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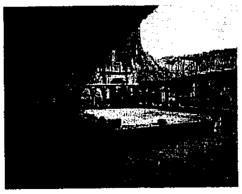

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ELECTROMECHANICAL INTERACTION AND STABILITY OF POWER GRIDS WITH WINDMILLS

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ABSTRACT

The phenomenon of the electromechanical interaction between the grid-connected windmills and the electrical power system is demonstrated with use of a simplified, but realistic enough network representation. It is found that the electromechanical interaction is excited in the soft windmill shafts (the torsional swings) and can be seen as voltages oscillations through a large part of the power system at transient failure events even of short duration. Excitation of the torsional swings in the soft windmill shafts is caused by the operational conditions of the power system caused by all kinds of disturbances, for instance by wind gusts and by failure events in the ac- system. It is explained that at deficit of reactive power the torsional swings in the windmill shafts contribute to worsening of dynamic stability of the power system as the whole.

KEYWORDS: Electrical power systems, Grid-connected windmills, Dynamic stability, Windmill mechanical system, Reactive compensation, Power reserves.

1. INTRODUCTION

Denmark has currently about 1500 MW of wind power corresponding to more than 5000 windmills in operation which are land-based and off-shore as well and implementation of a large amount of grid-connected wind power as a number of large-scale, offshore wind farms has been announced in Denmark. There is planned to install around 4100 MW of total power capacity offshore in the years to come. This will correspond to about 40 per cent of Danish electricity consumption (the peak power consumption at a winter day). In accordance with these plans, a total of 450 MW of power capacity offshore and about 200 MW of power capacity land-based will feed into the East Danish power grid, the Elkraft area, in the period by the year 2008. These counts have to be seen in relation to the maximum and minimum loads in the same area over the year of 2700 MW and 750 MW, respectively. The power production from conventional power plants will be reduced during the same period.

Such a change in the power production technology sets a number of questions as:

1. How to maintain dynamic stability of the electrical power system with large amount of windmills at failure events in the power system;
2. Influence of the interaction between grid-connected windmills and the power system [1] on the power system stability at failure events;
3. Whether the soft shafts of windmills contribute to worsening of dynamic stability and explanation of such facts;
4. Necessity and amount of the power reserves being in conventional power plants in case of loss of the power supply from windmills (due to several reasons).

When the electromechanical interaction between the grid-connected windmills and the electrical power system has been firstly predicted [1], the reason of such interaction has been connected with the windmill shafts that are found to be significantly softer than it is in case of conventional power plants. The mechanism of the electromechanical interaction has not been explained sufficiently enough. The transient behaviour in the windmill mechanical system is, however, important because, firstly, windmills are equipped with induction generators as the technology is today and, secondly, there is a strong coupling between electrical and mechanical properties in such induction generators.

This paper deals with explanation of the mechanism of the electromechanical interaction between the windmills and the electrical power system so that it is started with description of how the shaft torsional oscillations contribute to the windmill generator overspeeding at failure events and ended with the voltage oscillations through the power system at post-fault operation. The mechanism of the electromechanical interaction is illustrated with use of a simplified, but realistic enough network representation of the power system of the Danish island Lolland where incorporation of wind power develops extremely fast.

2. NETWORK MODEL

The network representation in the stability study is a simplified model of the 10/50/132 kV electrical power system of the Danish island Lolland, status 1998, just south to Zealand, see Fig. 1. The model is implemented in the simulation tool PSS/E.

The installed power capacity of onshore wind farms has been around 80 MW that is a significant part of the electricity consumption in the power system of Lolland. The windmills being on the island have been grouped into two larger wind farms, namely Munkeby (bus 10166) and Rødbyhavn (bus 10170). The wind farms feed into 10 kV radials in the distribution system, and the rated power capacity of each wind farm is 40 MW. These two wind farms are compensated by capacitor batteries at no-load. When making dynamic simulations, there is considered the power supply of 75 % of the rated value which corresponds to typical wind conditions of the island (the mean wind speed of 10 m/s).

