Variable-Speed Wind Power Plant Operating With Reserve Power Capability

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Variable-Speed Wind Power Plant Operating With Reserve Power Capability

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***Abstract*—As the level of wind penetration increases, wind turbine technology must move from merely generating power from wind to taking a role in supporting the bulk power system. Wind turbines should have the capability to provide inertial response and primary frequency (governor) response. Wind turbine generators with this capability can support the frequency stability of the grid. To provide governor response, wind turbines should be able to generate less power than the available wind power and hold the rest in reserves, ready to be accessed as needed. In this paper, we explore several ways to control wind turbine output to enable reserve-holding capability. The focus of this paper is on doubly-fed induction generator (also known as Type 3) and full-converter (also known as Type 4) wind turbines.**

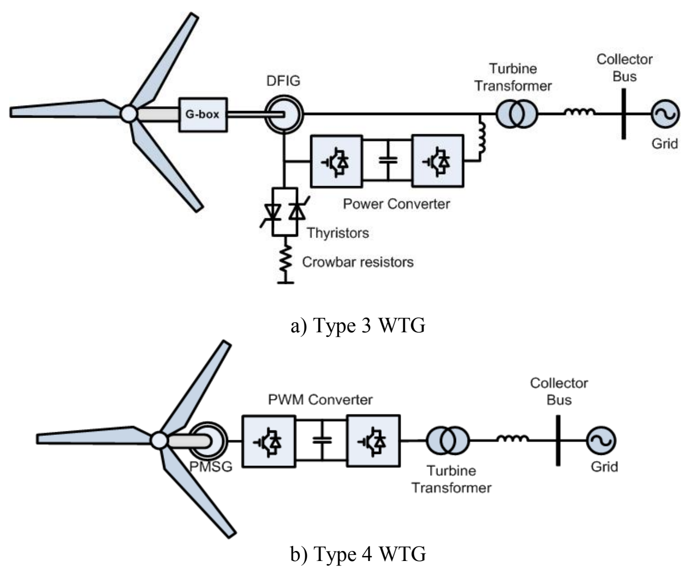
***Index Terms*—wind turbine generator, variable speed, induction generator, governor response, inertial response, renewable energy**

I. Introduction

Wind power generation may reach 300 GW by 2030, achieving a level of penetration of 20% total energy production [1]. Recent advances in wind turbine technology allow efficient and rapid deployment of wind power plants (WPPs). As more WPPs are integrated into the bulk utility power system, the adverse effects of wind power uncertainty and variability on the power system are expected to become more noticeable. The issue of frequent and significant frequency excursions from nominal value is of particular concern, especially in a synchronous power system with high wind power penetration [2]. The material reported in [3–9] laid the groundwork for understanding inertia and frequency issues related to wind. WPPs with doubly-fed induction generator (Type 3) wind turbines as well as full-converter (Type 4) wind turbines typically do not contribute to system frequency support because each wind turbine generator (WTG) is indirectly connected to the power grid. The work reported here seeks to develop a control method to improve individual wind turbine response to frequency events. Individual wind turbine reserve-holding capability scales up to provide significant reserve-holding capability at the WPP level. Control modifications needed to operate Type 3 and Type 4 WTGs with reserves are presented in this paper. Detailed simulations in the time domain have been conducted to demonstrate the efficacy of the proposed control modifications. The unique feature of this proposed controller is that the wind turbine is always operated at the optimal (rated) value of the tip speed ratio (TSR).

Different wind turbine types use different energy conversion systems (generator, power converter, and control algorithms). The strategies used to control the prime mover are generally similar. Common elements include mechanical brakes and blade pitch control to avoid a runaway condition and reduce stresses on the mechanical components of the wind turbine. Type 3 and Type 4 turbines have power converters as well to allow additional control and conditioning of the output real and reactive power. The topologies of the Type 3 and Type 4 turbines are shown in Figure 1.

