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Operation and control of large wind turbines and wind farms. Final report

Sørensen, Poul Ejnar; Hansen, Anca Daniela; Thomsen, Kenneth; Buhl, Thomas; Morthorst, Poul Erik; Nielsen, Lars Henrik; Iov, F.; Blaabjerg, F.; Nielsen, H.Aa.; Madsen, H.; Donovan, M.H.

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Poul Sørensen, Anca D. Hansen, Kenneth Thomsen, Thomas Buhl, Poul Erik Morthorst, Lars Henrik Nielsen, Florin Iov, Frede Blaabjerg, Henrik Aalborg Nielsen, Henrik Madsen and Martin H. Donovan

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Title: Operation and control of large wind turbines and wind farms -

Abstract (max. 2000 char.):

This report is the final report of a Danish research project "Operation and control of large wind turbines and wind farms". The objective of the project has been to analyse and assess operational strategies and possibilities for control of different types of wind turbines and different wind farm concepts.

The potentials of optimising the lifetime/energy production ratio by means of using revised operational strategies for the individual wind turbines are investigated. Different strategies have been simulated, where the power production is decreased to an optimum when taking loads and actual price of produced electricity into account.

Dynamic models and control strategies for the wind farms have also been developed, with the aim to optimise the operation of the wind farms considering participation in power system control of power (frequency) and reactive power (voltage), maximise power production, keep good power quality and limit mechanical loads and life time consumption.

The project developed models for 3 different concepts for wind farms. Two of the concepts use active stall controlled wind turbines, one with AC connection and one with modern HVDC/VSC connection of the wind farm. The third concept is based on pitch controlled wind turbines using doubly fed induction generators. The models were applied to simulate the behaviour of the wind farm control when they were connected to a strong grid, and some initial simulations were performed to study the behaviour of the wind farms when it was isolated from the main grid on a local grid.

Also the possibility to use the available information from the wind turbine controllers to predict the wind speed has been investigated. The main idea has been to predict the wind speed at a wind turbine using up-wind measurements of the wind speed in another wind turbine.

Contents

Preface

This report describes results of the project titled "Control of wind power installations". The project was funded by the Danish TSO, Elkraft System as PSO project FU 2102, and it was carried out in cooperation between Risø National Laboratory, Technical University of Denmark, Aalborg University and Energy E2.

Dansk resumé

Den foreliggende rapport er slutrapporten for et dansk forskningsprojekt med titlen
"Drift, styring og regulering af vindkraft". Formålet med dette projekt har været at
analysere og vurdere reviderede driftsstrategier og mulighederne for styring og
regulering af forskellige typer af vindmøller og vindmølleparker.

Potentialet for optimering af forholdet mellem levetid og energiproduktion undersøges
ved hjælp af reviderede driftsstrategier for de individuelle vindmøller. En ny metode er
udviklet, som etablerer forudsigelse af levetidsomkostninger og indtægter for en
vindmøllepark med 5 vindmøller. Metoden gør det muligt at identificere potentialet for
at forbedre indtjeningen ved en revideret driftsstrategi for vindmøllerne i parken. Den
reviderede driftsstrategi kan baseres på en variabel markedspris for elektricitet, graden af
skyggevirkning fra andre møller i parken eller på vindmøllelaster generelt.

To forskellige strategier er undersøgt. Den ene – ny-design-strategien – er baseret på
omkostningsmodellering af vindmøllekomponenterne som bruger udmattelseslaster som
input, mens den anden – eksisterende-design-strategien – er baseret på en antaget levetid
for de enkelte komponenter. I den sidste ændres komponenternes design ikke, men
komponenten udskiftes når den er slidt.

Analyser med ny-design-strategien illustrerer at det er muligt at øge indtjeningen 5-10 %
hvis driftsstrategien optimeres med hensyn til såvel vindforhold som elpriser på
spotmarkedet. Analyser med eksisterende-design-strategien indikerer en mindre
indtjening end med ny-design-strategien.

Der er endvidere udviklet dynamiske modeller og styringsstrategier for forskellige
koncepter af vindmølleparker. Formålet har været at forbedre styringen af
vindmølleparkerne, først og fremmest med henblik på deltagelse i reguleringen af
elsystemet med effekt- og frekvensstyring, samt reaktiv effekt- og spændingsstyring.
Desuden er styringerne udviklede med henblik på at maksimere energiproduktionen så
vidt muligt, opretholde en god elkvalitet og begrænset de mekanisk belastning på
møllerne.

Projektet har udviklet modeller for tre forskellige typer af vindmølleparker. De udviklede
modeller er generelle i den forstand at de ikke refererer til specifikke møllemærker, men
derimod satser på at simulere de muligheder de forskellige teknologier giver. To af de
modelerede vindmølleparker anvender aktiv stall regulerede vindmøller, den ene med
AC (vekselstrømsforbindelse) og den anden med moderne HVDC / VSC
(jævnstrømsforbindelse med fuld styrbarhed). Den tredje type er baseret på pitch
regulerede vindmøller med dobbeltfødede asynkrongeneratorer.

Simuleringer med de udviklede modeller bekræfter at de to typer vindmølleparker som er
anvendt i de to store offshore vindmølleparker i Danmark (dvs. dobbeltfødede
pitchregulerede møller som i Horns Rev og Combi Stall eller aktiv stall som i Nysted)
kan styres af en central vinmølleparkstyring så de understøtter reguleringen af effekt /
frekvens og reaktiv effekt / spænding på nettet.

Dynamisk fasekompensering, som f.eks. anvendes i Combi Stall møllerne i Nysted, giver
mulighed for øjeblikkeligt respons på ændringer i behov for reaktiv effekt. Dette er
meget nyttigt, fordi spændingen kan reguleres meget hurtigt på den måde. Det
øjeblikkelige respons opnås uden overdreven koblingshyppighed ved hjælp af en

hysterese i den reaktive effektregulering. Alternativt kunne filtrering have været anvendt, men det ville have gjort reguleringen langsommere.

En Combi Stall / aktiv stall vindmølle kan også respondere relativt hurtigt på ændringer i børværdien for aktiv effekt. Simuleringer med tunede, hurtige og stabile regulatorer viser at en ny børværdi nås helt i løbet af 4 sekunder ved drejning af vingerne.

Der er også lavet foreløbige simuleringer af de styrede vindmølleparker forbundet til et lokalt net, som frakobles hovednettet i løbet af simuleringen. Disse simuleringer bekræfter at vindmølleparker med tilstrækkelig styrbarhed kan kontrolere et svagt lokalt net under forudsætning af at der er tilstrækkelig inerti i nettet.

Variable hastigheds vindmøller kan respondere øjeblikkeligt til ændringer i børværdi for både aktiv og reaktiv effekt. Simuleringer med vindmøllepark reguleringer med variabel hastighed viser hvordan dyk i vindhastigheden i en enkelt vindmølle kan kompenseres af de andre møller så den samlede effekt fra vindmølleparken bliver meget glat.

Vi har også undersøgt muligheden for at anvende information som parkstyringen får fra møllestyringerne til at forudsige vindhastigheder. Den bærende ide har været at forudsige vindhastigheden ved en vindmølle baseret på målinger fra en mølle som står opstrøms.

Kvaliteten af forudsigelserne er vurderet baseret på MAE (Mean Absolute Error) og RMS (Root Mean Square). Kvaliteten af forudsigelsen afhænger ikke overraskende af hvad middelvindhastigheden er i perioden. For 5 m/s, 10 m/s og 15 m/s er MAE-værdierne henholdsvis 0.07 m/s, 0.33 m/s og 0.58 m/s. Det bemærkes også at der er store variationer fra periode til periode i disse tal. Desuden har undersøgelsen vist at når opstrøms målinger er tilgængelige er autokorrelationen på de individuelle master ikke særlig vigtig, dvs. vindhastigheden ved en given mølle forudsiges bedre baseret på opstrømsmøllens nuværende vindhastighed en på møllens egen nuværende vindhastighed.

Oprindeligt var en af ideerne med projektet at bruge forudsigelserne i styringen af vindmølleparkerne. I projektet er undersøgt muligheder for konkret at anvende forudsigelserne, uden at der blev fundet oplagte muligheder. Derfor er forudsigelserne ikke implementeret i simuleringsmodellerne for styringerne.

En del af undersøgelsen gik på om det er muligt at øge produktionen for variable hastigheds vindmøller ved at styre hastigheden på forkant, så den altid er optimal i forhold til vindhastigheden. Som et markant resultat blev det fundet at det kun var muligt at øge produktionen med 0.09 %, det endda under forudsætning af at vindhastigheden kan forudsiges perfekt og at rotorhastigheden kan ændres så hurtigt at den følger den forudsagte vindhastighed 100 %. Det var et overraskende resultat, ikke mindst fordi forskning i USA indikerer at der spildes 1-3 % energi fordi reguleringen af rotorhastigheden ikke er optimal.

English resumé

This report is the final report of a Danish research project "Operation and control of large wind turbines and wind farms". The objective of the project has been to analyse and assess revised operational strategies and the possibilities for control of different types of wind turbines and different wind farm concepts.

The potentials of optimising the lifetime/energy production ratio by means of using revised operational strategies for the individual wind turbines are investigated. A new

methodology has been established for prediction of life time costs and income for a wind farm with five turbines. The method enables the possibility of identifying the potentials of improved cost-efficiency for a revised operational strategy for the wind turbines in the wind farm. This revised operational strategy can be based on a variable market price on electricity, degree of wind farm operation (wake degree) or wind turbine loads in general.

Two different approaches have been followed. One of these - the "re-design" or "new-turbine-design" approach - is based on cost modelling of the turbines components using the fatigue loads as inputs, while the second approach - the "existing-design" approach - is based on a presumed life time of the turbine components. In the latter one, the components do not change but are replaced if the design damage is reached.

The re-design analysis illustrates that increase in income of 5-10 % is possible if the operational strategy is optimized with respect to both wind conditions and electricity market spot price. The results from the existing-design approach illustrate a smaller improvement in cost-efficiency than the re-design approach.

Dynamic models and control strategies for the wind farms have also been developed, with the aim to improve the control of the wind farms considering participation in power system control of power (frequency) and reactive power (voltage). The developed control strategies also intend to maximise power production, keep a good power quality and limit the mechanical loads and life time consumption.

The project developed models for three different concepts for wind farms. The developed models are generic in the sense that instead of describing specific wind turbine types, they intend to describe the possibilities provided by the different technologies. Two of the wind farm concepts use active stall controlled wind turbines, one with AC connection and one with modern HVDC/VSC connection of the wind farm. The third concept is based on pitch controlled wind turbines using doubly fed induction generators.

Simulations with the developed models confirm that the two concepts used in the two large offshore wind farms in Denmark (Doubly-fed in Horns Rev and Combi stall in Nysted) can be controlled by a central wind farm controller to support power /frequency and reactive power / voltage control in the grid.

Dynamic phase control, which is used in the Combi stall wind turbines in Nysted, provides immediate response to reactive power demands. This is very useful, because the voltage can be controlled very quickly that way. The immediate response is obtained without excessive switching frequencies by introducing hysteresis in the control loop. Alternatively, a low pass filter would be required, which would have slowed down the response.

The Combi stall / active stall wind turbines can also provide a relatively fast response to changes in active power demands. Simulations with tuned, stable and fast controllers, show that a new set point is reached fully in approximately 4 seconds. This is obtained by blade pitching.

Initial simulations were performed with a controlled wind farm connected to a local grid, which was isolated from the main grid during the simulation. These simulations confirm that wind farms with sufficient grid support can control a weak, local grid, provided that sufficient inertia on the local grid.

Variable speed wind turbines can respond immediately to changes in active as well as reactive power demands. Simulations with wind farm controller show how wind speed dips in one wind turbine can be compensated immediately by other wind turbines, which ensures a constant and very smooth power from the wind farm in the point of common coupling.

Also the possibility to use the available information from the wind turbine controllers to predict the wind speed has been investigated. The main idea has been to predict the wind speed at a wind turbine using up-wind measurements of the wind speed in another wind turbine.

The potential prediction performance of a forecast system based on up-stream information is judged in terms of Mean Absolute Error (MAE) and Root Mean Squared Error (RMS). It is clear that the performance depends on the overall level of the wind speed for 5m/s, 10m/s, and 15m/s MAE-values of respectively 0.07m/s, 0.33m/s, and 0.58m/s are obtained. However, quite large deviations for the individual periods are evident. Furthermore, the results have shown that when up-stream information is available, the auto correlation of the wind speeds at the individual masts is not very important.

Originally, one idea in the project was to use the predictions in the wind farm controllers. A survey of opportunities to use the wind speed predictions has been performed. No obvious and promising use of the predictions was found, however. Thus, the prediction has not been implemented in the controllers described in the following.

As part of the survey, it has been studied if the power production of variable speed wind turbines can be increased using wind speed predictions to optimise the wind turbine rotor speed. A significant result was that only 0.09 % power increase could be obtained even with perfect prediction and infinitely fast speed control. This was surprising, since research in USA indicated an energy loss of around 1% - 3% due to not optimal speed control.

1 Background

The wind energy industry has developed rapidly through the last 20-30 years. The factories have developed from small workshops to mature industry, and technically the wind turbines have increased in size, the costs have been reduced, and the controllability developed. This places modern wind energy as a serious and competitive alternative to other energy sources.

The development has been concentrated on wind turbines for electrical power production, i.e. grid connected wind turbines. Grid connected wind turbines are a part of a power system, with which they interact. On one hand, the power system and its quality has an influence on the wind turbines performance, lifetime and safety, and on the other hand, the quality and the reliability of the wind turbine power will influence the power system quality, stability and reliability. Also, wind power is traded on market with variable prices, which influences the feasibility of wind power projects. On this background, the integration of wind power into the power systems has become an important area, also for research and development.

Wind farm control involves the control on wind turbine level as well as the overall control on the wind farm level. Historically, the automatic control of wind power installations has been implemented in the individual wind turbines. Remote control and

wind farm monitoring systems have been developed in an early stage, but the main aim has been to monitor the wind turbines and enable remote manual control such as shut down, start up etc. However, the recent development of large (typically offshore) wind farms has initiated the development of advanced, automatic wind farm controllers supporting extensive grid control. The large Danish offshore wind farms in Horns Rev and Nysted are significant step in this development.

Traditionally, the main aim of the wind turbine control is to ensure that the wind turbine is able to produce energy at the lowest possible cost, i.e. at minimum price per kWh. Normally, this means that the control should aim at maximum possible power production, limited only upwards to the rated power of the turbine. Another important control aim, which also reduces the price per kWh, is to reduce the structural loads on the mechanical components, which makes it possible to reduce the costs of the mechanical components. Finally, it is a control aim to improve the integration of the wind turbines in the power system, in order to secure quality, stability and reliability, and to reduce the required grid connection costs.

References to used literature are not given in the present report. Instead, references are given to the project publications in section 6.4. Substantial references to used literature are given in these project publications.

2 Objective

The objective of this project has been to develop and assess control and operational strategies of wind farms.

The potentials of optimising the lifetime/energy production ratio by means of using revised operational strategies for the individual wind turbines has been investigated. It has been one of the main objectives to clarify this potential by implementation of a strategy where the power production is decreased to an optimum when taking loads and actual price of produced electricity into account. This operational strategy describes the lifetime operation of the wind turbines in hourly steps.

Another related area is the dynamic control of the wind farms, typically working in the time range from milliseconds to minutes. In this area, models and control strategies for three different types of wind farms have been developed, with the aim to optimise the operation of the wind farms considering participation in power system control of power (frequency) and reactive power (voltage). The wind farm controllers interact with the wind turbine controllers to provide this grid support, but this is done in a way that the individual wind turbines maintain the ability of to maximise power production and limit mechanical loads and life time consumption.

The wind farm control receives signals from wind turbine controllers. These signals are used to predict the wind speed at the individual wind turbines on short term (i.e. from seconds to minutes). Such predictions could enable the individual wind turbine controllers to respond in an optimal way to the wind speed fluctuations. In this project, a model for the prediction is developed, and the possible use of the predictions is studies.

3 Prediction of wind fluctuations

The idea of this work is to use the signals, which the wind farm controller receives from the individual wind turbine controllers to predict the wind speed at the individual wind turbines on ultra short term (i.e. from seconds to minutes).