The island Lolland is connected to the 132 kV transmission network of Zealand which is lumped to the synchronous generator in bus 324. The generator is equipped with a governor, an excitation control system and a PSS. The short circuit capacity view into the 132 kV network is low, because the main load and production centres are in the north of Zealand.

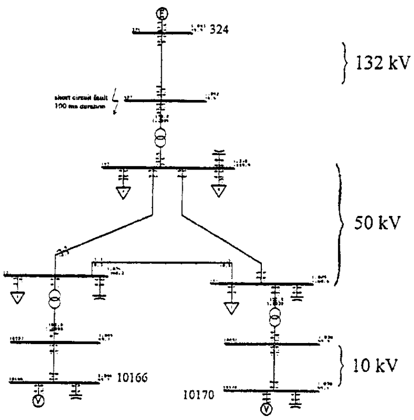


Fig.1. Model of power system with two wind farms.

Further, there is a long 50 kV ring distribution system which connects the 10 kV stations with the 132 kV network, and with local consumers at 50 kV net. The windmill generators feed, then, into a relatively weak power system [2].

The disturbance being applied to the power system is a 3-phases to ground, transient, short circuit fault in the 132 kV network, i.e. electrically far from the wind farms. The failure event is of 100 ms of duration.

3. DYNAMIC WINDMILL MODEL

It has been shown [1] that in dynamic stability investigations of electrical power systems with grid-connected windmills, it is necessary to represent a windmill as a complex electromechanical system with a correct model of the windmill induction generator and a detailed enough model of the mechanical system.

The dynamic windmill model, which has been used in this study, consists of [1]:

1. an induction generator model with stator transient representation,
2. a shaft model where the mill and the generator rotor are connected through a soft windmill shaft, i.e. a windmill is a two-speed system,
3. a model of the rotating mill with aerodynamic effects.

Representation of the soft windmill shaft and the two-speed system is necessary for description of the strong interaction between the grid-connected windmills and the electrical power grid with conventional power plants [1], which may influence on dynamic stability of the power system. This interaction is caused by transient behaviour in the windmill mechanical system that can be excited by disturbances in the electrical power grid.

4. TRANSIENT BEHAVIOUR IN SHAFT

A linearised model of the windmill shaft is expressed by the equation system

$$\begin{cases} 2 \cdot H_M \cdot \dfrac{d\omega_M}{dt} = T_M - K \cdot \theta, & \text{(1.a)} \\ 2 \cdot H_E \cdot \dfrac{d\omega_E}{dt} = K \cdot \theta - T_E, & \text{(1.b)} \\ \dfrac{d\theta}{dt} = \omega_M - \omega_E, & \text{(1.c)} \end{cases}$$

where H_M and H_E are the inertia constants of the mill and the generator rotor, respectively, T_M and T_E are the mechanical torque of the mill and the electric torque of the generator, respectively, ω_M and ω_E denote the mill speed and the generator rotor speed, respectively, K is the shaft stiffness, and θ is the shaft twist. In Fig.2, the shaft system of a grid-connected windmill is shown.

In steady-state conditions, see Fig. 2.a, the mechanical torque coming from the rotating mill, T_M, is balanced by the electric torque of the induction generator, T_E, and the whole construction is rotating with the speed $\omega_M = \omega_E$ that is constant. The symbols ω_M and ω_E denote the mill speed and the generator speed, respectively. As it is illustrated in Fig. 2.a., the torque couple (T_M, T_E) is acting on the shaft so that there will be an initial value of the twist shaft given by

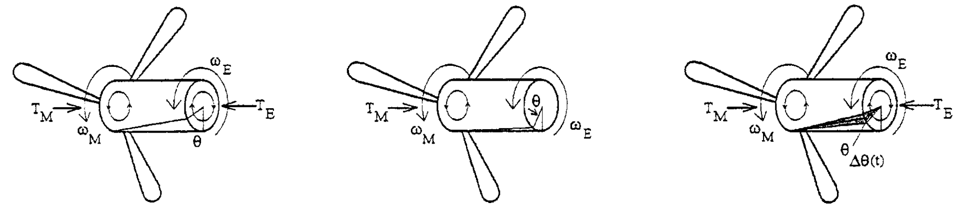
$$\theta_{INIT} = \frac{T_M}{K} \, . \tag{2.a}$$

Since the windmill shaft is relatively soft [1], the value of the initial shaft twist cannot be neglected and there will be an accumulated, non-negligible amount of the potential energy in the shaft twist. The initial values of the shaft twist in the two wind farms are marked "a" in Fig. 3.

