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MODELING AND AGGREGATION OF WIND PARKS FOR POWER SYSTEM STABILITY STUDIES

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ABSTRACT:

This paper discusses modelling of wind power plants for transient stability studies. Large wind power plants are rare components in power systems, but as they have a significant influence on power system stability in weak networks, the plants must be included in the power system stability models. However, there is a lack of guidelines for modelling wind power plants. This yields both in the construction phase and the operation phase of the wind power plant. Wind power plant models with different levels of aggregation and detail have been used to investigate their influence on simulation results, and general guidelines are identified. The results show that when using a simple model of the wind power plant, the simulation will result in significant better power system stability conditions as compared to more accurate models.

Keywords: Grid Integration - 1; Large Scale Integration - 2; Models (physical) - 3

1. INTRODUCTION

Norway has very good wind conditions and the potential for wind power amounts to approx. 40 TWh, or close to 30% of the Norwegian electricity consumption in 2004. This potential corresponds to 12.000 MW installed wind power capacity, equivalent to 45% of the installed hydropower capacity of 27.500 MW. Even if the installed wind power capacity is low today, many projects are underway to be implemented. Since the planned plant sites are located along the coast of Norway, where the networks are weak, new tie lines must be constructed. However, due to public resistance to new overhead lines contractors must limit new line constructions to a minimum. The transmission capability problem is mainly solved through upgrading of existing lines, but the weak point of connection problem is a larger obstacle. Studies have revealed flicker problems, problems concerning voltage stability, angle stability and oscillations between wind power plants and large groups of hydropower machines.

This paper will concern the engineering of a 140 MW wind power plant, the first wind power plant at this size ever constructed in Norway, integrated in a weak point of connection in the grid [1].

From other countries it is it is known that wind power plants affect power system stability [1], [2], [3]. Therefore, in the engineering phase of the project, the grid owner will be interested in the results from power system stability analysis which includes a dynamic model of the wind power plant. Furthermore, when the plant is put into operation, the grid owner and the system operator must include the wind power plant in existing dynamic models of the power system. However, there is a lack of guidelines for dynamic modelling of wind power plants. Hence, it is important to find a level of aggregation which gives adequate accuracy for the two modelling purposes mentioned above.

This paper discusses modelling of wind power plants for transient stability studies. Large wind power plants are rare components in power systems, but as they have a significant influence on power system stability in weak networks, the plants must be included in the power system stability models. Wind power plant models with different levels of aggregation and detailed description of the wind park have been developed to study their influence on the accuracy on the simulation results, and general guidelines are identified.

2. MODELLING OF WIND POWER PLANT

A wind power plant at the size of 140 MW is a complex installation. It consist of a large number of windmills spread over a vast area and connected to a substation via a MV-network with many kilometres of cable.

The most common windmills use induction generators operating at about 700 V and a step-up transformer. Usually the windmill is also equipped with shunt capacitors for reactive power compensation.

In the substation the voltage is once again transformed to a higher level, connecting the wind power plant to the regional nettwork.

This makes a wind power plant a more complex "component" to handle in power system simulations than for example a hydro power plant with the same nominal power, which usually consists of one or a few large generating units located close to each other.

In addition to the structural complexity of the wind power plant, there are also a variety of different technologies used in windmills that can give the individual windmill-types different characteristics. A traditional wind mill with an induction generator and large speed difference between the generator and the turbine have very different characteristics compared to a wind mill with a direct driven synchronous generator connected to the MV- network via a converter.

When performing the preliminary power system analysis in the planning phase of a wind powerproject, there are usually many uncertainties related to the technical details of the plant. Examples of uncertain factors are:

- Windmill technology in general
- Unit size
- Generator type
- Turbine type
- Internal MV-network: topology and voltage level
- Reactive power compensation strategy
- Measures to reduce plant impact on power quality
- Control- and protection schemes
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These are all factors which might influence the dynamic behaviour of the plant. The uncertainties make it impossible to model the wind power plant in detail and affects the accuracy of the simulation results. Even with more detailed information, the complexity of the wind power plant inspires to use aggregated models to represent the plant when studying its interaction with the rest of the power system.

3. DESCRIPTION OF CASE STUDY

3.1 The power system

In order to evaluate the influence the aggregation level has on simulation results, a site at the coast of the Mid part of Norway was selected as case study. The simulations have been carried out in a transient stability software tool; PSS/E, and include the dynamic response following a three-phase short circuit near the wind-park.

The power system model consists of the main grid in Norway including generators, overhead lines and cables, loads and connections to Sweden and Finland. An equivalent of the power systems of Sweden and Finland, respectively, are included in the model.

