Proceedings of the
2005 IEEE Conference on Control Applications
Toronto, Canada, August 28-31, 2005

Nonlinear Control of Variable Speed Wind Turbines for Power Regulation

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Abstract— **A nonlinear controller has been designed for variable speed wind turbines electric power regulation. The efficiency and reliability of wind power is shown to be depending on the applied control strategy of the wind turbine. Up to now, classical regulation are implemented only. However, under sudden wind profile variations, the wind turbine performance decrease which may cause troubles in the electrical network. For the limitation of mechanical loads and rotational speed variations, and to avoid the wind turbine stall above rated wind speeds while controlling the output power, a cascade structure asymptotic output tracking based approach has been applied. Simulations and validation have been performed using the wind turbine modelling and using wind turbine simulator as well. The wind turbine is torque generator controlled. The required performance are met for both.**

I. INTRODUCTION

Advances in wind turbine technology [1] made necessary the design of more powerful control systems. This is in order to improve wind turbines behavior, namely to make them more profitable and more reliable.

Compared to fixed speed turbines, variable speed wind turbine features higher energy yields, lower component stress, and fewer grid connection power peaks. To be fully exploited, variable speed should be controlled in meaningful way. Wind energy conversion systems have strong nonlinear characteristics. The variable speed, fixed pitch wind turbine is not so easy to control because it is stable at below rated wind speeds but becomes unstable, as power output is limited by stalling the turbine, at above rated wind speeds [2]. A control system is thus needed to stabilize it over this region.

The major part of the existing research works concerning wind turbines control deals with the optimization of the extracted aerodynamic power in partial load area. For this purpose, classical controllers have been extensively used, particularly the PI regulator [3], [4]. Optimal control has been applied in the *LQ* [5], [6], and *LQG* form [7], [8].

Robust control of wind energy conversion systems (WECS) has been introduced in [9] and also used in [10] - [11].

One may also find, in the literature, variable pitch wind turbines using linear [5] and nonlinear controllers [12]. The power regulation, in this case, is realized while acting on the blades pitch in the full load area.

For fixed pitch variable speed wind turbines above rated area, one can see for example [13], [6] based on an intuitive approach of the problem.

This work has been carried out within the project €nergie launched by Supélec.

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Above rated wind speeds, when the turbine blades stall, aerodynamic damping causes the turbine to become unstable, a condition comparable to negative friction, which causes the rotor to accelerate instead of decelerating. An efficient control strategy is then necessary to continue the wind energy extraction above rated wind speeds without causing the stall of the wind turbine while limiting this extracted power in order to reduce the wind turbine stress.

In this paper, a nonlinear control strategy is proposed, for variable speed wind turbine (VSWT), producing energy limitation above rated wind speed. The designed control strategy is based on a cascade structure for which the internal loop is input controlled by the external loop which consists on tracking a given desired reference power.

This paper is organized as follows : Section II describes the wind turbine modelling. Section III is devoted to the elaboration of control strategy. A cascaded structure has been adopted in order to reach the required specifications : In section IV, simulation results show the performance of the proposed approach on the mathematical model and have been validated through a wind turbine simulator.

II. WIND TURBINE MODELLING

The power extraction of wind turbine is being known to be a function of three main parameters : the wind power available, the power curve of the machine and the ability of the machine to respond to wind fluctuations [14]. The global scheme of a variable speed is displayed in Fig. 1.

Roughly speaking, a fixed pitch variable speed wind turbine (FPVS), mainly consists (Fig. 2) of an aeroturbine, a gearbox and a generator.

The expression for aerodynamic power captured by the wind turbine is given by the nonlinear expression

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda) v^3 \qquad (1)$$

where

$$\lambda = \frac{\omega_r R}{v}$$

is the so-called tip speed ratio, namely the ratio between the linear blade tip speed and the wind speed v. R is the rotor radius.

For the reader convenience, table of the symbols description is given at the end of this paper.

