Wind farm modeling and control: an inventory

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Abstract

Within the FLOW project "Wind Farm Wake Modelling, Fatigue Loads and Control" (FLOW P201102-004-ECN), research is performed on novel methods for improved modeling and control of wind farms. This document represents Deliverable 3.1 "An inventory of different control strategies and definition of cases to assess these control strategies" of the project, and provides an overview of the literature on the topics of active and reactive wind farm control and wind farm modeling for control.

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Introduction

This report represents Deliverable 3.1 “An inventory of different control strategies and definition of cases to assess these control strategies” of the FLOW project “Wind Farm Wake Modelling, Fatigue Loads and Control” (FLOW P201102-004-ECN). It provides an inventory of the existing literature on the following topics:

- active power control of wind farms (Section 2),
- reactive power control of wind farms (Section 3),
- wind farm models for controller design and evaluations purposes (Section 4).

This inventory is meant to serve as basis for the development of a wind farm controller that achieves improved power production and/or reduced loads operation of the whole wind farm under different operating conditions. However, the scope of this project is development of the active power dispatcher such that the power reference signals help in reducing wind turbine loads and maximizing the total produced power (or satisfy the produced power by the operator).

Purpose of a wind farm controller

Wind farm controller has many possible functions, objectives, and implementations, which depend on the physical design aspects as well as operator requirements. In this report it is assumed that wind turbines with power-electronic converters are applied. These wind turbines not only can control their active power output according to an external set-point, but also they can control their reactive power output independently. The control limitations are set by

- the current and voltage rating of the power-electronic converter and other electrical devices,
- the limitations of the aerodynamic torque (and rotor speed) control,
- the grid characteristics in combination with the wind turbine operational range and the grid cod requirements.

Main objectives of WF active power control can be as follows:

- To maximize the total wind farm power output, e.g. using active wake control
- To regulate the wind farm power output according to an external set-point, which usually includes power (ramp) limitations, maintaining a certain balancing reserve, and etc.
- To mitigate wind turbine loads

For the reactive power control these objectives can be as follows:

- To keep the voltages in the wind farm collection grid and in the transmission grid within the normal operating ranges
- To minimize transmission losses, e.g. through contributing to the reactive power compensation
- To control the reactive power at the grid connection point according the grid operator set-point

The active power set-point can be directly ordered by the network operator, e.g. to mitigate overloading in parts of the transmission system; or it can be obtained indirectly through a look up table based on the measured grid frequency in order to support the grid frequency control. In most of the large grids the rotating mass is very large, which results in considerable time constants such as several minutes. Therefore frequency support through active power control is relatively slow. Moreover, rapid changes of the active power are usually undesirable and often power ramp rate limitations are prescribed. The reactive power set-point can also be either a direct order or and indirect set-point through a look up table. This table can be based on the measured voltage at the grid connection point (or a remote measurement at another location in the grid). The reactive power produced by other components in the transmission line may also need to be controlled; therefore, in some cases coordinated reactive power control will be required.

A possible implementation is presented in Figure 1.1.

Generally speaking, a wind farm controller consists of the following main components (see grayed area in Figure 1.1):

Farm power reference, which computes the set-points for the active and reactive powers for the whole wind farm. These set-points are determined such as to comply with the demands from the **System Operator** (also referred to as Transmission System Operator, or TSO for short), which specifies the operation mode (unconstrained or constrained production) and the power constraints that need to be realized by the wind farm controller under constrained power operation (sometimes referred to as secondary control, not to be mistaken with grid frequency regulation). This can also be a fixed level below the available wind farm power, which requires a precise estimation of the available power. These power constraints can be, for instance (see [1]):

- *Maximum production constraint*, limiting the total power production of the wind farm to an absolute maximum.
- *Delta production constraint*, limiting the power output to a specified portion of the available farm power production,

- *Balance power regulation*, allowing the farm production to be reduced as fast as possible to a maximum production constraint. Balance regulation basically constitutes maximum production constraint in combination with a power gradient constraint, and may be equipped with automatic cancellation capability that ensures return to unconstrained power operation after specified time.
- *Stop regulation*, requiring that the wind turbine controller maintains the current power as long as possible (as long as the wind resource allows that, of course).
- *Power gradient constraint*, preventing the farm production from increasing or decreasing too fast due to abrupt wind speed variations, or due to the farm being start up at high wind speeds. At decreasing wind speed this constraint has only effect in combination with delta production constraints, i.e. when the available power is higher than the constrained power demand.
- *Inertia control*, Emulation of the rotational mass of conventional generators that counteract grid frequency deviations. This may also include a short-time power boost (can be up to 110% of the power-electronics current limits) that extracts up to typically 30% of the rotor energy. The recovery of the rotor energy can take tens of seconds to several minutes, so this should only be applied in extreme conditions. For example, when a big power plant failure leads to such fast grid frequency decrease that protection relays of the grid are activated and consumers are curtailed or even cut-off.

Furthermore, the **Farm power reference** block receives information from the wind turbines (estimate of the available power at each wind turbine, $P_{avail}(i)$, *based on the local wind characteristics*) and from the met mast(s) (atmospheric conditions such as wind speed, direction, air density, turbulence, etc). Based on this information, it determines the maximum available power for the whole wind farm.

Frequency control adds up an additional active power demand, either a positive or negative, to that produced by the **Wind farm reference** block, aiming to support the system operator in controlling the grid frequency on short time scales (called primary frequency control). The TSO specifies the frequency droop and dead-band to be implemented (depending on the regional grid code). It receives as input the measured frequency at the **Point of Common Coupling** (PCC) (which should be the same as the grid frequency).

Voltage control adds up an additional reactive power demand to that produced by the **Wind farm reference** block, in order to support the system operator in controlling the voltage. The TSO specifies the voltage droop and dead-band to be implemented. It receives the measured voltage at the PCC as input. Voltage control should be coordinated in the wind farm and all voltages in the WF should be kept within the normal operating limits and no voltage oscillations should occur.

Active power control is a feedback controller acting on the difference between the measured active power at the PCC, P_{meas}, and the active power reference input P_s. The feedback loop is important in order to achieve the desired active power at the PCC in the presence of modeling errors and electric losses throughout the farm. Also, the controller should include proper (anti-windup) limitation of its output P_{farm}, the final wind farm active power set-point to enter the dispatcher.

Reactive power control is a feedback controller acting on the difference between the measured reactive power at the PCC, Q_{meas}, and the active power reference input

Q_s. Similarly to the active power control block, here also proper anti-windup limitation scheme has to be applied. Since the reactive power production capability depends on the active power production, P_{farm} is input to this block as well.

Active power dispatcher distributes the wind farm active power set-point P_{farm} to the wind turbines. Even though the conventionally used industrial implementation of the power dispatcher is a straightforward proportional distribution of the power set-points, this algorithm becomes much more involved when one aims to maximize the farm power production and/or reduce the (fatigue) loading of the wind turbines in the farm.

Reactive power dispatcher distributes the reactive power set-points Q_{farm} among the wind turbines. Conventional proportional distribution is here usually sufficient.

Note 1: The frequency control and active power control are usually cascaded, as in Figure 1.1. For the voltage control and reactive power control several different solutions are possible or preferred, depending on the WF and the grid characteristics and on the grid code requirements.
Moreover, the voltage at the PCC and in the WF are not only controlled by the WF controller trough the wind turbine reactive power set-points. Most substation transformers are equipped with automated tap changers and if required dedicated power-electronic devices are installed to contribute the voltage control, such as SVCs (Static VAR Compensator) and STATCOMs.