The accumulated potential energy in the twisted shaft will be, then,

$$W_{POT,INIT} = ½ \cdot K \cdot \theta_{INIT}^2 = ½ \cdot K \cdot \left(\frac{T_M}{K} \right)^2 = ½ \cdot \frac{T_M^2}{K} \, . \tag{2.b}$$

When a short transient fault occurs, the voltage throughout the power system falls, including the voltage at the wind farm terminals, V_S. The electric torque of an induction generator, which is $T_E \propto V_S^2$, then, is significantly reduced. This leads to that the shaft, being still driven by the mechanical torque, T_M, starts relaxation, i.e. the shaft twist, $\theta(t)$, is decreasing during the failure event. This behaviour is illustrated in Fig. 2.b and marked "b" in the twist dynamic behaviour in Fig. 3.



(a) (b) (c)

Fig. 2. Windmill shaft model.

In such an operational situation, there will be two basic contributions to the generator acceleration:

1. The speed of the whole windmill mechanical construction increases as the result of the torque unbalance, where $T_M > T_E$.
2. The shaft relaxation where the shaft twist decreases and contributes to the generator acceleration, as shown in Fig. 2.b, during a failure event of a relatively short duration.

The movement of the shaft during a failure event is connected with disengagement of the potential energy accumulated in the soft windmill shaft, W_{INIT}. From Eq. (2) one may conclude that the lower the shaft stiffness is, the larger initial twist will be and the larger amount of the accumulated potential energy is in the twist.

As mentioned above, the generator rotor acceleration during a short circuit fault is contributed from the torque unbalance and from the shaft energy disengagement. The first mentioned contribution is well known from dynamic stability investigations of conventional power plants and is evident from superposition of Eq. (1.a) and Eq. (1.b) $2H_M \cdot \frac{d\omega_M}{dt} + 2H_E \frac{d\omega_E}{dt} = T_M - T_E$. This is re-written to $\frac{\sum_i H_i \cdot \frac{d\omega_i}{dt}}{\sum_i H_i} = \frac{d\omega_{LUMPED}}{dt} = \frac{T_M - T_E}{2 \cdot \sum_i H_i}$, as it is known for lumped mass systems, and in this case $i = M, E$.

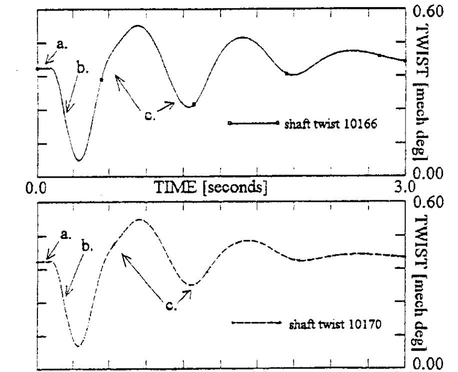


Fig. 3. Dynamic behaviour of windmill shaft twist of the two wind farms at a failure event, marking a to c in relation to Fig. 2.

Let us focus instead on the contribution to the generator rotor speed caused by the windmill soft shaft relaxation during a short circuit fault. The energy conservation is applied. Before the failure event the total energy of the rotating system has been

$$W_{KIN,INIT} + W_{POT,INIT} = H_M \cdot \omega_{M,INIT}^2 + H_E \cdot \omega_{E,INIT}^2 + ½ \cdot K \cdot \theta_{INIT}^2 . \tag{3.a}$$

During and after the failure event it is assumed:

1. An almost complete relaxation of the shaft during the fault so that the shaft twist is small, and
2. The mill is much heavier than the generator rotor [1] and the failure time is short enough so that the mill speed does not reach to change during the failure time.

