Dynamic Modelling of Windmills

Vladislav Akhmatov
Technical University of Denmark,
Lyngby, Denmark

Hans Knudsen
NESA Transmission Planning,
Denmark.

Abstract – **An empirical, dynamic model of windmills is set up based on analysis of measured Fourier–spectra of the active electric power from a wind farm. The model is based on the assumption that eigenswings of the mechanical construction of the windmills excited by the phenomenon of vortex tower interaction will be transferred through the shaft to the electric generator and result in disturbances of the active electric power supplied by the windmills. The results of the model are found to be in agreement with measurements in the frequency range of the model that is from 0.1 to 10 Hz.**

Keywords: Windmill, Vortex Tower Interaction, Mechanical Eigenswings, Dynamic Model, Modularity, Flicker Studying, PSS/E.

I. INTRODUCTION

Denmark has currently about 1100 MW of wind power corresponding to some 4,400 windmills in operation. Off-shore wind energy is a promising application of wind power in Denmark, and, therefore, major plans for installation of 4100 MW of wind energy off-shore in the years after the year 2000 have been announced. That will correspond to about 40 per cent of Danish electricity consumption (the peak power consumption at a winter day).

Questions about reactive compensation of windmills with induction generators, flickers, etc. are still topical. Hence, dynamic models are necessary, when planning the extension of the Danish utility grid with a number of large, off-shore wind farms. The existing, grid-connected wind farms, off-shore as well as land based, are applied to collecting the information about interaction between windmills and the utility grid. This makes it possible to predict the behaviour of the planned, off-shore wind farms with respect to reliable operation of the Danish utility grid, when those wind farms will be installed and connected to the grid.

II. PRACTICAL ASSUMPTIONS

In the following an empirical dynamic model of windmills representing disturbances of the mechanical power of windmills is introduced. The frequency range of the dynamic model is from 0.1 Hz up to 10 Hz. The dynamic model of windmills connects the disturbances of the mechanical power being in the frequency range of the dynamic model with the eigenswings in the mechanical construction of the windmill.

The dynamic model of windmills is based on the analysis of the Fourier–spectra of the measured active electric power of a windmill farm, where the windmills are with two speed, pole changing induction generators. The dual generator system implies the turbine has two rated speeds and runs at lower rotational speed at lower wind speed, respectively at higher rotational speed at higher wind speed. In this case, the rated rotational speeds are 18 rev./min. and 27 rev./min.

III. MODEL CONSIDERATIONS

The dynamic model of windmills has been developed under the following assumptions:

1. In the Fourier–spectra of the measured active electric power it is possible to separate the *systematic* contributions related to the mechanical swings of the windmill from stochastic contributions coming from the varying wind speed.
2. The mechanical swing contributions in the Fourier–spectra of the measured active electric power relating to each kind of mechanical swing will group into a number of frequency intervals due to their common nature. Therefore, these frequency intervals can be explained by the mechanical swings in the mill.
3. The mechanical swings initialised in the mill will through the shaft be transmitted to the electrical generator, thus, their contributions will be seen as disturbances of the same frequencies and relative magnitudes in the active electric power produced by the windmill.

IV. DETERMINATION OF EIGENSWINGS FROM MEASURED SPECTRA

A fragment of the active electric power of the wind farm measured in the day with lower wind speed and its Fourier–spectrum are shown in Fig. 1.a–b.

The necessary comments are given in the following in accordance with the numbering of the contributions in the Fourier–spectrum shown in Fig. 1.b. In Fig. 2 we illustrate swings that can occur in the mechanical construction of the windmill in accordance with the numbering given in Fig. 1.b.

