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Simulation of the impact of wind power on the transient fault behavior of the Nordic power system

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Abstract

In this paper the effect of wind power on the transient fault behavior of the Nordic power system is investigated. The Nordic power system is the interconnected power system of the countries Norway, Sweden, Finland and Denmark. For the purpose of these investigations the wind turbines installed and connected in eastern Denmark are taken as study case. The current and future wind power situation in eastern Denmark is modeled and short circuit faults in the system simulated. The simulations yield information on (i) how the faults impact on the wind turbines and (ii) how the response of the wind turbines influences the post-fault behavior of the Nordic power system.

It is concluded that an increasing level of wind power penetration leads to stronger system oscillations in case of fixed speed wind turbines. It is found that fixed speed wind turbines that merely ride through transient faults have negative impacts on the dynamic response of the system. These negative impacts can be mitigated though, if sophisticated wind turbine control is applied.

Keywords: Fault ride through; Nordic power system; Wind power; Transient fault

1. Introduction

The study of the effects of growing wind power penetration on the stability and reliability of power systems is of interest in many countries in the world. Wherever wind power will be installed on a large scale such studies are carried out to prevent severe consequences for the power system considered [1]. Besides the commonly discussed impacts of and on the system voltage, also the system frequency plays an important role. When wind power penetration increases, wind turbines have to be involved in the control of the grid frequency. This is a relatively straightforward task for normal operation, where load changes cause the system frequency to deviate [2]. Frequency control is a much more demanding task for wind turbines in the wake of transient faults [3]. Under transient fault situations both the voltage and frequency have to be considered to assess the impact of wind power on the system stability [4].

This paper considers the mutual effects of wind power in power systems under transient fault situations. As study case the Nordic power system is taken. It is analyzed (i) how the wind turbines behave in the system when it experiences a transient fault and (ii) what impact the wind turbines have on the dynamic behavior of the system after a fault.

The Nordic power system stretches the countries Norway, Sweden, Denmark and Finland. Not only is substantial amount of wind power already today installed in the Nordic power system, a lot more is expected to come due to the promising wind conditions in northern Europe. Characteristic for the Nordic power system is that it is geographically large, but at the same time it is of comparably small capacity, due to Norway, Sweden, Denmark and Finland being only sparsely populated countries. This makes it more vulnerable to high levels of wind power penetration if the installed turbines are uncontrolled distributed generators.

Until recently wind turbines connected to the Nordic power system were not engaged in the control and support of the

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system. If transient faults in the system lead to considerable excursions in voltage and/or frequency the wind turbines were to disconnect and to reconnect only once the system has returned to stable operation. Increasing wind power penetration leads to the problem that considerable amount of generation might disconnect in case of a transient fault in the system, causing the system to become unstable from an otherwise harmless fault situation. To prevent such situations newly installed wind turbines have to comply with new grid connection requirements that demand wind turbines to ride through transient faults [5].

Elkraft, which is the operator of the transmission system in eastern Denmark has already today one of the world's largest offshore wind farms connected to its system, and more even larger offshore wind farms are expected in the near future. Therefore, Elkraft along with the other system operators in the Nordic power system, is interested in the possible consequences of local high wind power penetration.

The model of the Nordic power system used in these investigations has been developed at SINTEF in Norway [6], and is an aggregation of a fully detailed transmission system model, whose validity has been proven with measurements. It is a model of the transmission system comprising aggregations of conventional power plants only; no wind farms have been included at SINTEF.

At Risø National Laboratory a model of the wind power connected to the Nordic power system in eastern Denmark has been added to SINTEF's Nordic power system model. This additional model has been developed in cooperation with Elkraft. The simulation tool used in these investigations is the power system simulation tool PowerFactory from DIgSILENT [7].

This article presents the results of joint efforts of Risø National Laboratory, SINTEF and Elkraft on the field of transient stability of wind power in the Nordic power system.

2. The Nordic power system model

The Nordic power system stretches the countries Norway, Sweden, Denmark and Finland, and has a nominal system frequency of 50 Hz. It is divided into two synchronous areas. The biggest part of the system, comprising Norway, Sweden, Finland and the eastern part of Denmark are one interconnected, synchronous AC system. The small rest of the Nordic power system, i.e. western Denmark, is AC connected to the big UCTE system, which is the interconnected AC system of central Europe. Several HVDC links connect the Nordic synchronous system with the central European system. There are, among others, HVDC links between Norway and western Denmark, between eastern Denmark and Germany and between southern Sweden and Germany.

Since in transient fault situations the HVDC links can be considered uncontrolled voltage dependent sources and sinks, the central European part of the system is of no relevance for transient fault simulations. Hence for simplicity the term "Nordic power system" will in the following refer to the Nordic synchronous system.

The model of the Nordic power system is an aggregation, which means that the generators, lines and loads in the model are lumped representations of several generators lines and loads in reality. It comprises 35 nodes and 20 synchronous generators. It is a model of the transmission system only; comprising the voltage levels 420, 300, 150 and 135 kV. In the location of eastern Denmark, the model is extended with a simplified grid to represent the connection of wind power. This simplified grid comprises all voltage levels from transmission system voltage down to generator terminal voltage. This extension is described in the following section.

