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NREL 15-kW: An Advanced Horizontal-Axis Reference Turbine for Distributed Wind

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NREL 15-kW: An Advanced Horizontal-Axis Reference Turbine for Distributed Wind

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Abstract. Distributed wind energy can play a significant role in the renewable energy landscape. A recent study conducted by the National Renewable Energy Laboratory (NREL) identified the lack of availability and utilization of reference wind turbine models as a major hindrance in the development of the distributed wind energy technology sector, even though such models are widely used in offshore and land-based wind research. Therefore, NREL is developing three reference wind turbine architectures, also called archetypes, for distributed wind energy applications. This paper describes the detailed design and modeling of the first of the three reference turbine archetypes, called the NREL 15-kW turbine. It is a passive-yaw, upwind turbine with a rated power of 15 kW.

1. Introduction

Wind energy has experienced remarkable growth in the past few decades. With the goal of integrating substantial wind energy systems into the grid, the primary focus of wind research has been toward large, utility-scale wind turbines. However, recent studies have shown that distributed wind energy can play a significant role in the renewable energy landscape [1]. Although distributed wind has attracted research efforts that aim to facilitate the integration of distributed wind into energy markets (e.g. IEA Wind Task 41 [2]), distributed wind technology is still relatively immature and faces several challenges [3].

The National Renewable Energy Laboratory (NREL) recently conducted an in-depth assessment of the distributed wind energy technology landscape and studied the current status of the role of aeroelastic modeling in distributed wind energy applications. The findings of the study were published in Damiani and Davis, 2022 [4]. A major issue identified in the study is that the current distributed wind technology sector lacks the availability and utilization of reference wind turbine models. Such models are a cornerstone of offshore and land-based wind energy research [5].

Based on the analysis and recommendations by Damiani and Davis, 2022 [4], NREL is developing three advanced reference turbines for distributed wind energy applications under the Distributed Wind Aeroelastic Modeling (DWAM) project [6]. These turbines are known as Advanced Reference Turbines for Distributed HAWT Archetypes (ARETHA), where HAWT stands for horizontal-axis wind turbine. The three archetypes are:

- Archetype-A: 15-kW, passive-yaw, upwind turbine
- Archetype-B: 90-kW, passive-yaw, downwind turbine

- Archetype-C: 20-kW, active-yaw, upwind turbine.

These reference archetype turbines are being designed based on three existing turbines and represent the current distributed wind energy landscape. Archetype-A is based on the Bergey Excel-15 turbine [7], Archetype-B is based on the Eocycle EOX M-26 turbine [8], and Archetype-C is based on the QED PHX-20 turbine [9]. These turbines are shown in Figure 1. All three turbines are horizontal axes and are stall-regulated.

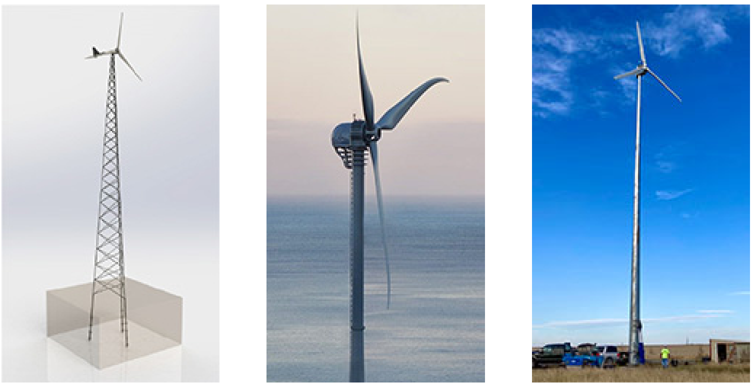

Figure 1. The three archetype reference turbines are based on a) Bergey Excel-15 turbine [7], b) Eocycle EOX M-26 turbine [8], c) QED PHX-20 turbine [9]

This paper describes the design and modeling of the first reference turbine (Archetype-A), which is named the "NREL 15-kW" turbine. The turbine blades use the stall-regulated S822 and S823 airfoils [10]. These airfoils were specifically designed for horizontal-axis wind turbines and are in the public domain [11]. An open-source aeroelastic model of the turbine was created in OpenFAST [12] and shared publicly in a GitHub repository [13].