At these assumptions, the total energy of the rotating system just after the failure event will be

$$W_{KIN} + W_{POT} = H_M \cdot \omega_{M,INIT}^2 + H_E \cdot (\omega_{E,INIT} + \Delta\omega_E)^2 + 0 . \tag{3.b}$$

Combining Eq. (3.a) and (3.b) it is reached

$$\Delta\omega_E \propto \frac{T_M^2}{H_E \cdot K} , \tag{4}$$

which expresses the contribution of the relaxation of the pre-twisted windmill shaft to the generator speed change during a short circuit fault.

As can be seen from Eq. (4), the softer the shaft is, the larger contribution to the generator speed increasing will be from the windmill shaft during the failure event. In other words, the soft windmill shaft can contribute to an extra acceleration of the generator during a short circuit fault and excitation of the shaft torsional swings – the behaviour has not been seen in case of conventional plant generators where the shafts are relatively stiff (lumped mass representation). The lumped mass systems do not have the contribution to the speed given by Eq. (4).

When the short circuit fault is cleared, the voltage at the wind farm terminals recovers and the electric torque, T_E, starts re-establishing and acting on the windmill shaft. This results in increase of the shaft twist, an overshot and, then, oscillation of the shaft twist around its steady-state position. The movement of the shaft system as the whole will consist of the rotation driven by the mill and of the oscillation due to the torsional swing in the shaft. This behaviour is illustrated in Fig. 2.c and the shaft twist is marked "c" in Fig. 3. The frequency of such oscillations is around or below [1] the torsional mode of the shaft and typically is in the range of 1 Hz.

The oscillating behaviour of the shaft twist during and after the failure event will be seen in the corresponding oscillations of both the generator speed and the mill speed, as shown in Fig. 4. As can be seen from the curves in Fig. 4, the mill and the generator are oscillating against each other and the area between these curves gives the shaft twist oscillation.

For comparison, the generator speed behaviours in case of windmills and a lumped mass representation, where the inertias of the mill and the generator rotor is lumped together, are given in Fig. 5.

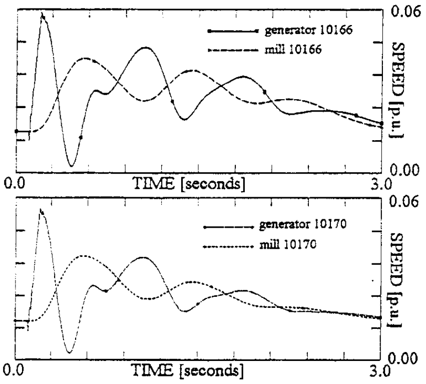


Fig. 4. Dynamic behaviour of generator speed and mill speed of the two wind farms at a failure event.

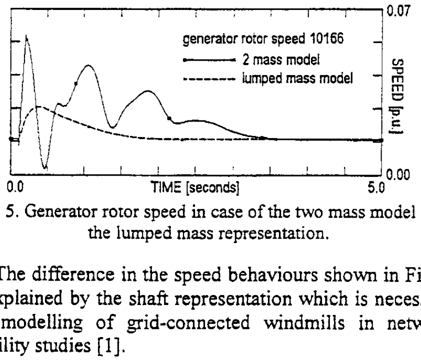


Fig. 5. Generator rotor speed in case of the two mass model and the lumped mass representation.

The difference in the speed behaviours shown in Fig. 5 is explained by the shaft representation which is necessary for modelling of grid-connected windmills in network stability studies [1].

A common reason for neglecting of the windmill mechanics in the stability investigations of electrical power systems has been the point of view that the mechanical swings may contribute a little to the electrical behaviours of the windmills and that the swings will be about the mean value obtained from the lumped mass representation.

As can be seen from Fig. 5, the mean value of the windmill generator rotor speed is above the value predicted by the lumped mass model. Only in case of small disturbances applied to windmills the oscillating behaviour will be about the values given by the lumped mass representation.

However, the failure event – a short circuit fault – is not any small disturbance and, hence, the argumentation for neglecting of the windmill mechanical system is not necessarily correct any longer.

5. INTERACTION

As the technology is today, the windmills are equipped with induction generators. In the following, it is focused on the dynamic behaviour of the windmill induction generators after the short circuit fault.

