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# Wake-effect Minimising Optimal Control of Wind Farms, with Load Reduction

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**Abstract:** A power generating wind turbine causes a speed reduction and an added turbulence to the wind. Wind turbines in wind farms are often caught in these wakes and are found to have a higher structural load than non affected wind turbines. This article investigates the possibility of designing a control strategy which optimizes the power production, while minimizing the effect of the wakes in the wind farm.

A generic wind farm model which is able to calculate the wind turbines influence on each other is developed. Models for the reduction in wind speed as well as turbulence in the wake effects are developed in order to simulate the wake effects. The models are of low complexity, making the wind farm model suitable for control purposes.

A model predictive wind farm controller (MPC) is developed and compared to a classical wind farm controller. The MPC is developed, with the ability to minimize the wake effects in the farm, while maintaining optimal power output. A feature which enables the MPC to spare certain turbines, while maintaining the power output is also implemented. The MPC controller is able to minimize the wake effect in the wind farm, when the power demand is not using the full potential of the wind farm.

*Keywords:* Wind Turbine, Wakes, Optimal Control, Wind Farm, Power-system Control.

## 1. INTRODUCTION

It is a known problem, that wind turbines in wind farms cause wakes which affect other wind turbines in the wind farm, Barthelmie and Jensen (2010). The wakes cause a speed reduction of the wind experienced by the wake influenced wind turbine, as a result of the power extracted from the wind, see Sanderse (2009). Furthermore, the wind turbines add turbulence to the wind, thus wind turbines caught in wakes are found to have a higher structural load than non affected turbines, shown in Frandsen et al. (2007). Because of this it would be beneficial to develop a wake minimizing control strategy for a wind farm. Current methods and models to calculate and simulate wakes are computationally heavy, and are therefore ill suited for control purposes, Crespo et al. (1999). This article proposes a method to develop a wake minimizing control strategy, through development of a low complexity model which can simulate the wakes in the wind farms. The methods used in this article are explained in *Modelling* and *Controllers and Estimators*. Hereafter the setup of the tests of the system is described, followed by the results of these tests. The article is concluded with an assessment and conclusion, described in *Discussion* and *Conclusion*.

## 2. MODELING

In order to develop a wind farm model suitable for wind farm control, a model of a single wind turbine is needed. A 2 MW turbine with a rotor diameter of 80 meters is modeled by following the structure described in Hammerum et al. (2007). To reduce the complexity of single wind turbine model is then reduced to a moving average filter, and function which limits the power output. This is required to be able to run the model in reasonable time, which would allow the model to verify that the controller can run at the desired sample rate. The moving average is used to model the dynamics of the wind turbine, which include the local controller for pitch and generator torque. The function is used to limit the power produced by the wind turbine in regards to the power trajectory and wind speed. Thus the single turbine model can be seen as the system shown in Fig. 1.

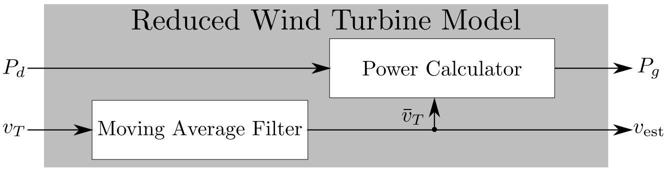

Fig. 1. SIMULINK® structure of the reduced wind turbine model.

The inputs to the model is the power demand ($P_d$) and wind to the turbine ($v_T$) and the outputs is the generated power ($P_g$) and the estimated wind speed at the turbine ($v_{\text{est}}$).

It is verified that the single turbine model and the reduced model share behaviour. This can be seen from the validation shown in Fig. 2.

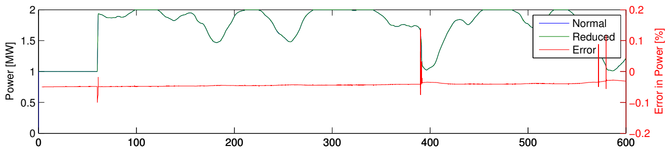

Fig. 2. Simulation results of the reduced, and the simple wind turbine model.