So, any change in the rotor speed or the wind speed induces change in the tip-speed ratio, thus leading to the power coefficient $C_p(\lambda)$ variation and therefore to the generated power one. Using the relationship

$$P_a = \omega_r T_a \qquad (2)$$

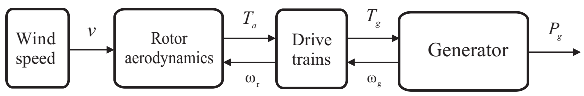


Fig. 1. Wind turbine scheme

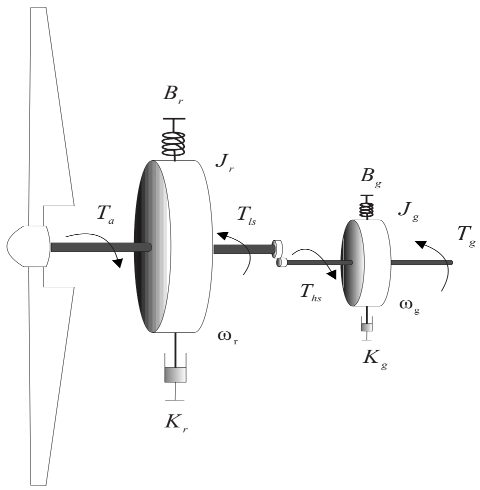


Fig. 2. Drive train dynamics

where the aerodynamic torque T_a expression is

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda) v^2 \quad (3)$$

$C_q(\lambda)$ is the torque coefficient depending nonlinearly upon the tip speed ratio.
From equations (1)-(3), it comes that

$$C_q(\lambda) = \frac{C_p(\lambda)}{\lambda}$$

The coefficients $C_p(\lambda)$ and $C_q(\lambda)$ are specific for each wind turbine, so for the one considered herein, Fig. 3 and Fig. 4 display $C_p(\lambda)$ and $C_q(\lambda)$ respectively. Driving by the aerodynamic torque T_a, the rotor of the wind turbine runs at the speed ω_r. The low speed shaft torque T_{ls} acts as a braking torque on the rotor. The generator is driven by the high speed shaft torque T_{hs} and braked by the generator electromagnetic torque T_g. Through the gearbox, the rotor speed is increased by the gearbox ratio n_g to obtain the generator speed ω_g while the low speed shaft torque is augmented.
The dynamics of the rotor together with the generator inertia are characterized by the first order differential equations

$$\begin{aligned} J_r\omega_r &= T_a - K_r\omega_r - B_r\theta_r - T_{ls} \\ J_g\omega_g &= T_{hs} - K_g\omega_g - B_r\theta_g - T_g \end{aligned} \quad (4)$$

taking into account the torsion effect through the term $B_r\theta_r$ and the friction one through $K_r\omega_r$.
The gearbox ratio is defined as

$$n_g = \frac{\omega_g}{\omega_r} = \frac{T_{ls}}{T_{hs}} \quad (5)$$

Upon using equations (5) and (4), one gets

$$J_t\omega_r = T_a - K_t\omega_r - B_t\theta_r - T_g \quad (6)$$

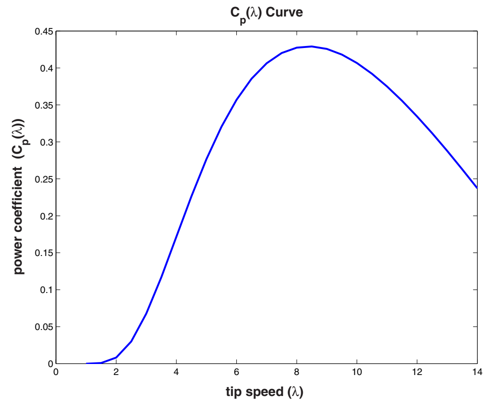


Fig. 3. Power coefficient curve

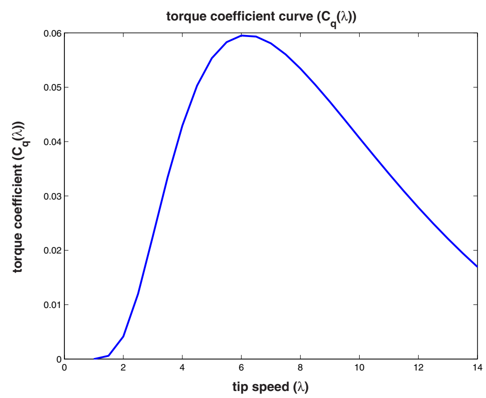


Fig. 4. Torque coefficient curve

where

$$\begin{aligned} J_t &= J_r + n_g^2 J_g \\ K_t &= K_r + n_g^2 K_g \\ B_t &= B_r + n_g^2 B_g \\ T_g &= n_g T_{em} \end{aligned}$$