This paper is organized as follows: Section 2.1 describes the distributed and aggregate structural properties, and Section 2.2 describes the aerodynamic properties of the turbine blades. The structural and aerodynamic properties of the tower are described in Section 3. The tail fin properties are discussed in Section 4.1. The nacelle, hub, and drivetrain of the turbine are discussed in Section 4.2. The baseline generator torque controller is presented in Section 4.3. The aeroelastic model of the turbine is publicly available, and details are provided in Section 5. The steady-state behavior of the turbine is obtained by running representative aeroelastic simulations, and results are discussed in Section 6. Finally, the main conclusions from this study are presented in Section 7.

2. Blade properties

2.1. Blade structural properties

The NREL 15-kW reference wind turbine has three blades, each 4.7 m long. Table 1 lists the distributed structural properties of the blades as a function of spanwise location, i.e., the distance from blade root toward blade tip. The NREL 15-kW turbine is a fixed-pitch turbine; therefore, the blades do not have a pitch actuator. The principal structural axes of the cross sections are oriented by the angle listed as "structural twist" in Table 1. The mass density is the mass per unit span of the blade. The flapwise and edgewise stiffnesses of the blades at various span locations are also included in Table 1.

The distributed structural properties of the blades can be integrated to obtain the structural properties of the undisturbed blades. These aggregate structural properties are described in

Table 1. Distributed structural properties of turbine blades

Spanwise location (m)	Blade fraction -	Structural twist (deg)	Mass density (kg/m)	Flapwise stiffness (N-m^2)	Edgewise stiffness (N-m^2)
0.00	0.00	22.25	7.01	1.40×10^5	7.00×10^5
0.47	0.10	22.25	7.01	1.40×10^5	7.00×10^5
0.94	0.20	22.25	7.01	1.40×10^5	7.00×10^5
1.41	0.30	22.22	5.80	9.50×10^4	4.75×10^5
1.88	0.40	22.19	3.90	3.60×10^4	1.80×10^5
2.35	0.50	22.10	2.85	1.50×10^4	7.50×10^4
2.82	0.60	21.79	2.27	7.00×10^3	3.50×10^4
3.29	0.70	21.48	2.08	3.70×10^3	1.85×10^4
3.76	0.80	21.14	1.90	2.45×10^3	1.23×10^4
4.23	0.90	20.04	1.54	1.30×10^3	6.50×10^3
4.70	1.00	18.93	0.45	2.00×10^2	1.00×10^3

Table 2. The total mass of the blade is 17.95 kg, and the center of mass is located at a span of 1.6 m from the blade root. The first and second mass moments of inertia are also listed in the table.

Table 2. Aggregate structural properties of the turbine blades

Property	Value
Length	4.7 m
Blade mass	17.95 kg
First mass moment of inertia (w.r.t. root)	28.68 kg-m
Second mass moment of inertia (w.r.t. root)	71.36 kg-m^2
Center of mass (w.r.t. root)	1.60 m
Structural damping (all modes)	0.477 %

Figure 2 shows the resulting structural mode shapes of the undisturbed blades. Two flapwise modes and one edgewise mode are shown. The mode shapes are normalized with respect to the tip deflections. The modal dampings of the two flapwise modes are assumed to be 3%, and the modal damping of the edgewise mode is assumed to be 5% based on the Bergey Excel-15 turbine [7].