Figure 2 shows the result of a test, where both the simple wind turbine model and the reduced experience the same scenario. Both models are supplied with the same wind, which have a mean of 12 m/s and a turbulence intensity of 10 %. The power demand to the wind turbine is at first 1 MW, but after 60 seconds, it is increased to 2 MW. Thus the reduced model is deemed suitable for use in the wind farm model, since it require less computation power than the normal model.

The wind farm model is of low complexity, making it suitable for control purposes. The model for the wind farm is modularised like shown in Fig. 3. The wake influence calculator is used to calculate the turbines influence on each other. The wind model is used to calculate different wind speeds in the farm which all have the same mean speed but different turbulence. The wake model describes the added turbulence in the wake and a drop in mean wind speed.

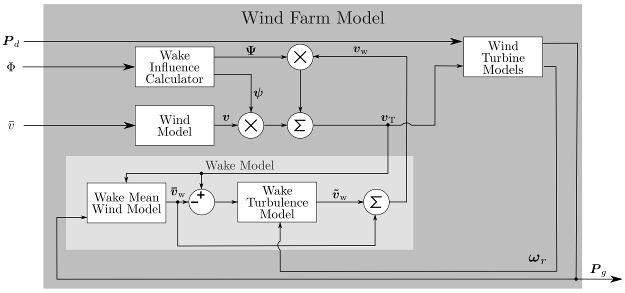

Fig. 3. Modularisation of the wind farm model.

The wake influence calculator utilizes geometry to calculate the wind turbines influence on each other. It is assumed that all wind coming to a wind turbine is uniformly distributed over the span of the blades. Normally the shape of the wakes are conical, but to simplify the model, it is assumed that they are rectangular. By this, the shape of the wakes can be seen in Fig. 4.

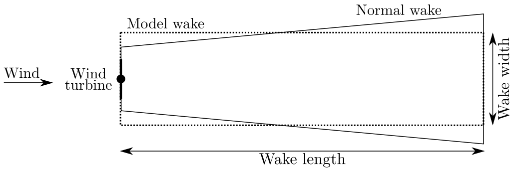

Fig. 4. The difference between the modelled and the normal wake, seen from above.

It is now possible, by using logics and geometry, to calculate to which extent the down wards wind turbines are affected by the wake. In Fig. 5 the length of the wake covered part of the wind turbine is shown. This is of course only possible if the positions of the wind turbines are known.

The coverage is calculated into percent by:

$$\text{Wake}_{\text{coverage}} = \frac{\text{length}_{\text{covered}}}{\text{length}_{\text{rotor}}} \tag{1}$$

Where $\text{Wake}_{\text{coverage}}$ is the percentage of the affected wind turbine which is covered by the wake, $\text{length}_{\text{covered}}$ is the length of the rotor covered by wake and $\text{length}_{\text{rotor}}$ is the length of the rotor.

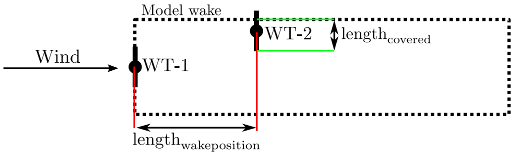

Fig. 5. Scenario with two wind turbines, WT-1 and WT-2, where WT-2 is affected by WT-1's wake.

It is however not only the percentage of wake coverage which is necessary to calculate the wind speed experienced by the wake affected wind turbine. The wake position of the affected wind turbine is also an important factor. The wake speed rises with the surrounding wind, as the $\text{length}_{\text{wakeposition}}$, from the start of the wake to the affected wind turbine increases. This is due to the surrounding wind speeds, and is therefore modelled as a loss in wake coverage, which means the affected wind turbine will be more affected by the non wake affected wind. Therefore, a second percentage is calculated describing the wake position of the affected wind turbine.

