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Hybrid Electro-Mechanical Simulation Tool for Wind Turbine Generators

M. Singh, *Member, IEEE*, E. Muljadi, *Fellow, IEEE*, J. Jonkman

***Abstract*—Wind turbine generators (WTGs) consist of many different components to convert kinetic energy of the wind into electrical energy for end users. Wind energy is accessed to provide mechanical torque for driving the shaft of the electrical generator. The conversion from wind power to mechanical power is governed by the aerodynamic conversion. The aerodynamic-electrical-conversion efficiency of a WTG is influenced by the efficiency of the blades, the gearbox, the generator, and the power converter.**

This paper describes the use of MATLAB/Simulink to simulate the electrical and grid-related aspects of a WTG coupled with the FAST aero-elastic wind turbine computer-aided engineering tool to simulate the aerodynamic and mechanical aspects of a WTG. The combination of the two enables studies involving both electrical and mechanical aspects of a WTG. For example, mechanical engineers can formulate generator control that may preserve the life of the gearbox or mitigate the impact of transient events occurring on the transmission lines (faults, voltage and frequency dips, unbalanced voltages, etc.). Similarly, electrical engineers can study the impact of high-ramping wind speeds on power systems, as well as the impact of turbulence on the voltage and frequency of a small balancing area.

***Index Terms*—aerodynamic control, electromechanical interaction, variable speed, wind turbine, wind power generation**

I. Introduction

THE deployment of wind energy has experienced substantial growth in the last decades. In the past, wind turbine generators (WTGs) utilized a very simple wind turbine with stall control and a fixed-speed directly-connected induction generator (Type 1). The affordable cost of power converters, advances in modern control and aeroelasticity, and the availability of fast computing microprocessors enabled wind turbine engineers to design very sophisticated, modern WTGs capable of delivering high-quality output power while at the same time enhancing power system operations.

To perform a holistic design, all aspects of a WTG need to be considered. In this paper, we attempt to demonstrate a holistic WTG model by using the NREL-developed FAST [1] software to simulate the detailed aerodynamics and mechanical aspects of a WTG, and MATLAB/Simulink [2] to simulate the electrical generators, converters, collector systems, and grid aspect of a grid-connected WTG. The references [1–9] cover the basic equations used in FAST as well as in drivetrain and generator models in more detail.

Mechanical load and stress in a wind turbine drivetrain is influenced by the torque and nontorque loads applied between the input shaft at the blade side and the output shaft at the generator side. For example, unwanted loads entering the input shaft are caused by things such as wind turbulence, tower shadow effect, uneven loading of the blades, and sudden changes in the wind direction, etc. Examples of unwanted disturbances on the output power (and thus torque) include transmission line disturbances (voltage and/or frequency dips, unbalanced voltage, under- or overvoltage, etc.). These differences between input and output torque manifest in the stresses, loads, and losses of the components (gearbox, shaft, bearing, etc.) in different parts of a WTG. Using FAST in conjunction with MATLAB/Simulink allows us to examine loading of different components under grid transients or wind turbulence, and also to design controllers to mitigate the effects of these unusual conditions on a turbine structure and components. If we do not have any control to influence the torque difference between input and output, there is very little we can do to influence the lifetime and operations and maintenance of these components, which eventually affects the cost of the energy for the life of a WTG. Figure 1 illustrates the interfacing of FAST and MATLAB/Simulink.

