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Optimizing the design of horizontal-axis small wind turbines: From the laboratory to market

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ABSTRACT

The design process for small wind turbines is usually based on standard methods and tools used for higher-scale turbines. However, small wind turbines have peculiar features due to their field of application. In this work, a laboratory to market approach for the design of blades for small wind turbines is proposed. The choice of profiles is based on the optimization of the aerodynamic behavior, compatibly with limitations due to the need of a simple mechanical structure. The blade is made of glass fiber-reinforced polymer, realized through injection molding. Finite Element Method is employed for numerical simulation of the distribution of the stresses along the blade. Static and dynamic experimental tests are conducted to validate the structural model against experiment. A mean difference of 3.8% between simulated and measured modal frequencies is recorded, and a maximum variation of 6.8%, as concerns strain values, is obtained. An example of structural optimization is proposed, and a twofold structural validation is conducted: in operation, at critical working conditions, and static at extreme wind conditions. In conclusion, wind tunnel tests reveal that the rpm–power curve displays significant rpm intervals along which the output is almost flat, supporting the use of the turbine also in considerably turbulent environments.

1. Introduction

In the near future, wind energy will be one of the main electricity sources: the 2050 Energy Roadmap of the European Commission puts the goal of a percentage of electricity generated by the wind between 31% and 48%. In the latest years, due to the financial crisis, new high power installations have decreased, on the other hand increasing attention to the microgenerators (power output <20 kW). Considerable attention is therefore being devoted, in the scientific literature, on the main features of design and performance analysis for small wind turbines, confirming the interest for this field of wind energy production (Onder and Ozgener, 2006; Hiroyuki et al., 2005; De Broe et al., 1999). A critical issue about the exploitation of micro wind turbines is the environment in which they are set. The perspective of integrating micro wind turbines in the urban context is fascinating in the context of energy production on domestic scale, but there are several shortcomings. Energy Saving Trust in UK (James et al., 2010) monitored performance of 39 horizontal axis turbines in urban, suburban and rural locations and argued that the performance of urban micro-wind sites under test was poor. Such studies have consolidated the storytelling according to which micro wind turbines intrinsically perform poorly, but this is rather a prejudice to which the present work aims at giving some response. As concerning urban terrain, the main problem is that it induces rapidly varying wind speed, and therefore considerable turbulence intensity which can be difficult even to estimate. This issue is analyzed, for example, in Sunderland et al. (2013), Tabrizi et al. (2015) and Emejeamara et al. (2015). In Lubitz (2014), it is shown that ambient turbulence might be favorable for power production at low wind speeds, while the opposite happens near the turbine furling speed: mapping gusts is therefore crucial (Bertényi et al., 2010). In Danao et al. (2013), the power factor of a vertical axis wind turbine (VAWT) is analyzed in its time evolution under unsteady wind flow. About optimization of VAWT under unsteady conditions, see also Nobile et al. (2014). Also from Drew et al. (2013), urban environments are often characterized by low mean annual wind speeds and therefore a micro wind turbine should be optimized in the starting regime. On the other

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hand, yet, the amount of producible energy under this regime is unavoidably low, and it is therefore needed to have non-trivial trade-off between starting performance and power output in high winds. For large-size wind turbines, this trade-off is dynamically adjusted through the variability of the inclination of the blade with respect to the rotor axis in function of the wind speed (variability of the pitch-angle). For micro wind turbines, this is not economically reasonable due to the size of the system: pitch control would have a high cost against a modest increase in energy extraction.