3. Model of wind power installations in the Nordic power system

As mentioned earlier the purpose of the extension of the Nordic power system model is that wind power can be implemented realistically into the model. The extension considers the transmission and distribution system in eastern Denmark. Eastern Denmark is a remote location in the system. In the south of eastern Denmark, which is where the majority of the wind turbines are connected, the grid is relatively weak.

Denmark is the country in the Nordic power system that has by fare the highest level of wind power penetration. Therefore, it is only natural to model the wind power connected there. It is assumed that wind power in eastern Denmark is the only wind power that has to be considered in the Nordic system. This is a sound assumption, as only faults in eastern Denmark will be simulated. Any wind power that is installed in another part of the system would hardly be affected by faults in eastern Denmark.

Inherent for wind power is that its resources are far away from load centers and hence almost invariable far away from strong transmission systems. This is even more applicable for offshore wind farms. The largest part of wind power that will be installed in eastern Denmark in future will be offshore.

The amount of wind power that is introduced, substitutes power of synchronous generators. Hence the total amount of active power transmitted through the system remains the same, apart from the losses of the extra components.

3.1. Topology of the grid in eastern Denmark

In the original model as developed by SINTEF eastern Denmark is represented by a single busbar with a synchronous generator and a load. This busbar is called Zealand, as can be seen in Fig. 1, which shows the topology of the whole power system extension. The synchronous generator at busbar Zealand (SG Zealand) is rated 2000 MVA and represents all the conventional power plants in eastern Denmark. The load connected to Zealand represents the load in the northern part of eastern Denmark.

In the extension (Fig. 1) three wind farms in the south of eastern Denmark are considered. One wind farm represents all the land-based wind turbines, which are distributed over the southern islands of eastern Denmark. These turbines are aggregated to one single induction generator. Another wind farm represents the Nysted offshore wind farm. This is one of the world's largest

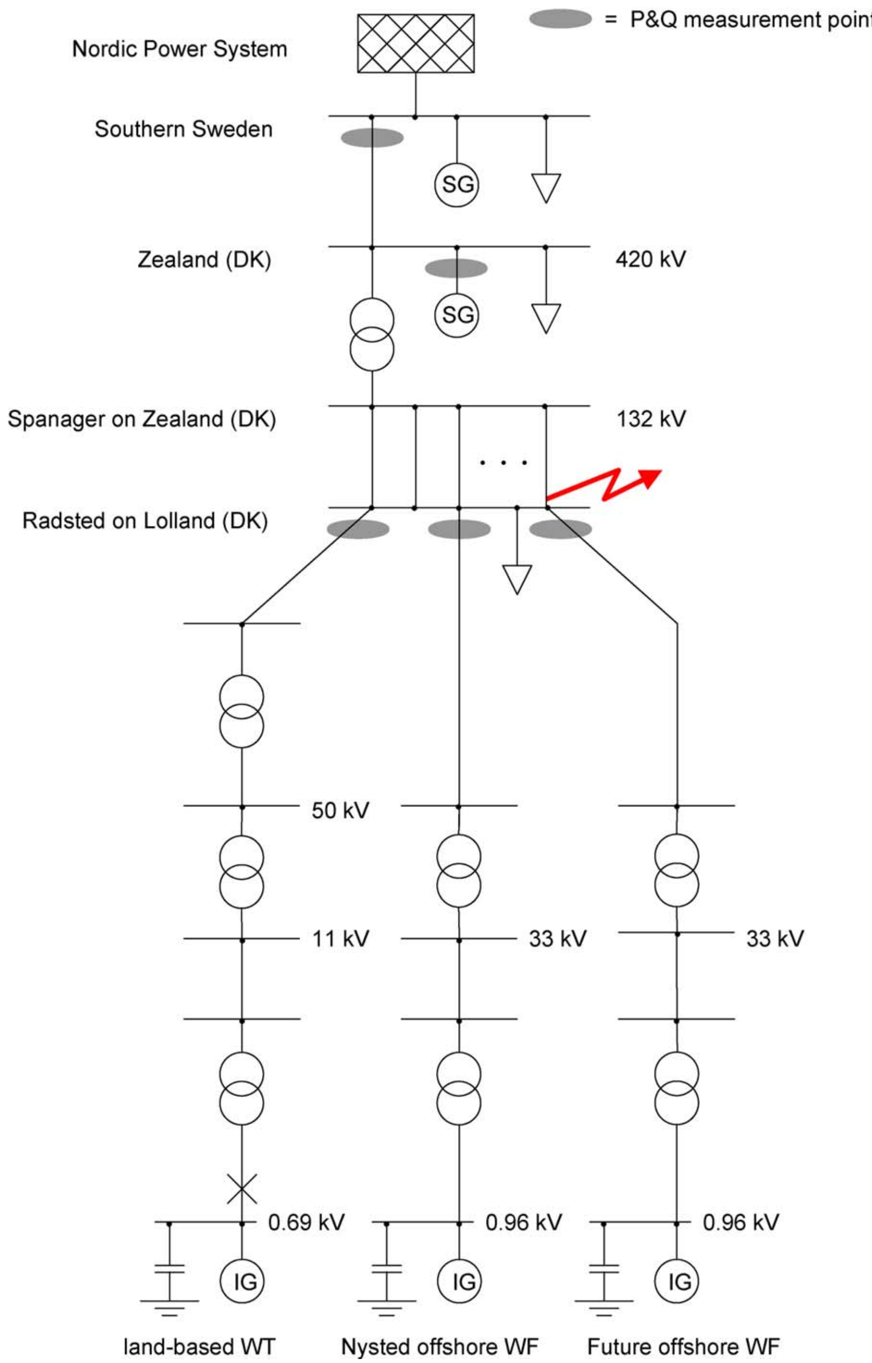

Fig. 1. Grid diagram of the extension of the Nordic system model introducing the wind power installed in eastern Denmark.

offshore wind farms and has been connected to the system since 2003 [8]. The third wind farm is an offshore wind farm that is likely to be installed in future.