Three data sets have been analysed and a prediction model has been developed to predict wind speed fluctuations based on up-stream measurements. First, predictability based on measurements in a single mast has been studied by Nielsen and Madsen [1] using a single 60 m mast on Eltras test site in Tjæreborg. Secondly, five 80 m high masts at Risøs Høvsøre test site have been analysed and used to develop the prediction model based on up-stream measurements [2], [3]. Finally, the same method has been applied to data in the Nysted wind farm [4]. In this report, the main results from the Høvsøre study are presented.

3.1 Data

The Høvsøre study considers forecasting of wind speed based on 10 sec averages. The relevant prediction horizons are in the range of minutes. For wind farms the individual turbines may obtain up-stream information regarding e.g. wind speeds measured by nacelle anemometers.

The data used in this study consists of 12 series of measurements of wind speed and direction approximately 80 m above ground from mast 1–5 at Høvsøre, see Figure 1. More specifically the anemometers are placed at the top of the masts (78 m for mast 1 and 80 m for the remaining masts). Wind vanes are placed at booms 2 m below the anemometers. Note that data from the meteorology mast is not used in this study.
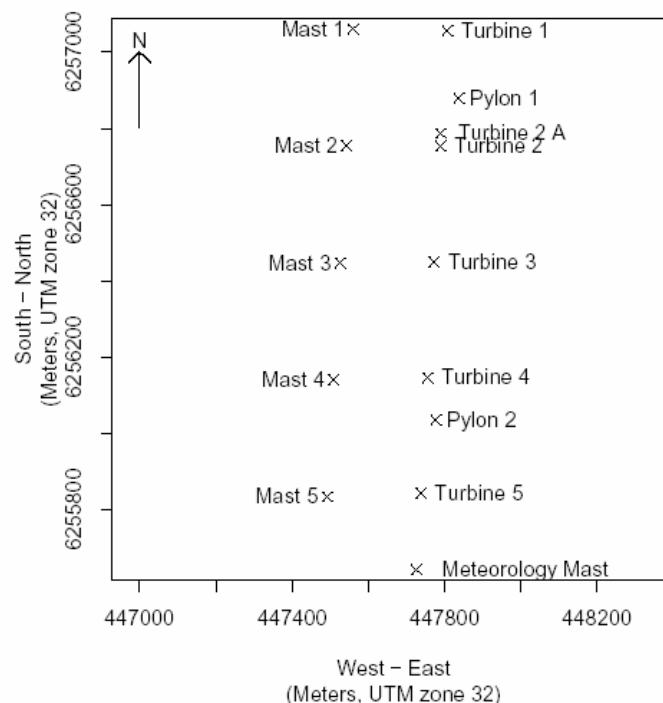

Figure 1. Location of masts and turbines in Høvsøre.

The series have been selected based on two main criteria:

. The wind direction should be Southerly.

. The series should have length one hour or more.

3.2 Analysis

The primary goal of the analysis is to suggest appropriate multivariate prediction models, which use both auto and cross correlation between the wind speed measurements at the five masts. To accomplish this a first step is to estimate the impulse response corresponding to all pairs of masts. To accomplish this the standard procedure of prewhitening followed by estimation of the cross correlation function is used. The resulting estimate is proportional to the impulse response.

However, to be able to prewhite the series an ARMA-model must be fitted to one of the series. Considering the series displayed in Appendix A this will be difficult since most of the series seems to be non-stationary on the time scale considered. More specifically the series seem to contain slow variations, which is not considered of direct interest from an analysis point of view. For this reason a high-pass filter is designed, which allows us to estimate the impulse responses of each of the periods separately.

The estimated impulse responses are presented in details in [2]. shows a summary of the results for neighbour masts. For the neighbouring masts, it is seen that the peak of the impulse response is significant and near the distance travelled by the wind at the average wind speed of the series. However, for series 12 the response seems to be faster than indicated by the distance between the masts and the average wind speed.
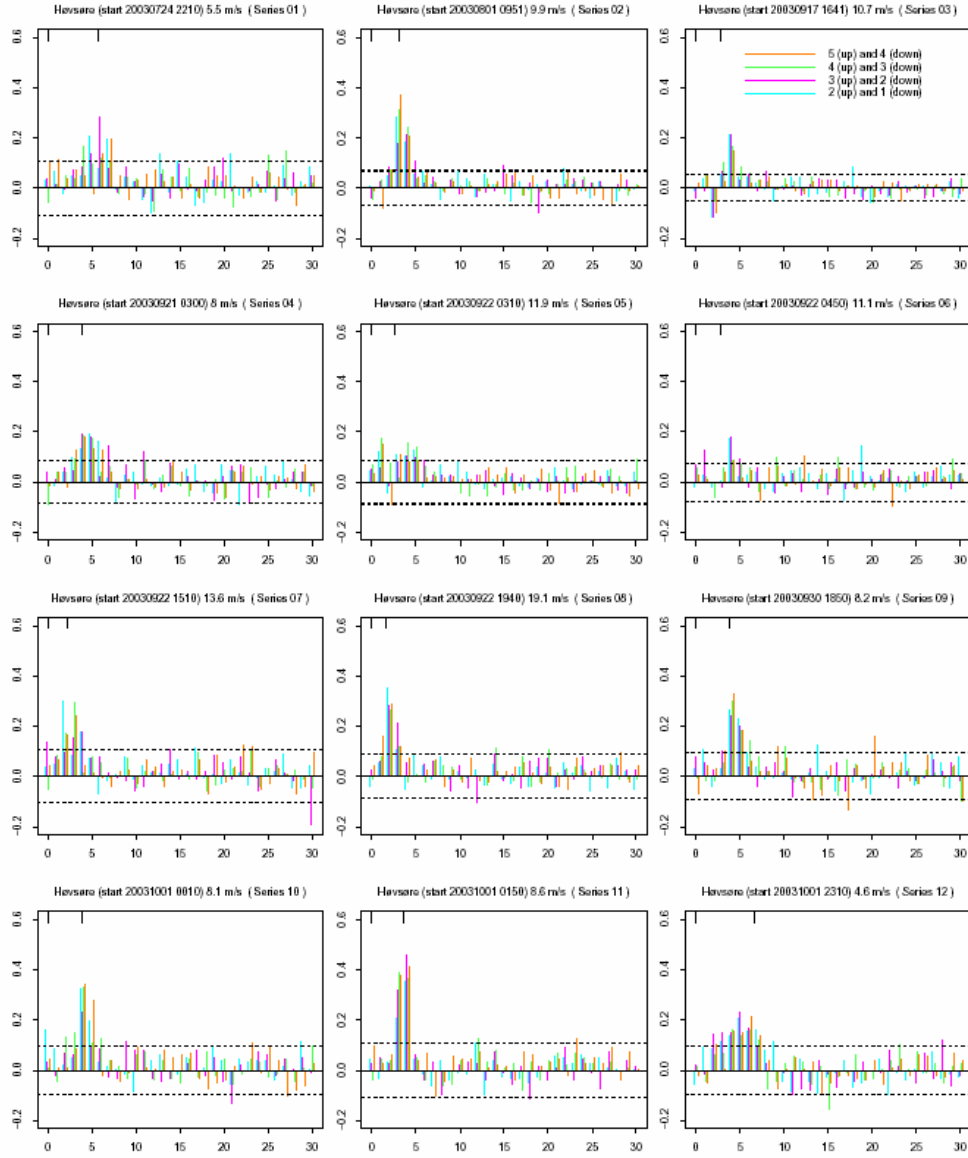
Figure 2. Impulse response for neighbour masts (300 m distance)

For pairs of masts with longer distances, it has generally been observed that the relation is weakened. Roughly, since the distance between masts is approximately 300 m, this implies that for wind speeds around 5 m/s there is a potential benefit of using multivariate wind speed forecast models for horizons up to 2 minutes. For 10 and 15 m/s this limit drops to 1 minute and 40 seconds, respectively. However, the relation is most clear for neighbour masts and in this case the time intervals mentioned drop down to respectively 60, 30, and 20 seconds.

3.3 Model

The basic idea of the model is expressed in ((1).

$$x_j(t) = \psi_0 + \int_0^\infty h\left(\frac{\mu(t)}{D}s\right) x_i(t-s)ds; \quad i > j, \quad i = 1,...,4, \tag{((1)}$$

Here, h is the impulse response, $x_j(t)$ is the wind speed at mast j at time t, ψ_0 is a constant, $\mu(t)$ is the average wind speed at time t, and D is the distance between the two masts.

3.4 Prediction performance

For each series and mast the Root Mean Squared error (RMS) and Mean Absolute Error (MAE) of the errors are obtained were plotted against the forecast horizon (not shown). From such plots it is clear that the performance measures change with horizon up to approximately 20 sec, i.e. for longer horizons the ARMA model is unimportant (assuming the input to be known). Figure 3 shows the two performance measures plotted against the average wind speed of the series for all horizons above 60 seconds.
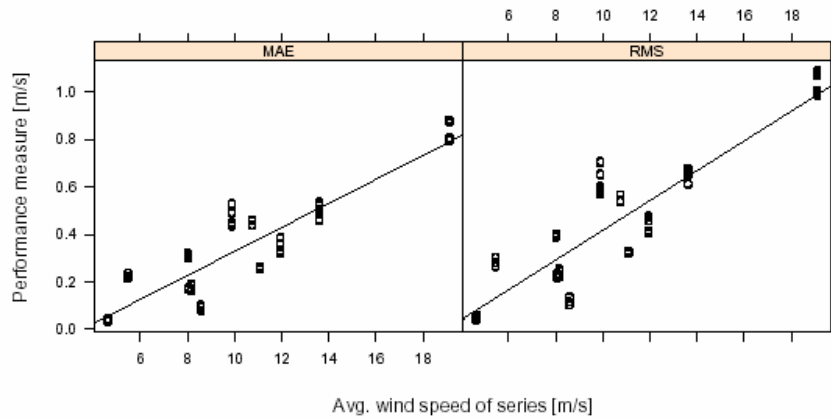

Figure 3. Performance measure for horizons 60 to 180 seconds versus average wind speed of the series.

There seems to be some dependence on the wind speed, but relatively large deviations from the line occur. If the lines are used as a rough guideline, a 95% confidence interval will have length $\pm 2 \times 0.2 = \pm 0.4$ m/s at 6 m/s, and at 10 m/s the corresponding length will be ± 0.8 m/s.

All these estimates are based on the assumption that the input, i.e. wind speed at the upstream mast, is known. Furthermore the performance measures are based on in-sample results, but since the models contain relatively few coefficients this is a minor problem, which presumably can be solved using adaptive methods for estimation. As is seen from the impulse responses (Figure 2) this assumption is roughly valid up to horizons defined by the average wind speed and the distance between masts.

4 Wind turbine and wind farm control

This chapter summarises the work done on modelling and development of the dynamic control of the wind farms. Models and control strategies for three different types of wind farms have been developed, with the aim to optimise the operation of the wind farms considering participation in power system control of power (frequency) and reactive power (voltage). The wind farm controllers interact with the wind turbine controllers to provide this grid support, but this is done in a way that the individual wind turbines maintain the ability of to maximise power production and limit mechanical loads and life time consumption.

4.1 Wind turbine models

Models for two different types of wind turbines have been developed: the active stall controlled wind turbine and wind turbines with doubly-fed induction generators (DFIGs).

Active stall wind turbine

The "active stall" was actually the name used by NEG-Micon and now Vestas, while a similar concept is named "combi stall" by Bonus – SIEMENS, e.g. for the wind turbines in Nysted wind farm. The models developed in this project are not referring to specific turbine types. Thus, the "active stall" turbine model presented here is also intended to cover turbines like the ones in Nysted.

Two versions of models for the active stall controlled wind turbine have been developed and used in the present project. The two models reflect the wind turbine development and according to requirements in e.g. the Danish grid codes.

The first version described in Jauch et. al. [5] was developed to simulate the first generation of active stall / combi stall turbines. Originally, the concept was developed because the blades became too big for tip breakers, and therefore the whole blade had to become pitchable. This pitch was further used to remove one of the problems with passive stall, namely that the maximum power and maximum shaft torque cannot be controlled actively, since the maximum power of a passive stall controlled wind turbine is influenced e.g. by weather conditions (air density) and grid frequency. This first generation of active stall controlled wind turbines would reduce the pitch activity to a minimum, and thus had a relatively slow power control. Also reactive power control was slow, because the capacitor bank used mechanical contactors.

The second model described in Hansen et. al. [6] was optimised for gird support, and it is in that respect expected to be quite similar to the Nysted wind turbine. On the active power control side, it responds within a few seconds to changes in the power setpoint, and on the reactive power side, it assumes dynamic phase compensation using a thyristor switched capacitor bank.

The layout of the active stall wind turbine is shown in Figure 4. Each wind turbine is connected to a 10 kV busbar. The induction generator, softstarter, the capacitor bank for reactive power compensation and the step-up transformer are all placed in the nacelle, and thus the transformer is considered part of the wind turbine. The control of active and reactive power is based on measured reactive power at the Main Switch Point MSP.
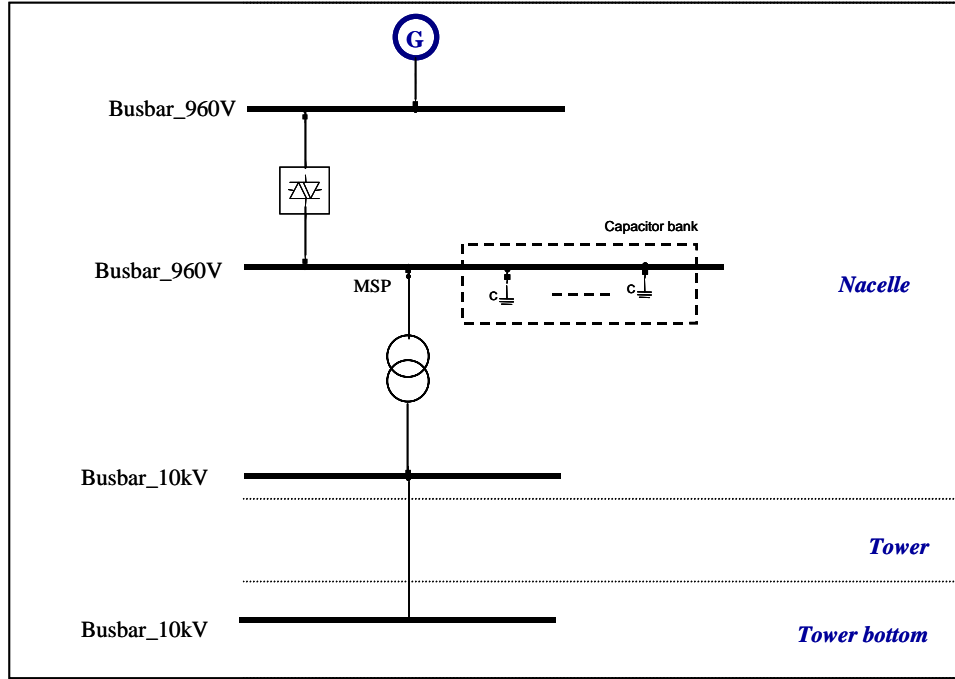
Figure 4: Active stall wind turbine layout including softstarter and capacitor bank.