2.2. Blade aerodynamic properties

The aerodynamic design of the turbine blades for the NREL 15-kW turbine uses the publicly available S823 and S822 airfoils [10]. These airfoils were designed at NREL as a part of a family of stall-regulated airfoils for horizontal-axis wind turbines for varying blade lengths and turbine power ratings [11]. S823 and S822 airfoils, in particular, are designed for a blade length of 1 to 5 m and for a turbine with a power rating of 5 to 20 kW. The S823 airfoil is used for the root sections of turbine blades and has a thicker profile with a max thickness of 21%. The S822 airfoil is used for blade tips and has a thickness of 16%. The nondimensional profiles of these airfoils are shown in Figure 3. The lift, drag, and moment polars of the airfoils are calculated using XFOIL [14] (NCrit = 9) and extrapolated to a range of −180 degrees to 180 degrees using the Viterna method [15]. The resulting airfoil polars are shown in Figure 4.

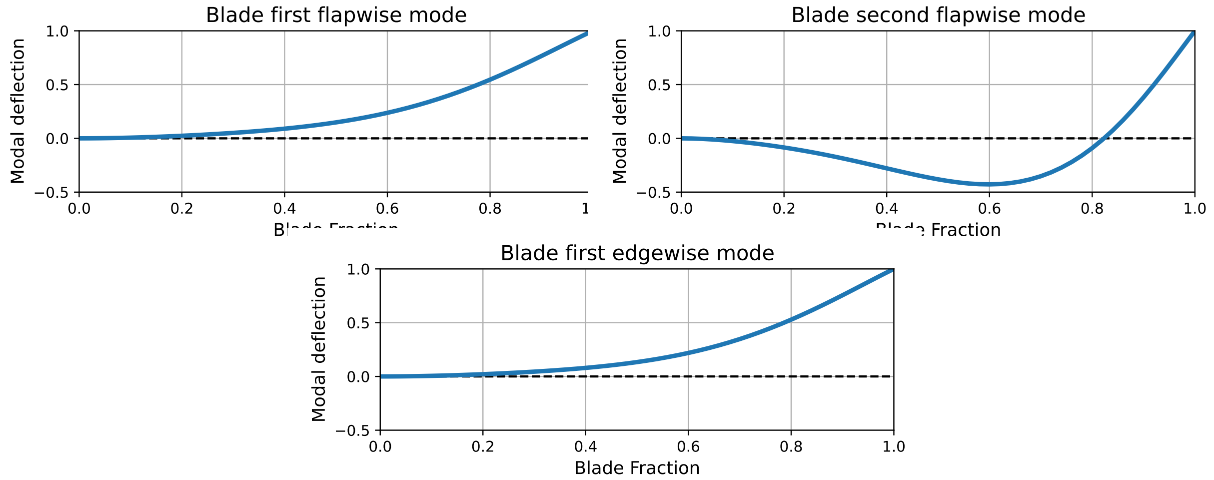

Figure 2. Normalized structural mode shapes of the turbine blades.

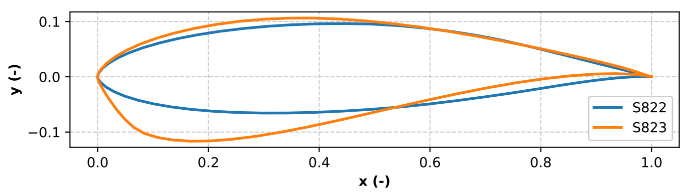

Figure 3. Nondimensional profiles of the S822 and S823 airfoils used in turbine blades.

The distributed aerodynamic properties of the turbine blades are tabulated in Table 3. The table describes the variation of airfoil twist and chord with the blade span. It also describes the type of airfoils used at each blade section.

3. Tower properties

The tower of the NREL 15-kW turbine is 28 m high. The tower is cylindrical with a constant diameter of 1 m from tower base to top. The drag coefficient of the tower cross sections is 0.5. Because the tower is axisymmetric, the lift and moment coefficients are zero. The overall mass of the turbine tower is 1952 kg. The distributed structural properties of the tower are tabulated in Table 4. The fore-aft and side-side stiffnesses are identical. The first two flexible mode shapes of the tower are shown in Figure 5.

