

# Wind Farms in Weak Grids Compensated with STATCOM

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*Abstract*—In this paper a distribution network in the vicinity of Narvik is modelled by using an ATP-EMTP application called ATPDraw. The network has a combination of wind power and hydro power and a weak grid connection. Three different scenarios are considered: Short circuit on wind power without hydro, wind fluctuation on a combined network, and the effect of both wind fluctuation and an arc fault. In each case, the system response with and without a STATCOM is analyzed.

## I. INTRODUCTION

THIS document is initiated by a final examination work at The Norwegian University of Science and Technology, Trondheim.

### A. Original Problem

The original problem was defined as: Simulation of a wind farm based on induction generators connected through a weak grid and compensated with a static compensation (STATCOM) device.

Develop a simulation model for a 100 MW wind farm using squirrel cage induction generators magnetised with fixed capacitor banks, and connected to the grid through a weak grid (low short circuit current: strong grid usually gives a short circuit ratio  $>20$ , use this assumption).

1. Model the STATCOM as a voltage source converter.
2. Use decoupled control of active and reactive power for controlling the STATCOM.
3. Simulate a short circuit and compare the transient response of the system with and without the STATCOM. See how much the transient stability margin is improved with the STATCOM and see what other beneficial effects the STATCOM has on the system stability.
4. Give a generalised expression for the rating of the STATCOM as a function of the system characteristics and contingency level, such as short circuit ratio and voltage sag.

### B. Modified Problem

Since there is a newly developed wind farm close to existing hydro power generators connected to the grid through a weak connection, the decision was made to deviate somehow from the original problem. The simulation model is based on the previous mentioned network, rather than the wind farm described initially.

Since the modified model contains both synchronous and asynchronous generators, the analysis also contains evaluations of different voltages and load angles. In order to limit the size of the work, point 4 in the original problem is replaced by an analysis of dynamic interaction between wind power and hydro power with and without STATCOM.

## II. SIMULATION MODEL

### A. Network description

The network of current interest is described Fig. 1, and it supplies the town Narvik and its surroundings. This distribution network is connected to the central network through the 132 kV bus bar at Narvik Transformer Station (Furumoen).

Most of the distribution network is passive, so the interesting parts are the hydro generators at Nygård and Sirkelvann, Nygårdstjell wind farm, the overhead lines and transformers in the area, and the undersea cable to the 36 kV bus bar at Frydenlund Transformer Station.

The network behind Frydenlund is considered as a stiff network in order to simplify the model. The connections between Nygård and Djupvik and between Nygård and Bjerkvik are quite weak connections and are not taken into account in the simulation model. This network also contains a passive load, Skogvann, but it is just a small company with a power consumption of 160 kilowatts and is also ignored.

The remaining network consists of an infinite bus at Frydenlund, the underwater cable (the weak connection), generators and transformers at Nygård hydro power plant, an overhead line to Sirkelvann, generator and transformer at Sirkelvann mini hydro generator, an overhead line to Nygårdstjell, and finally, Nygårdstjell wind farm with generators, transformers and possibly a STATCOM.

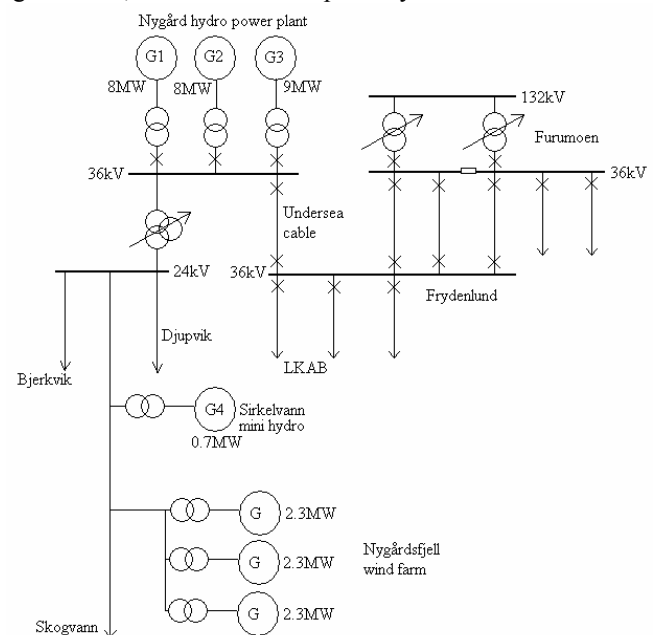


Fig. 1. Single line diagram of the distribution network in Narvik.

### B. Software

Due to the suitability of simulation tools from Alternative Transients Program – Electromagnetic Transients Program (ATP–EMTP), for power grid simulation, an ATP–EMTP application called ATPDraw was used for this purpose. The simulation tool is based on Windows and gives a clear picture of the model, much like a traditional single line diagram.