Figure 5 illustrates the used power control scheme for the simulation of an active stall wind turbine. A PI controller with anti wind-up ensures a correct active power production from the wind turbine both in power optimisation control mode and power limitation control mode. The input of the controller is the error signal between the measured active power at the Main Switch Point (MSP) (see Figure 4) and the active power reference p_{ref} imposed by the wind farm controller. The PI controller provides the pitch angle reference θ_{ref}, which is further compared to the actual pitch angle θ and then the error $\Delta\theta$ is corrected by the servomechanism. In order to get a realistic response in the pitch angle control system, the servomechanism model accounts for a servo time constant T_{servo} and the limitation of both the pitch angle and its gradient. The output of the actuator is the actual pitch angle of the blades.

p_{avail}

Power curve $\quad u_f \quad$ Filter $\quad u$

$\theta \qquad \lambda$ Tip Speed Ratio

$\lambda = \omega_{WTR} \, R / u_f \qquad \omega_{WTR}$

Gain scheduling $\qquad$ Look-up table θ_{opt}

$K_P \qquad \theta_{max} = \theta_{opt}$

$p_{ref} \qquad +\ \ominus\ - \quad \Delta P \quad K_P \left(1 + \dfrac{1}{T_I \, s}\right) \qquad \theta_{ref} \qquad +\ \ominus\ - \quad \dfrac{1}{T_{servo}} \quad \dfrac{d\theta}{dt} \quad \dfrac{1}{s} \qquad \theta$

θ_{min}

Filter power

PI controller $\qquad$ **Actuator**
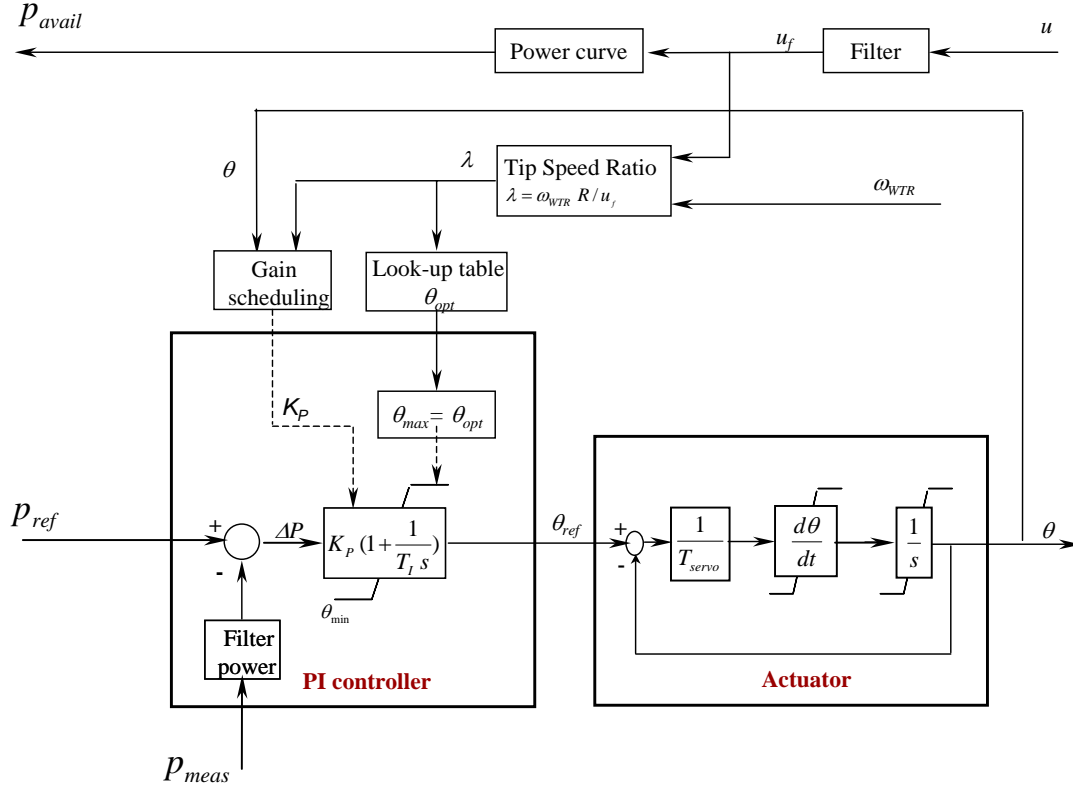
p_{meas}

Figure 5: Proposed active power control scheme.

The information about the available power of the wind turbine, sent back to the wind farm controller at each instant, is expressed, as illustrated in Figure 5, based on the wind turbine's power curve and the filtered wind speed u_f. The wind speed is filtered appropriately to avoid unnecessary fluctuations.

In the power optimisation control mode, the controller has to maximise the power production. In this case, the difference between the measured power and its reference value is all the time positive and it is integrated up until the pitch reference angle reaches the upper limit of the controller. The optimal pitch angle is therefore used as the upper limitation of the controller.

In the power limitation control mode, the error signal of the controller is negative and therefore the pitch angle is moving out the upper limitation and starts actively to drive the measured power to the power reference. Notice that the measured power used in the error signal is low-pass filtered in order to avoid that the 3p fluctuations in the power causes the pitch angle to fluctuate with the 3p frequency as well.

The control system of the capacitor bank has to switch the capacitors fast in order to be able to support the grid, but on the other hand it should not attempt to control the 3p fluctuations (three times the rotational frequency) in the reactive power consumption of the induction generator.

In the present work, the fast switching of the capacitors is assured by the clock time 20 ms, while the influence of the 3p fluctuations in reactive power is removed by implementing a hysteresis in the digital integrator. The hysteresis has been used instead of a low-pass filter in order to keep a very fast response to large changes in the reactive

power reference. This is regarded important for the ability of the wind turbines to support the wind farm controller with voltage control.

DFIG wind turbine

Also the wind turbine controller for the DFIG has been developed in two versions. The first one uses the converter to control the speed and the pitch system to limit the power. This controller is described by Hansen et.al. in [7], [8]. The second controller is expected to be closer to the real controllers in this type of wind turbines, although this is not easy to clear up because the actual control algorithm is kept confidential by the wind turbine industry. The second controller uses the converter to control the power, which provides a fast power control, and it then uses the pitch system to prevent overspeed. The second controller is described briefly in [9], [10], [11], and in more details in [12]. Here is given a short description.

Figure 6 sketches the overall control system of a variable speed DFIG wind turbine implemented in DIgSILENT. Two control levels using different bandwidths can be distinguished:

- Doubly-fed induction generator (DFIG) control level
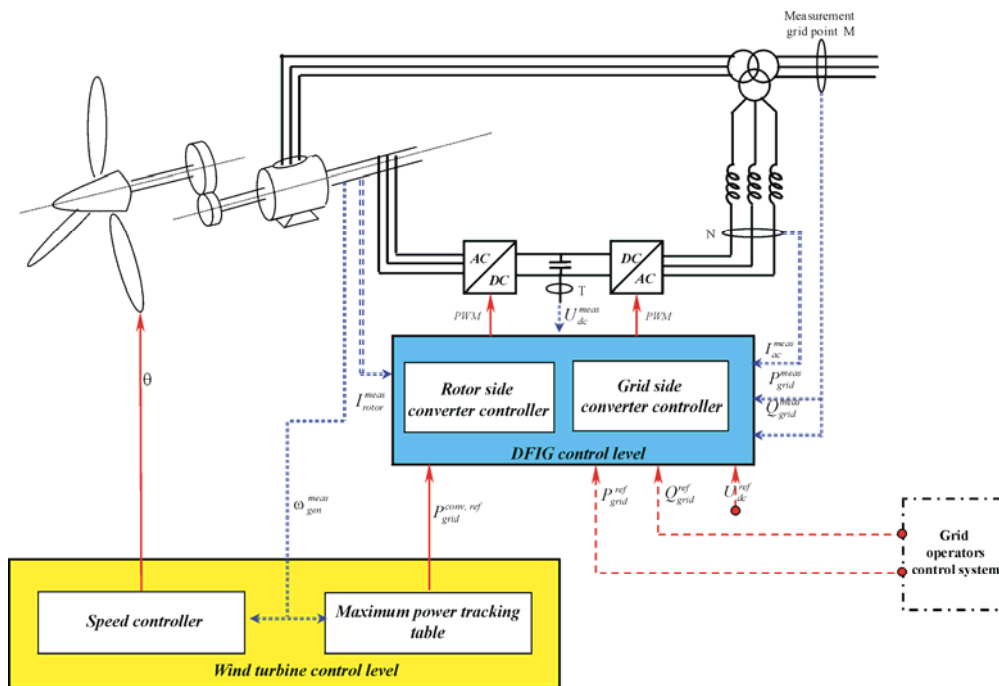
- Wind turbine control level

Figure 6: Overall control system of variable speed wind turbine with doubly-fed induction generator

The DFIG control, with a fast dynamic response, contains the electrical control of the power converters and of the doubly-fed induction generator. The DFIG control contains two controllers:

- **Rotor side converter controller** - controls independently the active and reactive power on the grid point M – see Figure 6.

- **Grid side converter controller** - controls the DC link voltage U_{DC} and unity power factor to the grid through the rotor branch. The transmission of the reactive power from DFIG to the grid is thus only through the stator.

The wind turbine control, with slow dynamic response, provides reference signals both to the pitch system of the wind turbine and to the DFIG control level. The control scheme is illustrated in Figure 7. It is referred to as the power-speed control scheme. The setpoint P_{ref} for the power control is obtained from a lookup table as a function of the measured rotor speed ω_{meas}. The lookup table is created as pairs of optimal speed and power for low wind speeds, whereas for higher wind speeds, the rotor speed is limited due to a combination of other design issues such as structural loads and noise emission. The steady state rotor speed is limited to the constant maximum value ω_{max} by the speed control loop, which sets the blade pitch angle θ_{pitch}. The speed controller is only active when the power is limited, while the power controller is continuously active.
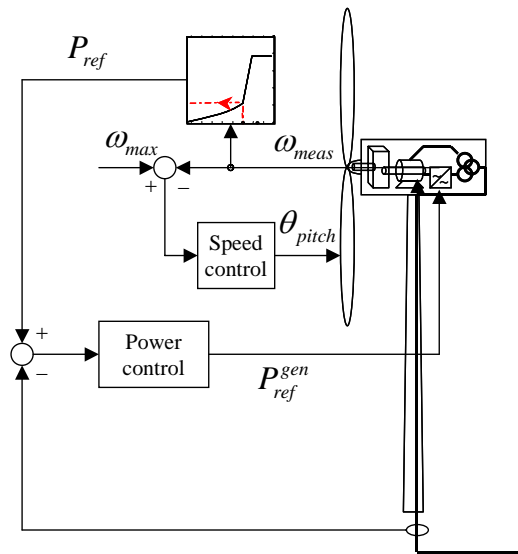

Figure 7. Power-speed control scheme illustrated on a variable speed wind turbine with double fed induciton generator.

4.2 Wind farm controller models

Two wind farm controllers have been developed. The first controller can in principle work on any wind turbine, but is here used only with AC connected active stall controlled wind turbines. The second controller only works with variable speed wind turbines, and it is here used with doubly-fed induction generators.

Originally, one idea in the project was to use the predictions in the wind farm controllers. A survey of opportunities to use the wind speed predictions is described in [12]. No obvious and promising use of the predictions was found, however. Thus, the prediction has not been implemented in the controllers described in the following.

As part of the survey, it has been studied if the power production of variable speed wind turbines can be increased using wind speed predictions to optimise the wind turbine rotor speed. A significant result was that only 0.09 % power increase could be obtained even with perfect prediction and infinitely fast speed control. This was surprising, since research in USA indicated an energy loss of around 1% - 3% due to not optimal speed control.

AC connected active stall wind turbines

This section describes a wind farm controller, which can in principle work on any wind turbine, although it has only been simulated using wind turbines with active stall wind turbines.

Figure 8 illustrates the diagram of the wind farm control level. The wind farm control level behaves as a single centralized unit. It has as input signals demands from the system operator, measurements from the point of common coupling (PCC) and available powers from the wind turbines. The available power of each wind turbine is determined at the wind turbine level based on the wind turbine's power curve and an estimated wind speed. The system operator can order the wind farm to operate either with normal (maximum) production or with limited production.
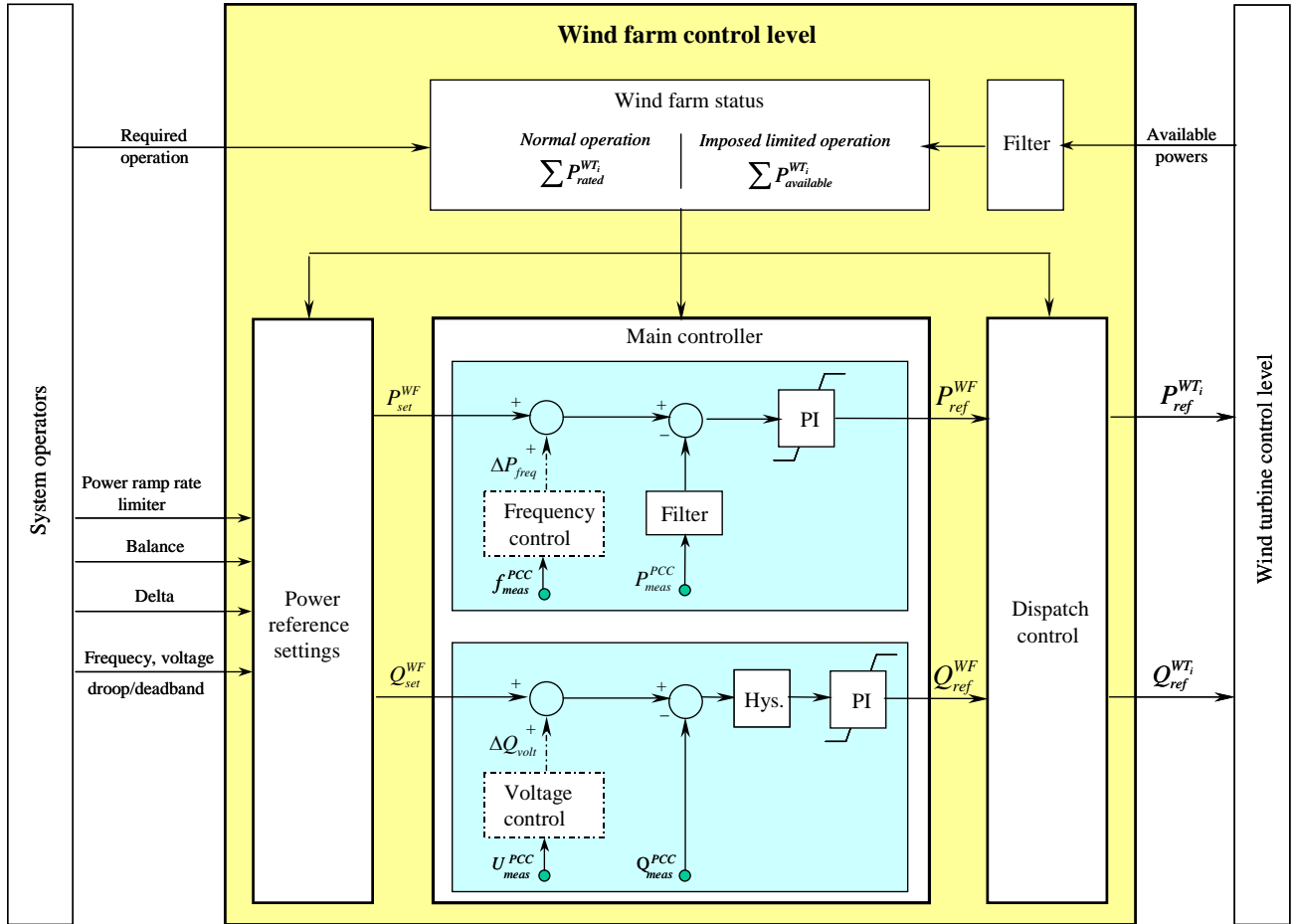

Figure 8: Wind farm control for the active stall wind farm.

The system operator also decides how fast the wind farm production should be adjusted (power ramp rate limiter), and if there is a need for a reserve capacity (balance and/or delta control), a frequency and a voltage control. The power ramp rate limiter reduces both the positive and negative excessive power ramp rates in the active power of the wind farm. Based on all these requirements from the system operators, the wind farm controller elaborates the power reference signals for each individual wind turbine control.

The wind farm control system contains typically a power reference settings block, a wind farm controller itself and a dispatch function block. At the present stage, delays due to

the signal communication between the wind farm control level and the wind turbines are neglected.

In the power reference settings block, different control functions for active and reactive power, as illustrated in Figure 8, are implemented in such a way that they can be active at the same time. There are two concomitant control loops in the wind farm controller itself: one for the active power control and the other for the reactive power control. The active control loop is based on a controller for the active power and a subordinated frequency control loop, while the reactive control loop is based on a controller for the reactive power and a subordinated voltage control.