This paper is arranged as follows. Section II presents basic characteristics of wind turbines as well as the proposed reserve power controls. Section III describes dynamic simulations to investigate different scenarios applied to a WPP with the implementation of reserve power controls.



a) Type 3 WTG

b) Type 4 WTG

Fig. 1. Physical diagram of variable-speed WTGs

II. Basic Wind Turbine Operation

A. *Type 3 and Type 4 WTGs*

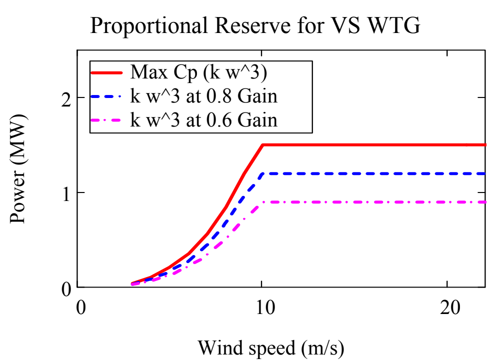
Type 3 and Type 4 wind turbines are converter-based turbines that offer maximum power point tracking as well as independent real and reactive power control. The generator-power converter is controlled to operate at maximum aerodynamic efficiency (C_{pmax}). The complete paper will contain a more detailed background of variable-speed operation for both Type 3 and Type 4 turbines. Modern wind turbines are usually equipped with pitch controllers to limit the aerodynamic power driving the generator. With the pitch controller, the blade pitch angle is activated in the high-wind-speed region to limit the stresses imposed on the wind turbine mechanical components, limit the output of generation, and avoid a runaway condition when the WTG loses connection to the grid. The controller design described here uses both power converter control as well as pitch control to achieve the holding and releasing of reserve power.

B. Reserve Power for Variable-Speed WTGs

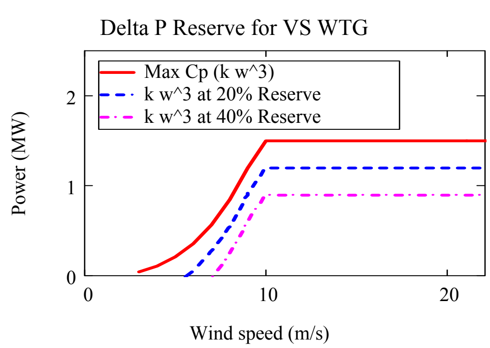
In variable-speed WTGs, the power versus rotational speed characteristic of a WTG is shaped by the power converter. The pitch controller adjusts the aerodynamic power.

1) Two Types of Reserve Power

If we want to set aside some reserve power, the portion of aerodynamic power that will be reserved should be included as a constant proportion of the rated power (constant reserve – ΔP) or a constant proportion of the available aerodynamic power (proportional reserve). This spinning reserve capability can be used to implement "governor control" to help the grid by decreasing or increasing the reserve power held from or delivered to the grid. In Figure 2a, the amount of reserve power is a constant output power as a percentage of rated power, and in Figure 2b, the amount of reserve power is a fraction of the target power (C_{pmax} operation).



a) Constant ΔP



b) Proportional reserve

Fig. 2. The reserve power for a variable-speed WTG using two different methods

2) Combining Control and Power Converter Control

Figure 3 illustrates how the control strategy works. The WTG is operated at variable speed. The electrical output power is commanded to follow the thick red line in normal operation without the reserve requirement. With the reserve requirement enabled, the dashed green line (indicating the proportional reserve) is the path followed. This is done via converter control. The thin red line represents the aerodynamic power of the WTG at 8 m/s without pitch action, and the operating point of the WTG is at Point A for optimal operation. To fulfill the reserve requirement, the pitch is controlled to ensure that the aerodynamic operation of the WTG will be maintained at optimal tip speed ratio (TSR), and the aerodynamic power moves from the thin red line to the dashed green line after the pitch angle is adjusted. The new operating point is Point B. Moving the operating point from Point A to Point B requires both the aerodynamic adjustment via pitch angle control and power converter control. The purpose of keeping the TSR at the optimal value is to optimize the response of the turbine when the pitch is returned to normal (pitch angle β=0^o); thus, the turbine will return to operating at optimum C_p right away. The operating point moves back from Point B to Point A when the reserve power of a WPP is recalled (i.e., reserve requirement is disabled) and it will return performance coefficient to C_{pmax} operation.

