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Numerical models for robust shape optimization of wind turbine blades

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ABSTRACT

A computational framework for the shape optimization of wind turbine blades is developed for variable operating conditions specified by local wind speed distributions. The numerical workflow consists of a genetic algorithm based optimizer, a computational fluid dynamics based simulator and a 3D geometric modeller. The developed numerical workflow also implements the coupling of the process flows as well as passing data amongst the individual applications including the corresponding data mining. Several approaches to modeling 3D shapes are developed and employed by the workflow. They include parametric curves defining 2D curves lofted into 3D shapes in combination with applying computational geometry operators and full 3D parametric surface models which enable generic 3D shapes to be represented. The proposed definitions of excellence include annual energy production for given wind speed distributions and net-present-value and internal-rate-of-return based indicators as potential constituents of the fitness functions. Several case studies are presented with promising results towards the aspired custom-shaped wind turbine blades for optimum performance for any given specific location. The developed computational workflow can therefore be seen as a numerical device for custom optimization of performance of renewable energy systems.

1. Introduction

Optimum design of wind turbines is a complex undertaking which can be defined in many different ways. It can generally be observed from the point of view of a system of devices generating energy subject to many constraints related to different components of the system. It is also representative of a situation where the term optimality can assume different meanings.

Even nowadays, most optimum design problems are formulated based on a single excellence criterion [1]. Nevertheless, multi-objective formulations generating non-dominated candidate designs [2,3] have meanwhile become a computationally viable option. Wind power systems particularly imply a number of criteria, the crucial ones being:

- High output in terms of energy production, i.e. high energy conversion efficiency,
- Low investment volume,
- Low operational expenses such as maintenance
- High reliability and low out-of-operation time

These basically business-related and financial objectives translate into engineering assignments. For example, the first criterion can be converted into the technical requirement of maximized adaptability to variable operational conditions or minimized loss of efficiency for operating regimes beyond the nominal (design) conditions. Even the notions of the 'nominal operating point' or 'design conditions' are somewhat outdated and obsolescent as they were primarily associated to the days with sparing numerical, algorithmic and computational resources. These resources have now matured to the extent that objectives can be specified in close-to-realistic terms.

This paper develops a procedure for shape optimization of wind turbine (WT) blades. The respective optimization model resembles a real-world situation:

> 'given a location specified by the respective wind energy distribution and given size limits produce a maximum amount of energy'.

The optimization deals with aerodynamic aspects of the WT blade design that affect WT power and its annual energy

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production. No structural limitations to the blade design are considered that usually ask for thicker airfoils in the inboard section of a blade. Neither the noise generated by the WT blades, especially produced by the blade tip, is considered.

This paper aims to shape a WT blade as 3D body that provides the best WT power performance regarding the WT energy production at specific site.

1.1. Elements of modeling performance-based design excellence

During the last 30 years, the objective function has evolved from the earlier 'nominal operating point' maximization of the power coefficient to the maximization of the annual energy production. Since it is still hard to compete with traditional fossil fuel energy sources the main objective has shifted towards minimizing the cost of energy. The cost of energy is usually restricted to the cost of rotor [4] where the total cost of producing, transporting and erecting the wind turbine rotor can also be considered. Another approach is multi-objective optimization where the goal is to obtain multiple designs known as Pareto optimal solutions of which no single one is better than the other. An example is Diveux et al. [5], who take into account a trade-off between the ratio of the annual energy production/wind park area (maximization) and the cost of energy (minimization) where a fixed charge rate is assumed and maintenance cost is also taken into account. In the case of multi-objective optimization, no single solution can generally be considered as optimal and the Pareto front of solutions is evaluated instead. In this paper, excellence is proposed to be benchmarked in realistic economic/financial measures across the entire respective lifecycle, borrowing and adapting the NPV/IRR/TCO aggregate indicators from investment analysis. The proposed approach results in geometries optimized for maximum overall profits based on discounted cash flows rather than the standard 'nominal operating point' approach which is based on a fuzzy concept of representative single-point operation. The proposed performance metrics based on the respective overall distribution of operating regimes, while more comprehensive to numerically encompass, provide far more truthful optimum shapes of the turbine in terms of the respective 'business excellence'. Since the annual energy production is an important part for calculating the cost of energy and the absence of a reliable structural and cost model [6], attention is still directed toward optimizing the aerodynamic performance as it will be the case in this paper. Two different models of excellence are considered. The basic one is related to the annual energy production. The second one introduced conceptually is related to more truthful benchmarking of financial performance of WTs.