This is given by:

$$\text{Wake}_{\text{position}} = \frac{\text{Wakelength} - \text{length}_{\text{wakeposition}}}{\text{Wakelength}} \tag{2}$$

Where $\text{Wake}_{\text{position}}$ is the percentage of how far down the wake the affected wind turbine is positioned, $\text{length}_{\text{wakeposition}}$ is length from start of wake to wake position and Wakelength is the length of the wake.

The wake coverage and position is collected into the matrix $\boldsymbol{\Psi}$ and $\boldsymbol{\psi}$ such that the wind speeds at the wind turbines, $\boldsymbol{v}_T$, can be calculated as:

$$\boldsymbol{v}_T = \boldsymbol{\Psi}\boldsymbol{v}_W + \boldsymbol{\psi}\boldsymbol{v} \tag{3}$$

$$\Psi_{i,p} = \text{Wake}_{\text{coverage},i,\,p} \cdot \text{Wake}_{\text{position},i,\,p} \tag{4}$$

$$\psi_{p,p} = 1 - \sum_{i=1}^{n} \Psi_{i,p} \tag{5}$$

Where $i$ is the index of the wake inflicting turbine, $p$ is the index wake affected turbine and $n$ is the total amount of wind turbines in the farm. $\boldsymbol{\Psi}$ is a square matrix while $\boldsymbol{\psi}$ is a diagonal matrix. The wake length is defined as 10 times the rotor diameter, 80 m. $v_{\mathrm{W},1}$ is the wind speed in the wakes and $v$ is the raw wind speed at the turbines.

The wind model calculates wind at the turbines which is not wake. It is assumed that the all wind turbines in the farm experience the same mean wind speed, which is a slow changing process. However turbulence is added for the individual turbine. This random turbulence is distributed utilizing the Kaimal spectrum. Thus the wind experienced by each turbine is different in turbulence, but the same in mean wind speed.

The wake model consists of two parts. The mean wind speed reduction and the added turbulence. The speed is calculated through the extraction of power from the wind. The formula for the available power in the wind is given as:

$$\boldsymbol{P}_{\text{available}} = \frac{1}{2}\rho A v_T^3 \tag{6}$$

The formula for which the turbine extracts power is the same as (6), but with the coefficient of power ($C_T$) multiplied onto it. Thus the formula for generated power, $\boldsymbol{P}_g = \boldsymbol{P}_{\text{available}} \cdot C_T$. Furthermore a loss in 10 % is added to mechanical loses in the power extraction. Through this, the available wind at the next turbine can be calculated as:

$$\bar{v}_W = \sqrt[3]{\frac{(\boldsymbol{P}_{\text{available}} - \boldsymbol{P}_g \cdot 1.1)}{\frac{1}{2}\rho A}} \tag{7}$$

The turbulence in the wake model is simulated as a sinusoid signal. The setup in which the turbulence model is used is shown in Fig 6. To calculate the turbulence in the wake, the following formula is used:

$$\tilde{v}_{W,i} = \sin\left(3 \cdot \frac{\omega_{r,i}}{60} \cdot t\right) \cdot T_I \cdot S_{D,i} \tag{8}$$

$$S_{D,i} = (v_{T,i} - \bar{v}_{W,i}) \tag{9}$$

Where $\tilde{v}_{W,i}$ is the turbulence in the wake of the i'th wind turbine, $\omega_{r,i}$ is the rotor speed of the i'th wind turbine, $t$ is the simulation time, $T_I$ is the turbulence intensity of the wake and $S_{D,i}$ is the speed reduction over the i'th wind turbine.

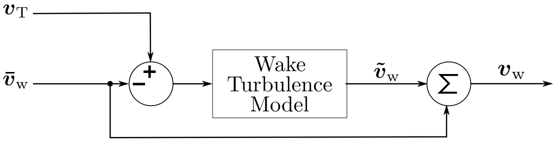

Fig. 6. Setup of the wake turbulence calculator.