For analysis of the simulation results, another ATP–EMTP application was used, namely ATP Analyzer. This program provides different types of plots and several kinds of analysis, e.g. power flow calculations, symmetrical components and Park transform.

These tools are adopted in our institute recently, so parts of the work have simply been to learn how to utilize the programs. In ATP–EMTP it is challenging and time consuming to initialize rotating electrical machines, and especially a combination of synchronous generators and squirrel cage generator turned out to be an obstacle. So far one has not succeeded in making a model with a combination of these elements.

One solution is to make a simplified model of the asynchronous machine, which was done in this work. Since there are two major problems to be simulated, two different overall models were developed. The first problem is a matter of how the system handles severe faults, like short circuits or voltage dips. The second problem is the interaction between different power sources.

In the first case, the model consists of a lumped wind farm with a STATCOM, the transformers and transmission lines, a model of the short circuit, and an infinite bus. This model is shown in Fig. 2, and there is a similar version without the STATCOM, not shown in this article. Since load angle stability is not part of the case, the synchronous generators are left out.

In the second case a simpler model of the wind farm is made, since the main focus of the analysis is to observe the stability of the synchronous generators when the wind power production fluctuates. The model, shown in Fig. 3, contains, in addition to the pervious mentioned lumped wind farm model, transmission lines, hydro generators and transformers, a model of the short circuit, and an infinite bus. The short circuit was added in order to simulate a combination of fluctuating power and contingencies.

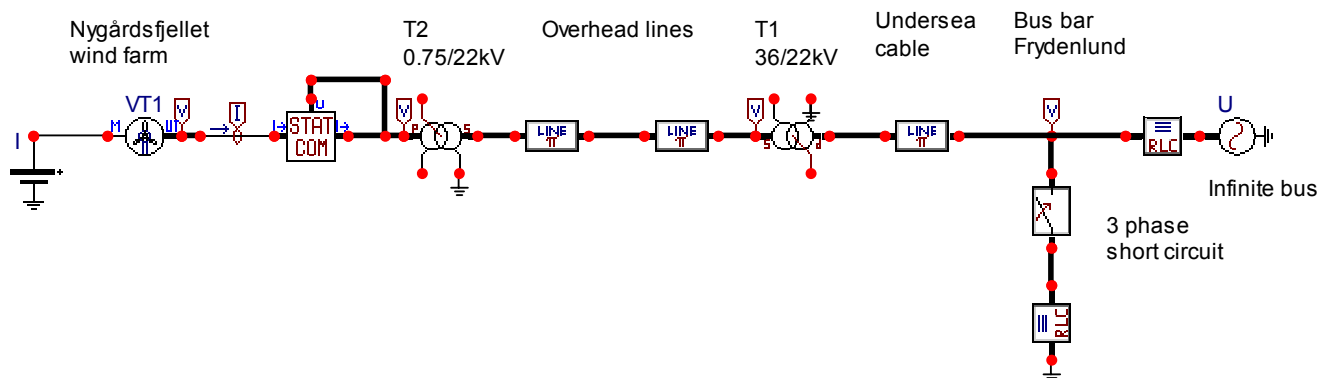


Fig. 2. ATPDraw simulation model of wind farm with STATCOM, connected to the main grid through a weak connection.

