

Framework of Multi-objective Wind Farm Controller Applicable to Real Wind Farms

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Abstract

Optimal wind farm control can mitigate adverse wake effects that can potentially cause up to 40% power loss and 80% increased fatigue loads in wind farms. The aim of this work is to outline a methodological framework of an optimal wind farm controller, which provides improved solutions to critical areas of optimal wind farm control research. The basis of this framework is a review of optimal wind farm control methodologies, which is presented first. It is observed that there is, at present, mainly a need for more advanced wind farm operation models. Thereafter the framework of a multi-objective optimal wind farm controller is outlined with the following key characteristics. Available control objectives are (i) to maximize the total wind farm power output or (ii) to follow a specified power reference for the wind farm's total power output while reducing the fatigue loads of the wind turbines in the wind farm. The controller design provides improved solutions for the modelling of wind farm aerodynamics and turbine operation, that is the PossPOW algorithm and a HAWC2-based turbine model, respectively. Moreover, all components of the framework are designed as to enable the applicability of the controller to real wind farms.

Keywords

Optimal wind farm control, review, power maximisation, fatigue reduction, operation modelling

Nomenclature

a	<i>axial induction factor</i>
c_p	<i>power coefficient</i>
u	<i>wind speed</i>
\underline{x}	<i>decision variable vector</i>
A	<i>rotor area</i>
F	<i>fatigue load measure</i>
J	<i>objective function value</i>
P	<i>power</i>
λ	<i>tip speed ratio</i>
ρ	<i>air density</i>

1. Introduction

Power losses of up to 30-40% and up to 80% higher fatigue loads [1] are caused by the interaction of wind turbine wake flow with downstream wind turbines. An approach for the mitigation of these wake effects is the use of optimal wind farm control. Such control approaches coordinate the operating point of wind turbines in a wind farm in order to achieve a given objective. The present work investigates control approaches that change the turbine operating point using tip-speed ratio and / or blade pitch angle. The objectives of optimal wind farm control are typically either (i) to maximize the total wind farm power output or (ii) to follow a specified power for the wind farm's total power output while reducing the fatigue loads of the wind turbines in the wind farm.

In the former approach the operational strategy is based on the hypothesis that a reduction in the power extraction of upstream turbines would increase the total power output. The reduced power extraction of upstream turbines weakens its wake and as a result downstream turbines are exposed to higher wind speeds. Numerical [2]–[6] and experimental [2], [7]–[10] studies show that such strategy can increase total power output. The use of models in these numerical or experimental studies however results in a different performance of the model farm with respect to the real wind farm. For instance, downscaled models of wind turbines, that are used in wind tunnel tests, result in a lower Reynolds number compared to the full-scale, and as a result in differences of the turbine performance [11]. There is however also evidence of a benefit of such operational strategy from a full-scale experimental study [8]. The study was carried out on two 2.5MW wind turbines. Control strategies developed with the latter approach operate the wind farm at a power reference while reducing the power extraction of upstream turbines in order to reduce wake turbulence intensity. As a result downstream turbines shall experience lower fatigue loads. This strategy is useful during the provision of balancing services from wind farms, as such services require the wind farm to operate at a specific total power. The importance of balancing services from wind farms is going to increase in the future. The increasing share of wind energy on the electricity production increases the total potential impact of such balancing services. Additionally, the increasing amount of electricity production from wind and solar requires the electricity system to expand its capability to accommodate variable power generation. As opposed to total power maximising control, there is mostly numerical studies on the effects of power reference following optimal wind farm control. The studies report a reduction of turbine loads by up to 30% [12]–[15]. To conclude, there is hence evidence that both discussed wind farm control objectives can yield beneficial results.

The present work therefore investigates the design of optimal wind farm control methodologies, in order to allow for observed results to come to fruition in real wind farms. First a review of optimal wind farm control methodologies is presented. The review pinpoints areas with the largest need of further research. Thereafter a framework of a multi-objective optimal wind farm controller is outlined with the following key characteristics. Presented controller can operate given one of the two objectives of wind farm control discussed above. The controller design provides improved solutions to the areas of further research that are identified in the review. All components of the framework are designed as to enable the applicability of the controller to real wind farms.

