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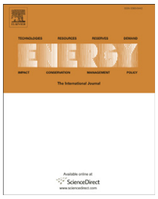

# Multi-objective differential evolution optimization based on uniform decomposition for wind turbine blade design

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ABSTRACT

Wind turbine blade design is a complicated multi-objective optimization task. In this article, a novel gradient-based multi-objective evolution algorithm based on both uniform decomposition and differential evolution is proposed for the design of wind turbine blades, to overcome unsatisfactory convergence performance and diversity of solutions usually existing in conventional evolution algorithms. A uniform decomposition mechanism is developed to achieve homogeneous discretion of the objective space for the purpose of controlling population distribution. Meanwhile, a differential evolution mechanism based on neighbourhood and gradient is developed to achieve exploration-exploitation balance and enhance optimization efficiency of the algorithm proposed. Two-objective, three-objective, and four-objective optimizations for the 1.5 MW wind turbine blade designs reveal that the proposed algorithm exhibits improved distribution, convergence, and converging efficiency compared to the conventional evolution algorithms such as NSGA-II. Additionally, the improvements are more significant with more objectives involved, demonstrating that the proposed algorithm can serve as a universal, high performance algorithm for the multi-objective optimization of wind turbine blade design.

## 1. Introduction

As a key wind turbine component, the blade is a determining factor for energy harvesting efficiency and a main source of complicated and extreme loads. A large-scale wind turbine blade design involves aerodynamic-structural integration, in which dozens of variables are needed to describe the feature of the blade aerodynamic configuration and structural layer. In the design optimization process, multiple objectives (e.g., maximum annual energy production, minimum cost of energy, minimum mass, minimum extreme load, and minimum noise) are usually included and may be contradictory with each other [1]. This means that various constraints, including geometry, loads, stress and strain, vibration, and fatigue, etc., must be taken into consideration.

Modern turbine blades are designed commonly using either single-objective approaches or multi-objective approaches. The former technique uses a single optimization objective or a weighted sum of several optimization objectives and the unique optimal solution is targeted. Considerable efforts have been made in single objective optimization of wind turbine design [1–11]. In most cases, the cost of energy (COE), a key indicator of economic benefits in wind energy harvesting, is used as the optimization objective [5–12]. In COE, all loads on components are converted into costs using pre-constructed empirical cost models. Slender blades and poor solidity are often seen with minimized COE, resulting in significantly reduced annual energy production (AEP) [1,12]. Indeed, a unique extreme solution under certain conditions is pursued in single objective optimizations; other objectives and constraints, especially those that are contradictory to the objective, are not accounted for [10].

Therefore, multi-objective optimization based on Pareto optimal theories have been intensively studied and widely applied. Instead of a unique optimal solution, multi-objective optimization targets trade-off solutions (known as Pareto optimal solutions), in which multiple objectives are balanced and the Pareto Front (PF), which is essentially the interface between feasible and infeasible zones in the objective space, are approximated based on Pareto optimal solutions. Due to the complexity of the optimization, the multi-objective design of wind turbine currently uses evolutionary algorithms, including hierarchical GA [12,13], PAES [14], SPEA2 [15,16], MOGA [17], NSGA-II [18–21], PSO [22,23], and their variants [24,25]. These algorithms are categorized as gradient-free

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algorithms (GFAs) [8]. Advantages of GFAs include tolerance of random errors occurring in the search process and applicability of optimizations of any number of design variables, objectives, and constraints. Despite their good performances in two-dimensional optimizations, GFAs are limited by poor convergence, low efficiency, and inaccurate PF in multi-dimensional optimizations involving more than two objectives. This can be attributed to two factors.

The first is the ineffective diversity maintaining mechanisms of GFAs, which can result in unacceptable population distributions that affect the convergence of the algorithm. The diversity of GFAs is maintained by clustering operators [12–16] and crowding distance [17–21], as well as their variants [22,25] where a virtual value is assigned to each individual to provide clues for the approximated value of the density of adjacent solutions. As distances from a specific solution to adjacent ones increase, this value increases, and therefore results in an increasing probability that this specific solution is selected. In the cases involving these two mechanisms, population distributions are in dynamic regulation for all generations, which causes performance fluctuations and efficacy degradation. Also, population aggregation induced by ineffective diversity maintenance may be observed, and an accurate PF cannot be achieved [13,26].

The second factor that limits GFAs is the curse of dimensionality [27]. In GFAs, the Pareto dominance principle, defined as such if it is not worse than another solution in terms of any objective and is better in terms of at least one objective, acts as the criteria for the comparison of individuals and the major driving force for population evolution. Hence, the probability that an individual can evolve into improved performance is $1/2^m$ [13] ($m$ is the number of objectives). For instance, the probability in a four-objective optimization (as in this study) is 1/16. Clearly, the probability decreases exponentially as the optimization dimension increases, making the algorithm pre-disposed to failure. To date, most wind turbine designs adopt two-objective optimization strategies; few optimizations adopt three-objective strategies, which definitely involve considerable simplifications. GFAs are not applicable for designs with high dimension optimization strategies due to the extremely challenging optimization process.

