WindPACT Reference Wind Turbines

Jennifer Rinker and Katherine Dykes

National Renewable Energy Laboratory

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April 2018

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NATIONAL RENEWABLE ENERGY LABORATORY

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List of Acronyms

HSS	high-speed shaft
LSS	low-speed shaft
NREL	National Renewable Energy Laboratory
PID	proportional-integral-derivative
WindPACT	Wind Partnership for Advanced Component Technology

Executive Summary

To fully understand how loads and costs scale with turbine size, it is necessary to have identical turbine models that have been designed for different rated powers. This report presents updated aeroelastic representations of the Wind Partnership for Advanced Component Technologies (WindPACT) baseline models, which are a series of four baseline models that were designed to facilitate investigations into the scaling of loads and turbine cost with size. The models have four different rated powers (750 kilowatts [kW], 1.5 megawatts [MW], 3.0 MW, and 5.0 MW), and each model was designed to its specified rated power using the same methodology. The models were originally implemented in FAST_AD, the predecessor to the National Renewable Energy Laboratory's (NREL's) open-source wind turbine simulator FAST, but had yet to be implemented in FAST version 7 (v7) or v8 with AeroDyn v14. This report contains the specifications for all four WindPACT baseline models—including structural, aerodynamic, and control specifications—along with the inherent assumptions and equations that were used to calculate the model parameters. We hope that these baseline models will serve as useful resources for investigating the scaling of costs, loads, and/or optimization routines.

The FAST v7 and v8 input files for the WindPACT baseline models can be downloaded from the following GitHub repository: https://github.com/WISDEM/Ref_Turbines.

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1 Introduction

To completely understand the ramifications of scaling wind turbines to different sizes—in terms of both loads and turbine cost—it is necessary to have a collection of similar wind turbine models of varying sizes. As a result, the U.S. Department of Energy National Renewable Energy Laboratory (NREL) funded a project in the early 2000s to investigate the effects on both loads and turbine cost when a wind turbine design is scaled to different sizes (Malcolm 2006). The project, which was part of the Wind Partnership for Advanced Component Technologies (WindPACT) program, resulted in four baseline wind turbine models with four different rated powers: 750 kilowatts (kW), 1.5 megawatts (MW), 3.0 MW, and 5.0 MW.

The process for developing the WindPACT baseline models sought to align them with technology that was present in the commercial sector at the time. The WindPACT 1.5 MW turbine had a configuration very similar to the GE 1.5s wind turbine that had a 70.5 m rotor diameter and 1.5 MW power rating with a specific rating of 0.39 kW/ m^2 (Malcolm 2003). The other baseline designs kept the same specific rating, and simple uniform scaling was used to scale the rotor to different sizes. However, to appropriately create baseline designs of different sizes, conventional practice would be to re-optimize the design for each new size and not simply scale the blades. Thus, the WindPACT 1.5 MW design is the closest to representing actual commercial wind turbine technology and was used most extensively in the WindPACT for studies of novel configurations and wind turbine technology innovations. The other baseline models were primarily used in the creation of scaling laws for costs.

It is important to note that these models are intended for use as baseline models in comparative studies; they are not models of any specific turbines in the real world, nor are they necessarily reflective of general trends for different-sized turbines in industry. Since the development of the WindPACT models, the wind industry has developed a large number of innovations in wind turbine technology such that any comparison between the original WindPACT models and modern wind turbines would be spurious. Nonetheless, there is significant value in open-source baseline wind turbine designs for use by the research community at large. For research, it is recommended that analyses using the WindPACT models be comparative and never absolute. For example, the WindPACT models serve as excellent tools for examining loads scaling to turbines of different sizes or for a comparison of different airfoil or control optimization techniques. However, they are not ideal for situations in which loads or costs of a WindPACT model are compared to the loads or costs from a different model. In short, the WindPACT models should only be used as baseline models to normalize calculations.

The models were originally implemented in FAST_AD, a predecessor to NREL's open-source wind turbine simulator FAST (Jonkman 2005). This report documents updated implementations of the models in FAST versions 7 and 8, including: the model parameters, methodology, and assumptions for the model implementation. The model files can be downloaded from the following repository: https://github.com/WISDEM/Ref_Turbines.

There were two main sources of information that had useful information for creating the FAST v7 and v8 input files for the WindPACT baseline models: 1) the Microsoft Excel design files from the original WindPACT project and 2) the "WP 1.5 MW" model from the CertTest folder in the FAST v7 distribution. The original FAST_AD input files could not be located, but the

Excel design files contained almost all of the required information on the turbine configuration, structural parameters, airfoil schedule, and so on. However, many different turbine configurations were tested during the WindPACT project, and none of the final configuration files listed in Table 4-3 of the final WindPACT report (Malcolm 2006) could be found in the available design files. To complicate matters, the file names of the final baseline configurations change in different sections of the final report. (E.g., compare Tables 4-3 and 4-6 in the WindPACT report.) Ultimately, the Excel design files that were in the project folder with the most recent updates were used. The list of Excel design files used to create the WindPACT baseline models documented in this report are listed in Table 1.

Table 1. Microsoft Excel Files Used to Generate WindPACT Parameters

Model	Filename
750 kW	0.75A08V00_InputData.xls
1.5 MW	1.5A08V03_InputData.xls
3.0 MW	3.0A02V02_InputData.xls
5.0 MW	5.0A04V00_InputData.xls

The second source of information for the WindPACT models, the WP 1.5 MW model in the CertTest folder in the FAST v7 distribution ("WindPACT 1.5 MW Baseline" in the v8 distribution), was used to fill in information that was not present in the Excel design files. According to the comment strings in the CertTest blade files, the values for this model were taken from the "InputData1.5A07V07adm.xls" file, which could not be located in the WindPACT project folder. Thus, there are slight differences between the 1.5-MW model parameters presented here and the WP 1.5 MW model in the FAST CertTest folders. These slight differences, however, were found to have no significant effect on the turbine's behavior or loads.

The gross properties of the four baseline models are given in Table 2. All four models are three-bladed, upwind configurations with variable-speed generators and collective blade-pitch-to-feather controllers. The rated powers for the four WindPACT baseline models were chosen to span from 750 kW to 5 MW that represented the span of turbine sizes thought to be practical at the time of their development. The rotor diameter for each model was originally selected assuming that the ratio of the rated power to swept area was 0.44 kW/m^2, but they were subsequently modified to the values given in Table 2 after an internal meeting that questioned whether the chosen results reflected industry standards (Malcolm 2006). All four baseline models had the same rated generator speed, and the gearbox ratio was chosen so that all four models had the desired tip speed at rated (viz., 75 meters per second [m/s]). The towers are modeled as tapered steel tubes. The hub height is 20% larger than the rotor diameter. More details into the design of each component can be found in the subsequent sections of this report or in the original design study (Malcolm 2006).

Table 2. Gross Properties for the WindPACT Baseline Wind Turbine Models

Parameter	750 kW	1.5 MW	3.0 MW	5.0 MW
Rotor Orientation, Configuration	Upwind, three blades			
Control	Variable speed, collective pitch			
Rated Tip and Generator Speed	75 m/s, 1,800 rpm			
Shaft Tilt, Cone Angle	5°, 0°			
Rotor Diameter, Hub Diameter	50 m, 2.5 m	70 m, 3.50 m	99 m, 4.95 m	128 m, 6.40 m
Hub Height	60 m	84 m	119 m	154 m
Overhang	2.33 m	3.30 m	4.65 m	6.00 m
Rotor Mass	12,381 kg	32,167 kg	101,319 kg	209,407 kg
Nacelle Mass	20,950 kg	52,839 kg	132,598 kg	270,669 kg
Tower Mass	53,776 kg	125,364 kg	351,798 kg	775,094 kg

2 Blade Structural Properties

Each WindPACT baseline model has three identical blades that are placed in an upwind configuration. The blades were designed as part of a previous project (Griffin 2001), and extensive details on the blade modeling methodology can be found in the project report by Malcolm (2006). The blade lengths were originally calculated assuming that the ratio of the rated power to the rotor area was 0.44 kW/m^2, but they were subsequently modified to the values in Table 3 after an internal meeting during the WindPACT project (Malcolm 2006). All four baseline blade models are composed of a 1.78-mm-thick fiberglass skin that surrounds a core of balsa wood. A box spar of uniaxial glass fibers extends longitudinally along the blades from 25% span to the end of the blade and laterally from 15% to 50% chord. The resulting distributed structural properties are summarized in Table A1 through Table A4 in Appendix A.

The first column in the distributed structural parameter tables is "Radius," which is the distance from the station on the blade to the hub center when the blade is mounted on the hub. The "BlFract" column indicates the fractional blade length (i.e., the distance to the blade root divided by the blade length). "AeroCent" is a FAST input parameter that defines the fractional distance from the pitch axis to the chord line (see Jonkman [2009] for more detail). "StrcTwst" and "BMassDen" define the structural twist and mass per unit length of the blade, respectively. The structural twist is assumed to be identical to the aerodynamic twist provided in Section 3. "FlpStff," "EdgStff," "FlpIner," and "EdgIner," respectively, represent the flapwise stiffness, edgewise stiffness, flapwise inertia, and edgewise inertia. The inertia values are calculated about the principal structural axis that is defined by StrcTwst.