2. Review of optimal wind farm control methodology

The following chapter reviews wind farm control approaches with the optimisation objectives of either total power maximisation or optimal following of a total power reference in combination with fatigue load reduction.

2.1. Wind farm control targeting total power maximisation

The following section discusses studies on WFC approaches with the objective to maximise total wind farm power. First optimisation approaches are discussed and thereafter an overview of wind farm operation models is given. The objective function is comparable between different optimisation

approaches. Most studies [13], [16]–[18] maximise the total, steady-state power output P_{tot} of a wind farm,

$$P_{tot} = \sum P_i(\underline{x}) \quad (1)$$

where $P_i(\underline{x})$ is the static power of turbine i and \underline{x} the decision variable vector. Alternatively, some approaches [19], [20] maximise the total farm efficiency, which is being defined as the sum of the normalised turbine powers. The turbine power is normalised by the incoming wind speed. The optimisation of the steady state however neglects the dynamic effects of wind farm operation such as, amongst others, the advection of flow through the wind farm or variations in ambient wind conditions. As discussed in [21] this can reduce the benefit obtained from using the optimised operational strategy in a real wind farm. An alternative to the optimisation of the steady state could be to optimise the total power over a finite time horizon. Thereby more dynamic effects of wind farm operation could be considered in the optimisation. The implications of this are discussed later with regard to the wind farm model.

The decision variable \underline{x} is typically either the axial turbine induction factor [5], [16]–[19] or the tip-speed ratio and / or blade pitch angle [13], [20]. Constraints to these decision variables are physical limits and the allowed range of turbine operation. The use of induction factor instead of tip-speed ratio and pitch angle is further simplifying the real aerodynamic interaction of turbines and their operation. This simplification is expected to result in a worse performance of the optimised operational strategy in a real wind farm.

The power maximisation problem is typically solved using iterative, non-linear optimisation techniques. This is because the aerodynamic interaction of wind turbines is a non-convex, non-linear phenomenon, and therefore also the total power output of the wind farm. These iterative, non-linear optimisation techniques can be grouped into methods that evaluate or approximate gradients of the objective function and gradient-free approaches that only evaluate the value of the objective function. Gradient-based approaches used for power maximisation are sequential quadratic programming [13], sequential convex programming [17] or the gradient descent method [19]. Investigated gradient-free approaches are dynamic programming [18] or heuristic algorithms [5], [20]. The choice of the optimisation algorithm needs to be aligned with the mathematical formulation of the objective function. Important aspects are the availability of objective function gradients and the time cost of the objective function evaluation.

The value of the objective function is obtained either from a model of the wind farm power production or from measurements of the real wind farm power. Model-based approaches have, to date, used static, deterministic models. These models are typically built of a model of the turbine power output and a model for the aerodynamic interaction of wind turbines. The turbine power output P is usually estimated using the standard power coefficient-based equation

$$P = \frac{1}{2} \rho A c_p u^3 \quad (2)$$

where ρ is the air density, u the incoming wind speed and A the rotor area. The power coefficient c_p is typically expressed as a function of the optimisation decision variables. This can be either through look-up tables of the power coefficient as a function of tip speed ratio and blade pitch angle or through the induction factor a as

$$c_p = 4a(1 - a)^2 \quad (3)$$

The aerodynamic interaction of wind turbines is typically simulated using a wake model, such as the Jensen model in [16], [17], [20], the actuator disc model in [18] or the ECN wake model in [9], [13]. More information on wake models and modelling approaches for multiple wakes and partial wakes can be found in [23]. The design of the wind farm model is an important part of the overall optimal wind farm controller design. This is because a larger accuracy in the estimated total wind farm power output is likely yield to a better performance of the optimised operational strategy in the real wind farm. In this regard, it is suggested to extend present aerodynamic models with further

parameters of wind condition and dynamic effects of wind farm simulation. As regards wind conditions, wake modelling approaches should be extended by ambient turbulence conditions and shear and veer of the atmospheric boundary layer. Turbulence conditions affect the wake recovery. The shear and veer shape the three dimensional wake deficit profile. With regard to dynamic effects of operation, it is suggested to incorporate wake meandering and wake advection induced time delays into the model. An example of such development can be found in [22], where the Jensen model is recalibrated using CFD data and extended to multiple wake zones. The addition of a wake transport model in combination with a Kalman filter further improves the estimate of turbine power.