Note 2: The figure only describes the normal operation of the wind farm. In case of the grid voltage dips, including voltage restoration after fault appearance, the priorities of the control are set to maximize voltage support c.w. reactive power injection.

Note 3: In case of HVDC grid connection the situation is again quite different, both in normal operation, where the WF voltage is NOT controlled by the WF but solely by the HVDC substation, and in congested operation.

Much information can be found in the literature regarding the **Farm Power Reference**, see for instance [79, 1, 33]. This block converts the constraints and set-points, received from the TSO, into wind farm power references in time. Therefore, no further attention will be paid on it in the sequel.

The blocks **Frequency control** and **Voltage control** in Figure 1.1 calculate additional active or reactive power to be added to the power set-points from the block**Farm power reference** as specified by the TSO. The additional active and reactive powers are typically piecewise linear functions (containing droop and dead-band) of the measured grid frequency and voltage, respectively. For more information on this, refer to [33, 1].

Following the lines further down Figure 1.1, the blocks **Active power control** and **Reactive power control** implement feedback controllers for the active and reactive powers. Typically, these controllers have a PI structure [33, 79] with saturation to ensure the total farm set-points do not exceed the maximum available power.

With respect to the current project, the active and reactive power dispatching is most relevant and will be the focus of the study. It is also the most involved part from the wind farm controller when it comes to optimizing power yield and farm loads at he same time.

The dispatcher basically receives the total power set-points (active and reactive) for the whole park, and decides how to distribute these among the wind turbines.

As can be observed from Figure 1.1, there is little to no interconnection between the active and reactive power control loops in the wind farm controller. These operate also on different time scales: the active power control loop is a much more dynamic loop due to the fact that at wind turbine level the active power regulation requires pitching of the blades of the wind turbine; reactive power, on the other side, is electrically controlled by the turbine power electronics and is much faster. Therefore, these two loops are typically designed and operated independent of each other.

The active power control is linked to the electromechanical quantities, while reactive power is linked to the electromagnetic quantities. When controlling active power the wind turbine torque and pitch controller should maintain the power balance, while keeping the rotor speed, generator voltage and current within safe limits. The reactive power generally does not affect the wind turbine operation, for instance it can even be controlled without the wind turbine being operational. For 3-phase sinusoidal voltages, the relation is:

$$\begin{aligned} P &= \sqrt{3} V I \cos(\phi_{V-I}) \\ Q &= \sqrt{3} V I \sin(\phi_{V-I}) \\ |I| &= \sqrt{{I_{act}}^2 + {I_{react}}^2} \leq I_{max-conv}, \end{aligned}$$

in which P, Q, V, and I are the active power, reactive power, voltage and current, respectively. Moreover, ϕ_{V-I} is the phase angle between V and I, I_{act} and I_{react} stand for active and reactive currents, and $I_{max-conv}$ represents the converter maximum current.

As can be observed from Figure 1.1, there is little to no interconnection between the active and reactive power control loops in the wind farm controller. The active and reactive current are orthogonal vectors and can be controlled independently using modern power-electronic converters, provided that the grid voltage is stable, so that the voltage angle can be tracked accurately by a PLL (Phase Locked Loop). The reactive power capability is determined by the power-electronic converter rating, which is either 100% (full-rated converters) or around 30% for doubly-fed induction generators (DFIG). The link between active power P and reactive power Q is the limitation of the current amplitude.

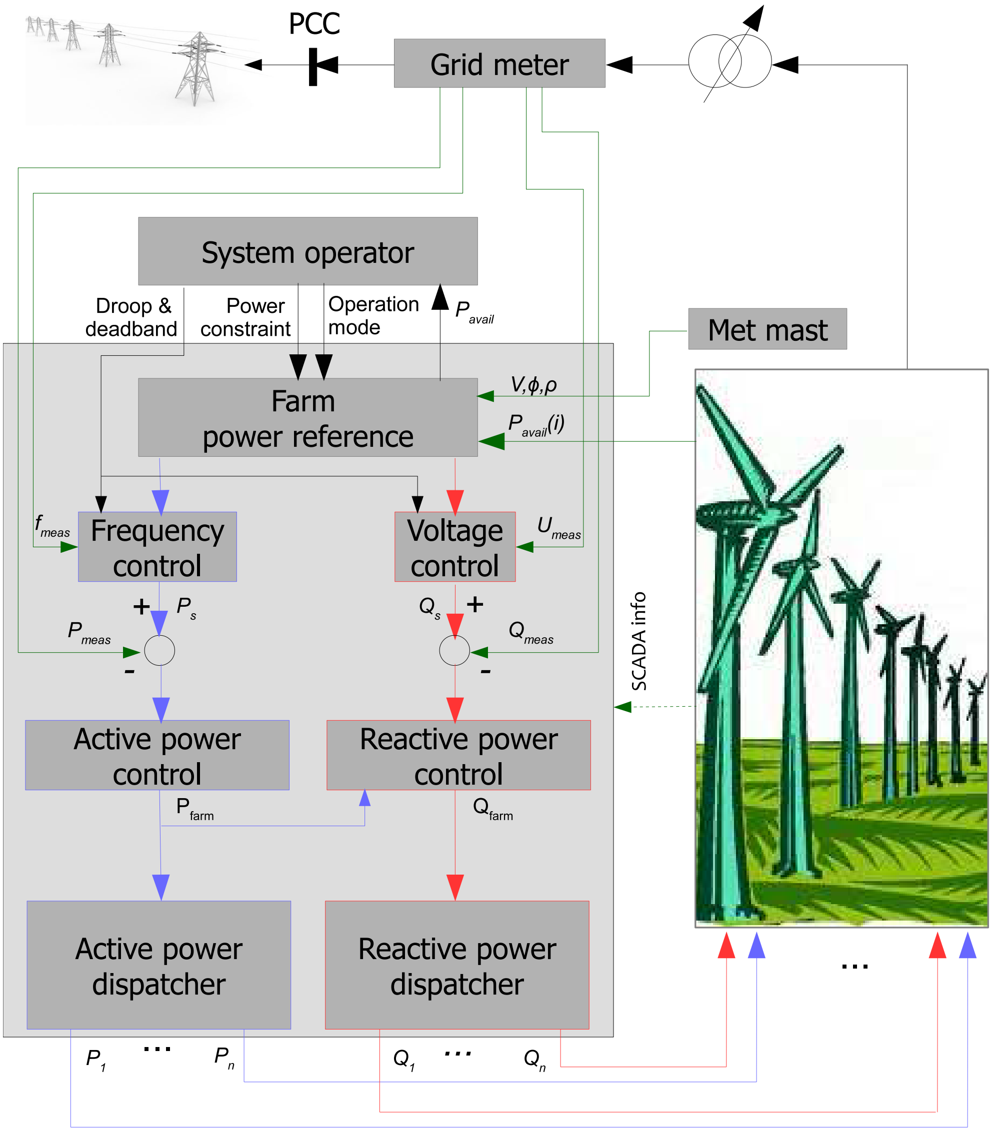

Figure 1.1: Schematic representation of a wind farm controller

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Active power control

Even though little has appeared in the literature about real-life implementations of wind farm control algorithms, there are quite some academical publications on this topic. The discussing below concerns publications related to the block **Active power dispatcher**, which is in some papers combined with the **Active power control** block in an attempt to include the objective of the dispatcher block into the cost function of a modern feedback controller.