In this work, a novel multi-objective differential evolution algorithm (known as MODE/D) is proposed based on a uniform decomposition mechanism for the design of wind turbine blades. Herein, the population diversity in the objective space is maintained by the uniform decomposition mechanism, and the optimization efficiency is significantly enhanced by a gradient-based evolution mechanism. To the best of the authors' knowledge, this is the first time that a uniform decomposition mechanism and differential evolution are combined to establish high performance multi-objective algorithms, and gradient-based methods are used in multi-objective design of wind turbine. Subsequently, two-to four-objective optimizations of 1.5 MW wind turbine blades are investigated based on the proposed algorithm, and the performance of this algorithm is evaluated and analysed.

## 2. Modelling of wind turbine blade

Fig. 1 shows the design procedure of a wind turbine blade in this study. First, some initial inputs including the blade structural type, materials, design standard and basic parameters of the optimization algorithm etc., are specified as a starting point of the optimization. Then the optimization variables are defined by the blade parametric modelling, and based on this, the initial population is generated. After that, each individual in the population is evaluated based on FAST codes to obtain objective values and constraint values. Subsequently, the population is brought into the optimization algorithm MODE/D and evolutionary operations are launched to generate the population of the next generation. The final step is to determine the convergence; if $t > T$ or other stopping principles are satisfied, the final population is stored as the ultimate optimal solutions; otherwise, the evaluation iteration is set to $t = t + 1$, and the iteration process of the next generation is continued.

### 2.1. Design variables

Design variables of a wind turbine blade can be categorized as aerodynamic shape variables and structural layer variables.

The aerodynamic shape variables are used to describe the geometrical features of the blade including the distributions of chord, twist, relative thickness, and pre-bending. These variables determine the blade aerodynamic performance. In this study, the blade chord, twist, and relative thickness distributions are, respectively, defined with five control points as design variables at the locations of 0.2$R$, 0.4$R$, 0.6$R$, 0.8$R$, and 0.96$R$ in the spanwise direction ($R$ represents the blade length), as shown in Fig. 1a–c. The relative thickness is fixed as 100% at the blade root. Third-order spline fitting is applied for the distributions of chord, twist, and relative thickness, as follows:

$$y\left(\frac{r}{R}\right) = a\left(\frac{r}{R}\right)^3 + b\left(\frac{r}{R}\right)^2 + c\left(\frac{r}{R}\right) + d$$

The pre-bending distribution is fitted by the exponential function with two variables at the locations of 0.6$R$ and $R$ in the spanwise direction, as shown in Fig. 1d. The fitting formula is defined as following:

$$y\left(\frac{r}{R}\right) = f\left(1 - e^{g\left(\frac{r}{R}\right)}\right)$$

where, $a$, $b$, $c$, and $d$, $f$ and $g$ are all the coefficients determined solving linear equation systems resulted from the above equations; $r$ represents the radial distance from the blade root.

The basic structure of the 1.5 MW wind turbine blade, as a design example in this study, is shown in Fig. 2, and its main components include the skins, spar caps, webs, trailing edge panels, and sandwich layers, etc. The materials used in the blade are glass fiber fabric, epoxy resin, polyvinyl chloride (PVC), balsa and structural adhesive. Among them, glass fiber fabric and epoxy resin are moulded into composites commonly called the glass fiber reinforced plastics (GFRP) [18]. In the 1.5 MW blade, skins are divided into inner skin and outer skin. They not only provide the blade aerodynamic shape, but also bear most of the shear load acting on the blade. Thus the biaxial or three-axis glass fiber fabric are used to strengthen the shear resistance ability. Spar caps are employed as the main load bearing units for resisting most of the bending moment, so unidirectional GFRP is used to enhance the strength and stiffness performance. Webs are mainly used as supporting components for the sustaining spar caps, and also are the shearing-resistance components of blade. A web is composed of two panels and sandwich layer. The panels are made of biaxial GFRP and the sandwich layer is filled with PVC foam. For resisting the flapwise bending moment, trailing edge panels are embedded into the blade. Similar to the spar caps, the trailing edge panels use unidirectional GFRP, but their thickness and width are obviously smaller than the spar caps. A plurality of cavities located at the leading edge and trailing edge regions of the blade are filled with sandwich materials to mainly enhance the blade anti-buckling and anti-instability capability. Along the spanwise direction of the blade, balsa is used near the blade root to further strengthen the anti-buckling

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