The connection between this 420 kV busbar and the wind farms is modeled in a more detailed manner than the rest of the Nordic system. It considers all voltage levels from 420 kV down to generator terminal voltages.

3.2. Model of wind farm feeders

The wind farms in the south of eastern Denmark are connected to the transmission system of the Nordic power system through the relatively weak grid of eastern Denmark. Therefore, the power system in eastern Denmark has to be modeled in more detail than the transmission system.

Between the busbars Zealand and Spanager (see Fig. 1) is one transformer that steps the voltage down from 420 to 132 kV. From Spanager, which is situated on the island of Zealand, close to Copenhagen, to the busbar Radsted, which is situated in the south, on the island of Lolland, are several parallel 132 kV lines. The number of parallel lines is varied depending on the level of wind power penetration simulated. (Different cases are simulated as will be seen in Section 4.) The distance between Spanager and Radsted is approximately 100 km.

Connected to Radsted is a load that represents the load in the south of eastern Denmark.

The wind farms are connected to Radsted through 132 kV feeders and medium voltage cables, representing the cable network in the wind farms.

The 132 kV feeder connecting the distributed land-based wind turbines is assumed to be 25 km long. This length is an approximate value found by considering the distance from Radsted to a central location between all the land-based turbines [9]. From this central location 24 parallel 11 kV cables, of 20 km length, represents the medium voltage cable network to the turbines. The length of the 11 kV cable is an average distance from the turbines to the central location mentioned above. Since the distributed land-based turbines are all connected to the distribution system, three transformers are chosen to step the voltage down from the transmission system voltage to the generator terminal voltage.

The connection from Radsted to the Nysted offshore wind farm is modeled with a 29 km long 132 kV line. The cable network inside the wind farm is represented by three parallel, 3.2 km long, 33 kV cables. The distance of 3.2 km is the average distance from the turbines to the transformer platform [10].

The 132 kV feeder connecting the future offshore wind farm with Radsted is assumed to be 30 km long. Just like in the case of the Nysted offshore wind farm, also here the internal farm cable network is represented by three parallel 3.2 km long, 33 kV cables.

With these feeders the generators of the wind turbines are connected to the Nordic power system. The generators and their prime movers, i.e. the wind turbines are described in the following section.

3.3. The wind farm models

3.3.1. Wind model

In this article only transient fault simulations are considered. The simulated events last up to a few seconds, therefore, natural wind variations need not be taken into account. Rotating wind speed variations like 3 pu (the tower shadow effect) [11] can be neglected as well, because the wind power plants considered are aggregations of many single wind turbines. If many turbines are connected together their rotating wind speed variations cancel each other out.

The wind speed is set to a constant 18 m/s, which is a wind speed that allows all turbines to produce rated power. A rated power operating point is chosen, as this is most burdening for the power system.

3.3.2. Model of the distributed land-based wind turbines

Substantial amount of wind power is distributed over the islands in the south of eastern Denmark. These distributed land-based wind turbines are aggregated and modeled by one squirrel cage induction generator. The prime mover is modeled by a constant mechanical torque that acts on a two masses spring and friction model, which then drives the generator (Fig. 2). Aerodynamics and control schemes of these turbines are neglected. They are not relevant for transient fault studies as the grid connection requirements that were applicable when these turbines were installed demand them to disconnect in case of a grid fault.

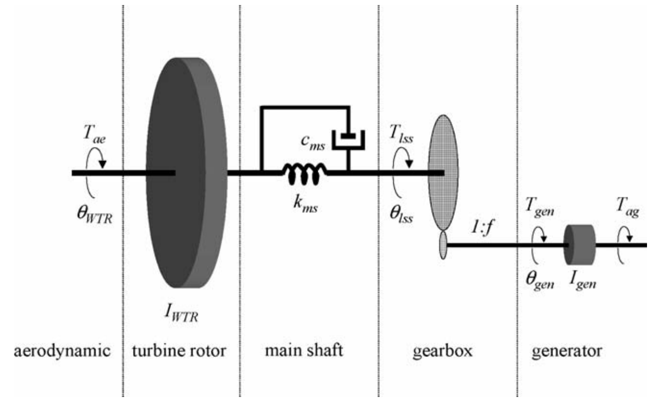

Fig. 2. Drive train model of wind turbine.

The capacity of the induction generator representing the aggregation of all the distributed land-based wind turbines is 235 MW. This is a value that can be worked out from the wind turbine data register of the Danish Energy Authority [9].