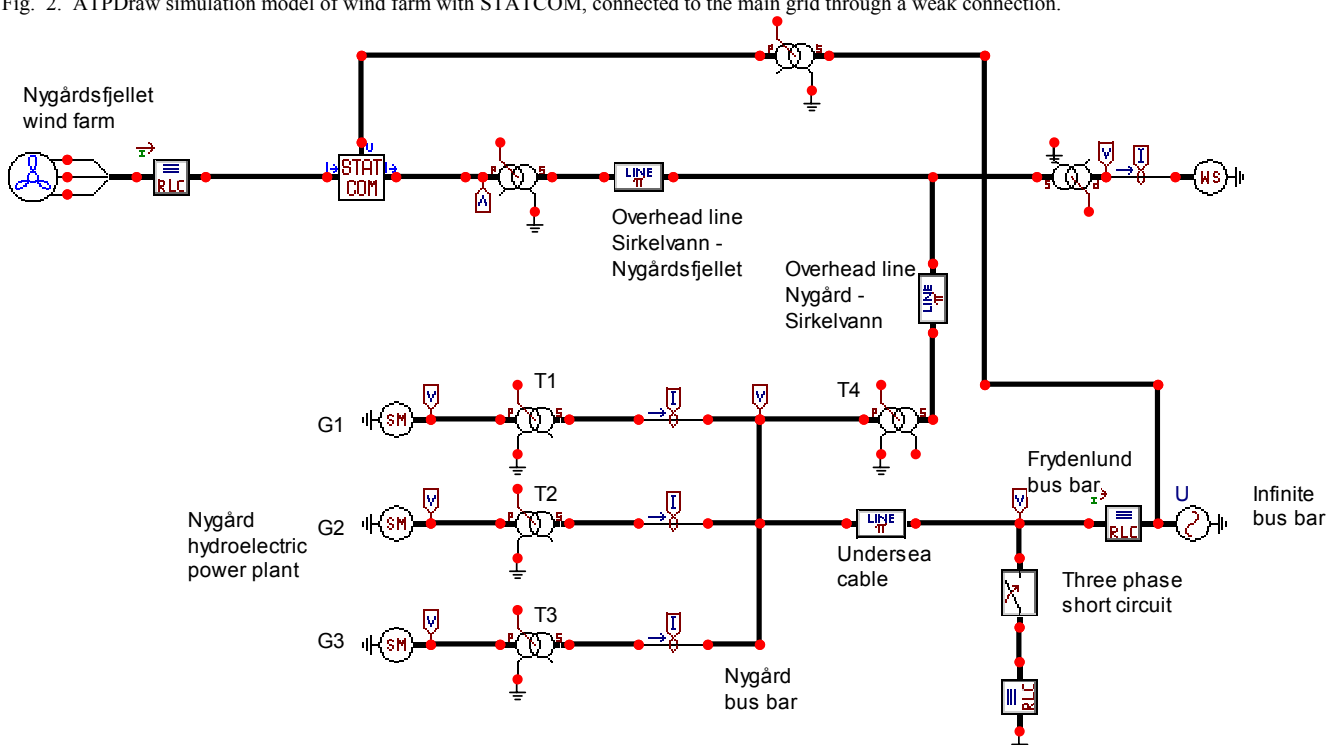


Fig. 3. ATPDraw simulation model of wind farm with STATCOM, combined with hydro power and a weak grid connection.

### C. Model implementation

Most of the elements in the simulation models are described in [1], and will not be described in detail in this article. A couple of new elements are developed for this certain purpose and will be thoroughly explained.

#### 1) Synchronous generators:

These are modelled without control, i.e. the dynamics in turbines and controllers are not included. Saturation is ignored, and some reactances, time constants and moments of inertia are based on assumptions. Table I shows some of the parameters for the generators.

TABLE I  
SOME RATED VALUES FOR THE DIFFERENT GENERATORS

Generator	Nominal power [MW]	Nominal voltage [kV]
G1, G2	8.0	4.2
G3	9.0	4.2
G4	0.7	6.9
G5–G7 (wind farm)	2.3	0.75

#### 2) Squirrel Cage Generators:

Each generator is equipped with a front end full size converter, but the turbine model is implemented as a squirrel cage generator connected directly to the grid, for simplicity. Rated values for the squirrel cage generators are also shown in Table I.

#### 3) Transformers:

The transformers are modelled with phase shifts, impedances, vector groups etc, but saturation of the core is ignored. Table II shows some rated values for the transformers. Data for the wind turbine transformers were not available during the work, but transformer impedance is included in the lumped wind turbine model.

TABLE II  
SOME RATED VALUES FOR THE TRANSFORMERS

Transformer	Nominal power [MVA]	Nominal voltage [kV]
T1, T2	10	35/4.2
T3	10	33.3/4.2
T4	1.1	22/6.9
T5	7.0	32.4/23

Transformer T5 is equipped by a tap changer, but since the simulations just span a few seconds, the tap changer is assumed to be in middle position without any action at all.

#### 4) Transmission Lines:

The transmission system consists of an underwater cable and a chain of overhead lines with transformers in between. The line length, maximum current, and the impedance components at the system frequency (50 Hz) is shown for the different lines in Table III.

TABLE III  
PARAMETERS FOR TRANSMISSION LINES

Length [km]	Max. current [A]	Resistance [ $\Omega$ ]	Inductance [mH]	Mutual capacitance [ $\mu$ F]
Underwater cable Frydenlund – Nygård				
7.55	400	1.18	4.01	4.54
Overhead line Nygård – Sirkelvann				
6.76	454	1.95	8.4	0.61
Overhead line Sirkelvann – Nygårdsfjell				
5.02	454	1.29	5.79	0.1

#### 5) Arc Fault

The arc fault is modelled as a Thevenin impedance, a ground resistance and a switch, all three phase. These components are shown in Fig. 4. The Thevenin impedance has a value of  $(0.1 + j0.4) \Omega$ , and the resistance has a value of  $0.1 \Omega$ .