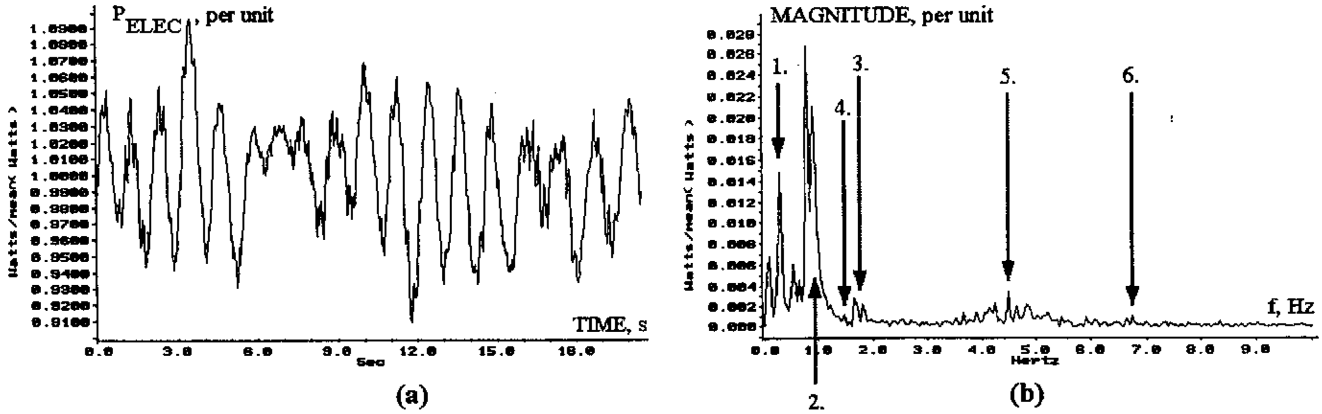


Fig. 1. (a) – Measured electric power, (b) – and its Fourier–spectrum.

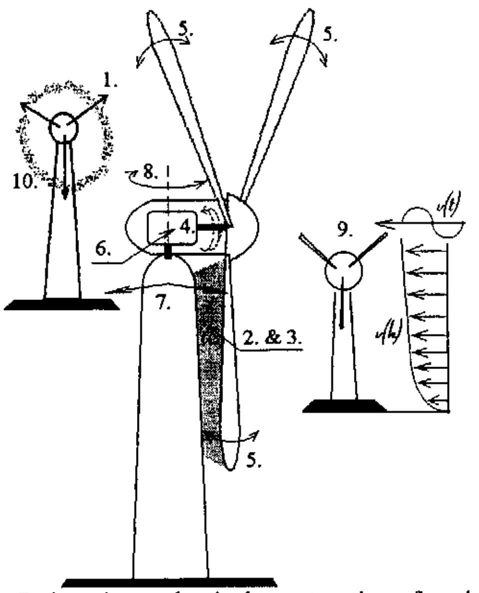


Fig. 2. Swings in mechanical construction of a windmill.

←

Classification of mechanical eigenswings, in accordance with Fig .1.b and Fig. 2:

1. – little asymmetry in the mill;
2. – fundamental of vortex tower interaction;
3. – second harmonic of vortex tower interaction;
4. – torsional swing in the shaft;
5. – swings in the rotor blades;
6. – swings due to delays and mismatches in the gearwheels.

Besides the following swings are physically possible:

7. – swing in the tower;
8. – swing due to yaw mechanism;
9. – swings due to wind speed versus height distribution (may be included into 2. and 3.);
10. – swings due to varying turbulence conditions round the rotor (may be included into 2. and 3.).

1. Little asymmetry in the windmill (Type No.1).

A little asymmetry of the mill, shown schematically in Fig. 2, is seen in the Fourier–spectra of the measured electric power of the windmills as a swing with the same frequency as the rotational speed of the windmills. At lower wind speed it is a swing at the frequency of 0.3 Hz (corresponding to 18 rev./min.), see Fig. 1.b, or a swing at the frequency of 0.45 Hz at higher wind speed (corresponding to 27 rev./min.). In both cases the contribution of the mill asymmetry into the disturbances of the electric power supplied by the windmills to the electric grid will be of a small order for well–designed windmills.