## 3. CONTROLLERS AND ESTIMATORS

The setup of the system consist of the wind farm model which is delivered its references for the individual wind turbines, $\boldsymbol{P}_d$, from the controller. The wind farm model outputs an estimate of the wind speed and direction from the individual wind turbines, $\hat{\boldsymbol{v}_T}$ and $\hat{\boldsymbol{\Phi}}$ respectively, to the controller and wind direction estimator respectively. The wind direction estimator, then outputs an estimate of the wind direction, $\hat{\Phi}$. The controller have the wind direction estimate, the estimate of wind speeds at the wind turbines, the power generated and the wind turbine farms power reference, $\boldsymbol{P}_D$, available to calculate the power demands for the individual turbines. This is depicted in Fig 7

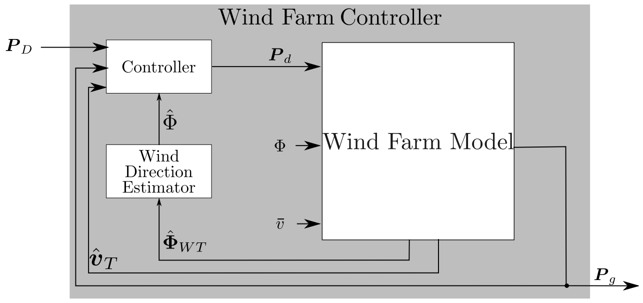

Fig. 7. The setup of the system, which shows the interfaces between the wind farm controller and the wind farm model.

The controllers use the wind speeds at the wind turbines to calculate the power available at the wind turbines. The MPC controller uses this together with the wind direction estimate, to estimate the raw wind coming to the farm. By meaning the wind speeds at the unaffected wind turbines.

The model predictive controller, MPC, uses the wind direction and therefore an estimator for this is developed. The wind turbines is assumed to always be facing the wind direction. The wind turbines do have a sensor for which direction they are facing, but these are often very noisy and possibly with a bias. Data for the output of these sensors is not available, but instead data is generated to represent the output of the sensors.

The wind estimator uses the sensor data from all wind turbines, which is summed into one signal. The mean of this signal over 10 samples, is used to estimate the wind direction.

The classical way of controlling a wind farm, is to distribute the demanded load to the wind turbines in such a way, that they will all produce the same percentage amount of their available power. This is implemented by:

$$P_{\text{d,i}}(k) = \frac{P_{\text{D}}(k) \cdot P_{\text{available,i}}(k)}{\sum P_{\text{available,i}}(k)}$$

$$0 \text{ MW} \leq P_{\text{d,i}}(k) \leq 2 \text{ MW} \tag{10}$$

Where $P_{\text{d,i}}$ is the power demand of wind turbine i, $P_{\text{D}}$ is the power demanded from the grid and $P_{\text{available,i}}$ is the power available at wind turbine i.

The MPC controller developed have three objectives with different priorities:

- **Priority 1:** Minimise error between the wind farms power demand and the total generated power of the wind turbines.
- **Priority 2:** Minimise power loads of predefined specific wind turbines.
- **Priority 3:** Minimise the effect of the wakes by maximising the wind speeds experienced by the wind turbines.

The first priority is implemented directly into the cost function as:

$$\min\left((P_D(k) - \sum_{i=1}^{N} P_{g,i})^2\right) \Rightarrow \min\left((P_D(k) - \sum_{i=1}^{N} P_{d,i})^2\right) \tag{11}$$

Where $i$ is the specifier for the wind turbine and $N$ is the number of wind turbines. This contribution is convex and it is assumed that the power demand is set instantly on the wind turbine.

The second priority is also implemented directly into the cost function as:

$$\min\left(\sum_{i=1}^{N} T_{C,i}P_{d,i}(k)\right) \tag{12}$$

Where $\boldsymbol{T}_C$ defines which wind turbines load to penalize.