The undistributed blade properties are given in Table 3. The mass and inertia values were calculated using the trapezoidal rule on the distributed blade properties provided in Appendix A. The center of mass location is measured from the blade root. The blade damping values were not provided in the original WindPACT design files, so the damping values provided in the WP 1.5 MW model were used. Users should note that these damping values are substantially larger than those used in the NREL 5 MW model.

Table 3. Undistributed Blade Structural Properties

Parameter	750 kW	1.5 MW	3.0 MW	5.0 MW
Flapwise Structural Damping		3.882% of critical		
Edgewise Structural Damping		5.900% of critical		
Blade Length	23.75 m	33.25 m	47.025 m	60.8 m
Total Mass	1,941 kg	4,336 kg	13,238 kg	27,854
First Mass Moment of Inertia	14,605 kg-m	46,497 kg-m	207,135 kg-m	563,188 kg-m
Second Mass Moment of Inertia	180,640 kg-m^2	798,506 kg-m^2	5,012,212 kg-m^2	17,475,408 kg-m^2
Center of Mass Location from Root	7.52 m	10.72 m	15.65 m	20.22 m

3 Aerodynamic Simulation Properties

The properties presented in this section are specifically those that pertain to AeroDyn v14. The chord and airfoil schedule for the WindPACT baseline models scale linearly with blade length. Thus, these parameters are identical for all four models when the blade span is normalized with respect to the blade length (see Figure 1). The maximum blade chord for all four WindPACT baseline models—which occurs at 25% radius—is 8% of the blade radius, and the hub radius is 5% of the blade radius. The originally assumed twist values were compared with optimal twist values during the blade design study and were concluded to be a close approximation to the optimal blade twist (Griffin 2001).

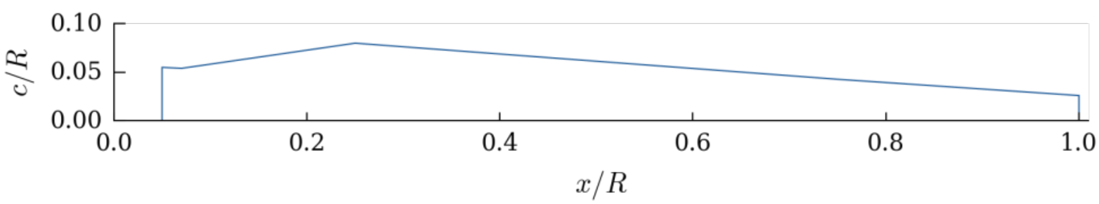

Figure 1. Normalized blade chord vs. normalized blade length for the WindPACT baseline models

The distributed aerodynamic properties are provided in Tables B1 to B4 in Appendix B. The distance along the pitch axis between the rotor center and the center of the aerodynamic node is given in the "RNodes" column. The length of each element is provided in "DRNodes," and the element lengths sum to the total length of each blade. The aerodynamic twist, which is the same as the structural twist, is given in the "AeroTwst" column. The rotor solidity for all four WindPACT baseline models—calculated by integrating the chord length along the blade span and dividing by the rotor area—is 5%.

The WindPACT baseline blades utilize a set of NREL S-series airfoils that have been scaled and whose trailing edges have been truncated to a finite thickness. The blade has a circular airfoil from 5% to 7% span, an S818 airfoil at 25% span, an S825 airfoil at 75% span, and an S826 airfoil at 100% span. The original Excel design files listed three airfoils wherein aerodynamic data could not be located (viz., s818_2702, s825_2102, and s826_2102), so the airfoil data from WP 1.5 MW were used (viz., s818_2703, s825_2103, and s826_2103). The analysis code used to generate the aerodynamic coefficients given in the .dat files for the three S-airfoils is not documented within the .dat files but notes in the blade design report indicate that the aerodynamic coefficients were calculated with the Eppler Design and Analysis code (Griffin 2001).

The undistributed aerodynamic properties are provided in Table 4. The WindPACT baseline models were found to be extremely susceptible to a numerical instability in the dynamic inflow model that caused limit-cycle oscillations in wind speeds below 9 m/s. To avoid this issue, the baseline models assume an equilibrium induction model. The aerodynamic model utilizes a Beddoes-Leishman stall model, a swirl-induction-factor model with a tolerance of 0.005, and Prandtl tip- and hub-loss models.

Table 4. Undistributed Blade Aerodynamic Properties

Parameter	750 kW	1.5 MW	3.0 MW	5.0 MW
Units	International System of Units (SI)			
Stall, Inflow Model	Beddoes, equilibrium			
Use Center of Mass?	No			
Induction Model, Tolerance	Swirl, 0.005			
Tip- and Hub-Loss Model	Prandtl			
Air Density, Kinematic Viscosity	1.225 kg/m^3, 1.4639×10^{-5} m^2/s			
AeroDyn Time Step	0.005 s			

4 Hub, Nacelle, and Drivetrain Properties

The nacelle and hub properties for the four WindPACT baseline models are summarized in Table 5. The hub is modeled as a sphere made of ductile iron with an outer diameter of 0.05×D, in which D is the rotor diameter. The initial value for the hub center was 0.05×D meters upwind of the tower centerline, but these values were modified during the WindPACT project to result in the values listed in Table 5. The rated generator speed is 1,800 rpm for all four baseline models, and the gearbox ratios were selected so that the correct rated tip speed is maintained with the prescribed blade lengths. The generator efficiency is 95%, which matches the WP 1.5 MW model instead of the more complicated loss models provided in the original Excel design files.

Several FAST parameters were not directly specified in the Excel files and needed to be extracted from the values provided in the design files. Specifically, the nacelle was originally modeled as three subcomponents—the main frame, high-speed shaft (HSS), and low-speed shaft (LSS)—whereas the FAST parameters only define a single value for the nacelle. The nacelle mass, m_{nac}, was calculated by summing the masses of the three components. The center of mass in a given spatial direction, i, was calculated according to

$$x_{CM,i} = \frac{1}{m_{nac}} \sum_j x_{j,i} \cdot m_j \tag{1}$$

where m_j is the mass of the j^{th} component. The nacelle y-inertia was calculated by summing the y-inertias of the three nacelle subcomponents. The generator inertia in the FAST input files must be provided with respect to the HSS reference frame, but the inertias given in the Excel files were calculated with respect to the LSS reference frame. Thus, the generator inertia was calculated by summing the inertias of the three subcomponents and dividing by the square of the gearbox ratio to convert to the HSS reference frame. Finally, the drivetrain torsional damping was calculated by assuming a 5% critical damping ratio based on the NREL 5-MW reference model (Jonkman 2009) and using Eq. (2), which can be derived from Eq. 4 in Girsang (2014)

$$c_{DT} = 2 \times 0.05 \times \sqrt{k_{DT} \frac{RotIner_{LSS} \times GenIner_{HSS} \times GBR^2}{RotIner_{LSS} + GenIner_{HSS} \times GBR^2}} \tag{2}$$

Here, k_{DT} is the drivetrain torsional stiffness constant, which was provided in the Excel design files; $RotIner_{LSS}$ is the rotor inertia with respect to the LSS reference frame; $GenIner_{HSS}$ is the generator inertia with respect to the HSS reference frame; and GBR is the gearbox ratio.

Table 5. Hub, Nacelle, and Drivetrain Properties

Parameter	750 kW	1.5 MW	3.0 MW	5.0 MW
Shaft Tilt, Cone Angle	5°, 0°			
Rated Generator Speed	1,800 rpm			
Electrical Generator Efficiency	95%			
Rated Rotor Speed	28.648 rpm	20.463 rpm	14.469 rpm	11.191 rpm
Gearbox Ratio	62.832:1	87.965:1	124.407:1	160.850:1
Generator Inertia about HSS	16.651 kg-m^2	56.442 kg-m^2	177.884 kg-m^2	438.855 kg-m^2
Equivalent Drive-Shaft Torsional Spring Constant	129,646,444 N-m/rad	483,129,640 N-m/rad	1,039,402,036 N-m/rad	2,300,693,030 N-m/rad
Equivalent Drive-Shaft Torsional Damping Constant	278,494 N-m/(rad/s)	1,355,794 N-m/(rad/s)	4,992,005 N-m/(rad/s)	14,909,175 N-m/(rad/s)
Overhang (Positive Upwind)	2.33 m	3.30 m	4.65 m	6.00 m
Hub Height	60 m	84 m	119 m	154 m
Tower Top to Hub Height	1.33 m	1.61 m	2.27 m	2.93 m
Hub Mass	6,573 kg	19,186 kg	61,670 kg	125,970 kg
Hub Inertia about LSS	5,160 kg-m^2	29,975 kg-m^2	197,987 kg-m^2	668,485 kg-m^2
Location of Nacelle Center of Mass from Tower Top	(-0.060 m, 0 m, 1.204 m)	(-0.168 m, 0 m, 1.385 m)	(-0.226 m, 0 m, 1.861 m)	(-0.326 m, 0 m, 2.343 m)
Nacelle Mass	20,950 kg	52,839 kg	132,598 kg	270,669 kg
Nacelle Inertia about Yaw Axis	8,623 kg-m^2	45,377 kg-m^2	211,744 kg-m^2	739,596 kg-m^2

5 Tower Properties

The towers are modeled as tapered steel tubes with the outer diameters and thicknesses provided in Table 6. The Young's modulus, shear modulus, and density are 200 gigapascals (GPa), 76.9 GPa, and 7,850 kg/m^3, respectively. The mass of the paint, bolts, welds, and flanges are modeled by assuming 5% parasitic mass. The tower's outer diameter and thickness scale linearly from the base to the top. Ten stations were specified along the heights of the tower.