The protection system that disconnects the land-based turbines in case of a fault is implemented in the form of undervoltage, overspeed and overcurrent protection. The protection scheme implemented in this model disconnects the generator and its compensation unit, when

- the voltage at the generator terminals drops below 0.85 pu for 100 ms;
- the speed of the generator exceeds 104% of its rated speed (when the generator cannot export as much power as is imported through the wind, it accelerates);
- the current exceeds 200% rated current for 100 ms.

It is assumed that the reactive power compensation is implemented in such a way that only the no load reactive power demand of the generator is compensated. This is in accordance with the applicable grid connection requirements.

3.3.3. Model of Nysted offshore wind farm

The Nysted offshore wind farm consists of 72 identical active-stall wind turbines, each rated 2.3 MW [8]. Therefore, this wind farm is modeled with 72 parallel 2.3 MW induction generators, driven by a wind turbine model with full mechanical (Fig. 2) and aerodynamic representation [12]. A similar wind turbine model has been verified in an islanding experiment of a real multi-megawatt active-stall turbine. This experiment proved that the model represents the behavior of the real turbine well [13]. Fig. 3 shows the topology of the wind turbine model.

An active-stall controller that finds the right pitch angle during normal, fault-free operation is implemented. It optimizes the active power production at wind speeds below rated wind speed. Above rated wind speeds it limits the active power output of the

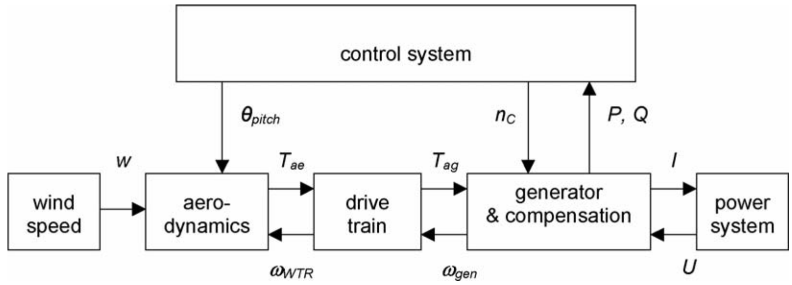

Fig. 3. Wind turbine model.

turbine to its rated value [14]. The Nysted offshore wind farm has to fulfill grid connection requirements that require certain fault ride through capabilities [5]. Therefore, also a transient fault controller is implemented that allows the turbines to ride through transient faults without experiencing damaging speed excursions [15].

In accordance with the applicable grid connection requirements, a reactive power compensation unit has to keep the wind farm neutral in reactive power demand at the grid connection point. A shunt capacitor bank is implemented at the generator busbar, and a controller controls the number of connected capacitors, n_C, such that the steady state power factor is one at the high voltage side of the 132/33 kV transformer.

3.3.4. Model of future offshore wind farm

The future offshore wind farm considered is also made of active-stall wind turbines. It consists of 99 identical 2 MW turbines. Hence the wind farm is modeled with 99 parallel induction generators driven by a wind turbine model similar to the one used in the Nysted wind farm (Fig. 3). The control of the wind turbines in the future offshore wind farm is more sophisticated as these turbines are not only required to ride through transient faults, but also to contribute to the damping of grid frequency oscillations in the wake of transient faults [3]. This is not demanded in current grid connection requirements, but if wind power penetration increases this will probably become a requirement.

Also here it is assumed that the wind farm controls its steady state reactive power production such that it is neutral in reactive power demand at the high voltage side of the 132/33 kV transformer. For that purpose also here a shunt capacitor bank is implemented. The switching frequency of the capacitor contactors is assumed to be somewhat higher than in the Nysted wind farm, emulating more sophisticated technology.

4. Simulations, results and discussions

Different scenarios are simulated to assess the impact of wind power in the current and the future situation. The faults simulated are 100 ms, zero impedance, three-phase short circuits on one of the lines between Spanager and Radsted, close to Radsted (see Fig. 1). The fault gets cleared by permanent disconnection of the faulted line. This is a fault situation described in Elkraft's grid connection requirements for wind farms connected to the transmission system [5].

4.1. Case 1

The current situation is simulated, i.e. only the land-based turbines and the Nysted offshore wind farm are connected. The feeder for the future offshore wind farm, as shown in Fig. 1 is not existent in this simulation.

Fig. 4 shows that the voltage at busbar Radsted drops to zero, as Radsted is closest to the fault location. Zealand is hardly affected by this fault as the relatively weak connection between Radsted and Zealand causes a substantial voltage drop. The voltage at the terminals of the land-based turbines gets suppressed in the beginning of the fault and after a few ms it drops to zero as the protection system of these turbines disconnects them. The voltage at Radsted recovers quickly after the clearance of the fault because the land-based turbines have disconnected, which means that they do not consume reactive power any more. In addition to that the now unloaded cables in the feeder to the land-based turbines act as capacitors generating noticeable amount of reactive power (Fig. 7). The voltage at Nysted recovers also relatively quickly because of the reduced reactive power demand of the Nysted generator in the first seconds.

The fault excites the inherently flexible drive train of the Nysted wind turbines (Fig. 2) to oscillations, which in the first instances after the clearance of the fault leads to a strongly reduced active power production [15]. At the same time the compensation capacitors stay connected helping the voltage to recover.