For this reason, the most common strategy for improving performances of micro wind turbines is the optimization of the design of rotor blades and this is also the topic of the present work. In particular, we deal with horizontal axis micro wind turbines. This issue has attracted a vast debate in the scientific literature: in Song and Lubitz (2014), interesting developments are achieved. A Bergey XL turbine is equipped with blades, designed by means of BEM (Blade Element Momentum Theory), and is tested at two pitch angles. It is shown that at high wind speeds the new custom blades perform better than the default ones, while at low wind speeds the opposite occurs. This sheds a powerful light on the crucial issue of pitch angle selection and blade design for micro wind turbines. In Ying et al. (2015), the focus is pointed on good starting feature compared with a conventional horizontal axis wind turbine, thus providing an interesting candidate for urban areas domestic application. In Lumbreras et al. (2014), the opposite choice is made and small wind turbine performance optimization is addressed in the high wind region: a soft-stalling control strategy is proposed, moving the operating point of the machine from the maximum power point trajectory (MPPT) to a decreased efficiency operating point. In Pourrajabian et al. (2014) the effect of altitude on small wind turbine blades is investigated: in particular it is shown that the starting performance and the power coefficient of a blade optimized for operating at sea level degrades at higher altitudes. This reveals that indeed turbine design and environment analysis are deeply intertwined. Another crucial issue for compromising between economic feasibility and performances is the selection of the material of the blades. The blades are characterized by a variable section depending on the distance from the axis of the rotor (Habali and Saleh, 2000) and are often made up of low cost composite materials, with variable mechanical properties depending on the chemical composition and on the manufacturing process. Typically, blades made of glass fiber reinforced polymers have lower weights than metals, but they have poor mechanical properties. Therefore, numerical analysis and simulations are particularly useful for structural assessment. For example, in Zafar et al. (2014), a fiberglass-epoxy blade is designed on the basis of aerodynamic simulations: structural testing is performed through the ANSYS simulation software and an acceptable structural integrity is predicted. In Pourrajabian et al. (2016a), at the crossroad between structural integrity and starting performance, the route of starting time optimization is selected and an aero-structural design is proposed for hollow blades of a small wind turbine. For a comprehensive review on most of the issues about micro wind turbine technology, we finally refer to Karthikeyan et al. (2015a).

As briefly discussed above, significant developments have recently been achieved in small wind turbine design for performance optimization: nevertheless, what in our opinion is still missing in the literature is a holistic approach, which interfaces science and technology for a market to laboratory approach, combining economic considerations to an high level of scientific contribution throughout all the process from blade design to structural analysis in dynamic and static conditions. Therefore, the present paper is basically a journey from the computer (i.e. mathematical models) to the laboratory to the production of a small wind turbine, whose performances are optimized in a low-cost framework. First, a design model for blades dedicated to small wind turbines (approximately with rotor diameter $\simeq$ 2 m and swept area $\simeq 3.14\ \mathrm{m}^2$, which is a size defined as small wind turbine (Wood, 2011)) is developed. The underlying principle is conjugating a reasonably good starting performance (thus making it reliable to employ the turbine also in urban settings) with optimum power extraction in the medium-wind range and with structural integrity under extreme conditions. For these reasons, a plastic material is selected with reinforcing fibers through an injection molding process: on one hand, this guarantees low costs, but on the other hand it requires particular attention to the need of avoiding structural damages under critical working conditions. Therefore, a structural model of the blade is developed, taking into account the features of the production process, and validated through static and dynamic experimental tests. Further, an example of structural optimization is analyzed, with particular attention to the need of avoiding structural damages under critical working conditions. Finally, experimental tests at the wind tunnel facility are analyzed and the results point out that, applying the indications coming from the numerical modeling, it is indeed possible to construct a wind turbine displaying considerable stability of the rpm–power curve, and thus appropriate for responding also to critical regimes (high turbulence). Considerable evidence is therefore collected that numerical modeling indeed provides useful caveat for improving structural safety of the blade and operational performance of the wind turbine: low costs can be safely maintained, by choosing such cheap plastic material and keeping the control system as simple as possible, if indications from numerical simulations are taken into account.

2. The laboratory to market approach

As hinted in Section 1, the philosophy of the present work is proposing a holistic approach for small wind turbine blade design: from laboratory to market, from numerical modeling for profile creation, to the choice of the material (aiming at conjugating satisfying power factor and low cost), to structural and operational validation, even under critical working conditions. This complex route encounters several scientific and technical challenges and should be faced as a whole, in order to harmonize innovation with market requests. The sub-objectives to achieve are basically the following:

- Defining swept area A, cut-in and cut-out $v_{\min}$ and $v_{\max}$, and therefore expected rated power P_m.
- *Choosing the profile*: by means of Blade Element Momentum Theory (BEM), define the number of blades and the expected revolutions per minute (rpm) in order to maximize the power coefficient C_p.
- *Choosing the blade geometry*: according to cost issues, define thickness and material of the blade. In the present test case, the blade is realized through an injection molding process and the profile is totally filled.
- *Choosing the injection strategy*: Finite Element Method (FEM) is employed for numerical modeling of stresses distribution on the blades for different loads, according to the chosen geometry. Effects of anisotropy induced by injection are simulated through an ad hoc software. A modal and a static analysis are performed.
- *Validating the numerical model by means of wind tunnel testing*: four strain gauges are placed on the surface of the blade characterized by higher strain; two of them are used to measure the strain due to the bending moment and to compare against numerical prediction. The support of the blade is connected to a load cell to compare numerical and experimental drag force.