Induction generators are characterised by the strong coupling between the generator speed and the electric power fed into the grid by the generators. This strong coupling between the mechanical (speed) and the electrical (power) properties implies that the oscillating behaviour of the generator speed, see Fig. 4, will be seen in a corresponding, fluctuating behaviour of the active power supplied by the wind farms, shown in Fig.6. The frequency of the power fluctuations from the wind farms is identical to the eigenfrequency of the shaft torsional mode, which is commonly around 1 Hz. The fluctuations of the active power from the wind farms have been excited by the torsional oscillations in the soft windmill shafts.

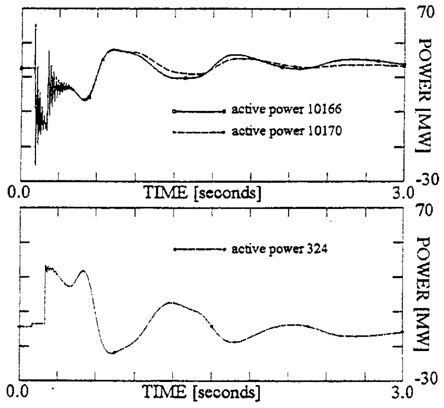


Fig. 6. Power fluctuations in the power system with 2 wind farms.

The eigenfrequency of the torsional mode of typical modern windmills is within the range of typical eigenfrequencies of electrical power systems and synchronous generators of conventional power plants, which are around or below 1 Hz. Thus, there may be a risk of excitation of corresponding fluctuations of the active electric power supplied from the synchronous generators of the conventional power plants, since the resonance frequencies of the windmills and the power plant generators are close to each other. The dynamic behaviour of the active power from the power equivalent of Zealand is shown in Fig. 6. As can be seen, the power oscillations from the windmills are absorbed by the network equivalent.

It has to be noticed that this oscillating behaviour may often look like the phenomenon of power oscillation that is analogous to the power oscillation between two groups of synchronous generators with lumped inertias oscillating against each other. The mechanism of such oscillation is given by the synchronising torque, K_S, of the synchronous generators

$$\Delta T_E = K_S \cdot \Delta\delta + K_D \cdot \Delta\omega \ , \tag{5}$$

where K_D is the damping coefficient, $\Delta\delta$ denotes the disturbed rotor angle difference between the two groups of the synchronous generators, and $\Delta\omega$ is the disturbed speed deviation.

In case of power fluctuations in the power systems with grid-connected windmills, the situation is different from the above-mentioned. The fluctuations are excited within the mechanical system of the windmills so that

$$\Delta T_E = K \cdot \frac{H_M + H_E}{H_E} \cdot \Delta\theta \ , \tag{6}$$

where H_M and H_E are explained above and $\Delta\theta$ is in this context the windmill shaft twist oscillation converted to electrical radians.

As can be seen, Eq. (5) and (6) look similarly, but they describe two quite different physical phenomena. Eq. (5) relates to the power system oscillations between synchronous machines with lumped inertias, whereas Eq. (6) describes the electromechanical oscillation within the windmill construction.

The voltage in the power system of Lolland is shown in Fig. 7. The power fluctuations being spread through the whole power system cause the voltage fluctuations in the entire system

$$\Delta V = -R \cdot \Delta P + X \cdot \Delta Q \ , \tag{7}$$

where ΔV is the disturbed value of the voltage of the bus and ΔP and ΔQ are the disturbed values of the active power and the reactive power, respectively, transported to the bus, $R+jX$ is the tie impedance to the bus.

Eq. (7) gives the connection between the active power fluctuations and the voltage fluctuations and explains the feedback effect so that the fluctuations of the active power and the voltage fluctuations can mutually enforce each other. The closer the bus is to the wind farm terminals, the larger the voltage fluctuations may be. In this case, the largest voltage fluctuations are in the 10 kV –net, where the wind farms feed into the grid. Due to the connection given by Eq. (7), the voltage fluctuations can be, however, seen through the whole power system. In this case, the voltage fluctuations are still developed even in the 50 kV – network, despite the wind farms feed into 10 kV –net. The frequency of the voltage fluctuations is the eigenfrequency of the windmill shaft torsional mode, i.e. around 1 Hz. Such voltage disturbances may be visible at the private consumers as short-time lamp-bulbs.