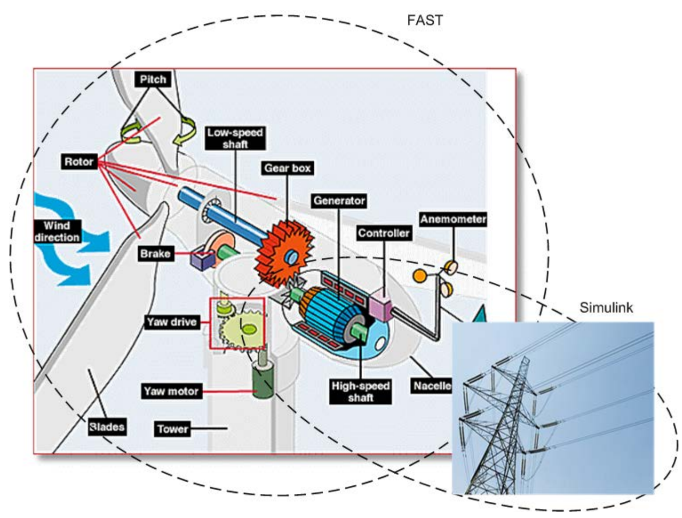
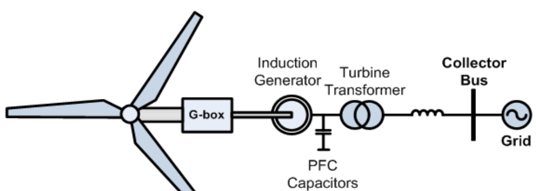


Figure 1. Hybrid simulation performed with the detailed aerodynamic and mechanical model of a wind turbine within FAST, and the detailed electrical and grid model in the Matlab/Simulink environment.

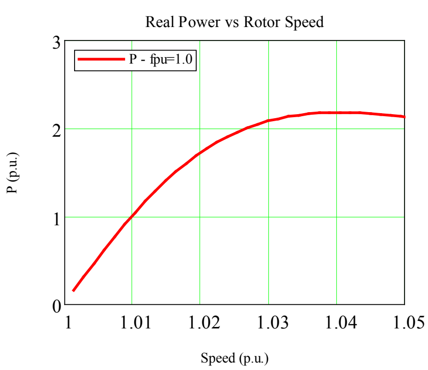
The intent of this paper is to provide a brief demonstration of the capabilities of the coupled FAST and MATLAB/Simulink models. Section II briefly discusses some results from a model of the simplest type of WTG, Type 1. In Section III, we highlight results from simulating voltage sags on a Type 3 (doubly-fed induction generator, or DFIG) turbine to illustrate the flexibility of variable-speed WTGs as well as illustrate that the strength of the grid connection can have an effect on mechanical transients experienced by a turbine during grid events. Section IV provides conclusions.

II. TYPE I WTG

Broadly, four electrical topologies are in use in commercial megawatt-scale WTGs today. In a Type 1 WTG (Figure 2a), there is no control input that can be used to influence the output of the generator except for the pitch controller, which is usually deployed when the power in the wind exceeds the rated power, and some form of yaw control would also be needed to follow the wind direction. On the other hand, in Type 2 (variable-slip), Type 3 (DFIG), and Type 4 (full-converter) WTGs, there is some controllability that can be implemented to affect the behavior of a WTG below and above rated wind speed. The characteristic of a Type 1 WTG is that it operates at nearly fixed speed with rated speed about 1% above synchronous speed; thus, the power vs speed characteristic (Figure 2b) is very steep.Another characteristic of this type of turbine is that the induction generator absorbs reactive power in the motoring mode or in the generating mode. A Type 1 WTG is normally equipped with a switched capacitor bank to compensate for the reactive power. As the wind speed varies, output level varies, and the slip varies between 0% and -1%. The reactive power requirement also varies with the slip, and the size of the capacitance providing reactive power to the induction generator is also varied, so that the output of the induction generator is maintained at unity power factor.



a) Physical diagram



b) Power vs. speed characteristic

Figure 2. Type 1 WTG physical diagram and power versus speed characteristic

Figure 3 shows a single-line diagram describing the common layout of a wind power plant connected to a power system network. The turbine is electrically connected to the power system through a network of cabling, transformers, and overhead lines. The interaction between the wind turbine and the power system network is very important to the stability of the power system, especially when the size of the wind power generation is very large (e.g., high penetration levels of wind power generation). The interaction occurs both ways. Any transients occurring at the transmission line will affect the generator and its components. Similarly, any perturbation in the wind speed at the turbine site will be reflected in the utility grid.