The distributed tower properties are given in Table C1 through Table C4 in Appendix C. The first and second columns in each table indicate the absolute and relative distances from the tower base, wherein the relative distance is normalized by the height of the tower. The remaining columns are very similar to those described for the tables with the distributed blade structural properties, except that the letters "FA" and "SS" indicate the "fore-aft" and "side-side" directions, respectively.

The undistributed tower properties are provided in Table 6. The tower masses and centers of gravity are calculated using the trapezoidal rule on the distributed properties. The tower damping values were taken from the WP 1.5 MW model. Users should note that the damping values are substantially larger than those found in the NREL 5 MW reference model.

Table 6. Undistributed Tower Structural Properties

Parameter	750 kW	1.5 MW	3.0 MW	5.0 MW
Young's Modulus	200 GPa			
Shear Modulus	76.p GPa			
Density, Parasitic Mass	7,850 kg/m^3, 5%			
Structural Damping, All Modes	3.435% of critical			
Base Outer Diameter	3.75 m	5.66 m	8.00 m	10.17 m
Base Thickness	15.00 mm	17.39 mm	26.10 mm	35.70 mm
Top Outer Diameter	2.00 m	2.57 m	3.70 m	4.41 m
Top Thickness	9.00 mm	10.26 mm	11.90 mm	16.00 mm
Tower Height	58.67 m	82.39 m	116.73 m	151.07 m
Tower Mass	53,776 kg	125,363 kg	351,798 kg	775,094 kg
Tower Center of Mass Location Above Ground	24.05 m	32.76 m	44.59 m	56.95 m

6 Baseline Control System Properties

A very simplistic, variable-speed, collective pitch-to-feather controller is implemented in the WindPACT baseline models. A nonoptimal generator-torque controller operates below the rated wind speed, and a full-span rotor-collective blade pitch controller operates above the rated wind speed. There is no filtering of the generator speed in the control loop, nor are there any control actions implemented for nonpower-production scenarios or for yaw angle control.

The torque controller is a nonoptimal quadratic controller

$$\tau_{gen} = \alpha \cdot {\Omega_{gen}}^2 \tag{3}$$

where τ_{gen} is the generator torque in N-m, α is the control constant, and Ω_{gen} is the generator speed in rpm. An optimal value for α can be defined by determining the tip-speed ratio that results in an optimal power coefficient (see Eq. 2.2 from Johnson [2004]). Using this optimal α, however, almost always results in a discontinuity at rated wind speeds unless a "Region 2.5" is implemented, which linearly scales the optimal torque below rated (Region 1) to the torque above rated (Region 2). For simplicity, the WindPACT baseline models utilize torque constants that are not optimal but result in a continuous torque controller without a Region 2.5

$$\alpha = \frac{\tau_{gen,rated}}{{\Omega_{gen,rated}}^2} \tag{4}$$

This choice of torque constant was based on the value for the torque constant from the WP 1.5 MW model, which was calculated with this simplistic assumption. Note that the rated generator torque is the ratio of the rated power over the product of the rated generator speed and the generator efficiency.

The pitch controller was developed by Craig Hansen of Windward Engineering, and it is a simple gain-scheduled proportional-integral-derivative (PID) controller, as documented in Appendix E of the final WindPACT report (Malcolm 2006). The pitch controller is identical for all four WindPACT baseline models, except for the pitch actuator dynamics. The PID controller is implemented in state space using two transfer functions

$$T_I(s) = \frac{2.22}{s} \tag{5}$$

$$T_{PD}(s) = \frac{0.08s + 5.14}{0.02s + 1} \tag{6}$$

where $T_I(s)$ and $T_{PD}(s)$ are the integral and proportional-derivative transfer functions, respectively. There is an anti-windup gain with a value of 0.3 rpm/degree. The gain scheduling is applied between 2.6° (the minimum pitch angle) and 30°—which is 0.0454 and 0.5236 radians (rad), respectively—by multiplying the PID coefficients by the following function

$$GS(\theta) = \begin{cases} 1 & \theta < 0.0454 \\ 0.213 \cdot \theta^{-0.5} & 0.0454 \le \theta \le 0.5236 \\ 0.2944 & \theta > 0.5236 \end{cases} \tag{7}$$

where θ is the blade pitch angle in radians. Lastly, the pitch actuator dynamics are modeled by the following transfer function

$$T_{PA}(s) = \frac{{\omega_{PA}}^2}{s^2+2\times0.80\times\omega_{PA}s+{\omega_{PA}}^2} \tag{8}$$

where ω_{PA} is four times the rated rotor speed in radians per second (s).

The controller parameters are summarized in Table 7.

Table 7. Control System Properties

Parameter	750 kW	1.5 MW	3.0 MW	5.0 MW
Rated Generator Speed	1,800 rpm			
Minimum, Maximum Pitch Angle	2.6°, 90°			
Pitch Controller Time Step	0.025 s			
Gain Schedule Start, End Angle	0.0454, 0.5236			
Gain Schedule Coefficient, Exponent	0.2130, -0.5			
Pitch Actuator Damping	80% of critical			
Rated Generator Torque	4188.29 N-m	8376.58 N-m	16,753.15 N-m	27,921.92 N-m
Region 2 Quadratic Constant	0.001293 N-m/ HSS rpm	0.002585 N-m/ HSS rpm	0.005171 N-m/ HSS rpm	0.008618 N-m/ HSS rpm
Pitch Actuator Natural Frequency	12.00 rad/s	8.57 rad/s	6.06 rad/s	4.69 rad/s

7 Full System Natural Frequencies and Steady-State Behavior

To provide more insight into the operational characteristics of the four WindPACT baseline models, the steady-state values and full-system natural frequencies and damping are presented as a function of wind speed. The steady-state values were calculated by running a series of time-marching simulations in FAST v7 with steady wind until the transient behavior had died out and then averaging the last 80 seconds. The steady-state values were also calculated using FAST v8 and the outputs compared to the FAST v7 results to verify that the models behaved similarly in both versions of FAST. The resulting steady-state values from FAST v7 are plotted in Figure 2 through Figure 5. The FAST v8 results are not shown because they are identical to the FAST v7 results shown in the figures.

The full-system natural frequencies were calculated by running a series of linearization calculations in FAST v7, applying the multiblade coordinate transformation (Bir 2010), and azimuthally averaging. The natural frequencies and damping were determined from the calculated state matrices using the following equations

$$\omega_n = |p| \tag{9}$$

$$\zeta = -\cos(\angle p) \tag{10}$$

where p is a complex eigenvalue from the linearized state matrix. The full-system modes were identified using a modified version of the CampbellDiagram.xls file available on the National Wind Technology Center forum. The undamped natural frequencies and identified modes for the four WindPACT baseline models are provided in Table 8 for a locked rotor. The modes are color-coded by type: blue is the tower, red is the blade-flapwise, orange is the blade-edgewise, and green is the drivetrain. The Campbell diagrams for the first four modes of each model are plotted in Figure 6 through Figure 9.

Table 8. Full-System Natural Frequencies in Hertz (Hz) at 0 rpm

Mode	750 kW	1.5 MW	3.0 MW	5.0 MW
1	0.547 1st Twr SS	0.394 1st Twr SS	0.283 1st Twr SS	0.219 1st Twr SS
2	0.548 1st Twr FA	0.394 1st Twr FA	0.284 1st Twr FA	0.219 1st Twr FA
3	1.559 1st Bld Flp	1.210 1st Bld Flp	0.870 1st Bld Flp	0.701 1st Bld Flp
4	1.576 1st Bld Flp	1.223 1st Bld Flp	0.917 1st Bld Flp	0.732 1st Bld Flp
5	1.580 1st Bld Flp	1.273 1st Bld Flp	0.929 1st Bld Flp	0.744 1st Bld Flp
6	1.701 1st DT Tors	1.373 1st DT Tors	0.974 1st DT Tors	0.783 1st DT Tors
7	2.416 1st Bld Edg	1.855 1st Bld Edg	1.392 1st Bld Edg	1.147 1st Bld Edg
8	2.450 1st Bld Edg	1.879 1st Bld Edg	1.413 1st Bld Edg	1.165 1st Bld Edg
9	3.833 2nd Twr FA	2.786 2nd Twr FA	1.996 2nd Twr FA	1.502 2nd Twr FA
10	4.030 2nd Twr SS	2.974 2nd Twr SS	2.133 2nd Twr SS	1.613 2nd Twr SS
11	4.962 2nd Bld Flp	3.749 2nd Bld Flp	2.811 2nd Bld Flp	2.248 2nd Bld Flp
12	5.003 2nd Bld Flp	3.781 2nd Bld Flp	2.839 2nd Bld Flp	2.271 2nd Bld Flp
13	5.125 2nd Bld Flp	3.871 2nd Bld Flp	2.908 2nd Bld Flp	2.325 2nd Bld Flp