4. Other turbine properties

4.1. Tail Fin Properties

The NREL 15-kW turbine is a passive-yaw turbine and has a tail fin to regulate its yaw orientation. The tail fin is a flat-plate delta wing with mean chord of 0.5 m and an area of 1.017 m^2. The tail fin apex is located 3.034 m behind the tower top with a vertical offset of 0.12

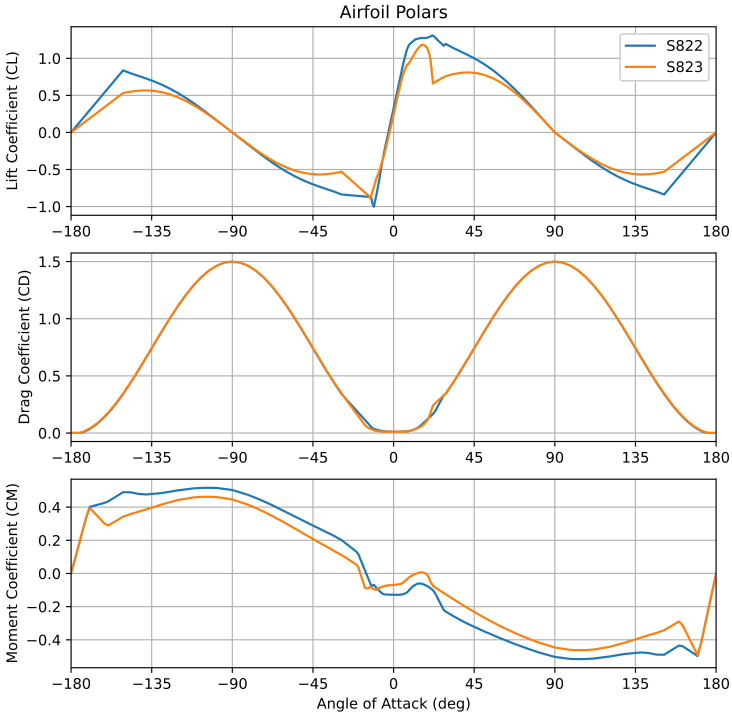

Figure 4. Lift, drag, and moment polars of the S822 and S823 airfoils.

Table 3. Distributed aerodynamic properties of turbine blades

Span (m)	Twist (deg)	Chord (m)	Airfoil -
0.208	22.25	0.355	S823
0.476	22.17	0.355	S823
0.796	21.17	0.355	S823
1.117	17.63	0.350	S823
1.437	13.40	0.310	S823
1.757	10.40	0.250	S823
2.078	8.06	0.205	S823
2.398	6.24	0.180	S823
2.719	4.96	0.160	S823
3.039	4.10	0.150	S822
3.359	3.60	0.145	S822
3.680	3.20	0.140	S822
4.000	2.80	0.130	S822
4.321	2.40	0.115	S822
4.641	2.00	0.070	S822

m above the tower top. The chord line of the fin is tilted by an angle of -8 degrees w.r.t. the nominally horizontal plane. A negative tilt angle means that that the leading edge of the tail fin is higher than the trailing edge. The chord line of the fin is also banked by an angle of 8 degrees in the clockwise direction. The definitions of these angles can found in the documentation for OpenFAST [12]. The polars of the tail fin cross section are shown in Figure 6. These polars are the same as used in the Bergey Excel 15 turbine [7].

Table 4. Distributed structural properties of the tower

Elevation (m)	Height factor -	Mass density (kg/m)	Fore-aft stiffness (N-m^2)	Side-side stiffness (N-m^2)
0.086	0.003	89.0	2.49×10^9	2.49×10^9
1.96	0.068	89.0	2.20×10^9	2.20×10^9
5.67	0.197	89.0	1.67×10^9	1.67×10^9
5.85	0.203	80.4	1.65×10^9	1.65×10^9
9.56	0.332	80.4	1.20×10^9	1.20×10^9
11.5	0.400	46.2	7.55×10^8	7.55×10^8
13.0	0.451	46.2	6.45×10^8	6.45×10^8
15.8	0.549	46.2	4.60×10^8	4.60×10^8
17.3	0.600	52.1	3.75×10^8	3.75×10^8
18.5	0.642	52.1	3.13×10^8	3.13×10^8
20.7	0.719	52.1	2.11×10^8	2.11×10^8
23.0	0.797	52.1	1.30×10^8	1.30×10^8
23.1	0.803	60.0	2.16×10^8	2.16×10^8
24.7	0.858	60.0	1.38×10^8	1.38×10^8
26.3	0.914	80.9	7.79×10^7	7.79×10^7
27.9	0.970	80.9	3.50×10^7	3.50×10^7
28.8	1.00	80.9	1.91×10^7	1.91×10^7