The principle of the active and reactive power control loops is as follows. First an active and reactive power reference signal (P_{set}^{WF} and Q_{set}^{WF}), respectively, are elaborated in the power reference settings block, based on one or several control functions required by the system operator. These reference signals can be, if necessary, adjusted further with some corrections ΔP_{freq} and ΔQ_{volt} from the subordinated control loops (frequency and voltage), in order to support power system control of frequency and voltage in PCC.

In the case when only the wind farm's capability to control the wind farm's active and reactive power production, i.e. secondary control capability is in focus, the frequency and voltage subordinated control loops can be neglected, their corrections being assumed zero.

Each control loop consists of a PI controller with anti wind-up that ensures a correct power production from the wind farm. The controller computes a power error and sets up the power reference (P_{ref}^{WF}, Q_{ref}^{WF} respectively) for the whole wind farm.

Notice that only the active and not the reactive power signal is low-pass filtered in order to avoid that the 3p fluctuation is amplified through the control system. Fast variations in the reactive power reference from the wind farm controller, due to 3p fluctuations, are removed using a hysteresis in the wind farm control level – see Figure 8. This is because the speed of the reactive power control has priority above the accuracy, in order to take full advantage of the fast response of the dynamic phase compensation. For active power control, the blade pitching will anyway slow down the possible control speed, and therefore a 3p filter will not slow down the active power control significantly more.

A dispatch function block converts further the power reference signals from the controller into power reference signals for each individual wind turbine of the wind farm. There are different ways to design the dispatch function but the one presented in this paper simply distributes the power references to the wind turbines $P_{ref}^{WT_i}$, $Q_{ref}^{WT_i}$ (i=1:n) based on a proportional distribution of the available active power and maximum reactive power, respectively:

$$P_{ref}^{WTi} = \frac{P_{av}^{WTi}}{P_{av}^{WF}} P_{out}^{WFC}, \qquad Q_{ref}^{WTi} = \frac{Q_{max}^{WTi}}{Q_{max}^{WF}} Q_{out}^{WFC} \qquad (2)$$

where the total active power and the maximum reactive power of the wind farm are expressed as follows:

$$P_{av}^{WF} = \sum_{i=1}^{n} P_{av}^{WT_i}, \qquad Q_{max}^{WF} = \sum_{i=1}^{n} Q_{max}^{WT_i} \qquad (3)$$

and where $P_{av}^{WT_i}$ is the available power for the *i'th* wind turbine in one specific point in time. $Q_{max}^{WT_i}$ is the maximum possible reactive power for the *i'th* wind turbine.

Notice in Figure 8 that all three mentioned blocks in the wind farm controller (power reference settings block, main controller block and dispatch block) have an upper limited supervisory signal, depending on the wind farm status. In normal operation, i.e. when the wind farm should produce maximum power, the upper limited signal is constantly equal to the rated power of the whole farm, while in limited operation this signal is given by the sum of the available power of each individual wind turbine. The available power received from each wind turbine is low-pass filtered in order to avoid that the 3p frequency is amplified through the control system. The reason why the upper limited signal is equal to the total rated power of the whole wind farm in normal operation is, that if the limit was equal to the available power, the wind turbine would pitch unnecessarily to limit the power to the estimated available power.

DFIG wind turbines

This section describes a wind farm controller, which can in principle work on any variable speed wind turbine, although it has only been simulated using wind turbines with doubly-fed induction generator. This controller was actually developed before the wind farm controller presented above, and it will not work properly with fixed speed wind turbines. The reason is that it uses wind turbine available power as wind turbine reference power when maximum power is requested. The general wind farm controller in presented above uses the rated power instead of available power as reference to request maximum power as explained above.

The wind farm controller has to take over the determination of the wind turbine power set point to be able to perform power control. But when the wind farm controller is not intended to limit the wind turbine power production, it is important that maximum power is still obtained. The present wind farm controller is designed to maintain the robust maximum power point tracking of the power-speed control scheme, as long as the power is not limited by the wind farm power control.

A block diagram of the wind farm controller is shown in Figure 9 together with the modified wind turbine power controller. Essentially, the power control loop in the wind turbine controller in Figure 7 is opened, which makes it possible for the wind farm controller to set the power reference in the wind turbine. Besides, the output of the power – speed table, which is not used as wind turbine power reference any more, is now send to the wind farm controller as available instantaneous power, P_{avail}^{inst} (Figure 9).
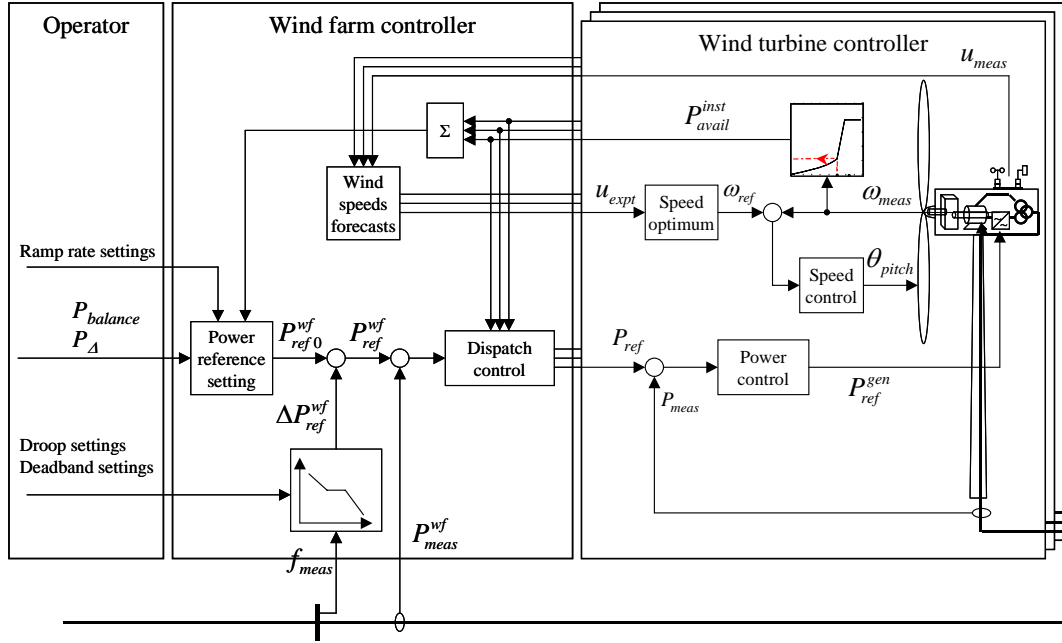
Figure 9 Model for wind farm power contoller with DFIG technology.

If the power is not limited by active balance, delta or ramp control, the wind farm controller will return the available power as set point to the wind turbine, P_{ref}. This is done in the way that the wind farm controller sums the available power from all wind turbines and uses that sum as reference for the wind farm power, P_{ref}^{wf}. The "dispatch control" block in Figure 9 simply distributes the power references to the wind turbines, proportionally to the distribution of available power.

This concept is very robust to maximum power point tracking, because it works like the autonomous wind turbine controller in Figure 7, but only with a small delay due to transmission of signals between wind turbine and wind farm controller.

If the power is limited, by ramp rate, balance or delta control, P_{ref}^{wf} is reduced to less than the sum of available power. As a consequence, the dispatch control will reduce the individual reference signals P_{ref} to the wind turbines.

Now, if the reference to the speed controller in Figure 9 was ω_{gen}^{rated} as with autonomous wind turbine control in Figure 7, the wind turbine would use the surplus power to accelerate to ω_{gen}^{rated} before the speed controller would pitch to limit the speed. This would cause higher fatigue loads on the wind turbine when the power control is taken over by the wind farm controller, because the rotational speed would be higher. To avoid this, a "speed optimum" block sets the reference speed continuously depending on the wind speed. An advanced wind speed forecast can be applied to provide the wind speed input to the speed optimum block, but because of the results in section 2.4 of this report, the wind speed input is simply obtained by filtering the measured wind speed from the wind turbine.

The frequency control and voltage control have also been implemented in the simulation model. The frequency control is shown in Figure 9. The voltage control is also done by the wind farm controller, which will determine the setpoints for the reactive power in the wind turbines. The reactive power control on the wind farm level is quite similar to the active power control, using available reactive power from each wind turbine in a

dispatch block, which distributes the required reactive power between the wind turbines to obtain the required reactive power or voltage in the PCC.

HVDC connected active stall wind turbines

HVDC with voltage source converters, described in [13], provide the ability to control the reactive power independently on the grid side (receiving) converter. The reactive power consumption of the wind turbine induction generators can in this case be provided by standard, thyristor switched capacitor banks, because the wind farm side (sending) converter will provide the necessary balancing of reactive power to the wind farm grid.

The wind farm controller presented in section 5.1 can be applied to this concept. Only, the reactive power control of the individual wind turbines should be performed by the wind turbines, independently on the wind farm controller. Instead, the wind farm controller should set the reactive power reference to the grid side converter of the HVDC.

The wind farm controller with grid support according to the functional description in chapter 3 has not been implemented and tested with the HVDC concept in the present work. The HVDC wind farm model has been built on an early stage in the project, with autonomous active and reactive power control of the active stall wind turbines, using the original model with slow power control response [5].

Instead, a wind farm controller for variable speed operation with maximum power tracking was been implemented [14], [15], [16].

4.3   Simulation examples with main grid connection

Simulations of wind turbines and wind farms with a strong connection to a main grid is presented in [12]. In this section, some selected examples are given.

Active stall AC connected

Figure 10 shows the power and the pitch angle response of a single active stall wind turbine when the reference power is stepped down from 2 MW to 0 MW. The new power reference is reached in approximately 4 seconds. The change in the pitch angle is limited to ±8 deg/sec by the pitch rate limiter modelled in the actuator. This is the fastest response we could obtain with a 3p filter on the power.
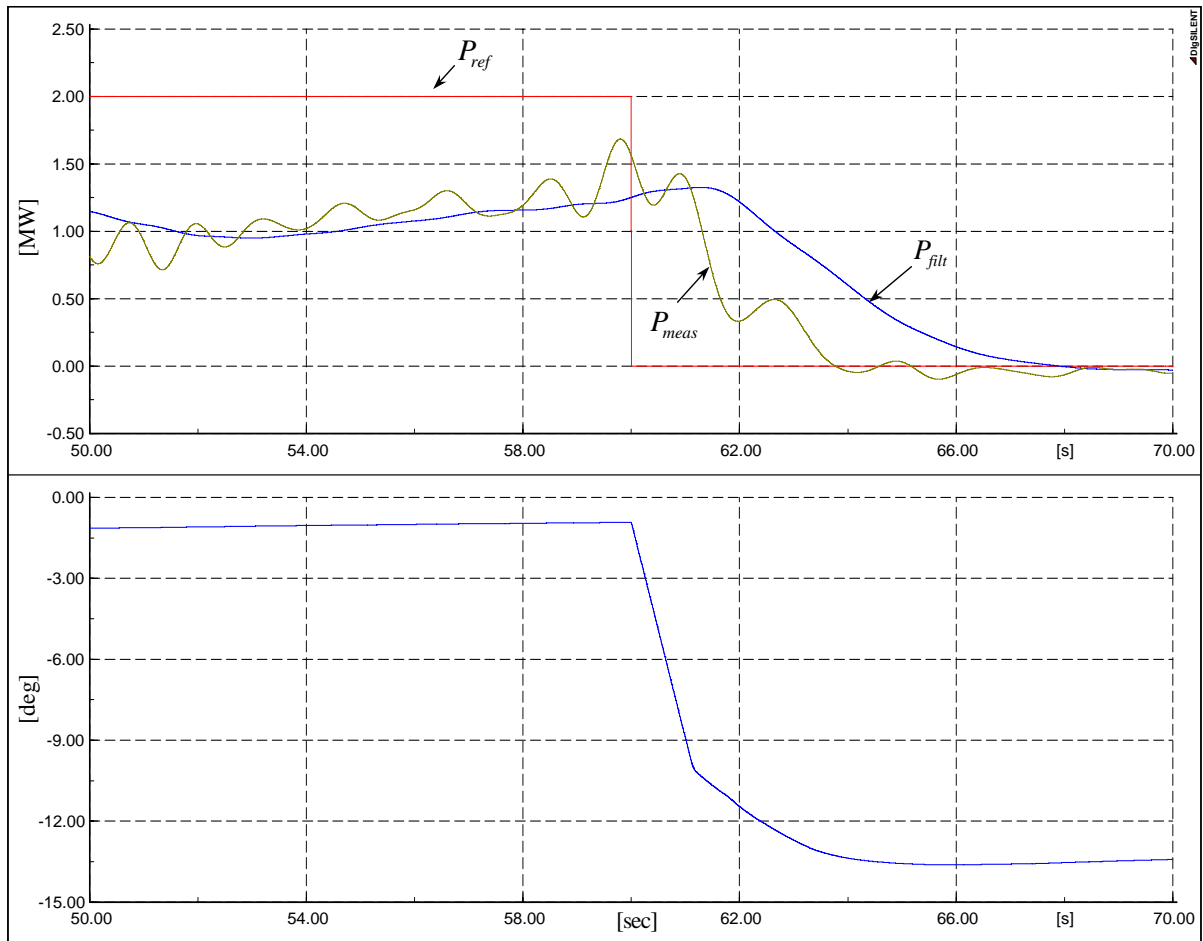
Figure 10: Power reference responses of active stall controlled wind turbine.

Figure 11 illustrates the performance of the wind farm power controller, when the active power demands from the grid operators is stepped down and up to different setpoints. The reactive power reference for the whole wind farm is kept to zero. The wind turbines in the wind farm are driven by different turbulent winds with 9 m/s mean speed value and 10% turbulence intensity. Figure 11 shows the estimated available power, the power demand, the power reference and the measured power in the PCC of the wind farm.
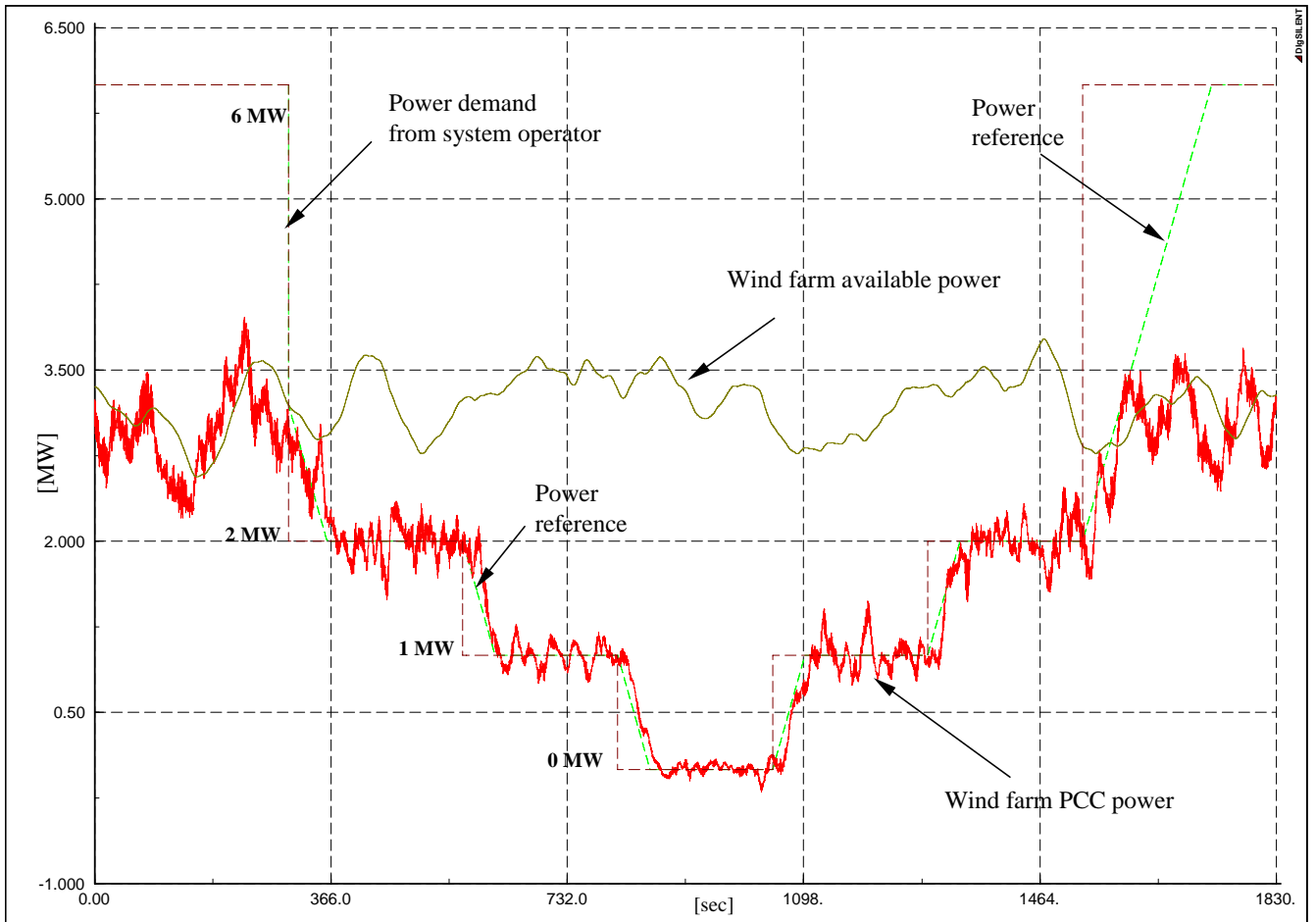
Figure 11: Wind farm response in balance control with stochastic wind speed of 9m/s and turbulence intensity of 10%.