2. Vortex tower interaction (Type No.2 & 3).

Each time when a rotor blade is passing the tower, the phenomenon of *vortex tower interaction* (or tower shadow) occurs, see Fig. 2. The vortex tower interaction creates a short–lived reduction of the mechanical power on the blade and thereby also on the shaft. This reduction means that the vortex tower interaction will consist of both a fundamental and a second harmonic.

In the Fourier–spectra corresponding to the active electric power measured at lower wind speed the vortex tower interaction is always observed as a swing with the first harmonic of 0.9 Hz. At higher wind speed it is always observed with the first harmonic of 1.35 Hz. This corresponds to the first harmonic of the vortex tower interaction being the product of the rotational speed of the windmill and the number of rotor blades (3 blades in this case).

When studying the behaviour of the first harmonic of the vortex tower interaction from the wind farm, we see that the swing corresponding to the first harmonic at the frequency of 0.9 Hz (or of 1.35 Hz depending on the wind speed conditions) is modulated by a lower frequency swing, as shown in Fig. 3.

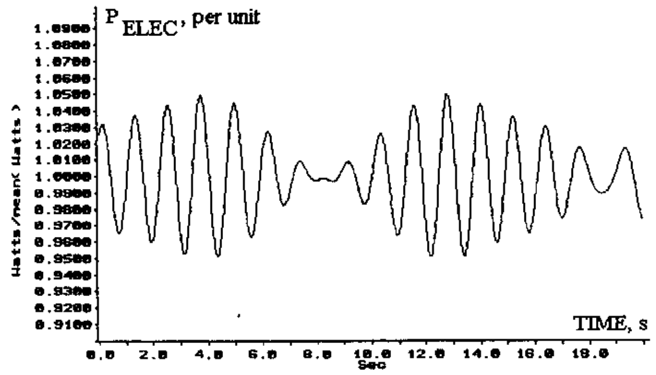


Fig. 3. The first harmonic of vortex tower interaction (measured) extracted from the measured Fourier–spectrum.

The explanation of the modulation is considered to be that, due to the wake effect and the park effect (wind slowing down behind each wind turbine and wind shadowing between wind turbines), the rotational speeds of the different windmills deviate a little from each other. This little, mutual deviation in the rotational speeds of the wind turbines results in the modulation of the first harmonic as well as the second harmonic of the vortex tower interaction.

The other observation with respect to the vortex tower interaction is that it is the largest contribution to the disturbances of the electric power of the windmills comes exactly from the first harmonic of the vortex tower interaction.

3. Consideration about eigenswings.

When subjected to all kinds of disturbances, including the vortex tower interaction and the little asymmetry of the mill, eigenswings in the mechanical construction of the windmill are excited. The overview of the possible swings in the mechanical construction of the windmill is marked in Fig. 2, but only some of those swings may actually exist.

The frequencies 1.67 Hz, 4.5 Hz, and 7 Hz are systematically observed in all the Fourier–spectra of the measured electric power supplied by the wind farm, independent from the wind speed value or from the rotational speed of the windmill. Hence, it is concluded that these swings are mechanical eigenswings of some part of the windmill.

4. Torsional swing in the shaft (Type No. 4).

It is known from other measurements that the eigenfrequency of the torsional oscillation between mill and generator is 1.67 Hz. The little contribution, which is at 1.67 Hz independently of the rotational speed of the mill, is therefore identified as the torsional swing.

5. Consideration about swings in the rotor blades and delays in the gearbox (Type No. 5 & 6).

Those are the swing at the natural frequency of 4.5 Hz considered to be the swings in rotor blades, and the swing at the natural frequency of 7 Hz that is considered to be the swing due to small delays and mismatches in the gearwheels.

The total relative magnitude of disturbances caused by the mechanical swings is about 10 % of the RMS–value of the electric power of the windmill; the largest contribution comes from the first harmonic of the vortex tower interaction and is about 5 %.