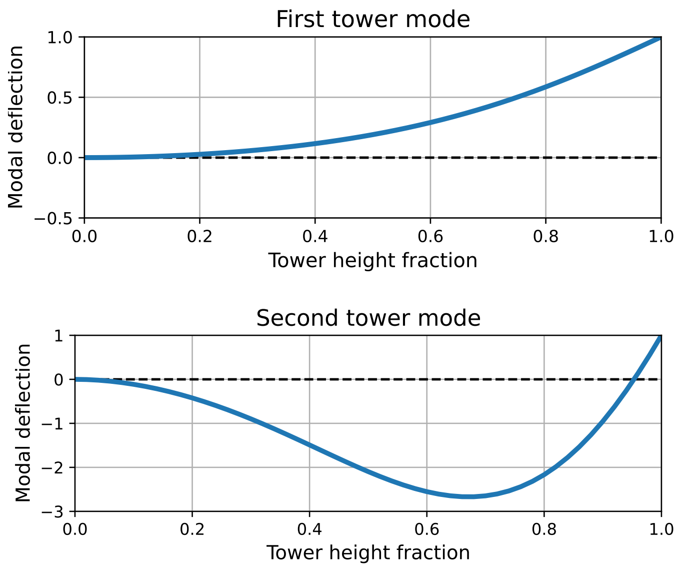

Figure 5. First two flexible mode shapes of the tower.

4.2. Hub, nacelle, and drivetrain properties

The properties of the hub and nacelle are tabulated in Table 5. The turbine uses a direct-drive system. Thus, the equivalent gearbox ratio is 1. Other properties of the drivetrain are described in Table 6.

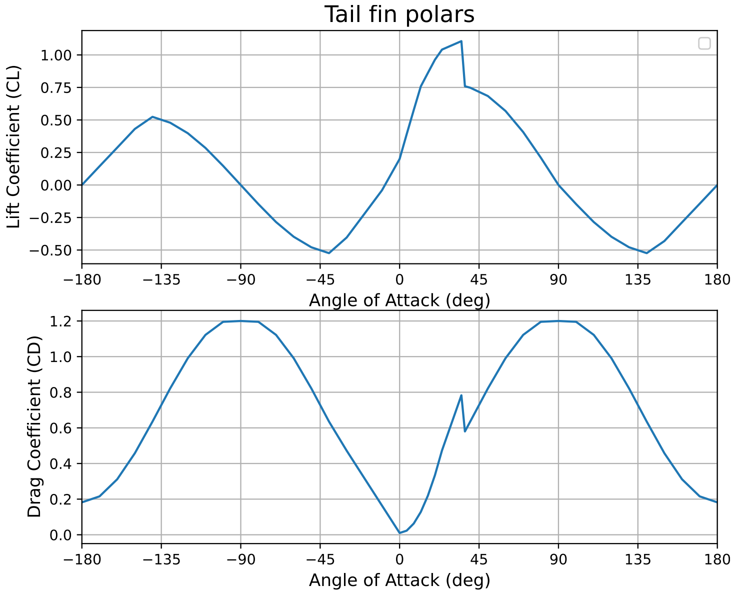

Figure 6. Polars of cross sections of the delta tail fin.