Evaluation of excellence is based on robust optimization principles. Numerical samples involving different operating regimes are generated to be representative of the respective wind energy distribution for the given location. Multi-point CFD simulations are subsequently carried out accordingly to evaluate excellence of candidate designs, Fig. 1.

Initially, this paper models excellence as being proportional to the overall energy produced by the candidate-shape WT for a given distribution of wind regimes at a given location. Nevertheless, more truthful modeling can be introduced based on the Net Present Value (NPV) and Internal Rate of Return (IRR) indicators borrowed from investment analysis, [7].

The optimization model should go beyond the engineering space towards being expanded to the resulting economic model for excellence benchmarking, which can measure all the financial (value-based) consequences of the design variables. Trustworthy value-based modeling of excellence is therefore mandatory. In order to be implemented, objectives from the engineering world need to be attributed the corresponding financial valuation such that optimum design becomes an overall value-based procedure.

This overall valuation typically embraces integral valuation of performance of an object over its entire life-span. All individual optimality criteria therefore need to be allocated corresponding value contribution terms to be aggregated. This is done for the given distribution of operational regimes during the corresponding life-cycle. Based on such a procedure, optimum design and shape optimization become steered by the total value used to construct the objective function in optimum design. Shape optimization is thereby shifted from the engineering space to coupled engineering − financial evaluation.

The NPV and IRR integral optimality criteria are based on the value-based elements presented next.

The net profit P_N of a single time period (i) is equal to:

$$P_N(i) = I(i) - MW_C(i) - A(i) - F(i) - T(i) \tag{1}$$

with I as the respective income, MW_C the cost of material and work, A the corresponding value depreciation of equipment, F the financial expenses, and T the taxes. The net economic flows (E_N), aggregate the economic potential of the project according to

$$E_N(i) = I(i) + R(i) - N_I(i) - MW_C(i) - T(i) \tag{2}$$

or

$$E_N(i) = P_N(i) + A(i) + R(i) - IN(i) \tag{3}$$

where R is the project's residual value, N_I the incremental investment during the life-cycle.

Applying time-based discounting of all the value-based entities, the integral NPV indicator is obtained as:

$$NPV = \sum_{i=0}^{n} \frac{E_N(i)}{(1+D)^i} \tag{4}$$

with D as the rate of discounting and n the number of successive periods. Another integral indicator is the IRR, defined as that particular rate of discounting (D^*) which drives the NPV value to zero,

$$IRR = D^* \Rightarrow NPV(D^*) = \sum_{i=0}^{n} \frac{E_N(i)}{(1+D^*)^i} = 0 \tag{5}$$

The NPV represents the equivalent cumulative value of all discounted E_N flows within the life-cycle as the economic valuation of the candidate design.

A simplified approach to excellence valuation which is applied here is to use the standard robust design methodology. The candidate WT designs are exposed to a numerically generated sample representing the actual distribution of wind speeds at the selected location. The respective overall energy outputs are evaluated using CFD simulations.

1.2. Elements of CFD simulation model

Fig. 2 illustrates the complexity of optimizing WT on annual energy production. Wind energy distribution $f_{sw} = \frac{1}{2}\rho v^3 f(v) T$ available at specific site is represented with a bell-shaped curve. It is coupled with the power coefficient c_{pm} distribution of various WTs. For the sake of simplicity, they are generated by altering the rotational speed of the same wind rotor. The limitation for the max WT output is the same for various rotational speeds and shown in Fig. 3. Post stall behavior is simplified as it was achieved with pitch to stall regulation and represented with $c_{Pm}v^3 = const$ in Fig. 2.