A good review of the available literature on active power control of wind farms can be found in [32], which is performed within the Aeolus project (funded by the European Commission FP7 programme). From control point of view, the purpose of the Aeolus project was to develop wind farm control algorithms for increasing power production and reducing fatigue loading throughout the farm. As result, there are much publications/deliverables from the project (see below) that are directly related to the topic of active power control of wind farms.

The simplest way to ensure that the wind farm production will follow the power set-points P_s and Q_s (see Figure 1.1), is by using simple PI controllers acting on the tracking errors, $(P_s - P_{meas})$ and $(Q_s - Q_{meas})$, for the active and reactive powers [33, 79]. The outputs of these PI controllers need to be limited (using anti-windup schemes) to ensure that the final farm references P_{farm} and Q_{farm} will not exceed the available active and reactive powers. The active power reference is then proportionally distributed between the wind turbines, derating each wind turbine with the same factor (the ratio between the farm reference and the available power, P_{farm}/P_{avail}) of its own available power $P_{avail}(i)$ as follows

$$P_i = \frac{P_{farm}}{P_{avail}} P_{avail}(i),\ i = 1, 2, \ldots, n. \tag{2.1}$$

Such **proportional dispatching** is discussed in [33, 79, 32].

The biggest advantage of such simple dispatching strategy is its computational simplicity and the fact that no wind farm model is required. If the wind farm loads distribution is of no importance, then this would be the recommended strategy. However, in wind farms there are often turbine that are more heavily loaded, e.g. these that are relatively often in the wake of other turbines. Due to the high turbulence intensity of the wakes, the fatigue loading at a turbine in the wake of another turbine is larger, even though the wind speed in the wake is lower than upstream. Therefore, wind farms owners may profit by distributing the loading more evenly throughout the wind farm, and for that purpose more involved dispatching strategies are required.

Proportional distribution is also used in [38], where a control algorithm is developed for a small power system using **Fuzzy logic**. The developed methodology there, however, is not directly applicable to the wind farm control problem posed in the previous section. The reason for that is that it determines the wind farm power reference P_{farm} using Fuzzy reasoning method that is only applicable for reducing frequency deviations and cannot deal with other demands from the TSO (such as active farm power production).

A bit more sophisticated weighting that the one in Equation (2.1) is proposed in [13], where the authors suggest to use higher deloaded margin at higher wind speeds (*wind speed dependent distribution*). For a wind turbine i operating at wind speed V_j, the power is derated according to the following rule

$$P_i = \frac{W(V_j)n(V_j)}{n(V_j)\sum_{j=1}^{n} W(V_j)n(V_j)} P_{farm},\ i = 1, 2, \ldots, n, \tag{2.2}$$

wherein $n(V_i)$ is the number of wind turbines that operate at wind speed V_j, and $W(V_j)$ is a wind speed-dependent weighing factor that increases with the wind speed. The authors propose to choose the weighing factor as follows:

$$W(V_j) = \begin{cases} 1, & \text{if } V_j\text{<8m/s} \\ k \in \{2, 3, 4\}, & \text{if } V_j \geq k\text{+6m/s and } V_j < k\text{+7m/s} \\ 5, & \text{if } V_j \geq 11 \text{ m/s} \end{cases}$$

The authors demonstrate in simulation that this dispatching rule indeed results in the total wind farm active power following the demand. Furthermore, they demonstrate that sudden wind speed variations result in fluctuations of the wind farm power, which they subsequently smooth by using Fuzzy logic.

Notice that this way of dispatching results in turbines operating at higher production level getting more derated that those being operated at lower wind speeds. As result, it achieves a more even power reference distribution than the proportional distribution in Equation (2.1). It is therefore expected that (2.2) also achieves a more even distribution of the fatigue loads throughout the farm, while at the same time still not requiring any wind farm model. This makes the method a very serious candidate for consideration in this project.

When the TSO specifies unconstrained power operation mode, the wind farm power should be maximized by the wind farm controller. To this end, the active wake control techniques Heat & Flux [17, 49] and Controlling Wind [16, 93], developed by ECN, can be used. These techniques change the operating conditions of the front side wind turbines by either decreasing the axial induction factor, e.g. by pitching the blades (Heat&Flux), or introduce yaw misalignment to sent the wake away from the downstream wind turbine(s). It should be pointed out that a GE patent application exists that also covers Heat&Flux [70]:

Claim 1 in [70]: "*...data received from at least one upstream wind turbine to predict a load impact of turbines downstream thereof, and selectively generating and transmitting control signals to at least one of (1) reduce power of at least one downwind wind turbine to minimize load impact and/or (2) reduce the speed of at least one said upstream turbine to reduce fatigue load and increase power capture in at least one downstream turbine.*"

At constrained power operation mode it seems reasonable to desire to distribute the wind farm power reference in such a way that the fatigue lifetime of the turbines are spatially equalized as much as possible so as to prevent, if possible, that some turbines are suffering much more fatigue loads than others. This problem is the focus of the Aeolus project, mentioned above, and a number of project reports (deliverables) have appeared on the topic of wind farm control based on modern control strategies for reducing fatigue[1)] loads [84, 69, 83, 50, 8]. Model Predictive Control (MPC) comes out of the project as a suitable candidate for solving the problem of power set-point tracking at minimum loading.

In Part I of Deliverable 3.4 of the Aeolus project [69], an MPC based wind farm controller is developed which receives as input the current and future farm power production set-points and the current and future tower bending moment set-points. The MPC cost function then penalizes deviations of the predicted farm power and tower moment from the specified set-points. The controlled variables are the individual wind turbines' active power set-points P_i. Notice that this formulation is rather unnatural in that the tower load set-point is required as input. As the MPC controller is based on optimizing predictions of the outputs (farm power and loads) in the future, it intrinsically requires, (i), a model of the wind farm, and (ii) predictions of the wind disturbance. In order to use linear MPC control, a linearized wind farm model is used, and since the wind speed is unpredictable it needs to be assumed constant over the prediction horizon (the wind should also remain constant because of the linear mode assumption). A simple switching strategy is used to cover the whole operating region of the wind with several local MPC controllers. Furthermore, the MPC controller requires that the state of the linear model is available for feedback, and so an observer (Kalman filter) is used to estimate the state of the whole linearized wind farm model, which includes wind turbine dynamics and wake dynamics.

The most significant drawbacks of using MPC for the wind farm control problem are as follows

- *Robustness*: a rather simple (linearized) farm model is used to make online predictions of the power and loads. The accuracy of such simple models as compared to the real-life wind farm dynamics is usually insufficient to ensure close-to-optimal operation of the MPC controller in real-life.
- *Observability*: a state observer is used to estimate the states of the farm model, and observability problems may arise when a dynamic wake model is used
- *Stability*: in its standard form (as the one used in the [69]), the MPC controller does not have guaranteed stability, not even with a perfect model. Even though there exist extensions to the MPC cost functions that ensure stability of the resulting feedback

1) It should be pointed out that all of the Aeolus publications misleadingly state to include fatigue loading in the wind farm control problem, but this is not the case. In fact, these methods include in their cost functions simply the wind turbine output signal itself (in a usually linearized framework), e.g. the tower bottom bending moment, rather than a measure of the fatigue.

loop (e.g. by inclusion of terminal state constraint), these additionally increase the computational complexity of the MPC optimization problem.

- *Scalability*: the applicability of MPC control to large scale wind farms is due to the scale of the resulting optimization problem. Depending on the chosen MPC prediction horizon, the optimization problem easily gets of large size with hundreds of variables and constraints. This is probably the reason that in [69] the authors choose to work with unusually short prediction horizons of 1-3 samples.