Table 5. Hub and nacelle properties

Property	Value
Elevation of yaw bearing above ground	28.8 m
Vertical distance along yaw axis from yaw bearing to shaft	0.515 m
Distance along shaft from hub center to yaw axis	0.7456 m
Distance along shaft from hub center to main bearing	0.345 m
Hub mass	116.14 kg
Hub inertia about low-speed shaft	7.71 kg-m^2
Nacelle mass	337.1 kg
Nacelle inertia about yaw axis	51.3 kg-m^2
Nacelle center of mass location downwind of yaw axis	0.2307 m
Nacelle center of mass location above yaw bearing	0.091 m

Table 6. Drivetrain properties

Property	Value
Gearbox ratio	1
Electrical generator efficiency	86.4 %
Generator inertia about shaft	0.5 kg-m^2

4.3. Baseline control system

Because the NREL 15-kW turbine is a passive-yaw, stall-regulated, variable-speed wind turbine, it does not have a blade pitch mechanism or yaw drive. The generator torque is controlled based on the current rotor speed using a lookup table scheme. The torque command T_{cmd} is calculated from the current rotor speed using the lookup table plotted in Figure 7. The applied generator torque is calculated from the torque command T_{cmd} by filtering it using a first-order time delay with a time constant of $\tau = 0.05$ s.

$$\text{Gen. Torque} = \frac{1}{\tau s + 1} T_{cmd} \tag{1}$$

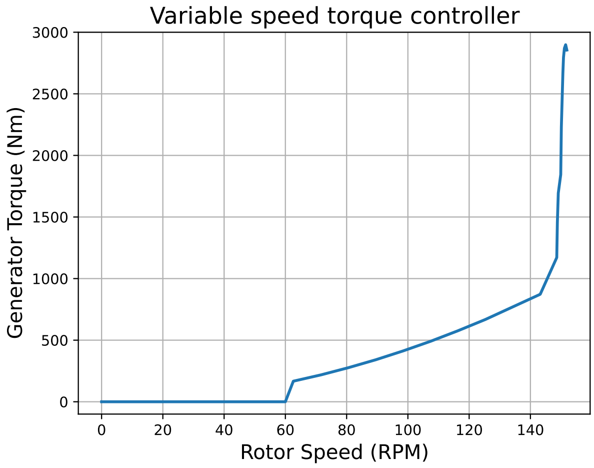

Figure 7. Plot of the lookup table of torque command as a function of rotor speed.

The torque command lookup table is designed to track a relatively constant rotor speed at high wind speeds and track the optimal tip-speed ratio at low wind speeds. The stall regulation at high speeds reduces the turbine power smoothly at high wind speeds.

5. Open-source turbine aeroelastic model

OpenFAST [12] is a multiphysics, multi-fidelity tool for simulating the coupled dynamic response of wind turbines. An OpenFAST (version 3.5.2) aeroelastic model of the NREL 15-kW turbine is publicly available in a GitHub repository [13]. The repository contains the detailed documentation of the turbine, including frequency domain loads data and Campbell diagram.

6. Steady-state behavior

The steady-state response of the NREL 15-kW baseline wind turbine is obtained by running a ramp simulation with steady inflow winds with OpenFAST. The simulation lengths are long enough to ensure that all transient behavior dies out. The variation of turbine power, rotor speed, and rotor torque with inflow wind speeds is shown in Figure 8. It can be observed that the rotor speed increases with the inflow wind speed at low wind speeds and slowly reduces at higher wind speeds. The turbine stalls smoothly at higher wind speeds, reducing the generated power as designed and providing adequate overspeed protection. However, the maximum turbine power reaches a higher than desired value around 45 kw before the turbine stalls. This behavior will be corrected by implementing a more advanced controller, as compared to a simple lookup-table-based approach.