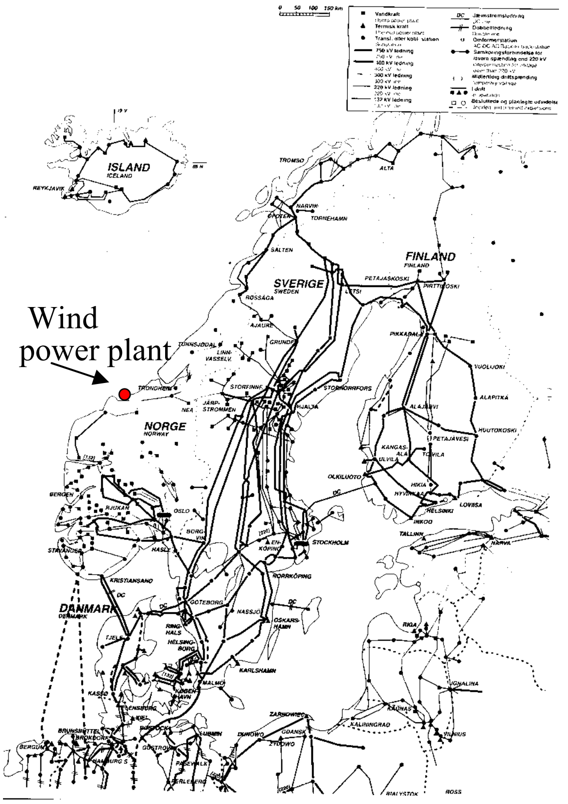

Figure 1: The Nordel power system.

The load and production in the power system is adjusted to fit the standard planning criteria in Norway, representing a full load situation during winter season.

The wind power plant is connected to the 132 kV main grid that is part of a typical rural electrification system, characterised by relatively long overhead lines, a small number of loads and some hydro power plants in a relatively weak network. The short circuit capacity in the area is approximately 1200 MVA, which gives a ratio of 1200 MVA/140 MW = 8,6.

3.2 Wind power plant models

The plant is planned to have an installed capacity of 140 MW, consisting of seventy 2 MW windmills spread over an area of 10 km^2 and using conventional technology with induction generators. The plant-internal cable network is assumed to operate at 22 kV voltage level.

The case studies consern four different models of the wind power plant. The models are presented in figure 2 to figure 5, as well as summarized in table I.

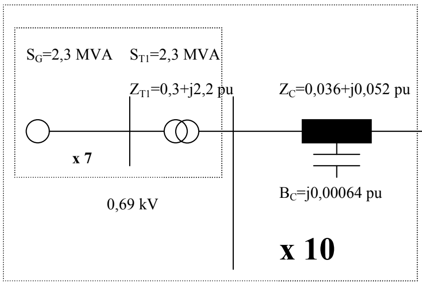

Figure 2: Plant model #1.

In plant model #1, figure 2, each single turbine is modelled in detail on the 0,60kV level, and the wind farm is represented by 70 turbines distributed along 10 distribution feeders (indicated by x10 in the figure) and each feeder containing 7 units (indicated by x7 to the left in the figure)

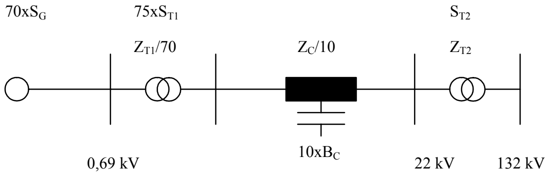

Figure 3: Plant model #2.

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In plant model #2, figure 3, all turbines are lumped together into one equivalent turbine of 140 MW, but it is still connected to the 0,69kV level, and hence an equivalent lumped 0,69kV/22kV step-up transformer is included in the model Also the internal distribution system is still represented by the lumped equivalent impedance shown in figure 3.

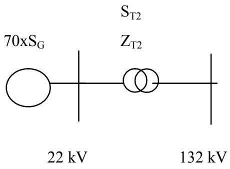

Figure 4: Plant model #3

In plant model #3, figure 4, the equivalent 1x140MW generator is connected directly to the 22 kV bus by removing the equivivalent 0,69kV/22kV step-up transformer and the internal distribution system /that is removing the left transformer and the equivalent network impedance in figure 3).

In plant model #4, figure 5, the system is further reduced by connecting the 140MW equivalent plant directly to the 132kV bus bar.. Compared to figure 4, we have now removed the 22kV/132kV step-up transformer.

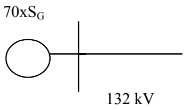

Figure 5: Plant model #4

The purpose of this model reduction ranging from a detailed representation of 70 turbines and the internal details, to a reduced and large equivalent model directly connected to the main grid, is to study how detailed we need to model the wind farm and how much we can simplify the modelling by aggregating the turbines, and still maintaine reasonable and accurate results from the stability study.