3) Control Block Diagram

The control block diagram for the proposed controller is presented in Figure 4. There are several groups of control blocks performing different functions:

- Block 1 ensures that the operation of the WTG is maintained at constant TSR. The input to this block is the wind speed. The average (filtered) value of the wind speed is used to compute the corresponding rotor speed to keep the TSR constant at the optimal target value (TSR_{tgt}). The reason we want to keep the TSR at TSR_{tgt} is to ensure that the WTG will respond instantaneously and return to its original operating point quickly when the pitch angle is returned to normal.
- Block 2 controls the pitch angle so that the rotor speed follows the target rotor speed ($\omega_{m\text{-}tgt}$) and the TSR is kept at TSR_{tgt}. Another function of this block is to ensure that the rotor speed will never exceed the rated (upper limit) rotor speed ($\omega_m < \omega_{m\text{-}limit}$). Thus, it will prevent the runaway problem when the turbine gets disconnected from the grid. The output of this block will be limited ($0^o < \beta < 30^o$).
- In Block 3, the target power is computed to guide the pitch controller in adjusting the output of the WTG. The input to Block 3 is the rotational speed that will be translated to the calculated power (P_{calc}) deliverable at maximum C_p operation. From this calculated power, the reserve power must be

subtracted to obtain the electrical power, including the reserve power – P_{tgt_rsv}. Another input is P_{aux}, to include the governor droop control capability if it is implemented (discussed in the next section). Finally, the output of the block is the target power. Note that the target power at lower-than-rated rotor speed must be checked to ensure the operating torque of the generator will not exceed the designed maximum torque (corresponding to output power at maximum rated torque P_{ratedT}). This precaution will allow the mechanical torque limit to be observed to preserve the gearbox, the shaft, and other mechanical components of the WTG. Finally, the target power P_{tgt} will be used to command the power converter so that the total output of the generator will be equal to P_{tgt}.

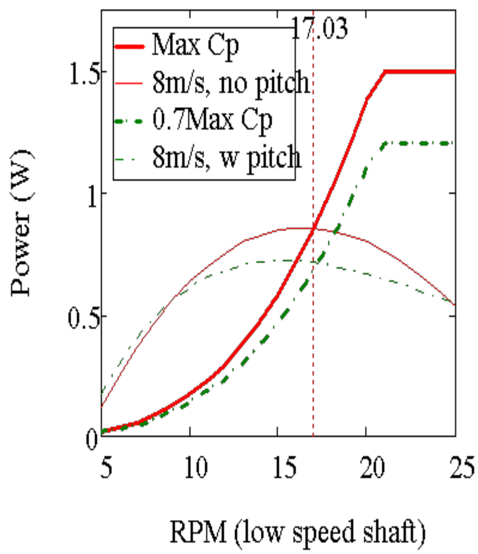


Fig. 3. Operating points for the proposed control

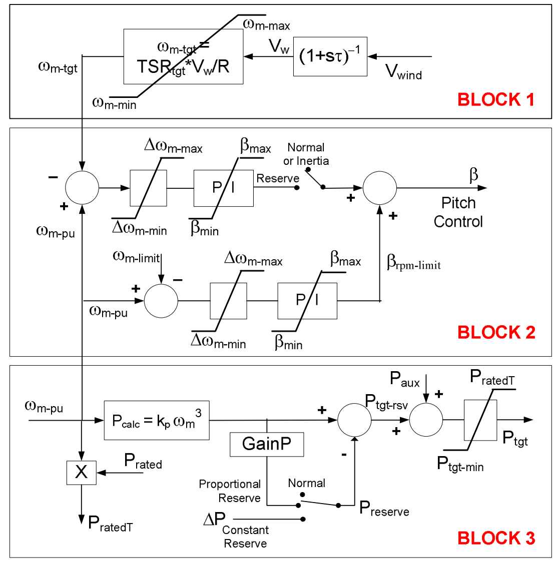


Fig. 4. Pitch controller and real power controller used to set reserve power for Type 3 and Type 4 WTGs

III. Dynamic Simulation

1) Constant Reserve Power Implementation

Type 3 and Type 4 turbines, including the controller described above, were developed in MATLAB/Simulink. Details of the model are presented in the complete version of the paper. Figure 5 shows a test wind speed time series, and the corresponding power output, for the cases with and without reserve requirement enabled. As shown in Figure 5, the requested reserve is 20% of the rated power output (constant ΔP).

2) Proportional Reserve Power Implementation

Figure 6 illustrates the result of proportional reserve power implementation. As shown in Figure 6, the requested reserve is 10% of the available aerodynamic power (proportional reserve). For both operations, the plots show that the reserve controller functions as desired.