When properly modelled, the significant communication delays in wind farm systems pose no problem for the MPC. The second part of deliverable 3.4 of Aeolus [83] considers the problem reconfiguring the power set-points computed by the wind farm controller in cases of fast local disturbances, such as local turbulence effects. This lower level farm control, called in [69] reconfigurable control, acts at wind turbine level and disregards the "coupling" between the wind turbine dynamics via the wakes. The reconfigurable control method assumes that a higher level wind farm controller is available that generates active power set-points and load set-points for each wind turbine. Working at a higher sample rate (1 second), the reconfigurable controller tries to ensure that the total farm power output equals the power demand by the TSO while at the same time trying to reduce the differences between the turbines power outputs and loads and their set-points generated by the wind farm controller. The authors develop a computationally efficient optimization methodology for solving the resulting constrained convex optimization problem online. The practical usefulness of this reconfigurable controller is, however, questionable, because of the turbines' ability to deal well with turbulence effects during constrained power operation. A possible situation wherein the use of this reconfigurable controller could be advantageous is when the power of a wind turbine is constrained just below the available power and the wind drops to a value that prevents the turbine to produce the requested constrained power. In such case the reconfigurable controller would adapt the power set-point to this, and other, turbine(s) so as to ensure that the total power production of the farm remains at the set-point. When the power limitation is sufficiently below the available power, the reconfigurable controller plays no role.

Deliverable 3.4 of Aeolus also has an addendum [68], wherein the developed MPC controller is evaluated in simulation studies by comparison to standard proportional and PI wind farm controllers. Based on a trivial example with just 4 turbines in a row the conclusion is made that, compared to the conventional farm controllers, the "MPC indicates worse performance in tracking the power set-point". Overall it is concluded that the performance of the MPC controller deteriorates significantly when constraints are set on the available power.

Deliverable 3.3 of Aeolus [84] is also dedicated to the reconfigurable control problem, and is prepared by the same authors as deliverable 3.4. Besides some additional details and comments, deliverable 3.3 does not seem to offer more than deliverable 3.4, so the comments made above for deliverable 3.4 are still valid here. This deliverable also has an addendum [82] wherein a simulation study is presented based on a simple wind farm model with 8 turbines. The study demonstrates that the reconfigurable controller improves on the higher level wind farm controller in that it achieves a better power demand tracking for the wind farm, and lower fatigue loading for the wind turbines. However, no comparison with conventional wind farm controller is presented

Yet another output of the Aeolus project, deliverable 4.3 [50], is concerned with the problem of distributing the power demand to the wind turbines in the farm while at the same time minimizing the loads on the tower and the main shaft. Also here it is misleadingly stated in the text that the method minimizes the mechanical fatigue; instead, the mean squared tower bottom moment and main shaft moments are minimized. The optimization problem posed here is very similar to the one proposed in deliverable 3.4, where loading is modeled in the same way in the cost function, only here a different solution is suggested. Opposite to deliverable 3.3 and 3.4, a distributed control approach is used here wherein information exchange (e.g. wind turbine states) only takes place between neighboring wind turbines. The computational complexity is not discussed, nor the scalability of the method, while the authors only present an academical 5-turbines-in-a-row example in their simulation study.

Finally, in deliverable 4.5 of Aeolus [8], a slightly different approach is used than in Deliverable 4.3 (prepared by the same authors). The difference is that the quadratic cost function is defined for an infinite horizon, giving rise to an LQR (linear quadratic regulator) state feedback problem formulation (as opposed to the MPC finite horizon cost function in deliverable 4.3). Also here, keeping in mind that the wind farm control solution must be well scalable, the authors pursue a distributed control solution by imposing structure on the state feedback gain matrix. This significantly complicates the optimization problem, destroying its LQR form. The authors propose an iterative approach for updating the state feedback matrix and show in linear simulations with 10 wind turbines that it takes as much as 250 iterations to converge to a suboptimal solution, while in a more realistic simulation the number of iterations increase way beyond 400. It is also shown that the performance significantly improves when the number of communicating turbines is increased.

In its second part, deliverable 4.5 also discusses the issues related to the planned field tests on the Thanet wind farm aimed to demonstrate the practical implementation of the possibilities and limitations of the wind farm control methods developed in the Aeolus project. The most limiting factor of the developed methods turned out to be the computational complexity, because the SCADA system of wind farm has only very limited capabilities for performing involved computations as it “makes it possible to update the power set-points based on multiplication and summation of measurements”. As result of this, the distributed wind farm control solution is no longer possible; instead, an offline designed LQR controller and Kalman filter is suggested for the real-life implementation. Unfortunately, the planned real-life experiments were never performed.

A comparison between the different wind farm controllers, developed in the Aeolus project and briefed above, is made in deliverable 5.6 [81]. To this end, again a very small-scale wind farm model is used consisting of 8 wind turbines in a row. The results indicate that a simple PI controller combined with the conventional proportional distribution of power references often leads to the best wind farm power reference tracking. With respect to fatigue loading, no consistent trend can be seen other than that the reconfigurable control seems to improve somewhat the fatigue loading at the expense of (sometimes significant) degradation of the power tracking quality.

Optimization based approaches to power dispatching in wind farms have also been considered in the literature. In [54], for instance, develops a two step approach wherein first the commitment of the wind turbines is determined by means of (computationally involved) mixed integer linear programming optimization problem. Next, a nonlinear optimization problem is defined for the determination of the active and reactive power set-points assuming that predictions are given of the available wind turbine powers.

A maximum power point tracking approach is proposed in [90] in a decentralized framework where the wind turbines can exchange information with their neighbors. This is a model-free method that tries to optimize the total power production of the wind farm (method only aims at maximizing the power production). To this end, perturbations of the control variables (power set-points) are made to compute the wind farm power gradient, so that a gradient descent optimization algorithm can be used to converge to the optimal solution. Even though the method is very attractive from computational point of view (no model needed, simple implementation), it has a serious drawback: it performs well under uniform wind conditions, but its performance degrades substantially under realistic turbulent wind conditions because the power derivative then not only depends on the controlled parameter (axial induction), but also on the unknown wind speed itself. A similar idea is also pursued in [36].

In [37], a non-convex optimization problem is formulated for achieving power reference tracking at minimal sum of fatigue loading of the wind turbines. To this end, an age function based on the integrated fatigue rate is used as a cost function to minimize under the constraint that the farm power production is kept within a small interval around the power reference. This nonlinear optimization problem is called by the authors "off-line distribution", and does not account for the available powers of the individual wind turbines. The idea is to design the offline distribution as the optimal average production of the turbines, without considerations to the specific transient variations of the available power for each turbine. In a second step, an convex "online" optimization problem is solved that accounts for the available powers of the wind turbines by using affine approximations of the fatigue rates around the currently valid operating point. The resulting overall wind farm control structure resembles somewhat the hierarchical control structure developed in deliverable 3.4 of the Aeolus project, as discussed above. It should be pointed out, however, this is the only paper found during this literature study where **fatigue loading** is actually included into the active power reference dispatcher. However, the complexity of the problem forces the authors to neglect the wake effects (wind turbines completely independent on each other) and assume that all turbines work under the same wind speed conditions.