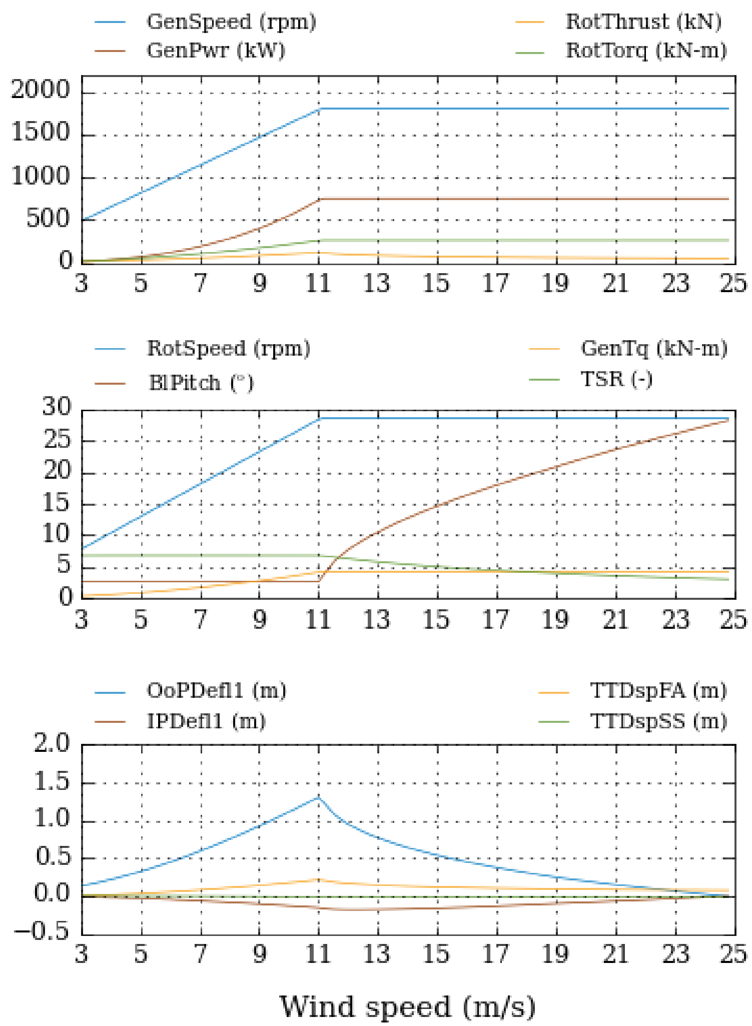

Figure 2. Steady-state behavior for the WindPACT 750-kW model

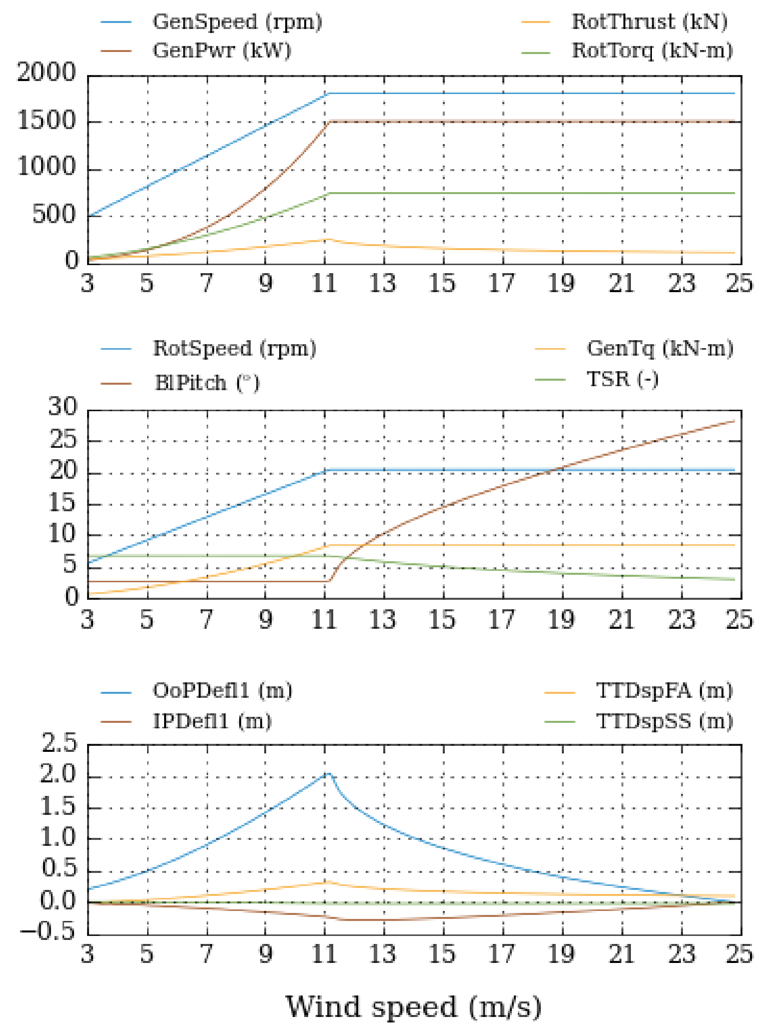

Figure 3. Steady-state behavior for the WindPACT 1.5-MW model

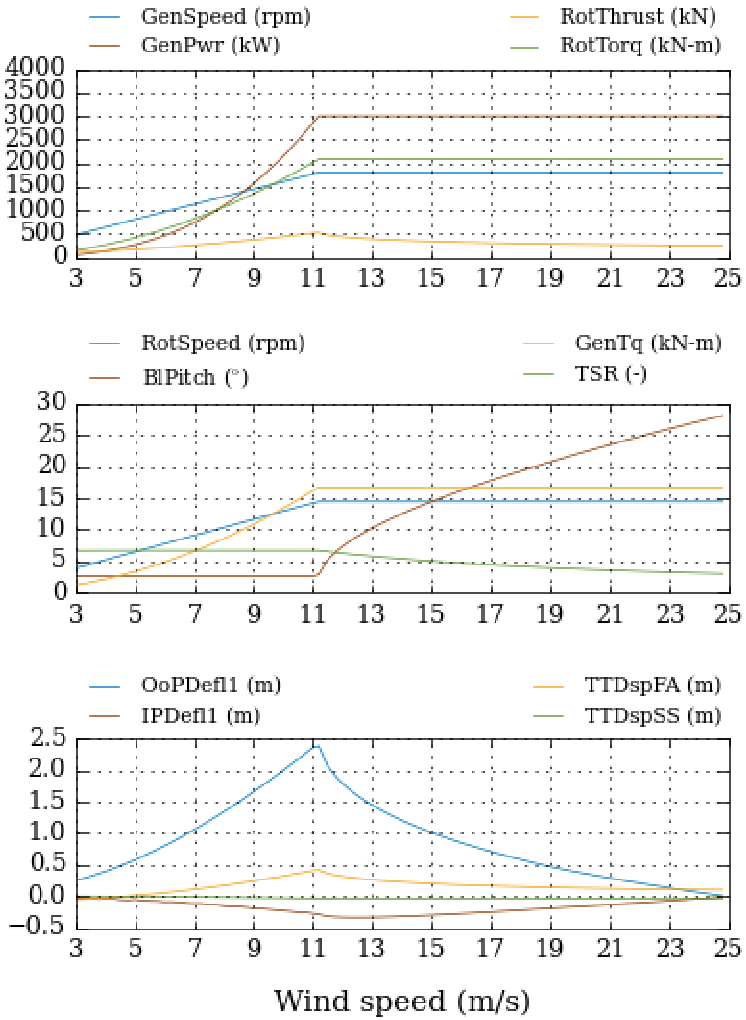

Figure 4. Steady-state behavior for the WindPACT 3.0-MW model

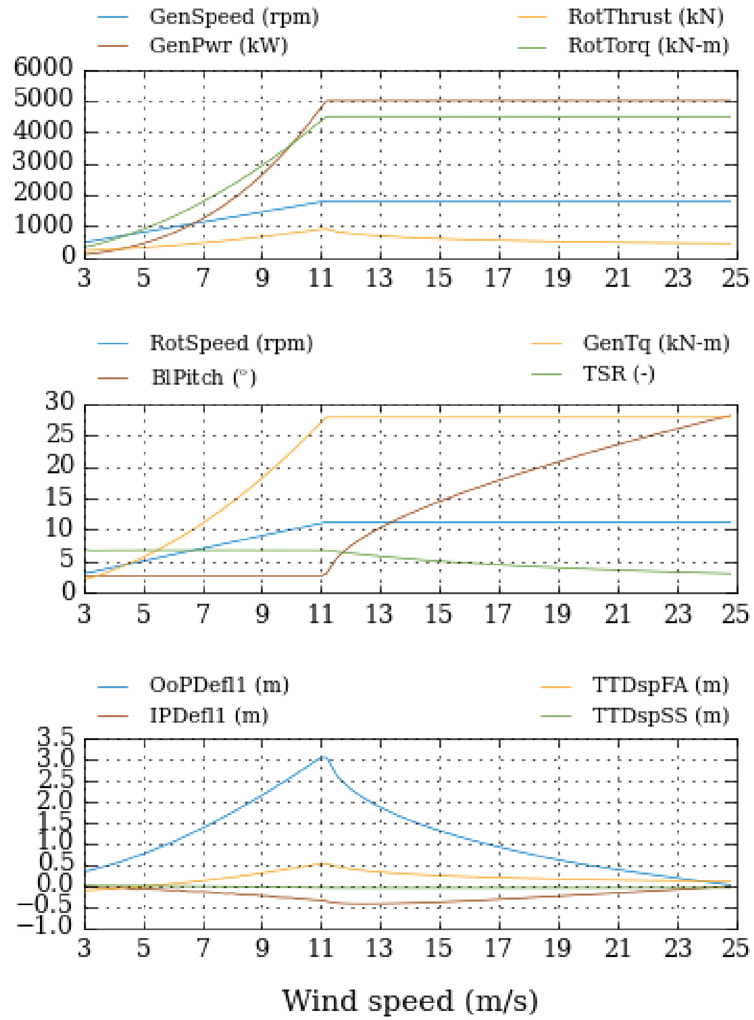

Figure 5. Steady-state behavior for the WindPACT 5.0-MW model

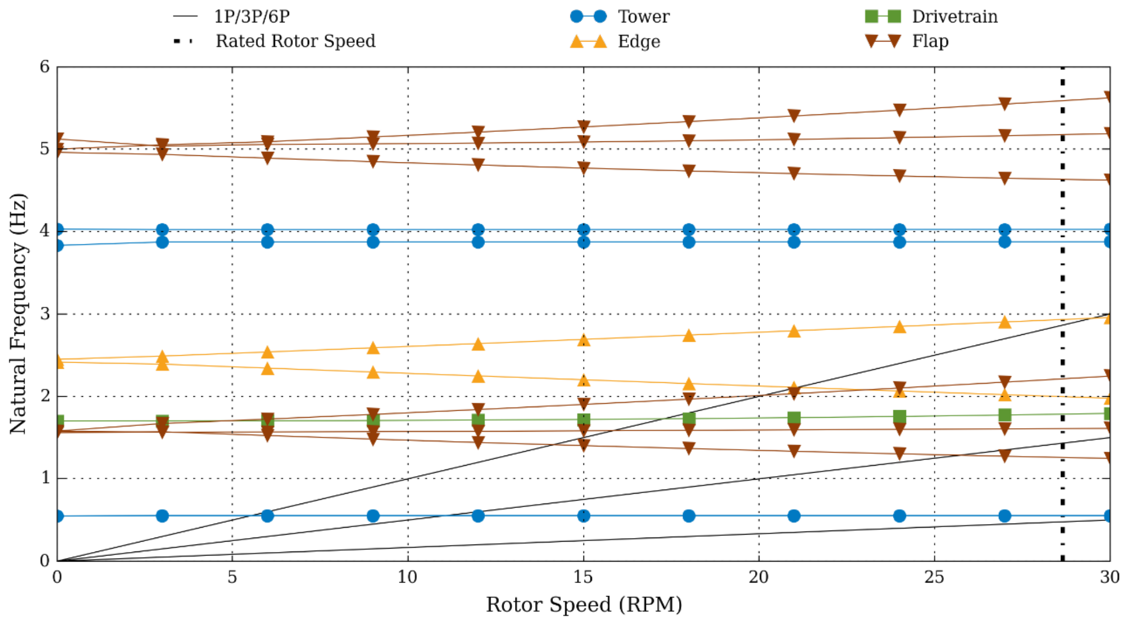

Figure 6. Campbell diagram for the WindPACT 750-kW model

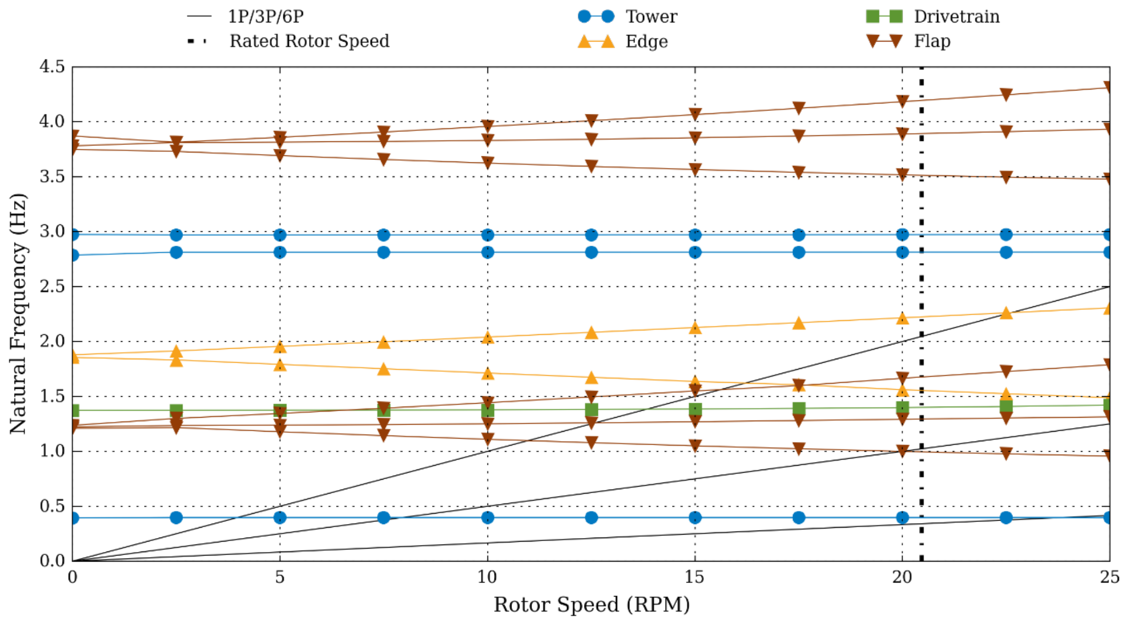

Figure 7. Campbell diagram for the WindPACT 1.5-MW model

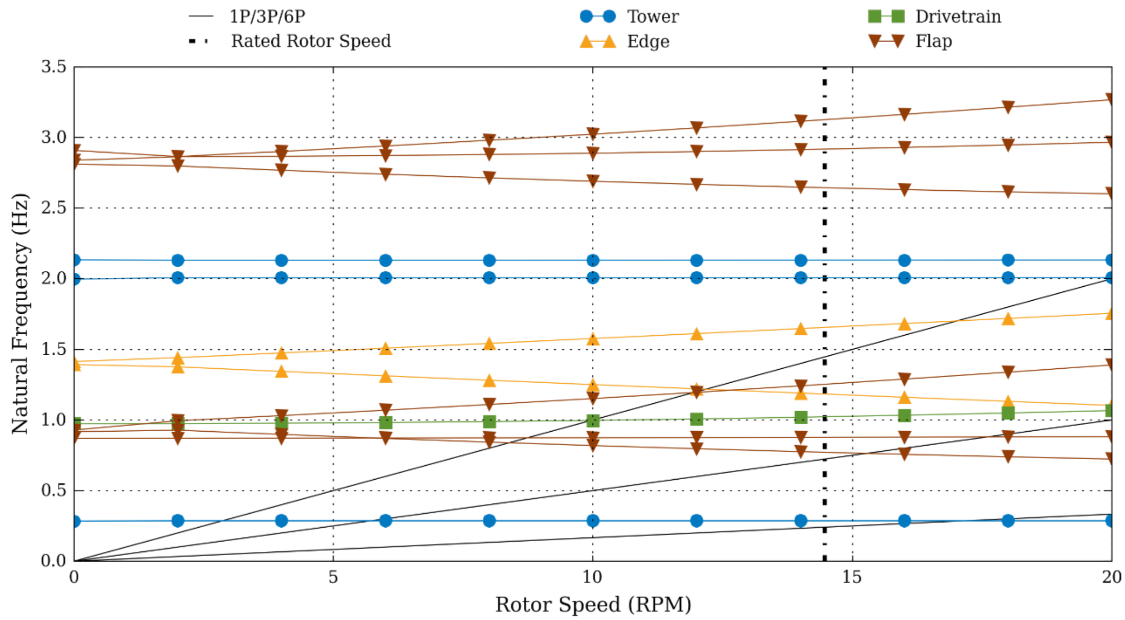

Figure 8. Campbell diagram for the WindPACT 3.0-MW model

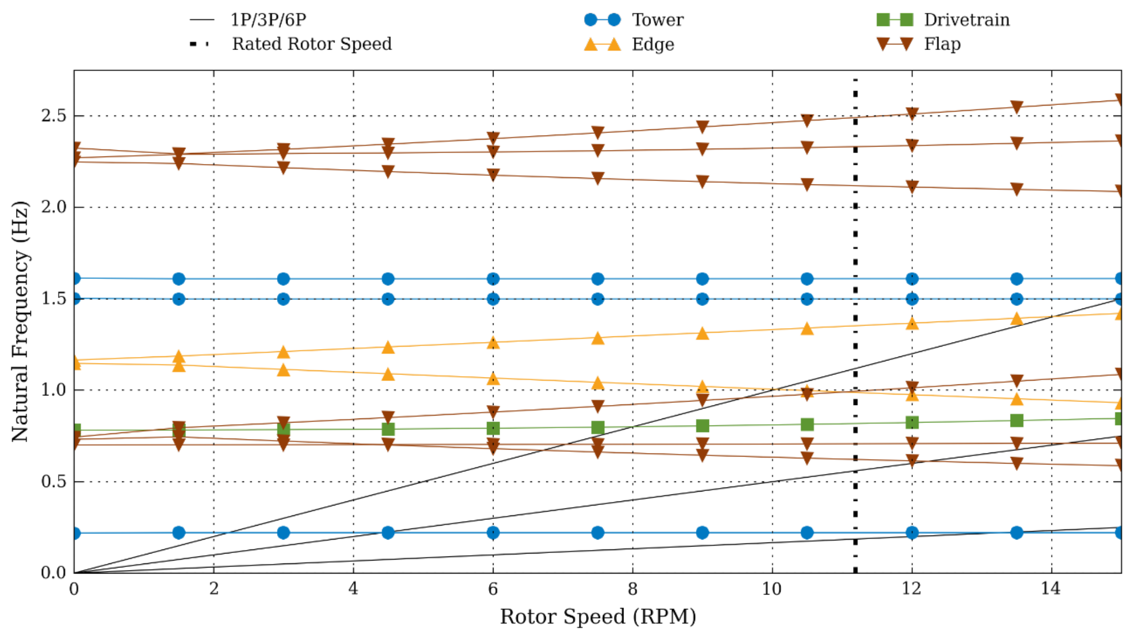

Figure 9. Campbell diagram for WindPACT 5.0-MW model

Conclusion

This report serves as a reference document for the WindPACT baseline models that have been implemented in FAST v7 and v8. The four models have different rated powers: 750 kW, 1.5 MW, 3.0 MW, and 5.0 MW. The 1.5-MW model was developed based on the GE 1.5s wind turbine, and the other three models were created by linearly scaling the airfoil characteristics for the 1.5 MW model to the different rotor sizes. The objective of this report is to document the conversion of the WindPACT baseline models to current versions of FAST, providing explanations of the different structural and aerodynamic properties utilized in the FAST input files. The WindPACT baseline models are intended to be used for comparative scaling studies because they are not reflective of general trends for different-sized turbines in industry. The FAST v7 and v8 input files for the WindPACT baseline models can be downloaded from the following GitHub repository: https://github.com/WISDEM/Ref_Turbines.

References