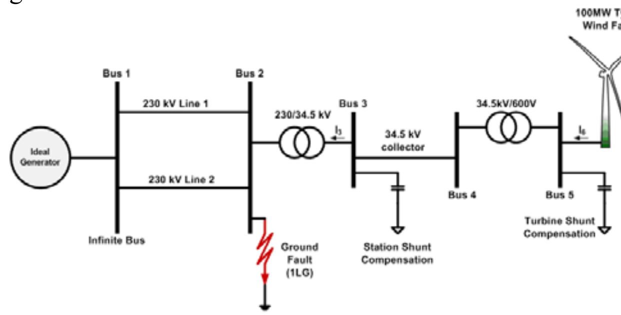


Figure 3. Single-line diagram for a small system for a Type 1 WTG.

Using FAST and MATLAB/Simulink, a model of the AOC AWT-27 turbine [10], a Type 1 WTG, was developed. A brief subset of the results is presented here. Because Type 1 WTGs are infrequently installed today, the bulk of this paper is devoted to modeling the Type 3 WTG behavior (described in the next section). However, the modeling of Type 1 turbines may be useful in academic settings because these models can illustrate many basic principles of wind turbines as well as show how far the technology has progressed and how many initial problems faced by these turbines have been resolved in more modern designs.

Figure 4 shows that under steady wind conditions, the generator torque and the speed of this WTG are affected by the tower shadow effect caused by the aerodynamic torque reduction every time one of the blades passes through the wake of the tower, thus creating torque pulsation (three times per full rotational angle).

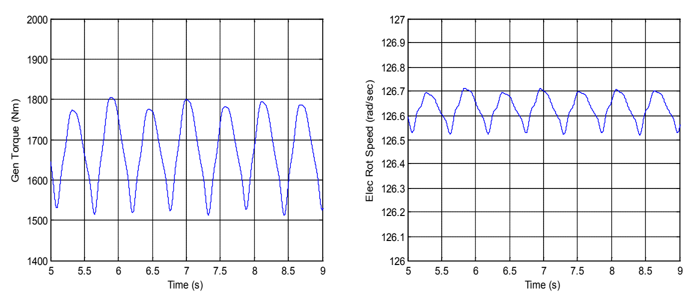


Figure 4. Simulation results showing the impact of tower shadow on the generator torque and speed for a Type 1 WTG.

Figure 5 demonstrates the unique capabilities of the FAST and MATLAB/Simulink coupling. The thrust loading and power output are shown under steady wind. As shown, the thrust loading varies because of the tower shadow as well. This result would not be obtainable from a dedicated power system transient modeling software. The plot on the right shows the power also varies because of the tower shadow, as expected from the variations seen in the speed and torque plots. This tower shadow effect is barely seen in more recent, advanced turbines, such as Type 3 and Type 4.

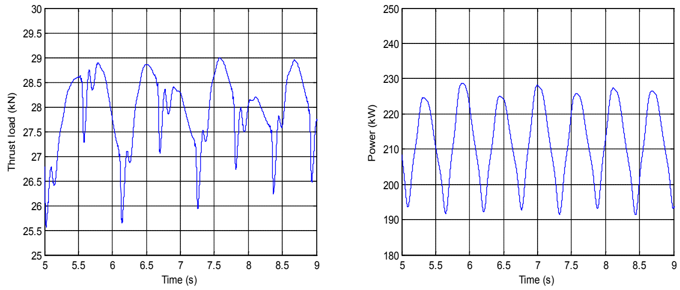


Figure 5. Simulation results showing the impact of tower shadow on the generator thrust load and the output power for a Type 1 WTG.

Figure 6 shows another interesting result. A 2% voltage unbalance on Phase A is shown to generate a torque pulsation at 120 Hz because of the negative sequence voltage during the unbalanced voltage event. Note that the small unbalanced voltage creates a large torque pulsation because the negative sequence impedance is very low (negative sequence slip ~ 200%) compared to the positive sequence impedance (positive sequence slip ~ 1%). These results illustrate the ability of the coupled FAST and MATLAB/Simulink models to provide insights into combined electrical and mechanical behaviors that would be difficult to extract with other softwares that are solely dedicated to electrical modeling, or aero/mechanical modeling.