Another work that attempts to reduce fatigue loading by including an approximation of it in the cost function dates back to 1993 (being also the oldest one!) [80]. The problem posed there is rather interesting as it aims at maximizing the financial income at the minimum possible fatigue loading. The fatigue damage is included as a constraint on the lifetime profit that can be achieved, rather than as a term within the cost function. However, not surprisingly, a very simple deterministic model for the development of the price of electricity in the future is used based on a fixed number of season-dependent tariffs. The controller works at time-steps of 10 minutes and more so as to avoid turbulence effects affecting the estimation process. Furthermore, it is assumed that the fatigue loads of a generalized wind turbine component is approximately proportional to the low speed shaft torque so that the supervisory controller can estimate the fatigue damage by using measurements of the generated power alone.

Another interesting approach to optimization-based wind farm control with loads reduction capabilities is proposed in [75, 74], wherein the authors define the optimization problem in terms of maximization of the damping factors of the fore-aft and sidewards tower motion models, aiming to reduce tower vibrations while keeping the power production at the desired power reference value. In a little bit different formulation, the same author add up the blades loads also to the cost function in [77]; however, instead of the damping parameter, the static load on the tower and blade are optimized there. In [76], the author proposes to reduce the static trust force and shaft moment while trying to keep the power output of the wind farm at the reference value. To this end, an H_2 optimization problem is defined in a distributed framework.

Somewhat more focused on the electrical system of the wind farm are the methods developed in [66, 65]. The focus of [66] is the coordinated control of cluster of wind farms with different technologies (active stall and pitch controlled). In [65] the control systems is developed with the aim of reducing the number of shutdowns due to voltage variations beyond the limits, and thus reduces the number of operation hours.

In [48], a control scheme is presented for the utilization of a fast and short-term energy storage and fast output control of a wind turbine or a farm. The authors concentrate on the improvement of power quality, i.e. reduction of power output fluctuations in the range of a few to tens of seconds.

3
Reactive power control

3.1 Introduction

In order to discuss reactive power control methods and to be able to choose the best relevant approach, we need to have some information such as the type of the wind turbines generators, grid code characteristics, specific control objectives and grid requirements. However, since in this project the required electrical system details are not certain yet, some general reactive power control methods developed in litterateurs are discussed. The reactive power controllers can be designed and used for power factor improvement, power loss reduction, and voltage regulations [7].

Development of small and large wind farms for electrical power production is increasing rapidly. The wind farms are connected to the grid, and have to operate like conventional power plants. However, there are new challenges in large wind farms as power plants that did not exist with conventional ones. A typical challenge is caused by the rapid changes in wind speed, which affects the active power production (wind turbines can go on and off) and that may cause considerable changes in reactive power demand. In some cases the power electronic grid interconnection supports the variable wind speed and controls the fluctuations in active and reactive power; yet, it generates other problems such as harmonic distortion that reduces power quality, and transformers saturation, and some other problems. However, if the wind turbines are not being turned-on and off frequently, this will not cause problem in modern power electronics converters (Forced Commuted Pulse-Width Modulated). Since, these converters enable both active and reactive power control (more or less independent) and generally do not deteriorate the voltage waveform.

Directly connected wind turbine generators are poorly controllable, both regarding active and reactive power. In addition, they have poor voltage quality and inability to ride through grid voltage dips. Therefore these wind turbine generator types do not comply with most common grid code requirements.

Long transmission lines produce (underground cables) or consume (overhead lines) reactive power. Thus, reactive power control is required to limit transmission losses, optimize transmission capacity, and to keep the grid voltage within the safe operational limits. Many wind turbines can help in controlling reactive power, and a controller for the reactive power can be used to minimize losses and to increase voltage stability in the wind farm and transmission lines [14].

There are many research efforts on voltage control and reactive power control in wind farms to make wind farms more reliable power plants. In this chapter some of the efforts are discussed briefly.

3.2 State-of-the-art - Reactive power control

The reactive power exchange in wind farm and transmission line controls the magnitude of the voltage and vice versa. Voltage drop along the circuit depends on the magnitude of the current and the distance from the substation (More precisely, the size and type of the grid impedance. Moreover, the impedance behind the wind farm substation may also be significant.) Since wind farms are usually located in far distances from the substation, the impedance is usually high and the voltage drop can be very important. Furthermore, based on the grid code requirements, the power factor is usually kept around unity. When the wind farm is producing low active power, the power factor may deviate from one to provide additional lead/lag current due to reactive power demand. The wind farm controller should keep the power factor close to unity to prevent excessive currents and power loss.

The maximum reactive power that the wind farm can inject or absorb depends on some factors, for example the wind turbines limitations provided by the manufacturer (mainly determined by the technology: e.g. Full-Rated converter versus DFIG), the allowable voltage limits at the turbine that depends on its distance from PCC, and allowable current in electrical elements such as converters, transformers, cables, etc. [6].

The reactive power control strategies state of the art has been divided by [26] into two main categories: control at the PCC and control at the wind turbine. The control strategies at the PCC can be designed to control the power factor, reactive power, or voltage. Power factor control can supply reactive power for the grid, as soon as the active power supply changes. But, the disadvantage of this control strategy (when implemented at the wind turbine generator level) is the change in PCC power factor, if the inductance in the line and transformers changes the wind turbine production. Type of Q/V-control requirements is often prescribed in the grid code, and it is often a combination of requirements. Controlling reactive power at the PCC is more common but, it also has some disadvantages in case of sudden changes in the output power. In order to prevent unwanted effect on the voltage, a fast control of reactive power set-point is required [26]. The other option was the voltage control at the PCC, which can also be used to reduce the effect of the changes in active power supply of the wind farm on the voltage change at the grid connection point. However, because of the communication delays, some changes in the voltage are inevitable [26]. The other category mentioned before was the control at the wind turbine, which can have different structures for which the reactive power set-points for each wind turbine are received as inputs. At the wind turbine, in addition to the reactive power set-point, the measured voltage is also an input. Therefore, if a grid fault happens, the operation mode is switched from reactive power control to voltage control [26].

The wind farm control strategies providing the grid requirements are strongly dependent on the type of the wind turbines. The study done by Slootweg in 2001 [72] reviews the basic principals of voltage control, discussing different types of wind turbine generators effects. The paper shows that wind farms with DFIG turbines and direct drive synchronous generators can control the terminal voltage and reactive power, while the directly grid coupled asynchronous generator turbines can't do the control. Afterward, in 2002- 2003 the control algorithms based on PI compensation have been developed by [86, 85] for wind farm reactive power regulation. These works, [86, 85], also present wind farm models with DFIG turbines to be used in reactive power control algorithm.

In [11] a controller has been designed for both active and reactive power control for a wind farm of 19MW located in the Northwest of Spain. In this work the steady-state behavior of the wind farm is investigated by load flow modeling, and based on the developed model the reactive control architectures have been specified with the purpose of reactive power optimization and reducing internal losses. On the other hand, the dynamic behavior of wind farms with different turbine types, DFIG and squirrel cage induction generator (SCIG), has been investigated in [41]. Furthermore, in [63] a wind farm controller has been developed for controlling the grid voltage in quasi-steady and dynamic conditions.

An investigation has been conducted by NREL in 2004 on using energy storage and reactive power compensator in wind farms [55]. It shows that by using a combination of fixed capacitors and static compensation at right places the reactive power can be controlled during variable and high wind speed with lower cost than when using only fixed capacitors. Furthermore, in [7] the reactive power control system is a combination of a capacitor, a thyristor controlled reactor and a small rated active filter to reduce the harmonic content of the currents and to avoid possibilities of resonances.