Model-free power maximisation approaches, which obtain the objective function value from wind farm power measurements, are used in [5], [19]. Since these approaches are based on in-operational learning, their disadvantage is that the full gain in wind farm power is achieved after an initial optimisation period. The duration of this period is estimated to be in the order of half an hour for the gradient descent approach by Gebraad et al. [19] or 100 hours for the game-theoretic approach by Marden et al. [5]. An advantage of model-free approaches is that the performance of derived operational strategies is not dependent on the quality of a wind farm model. The success of such optimisation techniques relies on the design of the post-processing of wind farm measurements. Gebraad et al. [19] deal with the effects of wake advection related time delay and wind speed. Additionally it would be necessary to design filters for wind direction, wind speed and turbine power measurements, in order to mitigate the effects of short-term phenomena of wind farm aerodynamics on the optimisation process.

2.2. Power reference following with fatigue load reduction

The following section discusses studies on the latter WFC objective that is operation of the wind farm at a total power reference while reducing turbine fatigue loads. As in the prior section, first the problem formulation is examined, that is the objective function, decision variables and constraints and thereafter optimisation algorithms are discussed. The objective of this type of WFC is usually translated into the following structure of the objective function

$$J(\underline{x}) = \Delta P(\underline{x}) + F(\underline{x}) \quad (4)$$

where N is the number of turbines in the wind farm and \underline{x} the decision variable vector. The two terms are often each weighted by a scalar in order to make a trade-off between the two optimisation goals. The first term ΔP is usually the square of the deviation of the total wind farm power from the reference, which is used to ensure that the wind farm follows the total power reference. The second term F of the objective function is typically a measure of the fatigue loads in the wind farm. Recent studies approximated the fatigue loads using the tower and blade bending moments [4], [13], [23]. As discussed in [21] this measure is however far from quantifying fatigue loads. More sophisticated methods are therefore required for the estimation of fatigue loading. Besides the quantification of fatigue loading, it is also important to decide on the objective of the fatigue load reduction. This can be either to minimize the total fatigue loads in the wind farm or to re-distribute the loads in the wind farm according to a given objective. The choice of the objective depends on the interests of the wind farm operator, which can be to extend the average lifetime of the turbines, or, for example, to reduce the loading on strongly exposed turbines.

The optimisation problem is formulated as to minimize the objective function $J(\underline{x})$ either for its steady-state, nominal value [13], for its expected value [23], [24] or over a finite time horizon [15]. This aspect of the optimisation needs to be in line with the wind farm model used to calculate the objective function value. As such the optimisation for the steady-state requires a static wind farm model. Optimisation over time requires models that include relevant dynamics of wind farm operation. Such models are therefore usually of a higher complexity than simple static models. Optimisation for the expected value is typically used in linear quadratic control, which requires a dynamic linear wind farm model and an estimate of the model uncertainty and measurement noise.

The benefit of such optimal control approach is that stability of the system and convexity of the objective function are guaranteed.

The decision variables used in power reference following wind farm control are the same as in wind farm control targeting the maximisation of total wind farm power. That is blade pitch angle [14], [15] and turbine power set-point [23], [24].

The optimisation algorithm depends on the problem formulation and mathematical characteristics of the wind farm model. As for wind farm control targeting the maximisation of total wind farm power, the wind farm model of this optimisation problem is non-linear and non-convex. Several studies therefore use non-linear, iterative optimisation techniques [13]–[15], [25]. The linearization of the wind farm model at different points of operation can allow for the use of linear optimisation algorithms such as linear quadratic control [23], [24]. The use of a linearized model is however likely to reduce the accuracy of the power reference following control and the possible amount of load reduction.

Wind farm models can be divided into a model for the aerodynamic interaction of wind turbines and a model for the operation of these turbines. The wind turbine operation models seen in literature are mostly static. These models typically use wind speed and turbine operational settings, for example power or blade pitch, as input. The output is usually a measure of the effect on the wind farm flow. Turbine power is usually modelled as a function of power coefficient and wind speed cubed. This is the same approach as discussed above for wind farm models of wind farm controllers with the objective of total power maximisation. Static tower and blade bending moments are estimated using c_p and c_t tables in [13]–[15]. As discussed earlier it is however not useful to employ static moments for the quantification of fatigue loads. Therefore more advanced load models are necessary.

