

MODELING, OPTIMIZATION AND CONTROL OF A WIND FARM TO MAXIMIZE THE EFFICIENCY OF POWER GENERATION

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GOAL AND FRAMEOWRK

The goal of this study is to construct the framework in which both the wind farm layout optimization and the cooperative control problems can be formulated and solved. The wind parameters, such as mean wind speed and direction, can be treated as random input variables, while the wind farm power output can be regarded as an output we are trying to maximize. Given certain wind conditions, as shown in Figure 1, the locations and the control actions of the wind turbines concurrently affect the wind speed experienced by wind turbines in a wind farm and thus their power outputs by modifying the wake interference pattern inside a wind farm. Two types of decision variables, wind farm design variables (location of wind turbines) and wind turbine control variables (induction factors and yaw offset angles), are optimized in this framework. The descriptions about each component in this framework are followed.

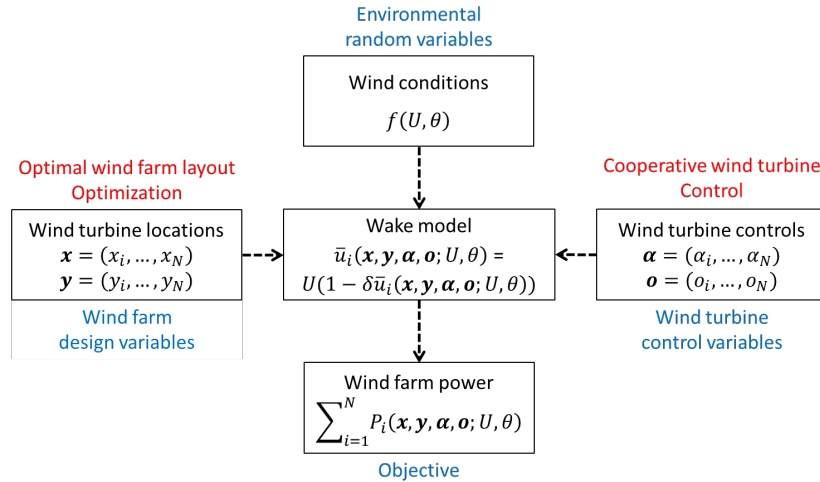


Figure 1. Framework for a wind farm power maximization problem

1. Characterizing site-specific wind characteristics using a Gaussian mixture model

Understanding the characteristics of wind at a certain site is the first step in optimizing wind farm layout and deriving control actions of wind turbines. Site-specific wind conditions have been described by time-averaged statistics, such as mean wind speed, mean wind direction, turbulence intensity and power exponent. Though these mean statistics are the most important, the distributions on such wind parameters are also important for evaluating wind turbine power production. However, only the distribution on the mean wind speed is described by the Weibul distribution in wind turbine design standard of the International Electrotechnical Commission (IEC 61400-1). In this study, we try to describe site-specific wind conditions by using multivariate probability density function for wind parameters. We construct the joint probability density function for wind parameters by applying a Gaussian mixture model (GMM) to measured wind data. In this approach, the joint PDF of the wind parameters are expressed as linear combinations of Gaussian probability functions, and data are used to determine the parameters and weights

of GMM. The constructed PDF for wind parameters concisely describe site-specific wind conditions, and it can be used to optimize the layout of the wind farm and to derive the cooperative control strategies of wind turbines.

2. Continuous version of the wake interaction model

The wake formed by the upstream wind turbine adversely affects the power performance of the downstream wind turbines due to the retarded wind speed inside the wake. The level of reduction of the wind speed inside of a wake depends on wind speed and direction (environmental random variables), locations of wind turbines (wind farm design variables) and the control actions of the upstream wind turbine (wind turbine control variables). A wake model describes the influences of these variables on the wind speeds and the power of the wind turbines, as shown in Figure 1. Therefore, the wake model has a significant role in optimizing the layout of wind farms and deriving the cooperative control strategy for the wind turbines. Instead of using the Park wake model, which classifies the wake affected and non-affected regions in a binary manner, we derive a continuous and smooth wake model that can better represent reality. Furthermore, the continuous and smooth wake model enables us to derive the gradient of wind farm power with respect to design and control variables. The gradient information then can be used for various numerical optimization algorithms to efficiently determine the optimal wind turbine locations and the control actions.

3. Wind farm layout problem using sequential quadratic programming

The effect of wake interference changes depending on the relative locations of wind turbines and the wind conditions such as wind speed and direction. The optimization of a wind farm layout is to find the locations of wind turbines that minimizes the wake interference and thus maximizes the expected wind farm power production, while preserving constraints such as the minimum distance between wind turbines and the total area of the wind farm. The expected power output is considered because wake interference patterns are strongly affected by wind conditions such as wind directions and wind speeds, which are treated as random variables. The joint PDF constructed by GMM can be used to estimate the expected power output. In optimizing the wind farm layout, we apply the sequential quadratic programming (SQP), instead of applying stochastic search based algorithms, because SQP is computationally efficient in optimizing a function in a continuous and large input space while guarantying the optimality conditions. To deploy this method, we derive the gradient of wind farm power with respect to the location variables of the wind turbines based on the continuous wake model.