Bir, G.S. 2010. *User's Guide to MBC3: Multi-Blade Coordinate Transformation Code for 3-Bladed Wind Turbines*. NREL/TP-500-44327. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy10osti/44327.pdf.

Girsang, I.P., Dhupia, J. S., Muljadi, E., Singh, M., Pao, L. Y. 2014. "Gearbox and Drivetrain Models to Study Dynamic Effects of Modern Wind Turbines." *IEEE Transactions on Industry Applications* (50:6); pp. 3777-3786.

Griffin, D.A. 2001. *WindPACT Turbine Design Scaling Studies Technical Area 1—Composite Blades for 80- to 120-meter Rotor*. NREL/SR-599-29492. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy01osti/29492.pdf.

Johnson, K. E. 2004. *Adaptive Torque Control of Variable Speed Wind Turbines*. NREL/TP-500-36265. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy04osti/36265.pdf.

Jonkman, J., Buhl Jr., Marshall. 2005. *FAST User's Guide*. NREL/EL-500-38230. National Renewable Energy Laboratory (NREL), Golden, CO (US).

Jonkman, J., Butterfield, S., Musial, W., Scott, G. 2009. *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*. NREL/TP-500-38060. National Renewable Energy Laboratory (NREL), Golden, CO, (US). http://www.nrel.gov/docs/fy09osti/38060.pdf.

Malcolm, D. J. and Hansen, A. C. 2003. *WindPACT Turbine Rotor Design, Specific Rating Study, Period of Performance: June 29, 2000 – March 1, 2003*. NREL/SR-500-34794. NREL/SR-500-32495. National Renewable Energy Laboratory (NREL), Golden, CO (US). https://www.nrel.gov/docs/fy04osti/34794.pdf.

Malcolm, D. J. and Hansen, A. C. 2006. *WindPACT Turbine Rotor Design Study: June 2000–June 2002 (Revised)*. NREL/SR-500-32495. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy06osti/32495.pdf.

Appendix A. Distributed Blade Structural Properties

This appendix contains the distributed blade structural properties for the four WindPACT baseline models.