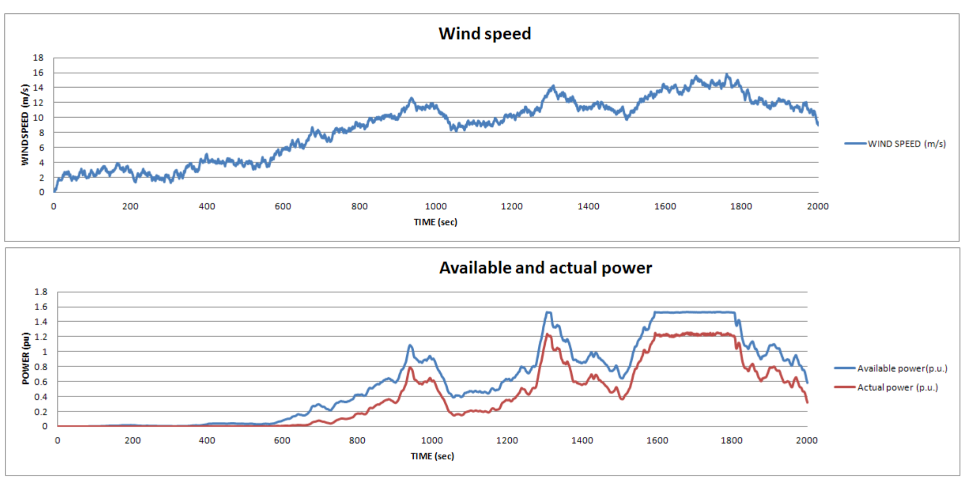


Fig. 5. Constant reserve power implementation ($\Delta P_{reserve} = 20\%$)

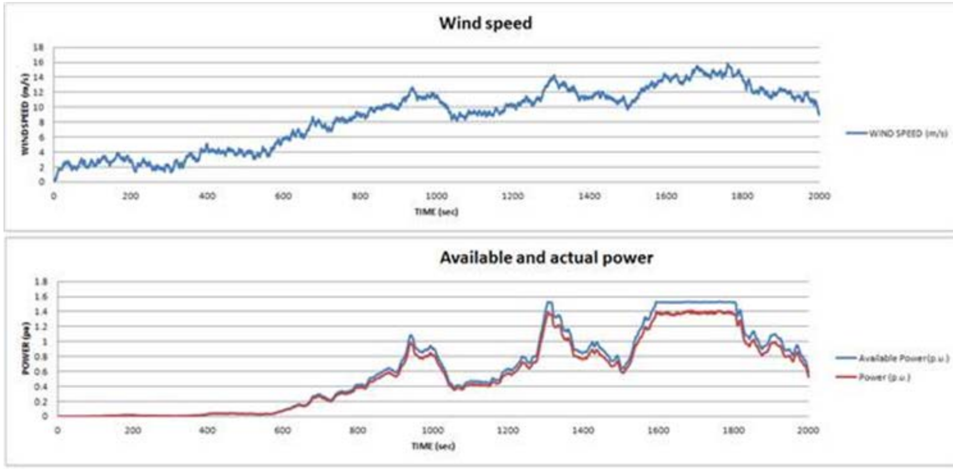


Fig. 6. Proportional reserve power implementation (reserve 10%)

3) *Inertial response capability*

The inertial response for variable speed WPP has been discussed earlier in reference [10]. This topic will not be presented in this paper. More detail discussion on this subject is not covered by this paper due to space limitation.

4) *Governor response capability*

To implement governor response capability, we will assume that the wind power plant is operated in the medium to rated wind speeds. A simple power system is constructed to simulate the power system behavior under sudden perturbation with a sudden load change. A comparison between system with and without governor response capability is compared.

With spinning reserve implemented in a WPP, non-symmetric droop characteristics similar to one shown in Figure 7 can be implemented in wind turbines.

As in the case of inertial response, the primary response parameters (dead bands, droops, reserve margin) can be tuned up for optimum system performance.

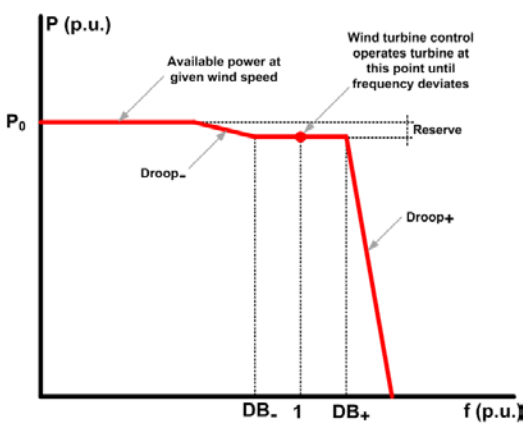


Fig. 7. Governor control implemented with a frequency droop on a wind power plant

The governor control will take the frequency of the grid as the input and the commanded additional power Po as the output. Note, that the WPP can respond to the system over-frequency by shedding the output power (droop+), and it can respond to the system under-frequency by deploying the reserve power (droop -). The P_{aux} shown in Block 3 in Figure 4 can be used with $P_{aux} = P_o$ (output of the governor control) to accomplish the governor control.