Since the external stiffness B_t is very low, so it may be neglected, the turbine dynamics brought back to the low speed side is then simplified

$$J_t\omega_r = T_a - K_t\omega_r - T_g \quad (7)$$

III. CONTROL STRATEGY

A. Problem Formulation

The variable speed turbine can be driven using two ways : pitch control or fixed blades. In the case where one wants to forfeit the mechanical complexity due to pitch control, one may use variable speed only to regulate the power output from the wind. As the rated power is reached, the blades of the turbine are stalled by maintaining constant rotational speed or even braking the turbine, as wind speed increases. However, stall control introduces some other problems. A variable speed , stall regulated (with fixed pitch) wind turbine becomes unstable above nominal wind speed [15].
Under stationary condition, one can deal equally with the

aerodynamic power or with the generator power. However, in dynamic point of view, there is a substantial difference. In partial load, an increase in wind speed should be followed by the rotational speed one. If a sudden change of the turbine speed is requested, this is accomplished by lowering the generator torque. Hence, the generator power should be momentarily decreased in order to increase the aerodynamic power. However, the overall production of electrical energy is improved, since the captured energy is only temporarily stored as kinetic energy. Therefore, the *aerodynamic power* should be controlled below rated wind speed.

In full load, the *generator power* should mainly be kept constant. The power can theoretically be set to any desired value, since one controls the torque. If, for instance, the speed increases, then constant output power can be maintained by decreasing the torque. In practice, this is not possible, because the aerodynamic torque increases with rotor speed in stall. The process is locally unstable. Therefore, the rotor must be slowed down by the generator to prevent unsafe overspeed. Hypothetically, if the generator power is kept constant at the rated value, then the rotor speed finally stabilizes. Thus, if the output power should be lowered, then it must be first increased. This indicates that the transfer function from the generator torque to generator power is not only unstable, but it is also non-minimum phase. Dynamically, the power of the generator then exceeds the rated value. This can normally be accepted, because the generator power is limited by temperature, which is marginally affected by short power transients. However, large torque transients are serious for the transmission device. There is also a limit on the feasible generator torque. If the driving torque goes over this limit, the generator then losses synchronism. Hence, in case of emergencies, like overspeed or grid failure, the turbine must be mechanically or aerodynamically braked. There are, of course, other possibilities than tracking constant power, like, for instance, using constant speed or constant torque, but then the overall energy capture decreases [6].

B. Controller Design

In variable speed wind turbines, the generator is connected indirectly to the grid via a rectifier and inverter. When connecting the generator to the grid via the frequency converter, the generator rotational speed ω_g will be independent of the grid frequency.

The wind turbine is controlled through the adjustment of the generator torque. The choice of T_{em} as a control input is motivated by the fact that when controlling the firing angle of the converter, it is possible to control the electrical torque in the generator. Well known control strategies have been used and achieve a fast and decoupled responses of torque and flux like vector control [16], [17] and Direct Torque Control (DTC) [18]. The torque control using the frequency converter allows the wind turbine to run at variable speed resulting in the reduction of the drive train mechanical stress and electrical power fluctuations, and also the increase of power capture [3].

In this context, the dynamics are sufficiently fast that no distinction needs to be made between the actual and the demanded generator torque.

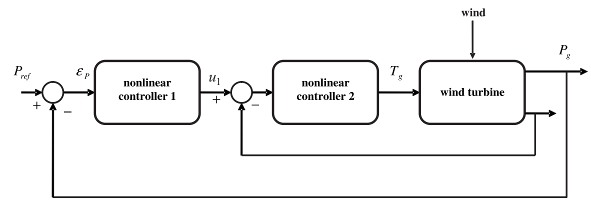


Fig. 5. nonlinear cascade controller scheme

1) Rotor speed (internal) loop control: In order to slow down the rotor speed using the generator torque, a static state feedback linearization control technic with asymptotic rotor speed reference tracking is used.

