are shown in Figure 8 and Figure 9. The case represents one of the tests where the 66 kV line Smørfjord-Skaidi was tripped at a time when the wind power was very low (2.5 MW or 6% of rated power). The only significant disturbance observed in this case is a small oscillation in power output when the line is tripped. This oscillation is captured also in the simulation shown in Figure 9, and by tuning the stiffness of the turbine shaft a good agreement can be obtained between simulation and measurement.

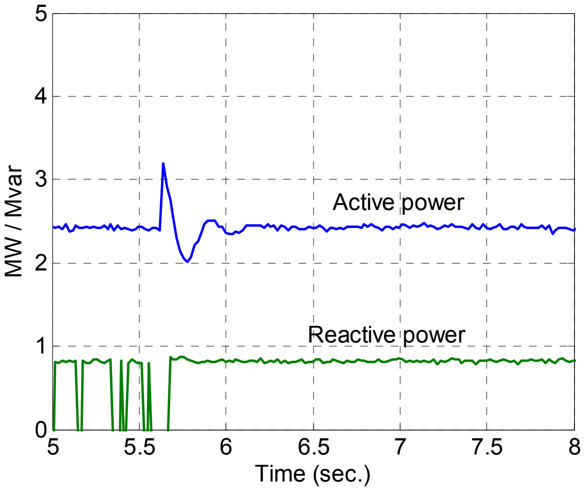

Figure 8. Case 1: Measured active and reactive power when tripping 66 kV Smørfjord-Skaidi. (The initial dips in reactive power are measurement errors).

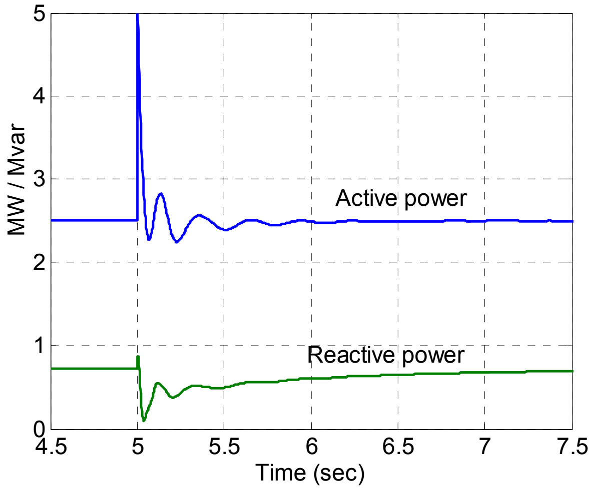

Figure 9. Case 1: Simulated active and reactive power when tripping 66 kV Smørfjord-Skaidi.

Results from the second case are shown in Figure 10 to Figure 12. This case represents another test where the 66 kV line Smørfjord-Skaidi was tripped and re-closed, this time when the wind power was considerably higher (17-20 MW or 50% of rated power). The measured active power is shown in Figure 5.

The measured and simulated reactive power responses are shown for comparison in Figure 10 and Figure 11, respectively. Disregarding the slow drift in the measured response, which is related to the active power variation, it is seen that the line switching causes very small variations and transients in reactive power. The simulated response shows higher transient peaks at the switching instants, but apart from these peaks the deviations are very small. It is also seen that the generator control system brings the reactive power quickly back to a constant steady state level. The first peaks in the simulated responses are probably due to the simplified modelling of the converter control system.

The simulated response in line voltage at 66 kV Havøygavlen is shown in Figure 12. Compared to the measured voltages (in Figure 6), which show that the line trip causes a voltage increase, it is observed that the simulation results in a voltage drop. This is, however, not a problem related to the wind farm model, but rather due to inaccurate modelling of the regional network and the actual power flow representation in this case.

The preliminary conclusion is that the model now works satisfactorily, taking into account the limited information that is available about component data and the control system implementation. Apart from getting the wind farm model as correct as possible, the validation study also shows that it is important to get the network and power flow model correct in order to obtain good correlation between simulations and measurements.

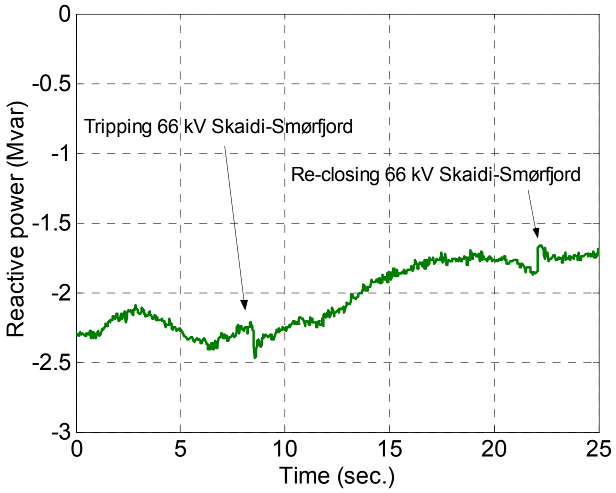

Figure 10. Case 2: Measured reactive power when tripping and re-closing the 66 kV Smørfjord-Skaidi line.