4. Cooperative wind turbine control using Bayesian optimization

Even though the layout of the wind farm may have been optimized, the power efficiency of the wind farm would drop significantly when the wind direction is not near its mean value. In this case, the cooperative wind turbine control strategy can increase the efficiency of a wind farm by adjusting the induction factors and the yaw offset angles of the wind turbines in a wind farm. Being optimally chosen, the induction factors can increase the overall wind farm power by re-allocating the wind flow energy among the upstream and the downstream wind turbines. The assigned induction factor to a wind turbine can be achieved by adjusting the blade pitch angle or the generator torque. On the other hands, the yaw offset angle can deflect the direction of wake, and it can be used to reduce wake interference to the downstream wind turbines, although offsetting the yaw angle decreases its own power production. The control actions can be determined either by an analytical model or by statistical learning about the influence of control actions on the wind farm power production. In this study, Bayesian optimization has been deployed to find the optimal control actions through the continuous inferring and observing procedure.

PRELIMINARY RESULTS

1. Optimization of the locations of 16 wind turbines given the fixed wind speed and direction

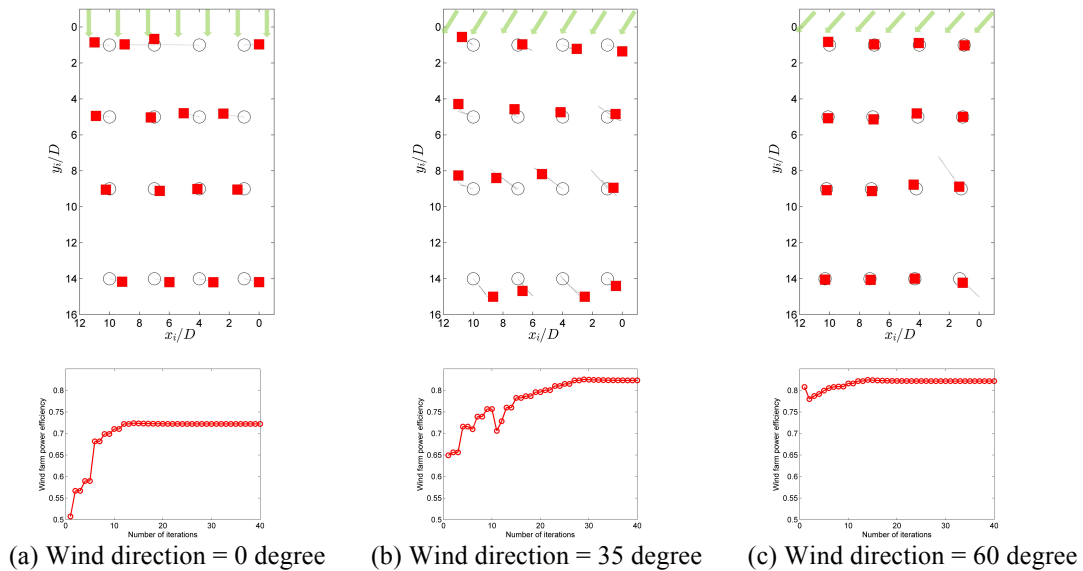


Figure 1. Optimized wind farm layouts depending on the wind directions: the circles represent the initial trial wind farm layouts while the squares represent the suboptimal wind farm layouts; curves shows the increases of wind farm power efficiency with the iterations of the optimization.

2. Optimization of the locations of 16 wind turbines given the fixed wind speed and direction distribution

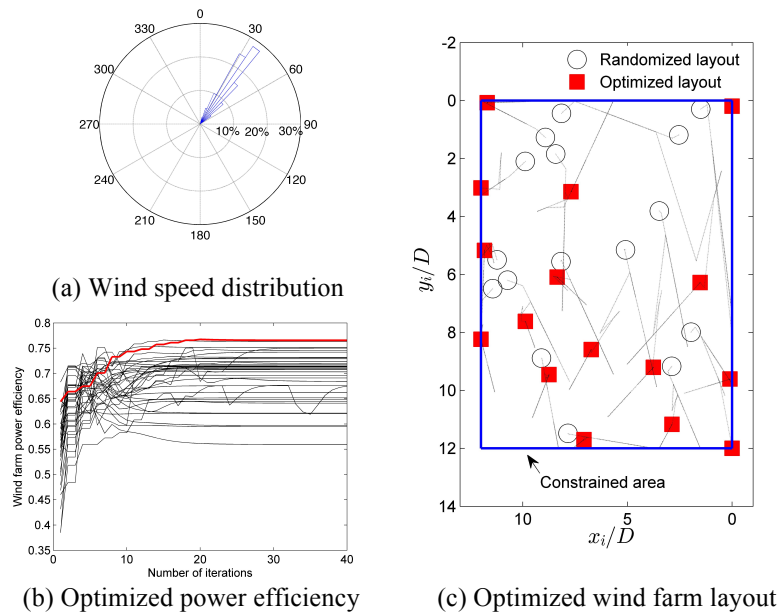


Figure 2. Suboptimal wind farm layout considering the distribution of wind direction: 40 random location vectors are used as initial trial layouts and optimizations are conducted. The corresponding power curves are shown in (b), and the wind turbines locations giving the maximum efficiency are shown in (c)