In 2004-2005 Risø performed some initial research with the purpose of making wind farms operate more like a conventional power plant. In [78, 33] the authors present a wind farm control concept with both centralized control and control for each individual wind turbine. In their approach, the controllers at turbine level ensure that active and reactive power reference commands provided by the centralized controller are followed. Furthermore, the electrical aspects of offshore wind farm has been investigated in [62], and a dynamic model has been developed to be used for reactive power and voltage control of wind farms and grid frequency support.

A practical implementation of a wind farm controller in this period was on Horns-Rev wind farm, which was built in 2002 in Denmark. The wind farm consists of 80 2MW wind turbines, and has a wind farm controller to make it act as a single production unit like a conventional power plant [44, 43]. The wind farm controller handles both secondary and primary control similar to a conventional power plant, and the controller modules such as active power and frequency control, voltage and reactive power control, are uploaded in the SCADA system and work as a centralized controller [44, 43]. The block diagram of the main controller is shown in Figure 3.1. Later, the controller has been discussed in more detail in [79] and based on the mentioned operational experiences, the controller makes the wind farm in primary frequency control mode to be the same as conventional power plants. Moreover, the advanced control functions of the wind farm controller are essential.

In 2006, a supervisory controller has been developed in [5] to dispatch active and reactive power reference signals in a wind farm with DFIG turbines. The controller has two levels, one is on the farm level that optimally dispatches the active and reactive power reference signals to satisfy the demanded value by the system operator. The other one is on turbine level to allow for the wind turbine response to external active and reactive power set-points. In addition, several reactive power control strategies are discussed in [6], as well as

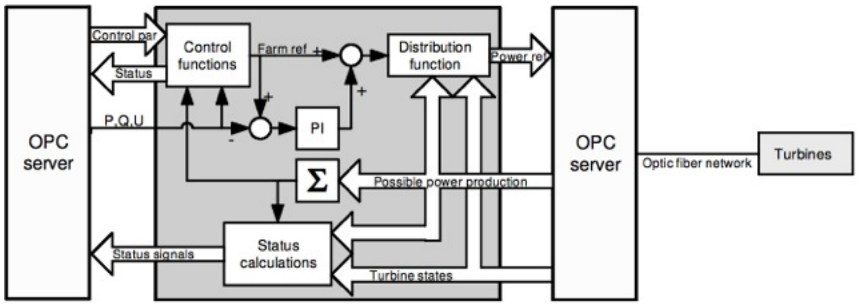

Figure 3.1: Block diagram of HornsRev wind farm main controller [44]

the grid impact of a wind farm reactive power based on a statistical wind farm model. This work also investigates the effect of the wind farm output on the active and reactive power losses in network elements. Moreover, the uncertainty of the presented data due to the approximation has been discussed [6]. Around the same time at ECN EeFarm toolbox was developed that was able to perform the above mentioned computations and analysis in steady-state. The latest version of the toolbox (EeFarm II) was published in [60].

In the year 2007, the grid codes that were adapted for wind power integration up to then, were introduced in [19], and the issues of connecting large wind power plants to the grid were addressed one more time. Moreover, some of the requirements for different wind turbine technologies such as DFIG and SCIG to help in reactive power compensation was discussed [19]. Modeling and control of wind farms with the purpose of following the grid code and connection to the grid (including reactive power and voltage control) was also discussed in 2008 ECN report [61].

Various reactive power control methodologies have been developed by academia and industry to use the inherent reactive power production capabilities of wind turbines, to improve the steady-state and dynamic performance of Power systems [52, 39, 88, 89]. The inherent capability of DFIG turbines for reactive power production and transmission loss reduction has been further studied in [42, 20]. In another study on the reactive power generation by DFIG based wind farms, an overview of different options for reactive power supply by the wind farms in steady-state has been evaluated [23]. Then, the reactive power supply during faults and fault ride through by the turbines has been discussed. It has been shown in this paper that using an optimization algorithm to control the reactive power in a wind farm and letting the wind turbines contribute in reactive power dispatch will help in cost saving considerably [23]. Similar study has been conducted by [95], in which theindividual wind turbine has been discussed and the wind power plant control has been developed, as well as fault ride through and study of different types of faults. A centralized wind farm controller with the focus on the wind turbine voltage control capabilities has been developed in 2008 [26], which uses the voltage reference settings from the wind farm controller to send set-points to the wind turbines. The controller shows improvements in reducing grid voltage change and voltage deviations between turbines as well as an improved voltage quality [26].

Afterward, in a study accomplished in 2009 [64], a coordinated control between a large DFIG based wind farm and a static synchronous compensator (STATCOM) has been developed. The reactive power compensation for transient and steady-state has been done for normal cases as well as grid fault conditions. The coordinated controller uses an interface neuro controller, which enhances the fault ride through capability of wind farm and also acts as an external damping controller for the wind farm and STATCOM [64].

In a later work, three strategies for reactive power control in wind farms with STATCOM are presented in [30]. The first control strategy addresses the case that the STATCOM is the only supplier of reactive power in the farm. The second is on proportional dispatch of reactive power between STATCOM and the turbines; and the last one handles the cases that the STATCOM reaches to its maximum capacity and the wind turbines have to supply the reactive power [30]. Some of the wind turbine types can be a controllable source of reactive power, such as DFIG turbines and full converter generator turbines. The reactive power limit of DFIG turbines and DFIG farms has been analyzed in [94]. Then, a reactive power controller has been explained and simulated for a DFIG turbine farm. It has been shown that the DFIG wind farm is able to contribute to the reactive power regulation of the grid, which helps to relief the reactive power pressure on the grid side [94]. In addition to wind turbines, there are other types of compensator for reactive power in wind power plants. For example, Shunt and Regulated Reactors, Static Var Compensator, Static Synchronous Compensator, etc., all introduced and explained in [12]. However, using different reactive power compensator and voltage controllers may cause stability issues for the system. In other words, when independent control laws for different equipment and compensator interact, the capacity of the wind turbine to generate reactive power can be limited and the system may become unstable [56].

In a work conducted by GE, a case study has been developed for a large scale offshore wind farm, and the effect of the drive-train type on grid voltage control has been evaluated [92]. There a supervisory VAR controller has been designed for wind farms that send reactive power set-points to the turbine and regulate voltage according to a reference value [92]. The block diagram of the wind farm VAR control has been presented in Figure 3.2. Each turbine of the farm has an inner voltage control loop and a reactive power control loop to regulate the wind turbines terminal voltage and the reactive power output [92].

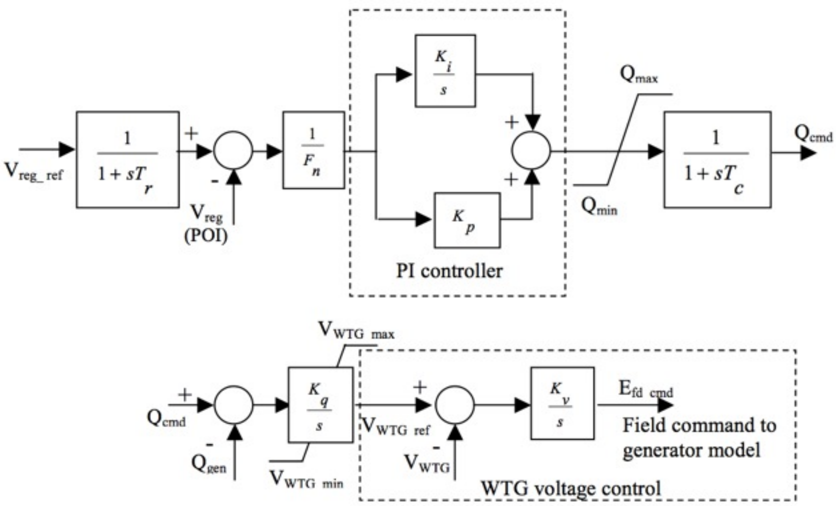

Figure 3.2: The block diagram of the wind farm VAR control - UPWind Project

Many advanced control methods has been developed for reactive power and voltage control in the last few years. A novel reactive power controller to be mentioned here, uses a central automation controller to regulate voltage and power factor [87]. It includes a microprocessor based relays to exchange control commands, as well as voltage, power flow and status information. An adaptive control algorithm has been used to prevent control requirement conflicts in regulating both power factor and voltage [87].

