INTEGRATIVE MODELING AND NOVEL PARTICLE SWARM-BASED OPTIMAL DESIGN OF WIND FARMS

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ABSTRACT

To meet the energy needs of the future, while seeking to decrease our carbon footprint, a greater penetration of sustainable energy resources such as wind energy is necessary. However, a consistent growth of wind energy (especially in the wake of unfortunate policy changes and reported under-performance of existing projects) calls for a paradigm shift in wind power generation technologies. This dissertation develops a comprehensive methodology to explore, analyze and define the interactions between the key elements of wind farm development, and establish the foundation for designing high-performing wind farms. The primary contribution of this research is the effective quantification of the complex combined influence of wind turbine features, turbine placement, farm-land configuration, nameplate capacity, and wind resource variations on the energy output of the wind farm. A new Particle Swarm Optimization (PSO) algorithm, uniquely capable of preserving population diversity while addressing discrete variables, is also developed to provide powerful solutions towards optimizing wind farm configurations.

In conventional wind farm design, the major elements that influence the farm performance are often addressed individually. The failure to fully capture the critical interactions among these factors introduces important inaccuracies in the projected farm performance and leads to suboptimal wind farm planning. In this dissertation, we develop the Unrestricted Wind Farm Layout Optimization (UWFLO) methodology to model and optimize the performance of wind farms. The UWFLO method obviates traditional assumptions regarding (i) turbine placement, (ii) turbine-wind flow interactions, (iii) variation of wind conditions, and (iv) types of turbines (single/multiple) to be installed. The allowance of multiple turbines, which demands complex modeling, is rare in the existing literature. The UWFLO method also significantly advances the state of the art in wind farm optimization by allowing simultaneous optimization of the type and the location of the turbines. Layout optimization (using UWFLO) of a hypothetical 25-turbine commercial-scale wind farm provides a remarkable 4.4% increase in capacity factor compared to a conventional array layout. A further 2% increase in capacity factor is accomplished when the types of turbines are also optimally selected. The scope of turbine selection and placement however depends on the land configuration and the nameplate capacity of the farm. Such dependencies are not clearly defined in the existing literature. We develop response surface-based models, which implicitly employ UWFLO, to quantify and analyze the roles of these other crucial

design factors in optimal wind farm planning.

The wind pattern at a site can vary significantly from year to year, which is not adequately captured by conventional wind distribution models. The resulting ill-predictability of the annual distribution of wind conditions introduces significant uncertainties in the estimated energy output of the wind farm. A new method is developed to characterize these wind resource uncertainties and model the propagation of these uncertainties into the estimated farm output. The overall wind pattern/regime also varies from one region to another, which demands turbines with capabilities uniquely suited for different wind regimes. Using the UWFLO method, we model the performance potential of currently available turbines for different wind regimes, and quantify their feature-based expected market suitability. Such models can initiate an understanding of the product variation that current turbine manufacturers should pursue, to adequately satisfy the needs of the naturally diverse wind energy market.

The wind farm design problems formulated in this dissertation involve highly multimodal objective and constraint functions and a large number of continuous and discrete variables. An effective modification of the PSO algorithm is developed to address such challenging problems. Continuous search, as in conventional PSO, is implemented as the primary search strategy; discrete variables are then updated using a nearest-allowed-discrete-point criterion. Premature stagnation of particles due to loss of population diversity is one of the primary drawbacks of the basic PSO dynamics. A new measure of population diversity is formulated, which unlike existing metrics capture both the overall spread and the distribution of particles in the variable space. This diversity metric is then used to apply (i) an adaptive repulsion away from the best global solution in the case of continuous variables, and (ii) a stochastic update of the discrete variables. The new PSO algorithm provides competitive performance compared to a popular genetic algorithm, when applied to solve a comprehensive set of 98 mixed-integer nonlinear programming problems.