DFIG wind turbines

Figure 12 shows available and actual power in each of the 3 DFIG wind turbines and on the wind farm. It is seen that the wind farm keeps the specified 4MW actual power very smoothly, although the power varies at the individual wind turbines. It can also be observed that the way the wind turbines distribute the power is proportional to the available power.
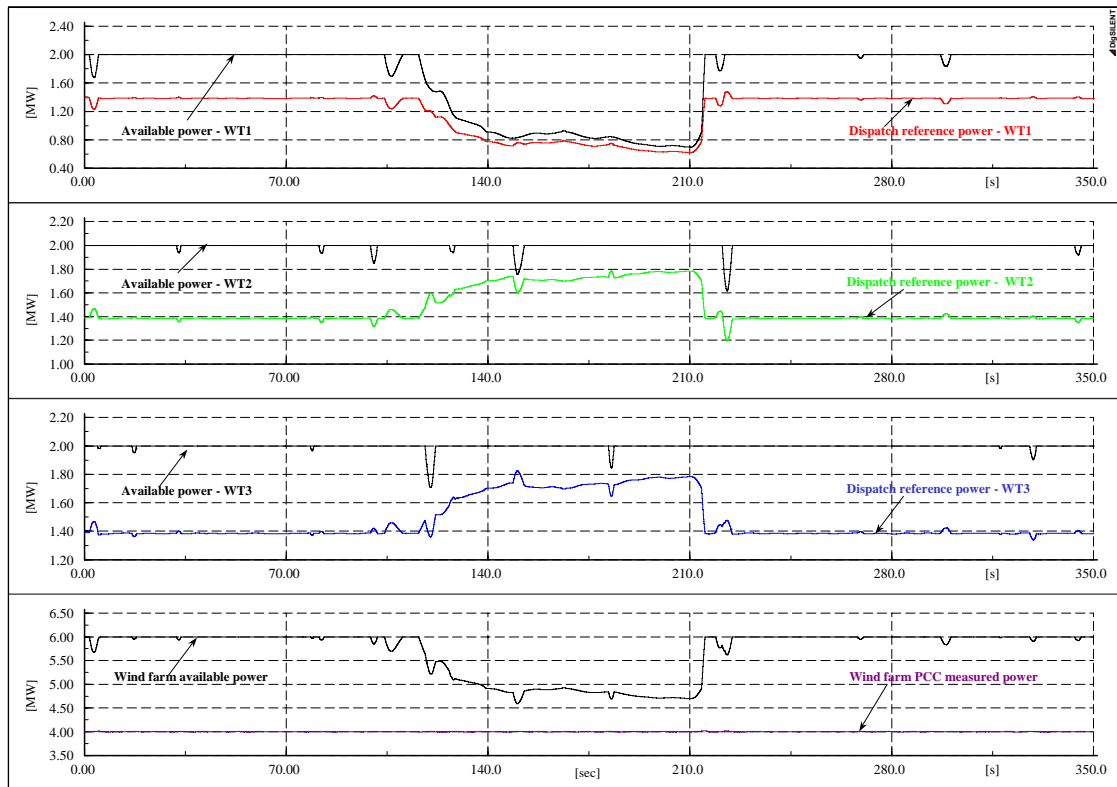
Figure 12 Actual and available power for simulations of wind farm balance control.

HVDC connected active stall wind turbines

Simulation of variable speed operation of HVDC connected wind turbines are shown in Figure 13 and Figure 14. Since the wind farm operate at the same variable frequency, all three wind turbines have the same average rotor speed as shown in Figure 13.
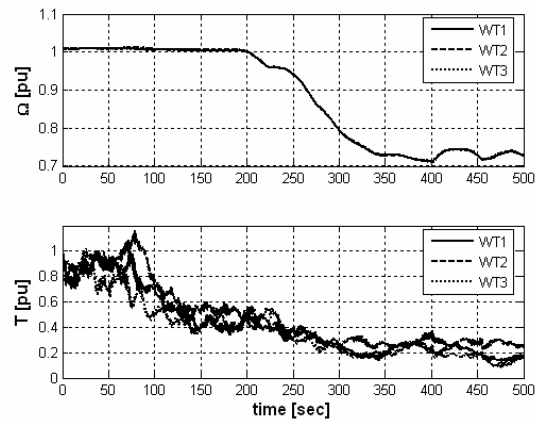

Figure 13. Mechanical torque and rotor speed for each wind turbine.

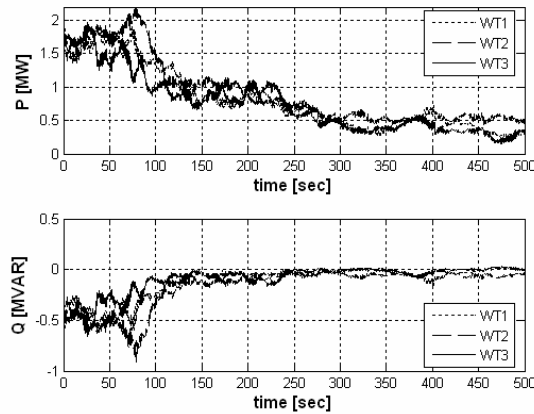The active and reactive power time series with production sign are presented in Figure 14.

Figure 14. Active and reactive power of the wind turbines

4.4 Simulations with isolated operation on local grids

One of the possible applications of the wind farm controllers is to support the power system control when the wind farm is isolated together with a part of the grid, e.g. a local area or a larger area like West Denmark. Some initial work has been done in this area and reported by Sørensen et.al. [17]. Here a selected example is given, which illustrates the ability of a wind farm controller.

The system used in the present simulation is shown in Figure 15. The wind farm consists of 3 active stall controlled wind turbines connected in a single line to the "Station 2" local system bus bar as shown. A static load, an induction motor load and a local CHP are connected directly to the local system bus bar. The local system bus bar is connected to a strong ac grid through a 50/10 kV transformer, and the isolation of the system is simulated by opening the 10 kV grid in the "disconnection point".
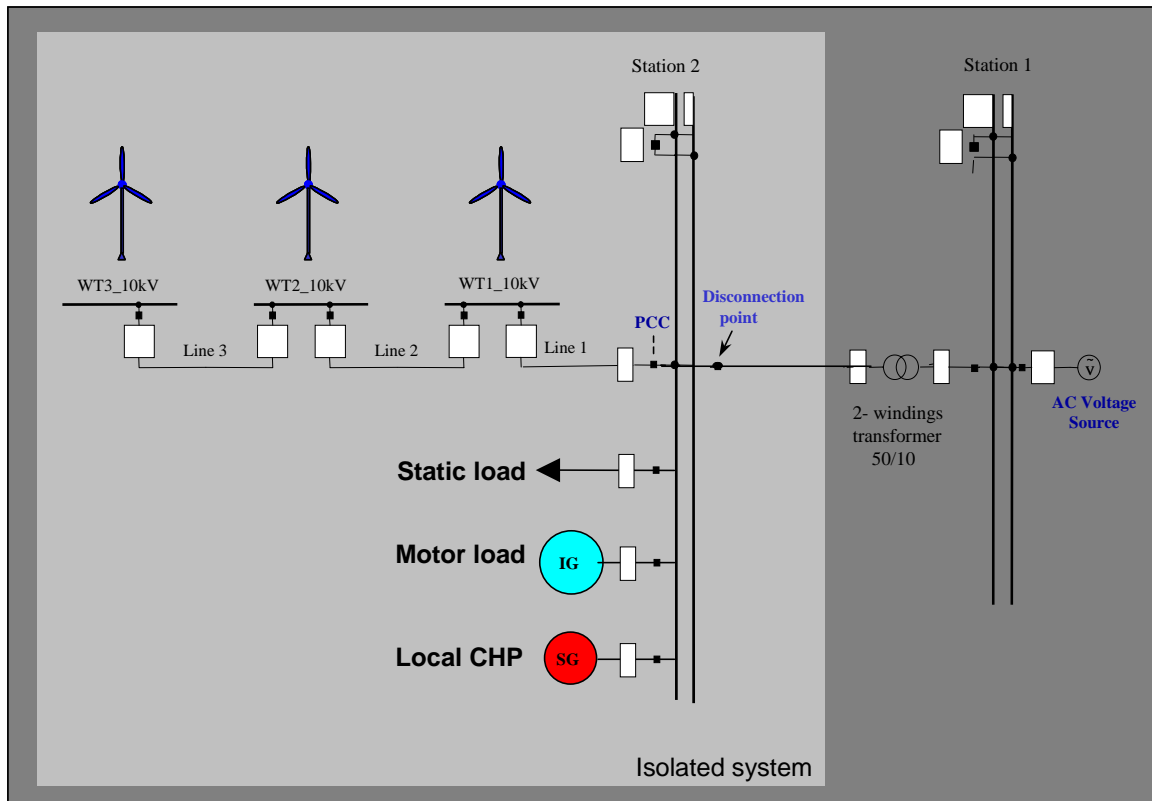
Figure 15: Wind farm grid layout.

Simulations have been done with different combinations of static load, motor load and local CHP. Here, only the simulation results with wind farm and motor load is shown. Figure 16 shows the simulated frequency, power and voltage in the wind farm PCC. It is seen that the wind farm controller is able to control the grid. If the motor load is replaced by the static, voltage dependent and frequency independent load, the system becomes unstable. Thus it is concluded that the wind farm controller can control the grid if there is sufficient inertia on the grid.
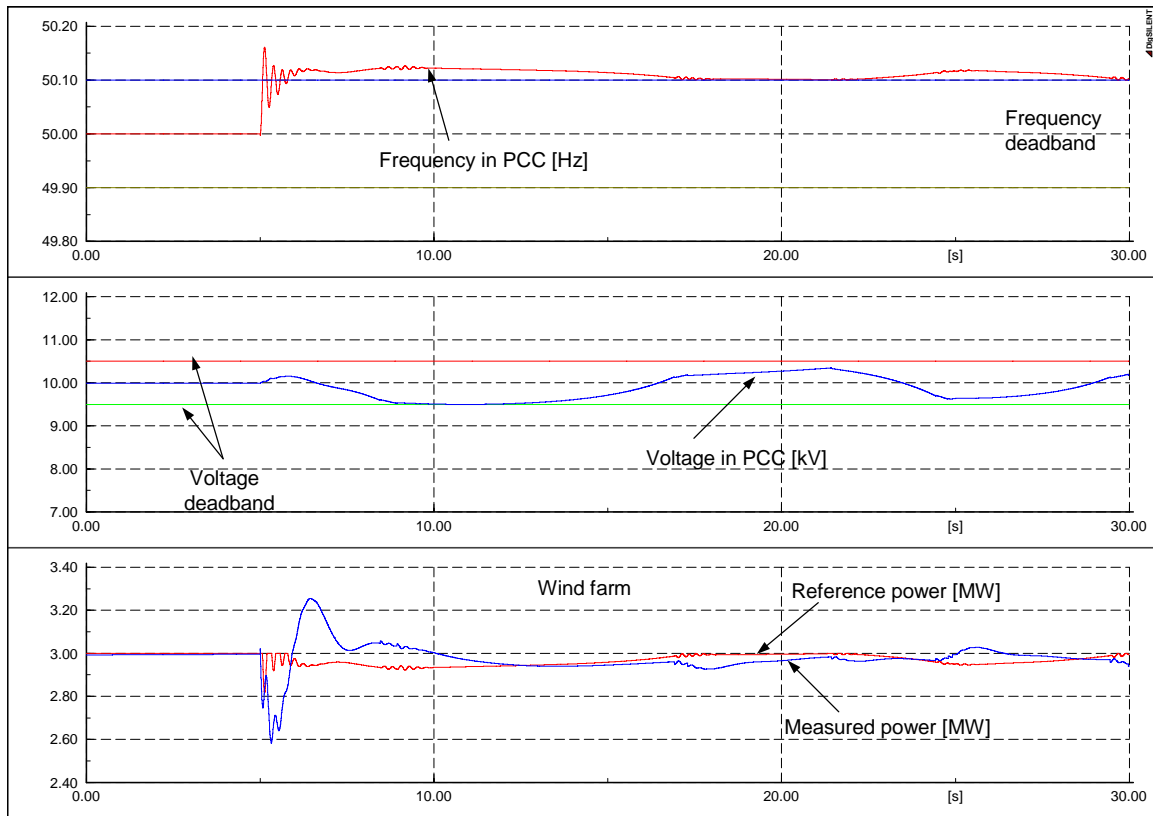
Figure 16: Case B - frequency and voltage control.

5 Revised operational strategies for wind farms

The main objective of this investigation is analyzing the potentials of optimizing the lifetime consumption/energy production ratio by means of using revised operational strategies for a wind turbine operating in a wind farm.

Usually, in the optimization of cost-efficiency of wind turbines the focus is on maximizing the power production with a constraint on the wind turbine loading and the cost calculation of the produced energy is based on an average ratio of total turbine installation cost and total production.

However, the lifetime consumption for a wind turbine is a highly non-linear process, which is not necessarily directly related to the power production. Since the lifetime consumption is related to the amount of material - and thus the cost of each component - it seems more reasonable to assume a relationship between the lifetime consumption, the cost of produced energy and the market price of the electricity produced. Thus, another way of calculating the cost of the produced energy is to calculate the ratio of actual cost - based on actual loading - and the market price of the actual produced energy for a certain load state. In the investigation, we only consider the spot market price variations. Furthermore, it should be noted that production losses and outage time is not included in the analysis.

It is thus one of the main objectives to clarify this potential by implementation of a strategy where the power production is decreased to an optimum when taking loads and actual production cost and the sales price of produced electricity into account.

The investigation in based on full aeroelastic simulations using the aeroelastic model HAWC, and wind farm operation has been simulated using a newly developed method. Simultaneously with the load prediction the variation of electricity spot market price is taken into account and the focus is on the operational strategies for wind farms. This is new compared with previous studies of wind farm optimization,

5.1 Method

In the investigation we use two different approaches. One approach is to redesign a turbine for a specific scenario of wind conditions, operational strategy and electricity spot market structure. This requires information on the cost of the turbine components as a function of the loading. Another approach is to model the operation cost of the turbine already installed and optimize the series of reinvestments - which is introduced as function of the fatigue damage of the different turbine components.

The first approach - **the re-design approach** or **new-turbine-design approach** - is illustrated in Figure 17. Time series of wind speed, wind direction and electricity price are established and the calculations are carried out on an hour-to-hour base. For each hour, the wind speed, the wind direction and the electricity spot price is taken from the input time series and the wake degree is determined from the wind farm layout combined with the wind direction. The first calculation is for the reference turbine and the partial load is chosen to 100%, thus assuming that maximum energy production is aimed in the reference case, despite potential deficit due to lifetime consumption. For the second calculation - with changed strategy – the partial load might be chosen differently. For the actual partial load, the fatigue damage is calculated and accumulated for each hour. At the end of the calculations - the reference case and the changed strategy case - the final fatigue damage is calculated and subsequently the cost of the two cases. Simultaneously the power production and income of the two strategies are calculated and the final cost-efficiency of the changed strategy relative to the reference case can be calculated. This approach can be used to convert lifetime consumption - and power production/income – from one load case to another, through the cost models.