As maximizing the wind speed over the wind farm is a direct measure of wake turbulence, with the given model, the last priority is implemented into the cost function as:

$$\begin{aligned}
&\max\left(\boldsymbol{v}_T(k+1)\right) && (13)\\
&= \max\left(\boldsymbol{\Psi}(k)\boldsymbol{v}_W(k+1) + \boldsymbol{\psi}(k+1)\boldsymbol{v}(k+1)\right) && (14)\\
&= \max\left(\boldsymbol{\Psi}(k)(\bar{\boldsymbol{v}}_W(k+1)\right) + \max\left(\boldsymbol{\Psi}(k)\tilde{\boldsymbol{v}}_W(k+1)\right) && (15)
\end{aligned}$$

It is chosen to omit the contribution of this in the cost function. This will result in non optimal solutions but also leaves room for improvement if a more adequate model of the wake turbulence is implemented. The definition for the wake mean speed model is used and we acquire:

$$\begin{aligned}
&\max\left(\boldsymbol{\Psi}(k)\bar{\boldsymbol{v}}_W(k)\right)\\
&= \max\left(\sum_{j=1}^{N}\sum_{i=1}^{N}\boldsymbol{\Psi}_{j,i}(k)\sqrt[3]{\frac{\boldsymbol{P}_{\mathrm{avaiable,i}}(k) - \boldsymbol{P}_{g,i}(k)\cdot 1.1}{\frac{1}{2}\rho A}}\right)
\end{aligned} \tag{16}$$

As it is not possible to extract more energy than available, the content of the root is positive semi definite. Thus the root can be removed in an optimization problem. And by removing the constants, variables which current state are independent of changes in $P_{g,i}$, and assuming that the power demanded from the turbine is applied instantly, we obtain:

$$\min\left(\sum_{j=1}^{N}\sum_{i=1}^{N}\Psi_{j,i}(k)p_{d,i}(k)\right) \tag{17}$$

Where $i$ is the specifier for the wake inflicting wind turbine and $j$ is the specifier for the wake inflicted wind turbine.

The constraints which need to be fulfilled when solving the optimization problem are; the power demanded from each wind turbine can only be set between 0 W and the maximal power extractable at the current wind speed and the wind speed calculated for the next sample must be positive semi definite. Thus the complete cost function and constraints of the MPC are then:

$$\begin{aligned}
\min\Bigg(&\left(P_D(k) - \sum_{i=1}^{N}P_{d,i}\right)^2\cdot K_1 && (18)\\
&+\left(\sum_{i=1}^{N}T_{C,i}P_{d,i}(k)\right)\cdot K_2 + \left(\sum_{j=1}^{N}\sum_{i=1}^{N}\Psi_{j,i}(k)p_{d,i}(k)\right)\cdot K_3\Bigg)
\end{aligned}$$

subject to

$$0 \le \boldsymbol{\Psi}(k)\sqrt[3]{\frac{\boldsymbol{P}_{\mathrm{avaiable}}(k) - \boldsymbol{P}_d(k)\cdot 1.1}{\frac{1}{2}\rho A}} + \boldsymbol{\psi}(k)v(k)$$

$$0 \le \boldsymbol{P}_d \le \boldsymbol{P}_{dmax}$$

Where the weights are chosen to be $K_1 = 10^9$, $K_2 = 10^{-6}$ and $K_3 = 10^{-9}$.

The MPC is implemented in MATLAB®, and solved by using Grant et al. (2008).

## 4. TEST DESCRIPTION

The test of the developed control method are designed to test the performance, in regards of power production, of the MPC controller compared to a classical controller which is used in some wind farms today, Grunnet et al. (2010) and Kristoffersen and Christiansen (2003). Furthermore the test of the system evaluates the difference in wind speeds experienced by the wind turbines and the difference in wake turbulence experienced by the wind turbines. The test of the system is conducted on a three by three wind farm using the reduced model to model the individual turbines, where the wind turbines are placed in a grid with a spacing of 300 meters. This farm is depicted in Fig. 8.