7. Conclusion

This paper describes the design and modeling of the NREL 15-kW advanced horizontal-axis reference turbine for distributed wind applications. The turbine is a passive-yaw, stall-regulated, variable-speed wind turbine and is designed based on the Bergey Excel-15 turbine. The OpenFAST-based aeroelastic model of the turbine is publicly available. The model includes details of the blade structural properties, blade aerodynamic properties, tail fin properties,

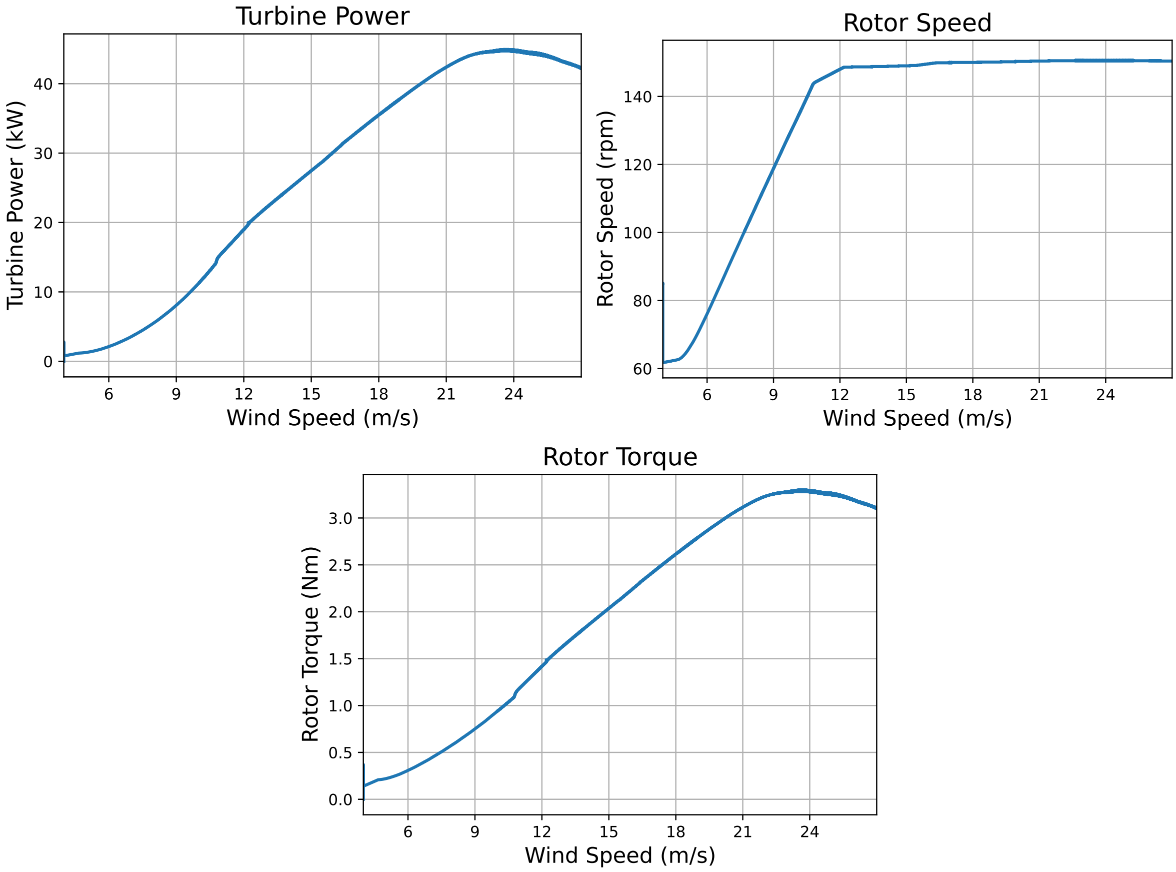

Figure 8. Variation of turbine power, rotor speed, and rotor torque with inflow wind speed.

tower structural and aerodynamic properties, and hub and nacelle properties. The baseline control of the turbine is implemented in the form of the lookup-table-based generator torque controller. Finally, the steady-state turbine characteristics of the turbine are discussed. This reference turbine fills an important gap in the distributed wind aeroelastic modeling landscape and will facilitate further research and development in the field. A new turbine controller would be implemented to regulate the turbine power output at high wind speeds.

8. Acknowledgments

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