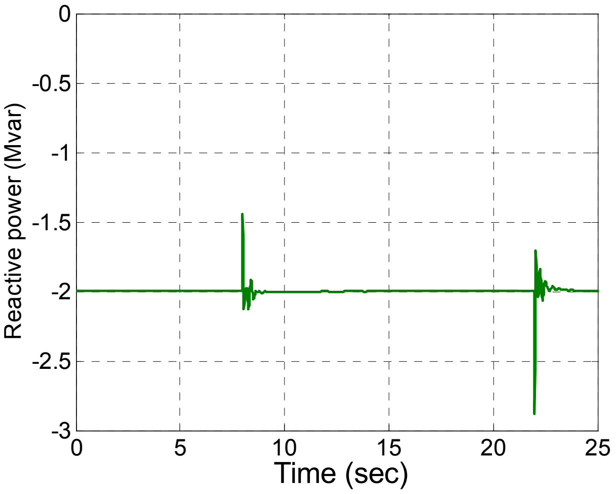

Figure 11. Case 2: Simulated reactive power when tripping and re-closing the 66 kV Smørfjord-Skaidi line.

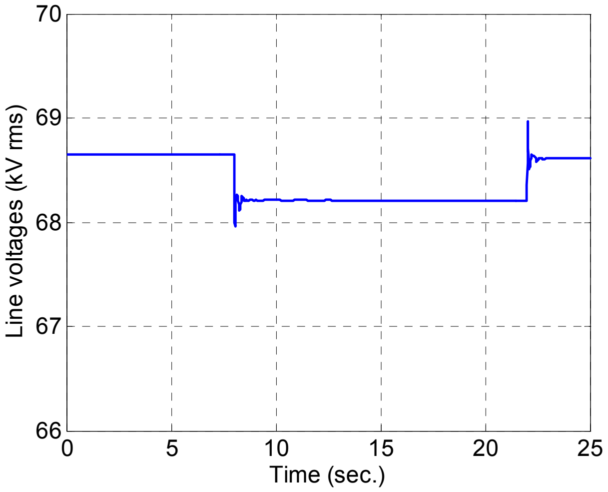

Figure 12. Case 2: Simulated line voltages at 66 kV Havøygavlen when tripping and re-closing the 66 kV Smørfjord-Skaidi line.

V. DISCUSSION AND CONCLUSIONS

The wind turbine is protected against various types of faults and disturbances in the grid, such as e.g. voltage- and frequency variations. The protection ensures that the wind turbine is stopped and disconnected from the grid in case of violation of these settings.

The field tests demonstrated that the wind park remained in operation when a single phase-to-ground fault was applied in the 66 kV grid. This behaviour is expected since the 66 kV grid is resonant grounded and should thus continue operation during a sustained single phase-to-ground fault.

The wind park did not demonstrate ride-through capability against double line-to-ground faults. This observation is somewhat surprising since the under-voltage protection setting is 0.9 per unit with a 0.1 second time delay. In this case, the fault was cleared after 60 ms as shown in Figure 4. It therefore appears as the setting provides instantaneous protection against low voltage disturbances.

Using the measured dynamic responses from the field tests, initial attempts have been made to validate a simulation model of the wind farm. The dynamic simulation model demonstrates that it is able to capture main dynamic responses and control features of the wind farm. There is still a need for more data and information on the wind farm components and control systems in order to fine-tune the model.

Valuable experiences have been gain through the field tests and modelling work. From the point of view of the transmission system operator, important issues have been clarified. The capability of reactive power generation and voltage control at wind farms and the reactive power exchange with the transmission network is of particular concern.

ACKNOWLEDGMENT

The authors acknowledge Statnett SF, Nordic Energy Research and the Norwegian Research Council for their financial contributions to this work.

REFERENCES

[1] http://odin.dep.no/oed/norsk/

[2] http://www.nve.no

[3] R. Pena, J.C. Clare and G. M. Asher, "Doubly-fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation", IEE Proceedings Electrical Power Application, Vol. 143, No. 3, May 1996.

[4] L. Holdsworth, J. Ekanayake, X. Wu and N. Jenkins, "Fixed Speed and Doubly Fed Induction Generator Wind Turbine Models for Power System Studies", Noted from the EPSRC project Electrical Stability of Large Offshore Wind Farms. Manchester Centre for Electrical Energy, UMIST, UK.

[5] Ian Norheim, Kjetil Uhlen, Trond Toftevaag, John Olav Tande, Magni P. Pálsson, "Doubly Fed Induction Generator Model for Power Systems Simulation Tools", Nordic Wind Power Conference, March 2004, Göteborg, Sweden.

BIOGRAPHIES

M. Meisingset obtained a Sivilingeniør degree in Electrical Engineering from the Norwegian Institute of Technology (NTH) in 1991. He received a Ph.D. degree from the University of Manitoba, Canada in 2000, where he conducted research in the fields of HVDC and power electronics. He has since 1993 been employed at Statnett SF (the Norwegian Power Grid Company) in Oslo and has mainly carried out system studies / feasibility studies in the areas of power system planning and operation. Email: Magne.Meisingset@statnett.no

T. M. Ohnstad graduated from the Oslo College, Faculty of Electrical Engineering in 1981. His employment experience includes the Norwegian State Power Board, the Norwegian State Power Company and the Norwegian Power Grid Company, Statnett. His special fields of interest are Insulation Co-ordination and Surge protection, Power Quality and Power System Transients. Email: Trond.Ohnstad@statnett.no

K. Uhlen obtained a Sivilingeniør degree from the Norwegian Institute of Technology, Department of Engineering Cybernetics in 1986. He received a dr. ing. degree in control engineering from the same institute in 1994. He has since 1987 been employed as a research scientist at Sintef Energy Research in Trondheim. His main technical interests are operation and control of electrical power systems. Email: Kjetil.Uhlen@sintef.no

L. F. Strand graduated with a B.Eng. from Strathclyde University in Glasgow in 1989. He is presently employed at Hydro Oil & Energy, where his main responsibility is operation of wind parks. He is based at Rjukan. Email: Leif.Ragnar.Strand@hydro.com