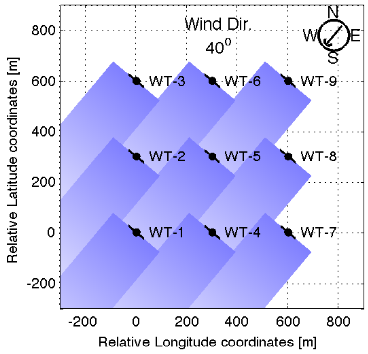

Fig. 8. The virtual wind farm on which the controllers are tested. Wakes developed with a wind direction of 40° and their intensity are depicted in shades of blue.

The wind experienced by the wind turbines are generated by using the wind model developed which is supplied with the average wind speed. The average wind speed is extracted from a real data set. The data set is chosen such that the average wind speed is sufficient for the wind turbines to operate, but not high enough for the wind farm to operate at full capacity.

The wind direction will be modelled as a random walk, such that the wind direction change with time. The process is modelled as shown in (19), where $\nu$ is a normally distributed random number. In order to be able to compare the test results, it is chosen that all tests have a starting wind direction of 180°.

$$\Phi(k+1) = \Phi(k) + \nu \tag{19}$$

A rate limiter is implemented on both controllers. The maximum rate the reference can change is chosen to be 20 % of the rated power, therefore the wind turbines individual power demand can not change faster than:

$$\max(\dot{P}_{\mathrm{d,i}}) = 0.4\ {}^{\mathrm{MW}}\!/_{\mathrm{s}} \tag{20}$$

To avoid aliasing in the wakes the wind farm model is sampled at 4 Hz. The overall power demand for the wind farm, $P_D$, changes at 0.25 Hz. The controllers however are setting power demands for the wind turbines at 1 Hz. This ensures that it will be possible to implement the MPC in real time.

The controllers are tested in three test scenarios.

In the first scenario the wind farm must produce as much power as possible, and the power demand of the farm is therefore the rated power of the farm. This scenario evaluates the controllers ability to maximise the power available.

The second scenario evaluates how well the controllers can make the wind farm follow a power reference, therefore the power reference is set to half of the rated power of the wind farm.

The third scenario evaluates the controllers, when inflicted with a random power demand to the farm. This test is made in order to analyse the behaviour of the controllers when the power demand is switching. A random walk ensures correlation between the power demands and sets a soft boundary on the speed of the change in demanded power.

All three scenarios are evaluated firstly with all wind turbines functioning properly, and secondly with 2 of the wind turbines, 6 and 7, simulated damaged. The second term evaluates the controllers ability to reduce loads on damaged turbines.

In total six tests will be conducted on the system, and the tests will all be executed 10 times to ensure that the behaviour is consistent. The complete list of tests is listed in Table 1.

| Test no. | Description | Scenario |
|---|---|---|
| **Test 1**: | 18 MW power reference. | Scenario 1 |
| **Test 2**: | 18 MW power reference whilst reducing loads on wind turbines 6 and 7. | Scenario 1 |
| **Test 3**: | 9 MW power reference. | Scenario 2 |
| **Test 4**: | 9 MW power reference whilst reducing loads on wind turbines 6 and 7. | Scenario 2 |
| **Test 5**: | Random power reference initiated in 9 MW. | Scenario 3 |
| **Test 6**: | Random power reference initiated in 9 whilst reducing loads on wind turbines 6 and 7. | Scenario 3 |

Table 1. List of tests conducted on the setup.

As the purpose of the comparison is purely to evaluate the MPC against the classic controller, there is only one strict success criterion:

*For 95 % of the time the wind farm must produce power within 5 % of the power demanded, when available, throughout all test runs. Otherwise the wind farm must produce power within 5 % of the power available.*

## 5. RESULTS

The deviation from the power reference is evaluated over all test-runs. For all of the data collected throughout the test, the classical controller was within 5% deviation for 99.9091% of the time, whilst the MPC was within 5% for 99.8410% of the time.