Table A1. Distributed Blade Structural Properties for the WindPACT 750-kW Model

Radius (m)	BlFract (-)	Aero-Cent (-)	Strc-Twst (°)	BMass-Den (kg/m)	FlpStff (N-m^2)	EdgStff (N-m^2)	GJStff (N-m^2)	EAStff (N)
1.25	0.00000	0.250	11.10	1181.95	2.3624E+09	2.3624E+09	8.1559E+08	1.0327E+10
1.75	0.02105	0.250	11.10	89.22	2.9287E+08	2.9287E+08	1.0234E+08	1.2958E+09
2.50	0.05263	0.229	11.10	93.88	2.5593E+08	2.7617E+08	8.6294E+07	1.3358E+09
3.75	0.10526	0.201	11.10	101.66	1.9435E+08	2.4835E+08	5.9549E+07	1.4025E+09
5.00	0.15790	0.179	11.10	109.43	1.3278E+08	2.2052E+08	3.2804E+07	1.4691E+09
6.25	0.21053	0.160	11.10	117.21	7.1200E+07	1.9269E+08	6.0598E+06	1.5358E+09
7.50	0.26316	0.165	9.50	110.36	6.1418E+07	1.6997E+08	5.4250E+06	1.4476E+09
8.75	0.31579	0.170	7.90	103.51	5.1635E+07	1.4726E+08	4.7902E+06	1.3594E+09
10.00	0.36842	0.176	6.30	96.66	4.1852E+07	1.2454E+08	4.1554E+06	1.2712E+09
11.25	0.42105	0.183	4.70	89.81	3.2070E+07	1.0183E+08	3.5206E+06	1.1829E+09
12.50	0.47368	0.190	3.10	82.96	2.2287E+07	7.9117E+07	2.8858E+06	1.0947E+09
13.75	0.52632	0.194	2.60	74.19	1.8539E+07	6.7558E+07	2.4236E+06	9.7558E+08
15.00	0.57895	0.200	2.10	65.43	1.4792E+07	5.5999E+07	1.9614E+06	8.5646E+08
16.25	0.63158	0.205	1.60	56.66	1.1044E+07	4.4441E+07	1.4993E+06	7.3734E+08
17.50	0.68421	0.212	1.10	47.89	7.2967E+06	3.2882E+07	1.0371E+06	6.1822E+08
18.75	0.73684	0.220	0.60	39.13	3.5492E+06	2.1323E+07	5.7493E+05	4.9909E+08
20.00	0.78947	0.224	0.48	32.85	2.8553E+06	1.7599E+07	4.7218E+05	4.1542E+08
21.25	0.84210	0.229	0.36	26.58	2.1615E+06	1.3875E+07	3.6942E+05	3.3175E+08
22.50	0.89474	0.234	0.24	20.30	1.4676E+06	1.0151E+07	2.6666E+05	2.4808E+08
23.75	0.94737	0.241	0.12	14.03	7.7369E+05	6.4264E+06	1.6390E+05	1.6441E+08
25.00	1.00000	0.250	0.00	7.75	7.9812E+04	2.7022E+06	6.1146E+04	8.0734E+07