During the past few years there has been many more research on the optimization of the capability of the wind farms to compensate reactive power. An example is the work done in [22], which explains the modeling and improved analysis of the effective reactive power control by DFIG turbines in grid-connected wind farms. Another recent work addresses a multi-objective reactive power controller, which investigates the capability of DFIG turbines in a wind farm to deliver multiple reactive power objectives during variable wind conditions [51]. Furthermore, [71] proposed a new reactive power optimization for a DFIG turbine farm, based on genetic algorithm, to reduce the distribution losses. In this approach the control variable is the reactive power output of the wind farm that is used for minimizing losses and improving voltage profiles. Another example of utilizing genetic algorithms for reactive power control is the work in [47] that considers wind farms connected to grid and addresses modeling and economic issues in reactive power and voltage optimization.

Lately, the number of optimization methods on reactive power and voltage control, and the approaches with simpler methodologies to be substituted by the previous methods has been increasing. As an example, a general common method for reactive power and voltage control of wind farms is using an optimal power flow that has been addressed in many literature such as [40, 34]. Recently, some research work has proposed novel methodologies instead of optimal power flow. For example [67] suggests a simple method for optimal voltage control using regression functions. However, this approach depends on the reactive power capacity of the wind farm and seems to work only for some cases, and it may cause some issues on other wind power plants. The fundamental issues of voltage and reactive power control for different countries has been studded in [4], and a thorough literature survey has been provided [4].

4

Wind farm models

Different aspects are important when it comes to modelling of wind farms for wind farm control design, depending on the objective of the control strategy. In this project, the focus is on optimization of both power and loads, including grid requirements. At least (quasi)static cases will be considered, but dynamic cases might also be included in a later stage.

Also important to consider is the use of the model; different requirements are foreseen for control design and for control evaluation.

A wind farm generally consists of the following subsystems:

- flow field (ambient wind and wake effects)
- wind turbine (including relevant dynamics and control)
- electrical system
- grid (with network operator and load)
- wind farm controller
- energy buffer (including conversion components)

This chapter gives an overview of the work that has been done in the past on the modelling of wind farms in Section 4.1 and the available tools in Section 4.2

4.1 Literature review

As the first two components of the list above are most directly related to the power production and mechanical loading, these are treated in more detail below.

Flow field modelling

The development of wind farm flow field models can roughly be divided in two directions: the analytical/engineering models and the CFD based models. A lot of work has been done in both these fields, which will briefly be discussed below.

In one of the early works on the influence of wind turbines on each other [35], Jensen derived an analytical relation for the wake effect. This model is often referred to as the 'Jensen' model. Since then, several refinements have been made, from accurate modelling of wind speed deficit [27] to dynamic wake meandering [45].

Also the ambient wind field and its interaction with the wake has got attention. In [57], generation of a wind field suitable for wind farm power prediction is discussed. The suggested wind field takes both the farm scale effect (wind speed at hub height of each turbine including coherence) and the rotor scale effect (rotational sampling of the turbulence) into account.

Ainsly [3] modelled the development of the far wake with a eddy-viscosity model, taking into account the ambient turbulence as well as the wake deficit induced turbulence. On this basis, Crespo [18] developed the UPMWAKE code, which is later used as the basis of FarmFlow.

In the Aeolus project [2] on distributed control for large scale offshore wind farms, focus has been on control oriented model development. Several different approaches have been undertaken for the flow field modelling, both (quasi)static as well as dynamic.

In [10] the author describes a quasi-static wind farm flow model that relates external conditions of the wind farm (wind speed, direction and turbulence intensity) to the state (rotor speed, pitch angle) and output (power production, mechanical loading) of all the turbines in the farm.

Also developed in the Aeolus project is a dynamic wind flow model [73], based on spatial discretization of the linearized Navier-Stokes equation combined with the vortex cylinder theory. The spatial discretization using finite difference form provide the dynamic flow model as state space representation, convenient for control purposes. Two approximations are made to speed up the model: 1) 2D approximation of the flow equation at hub height and 2) a course grid. Comparison of the modelled and measured mean wind speeds at hub height on the ECN Wind turbine Test site Wieringermeer (EWTW) show a good match. However, turbulence, both ambient and wake induced, is not considered in this model.

Wind turbine modelling

The wind turbine subsystem serves two purposes in a wind farm model: 1) to include the influence of the wind turbine on the flow and 2) to provide information on the power production and mechanical loading.

If only the (quasi)static power production is of interest, a relatively simple model might be sufficient. Most of the flow field model use the thrust coefficient to include the wind turbine effect on the flow. If accurate prediction of the loads is required, the model can become fairly complex, even including dynamics and control. Obviously, the number of DOF of this submodel will be multiplied by the number of turbines in the farm.

To reduce computational effort, a (partly) linearized wind turbine model might be of value, such as derived by the ECN code TURBU [91].

Major question here is how to relate the instantaneous mechanical loading to fatigue, which will be part of the farm control cost function. The common way to calculate fatigue is rain flow counting on simulated or measured time series. The relation between turbulence and fatigue has been extensively studied by Frandsen [29]. In [28], Frandsen derived an equivalent turbulence intensity including the farm effect to be used in fatigue calculations.

For the (quasi)static cases, a database or look-up-table with the relation between local flow conditions and fatigue can be used to speed up the optimization.

4.2 Wind farm models/tools

This section discusses a number of models/tools for wind farm simulation that are available.

SimWindFarm

SimWindFarm is a tool for wind farm simulation and control evaluation ([31],[53]), which has been developed within the Aeolus project [2]. The tool contains:

- simple wind turbine model
- ambient wind field based on [57]
- wake effects (deficit, expansion and center) as formulated in [27]

The latest version (v0.8) of SimWindFarm assumes Taylor's frozen turbulence hypothesis to be true for the wake, but not for the ambient wind field. This makes the ambient wind field description much more realistic. However, a model for wind turbine (wake deficit) generated turbulence is lacking.

FarmFlow

The FarmFlow program [21] is an advanced and validated tool for the calculation of wake effects of offshore wind farms. The tool computes both the average wind speed and the turbulence intensity in the wake of each wind turbine.

The wake model in FarmFlow is based on the UPMWAKE code [18], originally developed by the Universidad Polytecnica de Madrid. UPMWAKE is a 3D parabolised Navier-Stokes code, using a k-ϵ turbulence model that accounts for turbulent processes in the far wake. The ambient flow is modelled in accordance with the method of Panofsky and Dutton [58]. The free stream wind as a function of height is calculated for a prescribed ambient turbulence intensity and Monin-Obukhov length, which takes the atmospheric stability into account.

