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Control design for a two-bladed downwind teeterless damped free-yaw wind turbine

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ABSTRACT

In this paper, a control architecture for a two-bladed downwind teeterless damped free-yaw wind turbine is developed. The wind turbine features a physical yaw damper which provides damping to the yawing motion of the rotor-nacelle assembly. Individual Pitch Control (IPC)[1] is employed to obtain yaw control so as to actively track the wind direction and to reduce the turbine loads. The objectives of both load and yaw control by IPC are conflicting and therefore two decoupling strategies are presented and compared in terms of controller design, stability, and turbine loads. The design of the different controllers and the physical yaw damping are coupled and have a large impact on the turbine loads. It is shown that the tuning of the controllers and the choice of the yaw damping value involve a tradeoff between blade and tower loads. All results have been obtained by high-fidelity simulations of the state-of-the-art 2-B Energy 2B6 wind turbine.

1. Introduction

With the goals set by the European Union for the year 2020 and 2030 [1,2], offshore wind energy has a bright future. Although the total amount of offshore wind power is planned to strongly increase during the next decades, offshore wind has, however, still a bottleneck; the cost of energy. To drive down the cost of (offshore) wind energy, different opportunities exist. Considering the past decades, manufactures have steadily increased the size of wind turbines. With increasing size, rated speed and power are reached at lower wind speeds yielding an increase in annual generated power and enables deployment in easier accessible areas. Moreover, with the implementation of active load reduction techniques, loads can be kept at a lower level such that a lighter design can be obtained, which means a reduced amount of material.

In the ongoing effort of reducing the cost of energy, an interesting opportunity can be found in two-bladed wind turbines. Two-bladed wind turbines have been developed and built during the seventies and eighties of the previous century (see for example [3,4] or refer for more details of wind turbine developments in that period to [5] and [6]). For different reasons, including noise [7], visual, and dynamic aspects [3], the focus at the end of the eighties completely shifted to three-bladed wind turbines, which to this day dominate the landscape. However, with the increased deployment of wind turbines at offshore locations, two-bladed wind turbines can become a viable choice in order to further decrease the cost of energy. This is mainly motivated by the fact that at offshore locations several drawbacks cease to exist, i.e., the noise and visual aspects. Moreover, with more advanced control techniques becoming available, the dynamic drawbacks of a two-bladed wind turbine

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[1] List of abbreviations: Individual Pitch Control (IPC); Collective Pitch Control (CPC); Linear Individual Pitch Control (LIPC); Multi-Blade Coordinate (MBC); Multi-Blade Coordinate (MBC); Out-of-Plane (OoP); In-Plane (IP); Variance Accounted For (VAF); Damage Equivalent Load (DEL); Extreme Direction Change (EDC); Proportional Integral (PI).
List of symbols: T_{trq}: Demanded generator torque for speed regulation; T_{dtd}: Demanded generator torque for drivetrain damping; T_{gen}: Demanded generator torque; Ω_{rated}: Rated generator speed setpoint; Ω_{gen}: Generator speed control setpoint; θ_{col}: Collective blade pitch angle; θ_{col}: Collective blade pitch angle; θ_1: Individual blade 1 pitch angle; θ_2: Individual blade 2 pitch angle; Θ_1: Blade 1 pitch angle; Θ_2: Blade 2 pitch angle; θ_{tilt}: Non-rotating blade pitch setpoint for tilt coordinate; θ_{yaw}: Non-rotating blade pitch setpoint for yaw coordinate; $M_{y,\,1}$: Blade 1 Out-of-Plane root bending moment; $M_{y,\,2}$: Blade 2 Out-of-Plane root bending moment; $M_{x,\,1}$: Blade 1 In-Plane root bending moment; $M_{x,\,2}$: Blade 2 In-Plane root bending moment; M_{tilt}: Rotor tilt moment; M_{yaw}: Rotor yaw moment; ψ: Rotor azimuth angle; ψ_{off}: Azimuth angle offset; ϕ_{ref}: Yaw setpoint angle; $\dot{\phi}_{\mathrm{yb}}$: Yaw bearing angular velocity; n: n'th harmonic of load; ϕ_{yaw}: Yaw misalignment (between turbine yaw position and wind direction); ϕ: Yaw error (controller input); $\mathcal{L}_{\theta}$: Low-pass filter for individual pitch angles; $\mathcal{L}_{\phi}$: Low-pass filter for yaw misalignment signal; $\mathcal{H}_{\mathrm{IPC}}$: High-pass filter for individual blade pitch signals; $\mathcal{L}_{\mathrm{yb}}$: Low-pass filter for yaw bearing angular velocity signal; f_{IPC}: Cut-off frequency of high-pass filter for individual pitch control κ: Gain of yaw model; τ: Time constant of yaw model; T_d: Time delay in yaw model.

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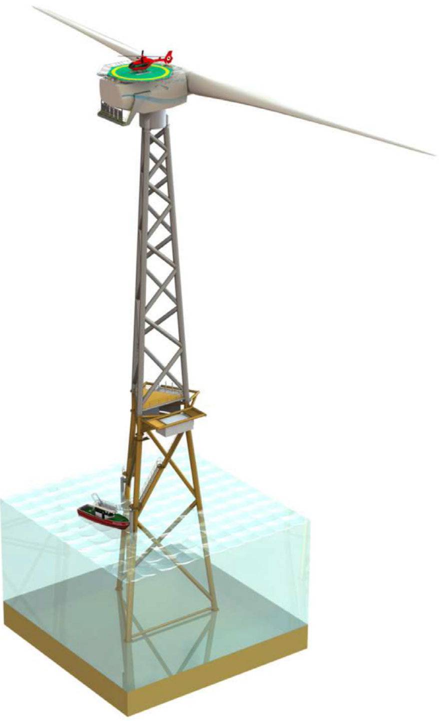

Fig. 1. Illustration of the 2-B Energy 2B6 wind turbine.

can be overcome. The potential of two-bladed wind turbines can then be found in saving the costs of a blade, several transportation and installation advantages, and, due to the fact that two-bladed rotors typically operate at higher rotational speeds [3], the drive-train and nacelle can be lighter.