The modelling of the aerodynamic interaction of wind turbines is either not modelled or approached using static or dynamic models. In [23], [24] no aerodynamic interaction model is used. Such simplifications are questionable if the objective of the wind farm control is to reduce the turbine fatigue loading from a wind farm level perspective. Static aerodynamic models, for example in [13], are comparable with those used in wind farm control with the objective of total power maximization. A dynamic flow model is used in [14], [15]. Both studies use the same model, which is based on a 2D finite volume discretization of the Navier-Stokes equations. The advantage of such approach is that dynamic effects such as wake advection or variable wind inflow are included in the wind farm operation modelling. A disadvantage can be larger computational costs. Above discussed linearized Navier-Stokes-based model, for instance, requires 168 states for a five turbine wind farm

2.3. Controller inputs and outputs

Another important part in the design of an optimal wind farm controller is the choice of controller inputs and outputs. The choice should be primarily in line with the present control framework of the wind farm or otherwise at least within the economically reasonable range of extension of this framework. Most studies use at least freestream wind speed, wind direction and wind turbine power as controller inputs. The available direct measurements of wind speed and wind direction are however not useful, since the measured flow is not representative of the inflow conditions of the wind farm. This is because the sensors are positioned on the wind turbine nacelle, where the ambient flow has already been disturbed by rotor and the nacelle itself. Instead of direct measurements, wind speed can be estimated using rotor effective wind speed. An estimate of wind direction can, for example, be obtained from the nacelle direction of wind turbines. The accuracy of these estimates however still requires further investigation. Wind turbine power is a readily available measurement. Some studies on wind farm control with the objective of fatigue load reduction [13], [23] assume the availability of load measurements at wind turbines. However, it is unlikely that such measurements become commonly available at a standard wind turbine. The use of the inputs depends on whether the optimisation is performed offline or online. In case of the former, that is offline optimisation or pre-optimisation, the controller inputs are used to select the operational strategy from a pre-calculated look-up table. An example of such approach can be found in [26]. For

online optimisation the controller inputs are used as input parameters to the wind farm model that is used to calculate the objective function value.

The output of the wind farm controller is typically specifying the operational settings of wind turbines. Hence the wind farm controller output coincides with the input to the wind turbine controller. Those studies that specify the input to the turbine controller use either turbine power set-point, or blade pitch angle and / or rotor rotational speed. The power set-point is a commonly available controller input. Blade pitch angle and rotational speed reference are however usually not a standard input to the controller. Nonetheless if a wind farm control strategy that uses a non-standard turbine input proves to be successful on a real wind farm, it is likely that the turbine controller can be adapted accordingly by the manufacturer.

2.4. Conclusions

To conclude, the main need for further development of optimal wind farm control approaches is to create and use more advanced wind farm operation models. Modelling efforts should mainly focus on wind farm aerodynamics and turbine fatigue loads. Further, those models should include relevant dynamics of wind farm operation. Besides research on wind farm control approaches, there has been yet little attention on the application of optimal wind farm controllers to the control framework of real wind farms. That is aligning the optimal wind farm control approach with the sensors available in real wind farms. Further, assumptions made in the optimal control approach should be in line with the operation of the real wind farm.

3. Framework of multi-objective wind farm controller

This chapter presents a flexible, modular framework of a multi-objective wind farm controller that is applicable to modern wind farms. In the following first the functionality of the wind farm controller is discussed and thereafter the optimal control approach is presented.

3.1. Functionality

Presented wind farm controller allows for an optimised performance of the wind farm in all main operation modes. Figure 1 shows these operation modes and their translation into objectives of the optimal wind farm controller. During normal operation the objective of the wind farm controller is to maximise the total power of the wind farm. During other operation modes that are power limitation, balance control, power rate limiter and delta control, the objective of the wind farm controller is to operate the wind farm at a total power reference while reducing turbine fatigue loads. These operation modes are typically used to provide grid balancing services. The translation of an operation mode into a total power reference is performed using the PossPOW algorithm. More details on this algorithm are provided in the next section on the optimal control approach.