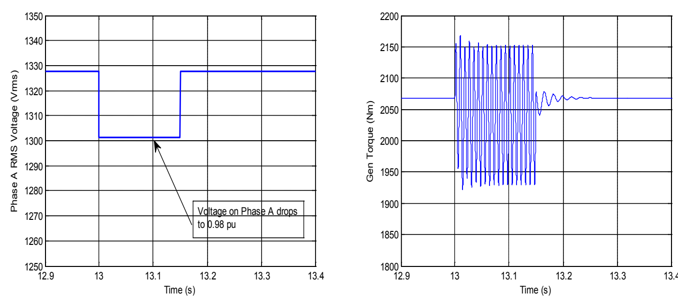


Figure 6. Simulation results showing the impact of voltage unbalance with 2% voltage drop on Phase A for a Type 1 WTG.

III. Type 3 WTG

Type 3 WTGs are variable-speed wind turbines with doubly-fed induction generators. The DFIG is operated in variable-speed mode using a partial-size power converter connected to the rotor winding of the wound-rotor induction generator (WRIG). The stator winding of the WRIG is connected to the grid at a frequency of 60 Hz.

This turbine type is probably the most popular type available in the market, and it has been deployed in very large quantities. A WTG is normally operated between 30% slip (subsynchronous speed) and -30% slip (supersynchronous speed), and the converter is typically at about 30% of rated power output. Figure 7 shows a schematic of a Type 3 WTG. The power converter performs a back-to-back AC-DC-AC conversion using two pulse-width modulation–switched voltage-source inverters coupled with a DC link. A crowbar circuit is also provided as protection, to allow the shorting of the rotor circuit if necessary.

A Type 3 WTG has a torque characteristic that is a quadratic function of the rotational speed. Type 3 WTGs allow maximal extraction of wind power because their power output can be electronically controlled to follow the optimal power curve. The optimal power curve is a cube function of the rotational speed (refer to Figure 8). If the rotor speed exceeds its rated value, the pitch controller must be deployed to limit the rotational speed at its rated speed. If the pitch controller could not control the aerodynamic power of the wind turbine, a WTG may experience a runaway event. Note that the speed range of a Type 3 WTG is much larger than the speed range of a Type 1 WTG; thus, the kinetic energy stored in the rotating blades and other components within the wind turbine is sufficiently large, and the output of the generator is not impacted as much by the wind fluctuations and turbulence because some of the energy is stored and restored in the kinetic energy of the rotating mass.

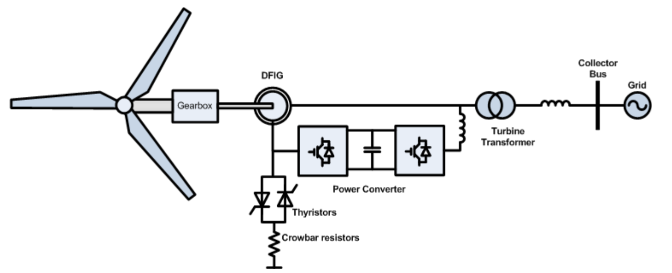


Figure 7. Physical diagram of a Type 3 wind turbine.

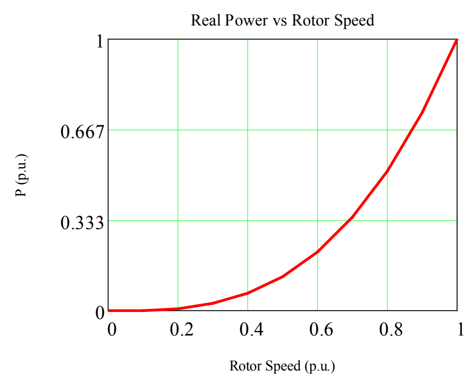


Figure 8. Power versus speed characteristic for a Type 3 WTG.