The second approach - the **existing-design approach** - is based on a slightly different methodology. Now it is assumed that the turbine is an already designed turbine and the cost is mainly calculated from the initial investment made. However, some of the turbine components are assumed to experience a reduced lifetime than the design lifetime, and some reinvestments are needed throughout the lifetime. If it is possible to establish a changed operational strategy, which result in a reduction in total cost (initial and reinvestments) than in total income, then the cost-efficiency increases. This approach does not require any pre-knowledge of the initial component cost as function of load, but it is necessary to decide on the actual lifetime of the turbine components for a standard wind condition. Furthermore, the initial investments and the reinvestment cost of components must be known in advance.
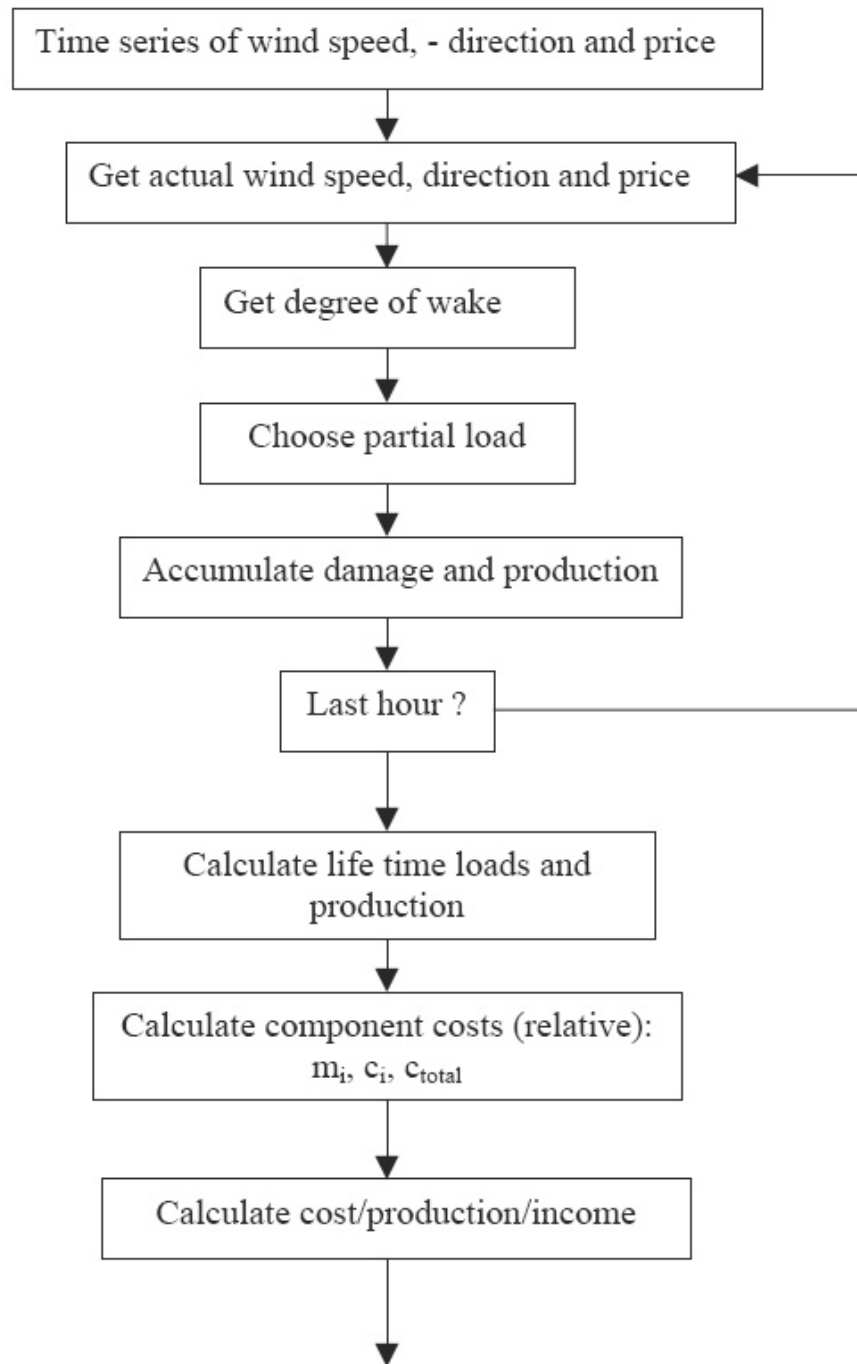
Figure 17 Overview of the model.

5.2 Scenario analysis for the re-design approach

The analysis of the re-design approach is presented in this section. In order to illustrate the method, a simple example of a simulation is presented.

Different input data are used for the simulations. The first input scenario to the model is data from the year 2003[1] and hourly values of wind speed, wind direction and spot market price is used. The data from 2003 is repeated over and over again.
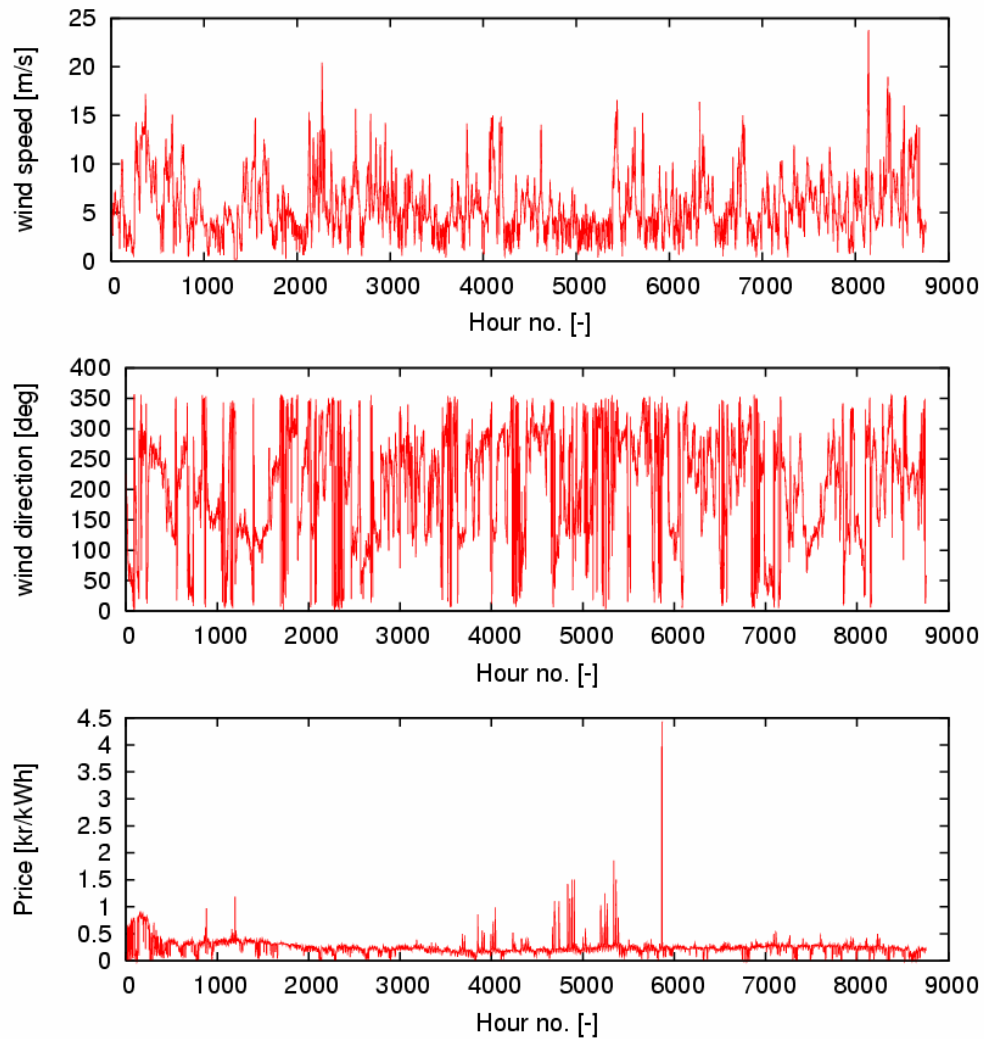

Figure 18 Wind speed, direction and spot market price for year 2003.

The second set of input data used in the simulations is data from the years 2002, 2003 and 2004 - repeated in a three-years sequence.

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[1] All data used is a combination of spot market prices from the ELTRA database and wind measurements from the Risoe meteorology mast
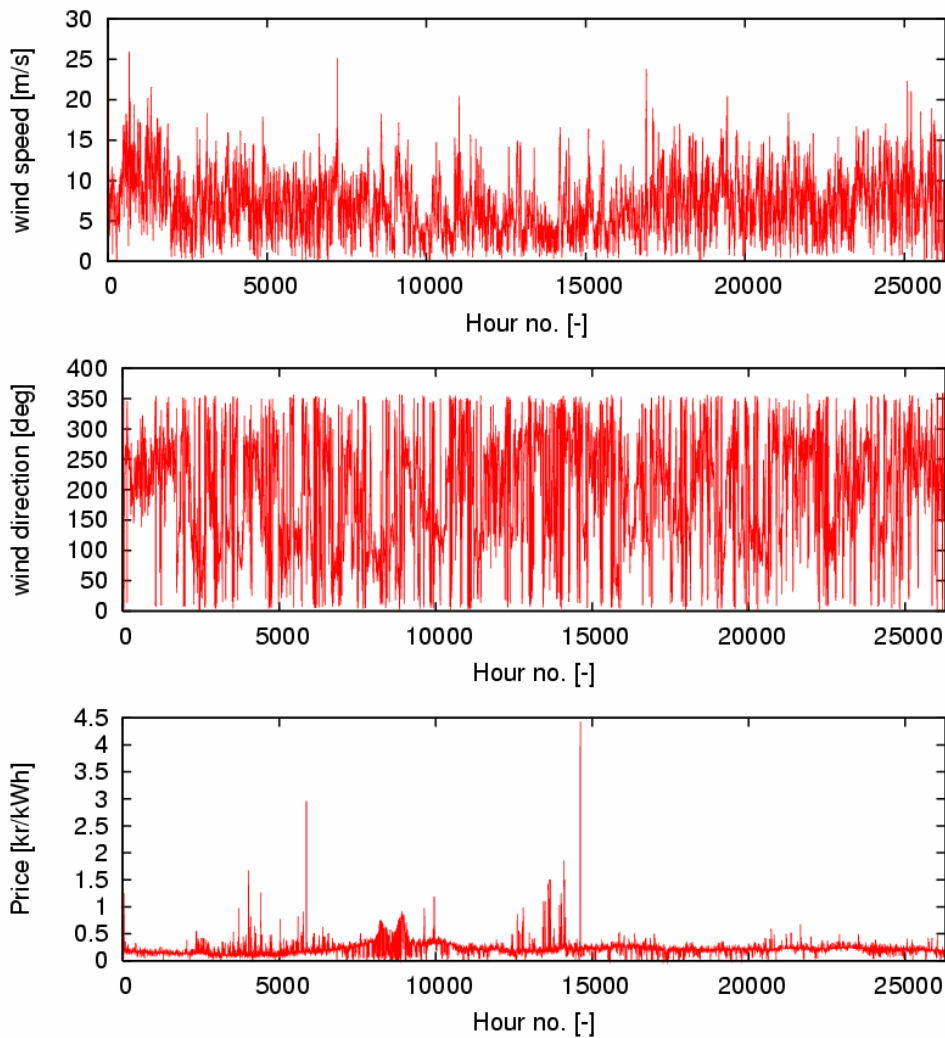
Figure 19 Wind speed, direction and spot market price for years 2002-2004.

Now two scenarios are considered, one where the turbines operates at 100% throughout a lifetime of 20 years and another one where the turbines are shut down if the price is less than 0.1 kr/kWh.

The results for all five turbines illustrate some differences between the individual turbine results. This is mainly due to the correlation between wind direction, wind speed and price. Since these parameters are not uniformly distributed, the wake conditions differ for the individual turbines.

The overall results are that the total production of the wind farm decreases to 86% for the scenario where the turbines are stopped at low prices. At the same time, the income only reduces to 97.5% - since the low price hours are removed. The value of the reduced lifetime consumption amounts only to 0.5% and thus the reduction in total cost is minimal: 99.5%. This is due to a low sensitivity of the cost functions to the loads. The total income relative to the cost covering the 20 years of operation decreases to 98% for the alternative scenario.

A very limited effect on the cost of the turbines is seen. For all cases the relative cost of the revised strategies is approximately 0.995-0.996 while the production is significantly reduced. This illustrates that the cost model sensitivity to loads is low.

5.3   Scenario with variable life time

Another scenario is a case where the number of operational hours at each load case is limited to the number for the reference case. Simultaneously, the price is limited, meaning that below a certain price, the turbines are stopped. For such scenarios, the life time in calendar year can be extended without increasing the fatigue damage above the reference case. The actual operational hours are then the once with a high price and for each load case, the hours are counted. If the numbers of hours reach the reference case, the turbine cannot operate more at this load case. Note, that no conversion of fatigue life time from one load case (through cost models) is carried out, i.e. even if it would be better to spend more hours at 10 m/s than the reference case this is not allowed.

The reference turbine lifetime is selected as 15 years and the price limit is varied from 0.01 kr/kWh to 0.25 kr/kWh. Again, the 2003-year data are used repeatedly. The lifetime of the actual turbine must now be limited in order not to obtain infinite lifetime (depending on the correlation between wind speed, price and actual price limit). The results are calculated for maximum life times of 17-22 years.

The results illustrate a potential increase in income of approximately 10%. For these data, the optimum is for a lifetime of 25 years and a price limit of 0.15 kr/kWh. The results are expected to be highly depended on the input data (the time series of wind speed, direction and prices). Furthermore, operation and maintenance costs are not included in the analysis.
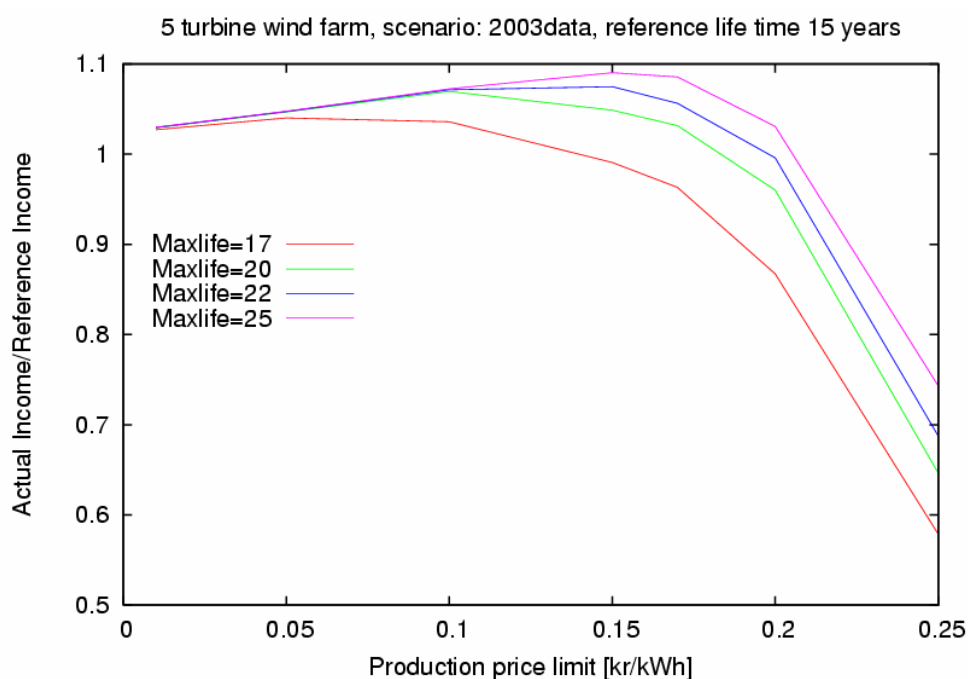

Figure 20 Results for the variable life time case with 2003 data input.