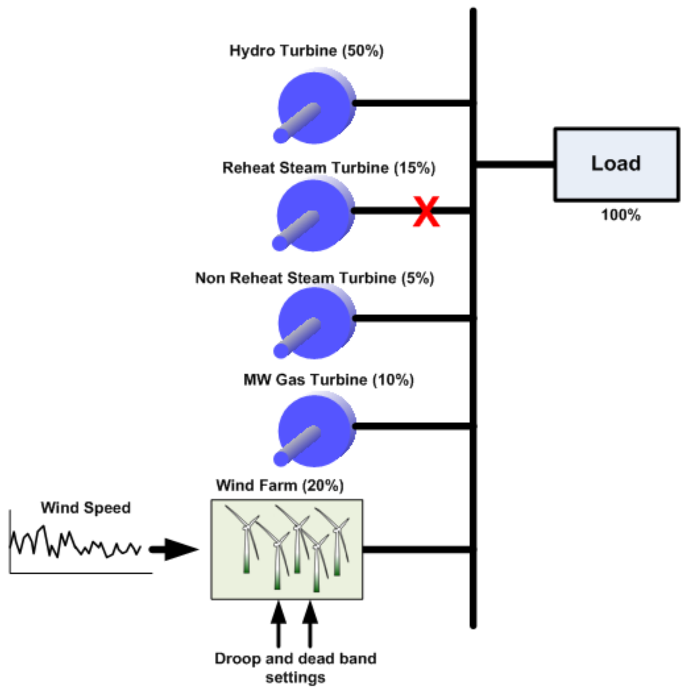


Fig. 8. Small power system network

A small power system network is assembled to simulate the system with governor control capability as shown in Figure 8. The balance of real power generation and the load is perturbed by disconnecting one of the generators. As the frequency of the power system drops.

An example in Figure 9, shows sensitivity to different individual wind turbine droop settings (5, 4, 3 and 2 %). In this particular example, the difference in frequency trajectories are not significant and not affecting neither nadir nor recovery times. However, this picture may be different at higher levels of the wind penetration.

