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A data-driven, cooperative wind farm control to maximize the total power production

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HIGHLIGHTS

- The Bayesian Ascent algorithm can monotonically increase the total wind farm power.
- The cooperative control strategy can further increase the total wind farm power.
- The decentralized wind farm control approach can reduce the required iterations.
- A data-driven, cooperative wind farm control approach is a promising alternative.

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ABSTRACT

This study investigates the feasibility of using a data-driven optimization approach to determine the coordinated control actions of wind turbines that maximize the total wind farm power production. Conventionally, for a given wind condition, an individual wind turbine maximizes its own power production without taking into consideration the conditions of other wind turbines. Under this greedy control strategy, the wake formed by the upstream wind turbine, resulting in reduced wind speed and increased turbulence intensity inside the wake, would affect and lower the power productions of the downstream wind turbines. To increase the overall wind farm power production, cooperative wind turbine control approaches have been proposed to coordinate the control actions that mitigate the wake interference among the wind turbines and would thus increase the total wind farm power production. This study explores the use of a data-driven approach to identify the optimum coordinated control actions of the wind turbines using limited amount of data. Specifically, we study the feasibility of the Bayesian Ascent (BA) algorithm, a probabilistic optimization algorithm based on non-parametric Gaussian Process regression technique, for the wind farm power maximization problem. The BA algorithm is employed to maximize an analytical wind farm power function that is constructed based on wind farm configurations and wind conditions. The results show that the BA algorithm can achieve a monotonic increase in the total wind farm power production using a small number of function evaluations and has the potentials to be used for real-time wind farm control.

1. Introduction

Modern wind turbines allow adjusting the blade angle, the yaw angle and the generator torque to maximize the power production and to protect the mechanical and electrical components from excessive structural or electrical loads. Not only affecting its own power production, these control actions can influence the power productions of the downstream wind turbines by changing the wake characteristics of the wind flow. In spite of wake interference, a wind turbine in a wind farm is conventionally operated to maximize its own power production, which can possibly lead to lower efficiency on the total power production of a wind farm.

Realizing that the interactions among the wind turbines can have impact on power production, cooperative control approaches have been proposed to maximize the total energy production of a wind farm by manipulating the wake interference pattern. The induction factor and the yaw-offset angle of a wind turbine have been used as control inputs to adjust the wake interference pattern. The induction factor, which is determined by the blade pitch angle and the generator torque, is used to determine the power production of a wind turbine and, at the same time, to control the amount of wind speed reduction inside the wake, thereby influencing the energy production of the downstream wind

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turbines. The joint set of induction factors for wind turbines have been employed to optimize and to increase the total energy production of a wind farm [1–9]. The yaw-offset angle, defined as the misalignment angle between the wind direction and the rotor, decreases the power production of the wind turbine but can possibly increase the power productions of downstream wind turbines by deflecting the wake trajectory. The joint set of yaw-offset angles has also been used to maximize the total wind farm power production [10–16]. To maximize the total wind farm power production, both the yaw-offset angles and the induction factors can be used simultaneously as control variables [17].

Most cooperative control approaches find the optimum control actions by optimizing the analytical wind farm power functions that mathematically relate the control inputs of wind turbines and the total power production of a wind farm. For example, a mathematical optimization approach using sequential quadratic programing (SQP) has been applied to determine the optimum control actions for maximizing the wind farm power [17]. However, the analytical wind farm power functions are often constructed based on simplified wake models, e.g., the Jensen wake model [18,19]. Such simple wake models do not accurately reflect the conditions of a wind farm site or a wind turbine model. To overcome the limitations of simplified wind farm power functions, Gebraad et al. [14] has used high-fidelity Computational Fluid Dynamics (CFD) simulation to construct the parametric wind farm power function. The constructed wind farm power function is then used to derive the optimal yaw-offset angles of wind turbines. However, a CFD model itself requires the specification of a large number of parameters representing the environmental and wind turbine conditions. To avoid the use of the wind farm power functions, data-driven optimization methods have been proposed. For example, game-theoretic search algorithm [5], gradient ascent type algorithm [20], maximum power point tracking methods [21,6], and simultaneous perturbation stochastic approximation method [22] have been employed to maximize the total wind farm power production. One issue for the data-driven approaches is that they often require a large number of measurement data to reach an optimum.