In Fig. 8, the dynamic behaviours of the terminal voltage of the wind farm 10166 are shown when computed with use of the windmill model and with the lumped mass representation. As can be expected, there are no oscillations in case of the lumped mass representation.

Another important observation is that the mean value of the voltage obtained with use of the windmill model (in Fig. 8 it is denoted as 2 mass model) is below the value predicted by the lumped mass model. The recovery time is also longer in case when the windmill model is used compared with the result of the lumped mass model. A similar discussion has been made above for the generator rotor speed.

As can be seen, the presence of the soft shaft system in the windmill mechanical construction results in worsening of the dynamic stability of the whole electrical power system, not just oscillations. The reason for worsening of the dynamic stability is found in the extra contribution to the generator rotor speed caused by the shaft relaxation during the failure event.

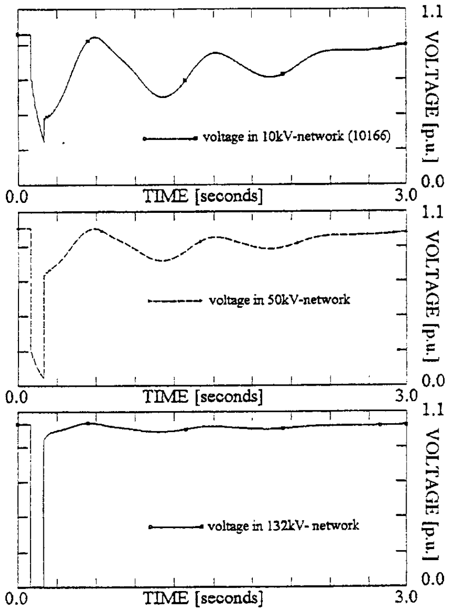


Fig. 7. Voltage oscillations through the 10/50/132 kV power system with the two wind farms.

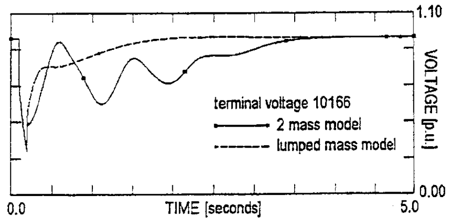


Fig. 8. Terminal voltage of the wind farm 10166 computed with the 2 mass model versus the lumped mass model.

This makes it necessary to have an adequate representation of the mechanical system in stability investigations of electrical power systems with grid-connected windmills.

6. VOLTAGE RECOVERY VERSUS COLLAPSE

The windmills are equipped with induction generators that have not any voltage control. The outcome of the failure event – in the above-introduced case it has been voltage recovery, - depends, no-doubt, on the control ability of the conventional power plants or other control equipment, for instance SVC.

The equivalent of the electrical power system of Zealand has been given by a synchronous generator equipped with a governor, an excitation control system, and a PSS. The equivalent is in bus 324. This control equipment is used for keeping the power system of the island Lolland with grid-connected wind farms at a stable operation after the short circuit fault in the 132 kV –net has been cleared.

Let us see which kind of the control ability in the conventional power plants may be the most significant for the voltage stability at failure events in the power system with grid-connected windmills. Each one control ability is given by a corresponding control equipment. For verifying which control equipment of the synchronous generator in bus 324 is the most significant for the voltage recovery after the short circuit fault, the equipment were switched off one by one when simulating the dynamic behaviour of the power system at the short circuit fault.

In case of induction generators, being grid-connected and driven by a lumped mechanical system, it would be clear that dynamic reactive compensation was the most significant part of the control ability. As it is shown previously, the soft shafts of wind farms contribute to worsening of the dynamic stability by the extra acceleration of the windmill induction generators and providing electromechanical oscillations. In case of windmill induction generators, where the electrical properties are related to the generator speed, such an extra overspeeding of the generators during failure events will result in larger demand of the reactive power of the windmill induction generators when the network is at post-fault operation. It can be expected that the dynamic reactive compensation is the most important.

Switching off the governor or the PSS has not leaded to collapse. Only some small deviations from the voltage behaviour have been observed when compared with the corresponding behaviour with the equipment on.