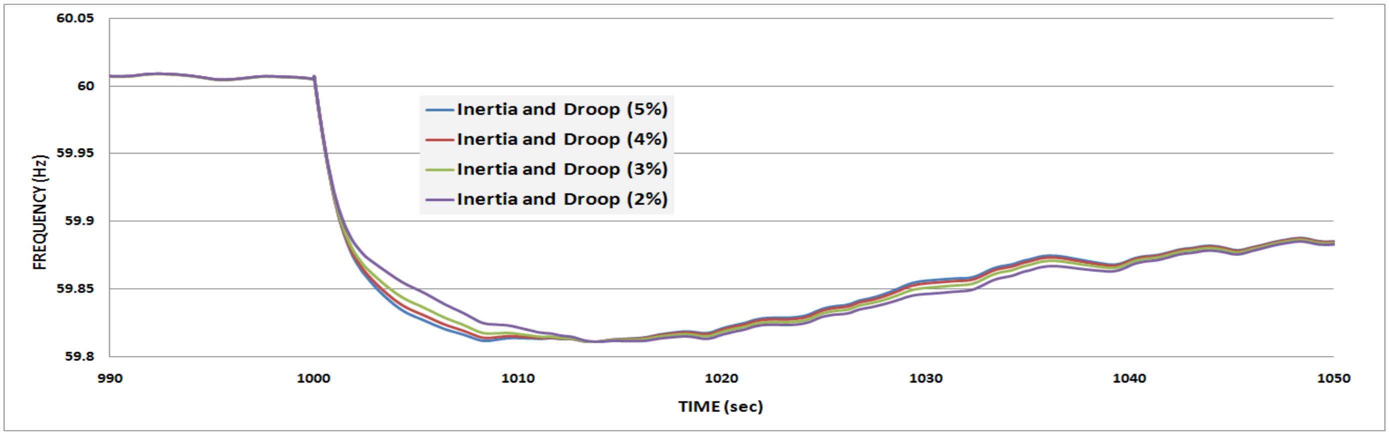


Fig. 91. Sensitivity to wind turbine droop characteristic

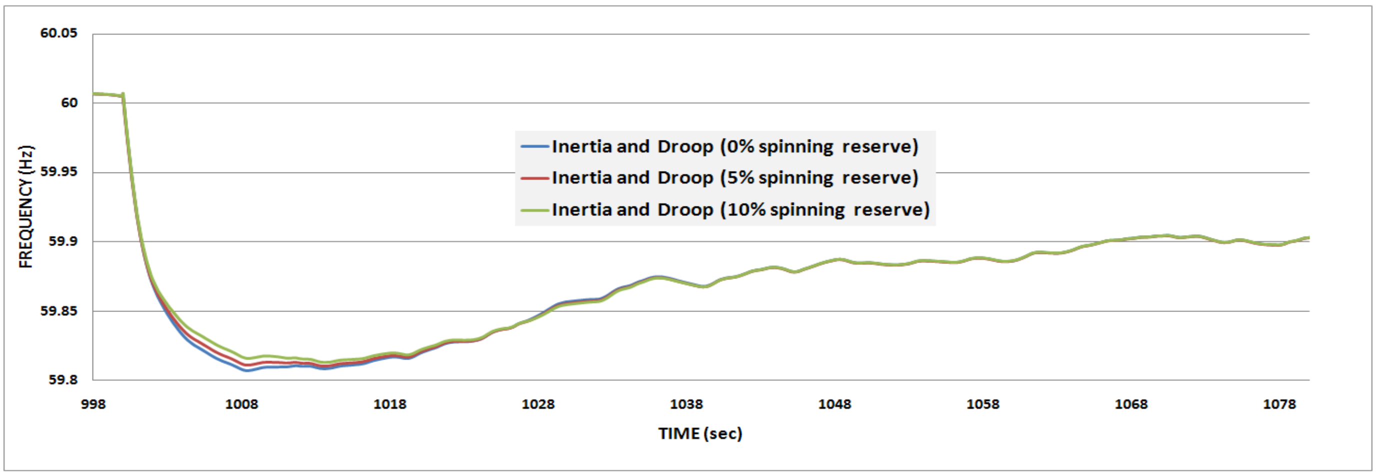


Fig. 10. Frequency response for different spinning reserve by wind power

The amount of spinning reserve available from wind turbines impacts the amount of power that wind turbine can inject into power system during the fault. The example in Figure 10 shows some improvements in minimum frequency for cases with no spinning reserve, 5% and 10% spinning reserves respectively. The higher spinning reserve capacity, the higher the frequency nadir and the sooner the frequency restoration to normal range.

The primary frequency control by wind turbines can be integrated into the rotor-side active power control loop for Type 3 WTG or directly to the full power converter for Type 4 WTG and demonstrate behavior similar to conventional synchronous generators.

IV. Conclusion

This paper is written to illustrate the capability of WPPs to provide auxiliary functions such as spinning reserve. In this paper, variable-speed WTGs (Type 3 and Type 4) are considered. The control method to implement the reserve holding capability is described in detail. A controller is developed that controls the pitch angle and the power converter simultaneously to allow individual WTGs to hold power in reserve. The reserved power may be delivered to the grid in the event of a frequency event. The unique feature of this controller is that the turbine always remains at the optimal TSR, with or without the reserve requirement enabled.

Acknowledgment

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V. BIOGRAPHIES

Mohit Singh (M'11) received his M.S. and Ph.D. in electrical engineering from the University of Texas at Austin in 2005 and 2011, respectively. His research thesis focused on dynamic modeling of WTGs.

Dr. Singh is a postdoctoral research engineer at the National Renewable Energy Laboratory in Golden, Colorado. His research interests include modeling and testing of various applications of WTGs and other renewable energy resources. He is member of IEEE and is involved in the activities of the IEEE PES.

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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 research interests are in the fields of electric machines, power electronics, and power systems, with an emphasis on renewable energy applications. He is a member of Eta Kappa Nu and Sigma X, and a fellow of the Institute of Electrical and Electronics Engineers (IEEE). He is involved in the activities of the IEEE Industry Application Society (IAS), Power Electronics Society, and Power and Energy Society (PES), and an editor of the IEEE Transactions on Energy Conversion.

Dr. Muljadi is a member of various committees of the IAS, as well as 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.

Erik Ela (M '05) received the B.S.E.E degree from Binghamton University and the M.S. degree in Power Systems at the Illinois Institute of Technology.

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