Table A2. Distributed Blade Structural Properties for the WindPACT 1.5-MW Model

Radius (m)	BlFract (-)	Aero-Cent (-)	Strc-Twst (°)	BMass-Den (kg/m)	FlpStff (N-m^2)	EdgStff (N-m^2)	GJStff (N-m^2)	EAStff (N)
1.75	0.00000	0.250	11.10	1447.61	7.6815E+09	7.6815E+09	2.6552E+09	1.7153E+10
2.45	0.02105	0.250	11.10	175.10	1.1359E+09	1.1359E+09	3.9692E+08	2.5641E+09
3.50	0.05263	0.229	11.10	177.06	9.9187E+08	1.0638E+09	3.3391E+08	2.5439E+09
5.25	0.10526	0.201	11.10	180.34	7.5183E+08	9.4364E+08	2.2889E+08	2.5103E+09
7.00	0.15790	0.179	11.10	183.63	5.1180E+08	8.2349E+08	1.2386E+08	2.4767E+09
8.75	0.21053	0.160	11.10	186.91	2.7176E+08	7.0333E+08	1.8843E+07	2.4431E+09
10.50	0.26316	0.165	9.50	177.15	2.3246E+08	6.1384E+08	1.6770E+07	2.3164E+09
12.25	0.31579	0.170	7.90	167.39	1.9315E+08	5.2435E+08	1.4697E+07	2.1897E+09
14.00	0.36842	0.176	6.30	157.64	1.5385E+08	4.3486E+08	1.2624E+07	2.0630E+09
15.75	0.42105	0.183	4.70	147.88	1.1454E+08	3.4536E+08	1.0550E+07	1.9363E+09
17.50	0.47368	0.190	3.10	138.12	7.5235E+07	2.5587E+08	8.4774E+06	1.8096E+09
19.25	0.52632	0.194	2.60	122.90	6.2495E+07	2.1787E+08	7.1175E+06	1.6053E+09
21.00	0.57895	0.200	2.10	107.67	4.9755E+07	1.7986E+08	5.7576E+06	1.4011E+09
22.75	0.63158	0.205	1.60	92.44	3.7015E+07	1.4186E+08	4.3978E+06	1.1968E+09
24.50	0.68421	0.212	1.10	77.22	2.4274E+07	1.0385E+08	3.0379E+06	9.9256E+08
26.25	0.73684	0.220	0.60	61.99	1.1534E+07	6.5849E+07	1.6780E+06	7.8831E+08
28.00	0.78947	0.224	0.48	51.86	9.2738E+06	5.4254E+07	1.3783E+06	6.5434E+08
29.75	0.84210	0.229	0.36	41.73	7.0132E+06	4.2659E+07	1.0786E+06	5.2038E+08
31.50	0.89474	0.234	0.24	31.61	4.7526E+06	3.1064E+07	7.7888E+05	3.8641E+08
33.25	0.94737	0.241	0.12	21.48	2.4919E+06	1.9469E+07	4.7916E+05	2.5244E+08
35.00	1.00000	0.250	0.00	11.35	2.3129E+05	7.8741E+06	1.7943E+05	1.1847E+08

Table A3. Distributed Blade Structural Properties for the WindPACT 3.0-MW Model

Radius (m)	BlFract (-)	Aero-Cent (-)	Strc-Twst (°)	BMass-Den (kg/m)	FlpStff (N-m^2)	EdgStff (N-m^2)	GJStff (N-m^2)	EAStff (N)
2.475	0.00000	0.250	11.10	2514.27	2.5916E+10	2.5916E+10	8.9665E+09	2.8944E+10
3.465	0.02105	0.250	11.10	378.46	4.9958E+09	4.9958E+09	1.7457E+09	5.6352E+09
4.950	0.05263	0.229	11.10	382.96	4.4058E+09	4.8142E+09	1.4653E+09	5.5856E+09
7.425	0.10526	0.201	11.10	390.46	3.4226E+09	4.5115E+09	9.9797E+08	5.5030E+09
9.900	0.15790	0.179	11.10	397.96	2.4394E+09	4.2088E+09	5.3064E+08	5.4204E+09
12.375	0.21053	0.160	11.10	405.46	1.4562E+09	3.9062E+09	6.3313E+07	5.3378E+09
14.850	0.26316	0.165	9.50	388.30	1.2374E+09	3.3226E+09	5.5747E+07	5.1154E+09
17.325	0.31579	0.170	7.90	371.13	1.0187E+09	2.7389E+09	4.8181E+07	4.8931E+09
19.800	0.36842	0.176	6.30	353.96	7.9990E+08	2.1553E+09	4.0614E+07	4.6708E+09
22.275	0.42105	0.183	4.70	336.79	5.8113E+08	1.5716E+09	3.3048E+07	4.4484E+09
24.750	0.47368	0.190	3.10	319.62	3.6236E+08	9.8801E+08	2.5482E+07	4.2261E+09
27.225	0.52632	0.194	2.60	283.57	3.0106E+08	8.3897E+08	2.1407E+07	3.7374E+09
29.700	0.57895	0.200	2.10	247.51	2.3977E+08	6.8994E+08	1.7332E+07	3.2487E+09
32.175	0.63158	0.205	1.60	211.46	1.7847E+08	5.4090E+08	1.3258E+07	2.7600E+09
34.650	0.68421	0.212	1.10	175.41	1.1717E+08	3.9187E+08	9.1831E+06	2.2713E+09
37.125	0.73684	0.220	0.60	139.36	5.5877E+07	2.4283E+08	5.1085E+06	1.7826E+09
39.600	0.78947	0.224	0.48	114.82	4.4840E+07	1.9900E+08	4.1955E+06	1.4612E+09
42.075	0.84210	0.229	0.36	90.29	3.3803E+07	1.5518E+08	3.2826E+06	1.1399E+09
44.550	0.89474	0.234	0.24	65.75	2.2766E+07	1.1135E+08	2.3696E+06	8.1854E+08
47.025	0.94737	0.241	0.12	41.22	1.1729E+07	6.7518E+07	1.4567E+06	4.9720E+08
49.500	1.00000	0.250	0.00	16.68	6.9195E+05	2.3690E+07	5.4377E+05	1.7586E+08

Table A4. Distributed Blade Structural Properties for the WindPACT 5.0-MW Model

Radius (m)	BlFract (-)	Aero-Cent (-)	Strc-Twst (°)	BMass-Den (kg/m)	FlpStff (N-m^2)	EdgStff (N-m^2)	GJStff (N-m^2)	EAStff (N)
3.2	0.00000	0.250	11.10	3708.41	6.3721E+10	6.3721E+10	2.2058E+10	4.2583E+10
4.5	0.02105	0.250	11.10	622.32	1.4037E+10	1.4037E+10	4.9050E+09	9.4692E+09
6.4	0.05263	0.229	11.10	632.67	1.2398E+10	1.3799E+10	4.1117E+09	9.4146E+09
9.6	0.10526	0.201	11.10	649.91	9.6664E+09	1.3403E+10	2.7896E+09	9.3235E+09
12.8	0.15790	0.179	11.10	667.16	6.9348E+09	1.3008E+10	1.4674E+09	9.2325E+09
16.0	0.21053	0.160	11.10	684.40	4.2033E+09	1.2612E+10	1.4530E+08	9.1414E+09
19.2	0.26316	0.165	9.50	650.77	3.5661E+09	1.0597E+10	1.2782E+08	8.6929E+09
22.4	0.31579	0.170	7.90	617.15	2.9289E+09	8.5831E+09	1.1033E+08	8.2443E+09
25.6	0.36842	0.176	6.30	583.52	2.2917E+09	6.5688E+09	9.2838E+07	7.7958E+09
28.8	0.42105	0.183	4.70	549.90	1.6545E+09	4.5546E+09	7.5350E+07	7.3472E+09
32.0	0.47368	0.190	3.10	516.27	1.0173E+09	2.5403E+09	5.7861E+07	6.8987E+09
35.2	0.52632	0.194	2.60	458.05	8.4566E+08	2.1543E+09	4.8610E+07	6.1004E+09
38.4	0.57895	0.200	2.10	399.83	6.7405E+08	1.7684E+09	3.9359E+07	5.3021E+09
41.6	0.63158	0.205	1.60	341.60	5.0244E+08	1.3824E+09	3.0108E+07	4.5038E+09
44.8	0.68421	0.212	1.10	283.38	3.3083E+08	9.9640E+08	2.0856E+07	3.7056E+09
48.0	0.73684	0.220	0.60	225.16	1.5922E+08	6.1041E+08	1.1605E+07	2.9073E+09
51.2	0.78947	0.224	0.48	184.52	1.2769E+08	4.9906E+08	9.5317E+06	2.3730E+09
54.4	0.84210	0.229	0.36	143.89	9.6158E+07	3.8770E+08	7.4582E+06	1.8387E+09
57.6	0.89474	0.234	0.24	103.25	6.4625E+07	2.7634E+08	5.3846E+06	1.3044E+09
60.8	0.94737	0.241	0.12	62.62	3.3093E+07	1.6498E+08	3.3111E+06	7.7003E+08
64.0	1.00000	0.250	0.00	21.99	1.5598E+06	5.3624E+07	1.2375E+06	2.3571E+08

Appendix B. Distributed Aerodynamic Properties

This section contains the distributed aerodynamic properties for the four WindPACT baseline models.