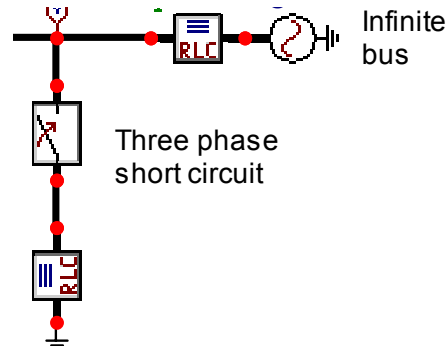


Fig. 4. The three phase switched voltage divider representing the temporary arc fault at Frydenlund bus bar.

#### 6) STATCOM

The STATCOM is modelled as a voltage source converter. Since the switching period will be much shorter than the different mechanical time constants of the system, the voltage source is implemented simply by an inverse Park transform, as shown in Fig. 5. The other elements of the STATCOM are voltage and current measurement units, a Park transform and current controllers for the d-axis and the q-axis, respectively. By choosing zero reference for the q-axis,  $\cos \phi$  is forced to be equal to one. By using a PI-controller, the static error disappears. For the d-axis, a P-controller is sufficient, since the active power flow changes a lot and is limited by the power source. By choosing a high reference value, the d-component will be as high as possible.

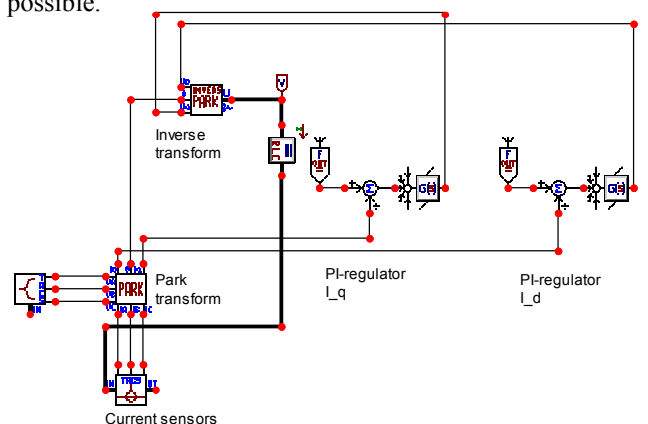


Fig. 5. STATCOM simulation model for ATPDraw.

### 7) Simplified Wind Generator Model

There is still some work to be done in order to initialize the asynchronous generator in a proper way. By the moment the machine model generates quite heavy false transients, and these disturbances prevent the simulation model from reaching a convergent solution. That is particularly a problem in combination with synchronous generators.

The purpose of the simplified wind generator model is to supply the network with intermittent wind power, which is done by a voltage source behind an impedance, as shown in Fig. 6. The voltage magnitude is controlled by a 'Transient Analysis of Control Systems'-signal (TACS-signal).

The TACS-sources and multipliers to the left in the figure generate sinusoidal signals with varying amplitude, and the sources to the right convert the TACS-signals into phase voltages. As can be seen in Fig. 3, there is an impedance behind this three phase voltage source. The model does not show the rotor speed or any other dynamic properties.

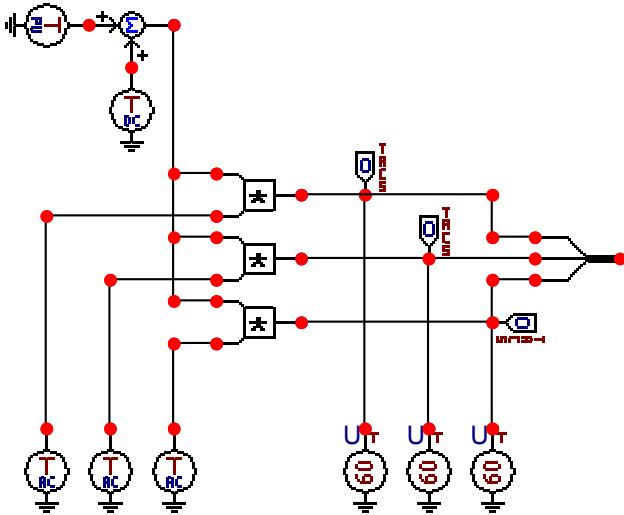


Fig. 6. Simplified wind generator model without rotor speed and turbine dynamics.

### 8) Complex Wind Generator Model

In some of the simulations, the performance and behaviour of the electromechanical wind turbine system is essential, and for that reason there was a need for a more complex model with a dynamical behaviour. This model is shown in Fig. 7.