The assumption that the input data from 2003 is repeated over and over again is a crude assumption and in order to illustrate the sensitivity to the input data, another example scenario is investigated. Now, the input data is a sequence built of 2002, 2003 and 2004 data, three year, which then are repeated over and over again. The results are illustrated below and the tendency from the 2003-only case is seen for these input data too.
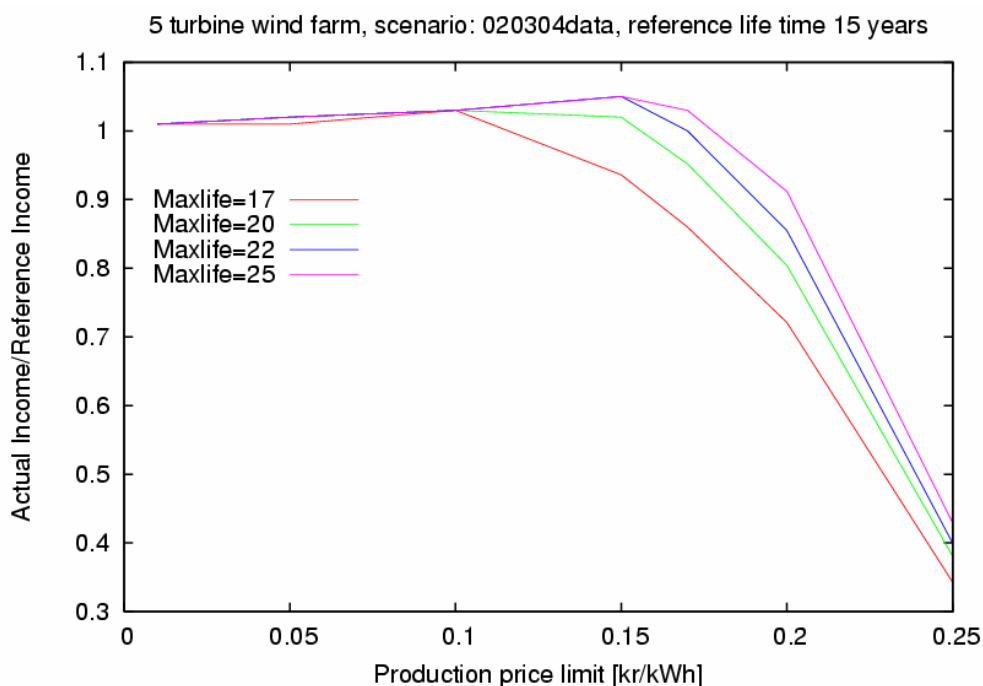

Figure 21 Results for the variable lifetime case with 2002-2003-2004 data input sequence.

The correlation of the market price and the wind conditions is important for the results, and in the future this correlation might change - depending on the wind energy contribution to the energy market. For increasing amount of wind energy, it is realistic to assume that larger variations in the price will occur. The importance of this has been investigated by modifying the 2002-2004 data time series for a 30-year sequence. Variations around the average value have been scaled by a factor of 1.5 and 2.0, respectively. Slightly larger improved cost-efficiency is seen compared to the unscaled case.
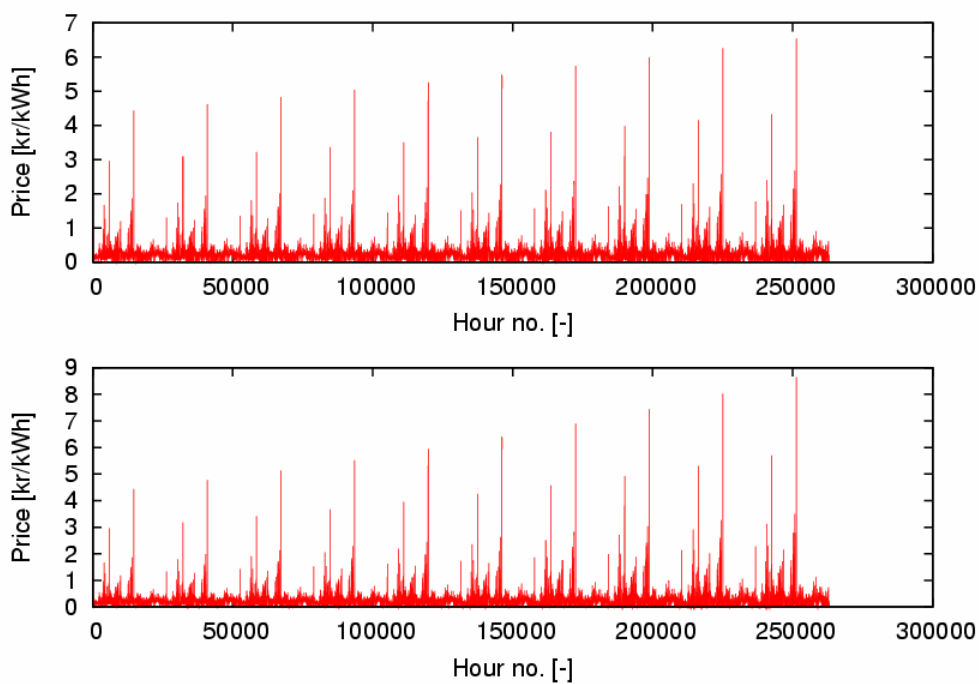
Figure 22 30 year sequence of the price for 2002-2004 scaled with a factor of 1.5 and 2.0.
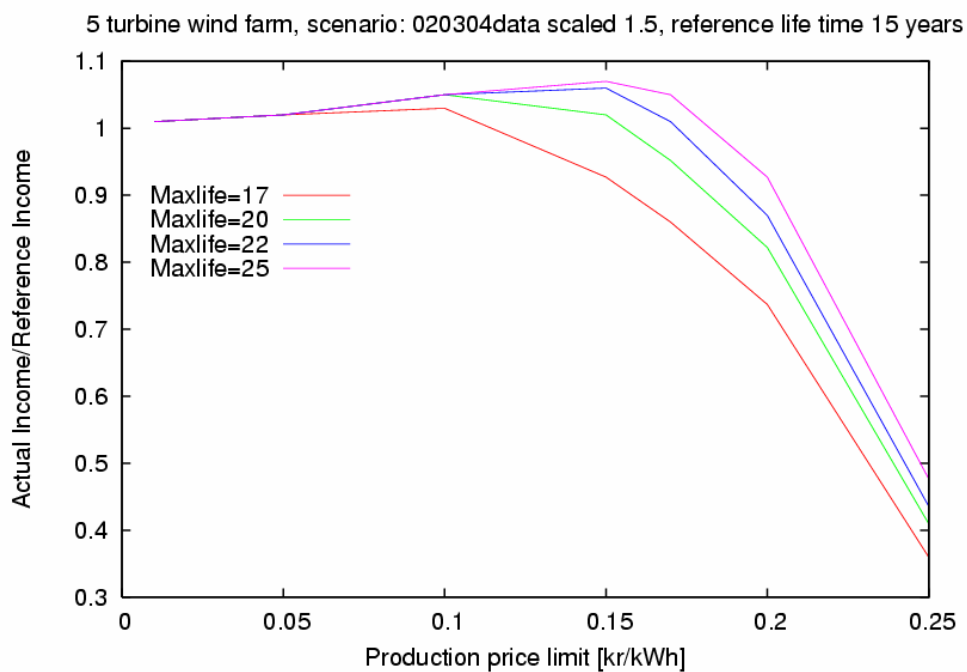

Figure 23 Results for the variable lifetime case with the scaled 2002-2003-2004 data input sequence. The scaling factor is 1.5.
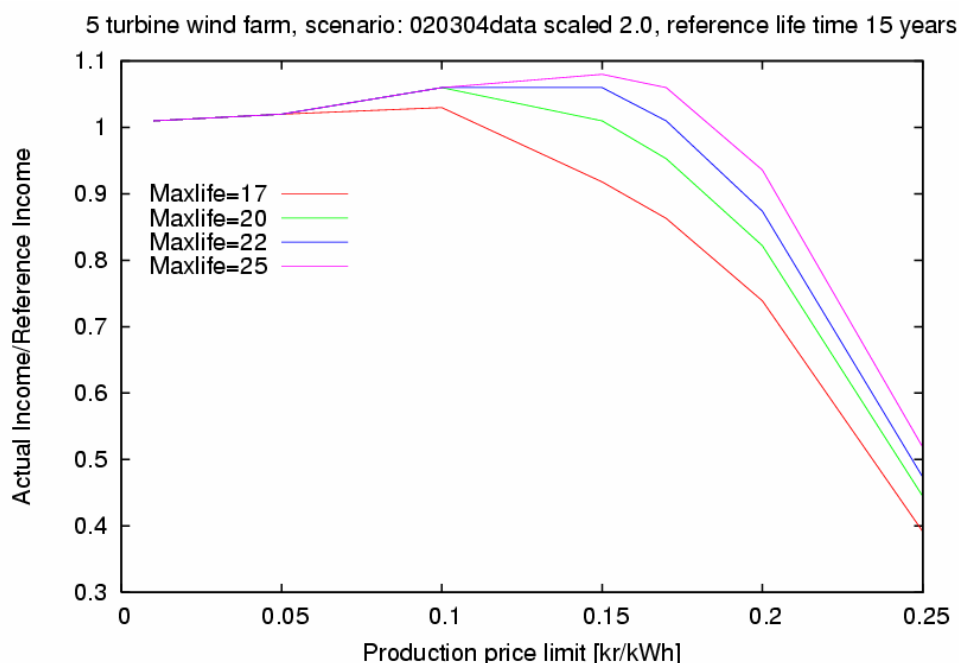
Figure 24 Results for the variable lifetime case with the scaled 2002-2003-2004 data input sequence. The scaling factor is 2.0.

5.4 Scenario analysis for the existing-design approach

In the scenario analysis for the existing-design approach similar input data as in the re-design approach have been used.

The first step in this approach is to run through a standard wind situation (speed and direction) and identify the design damages for each component. These design damages are defined as the damage of relevant load sensors when the component life time is reached. E.g. for the blades - if a life time of 10 years is chosen - the damage of the edge- and flapwise root moments are summarized in a 10 year period and the total damage during these 10 years is then the design damage for the blade component.

The next step is then the reference case, where all turbines are operated at 100% limit. Finally, a revised strategy with a different operational strategy is calculated and the potential improvement in cost-efficiency relative to the reference case is calculated. To illustrate the method a simulation is carried out with the input data from the 2002-2004 series of wind speed and direction and market prices. For this analysis, the revised strategy is a combination of a price limit and a wake degree limit. The price limit is varied from 0.0 to 0.25 kr/kWh and the turbines are all stopped if the actual price is lower than the price limit. Furthermore, the wake degree limit is varied from 1 (no wake operation allowed at all) to 5 (all wake operation is accepted). Note that in these simulations, the operational state of each turbine is either 0% or 100%. The potential of using an intermediate loading (e.g. 25%) has not been included.

It is seen that for most of the wake degree limits the cost efficiency is reduced for the revised operational strategy. For the wake degree limit 5, a minor increase is seen for the lowest price limit values.
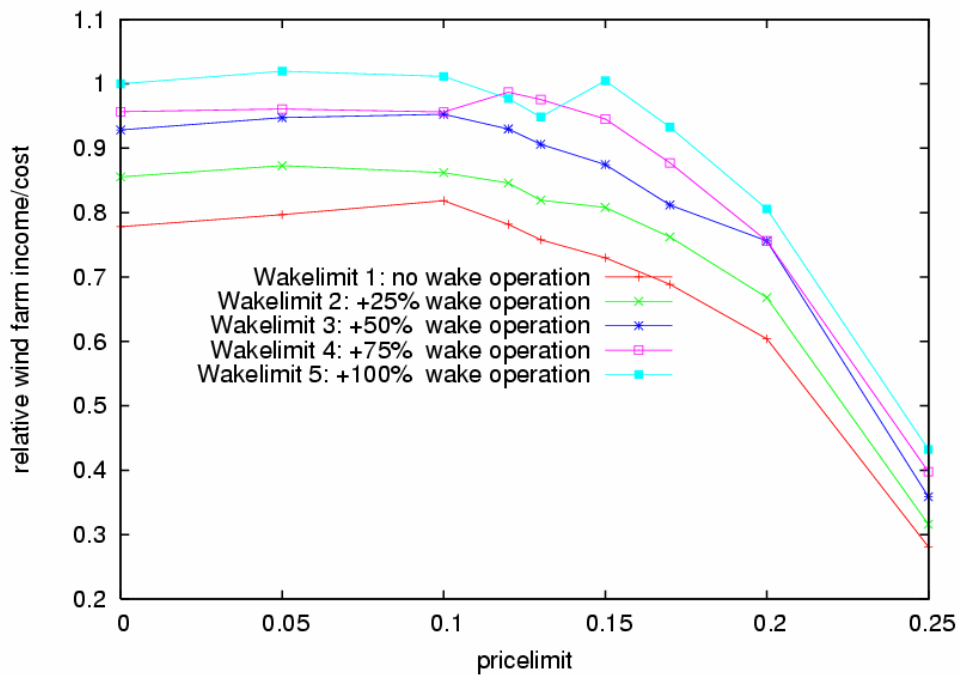
Figure 25 Relative income/cost for different price limits and wake degree limits.

The results from the existing-design approach depend significantly on the ratio of selected lifetime and the assumed lifetime of the individual components. In Figure 26, results from simulations with a lifetime of 16, 20 and 24 years are presented. In the 24-year case, the potential improvement of cost efficiency is relatively large, of the order of 10%. This is due to the fact that in the reference case, an extra set of blades is used for all turbines, since the lifetime of the blades is chosen to be 20 years. For a revised operational strategy, these extra blade replacements can be avoided, i.e. the cost is reduced.
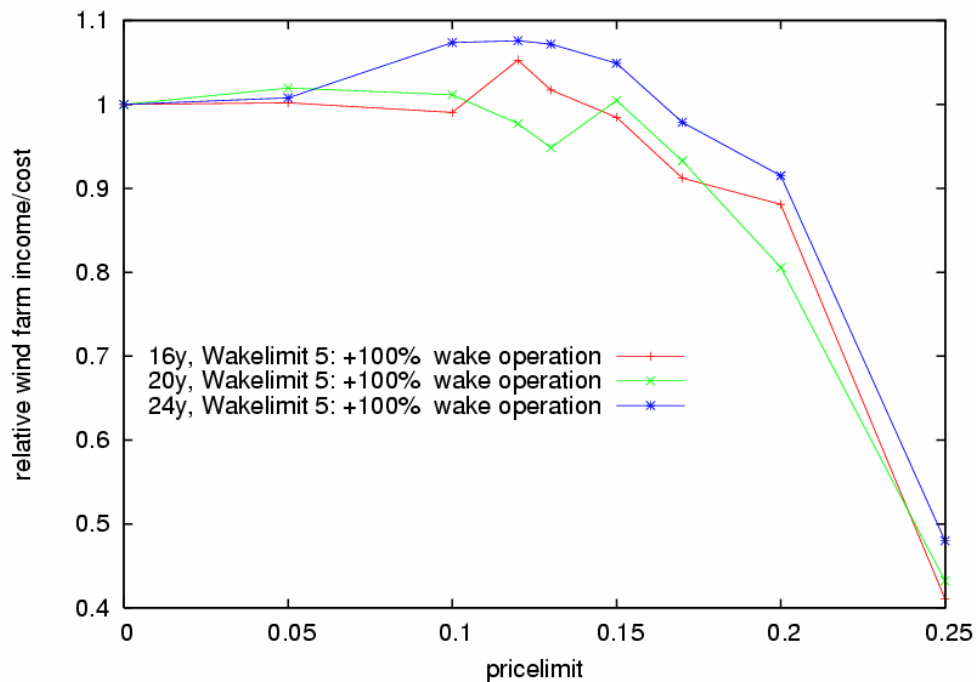
Figure 26 Relative income/cost for different price limits and wake degree limit 5 for a life time of 16, 20 and 24 years, respectively.