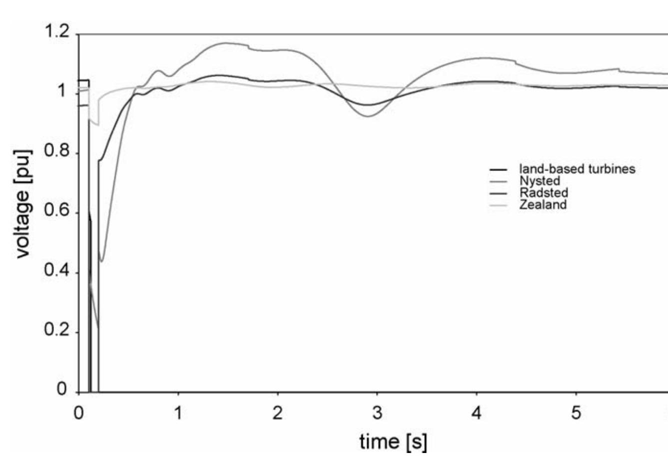

Fig. 4. Case 1: voltage at different locations in the system.

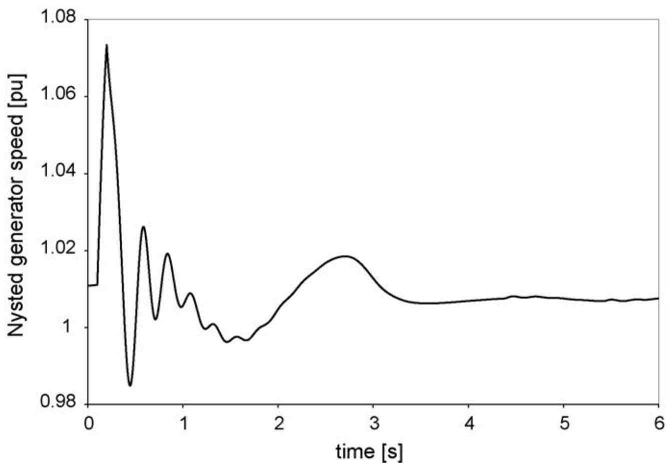

Fig. 5. Case 1: speed of the Nysted wind farm generator.

Fig. 5 shows the speed of the generator of the Nysted offshore wind farm. During the fault the speed of the generator accelerates steeply. Just after the clearance of the fault it exhibits oscillations with the resonance frequency of the small inertia of the generator rotor (Fig. 2). While these oscillations subside within the first 2 s after the fault, the underlying low resonance frequency of the turbine rotor with its large inertia becomes dominant. At simulation time 3 s these low frequency oscillations cause a noticeable increase in generator speed, which in turn means that the generator requires more reactive power. Increasing speed in a squirrel cage induction generator means increasing slip, s. From Fig. 6, which shows the equivalent circuit diagram of such a squirrel cage induction generator, it can be seen that with increasing slip, s, the overall rotor resistance decreases $R_{\mathrm{rotor}} = R_{\mathrm{r}}/s$. Lower resistance leads to more current flowing through the mainly inductive circuit of the generator, causing higher reactive power demand. For these considerations it is sufficient to use the steady state equivalent circuit of the generator as shown in Fig. 6. The wind turbine drive train, which causes the speed oscillations, has considerably larger time constants than the electrical circuit of the generator.

Fig. 7 shows that this reactive power demand has to be covered by SG Zealand, which produces reactive power to be transferred to Sweden (line DK-S). This reactive power surge causes a voltage drop between Zealand and Radsted, which can be seen in Fig. 4 around the simulation time 3 s. Eventually the voltages in eastern Denmark settle to a slightly higher value because of the extra reactive power being generated in the cables of the land-based turbines feeder.

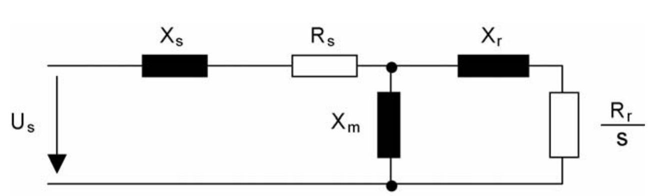

Fig. 6. Equivalent circuit diagram of a squirrel cage induction generator.

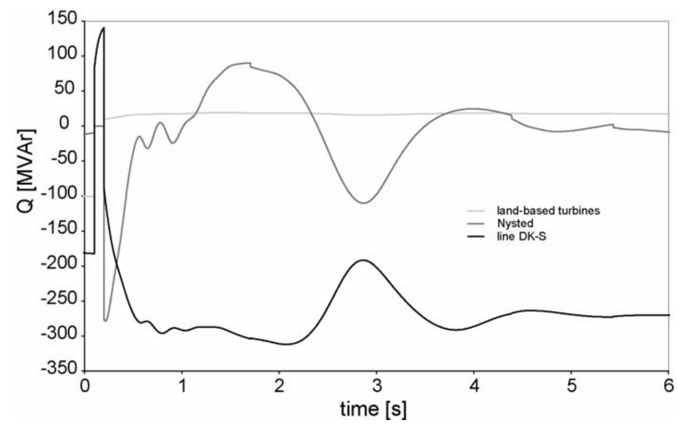

Fig. 7. Case 1: reactive power at different locations in the system as shown in Fig. 1.