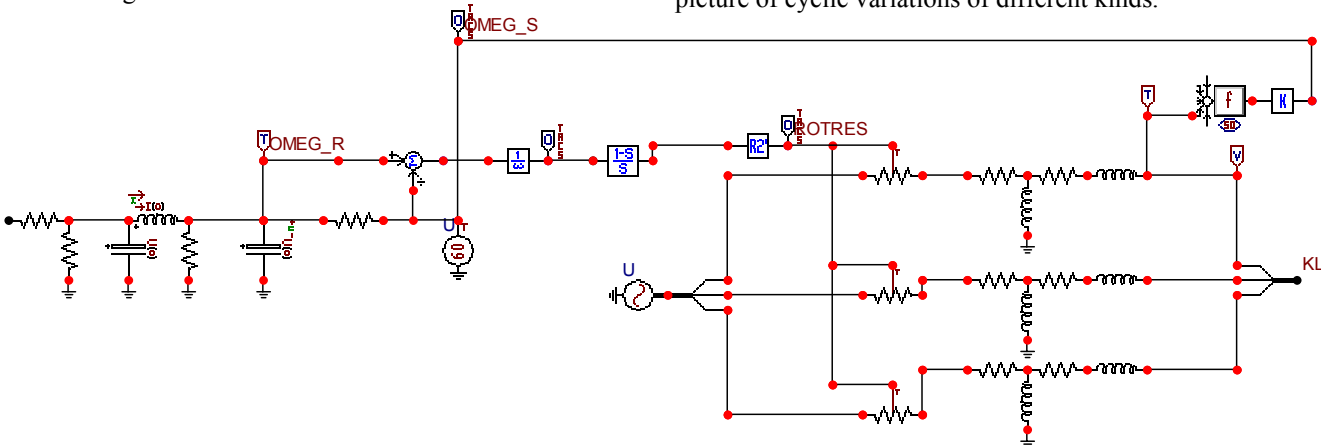


Fig. 7. Complex wind generator model with turbine dynamics.

The dc network to the left represents the mechanical two-mass system of the turbine. The capacitances are equal to moments of inertia, and the inductance equals the spring constant of the shaft. The resistances resemble the friction of the system.

The generator is modelled by phase equivalents with a TACS-controlled rotor resistance expressed by (1), where  $s$  is the slip of the generator. The frequency measurement of the stator voltages gives a speed reference  $\omega_s$  for the electromechanical system.

$$R_2' \cdot \frac{1-s}{s} \quad (1)$$

The model does not take into account non-linear and time variant properties, and the voltage source will have a fixed phase angle even if the grid voltage is slightly phase shifted.

## III. SIMULATION RESULTS

Three different scenarios were simulated. First, the simulation model of Fig. 2 was used, and a short circuit took place after 3 seconds and lasted for 0.3 seconds. Voltages, rotor speed and power flow was measured and analyzed both with and without the STATCOM.

Next simulation used the model in Fig. 3, but without activating the arc fault. The wind power changes from rated output to zero in pulses of one second duration. Load angles, voltages and power flow are measured and analyzed with and without the STATCOM.

In the final simulation the same model is used, but the arc fault at Frydenlund bus bar is activated at 3.3 seconds and lasts for 0.3 seconds. This is obviously a worst case scenario, and since the model do not contain any relay protection or other protection devices, the simulation result in unrealistic. Still, it gives a picture of the forces and energies present under such circumstances. Load angles, voltages and power flow are measured and analyzed with and without the STATCOM.

All simulations went without convergence problems, and the time span was from zero seconds to five seconds. It is possible to simulate over a longer period, but it is very time consuming, and this five second interval gives a clear picture of cyclic variations of different kinds.

#### A. Short Circuit Simulations without Hydro Power

The simulation model for these simulations is presented in Fig. 2. Comparisons were made with and without use of STATCOM.

Fig. 8. shows rotor speed without STATCOM (red graph) and with STATCOM (blue dashed graph). It can be noticed that the fluctuations of the rotor speed are heavier with the STATCOM, probably due to increased dynamics, while the rotor speed stabilizes faster after the short circuit with the STATCOM. The explanation for the ‘ringing’ of the rotor speed without the STATCOM might be numerical round-off problems or other numerical problems. Slight changes of the model parameters changed this phenomenon.

Fig. 9. shows rms-values of the wind farm currents. In (a) one can see the currents from the wind farm into the grid without STATCOM (black graph) and with STATCOM (red graph). In (b) the currents from the lumped wind generator model are shown, both without STATCOM (black graph) and with STATCOM (red graph). It can be noticed that the STATCOM increases the current from the wind farm to the grid during the fault, but it decreases the generator current. Thus, it should increase the stability margins of the wind farm.

Fig. 10. shows rms voltages for the system, the grid connection of the wind farm in (a), Nygård bus bar in (b) and Frydenlund bus bar in (c). Black graphs show voltages without STATCOM and red graphs with STATCOM. For Frydenlund there is no difference with or without STATCOM. It can be seen that the STATCOM improves the voltage condition at the wind farm, but has little effect at Nygård. The voltage at Frydenlund drops to approximately 20% of rated voltage for 0.3 seconds, which is a typical voltage drop scenario [2].