The wake model has been improved by prescribing the stream wise pressure gradient as a source term in the flow equations. The stream wise pressure gradients are calculated via an inviscid, axisymmetric, free vortex wake method. With this method, the pressure gradients are a function of the axial force coefficient only. To save computational effort, the pressure gradients are calculated a priori for a large number of axial induction factors, so that the wake model only needs to interpolate the pressure gradients between the two nearest induction factors in this database. This hybrid method of wake modelling in the near wake region, including an adapted near wake turbulence model, gives very accurate results in an acceptable amount of computational time.

The code FarmFlow has been validated in [9] using a large amount of accurate experimental data from ECN Wind Turbine test station Wieringermeer (EWTW). Additionally, experimental data from three large offshore wind farms have been compared with FarmFlow model results. The calculated wake velocity deficits and turbulence intensities agree very well with experimental data for all wind speeds and ambient turbulence intensities. Excellent agreement between calculated and measured turbine performance is found.

EeFarm-II

The ECN code EeFarm-II [59] derives a (quasi)static model of the electrical system in a wind farm. It is built as a library in the GUI MatLAB Simulink. The EeFarm-II library contains wind farm component models (such as wind turbine, generator, cable, convertors etc.). Each EeFarm-II component model calculates the output voltage and current based on the input voltage and current and the component parameters. Furthermore, EeFarm-II includes network models including converters, DC-components and grids, it calculates annual energy production using realistic wind turbine aerodynamic output distribution, component losses and component outages due to failure and repair. it also includes a cost database and some economic parameters with which the levelized cost of energy are calculated.

TOPFARM

The TOPFARM optimization tool [46] is developed in the FP6 project with the same name [24] led by Riso DTU. This project addressed the optimization of wind farm topology and control strategy based on turbine loads as well as of power production as seen in an economical perspective.

The TOPFARM optimization platform consists of modules for 1) wind farm flow field, 2) wind turbine including control, 3) costs and 4) optimization. The first two modules offer different solutions to enable a good trade off between accuracy and speed. For example, the flow field models range from a simple empirical model to the advanced Dynamic Wake Meandering model [45].

A database with generic load cases has been used to speed up the optimization process.

Look-up-tables based tools

Currently, a lot of attention goes to wind farm design/optimization tools based on look-up-tables, or some other kind of database. In the FP6 project TOPFARM ([46]), a database has been used to speed up part of the model. In the FP7 project ClusterDesign, a wind farm optimization tool based on look-up-table is being developed.

In the ClusterDesign project, the approach is to derive tables for wake flow, turbine loads, generated power and relate these to the global conditions. As a result, the look-up-tables can easily become very large. Consider a (10×10) wind farm with a single wind turbine type, allowing two control signals (such as pitch angle offset [affecting the power] and yaw angle misalignment). First the relation between global and local flow parameters needs to be established. With a typical distribution of global parameters (25 wind speeds, 360 wind directions, 3 turbulence intensities, 3 wind shears and 3 air densities), the wake flow tables for normal operation alone will have more than 24×10^6 entries. This will be multiplied with the number of different control settings to apply. Also the tables that relate the local conditions to the wind turbine loads and power easily get very large, resulting in large computational effort. Another downside to this approach is that the look-up-tables are typically farm and turbine specific and thus need to be generated again with changes in farm layout (wake flow) or turbine design (loads).

SOWFA

NREL has developed the wind farm simulation tool SOWFA [15] (Simulator for Off/Onshore Wind Farm Applications), which is a computational fluid dynamics solver based on OpenFOAM coupled with FAST. SOWFA allows users to investigate wind turbine performance in a wind farm under variable atmospheric conditions.

Recently, a so called 'super controller' has been added to the code [25], to allow evaluation of wind farm control strategies. However, simulating a complete wind farm with this code requires a supercomputer/computercluster.

5

Discussion and future work

This document represents Deliverable 3.1 “An inventory of different control strategies and definition of cases to assess these control strategies” of the FLOW project “Wind Farm Wake Modelling, Fatigue Loads and Control” (FLOW P201102-004-ECN), and provides an overview of the literature on the topics of active and reactive wind farm control and wind farm modeling for control.

Regarding the wind farm active power control, it can be concluded that when it comes to optimizing the farm power output in combination with minimization of the *fatigue loads*, not one single algorithm was found suitable. The only algorithm actually including fatigue loading in the cost function uses an unrealistically simple wind farm model with no turbine wake interactions. There are, however, many suitable candidates when it comes to inclusion of some other measure of load into the cost function. These candidates are in the form of MPC-like control algorithms, or online optimization problems, with significant computational complexity and often without stability guarantees. The applicability of these wind farm control algorithms to large scale wind farms is therefore questionable; even though the SCADA system may be capable of bearing the computational load, the owners of the wind farm can be expected to be very reserved with respect to such complicated online computations with uncertain output (convergence, stability, reliability).

From practical implementation viewpoint, static control solutions have the advantage that the optimization can be performed offline and the solutions stored in a database (look-up table) for online use. The advantage is that this approach allows to perform involved optimizations offline, including e.g. fatigue loads in the cost function. However, this approach is only possible for a very small number of input variables (e.g. average wind speed, direction, power set-point) as the size of the data base increases exponentially with the number of inputs.

A very attractive approach is found to be the wind speed dependent distribution, where the deloaded margin increases with higher wind. This has an implicit smoothing effect on the loads distribution along the farm, while the computational complexity remains minimal. Possible improvement could be to make the weighting factors depend on the fatigue-based “lifetime consumption” of the turbines, rather than the local wind speeds.

There have been many efforts in development of control methods to regulate voltage and optimize reactive power in the wind power plants, in order to make them more reliable. The method of reactive power/voltage control development in wind farms strongly depends on the type of the wind turbines, the grid requirements, potential issues and many other factors. In spite of all the efforts made by academia and industry, development of controllers that include all the aspects is still lacking; in other words, a controller that optimizes active and reactive power in wind farms along with reducing the structural loads of the wind turbines will contribute to the field.

Conclusion regarding modelling for wind farm control design is that some work is still needed, as none of the models is completely suitable. For offline optimization in the (quasi)static cases, the combination of FarmFlow+EeFarm and a loads database is a promising solution. However, this approach is very computationally expensive and lacks flexibility (being turbine specific).

For the dynamic wind farm control cases that might be considered in this project, no complete and fast enough model exists. In Aeolus and in the TOPFARM project emphasis has been on both power and loads, while keeping the computational effort limited. The resulting models however all lack a certain aspect (mostly an accurate turbulence description is missing) of the wind farm. A more detailed evaluation of these models is recommended.

For final control evaluation (last stage before implementation), the SOWFA code is a candidate. However, that route is very computational expensive and will only be possible for limited cases.

Within the project, the following list summarizes the topics on which the future work will be focused:

- Development of a cost function to be used for optimizing the wind farm control algorithm. The cost function should be generic to capture different embodiments of the Active Wake Control concept of ECN (including Heat & Flux and Controlling Wind). The cost function should be such that it should allow wind farm control as a power plant, i.e. should allow for specifying a wind farm power demand less than the maximum achievable one, making it possible to optimize the loads in such cases.
- The Active Wake Control strategy will be used to optimize the operation of a representative reference wind farm in the case of unconstrained power operation and when all turbines are assumed operational. The gains (in terms of power production, loads and cost function) will be quantified.
- The Active Wake Control strategy will then extended to allow control under specific cases/constraints, such as constrained power reference operation, a number of wind turbines that are not operational, etc.

Due to the limited scope of this project, it has been decided to focus the work on focus the work on control of active power. Therefore, there will be further no work performed in this project on the topics of reactive power control and wind farm modeling.

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