4.2. Case 2.0

Here the situation is simulated that the future offshore wind farm has been connected and that the turbines in this wind farm have the same control capabilities as the Nysted turbines, i.e. only fault ride through as demanded by the current grid connection requirements. The rating of the 420/132 kV transformer and the number of lines between Spanager and Radstad are increased to suit the extra power installed in the new wind farm. In addition the dispatched power of SG Zealand is reduced by 200 MW and its rated power is reduced by 200 MVA to reflect the situation that future installed wind power will substitute conventional power plants.

In Fig. 8 the voltage of the land-based turbines is not shown as this drops to zero like in the previous case. From Fig. 8 it can be seen that the voltage at Radsted, and consequently at the terminals of the wind farms, is under considerably more strain than in the previous case. The drive trains of the turbines in the two offshore wind farms oscillate similarly causing the speed of the generators to oscillate (Fig. 2), which causes the reactive power demand to oscillate (Fig. 6), and this in turn causes the voltage to oscillate strongly too.

Due to the stronger connection between Zealand and Radsted the voltage at Zealand is slightly lower than in case 1. This

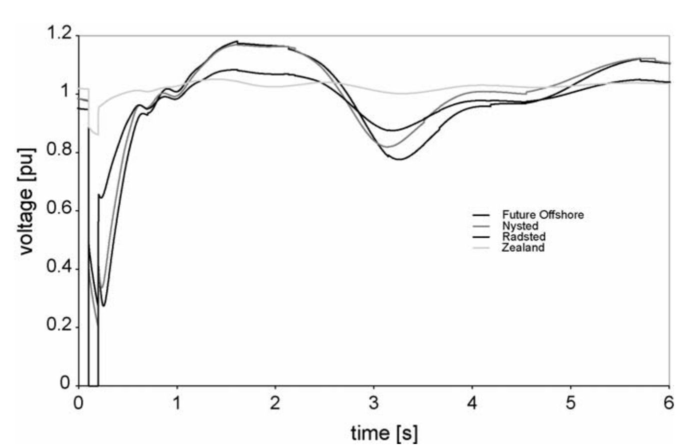

Fig. 8. Case 2.0: voltage at different locations in the system.

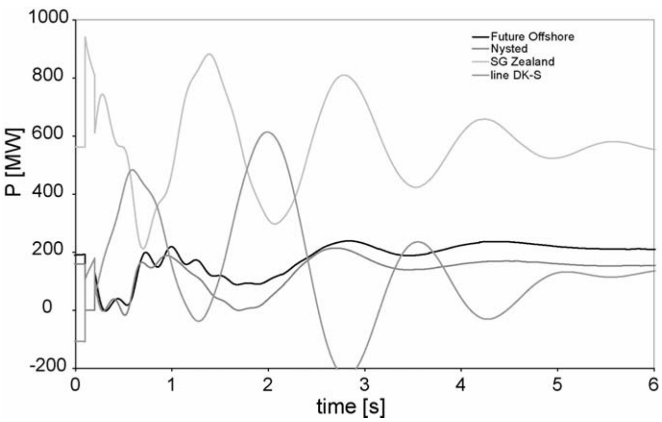

Fig. 9. Case 2.0: active power at different locations in the system as shown in Fig. 1.

is of no consequence for the voltage in the rest of the Nordic system.

The fault does however upset the grid frequency, because SG Zealand exhibits strong rotor speed oscillations, which is visible in strong active power oscillations as shown in Fig. 9. These power oscillations can only propagate through the line between Zealand and Sweden (called 'line DK-S' in Fig. 9) into the rest of the Nordic power system and be absorbed by other bulk power plants.

4.3. Case 2.1

In the case simulated here the future offshore wind farm employs its grid frequency stabilizer to counteract the frequency oscillations caused by the short circuit [3]. This emulates the situation that in future wind turbines will be involved in the stabilization of the power system.

In the first instance these turbines have to tackle their own drive train oscillations before they can contribute to grid frequency stabilization. Therefore, the rise in voltage (Fig. 10) just after the clearance of the fault is similar to that in the previous case. The voltage dip after simulation time 3 s is much less severe, which is due to the pitching actions of the grid frequency stabilizer. Consequently also the power oscillations as plotted in Fig. 11 are less severe than in the previous case.

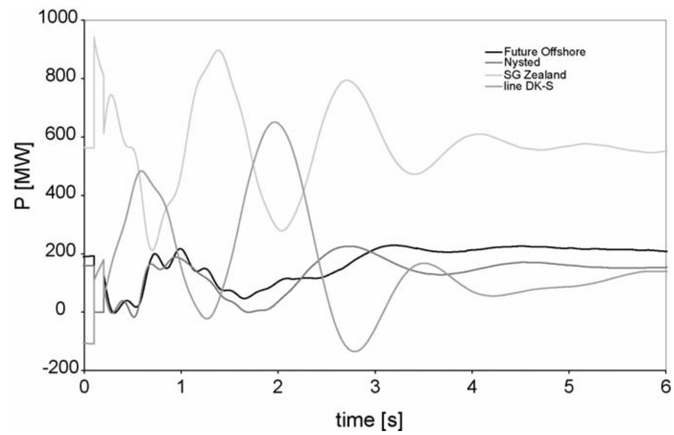

Fig. 11. Case 2.1: active power at different locations in the system as shown in Fig. 1.