V. MODULAR MODEL OF WINDMILL WITH MECHANICAL EIGENSWINGS

In Fig. 4 we introduce the simple modular description of the dynamic model of windmills. The input of the model is the mean wind speed, v. The mean mechanical power, P_{RMS}, is adjusted according to the mean wind speed, v, as

$$P_{RMS} = P_{WIND} \cdot C_P(\lambda) \quad , \tag{1}$$

where the power available from the wind, P_{WIND}, on the rotor swept area, πR^2, is

$$P_{WIND} = \frac{1}{2} \rho_{AIR} \cdot \pi R^2 \cdot v^3 \quad , \tag{2}$$

and the air density, ρ_{AIR}, is 1.225 kg/m^3. The power coefficient, C_P, is a function of the tip speed ratio, λ, and

$$\lambda = \frac{\omega_{MILL} \cdot R}{v} \quad . \tag{3}$$

The blade pitch angle, α, has also an influence on the C_P–λ–curve, however, this is not further dealt with here.

The model block relating to the mechanical power versus wind speed curve is given by Eq.1.

When the dynamic behaviour of the windmill with time varying values of the mill and generator rotor speed have to be examined, the feedback by the mill speed between the mechanical mill and the generator is described by the following relationship

$$\omega_{MILL} = \frac{\omega_{ROTOR}}{N} \quad , \tag{4}$$

where N is the gear box ratio, respectively, and ω_{ROTOR} is the generator rotor speed.

However, this speed feedback may be neglected in normal operation, because at normal operation the rotational speed is almost constant.

The total mechanical power of the windmill, P_{MECH}, consists of its mean value, P_{RMS}, and the contributions coming from the mechanical eigenswings We introduce the following mathematical expression for the mechanical power, P_{MECH}

$$P_{MECH}(t) = P_{RMS} \cdot \left(1 + \sum_{n=1}^{6} A_n \cdot g_n(t) \cdot h_n(t)\right), \qquad (5)$$

where the contributions from the swings in the windmill mechanical construction are represented as the sum of the products of the mechanical eigenswings, $A_n \cdot g_n(t)$, where

$$g_n(t) = \sin\left(\int_0^t 2\pi f_n(t') \cdot dt'\right), \qquad (6)$$

and the modulation functions, $h_n(t)$.

The indices, n, are in accordance with the marking at the Fourier–spectra applied in Fig.1, and the magnitudes, A_n, the eigenfrequencies of the mechanical eigenswings, f_n, and the modulations, $h_n(t)$, are collected in Tab.1.

Through the shaft and the gearbox the mechanical power, P_{MECH}, is supplied to the generator, where the mechanical energy is transformed to electric energy. The electric power, P_{ELEC}, is, then, supplied to the utility grid.

Note that a shaft model can be set up as in [3] to replace the shaft eigenswing described by '4.'.

VI. IMPLEMENTATION OF WINDMILL MODEL

The developed windmill model is a general model in the sense that it can be implemented in several dynamic simulation tools. We have implemented and tested the windmill model in both ATP and PSS/E using MODELS [4], where identical simulation results have been obtained.

The modularity of the windmill model makes it possible to apply only the components of interest to represent windmills in dynamic simulations, and different models of the generator, depending on the situation and on the difficulty of the description.

In [1] two different models of an induction generator including a shaft model are applied to simulations of windmills connected to the utility grid. Both models are implemented in PSS/E using MODELS.

When simulating dynamic behaviour of wind farms including varying power output and flickers, the disturbances coming from mechanical swings and the feedback by the mill speed may be added to the mean power.

When studying post–fault behaviours in the net with connected windmills, it will be necessary to include a shaft model [1].

VII. WINDMILL MODEL VERIFICATION

In Fig. 5.a–b the simulated electric power and its Fourier–spectrum are shown. The simulation is made for windmills with induction generator, and the mean wind speed is 8 m/s. The simulated results are in agreement with the corresponding measured results in Fig. 1.a-b, in the frequency range of the model developed.