Recently, efforts have been made to optimize a target system using scarce data by exploiting the expressivity of non-parametric regression model. For example, Bayesian Optimization (BO) iteratively approximates the input and the output relationship of a target system using Gaussian Process (GP) regression and uses the probabilistically approximated target function to find the inputs that improve the target values [23,24]. Because BO uses the nonparametric GP regression that does not rely on a specific type of basis function, it can model complex relationship between the input and output of the target system using a smaller number of data points when comparing to search based algorithms. However, BO with the conventional sampling strategies still requires a large number of data points over a large input space of the target system in order to reach the optimal operational conditions. Because sampling the target values is associated with cost (time, energy, etc.) or loss (reduction in a target value), it is difficult to deploy conventional sampling strategies of BO for real-time control applications. We have developed the Bayesian Ascent (BA) algorithm that combines the strengths of the BO and gradient-free trust region algorithms to minimize the number of sampling points as well as ensure sequential improvements in the target value of the objective function at each iterative step [25]. BA is built upon the BO framework so that the target function can be efficiently modelled using GP regression with a small number of data points. Furthermore, BA adapts the strategy of regulating the optimization scope, as used in the Trust Region method, into a BO framework to select the sampling point that can monotonically increase a target value. Due to the use of trust region constraint on the sampling procedure, BA tends to increase the target value at each iterative step during the optimization, rapidly converging toward near the optimum.

This study investigates the feasibility of using the BA algorithm developed in our previous study [25] to determine the optimum coordinated control actions of wind turbines using only the input and the power output data. To emulate procedure of executing the control actions and observing response, we use the analytical wind farm power function derived in our previous study [17]. For the BA algorithm to be used for real time wind farm control, the algorithm should scale up favorably to optimize the control actions of a large number of wind turbines without incurring an excessive number of iterations. In addition, the algorithm should be able to perform well even with noisy measurement data. To evaluate the performance of the BA algorithm, we conduct parametric studies with varying wind conditions and the number of wind turbines. For various cases, the effectiveness of the BA algorithm is evaluated in terms of its convergence rate and the gap between the converged value and the theoretical maximum computed by mathematical approach (i.e., SQP algorithm). In addition, we compare the wind farm power efficiencies between the greedy and cooperative control strategies under different wind conditions for different wind farm configurations.

This paper is organized as follows: First, the analytical wind farm power function employed in this study is described. The cooperative wind farm control problem is then formulated using the analytically derived wind farm power function. The BA algorithm, which is employed to solve the cooperative wind farm control problem in this study, is discussed. Parametric studies of using the BA algorithm for the cooperative wind farm control problem are presented. The paper concludes with a summary and a discussion on future works.

2. Wind farm power function

For a wind farm, the total power production is simply an aggregation of the powers produced by the wind turbines in the wind farm. However, because of wake interference, the operational condition of a wind turbine can influence the power productions of other wind turbines. In this section, we briefly review the wind turbine power function, derived in our previous study [17], that can take into consideration of the control actions of the other wind turbines in a wind farm.

2.1. Effect of yaw offset angle on the power of a single wind turbine

Based on the actuator disk theory in aerodynamics, the power of a wind turbine due to a wind flow with wind speed U can be expressed as [26]:

$$P = \frac{1}{2}\rho A U^3 C_P(\alpha, o) \tag{1}$$

where ρ is the air density and A is the rotor area. $C_P(\alpha, o)$ is termed the power coefficient, which is expressed as [26]:

$$C_P(\alpha, o) = \frac{P}{\rho A U^3/2} = 4\alpha(\cos(\beta o) - \alpha)^2 \tag{2}$$

where, as shown in Fig. 1, o denotes the yaw offset angle between the wind direction and the wind turbine rotor, and $\alpha = (U\cos(o) - U_R)/U$ is the induction factor representing the ratio between the wind speed change across the rotor $(U\cos(o) - U_R)$ and the free stream wind speed U. The induction factor α can be controlled by the blade pitch angle and the generator torque to maximize or regulate the power produced by the wind turbine. A parameter β is introduced to the yaw offset angle o so that Eq. (2)