For better comparability of the cases 2.0 and 2.1 the active power of SG Zealand and in line DK-S are plotted in one graph in Fig. 12. From Fig. 12 it becomes visible that the oscillations in the rotor speed and hence the active power of SG Zealand and in line DK-S, are noticeably dampened by the control actions of the grid frequency stabilizer in the future offshore wind farm.

4.4. Comparison of the grid frequency response of cases 1, 2.0 and 2.1

As noted above, the voltage variations caused by the faults, simulated in the different cases, has a negligible impact on the Nordic power system. The frequency and hence the active power flow through the system gets affected though. An effective means of comparing the consequence of the different scenarios on the Nordic power system is comparing the speed responses of SG Zealand, i.e. the grid frequency.

Fig. 13 shows the speed of SG Zealand for the cases 1, 2.0 and 2.1. The comparison of cases 1 and 2.0, which both do not include any active frequency damping by the installed wind turbines, shows that in the case of larger wind power installation the speed of SG Zealand gets more upset. As shown

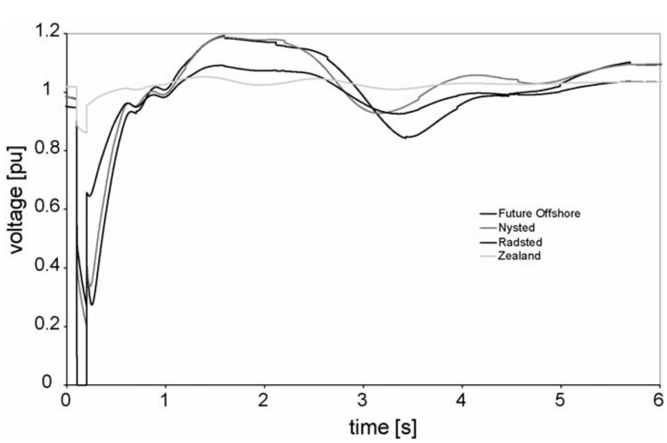

Fig. 10. Case 2.1: voltage at different locations in the system.

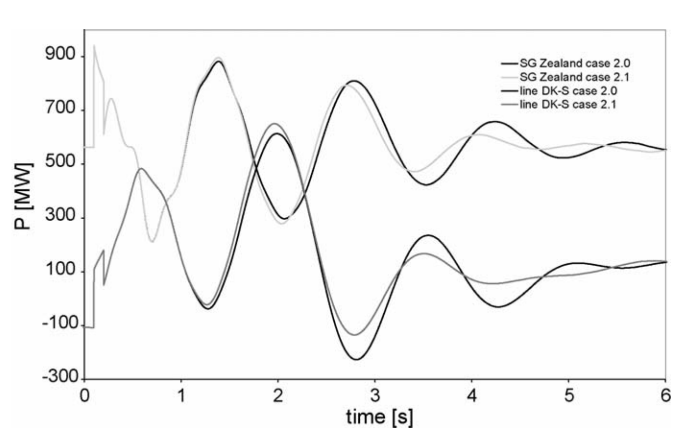

Fig. 12. Active power in line DK-S and SG Zealand in the cases 2.0 and 2.1.

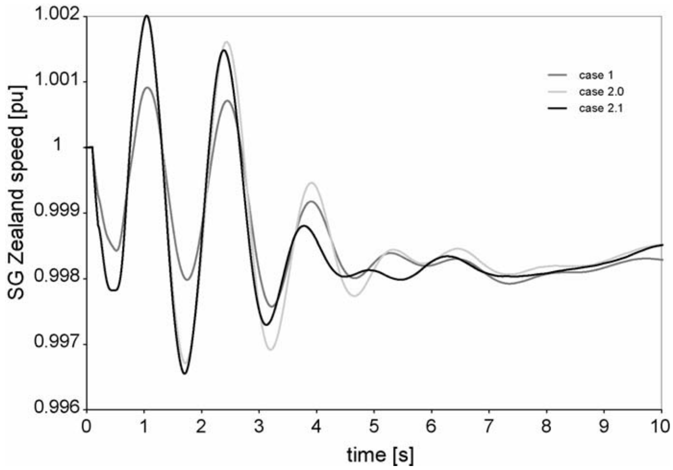

Fig. 13. Comparison of the rotor speed of SG Zealand for the cases 1, 2.0 and 2.1.

in Figs. 4 and 8 this is not caused by the stronger connection between the fault location and Zealand. The voltage at Zealand dips during the fault almost equally low in both cases. Instead it is the power that the wind farms have to inject into the Nordic system to dampen their drive train oscillations. While in case 1 most of the installed wind power disconnects during the fault, hence does not contribute to the excitation of oscillations, in case 2.0 there are two wind farms that stay connected. The turbines of both wind farms exhibit only relatively lightly damped drive train oscillations, which cause corresponding power oscillations that excite rotor speed oscillations in SG Zealand.

The comparison of cases 2.0 and 2.1 in Fig. 13 shows how the future offshore wind farm can contribute to the damping of such oscillations when it employs its pitch angle grid frequency stabilizer [3].