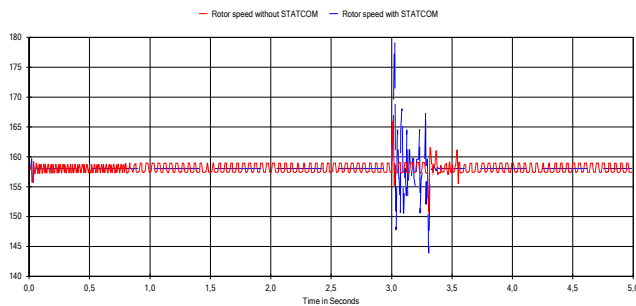


Fig. 8. Wind generator rotor speed, without STATCOM (red graph) and with STATCOM (blue dashed graph).

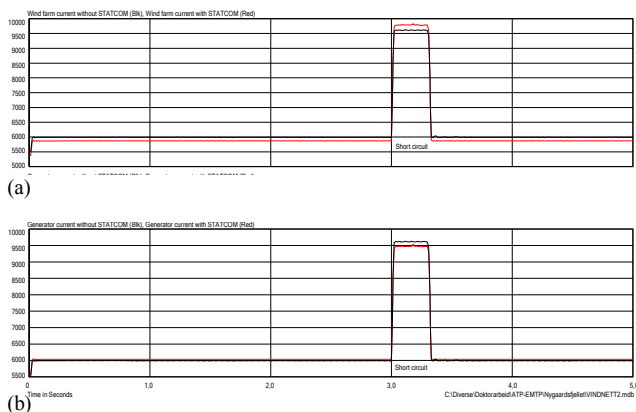


Fig. 9. Wind farm rms currents (a) to the grid, and (b) from the generators without STATCOM (black graph) and with STATCOM (red graph).

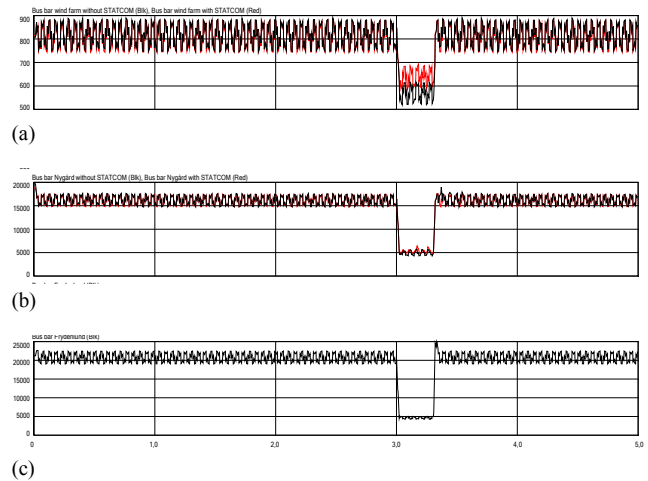


Fig. 10. rms voltages (a) at the wind farm, (b) at Nygård bus bar, and (c) at Frydenlund bus bar, without STATCOM (black graph) and with STATCOM (red graph).

#### B. Simulation of Wind Fluctuations with Hydro Power

The simulation model for these simulations is presented in Fig. 3, but with the arc fault deactivated. Comparisons were as usual made with and without use of STATCOM.

Fig. 11. shows load angles for G1 and G2 (a), G3 (b), and G4 (c), without STATCOM (black graph) and with STATCOM (red graph). For (a) and (b) there is only a slight increase in the load angle, which indicates a slight increase in the power flow when the STATCOM is applied. For (c) there is a significant change, both since G4 is much closer to the wind farm and a since it is a much smaller generator.

Fig. 12. shows rms voltages at the wind farm (a), and at Nygård bus bar (b) without STATCOM (black graph) and with STATCOM (red graph). The figure shows that the voltage quality is improved significantly at the wind farm and only slightly at Nygård bus bar.

Fig. 13. shows active (black graph) and reactive power flow (red graph) at Frydenlund bus bar without STATCOM (a), and with STATCOM (b). It can be seen that these heavy wind farm perturbations causes the active power flow to waver between the wind farm and the grid when the STATCOM is absent, while the use of STATCOM gives a more smooth power flow. One should take into account that the simulation model provides a STATCOM without boundaries and with capability of injecting active as well as reactive power to the grid.