Switching off the excitation control system leads to voltage instability, as shown in Fig. 9. As can be seen, the mean values of the voltage through the whole power system show the decreasing tendency following by intensive voltage oscillations and by the power fluctuations. The voltage collapse is in progress.

The voltage collapse will be, however, of another behaviour than simply decreasing voltage as it may be viewed in the power systems with induction generators with lumped mass mechanical systems [3]. Instead of simply decreasing behaviour the voltage will show an oscillating behaviour about a decreasing mean value.

As can be seen, the voltage collapse will occur when the excitation control system is switched off. This implies that there is deficit of dynamic reactive compensation in the power system that is similarly with case of if windmills were with lumped mass mechanical systems.In case of the windmill soft shafts there will be necessary to apply a larger amount of reactive compensation than in case of lumped mass systems (equipped with the same induction generators) due to an extra overspeeding caused by relaxation of the windmill soft shafts during the failure events. This conclusion can be intended from the voltage behaviours shown in Fig. 8 where the mean value of the wind farm terminal voltage is below the value predicted by the lumped mass model (in case given in Fig. 8 the excitation control system has When the excitation control system is off, let us compare the voltage behaviours obtained with use of the windmill model (two mass representation of the windmill mechanical system) versus with the lumped mass model. The simulation results are shown in Fig. 10. been on).

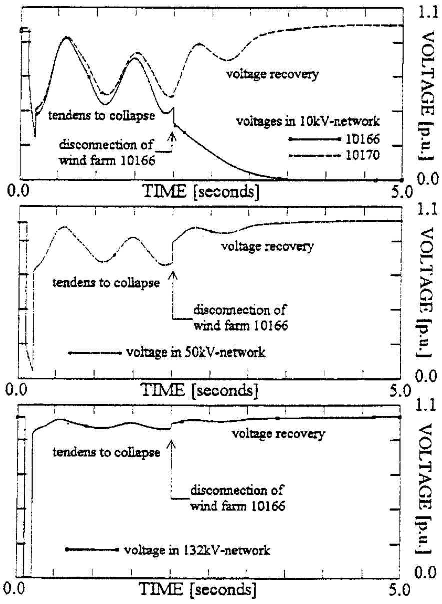


Fig. 9. Voltage behaviour in the power system at the short circuit fault in case of the excitation control system of the synchronous generator in bus 324 is switched off.

The lumped mass model has predicted voltage recovery (a slower recovery than in case with the excitation control system been on), when the actual outcome will be voltage instability (tendency to voltage collapse). Thus, the soft windmill shafts are a significant, non-negligible part of the windmill representation when making dynamic stability investigations of electrical power systems with grid-connected windmills. The contribution from the soft windmill shaft relaxation to the windmill generator acceleration during failure events cannot be neglected.

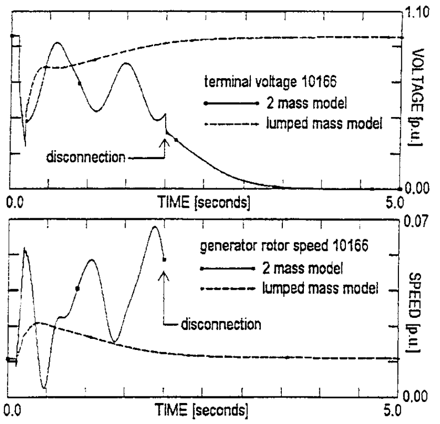


Fig. 10. Comparison between results of the lumped mass model and the two mass model of windmills.

The mean reason of voltage instability in the shown operational situation is deficit of the dynamic reactive compensation in the power system so that the amount of the reactive power (of necessary amount at correct time) being supplied to the windmill induction generators. The fact that windmills are equipped with soft shafts [1] results in more demand of dynamic reactive compensation.

7. ACTIVE POWER RESERVES

At some abnormal operational conditions, the windmills will be disconnected from the electrical power system and stopped for self-protection. Disconnection occurs when the windmill generators are overspeeding too much or when the terminal voltage has been too low etc. From this point of view there is no sense to talk about voltage collapse caused by the windmills because the windmills will be disconnected from the power system anyway.