Using FAST and MATLAB/Simulink, a model of the GRC 750-kW turbine [11], a Type 3 WTG, was developed. The model was used to demonstrate that turbines connected in stiff grids will experience slightly different transient behavior than turbines connected in weaker grids. These demonstrations may have a value in determining turbine operations and maintenance schedules or turbine life.

In the simulations, at $t=10s$, a voltage sag occurred. (Both single-phase unbalanced and three-phase balanced faults are modeled.) The sag dropped the grid voltage from 1 p.u. to 0.1 p.u. The sag persisted for nine cycles (150 ms) and then cleared. The simulations were carried out for relatively strong and weak grids, and the results were plotted together. Note that the weak grid was simulated by doubling the line impedance of the grid. The wind speed was held steady at 12 m/s, below the rated speed, so pitch control was inactive.

Figures 9 and 10 show some results from simulation of a single-phase sag. Figure 9 shows torque, speed, and power at the high-speed shaft. The sag caused an approximately 2.5-Hz oscillation to occur that persisted long after the fault cleared, indicating that some mechanical oscillation mode within the drivetrain was likely excited. The plots also show that the amplitude of the oscillation was greater for the weak-grid case, potentially leading to more damage to the high-speed shaft and drivetrain over the life of a turbine.

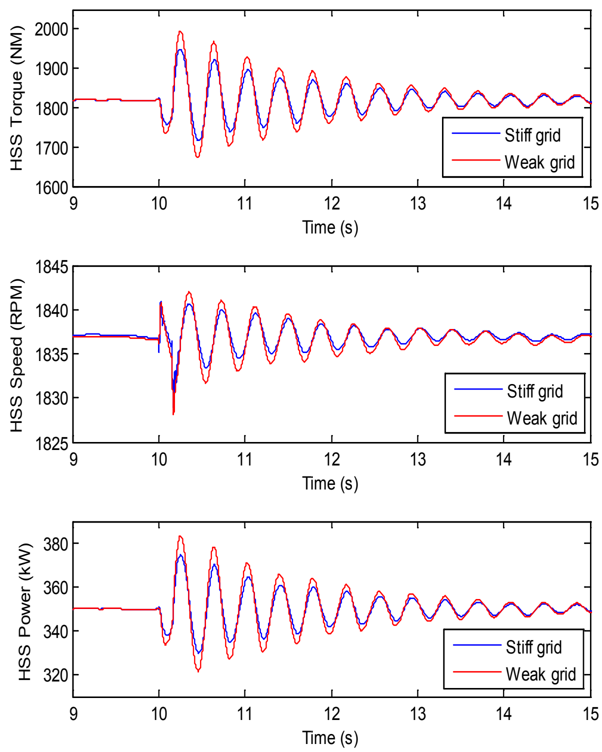


Figure 9. Simulation results showing the impact of a single-phase voltage sag for a Type 3 WTG on a high-speed shaft torque, speed, and power.

Although Figure 9 is informative, Figure 10 shows the true potential of the FAST and MATLAB/Simulink coupling. Figure 10 shows the edgewise and flapwise blade moments at the blade root during the single-phase sag. As shown, the sag produced no noticeable between the turbine connected to the weak grid and when it is connected to a stiff grid. It is also shown that the strength of the grid connection had no impact on these moments. These insights would be difficult to obtain without the coupled FAST and MATLAB/Simulink model.

Figure 11 shows results for the three-phase sag. In this case, the transient was much more severe. The torque swing was near an order of magnitude greater than in the single-phase case (compare Figure 11 to Figure 9). Similar swings can be seen in the speed and torque, indicating the severity of the event. It is also shown that the level of grid stiffness affects the response both in frequency and damping. Note that this was a worst-case scenario: in this case, the crowbar was inactive; thus, the crowbar did not operate to limit the rotor currents and the turbine was exposed to the full intensity of the event. A noticeable difference can also be seen between the weak-grid and stiff-grid cases: a phase shift occurred in the weak-grid case for which the cause was unknown. Again, the oscillations had higher amplitude in the weak-grid case.