by choosing a first order dynamic to the rotor speed tracking error ε_ω

$$\dot{\varepsilon}_\omega + a_0\varepsilon_\omega = 0 \tag{8}$$

with

$$\varepsilon_\omega = \omega_{ref} - \omega_r$$

and using (7) and (8), it comes out to the generator torque

$$T_g = T_a - K_t\omega_r - a_0 J_t\varepsilon_\omega - J_t\dot{\omega}_{ref} \tag{9}$$

by setting

$$w = a_0\omega_{ref} + \dot{\omega}_{ref} \tag{10}$$

equation 9 may be re-written as

$$T_g = T_a - (K_t - a_0 J_t)\omega_r - J_t w \tag{11}$$

w is the new input of the internal loop

by substituting (11) in the open loop dynamics (7), the internal loop, in closed form equation, is then

$$\dot{\omega}_r = -a_0\omega_r + w \tag{12}$$

2) Generator power (external) loop control: Neglecting losses, the generated power P_g is

$$P_g = T_g \cdot \omega_r \tag{13}$$

Similarly, let us choose a first order dynamics for the power tracking error ε_p, i.e. satisfying the differential equation

$$\dot{\varepsilon}_p + b_0\varepsilon_p = 0 \tag{14}$$

where

$$\varepsilon_p = P_{ref} - P_g \tag{15}$$

From the time derivative of (15), and using (14), one obtains

$$\dot{P}_{ref} - \dot{T}_g\omega_r - T_g\dot{\omega}_r + b_o\varepsilon_p = 0 \tag{16}$$

From (11), one deduces the time derivative of T_g that is substituted in (16), so then

$$\begin{aligned}\dot{P}_{ref} &- (\dot{T}_a - (K_t - a_0 J_t)\dot{\omega}_r - J_t\dot{w})\omega_r \\ &- (T_a - (K_t - a_0 J_t)\omega_r - J_t w)\dot{\omega}_r + b_0\varepsilon_p = 0\end{aligned} \tag{17}$$

Fig. 6. NREL wind turbine

TABLE I
WIND TURBINE CHARACTERISTICS

Rotor diameter	43.3 m
gearbox ratio	43.165
Hub height	36.6 m
Generator system electrical power	650 KW
Maximum rotor torque	162 KN.m

replacing $\dot{\omega}_r$ from (12) in (17) leads to the following equation for w

$$\begin{aligned}\dot{w} &= \frac{1}{J_t\omega_r}\left[-\dot{P}_{ref} + \left[\dot{T}_a - (K_t - a_0 J_t)(-a_0\omega_r + w)\right]\omega_r\right.\\ &\quad + \left[T_a - (K_t - a_0 J_t)\omega_r - J_t w\right](-a_0\omega_r + w)\\ &\quad \left.-b_0\left[P_{ref} - \omega_r(T_a - (K_t - a_0 J_t)\omega_r - J_t w)\right]\right] \qquad (18)\end{aligned}$$

For a constant power reference, equation (18) becomes

$$\begin{aligned}\dot{w} &= \frac{1}{J_t\omega_r}\left[\left[\dot{T}_a - (K_t - a_0 J_t)(-a_0\omega_r + w)\right]\omega_r\right.\\ &\quad + \left[T_a - (K_t - a_0 J_t)\omega_r - J_t w\right](-a_0\omega_r + w)\\ &\quad \left.-b_0\left[P_{ref} - \omega_r(T_a - (K_t - a_0 J_t)\omega_r - J_t w)\right]\right] \qquad (19)\end{aligned}$$

In order to reduce power converter currents fluctuations, a low pass filter may be added to the control torque T_g.
The corresponding control scheme is shown in Fig. 5.

IV. VALIDATION RESULTS

As already mentioned, the wind turbine considered in this study is variable speed one. It consists of two blades rotor coupled with a gearbox. The high speed shaft drives an induction generator connected to the grid via a power electronics device.
The numerical simulations have been performed using the wind turbine shown in Fig. 6 whose characteristics are given in TABLE I. The validation tests have been performed using the wind turbine simulator.[1].
The variable speed option interest comes out from the fact that it reduces stress, due to the transient loads in the main shaft during the full load operation of the wind turbine and optimizes energy extraction over all wind speeds below rated. An additional benefit is that the variable speed turbines rotate not so much during their life time ; i.e. they can be brought to a lower rotational speed in the low wind speed region.
The applied input wind speed profile of 20 m s^{-1} mean value is shown in Fig. 7