As described above, the rotor speed oscillations in SG Zealand cause power fluctuations that propagate through the entire Nordic power system. Hence the other synchronous generators in the system experience rotor speed oscillations too, as they have to absorb the power fluctuations. Fig. 14 shows the speed of three arbitrarily chosen synchronous generators, which are in different, relatively remote locations in the system. Also here the three cases are compared with each other. The same observations that have been made with the speed of SG Zealand can be made here too. The most important observation is that

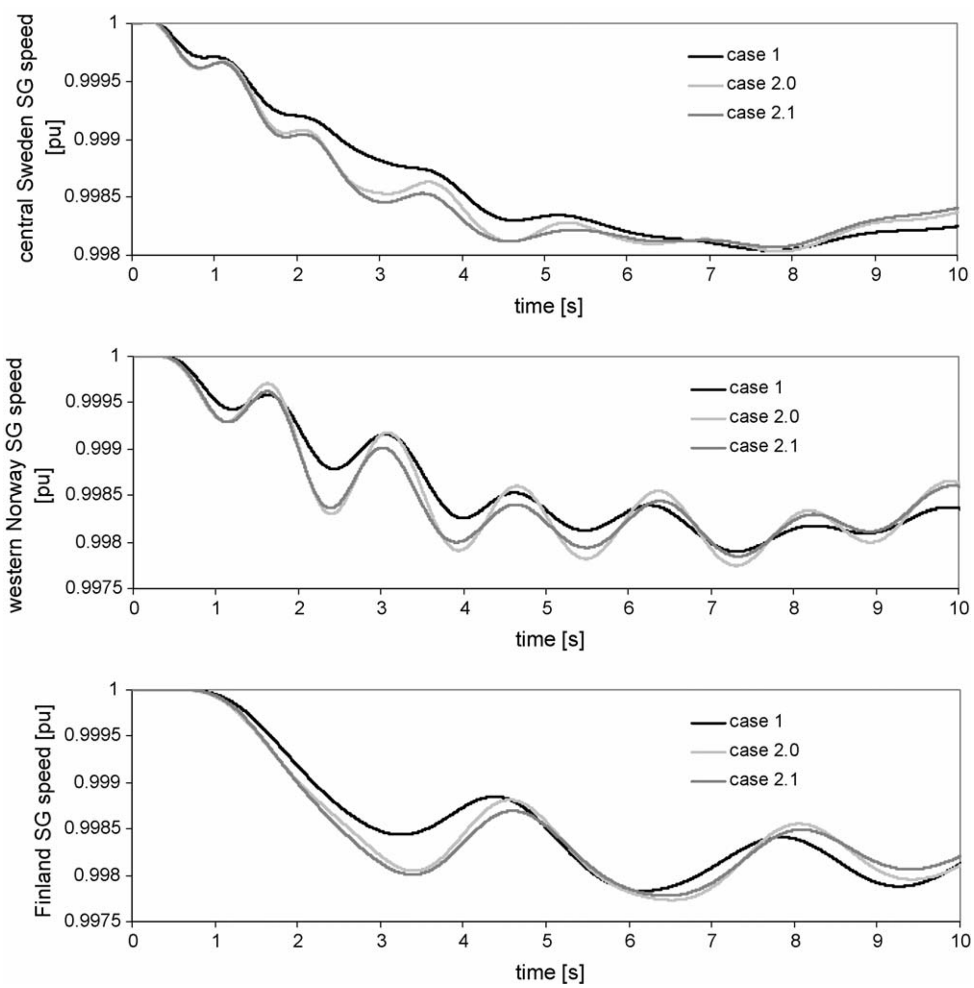

Fig. 14. Rotor speed oscillations in the synchronous generators (i) central Sweden, (ii) western Norway and (iii) Finland for the cases 1, 2.0 and 2.1.

higher levels of wind power penetration lead to increased excitations of the power system. Also here it can be observed that the future offshore wind farm with its grid frequency stabilizer is capable of impacting positively on the damping of system-wide oscillations.

When quantifying the damping effect of the future offshore wind farm it has to be kept in mind that its rating is only about a tenth of the rating of SG Zealand, and much less compared to the total active power transmitted through the system (43,000 MW).

5. Conclusion

Due to the location of wind resources wind farms are mostly connected to weak parts of the power system. A transient fault happening in such a weak part (comparably low short circuit power) has only a local impact on the system voltage. The local voltage depression can hardly be noticed in other parts of the transmission system. It does however upset the wind turbines in the vicinity and cause their flexible drive trains to exhibit torsional oscillations. These oscillations manifest themselves in power fluctuation. Such power fluctuations are not only local effects but propagate through the system causing synchronous generators to exhibit speed oscillations, which are effectively frequency oscillations. It is shown that these frequency oscillations are visible in the entire system.

It has been proven that a high level of wind power penetration with fixed speed turbines, leads to stronger power fluctuations in the system, and hence to stronger grid frequency oscillations.

Recently issued grid connection requirements demand wind turbines to ride through transient faults. This requirement has been made to avoid that substantial amount of generation is lost in the wake of otherwise harmless transient faults. The simulations show that the goal of keeping turbines operational can be achieved. However, the simulations presented here show also, that these requirements have an immediate disadvantage. Demanding fixed speed turbines to only ride through transient faults leads to system-wide oscillations. It has been proven though, that wind turbines, when equipped with sufficient control mechanisms can actively contribute to the damping of these oscillations.

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