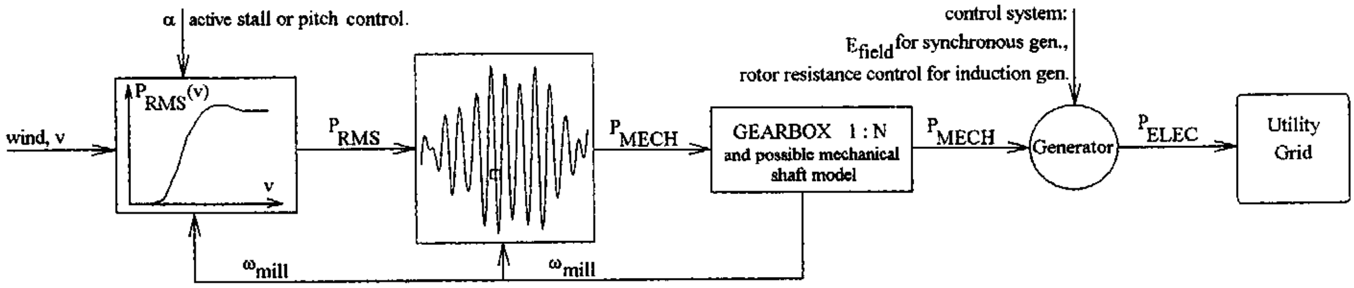
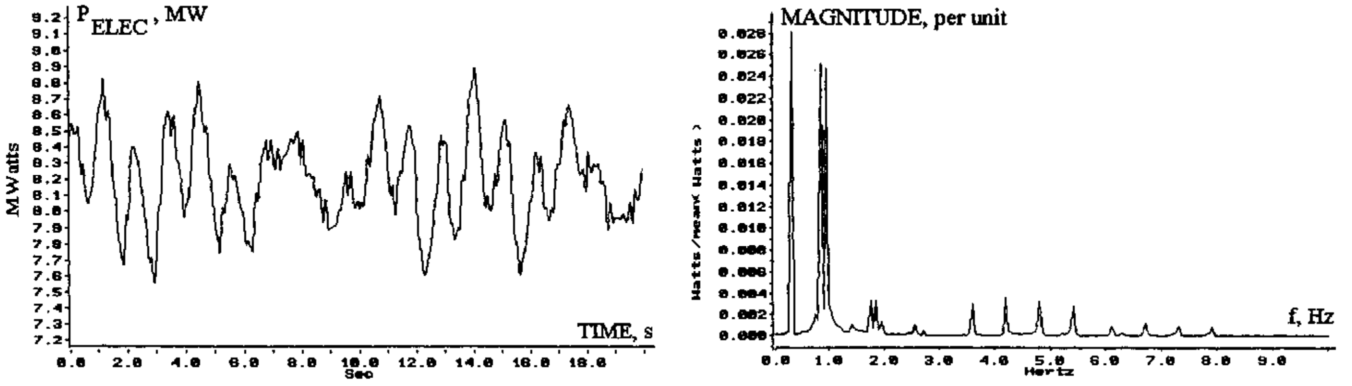


Fig. 4. Modular dynamic model of windmill with mechanical swings.

Marking at the Fourier–spectra shown in Fig. 1, n	Classification	Relative contributions to disturbances of the electric power, A_n, per unit	Eigenfrequency, $f_n(t)$, Hz	Modulation function, $h_n(t)$
1.	little asymmetry of the windmill	approx. 0.02	$\omega_{MILL}/2\pi$	1.0
2.	first harmonic of vortex tower interaction	approx. 0.05	$3 \cdot \omega_{MILL}/2\pi$	$sin(2\pi f_{MOD,2} \cdot t)$, $f_{MOD,2}$=0.045 Hz
3.	second harmonic of vortex tower interaction	less than 0.02	$6 \cdot \omega_{MILL}/2\pi$	$sin(2\pi f_{MOD,3} \cdot t)$, $f_{MOD,3}$=0.090 Hz
4.	eigenswing in the shaft	less than 0.005	1.67	1.0
5.	eigenswings in the blades	less than 0.01	4.5	$\frac{1}{2} \cdot g_1(t) + \frac{1}{2} \cdot (7/8\, g_2(t) + 1/8 \cdot g_3(t))$
6.	delays and small mismatches in the gearwheels	less than 0.005	7.0	$\frac{1}{2} \cdot g_1(t) + \frac{1}{2} \cdot (7/8\, g_2(t) + 1/8 \cdot g_3(t))$

Table 1. Eigenswings in the mechanical construction of the windmill in accordance with the developed windmill model.