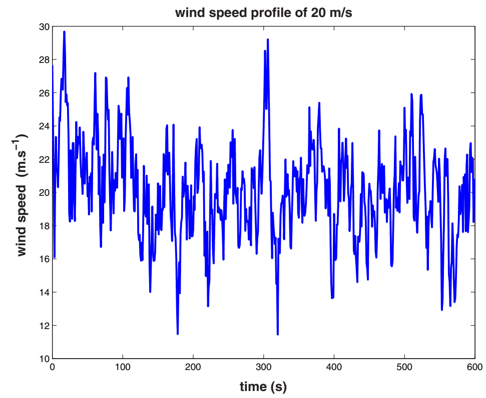


Fig. 7. Wind speed profile of 20 m s^{-1} mean value

In the aim of controlling the wind turbine power with avoiding its stalling, the proposed nonlinear controller is shown to be quite efficient.

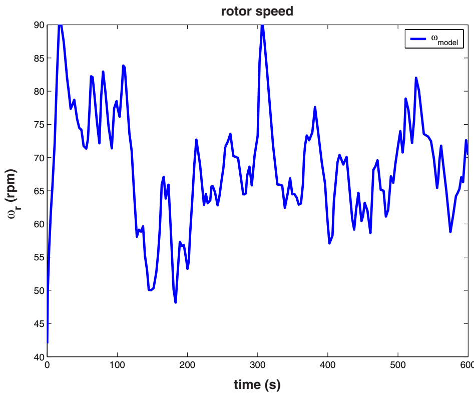
A. Using the model

First, the mathematical model is used with the proposed controller. One may observe (Fig.10(a)) a satisfactory behavior of the controlled system. P_g converges very fast to the reference value P_{ref}. The generator torque T_g is depicted in Fig. 9(a). Its value goes up to 118 KN.m, while the maximum one is set to be 162 KN.m. The generator torque remains smooth, and induces low frequency variations in the generator currents. This allows a better preservation of the electrical wind turbine devices. Moreover, one may observe in Fig. 9(a) a low moment loads together with the satisfactory power tracking performance.

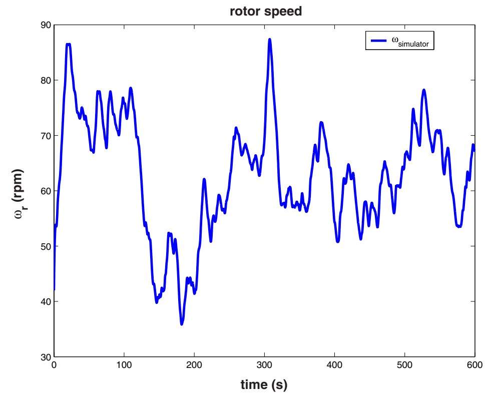
B. Validation by using the wind turbine simulator

The validation of the controller is carried out upon the wind turbine simulator. The performance obtained are shown to be as expected. The high speed shaft torsional moment with the simulator is greater than the one obtained with the mathematical model (Fig. 9(b)), nevertheless, it remains below the maximum acceptable value. P_g converges also fast to the reference value P_{ref} (Fig. 10(b)).
As shown in Fig 8(b), the rotor speed variations are smooth, so the oscillations will be reduced in the drive train components.
The fast reference tracking response of the controlled system is due to the cascade structure on the one hand, and on the other hand to the instantaneous torque reference tracking, this is realizable, as mentioned in subsection III-B by the use of efficient torque control technics.

[1]developed by NREL (National Renewable Energy Laboratory), Golden, CO.