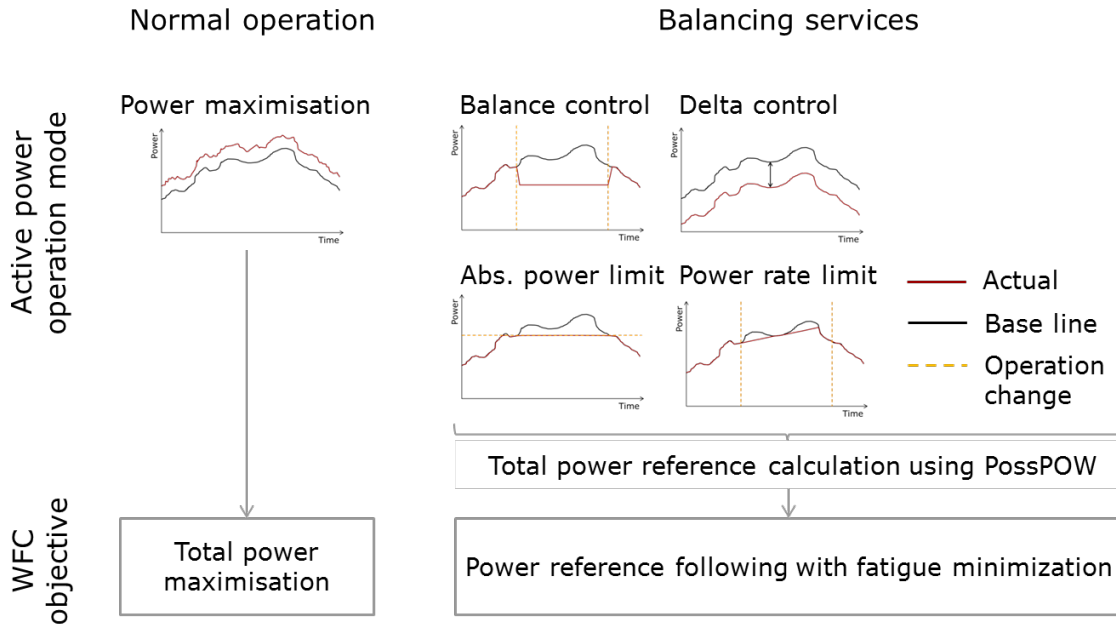


Figure 1: Translation of wind farm operation modes into objectives of optimal wind farm control.

Wind farm controllers of present wind farms provide the various functions for the operation of the wind farm illustrated in Figure 1, but do not yet employ optimal wind farm control approaches. In order to close this gap, the presented wind farm controller is designed as add-on that can be incorporated into existing wind farm control architecture. Thereby optimal wind farm control can be added as a new feature to the controller while keeping the existing functionality of the original wind farm controller.

The software architecture of the presented optimal wind farm controller is designed in a flexible, modular manner. This allows for an easy adaptation of the wind farm controller to the technology of the wind farm to which it is applied. Such technology can be the sensor types that are used as input

to wind farm controller or the wind turbine type present in the wind farm. As such the software architecture also allows using measurements from novel remote sensing devices such as LiDARs as input to the controller. The use of such devices extends the observability of the wind farm system to the wind farm controller. As a result the performance of the wind farm controller is expected to improve. A modular wind farm controller structure furthermore allows updating selected areas with the newest developments or testing different approaches of, for example, wind farm modelling.

Figure 2 below shows a sketch of this modular architecture. Several main modules of the wind farm controller - that is the optimisation algorithm, the wind farm model and the measurement post-processing - are shown. The actual structure is of a much larger complexity than shown in this sketch. It includes multiple sublayers as well as several further categories.