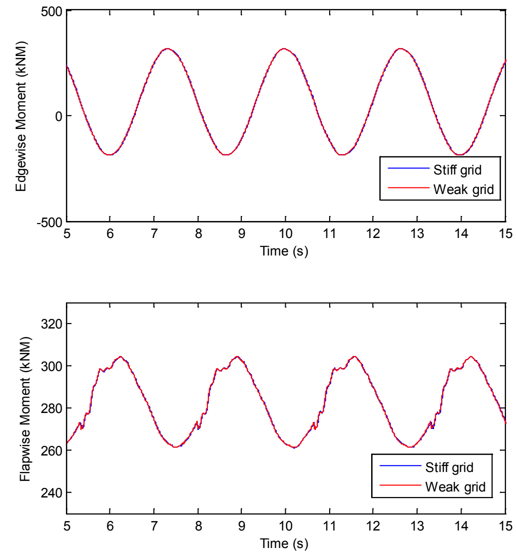


Figure 10. Edgewise and flapwise blade moments at the blade root during a single-phase voltage sag on a Type 3 WTG.

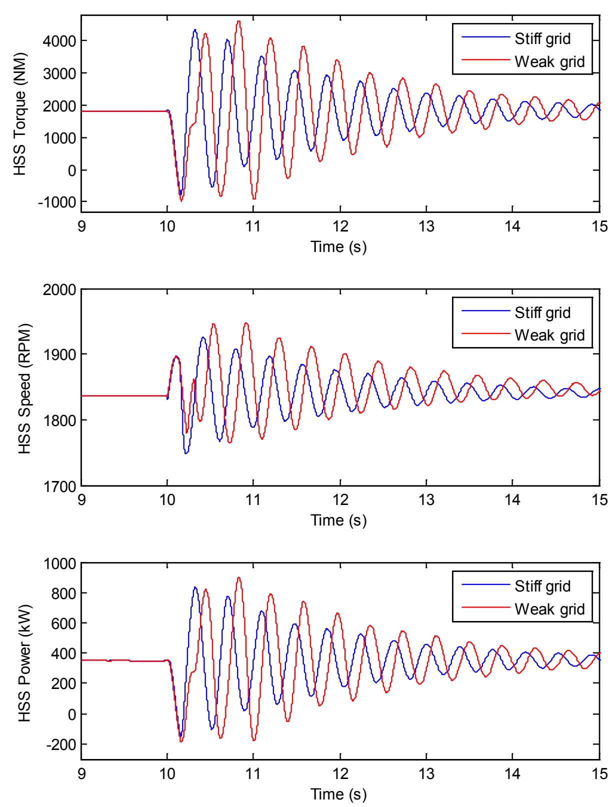


Figure 11. Simulation results showing the impact of a three-phase voltage sag on the output power of a Type 3 WTG on a high-speed shaft torque, speed, and power.

Figure 12 shows that in the three-phase fault case, in contrast to the single-phase case shown in Figure 10, the severity of the three-phase fault actually led to noticeable oscillations in the edgewise and flap-wise moments at the blade root. It is shown in Figure 12 that the system with stiff grid responded more favorably than the system connected to a weak grid.

Although the models display the ability to provide valuable insights into turbine mechanical and electrical coupled transients, the reliability of the results cannot be confirmed yet. In further work, efforts will be made to validate results obtained from coupled FAST and MATLAB/Simulink models using real field measurements. Potential methods to mitigate stresses using advanced controls will also be studied [12,13].