Somewhere at 2 s after the voltage collapse has been initialised by the failure event, the disconnection conditions for the wind farm 10166 will be fulfilled, and the farm is disconnected from the power grid by its protection system. The voltage throughout the electrical power system will, then, recover where the recovery process is followed by the voltage oscillations through the whole system.

It has to be noticed that there are used the power reserves of conventional power plants, when the wind farm at bus 10166 has been disconnected. This situation is clearly illustrated in Fig. 11 where one can see that the active electric power deficit (due to disconnection and, then, lose of the active electric power of the wind farm in bus 10166) is covered by the equivalent of the power system of Zealand.

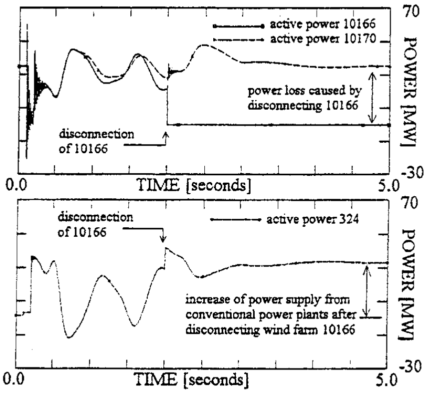


Fig. 11. Behaviour of active power in the power system at the short circuit fault in case of the excitation control system of the synchronous generator in bus 324 is switched off.

The conclusion of necessity of the active power reserves is clear, but often overseen since amount of the grid-connected wind power has not been large enough. When the amount of wind power is fast increasing, the question about the active power reserves will become more actual. Such aspects need, however, more detailed investigations.

8. CONCLUSIONS

It has been demonstrated that the windmill mechanical system representation is necessary in dynamic stability investigations of the power systems with grid-connected windmills. It has been demonstrated that the transient behaviour in the windmill shafts contributes to the generator rotor speed increase during a failure event, and the softer the windmill shafts are, the larger this contribution will be. It has been found that the soft windmill shafts contribute to worsening of dynamic stability by the way that the larger overspeeding leads to the larger reactive power demands in the windmill induction generators at failure events.

As the technology is today, windmills are characterised by soft shafts and there is a risk of the strong interaction between the windmills and the electrical power system. The interaction between grid-connected windmills and electrical power systems is expressed by power fluctuations and voltage oscillations through the whole power system. The strength of the interaction depends on the amount of the power capacity in the wind farms and the power system. It is shown that the nature of the power fluctuations and the voltage oscillations is the electromechanical oscillation in the windmill mechanical construction, namely the torsional swing in the soft windmill shafts. It has shown how the torsional swing in the soft windmill shafts develops to the voltage oscillations in the power systems.

Excitation of the electromechanical oscillations has been connected with deficit of reactive power and of dynamic reactive compensation in the electrical power system at failure events. This result is analogous to the case if windmills were just induction generators with lumped mechanical systems, i.e. with stiffer shafts. One may, however, expect that the windmills being with soft shafts need a larger amount of reactive power than in case of stiffer windmill shafts, because the soft windmill shafts contribute to worsening of the dynamic stability of the windmills and the electrical power system as the whole.

It has been noticed that in case of disconnection of wind farms at failure events, the active electric power deficit has to be compensated, presumably, by the conventional power plants. This shows that keeping of the active power reserves in the conventional power plants in operation is an important part of dynamic stability of the power system.

REFERENCES

[1] V.Akhmatov, H.Knudsen, A. H. Nielsen, Advanced simulation of windmills in electric power supply, *Int. J. of Electrical Power and Energy Systems*, vol.22, 2000, pp.421-434.

[2] V. Akhmatov, H. Knudsen, Dynamic modelling of windmills, In: *Proceedings of the International Conference on Power System Transients IPST'99*, 20-24 June, Budapest, Hungary, 1999, pp.289-295.

[3] M. Bruntt, J. Havsager, H. Knudsen, Incorporation of wind power in the East Danish power system, *Paper BPT99-202-50 presented at Int. Conf. IEEE Pow Tech'99*, Budapest, Hungary, 29.Aug –02. Sept., 1999.