It is wanted to evaluate the difference in, power generation in the farm, **PGF**, The wind speeds- **WS**, and wake turbulence experienced by the turbines, **WT**, between the controllers. The data is presented in Table 2, where the differences between the results from the MPC controller and the classic controller are shown. These values are the mean for all ten test runs.

| | PGF | WS | WT |
|---|---|---|---|
| **Test 1** | -0.0045% | 0.0000% | -0.0060% |
| **Test 2** | -0.0052% | 0.0000% | -0.0079% |
| **Test 3** | -0.0438% | 0.8938% | -14.4299% |
| **Test 4** | -0.9456% | -0.0640% | 7.8491% |
| **Test 5** | -0.1099 % | 0.0142% | -11.2595% |
| **Test 6** | -0.3817% | 0.1257% | 0.5126% |

Table 2. The difference in **PGF**, **WS** and **WT** for the MPC controlled wind turbine farm, compared to the classically controlled

The differences, in individual power generation of the turbines, for the MPC controlled wind turbine farm compared to the classically controlled, are shown in Table 3. These results are the mean for all ten test runs.

| Test | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| **WT-1** | 0% | 0% | -14% | 18% | -10% | 5% |
| **WT-2** | 0% | 0% | -11% | 18% | -9% | 9% |
| **WT-3** | 0% | 0% | 27% | 19% | 21% | 28% |
| **WT-4** | 0% | 0% | -14% | 20% | -11% | 6% |
| **WT-5** | 0% | 0% | -11% | 16% | -10% | 8% |
| **WT-6** | 0% | 0% | 27% | -80% | 21% | -54% |
| **WT-7** | 0% | 0% | -10% | -88% | -9% | -56% |
| **WT-8** | 0% | 0% | -11% | 36% | -9% | 18% |
| **WT-9** | 0% | 0% | 27% | 30% | 22% | 34% |

Table 3. The difference in power generation for the MPC controlled wind turbines, compared to the classically controlled.

## 6. DISCUSSION

Both controllers are evaluated on their ability to track the power reference of the wind farm. It is seen that for both controllers, the generated power deviate from the reference. The deviation is however less 0.2 % in the MPC case, and 0.1 % in the classic case. These deviations are due to the rate limits of both wind farm controllers.

In test 1 it is seen that both controllers behave alike with regards to power production, wind speeds, wake turbulence and individual power generation of the turbines. This was expected since they both run the same model and both run at maximum capacity.

As scenario 1 maximises the farm power production, there is no room for wind turbine 6 and 7 to be spared in test 2. Like in test 1, the differences between the control of the two farms are almost equal to none.

It can be seen in test 3 that the wake is minimised and as a result of this, the wind speed in the wind farm increases. The difference in power production is seen to be below 1 %. The individual wind turbines power production show that wind turbines 3, 6 and 9 are producing more power, when using the MPC. These are producing more power as the wind direction, initiated at 180°, cause that these wind turbines will not produce any wake which affects other wind turbines.

In test 4 the wake turbulence is lower in the classical controlled farm, as the wind turbine 6 and 7 being spared.

The MPC see the sparing of these wind turbines as of greater importance than minimising the wakes. It is also seen that the power generated by the MPC is about 2 % lower than the classical controller. It can be seen that wind turbine 6 and 7 are spared resulting in the rest of the wind turbines are producing more, as these wind turbines have to compensate for the lack of power production from wind turbine 6 and 7.

In test 5 it is seen that the wake turbulence is decreased by using the MPC. The difference in generated power is close to zero, but in favour of the classic controller. This is again believed to be due to the rate limit. Wind turbine 3, 6 and 9 are producing most power, seeing that the wind direction is approximately 180° and the wake of these therefore would affect none of the remaining wind turbines, whilst the remaining wind turbines compensate for the loss in power generation.

The overall the power production, in test 6, is lower when using the MPC, than the classical. It is seen that wind turbines 6 and 7 are producing less power, and the remaining produce more when compared to the classical controller in order to compensate for the sparing of the two damaged wind turbines.