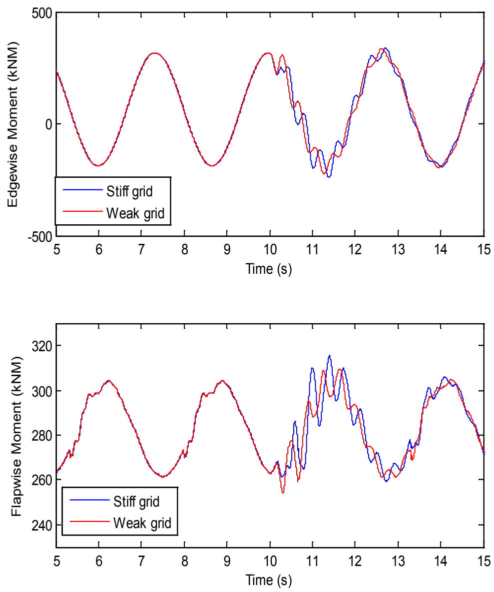


Figure 12. Edgewise and flapwise blade moments at the blade root during a three-phase voltage sag on a Type 3 WTG.

IV. Conclusions

This demonstration of the ability of the coupled FAST and MATLAB/Simulink models to provide insights about the effects of strong and weak grid connections is but one example of the potential of this coupling. Many other such analyses can be conducted—for example, the effects of electrical faults on mechanical components (gearbox thrust loading, etc.); the effects of mechanical oscillations on output power/current/voltage; effects of voltage unbalance; benefits of soft-starting and other power-electronic–based damping mechanisms; converter-control effects on mechanical systems (and other controller interactions); and effects of wind gusts and turbulence on electrical systems.

V. Acknowledgment

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VII. Biographies

Mohit Singh (M’11) received his M.S. and Ph.D. in electrical engineering from the University of Texas at Austin in 2007 and 2011, respectively. His research is focused on dynamic modeling of wind turbine generators. Dr. Singh is currently working at the National Renewable Energy Laboratory in Golden, Colorado, as a postdoctoral researcher in transmission and grid integration of renewable energy. His current interests include modeling and testing various applications of wind turbine generators and other renewable energy resources. He is a member of the IEEE. He is involved in the activities of the IEEE Power and Energy Society.

Eduard Muljadi (M’82, SM’94, F’10) received his Ph.D. in electrical engineering from the University of Wisconsin at Madison. From 1988 to 1992, he taught at California State University at Fresno. In June 1992, he joined the National Renewable Energy Laboratory in Golden, Colorado. His current research interests are in the fields of electric machines, power electronics, and power systems in general with an emphasis on renewable energy applications. He is member of Eta Kappa Nu and Sigma Xi, a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), and an editor of the IEEE Transactions on Energy Conversion. He is involved in the activities of the IEEE Industry Application Society (IAS), Power Electronics Society, and Power and Energy Society (PES). He is currently a member of various committees of the IAS, and a member of the Working

Group on Renewable Technologies and the Task Force on Dynamic Performance of Wind Power Generation, both of the PES. He holds two patents in power conversion for renewable energy.

Jason Jonkman is a senior engineer at the National Renewable Energy Laboratory's National Wind Technology Center. He received his Ph.D. in aerospace engineering sciences from the University of Colorado, his M.S. in mechanical engineering from Colorado State University, and his B.S.E. in mechanical engineering from Dordt College. Jonkman joined NREL in 2000 and is the lead developer of the FAST and FAST-to-ADAMS preprocessor computer simulation software for modeling the dynamic response of land- and offshore-based wind turbines. He also provides technical support to designers, consultants, and researchers throughout the wind energy industry. He has performed studies to verify and validate the simulation software, published many papers on wind turbine dynamics, and assisted in the certification of wind turbine design loads.

Jonkman is currently leading the wind turbine dynamics model development activities at NREL. He is co-chairing an IEA research annex on developing and verifying simulation models for fixed-bottom and floating offshore wind energy concepts. He is the principle investigator for a DOE-funded project to improve the modeling of offshore floating wind system dynamics and is providing guidance to several projects aimed at validating these models. He also is a U.S. representative on the IEC working group to develop an international standard for the design of offshore floating wind turbines.

Prior to joining NREL, Jonkman worked as a researcher at DOE's Industrial Assessment Center at Colorado State University and as a tool design engineer at the commercial airplane division of Boeing.