Table I gives a summary of the different models.

Table I: Wind power plant models

Plant model #	Voltage level [kV]	Generators	Internal network [Yes/No]
1	0,69	75x2 MW	Yes, ten 1,4 km cables with 7 mills connected to each cable
2	0,69	1x150 MW	Yes, equivalent impedance
3	22	1x150 MW	No
4	132	1x150 MW	No

In models #1 and #2, each generator is fully compensated and connected to the 22 kV plant-internal network via a 0,69/22 kV transformer. A shunt device at the 22 kV busbar regulates the voltage at the 132 kV busbar to 132 kV.

In models #3, and #4 the generators are compensated until the voltage at the 132 kV busbar equals 132 kV.

We assume that the wind power plant is subjected to constant wind speed; i.e. all windmills in the plant are running at the same point of operation.

3.3 Simulation cases

The different wind power plant models influence on the dynamic response is examined by imposing a temporary 150 msec three-phase short circuit at a 132 kV bus, five kilometres from the wind power plant. As a measure to maintain the stability after the fault is cleared, wind power production is shed

100 ms after imposing the fault [2]. Results from these simulations are shown in the next section.

Table II: Simulation cases

Case #	Plant model #	Description
1	1	Disconnection of 6 22 kV cables with 42 windmills. Post-fault production is 56 MW
2	2	Reduction of generator size and corresponding shunt capacitors. Post-fault production is 56 MW
3	3	Reduction of generator size and corresponding shunt capacitors. Post-fault production is 56 MW
4	4	Reduction of generator size and corresponding shunt capacitors. Post-fault production is 56 MW

4. SIMULATION RESULTS

4.1 Simulation case #1 and #2

In figure 6 the generator terminal voltage in the wind power plant is presented for case #1 and #2.

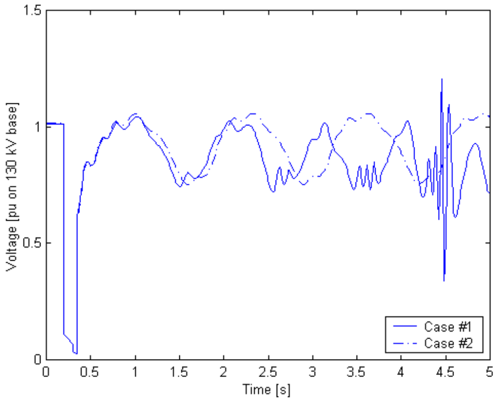

Figure 6: Generator terminal voltage in case #1 and case #2.

As can be seen from figure 6, the results in case #1 and #2 are rather similar. Case #1 is marginally unstable while case #2 is stable. The difference is caused by the different impedance between the generator and the 22 kV bus after shedding production in two different ways. However the difference between the two cases is small. Decreasing the generator size corresponding to 83 MW instead of 84 MW in case #2 leads to instability, similar to case #1.

4.1 Simulation case #2, #3 and #4

In figure 7 the generator terminal voltage in the wind power park is presented for case #2, #3 and #4. As can be seen from figure 7 the principal behaviour of the three cases #2, #3 and #4 are much the same, but there are differences in amplitude and damping. The different impedance between the generators and the 132 kV bus in the two cases causes the differences.

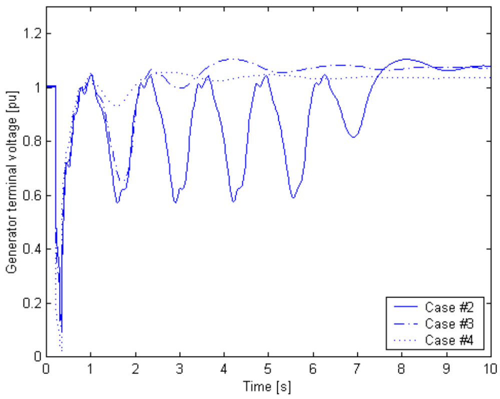

Figure 7: Generator terminal voltage in case #2, #3 and #4.

By decreasing the amount of production which is shed during the fault in case #3 and #4, marginal stability is obtained for post-fault nominal productions of 62 MW and 91 MW respectively. The results are presented in figure 8 and table III.

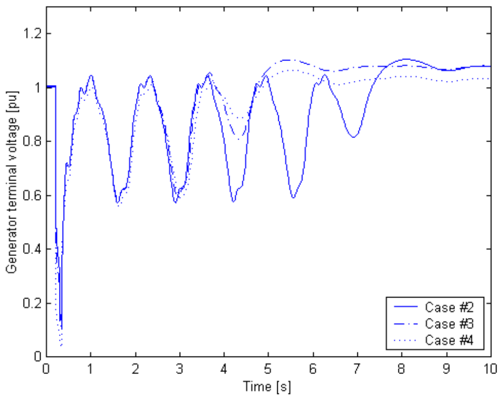

Figure 8: Generator terminal voltage in case #2, #3 and #4 at marginal stability.

