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Numerical Optimization and Noise Analysis of High-Tip-Speed Wind Turbine

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Abstract. With lower turbulence and less rigorous restrictions on noise levels, offshore wind farms provide favourable conditions for the development of high-tip-speed wind turbines. In this study, the multi-objective optimization is presented for a 5MW wind turbine design and the effects of high tip speed on power output, cost and noise are analysed. In order to improve the convergence and efficiency of optimization, a novel type of gradient-based multi-objective evolutionary algorithm is proposed based on uniform decomposition and differential evolution. Optimization examples of the wind turbines indicate that the new algorithm can obtain uniformly distributed optimal solutions and this algorithm outperforms the conventional evolutionary algorithms in convergence and optimization efficiency. For the 5MW wind turbines designed, increasing the tip speed can greatly reduce the cost of energy (COE). When the tip speed increases from 80m/s to 100m/s, under the same annual energy production, the COE decreases by 3.2% in a class I wind farm and by 5.1% in a class III one, respectively, while the sound pressure level increases by a maximum of 4.4dB with the class III wind farm case.

AMS subject classifications: 34H05, 45L05, 47F05,76G25

Key words: Wind turbine design, high tip speed, multi-objective optimization, noise analysis.

1 Introduction

The tip speed of most commercially operating onshore wind turbines is usually limited to 80m/s, based on the consideration of both the power generation cost and the aerodynamic noise limitations of wind turbine. It is known that increasing the tip speed of wind

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turbines will increase the aerodynamic noise [1,2]. Although wind turbine noise limitations are not specified in IEC and GL standards, the tip speed is generally kept no higher than 80m/s to avoid causing considerable harm to the human population nearby wind farms. Nevertheless, increasing the tip speed brings a lot more benefits. For example, the wind speed range corresponding to the optimum rotor power coefficient can be expanded [3], thus promoting the power output of the wind turbine. In addition, increasing the tip speed will reduce the rotation moment acting on the blade as well as the loads acting on the drive train and generator, thus lowering the power generation cost [4].

The offshore wind turbine design may allow higher tip speed than onshore one. Because the sea is uninhabited by humans, there are less noise restrictions on noise propagation. Moreover, vertical air convection over an open sea is less violent and less affected by topographic factors; the turbulence intensity of offshore is much lower than that of onshore [5,6]. Long-term field measurements of wind over an open sea can be found in the existing literature [7]. The characteristic value of the turbulence intensity at 15m/s I15 is 4.9% at the height of 90 m above sea level, which is much lower than the onshore turbulence intensity (minimum 12%) given in the IEC standard. This means that turbulent inflow noise, which is the main source of aerodynamic noise, greatly decreases for offshore wind turbines and therefore may leave much space for increasing the tip speed.

The optimization design of the wind turbine is in a process that involves many constraints, design variables and objectives among which there may exist conflicts with one another, whether the wind turbine tip speed is high or not. For large wind turbine design, a delicate balance must be achieved among several objectives including power generation cost and generating capacity [8]. A large number of design variables must be considered with respect to the aerodynamic configuration and the structural features as key components. Additionally, constraints are also needed to satisfy the requirements pertaining to geometry, loads, vibration and fatigue. Therefore, optimization design of large wind turbines is a multi-objective, multi-variable and multi-constraint problem. In the existing literature about wind turbine design [9], as many as 32 design variables and 102 constraint conditions are considered, making the optimization much challenging.

There exists no unique optimal solution for the multi-objective optimization of wind turbine design. Rather, the purpose of multi-objective optimization is to identify a group of trade-off solutions, known as Pareto optimal solutions, which are used to find the Pareto Front (PF). In essence, PF is the interface separating the feasible and infeasible solution regions in the objective space. Due to the complexity of the optimization, the multi-objective design of wind turbine currently uses evolutionary algorithms, including Hierarchical GA [10], PAES [11], SPEA2 [12,13], MOGA [14], NSGA-II [15–18] and PSO [19,20]. These algorithms are categorized as gradient-free algorithms (GFAs) [21]. The most salient advantage of GFAs is the tolerance of random errors generated in searching, which makes the algorithms suitable to optimization problems with any number of variables, objectives and constraints. However, when applied to complex multi-objective optimization, GFAs may have the defects of poor convergence, low efficiency and inability to find the precise PF [22–24]. The reasons are two-fold. First, the optimization