In test 4, 5, and 6 the MPC controller reduces the power production compared to the classical controller. This is undesirable but it is coming from the fact that the MPC controller is not taking the rate limits into account, another source for the reduced power is coming from the design of the cost function (18). Since the error on the power production is included in the cost function, the MPC cost might be reduced if it is not following the power reference and thereby enable and reduction in the loads and the turbulence over the farm causing a reduction of the over all cost at the cost of a small loss in production.

## 7. CONCLUSION

To be able to control the wind farm, a generic wind farm model for the wind turbines including the wake influence on one another is developed. The generic model is developed with the purpose of testing and designing wind farm controllers.

A MPC wind farm controllers is developed, and a classic controller is implemented. The classic controller uses the control method currently used in wind farms. The MPC uses model predictive control to minimise wakes in the wind farm. The MPC also holds a function to spare specific wind turbines in the wind farm. In order to optimize the power production, the wind farm has to produce as much power as possible, however the optimal power production of the MPC cannot exceed the production of the classical controller.

A comparison test of the two control methods is carried out, where the controllers are tested in three different scenarios. The tests show that the classical and MPC behave the same in the first scenario, which is to be expected due to both controllers are maximising power production. The second scenario shows that the MPC is able to reduce the wake turbulence in the wind farms. The test in this scenario where two wind turbines is spared shows that the wind turbines are spared, as much as possible. This however has impact on the reduction of wake turbulence in the wind farm, since the remaining wind turbines have to compensate for the loss of power generation of the two. In the third scenario, where the power demand is a random walk, it is shown that the MPC is able to minimise the wakes when the power demand is not maxing out the winds potential.

It can be concluded, that the MPC is able to maximise the power production of the wind farm, with regards to maximum production. It is also able to minimise wakes when the power demand allows it. Furthermore the MPC is able to spare certain wind turbines, when the power demand allows it.

The wake minimising will reduce the turbulence in the wind farms and thus reduce the loads on the wind turbines. The ability to spare a wind turbine which is worn down gives the wind farm owner the ability to spare these wind turbines as much as possible, without having to shut them completely down and thereby reducing the maximum potential of the wind farm.

The developed MPC does currently not take the rate limit of the wind turbines into consideration. To improve the MPC this could be included in the optimization, as well as a horizon which would predict the future control signals to the wind turbines in the farm. When introducing this horizon, the MPC could benefit of a prediction of future "raw" wind coming to the wind farm, together with the future power demands. By this, the MPC would be able to smooth the power demands to the wind farm, and thus decrease quick changes in loads. And thereby outperform the classical controller which does not have these possibilities.

## REFERENCES

Barthelmie, R.J. and Jensen, L.E. (2010). Evaluation of wind farm efficiency and wind turbine wakes at the nysted offshore wind farm. *Wind Energy*, 13(6), 573–586.

Crespo, A., Hernandez, J., and Frandsen, S. (1999). Survey of modelling methods for wind turbine wakes and wind farms. *Wind energy*, 2(1), 1–24.

Frandsen, S.T. et al. (2007). *Turbulence and turbulence-generated structural loading in wind turbine clusters.* Risø National Laboratory.

Grant, M., Boyd, S., and Ye, Y. (2008). Cvx: Matlab software for disciplined convex programming.

Grunnet, J.D., Soltani, M., Knudsen, T., Kragelund, M.N., and Bak, T. (2010). Aeolus toolbox for dynamics wind farm model, simulation and control.

Hammerum, K., Brath, P., and Poulsen, N.K. (2007). A fatigue approach to wind turbine control. In *Journal of Physics: Conference Series*, volume 75, 012081. IOP Publishing.

Kristoffersen, J.R. and Christiansen, P. (2003). Horns rev offshore windfarm: its main controller and remote control system. *Wind Engineering*, 27(5), 351–359.

Sanderse, B. (2009). Aerodynamics of wind turbine wakes. *Energy Research Center of the Netherlands (ECN), ECN-E–09-016, Petten, The Netherlands, Tech. Rep.*