In the past couple of years, the wind energy community has recognized this potential and has renewed its interest in two-bladed wind turbines. That is, there has been a substantial number of publications regarding two-bladed wind turbines (to mention a few [8–14]), but also a number of new two-bladed designs have been developed and built in recent years. An overview of two-bladed wind turbine designs since the year 2000 can for instance be found in [9] (including the references therein) and in [15]. One of these novel designs is the subject of this paper and is being developed by 2-B Energy in the Netherlands [16]. The novel two-bladed wind turbine design, called the 2B6, is a 6 MW turbine with a 140.6 m rotor diameter and a damped free-yaw system. Among others, the novelties of the full modular two-bladed 2B6 wind turbine are

1. a downwind[2] rotor configuration;
2. a damped free-yaw system, i.e., in a damped free-yaw system the rotor-nacelle assembly is free to rotate on the tower and is only damped in its motion;
3. a full three-leg jacket support structure.

Moreover, the 2B6 has a helicopter deck on top of the nacelle for ease of access and has the possibility to include a transformer deck in the jacket support structure. An illustration of the turbine is shown in Fig. 1. An extensive description of the novelties of the 2B6 turbine is given in Section 2.

As mentioned before, two-bladed wind turbines have a number of disadvantages compared to three-bladed wind turbines. One of these is the increased fatigue loadings due to the dynamics of a two-bladed rotor. Three-bladed wind turbines have a rather uniform load transfer from the blades to the shaft, whereas the load transfer of a two-bladed wind turbine is varying with rotor azimuth causing higher shaft bending loads and yaw moments [3]. This drawback could be overcome with active control methodologies and it is well-known within the wind energy community that loads can be reduced by using IPC [17], which has been a topic of interest over the past decade. In [18,19], IPC based on the Multi-Blade Coordinate (MBC) [20–22] transformation is proposed. By using the MBC transformation, the blade root moments of a wind turbine can be transformed to a decoupled tilt and yaw moment. Then, by applying integral control to the obtained tilt and yaw moments and reverse transforming the integrated moments, periodic blade pitch signals are obtained. A fair amount of literature has appeared on IPC, e.g., see [23–31]. A number of field test experiments of IPC have been performed, of which the most notable can be found in [32]. It is expected that IPC remains effective when upscaling wind turbines to the 10–15 MW range [33].

Only few publications are available that discuss IPC for two-bladed wind turbines. Recently, a Linear Individual Pitch Control (LIPC) strategy specifically intended for two-bladed wind turbines was proposed in [10]. In this strategy the nonlinear MBC transformation is replaced by a linear coordinate transformation. The coordinates obtained with the linear transformation can be thought of as a collective mode and a differential mode. In the former mode, all even blade load harmonics are contained and in the latter mode all odd blade load harmonics are contained. As such, only a single feedback loop is required to reduce the dominant once-per-revolution (1P) blade loads. Moreover, at most two feedback loops are needed to potentially reduce all periodic blade loads. The LIPC strategy has been successfully demonstrated in simulations [10,34], wind tunnel tests [35], and on the NREL CART2 wind turbine [11]. In the latter reference it is shown that the LIPC strategy and IPC using the MBC transformation yield similar load reductions.

Besides load reduction, IPC can also be deployed for a free-yaw wind turbine to actively track the wind direction. A downwind free-yaw configuration will naturally track the wind with some misalignment and variations around an equilibrium yaw angle depending on the wind speed. The equilibrium yaw angle is the angle where the 1P blade tends to be minimal [36] and, hence, in operating conditions below the rated wind speed, not the maximum amount of power will be extracted from the wind. In order to improve wind direction tracking and thereby electrical power output in below-rated winds for free yawing wind turbines, one could employ yaw control by means of IPC (denoted yaw-by-IPC). That is, by individually pitching the blades over a rotor revolution, a yawing moment can be generated that aligns the rotor-nacelle assembly with the wind. IPC for yaw control has been applied to wind turbines by means of periodic state-space control in [37] and by using the MBC transformation in [38]. These studies have demonstrated that IPC is able to keep the rotor-nacelle assembly of three-bladed wind turbines in upwind yaw configurations aligned with the wind.

In this paper, the controller design for a downwind two-bladed damped free-yaw wind turbine is analyzed. An important factor during the design process is the amount of yaw damping provided by the system and is therefore also investigated. Designing the controller and finding the optimal yaw damping value is an interesting case study from a mechatronics point of view, because the design of the involved controllers and the yaw damping are coupled and both significantly affect the turbine loads. Throughout the paper, different control configurations are discussed and demonstrated for various yaw damping values using high-fidelity

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[2] In a downwind rotor configuration the rotor is ‘behind’ the tower seen from the wind flow, i.e., the wind flow first hits the tower and then the rotor. Referring to Fig. 1, the wind is flowing from the lower left corner to the upper right corner assuming the rotor plane is approximately perpendicular to the wind direction. In an upwind configuration the wind flow first hits the rotor and then the tower.