(a) (b)

Fig. 5. (a) – The simulated active, electric power of wind farm, (b) – its Fourier–spectrum.
(Compare the curves with the corresponding ones in Figure 1).

VIII. MODEL APPLICATION TO FLICKER STUDIES

1. Network description

The first practical application of this model was in a study of the voltage quality at the island of Lolland, just south of Zealand. The installed wind power capacity at the island is today at a total of 85 MW, and this number is expected to increase up to around 225 MW in the year 2008. Most of these mills are connected at 10 kV radials in the distribution system.

The island is connected to the 132 kV transmission network of Zealand, but the short circuit capacity is rather low, since the main load and production centres are in the north of Zealand. Furthermore there is a long 50 kV ring distribution system, which connects the 10 kV stations with the 132 kV network. Thus, the windmills feed into a relatively weak system.

2. Flicker

In weak networks flicker is often a concern. Flicker is low-frequency variations of the rms voltage in the range 0.5 - 20 Hz, and are created by all sorts of disturbances. Flicker can be measured with a flickermeter. As a definition a flicker level of 1.00 is the recommended maximum limit.

In [2] a functional description of a flickermeter is given. Based on the functional description of a flickermeter, and knowing the flicker limit at various low frequencies (Table 1 in [2]) it is relatively straight-forward to estimate the flicker level in a (measured or simulated) rms voltage, if one has performed an FFT analysis of the voltage and determined the relative amplitudes of all the low-frequency variations in the signal.

For that reason simulations in dynamic stability programs - with a realistic representation of the most important low-frequency disturbances in the network - can provide a good estimate of the flicker level in the network. The advantage of using dynamic stability programs is that they make it possible to have a very accurate network model that could not have been achieved in transient programs with any reasonable effort. The only constraint to take into account is that the frequency of the disturbances is not too high when compared with the frequency limitations of the dynamic stability program. For PSS/E this limit is around 10 Hz.

This is of course not enough to cover the entire flicker range, but when the discussion is on windmills then it is clear from the previous model description that all the contributions are below 10 Hz. Therefore a good estimate of the flicker from the windmills can be obtained using the windmill model in PSS/E.

Now, measurements performed by the local utility SEAS has recently indicated that the flicker level in some 10 kV distribution radials on the island is close to - or maybe even slightly above - the recommended maximum flicker level, when the wind is strong. Considering the expected increase of wind power it is therefore necessary to take some countermeasures in order to reduce the flicker level in the future. It has been decided to commission an additional 132 kV cable and an additional 50 kV cable on the island as soon as possible. These cables are of course also needed for other reasons than flicker.

3. System studies

SEAS naturally wanted to know for how long this solution would be sufficient to keep the flicker problems at bay. For that reason a number of system studies were performed. Three stages was investigated; in all cases assuming full production on the windmills:

1 - Todays network with 85 MW installed windmill capacity, and without the planned reinforcements.
2 - Todays network, but with the cable reinforcements.
3 - Network stage 2008 with cable reinforcements and approx. 225 MW installed windmill capacity.

The windmill model was used, and the voltages at selected 10 and 50 kV stations were monitored. Simulation results from the 3 stages for the 50 kV station Munkeby (MBY050) are shown in Fig. 6.