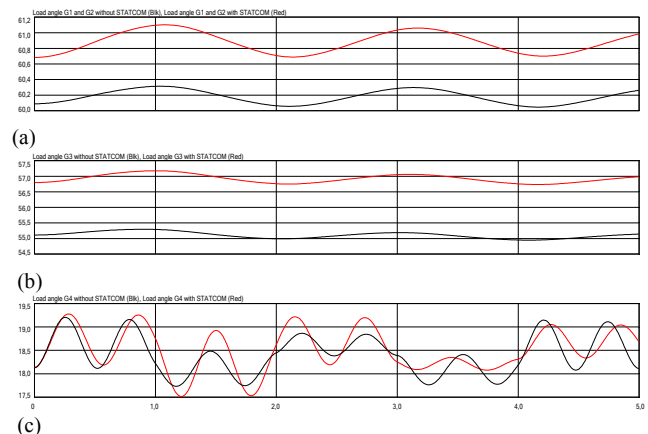


Fig. 11. Load angles for (a) G1 and G2, (b) G3, and (c) G4, without STATCOM (black graph) and with STATCOM (red graph).

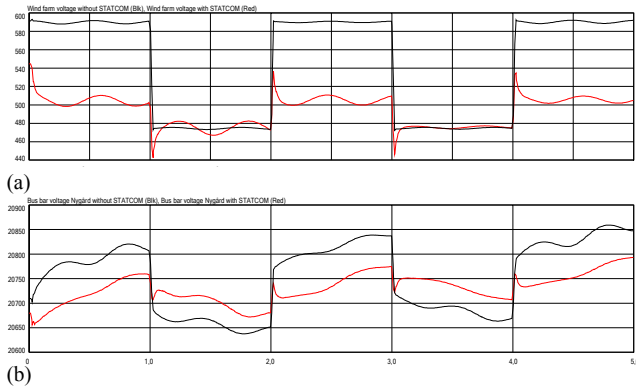


Fig. 12. rms voltages at (a) the wind farm, and (b) Nygård bus bar, without STATCOM (black graph) and with STATCOM (red graph).

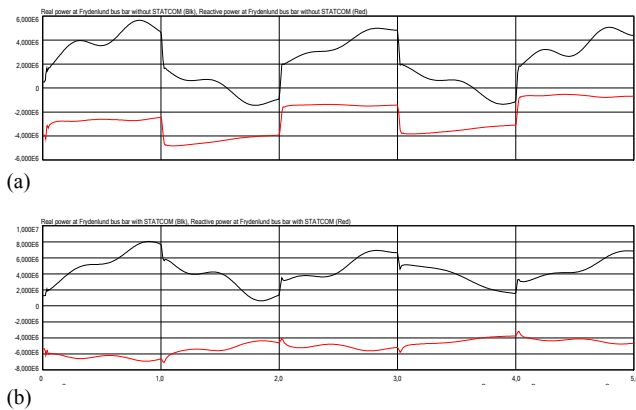


Fig. 13. Active (black graph) and reactive power flow (red graph) at Frydenlund bus bar, (a) without STATCOM, and (b) with STATCOM.

### C. Simulation of Wind Fluctuations with Hydro Power and Arc Fault

The model for these simulations is presented in Fig. 3, with the arc fault activated. Comparisons were as usual made with and without use of STATCOM.

Fig. 14. shows load angles for G1 and G2 (a), G3 (b), and G4 (c), without STATCOM (black graph) and with STATCOM (red graph). For (a) and (b) there is a significant change in the load angle after the short circuit, and the power will go back and forth for several seconds until the swing is completely damped. The STATCOM has very little influence on this dynamic behaviour. For (c) there is an increased swing when the STATCOM is applied, probably because G4 is much closer to the STATCOM and the STATCOM is able to influence on this relatively small machine.

Fig. 15. shows rms voltages at the wind farm (a), at Nygård bus bar (b), and at Frydenlund bus bar (c), without STATCOM (black graph) and with STATCOM (red graph). The figure shows that the wind farm voltage to a small extent is reduced during the short circuit, and surprisingly enough, even less without the STATCOM. At Nygård bus bar and Frydenlund bus bar one observes a severe voltage drop during the fault contingency.

Fig. 16. shows active (black graph) and reactive power flow (red graph) at Nygård bus bar without STATCOM (a), and with STATCOM (b). The disturbances caused by the short circuit are so heavy that the influence of the STATCOM is negligible during these violent transients.

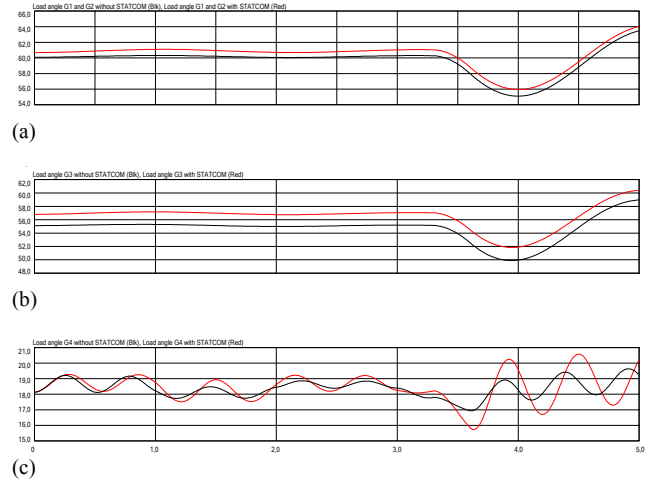


Fig. 14. Load angles for (a) G1 and G2, (b) G3, and (c) G4, without STATCOM (black graph) and with STATCOM (red graph).

