Multi-MW wind turbine CoE reduction via a multi-disciplinary design process

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Introduction

The automated design of wind turbines is a multi-disciplinary process that requires the combination of high fidelity physic-based models and optimization algorithms driven by suitable metrics, as for example the cost of energy (CoE) [1]. An effective integration of structures, aerodynamics, controls and sub-systems design allows one to account for the many complex and subtle couplings among the various aspects and constraints, to perform the detailed sizing of the various components and to identify the global optimum configuration of the wind turbine. Such a high fidelity automated method proves to be most valuable in the design process of very large machines, which lay outside of the usual well known design space and which pose particular challenges.

Methodology

The wind turbine design activities performed in collaboration at Technische Universität München and at Politecnico di Milano aim at developing automated tools for the holistic design of wind turbines [2,3]. The design tool Cp-Max (Code for performance Maximization) is based on the high fidelity multi-body aeroelastic code Cp-Lambda (Code for Performance, Loads, Aeroelasticity by Multi-Body Dynamics Analysis) and has recently undergone major developments to successfully tackle the challenge of reducing the CoE of multi-MW machines. Cp-Max is structured following an industrial and certification perspective, and combines all relevant sub-optimization processes into a global nested loop. The code integrates a blade aerodynamic optimization step with a high fidelity structural optimization algorithm. The former aims at maximizing the power performance of a machine by finding the optimum chord, twist and thickness distributions, while the latter performs the optimal structural sizing of blades and tower for minimum initial capital cost (ICC) and fulfillment of all structural constraints [3]. These two sub-loops have been successfully integrated into a single working environment, which allows one to globally investigate the wind turbine configuration corresponding to a minimum CoE. Wind turbine variables such as rotor diameter, hub height, rotor cone angle, nacelle uptilt and rotor solidity are automatically handled by an optimization algorithm to achieve the optimum configuration of minimum cost. In this framework, CoE is calculated from two sophisticated cost models, the INNWIND CoE and the SANDIA blade cost models [4,5], which have been integrated together.

Applications

The design methodology briefly exposed above has been applied to a conceptual 10 MW wind turbine model designed by the INNWIND consortium, and representative of the next generation offshore machines [6]. The analysis of a complete set of design load cases (DLC) identified DLCs 1.1, 1.3, 2.1, 2.3 and 6.2 [3,7] as the main design drivers. The same analysis also showed a strong potential for reducing the CoE by a fairly radical resizing of the whole machine.

Table I compares some parameters of the 10 MW baseline machine with the optimum output of Cp-Max. Qualitatively, the general trend of the optimizer is to significantly upscale the wind turbine. A larger rotor diameter allows in fact for a reduction of the rated wind speed and therefore for a higher energy capture. A similar trend is observed for the hub height, which identifies an optimum at +16% compared to the baseline, thanks to a higher average wind speed and lower wind shear in the blade swept area. Blades and tower are simultaneously designed using a monolithic approach, and show coupling effects from the frequency and clearance constraints. For instance, a reduction in the tower diameter allows for an increased blade tip deflection; this is beneficial up to the point where tower resonance starts driving the tower stiffness, in turn increasing its cost. All these combined effects are also influenced by the rotor cone angle and nacelle uptilt, which reach an optimum that finds the best trade-off in terms of tower clearance, blade frequency constraints, centrifugal loads and rotor aerodynamic efficiency. At the blade level, twist and chord distributions are adjusted to account for the longer span. In addition, thinner profiles are adopted in the inboard region to increase power coefficient, while thicker structural components are selected to successfully withstand the increased loads and satisfy frequency and stiffness constraints. From the optimum configuration, a further upscaling of the wind turbine would imply relatively small annual energy production (AEP) advantages (because of the appearance of a transition region in the power curve caused by blade tip speed limits, and because of reduced benefits from the lower wind shear), as well as a higher ICC, eventually resulting into an overall growth of the CoE.

Table 1: Results of the global optimization for the 10 MW machine

	INNWIND Baseline	**Cp-Max Optimum**	**Difference**
P_{rated} [MW]	10	10	--
Rotor diameter [m]	178.3	223.2	+ 25.2%
Hub height [m]	119.0	138.3	+ 16.2%
Cone angle [deg]	4.65	5.51	+18.5%
Nacelle uptilt [deg]	5.00	5.25	+5.0%
Rotor solidity [%]	4.66	4.08	-12.3%
V_{rated} [m/s]	11.3	9.8	-13.3%
Blade mass [tons]	42.5	75.6	+77.9%
Tower mass [tons]	618	886	+43.6%
AEP [GWh/y]	48.8	57.2	+17.2%
ICC [M€]	30.0	34.3	+14.3%
CoE [€/MWh]	70.73	65.79	-7.0%

Motivated by the recent interest in low induction (LI) rotors [8,9], LI configurations were also investigated in this study using Cp-Max. LI solutions are analyzed by including a new optimization variable representing an offset to the aerodynamic optimum pitch angle; this allows the algorithm to select a rotor operating at low axial induction, if this is overall beneficial for the figure of merit. Current results from Cp-Max do not show the natural appearance of a low induction configuration as the result of an integrated global optimization; in this sense, the optimal solution for the large machine studied here appears to be a standard high-efficiency high-induction rotor.

On the other hand, LI solutions may be found by introducing external constraints on the blade root combined moment or on global rotor loads transmitted to the rest of the machine. In this case, one is trying to improve CoE by increasing the rotor diameter, while at the same time not exceeding some of the loads of the baseline machine, an approach akin to a machine reblading. Compared to the INNWIND baseline, a LI optimum configuration has a 5.6% larger rotor diameter and a 1.8% lower CoE, with the same blade root combined moment and a lower rotor thrust. The limit of these solutions is that not all loads can be constrained to the ones of the baseline, as for example in the case of storm loads.

The design methodology just described is currently being replicated on a 2 MW wind turbine model, representative of mid-size onshore machines. The results of this second study, when compared to the ones of the large machine illustrated above, will highlight differences in configurations, drivers and tradeoffs across these two different power classes.

Conclusions

The work presented here describes a new design methodology for wind turbines, based on an integrated optimization process using high fidelity system models, advanced cost models and robust optimization algorithms. The method is applied on a conceptual 10 MW machine representative of the future generation very large offshore machines. Results indicate a significant margin for improving a baseline manually-derived solution, with CoE savings of 7.0%. The method is also applied to the investigation of a low induction rotor concept, producing smaller advantages in terms of CoE but also reduced loads on the structure.

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