Another important parameter for the results is the assumed lifetime of the turbine components. To illustrate this, two extreme simulations have been carried out. The first is for a case with a blade lifetime of 5 years. The second one is for a gearbox lifetime of 2 years. Even for these extreme cases, the increases in cost efficiency are limited for most of the simulations, and the large variation around 1.0 indicates some uncertainty in the method (or in the assumed parameters).
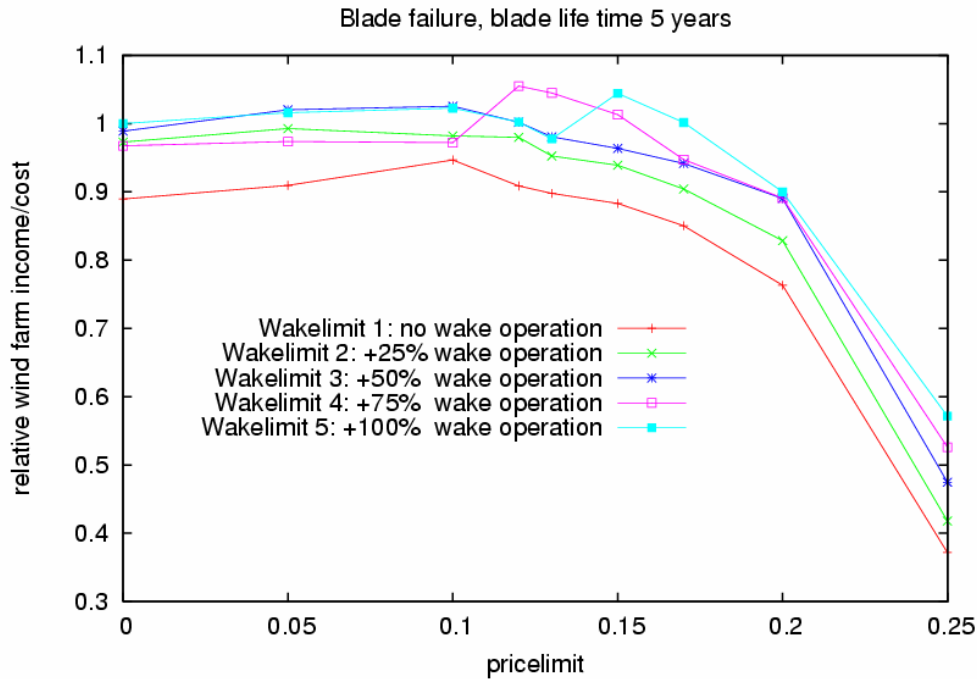

Figure 27 Relative income/cost for different price limits and wake degree limits for a blade lifetime of 5 years.
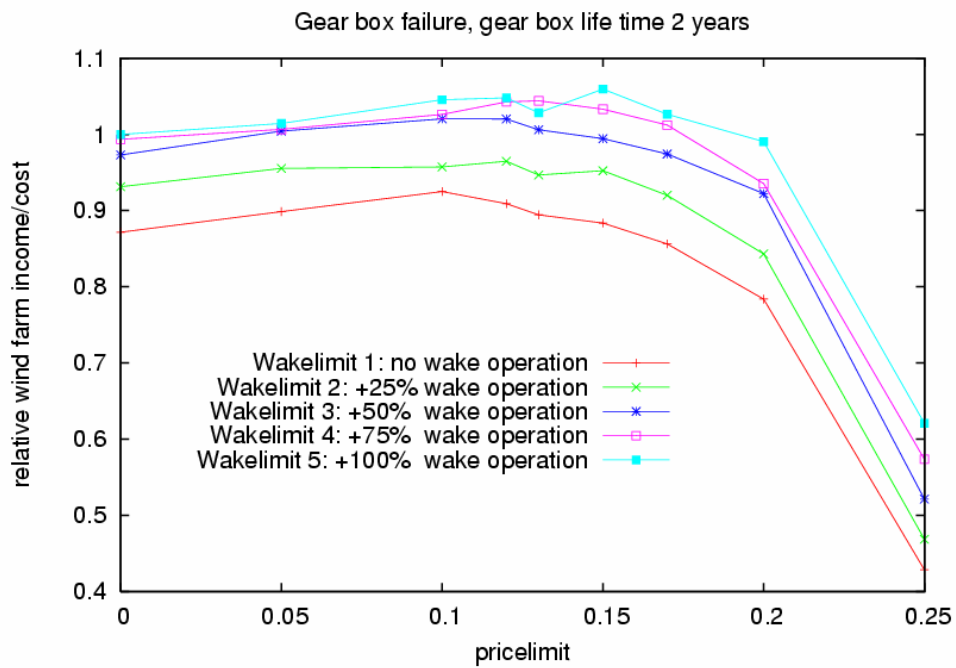
Figure 28 Relative income/cost for different price limits and wake degree limits for a gearbox lifetime of 2 years.

Similar to the re-design approach, modified input data have been used. These data are the 2002-2004 series in a 30 years sequence scaled with a factor of 1.5 and 2.0, respectively. A small influence is seen for price limits between 0.1 and 0.15 kr/kWh, but the overall tendencies are similar for the different sets of input data.
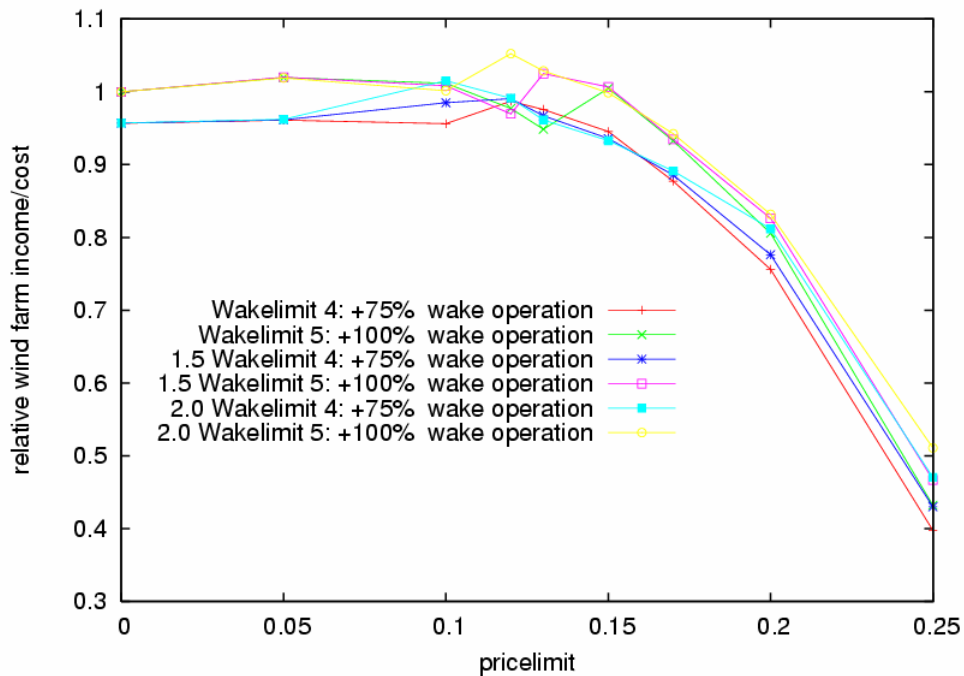

Figure 29 Relative income/cost for different price limits and wake degree limits for scaled market price scenarios.

6 Results

6.1 Prediction of wind fluctuations

Ten second averages of wind speed measured at five masts placed 300m apart is considered in this report and forecasting methods in the minute range is investigated. The data consists of 12 periods of length one hour or more. Initially, the data are analyzed and it is clear that the time delay between masts is roughly determined by the current overall wind speed. Varying time delays are difficult to handle using traditional transfer models and instead a, to our knowledge, novel method is developed. The method applies a continuous time formulation together with spline basis expansions and it is shown that the problem can be reduced to a multiple linear regression problem. Hence, adaptive estimation methods are also available.

The potential prediction performance of a forecast system based on up-stream information is judged in terms of Mean Absolute Error (MAE) and Root Mean Squared Error (RMS). It is clear that the performance depends on the overall level of the wind speed for 5m/s, 10m/s, and 15m/s MAE-values of respectively 0.07m/s, 0.33m/s, and 0.58m/s are obtained. However, quite large deviations for the individual periods are evident. Furthermore, the results have shown that when up-stream information is available, the auto correlation of the wind speeds at the individual masts is not very important.

6.2 Wind turbine and wind farm control

Simulations confirm that the two concepts used in the two large offshore wind farms in Denmark (Doubly-fed in Horns Rev and Combi stall in Nysted) can be controlled by a central wind farm controller to support power /frequency and reactive power / voltage control in the grid.

Dynamic phase control, which is used in the Combi stall wind turbines in Nysted and can be used in similar active stall wind turbines, provides immediate response to reactive power demands. This is very useful, because the voltage can be controlled very quickly that way. The immediate response is obtained in the simulations by introducing hysteresis in the control loop. Alternatively, a low pass filter would be required, which would have slowed down the response.

The Combi stall / active stall wind turbines can also provide a relatively fast response to changes in active power demands. Simulations with tuned, stable and fast controllers, show that a new set point is reached fully in approximately 4 seconds. This is obtained by blade pitching.

Variable speed wind turbines can respond immediately to changes in active as well as reactive power demands. Simulations with wind farm controller show how wind speed dips in one wind turbine can be compensated immediately by other wind turbines, which ensures a constant and very smooth power from the wind farm in the point of common coupling.

6.3 Revised operational strategies for wind farms

A new methodology has been established for prediction of life time costs and income for a wind farm with five turbines. The method enables the possibility of identifying the potentials of improved cost-efficiency for a revised operational strategy for the wind turbines in the wind farm. This revised operational strategy can be based on a variable

market price on electricity, degree of wind farm operation (wake degree) or wind turbine loads in general. It should be noted that production losses and outage time is not included in the analysis.

Two different approaches have been followed. One - the re-design or new-turbine-design approach - is based on cost modelling of the turbines components using the fatigue loads as inputs, while the second approach - the existing-design approach - is based on a presumed life time of the turbine components. In the latter one, the components do not change but are replaced if the design damage is reached.

The results from the re-design approach illustrate that it is necessary to take the variation in electricity price into account when designing operational strategies, rather than concentrate on the total production. In one of the calculations, the total production in a revised operational strategy is 86\% of the reference case, but the income is 98% - indicating the large variation in electricity price and the varying correlation with wind speed/production.

The re-design analysis illustrate that increase in income of 5-10\% is possible if the operational strategy is optimized with respect to both wind conditions and electricity market spot price.

In the re-design scenarios the cost modelling is crucial and in the present investigation the lack of precise input data dominate some of the results. The model is established and the approach seems promising, but better cost model data are needed.

The results from the existing-design approach illustrate a smaller improvement in cost-efficiency than the re-design approach. The largest improvement is seen for the extreme case with a very limited life time of the gear box, and for this case the improvement is of the order of 5%. For more realistic cases, the improvements are limited. One of the reasons for this could be the fact that existing turbines are optimized - in terms of life time consumption - to the typical Danish site wind conditions, which the analysis is based upon. In case of more extreme wind conditions, e.g. complex terrain sites, the established methodology is directly applicable - and the potential of site-specific design of the operational strategy with respect to electricity market price could prove important.

6.4   Project publications

The following publications have been made fully or partly within the project:

[1]   H. A. Nielsen, H. Madsen. Analysis of high-frequency wind speed data. Technical University of Denmark April 2004.

[2]   H. A. Nielsen, H. Madsen. Forecasting wind speeds on the minute time-scale using up-stream information. Technical University of Denmark November 2004.

[3]   H. A. Nielsen, H. Madsen, P. Sørensen. Ultra short term wind forecasting. 2004 European Wind Energy Conference and Exhibition, London (GB), 22-25 Nov 2004.

[4]   M. H. Donovan, H. A. Nielsen. Forecasting wind speeds inside a wind farm. Energy E2. July 2005.

[5]   Jauch, C.; Hansen, A.D.; Sørensen, P.; Blaabjerg, F., Simulation model of an active-stall fixed-speed wind turbine controller. Wind Eng. (2004) 28 , 177-198.

[6]   A. D. Hansen, P. Sørensen, F. Iov, F. Blaabjerg. Grid support of a wind farm with active stall wind turbines and AC grid connection. Submitted to Wind Energy.

[7]   Hansen, A.D.; Iov, F.; Sørensen, P.; Blaabjerg, F., Overall control strategy of variable speed doubly-fed induction generator wind turbine. In: Grid integration and electrical systems of wind turbines and wind farms (CD-ROM). Nordic wind power conference 2004 (NWPC 04), Göteborg (SE), 1-2 Mar 2004. (Chalmers University of Technology, Göteborg, 2004) 7 p.

[8] Hansen, A.D.; Sørensen, P.; Iov, F.; Blaabjerg, F., Control of variable pitch/variable speed wind turbine with doubly-fed induction generator. Wind Eng. (2004) 28 , 411-432

[9] Sørensen, P.; Hansen, A.D.; Thomsen, K.; Madsen, H.; Nielsen, H. Aa.; Poulsen, N. K.; Iov, F; Blaabjerg; F; Okkels, B.K. Simulation and optimisation of wind farm controllers. Proceedings of 2004 European Wind Energy Conference and Exhibition (CD), London (GB), 22-25 Nov 2004.

[10] Sørensen, P.; Hansen, A.D.; Thomsen, K.; Madsen, H.; Nielsen, H.Aa.; Poulsen, N.K.; Iov, F.; Blaabjerg, F.; Donovan, M.H., Wind farm controllers with grid support. In: Proceedings. 5. International workshop on large-scale integration of wind power and transmission networks for offshore wind farms, Glasgow (GB), 7-8 Apr 2005. Ackermann, T.; Matevosyan, J. (eds.), (Royal Institute of Technology, Stockholm, 2005) p. 157-166

[11] Sørensen, P.; Morthorst, P.E.; Thomsen, K.; Nielsen, C.; Hansen, J.C., Wind power plants - status and visions. In: Technologies for sustainable energy development in the long term. Proceedings. Risø international energy conference, Risø (DK), 23-25 May 2005. Sønderberg Petersen, L. ; Larsen, H. (eds.), Risø National Laboratory (DK). Systems Analysis Department; Risø National Laboratory (DK). Information Service Department. Risø-R-1517(EN) (2005) p. 259-271

[12] P. Sørensen, A. D. Hansen, F. Iov, F. Blaabjerg and M. H. Donovan. Wind farm models and control strategies. Risø-R-1464(EN)

[13] F. Iov. VSC based DC transmission system for connecting fixed speed wind farms to grid. Aalborg University September 2004.

[14] F. Iov, P. Soerensen, A. Hansen, F. Blaabjerg Grid connection of active stall wind farms using a VSC based DC transmission system, in Proc. of European Power Electronics Conference EPE 2005, 11-14 September, Dresden, Germany, 10 pp., ISBN 90-75815-08-5

[15] F. Iov, P. Soerensen, A. Hansen, F. Blaabjerg - Variable Frequency operation of Active Stall Wind farms using a DC Connection to Grid, in Proc. of IASTED - Energy and Power System Conference EPS 2005, 18-21 April 2005, Krabi, Thailand, 8 pp., ISBN: 0-88986-494-2

[16] F. Iov, P. Soerensen, A. Hansen, F. Blaabjerg - Modelling and Control of VSC based DC Connection for Active Stall Wind Farms to Grid, in Proc. of IEE - International Power Electronics Conference IPEC 2005, 4-8 April, Niigata, Japan, ISBN 4-88686-065-6

[17] P. Sørensen, A. D. Hansen, F. Iov, F. Blaabjerg. Initial results of local grid control using wind farms with grid support. Risø-R-1529(EN)

[18] K. Thomsen. Operation and control of large wind turbines and wind farms – Design load basis. Risø-I-1967 (April 2003)

[19] Kenneth Thomsen, Thomas Buhl, Poul Erik Morthorst, Lars Henrik Nielsen. Revised operational strategies for wind farms. Risø-I-2387(EN)

Mission

To promote an innovative and environmentally sustainable technological development within the areas of energy, industrial technology and bioproduction through research, innovation and advisory services.

Vision

Risø's research **shall extend the boundaries** for the understanding of nature's processes and interactions right down to the molecular nanoscale.

The results obtained shall **set new trends** for the development of sustainable technologies within the fields of energy, industrial technology and biotechnology.

The efforts made **shall benefit** Danish society and lead to the development of new multi-billion industries.