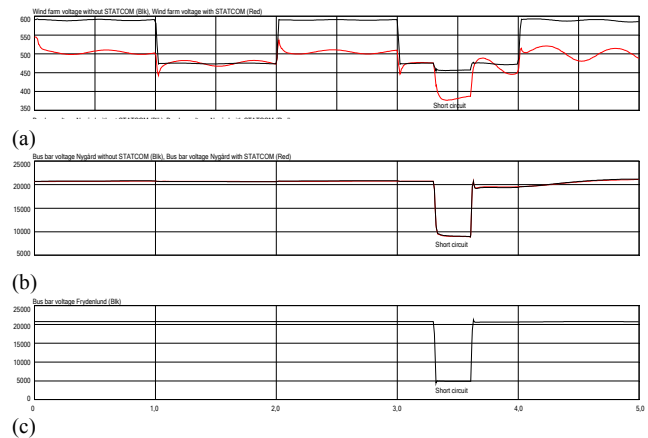


Fig. 15. rms voltages at (a) the wind farm, (b) Nygård bus bar, and (c) Frydenlund bus bar, without STATCOM (black graph) and with STATCOM (red graph).

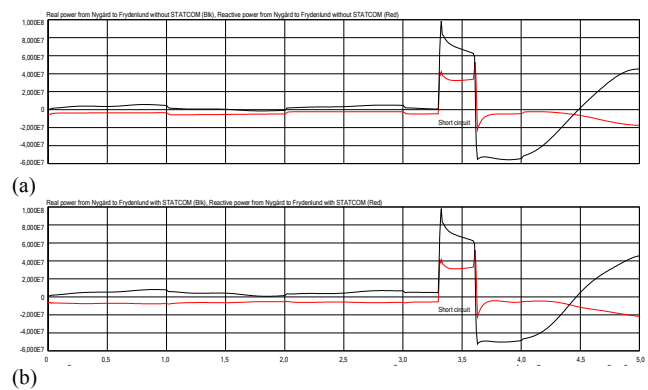


Fig. 16. Active (black graph) and reactive power flow (red graph) at Nygård bus bar, (a) without STATCOM, and (b) with STATCOM.

It should be noticed that the voltage sensors of the STATCOM was connected to the infinite bus through a transformer for the model in Fig. 3. This was done to make the system stable. If the voltage sensors are coupled straight to the overhead line between Sirkelvann and the wind farm, the system is unstable, probably caused by coupling between the active and reactive power properties.

#### IV. CONCLUSIONS

This work has been successful in developing suitable simulation models for different faults and disturbances. The software tools have worked as expected, and the work has yielded increased insight and understanding in ATP-EMTP simulations.

The simulation model needs further improvement, and even though it simulates an existing distribution grid, on-site measurements are required to validate the model. Both the wind turbine model and the STATCOM model might have been simplified beyond realistic behaviour.

Even if the existing model should turn out to be inadequate, it still gives a rough picture of expected dynamic behaviour of the system.

From Fig. 9. it can be seen that the rise of the wind farm current during a short circuit at Frydenlund is not very dramatical. The reason is obvious: Due to the weak grid connection, the total transmission impedance limits the short circuit current of the wind farm.

The benefit of a weak grid connection is by other words the inherent current limiting properties. The disadvantage is naturally the reduced stiffness of the network, and thereby increased dynamics and reduced stability limits.

This work has shown that a STATCOM is beneficial both for voltage control and in order to increase transient stability during fault conditions. In some cases it might increase the dynamics of the wind farm and its closest surroundings and maybe be a source of instability under certain conditions.

As can be seen from Fig. 11. and Fig 14, generator G4 (Sirkelvann mini hydro generator) can be quite heavily perturbed by the wind farm, because it is situated quite close to the wind farm and because it is a relatively small machine with a low moment of inertia. During rated wind production one should probably keep the hydro production of G4 significantly below the stationary stability margin, in order to avoid generator tripping.

#### V. REFERENCES

- [1] L. Prikler, H. K. Høidalen, "ATPDraw Users' Manual", *SINTEF Energy Research*, 2002
- [2] T. Ackermann, *Wind Power in Power Systems*, England: Wiley, 2005