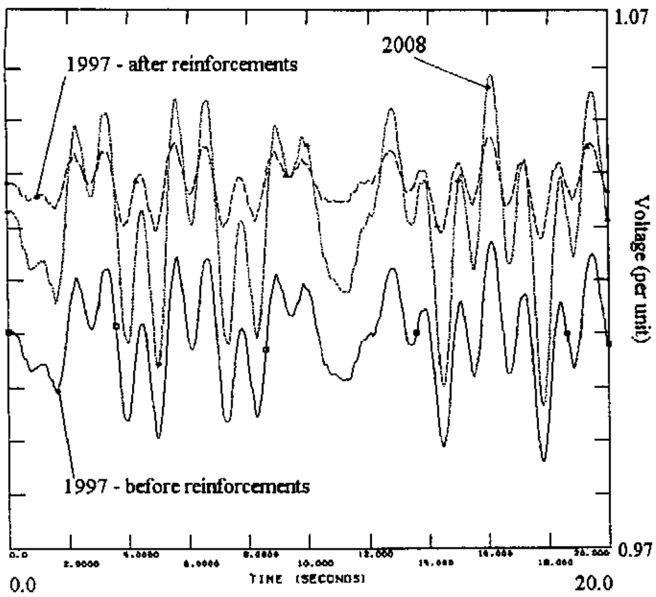


Fig. 6. Voltages at the 50 kV station Munkeby.

A number of other wind production scenarios were also examined, just to verify that the maximum wind production situation indeed is the most severe. During this it was surprisingly observed that at approximately half production the flicker level was remarkably low, even though the active power disturbances were quite significant in the situation. The reason for this is expected to be a combination of the P-Q characteristic of the windmill generators, and the R-X ratio in the 50 kV distribution network. On one hand the windmill will impose variations in the active power production, which will cause an incremental active voltage rise. On the other hand the reactive power consumption of the generator will change with the active power, and this will cause an incremental reactive voltage drop. And the P-Q characteristic of the induction generator is so, that there will be a specific production level, where the two contributions can balance out each other. This is expected to be the explanation for this unexpected observation.

4. Simulation results

Using numerical post-processing of these curves it was possible to determine the amplitude of the various low-frequency oscillations, which are present in the voltage. The contribution of each of these frequencies to the flicker level were then calculated, and the total flicker level was calculated to be as shown in Table 2.

Network stage	1	2	3
Flicker level	0.41	0.09	0.88

Table 2. Flicker level at Munkeby 50 kV.

The flicker levels were also calculated at the 10 kV station Rødbyhavn (RBH010), and the results are shown in Table 3. RBH010 is the station, where measurements had indicated occasional flicker problems, and as can be seen the simulation verified that the flicker level today is a little bit above the maximum limit of 1.00, when the wind is strong.

Network stage	1	2	3
Flicker level	1.09	0.33	1.08

Table 3. Flicker level at Rødbyhavn 10 kV.

The results show that the cable reinforcements are enough to solve the current flicker problems, and that it will only become necessary to do additional reinforcements when the installed wind power capacity on the island exceeds approx. 200 MW. This is expected to happen around the year 2007. At that time the solution can be either additional cable reinforcements, or - if there is no need for the transmission capacity - a synchronous compensator, an SVC, or a STATCOM.

IX. CONCLUSIONS

A dynamic model of windmills, that may be applied to a single windmill connected to the utility grid as well as to a windmill farm consisting of a large number of windmills, has been developed and implemented in PSS/E and ATP using MODELS. The model may be implemented in other tools due to its modularity.

The windmill model has been applied in a flicker study on the Danish island of Lolland, where the simulation results for todays network are in accordance with actual measured events. Based on this it is concluded that the model can be used to provide a reasonably good estimate of the windmill generated flicker contribution in real networks.

X. REFERENCES

[1] H. Knudsen & V. Akhmatov, 'Induction generator models in dynamic simulation tools.', IPST'99, International Power System Transients, 1999, Budapest, Hungary.

[2] International Electrotechnical Commission, IEC Report, publication 868, 'Flickermeter - Functional and Design Specifications'.

[3] P. Kundur, 'Power System Stability and Control', McGraw-Hill Inc, ISBN 0-07-035958-X, in Ch.15.

[4] L. Dube, 'User Guide to MODELS in PSS/E', DEI Simulation Software, August 1998.