Table B1. Distributed Blade Aerodynamic Properties for the WindPACT 0.75-kW Model

Node (-)	RNodes (m)	AeroTwst (°)	DRNodes (m)	Chord (m)	Airfoil (-)
1	2.04167	11.10	1.58333	1.392	cylinder.dat
2	3.62500	11.10	1.58333	1.621	s818_2703.dat
3	5.20833	11.10	1.58333	1.849	s818_2703.dat
4	6.79167	10.41	1.58333	1.960	s818_2703.dat
5	8.37500	8.38	1.58333	1.841	s818_2703.dat
6	9.95833	6.35	1.58333	1.723	s818_2703.dat
7	11.54167	4.33	1.58333	1.605	s818_2703.dat
8	13.12500	2.85	1.58333	1.487	s825_2103.dat
9	14.70833	2.22	1.58333	1.369	s825_2103.dat
10	16.29167	1.58	1.58333	1.250	s825_2103.dat
11	17.87500	0.95	1.58333	1.132	s825_2103.dat
12	19.45833	0.53	1.58333	1.019	s825_2103.dat
13	21.04167	0.38	1.58333	0.913	s825_2103.dat
14	22.62500	0.23	1.58333	0.807	s826_1603.dat
15	24.20833	0.08	1.58333	0.700	s826_1603.dat

Table B2. Distributed Blade Aerodynamic Properties for the WindPACT 1.5-MW Model

Node (-)	RNodes (m)	AeroTwst (°)	DRNodes (m)	Chord (m)	Airfoil (-)
1	2.85833	11.10	2.21667	1.949	cylinder.dat
2	5.07500	11.10	2.21667	2.269	s818_2703.dat
3	7.29167	11.10	2.21667	2.589	s818_2703.dat
4	9.50833	10.41	2.21667	2.743	s818_2703.dat
5	11.72500	8.38	2.21667	2.578	s818_2703.dat
6	13.94167	6.35	2.21667	2.412	s818_2703.dat
7	16.15833	4.33	2.21667	2.247	s818_2703.dat
8	18.37500	2.85	2.21667	2.082	s825_2103.dat
9	20.59167	2.22	2.21667	1.916	s825_2103.dat
10	22.80833	1.58	2.21667	1.751	s825_2103.dat
11	25.02500	0.95	2.21667	1.585	s825_2103.dat
12	27.24167	0.53	2.21667	1.427	s825_2103.dat
13	29.45833	0.38	2.21667	1.278	s825_2103.dat
14	31.67500	0.23	2.21667	1.129	s826_1603.dat
15	33.89167	0.08	2.21667	0.980	s826_1603.dat

Table B3. Distributed Blade Aerodynamic Properties for the WindPACT 3.0-MW Model

Node (-)	RNodes (m)	AeroTwst (°)	DRNodes (m)	Chord (m)	Airfoil (-)
1	4.04250	11.10	3.13500	2.756	cylinder.dat
2	7.17750	11.10	3.13500	3.209	s818_2703.dat
3	10.31250	11.10	3.13500	3.662	s818_2703.dat
4	13.44750	10.41	3.13500	3.880	s818_2703.dat
5	16.58250	8.38	3.13500	3.646	s818_2703.dat
6	19.71750	6.35	3.13500	3.412	s818_2703.dat
7	22.85250	4.33	3.13500	3.178	s818_2703.dat
8	25.98750	2.85	3.13500	2.944	s825_2103.dat
9	29.12250	2.22	3.13500	2.710	s825_2103.dat
10	32.25750	1.58	3.13500	2.476	s825_2103.dat
11	35.39250	0.95	3.13500	2.242	s825_2103.dat
12	38.52750	0.53	3.13500	2.018	s825_2103.dat
13	41.66250	0.38	3.13500	1.808	s825_2103.dat
14	44.79750	0.23	3.13500	1.597	s826_1603.dat
15	47.93250	0.08	3.13500	1.386	s826_1603.dat

Table B4. Distributed Blade Aerodynamic Properties for the WindPACT 5.0-MW Model

Node (-)	RNodes (m)	AeroTwst (°)	DRNodes (m)	Chord (m)	Airfoil (-)
1	5.22667	11.10	4.05333	3.564	cylinder.dat
2	9.28000	11.10	4.05333	4.150	s818_2703.dat
3	13.33333	11.10	4.05333	4.735	s818_2703.dat
4	17.38667	10.41	4.05333	5.016	s818_2703.dat
5	21.44000	8.38	4.05333	4.714	s818_2703.dat
6	25.49333	6.35	4.05333	4.411	s818_2703.dat
7	29.54667	4.33	4.05333	4.109	s818_2703.dat
8	33.60000	2.85	4.05333	3.806	s825_2103.dat
9	37.65333	2.22	4.05333	3.504	s825_2103.dat
10	41.70667	1.58	4.05333	3.201	s825_2103.dat
11	45.76000	0.95	4.05333	2.898	s825_2103.dat
12	49.81333	0.53	4.05333	2.609	s825_2103.dat
13	53.86667	0.38	4.05333	2.337	s825_2103.dat
14	57.92000	0.23	4.05333	2.065	s826_1603.dat
15	61.97333	0.08	4.05333	1.793	s826_1603.dat

Appendix C. Distributed Tower Structural Properties

This section contains the distributed tower structural properties for the four WindPACT baseline models.

Table C1. Distributed Tower Structural Properties for the WindPACT 750-kW Model

Elevation (m)	HtFract (-)	TMassDen (kg/m)	TwFAStif (N-m^2)	TwSSStif (N-m^2)	TwGJStif (N-m^2)	TwrEAStif (N)
0.000	0.00000	1456.570	6.213e+10	6.213e+10	4.779e+10	3.534e+10
6.519	0.11111	1319.664	5.060e+10	5.060e+10	3.892e+10	3.202e+10
13.038	0.22222	1189.472	4.076e+10	4.076e+10	3.135e+10	2.886e+10
19.557	0.33333	1065.993	3.242e+10	3.242e+10	2.494e+10	2.587e+10
26.076	0.44444	949.228	2.543e+10	2.543e+10	1.956e+10	2.303e+10
32.594	0.55556	839.176	1.964e+10	1.964e+10	1.511e+10	2.036e+10
39.113	0.66667	735.838	1.489e+10	1.489e+10	1.146e+10	1.785e+10
45.632	0.77778	639.212	1.106e+10	1.106e+10	8.511e+09	1.551e+10
52.151	0.88889	549.301	8.023e+09	8.023e+09	6.172e+09	1.333e+10
58.670	1.00000	466.102	5.655e+09	5.655e+09	4.350e+09	1.131e+10

Table C2. Distributed Tower Structural Properties for the WindPACT 1.5-MW Model

Elevation (m)	HtFract (-)	TMassDen (kg/m)	TwFAStif (N-m^2)	TwSSStif (N-m^2)	TwGJStif (N-m^2)	TwrEAStif (N)
0.000	0.00000	2549.997	2.480e+11	2.480e+11	1.908e+11	6.187e+10
9.154	0.11111	2285.894	1.961e+11	1.961e+11	1.509e+11	5.547e+10
18.309	0.22222	2035.913	1.528e+11	1.528e+11	1.175e+11	4.940e+10
27.463	0.33333	1800.055	1.170e+11	1.170e+11	9.004e+10	4.368e+10
36.618	0.44444	1578.318	8.794e+10	8.794e+10	6.765e+10	3.830e+10
45.772	0.55556	1370.703	6.460e+10	6.460e+10	4.969e+10	3.326e+10
54.927	0.66667	1177.211	4.621e+10	4.621e+10	3.555e+10	2.856e+10
64.081	0.77778	997.840	3.203e+10	3.203e+10	2.464e+10	2.421e+10
73.236	0.88889	832.592	2.137e+10	2.137e+10	1.644e+10	2.020e+10
82.390	1.00000	681.465	1.360e+10	1.360e+10	1.046e+10	1.654e+10

Table C3. Distributed Tower Structural Properties for the WindPACT 3.0-MW Model

Elevation (m)	HtFract (-)	TMassDen (kg/m)	TwFAStif (N-m^2)	TwSSStif (N-m^2)	TwGJStif (N-m^2)	TwrEAStif (N)
0.000	0.00000	5408.139	1.050e+12	1.050e+12	8.079e+11	1.312e+11
12.970	0.11111	4777.684	8.203e+11	8.203e+11	6.310e+11	1.159e+11
25.940	0.22222	4186.287	6.304e+11	6.304e+11	4.849e+11	1.016e+11
38.910	0.33333	3633.948	4.755e+11	4.755e+11	3.657e+11	8.818e+10
51.880	0.44444	3120.668	3.510e+11	3.510e+11	2.700e+11	7.572e+10
64.851	0.55556	2646.445	2.528e+11	2.528e+11	1.945e+11	6.421e+10
77.821	0.66667	2211.281	1.768e+11	1.768e+11	1.360e+11	5.366e+10
90.791	0.77778	1815.175	1.194e+11	1.194e+11	9.181e+10	4.404e+10
103.761	0.88889	1458.128	7.720e+10	7.720e+10	5.938e+10	3.538e+10
116.731	1.00000	1140.138	4.734e+10	4.734e+10	3.642e+10	2.766e+10

Table C4. Distributed Tower Structural Properties for the WindPACT 5.0-MW Model

Elevation (m)	HtFract (-)	TMassDen (kg/m)	TwFAStif (N-m^2)	TwSSStif (N-m^2)	TwGJStif (N-m^2)	TwrEAStif (N)
0.000	0.00000	9401.518	2.949e+12	2.949e+12	2.269e+12	2.281e+11
16.786	0.11111	8269.715	2.278e+12	2.278e+12	1.752e+12	2.007e+11
33.572	0.22222	7210.463	1.728e+12	1.728e+12	1.330e+12	1.750e+11
50.357	0.33333	6223.762	1.285e+12	1.285e+12	9.883e+11	1.510e+11
67.143	0.44444	5309.611	9.326e+11	9.326e+11	7.174e+11	1.288e+11
83.929	0.55556	4468.012	6.584e+11	6.584e+11	5.064e+11	1.084e+11
100.715	0.66667	3698.963	4.495e+11	4.495e+11	3.458e+11	8.975e+10
117.500	0.77778	3002.465	2.948e+11	2.948e+11	2.268e+11	7.285e+10
134.286	0.88889	2378.518	1.840e+11	1.840e+11	1.415e+11	5.771e+10
151.072	1.00000	1827.121	1.078e+11	1.078e+11	8.291e+10	4.433e+10