Table III: Comparison of results when using different plant models.

Plant Model #	Nominal post-fault production [MW]	Deviation from the detailed aggregation level
2	56	Reference
3	62	11%
4	91	63%

5. DISCUSSION

5.1 The influence of different wind power plant models on simulation result.

A number of identical generating units working in parallel at the same point of operation can be represented with one unit of the size of the sum of the parallel units [4]. This is also valid when the units are connected to a common bus over identical impedances representing for example a step-up transformer.

The results presented in section 4.1 show that representing the internal MV-netwok and all the generating units with one aggregated unit behind an equivalent impedance, that includes both the step-up transformer in each unit and the MV-network, gives just as accurate results as obtained with the more complex model. This is becuse the two models contain the same information about the plant. The little difference in the simulation results in section 4.1 can be totaly eliminated by correcting the equivalent net impedance, while changing the size of the equivalent generator. For simulation of events that does not lead to any changes in the wind power plant, the two models give identical results.

Section 4.2 compares the simulation results obtained with different levels of detail in representing the wind power plant. Using the nominal post-fault power in case #2 as a basis of comparison, the results clearly show the importance of including the main transformer since the difference in post-fault nominal power is 63%. The importance of the internal MV-network and the step-up transformer in each unit is much smaller; in this case the difference is down to 11% compared to case #2.

5.2 The influence of other factors on simulation result

It is important to notice that the principal behaviour is similar in all simulations presented in section 4, and that the aggregation and simplification of the park-representation mainly influence the amplitudes and damping of the post-fault oscillations. The nature of the oscillations is mainly a result of the shaft-model used in the simulations [3]. Different shaft characteristics, or another distribution of the rotating masses, will have a large influence on the simulation results.

The breakdown torque in the induction generator is basically a function of the square of the terminal voltage, the leakage inductance and the rotor resistance. Different generator types will have different parameters and therefore different breakdown torque that will affect the stability limit.

The induction generator models used in the simulation tool also affect the results [3]. Traditionally in dynamic simulations with wind turbines, a classical dynamic model of the induction generator is used. This model represents the transients in the rotor circuits, and neglects the fast transients in the stator circuit. This assumption leads to inaccurate calculation of the speed in the first period of a transient sequence. Hence, the machine terminal voltage will be incorrectly derived and thereby affect the outcome of the simulation.

Since avoiding low generator terminal voltage is crucial to avoid overspeed of induction generators, the strategy for how to handle reactive power compensation under and after a transient sequence affect the transient stability. The simulations presented in this paper assume that the shunt capacitors in each generating unit are disconnected along with the generator when shedding production to maintain stability. Another strategy that disconnects a smaller amount of shunt capacitors results in higher voltages, and will have a positive influence on induction generator stability.

6. CONCLUSIONS

Large wind power plants are rare components in power systems, but as they have a significant influence on power system stability in weak networks, the plants must be included in the power system stability models. This yields both in the construction phase and the operation phase of the wind power plant.

This paper has described and shown results derived from simulations of dynamics in a power system with wind turbines. The simulation cases represent a typical wind park site in Norway, located at the coast and connected to a relatively weak regional 132 kV grid.

Wind park models with different levels of aggregation and detail have been used to investigate their influence on simulation results. Two general guidelines are identified:

1. **Early planning stage.**

This stage is characterised by the presence of many uncertain factors. The simulations show that representing the wind power plant by one generator equivalent connected to the secondary side of the main transformer is sufficient, corresponding to plant model #3 in section 3.3. Using the very simplified model #4 gives too optimistic results and will not give the real power system conditions. If the capacity of the wind power plant is to be decided by model#4, the wind park will be over dimensioned.

2. Later planning stage/operational stage.
In this stage the number of uncertain factors are lower as the number and size of units are given as well as the internal distribution grid. . This makes it possible to include the step-up transformers and the internal network in the wind power plant model. As long as it is assumed that all generators run at the same point of operation, and the impedance in the internal network is small compared to the impedance in the step-up transformers, a one-generator equivalent is sufficient for this kind of study, corresponding to plant model #2 in section 3.3.

The results show that when using a simple model of the wind power plant, corresponding to model #4 in section 3.3, the simulation will result in significant better power system stability conditions as compared to more accurate models. Hence, using a too simplified model will give too optimistic results and will noit reflect the real power system conditions.

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