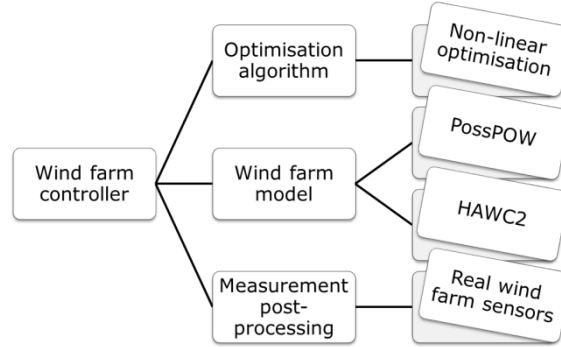


Figure 2: Schematic sketch of modular structure of multi-objective wind farm controller. Shown is only a fraction of the actual modular structure.

3.2. Optimal control approach

The following section presents the optimal wind farm control approach. The problem formulation is discussed in the beginning and thereafter a description is given of the design of the wind farm model. For both wind farm control objectives the problem formulation is comparable to the approaches outlined in the review section above. As regards wind farm control targeting total power maximisation, the objective function maximises the steady-state power output P_{tot}

$$P_{tot} = \sum_{i=1}^N P_i(\lambda_i, \beta_i) \quad (5)$$

where $P_i(\lambda_i, \beta_i)$ is the turbine power of turbine i , which is operating at tip-speed ratio λ_i and blade pitch angle β_i . N is the number of turbines of the wind farm.

The objective function for power reference following wind farm control is equivalent to Eqn. (4). As above the first term ΔP minimizes the squared deviation from the total power reference. The second term shall quantify the fatigue loading on the turbine. More details on the quantification of mechanical loads is discussed below with respect to the wind farm model. For both objectives the optimal distribution of turbine power set-points is derived using a numerical optimisation tool. The optimised power set-points are introduced to the wind farm using a feedforward controller. In power reference following operation a feedback controller additionally ensures the operation of the wind farm at its reference power.

The total power reference is obtained as described by J. Kristoffersen [28] for each turbine operation mode. The calculation of the power reference during operation in balance control mode or in delta control mode requires an estimate of the total possible wind farm power. This estimate is obtained using the PossPOW algorithm. Furthermore, the PossPOW algorithm is used to estimate

the total possible wind farm power in order to allow for an accurate compensation of the wind farm operator during down-regulated wind farm operation. More details on this algorithm are provided below.

As discussed above, there is a need for more advanced wind farm operation modelling in optimal wind farm control. The present optimal control approach therefore uses the most advanced, low computational cost models. The wind farm operation model is build-up of the PossPOW tool [29] for wind farm aerodynamics and a HAWC2-based turbine model [30].

PossPOW is an experimentally validated tool for the real-time estimation of total wind farm power. Turbine interaction through wake flow is modelled using a recalibrated version of the Gunnar Larsen wake model [31]. The wake model is recalibrated as such that model input variables can be retrieved from measurements available in real wind farms. The model inputs are rotor effective wind speed, turbulence intensity and wind direction. These quantities are estimated using SCADA signals commonly available in wind farms. The wake model was furthermore recalibrated to high frequency data, in order to better capture the dynamic effects of wind farm operation. As opposed to that approach, wake models used in other wind farm control studies are calibrated to 10-min averaged measurements. The PossPOW algorithm is validated for the operation range of wind turbines relevant for optimal wind farm control, that is normal and downregulated turbine operation. More information on the aerodynamic modelling can be found in [29].

The turbine model shall be based on the aeroelastic turbine simulation tool HAWC2, which is widely used in industry [30]. At present the turbine model is under development. The plan is to develop a simplified, low computational cost version of HAWC2 that can be used for in-operation optimisation of turbine set-points. The model shall provide estimates of turbine fatigue loads and power output.

4. Summary

This work presents a review of optimal wind farm control methodologies as well as a framework of a multi-objective wind farm controller. The review shows that there is a need of more advanced wind farm operation models for optimal wind farm controllers. Such more advanced models are used in the presented control framework. This is the PossPOW algorithm for wind farm aerodynamics simulation and a HAWC2-based wind turbine operation model that is used for the estimation of power and turbine fatigue load. The use of these advanced models is expected to result in a better performance of the controller in real wind farms. The design of the framework allows for the application of the optimal wind farm controller to real wind farms. The wind farm control approach allows for an optimised operation of the wind farm in all operation modes. Thus, the overall the design of the wind farm controller shall enable the optimised operation of real wind farms. Future work aims on testing the controller first in simulation and later in a real wind farm.

5. References

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