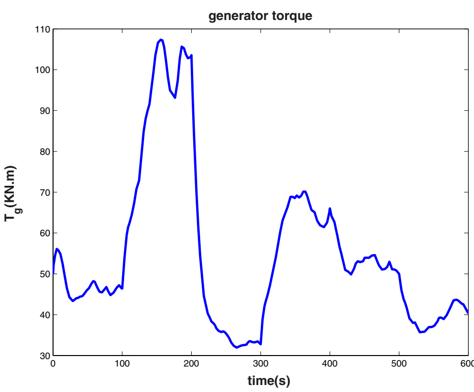


(a) Using the model

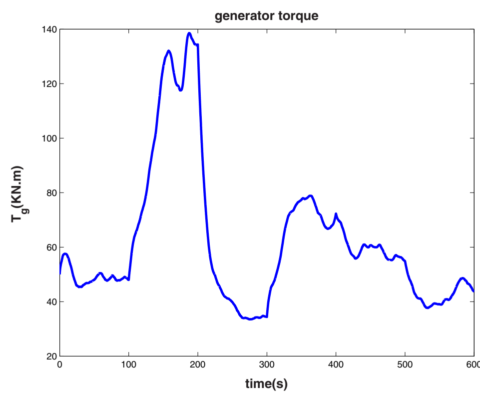


(b) Validation using the simulator

Fig. 8. Rotor speed using the nonlinear cascade control law

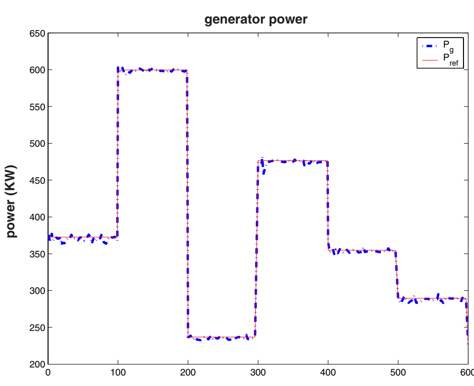


(a) Using the model

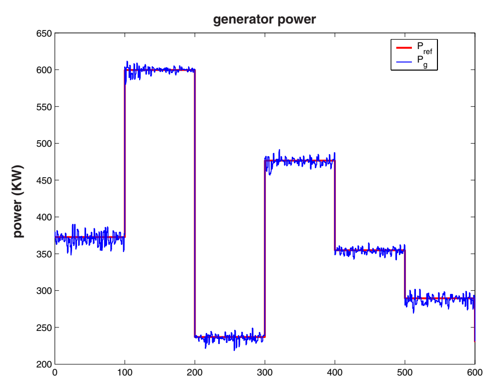


(b) Validation using the simulator

Fig. 9. Generator torque using the nonlinear cascade control law



(a) Using the model



(b) Validation using the simulator

Fig. 10. Produced power with the nonlinear cascade control law

V. CONCLUSION

Nonlinear cascade controllers have been developed for wind turbine power regulation. It allows to track a desired generator power without causing the stall of the wind turbine in full load operation mode. the first nonlinear controller is quite for the internal loop (speed loop), and the second nonlinear controller guarantee the regulation of the external loop (power loop). Moreover, the control loads stand acceptable even when relatively high wind speeds occurs. The control strategy developed has been validated with an aeroelastic wind turbine simulator and has led to satisfactory results.

NOTATION AND SYMBOLS

v	wind speed $(\mathrm{m}\cdot\mathrm{s}^{-1})$
ρ	air density $(\mathrm{kg}\cdot\mathrm{m}^{-3})$
R	rotor radius (m)
P_a	aerodynamic power (W)
T_a	aerodynamic torque $(\mathrm{N}\cdot\mathrm{m})$
λ	tip speed ratio
$C_p(\lambda)$	power coefficient
$C_q(\lambda)$	torque coefficient
ω_r	rotor speed $(\mathrm{rad}\cdot\mathrm{s}^{-1})$
ω_g	generator speed $(\mathrm{rad}\cdot\mathrm{s}^{-1})$
T_{em}	generator (electromagnetic) torque $(\mathrm{N}\cdot\mathrm{m})$
T_g	generator torque in the rotor side $(\mathrm{N}\cdot\mathrm{m})$
T_{ls}	low speed shaft $(\mathrm{N}\cdot\mathrm{m})$
T_{hs}	high speed shaft $(\mathrm{N}\cdot\mathrm{m})$
J_r	rotor inertia $(\mathrm{kg}\cdot\mathrm{m}^2)$
J_g	generator inertia $(\mathrm{kg}\cdot\mathrm{m}^2)$
J_t	turbine total inertia $(\mathrm{kg}\cdot\mathrm{m}^2)$
K_r	rotor external damping $(\mathrm{Nm}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}^{-1})$
K_g	generator external damping $(\mathrm{Nm}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}^{-1})$
K_t	turbine total external damping $(\mathrm{Nm}\cdot\mathrm{rad}^{-1}\cdot\mathrm{s}^{-1})$
B_r	rotor external stiffness $(\mathrm{Nm}\cdot\mathrm{rad}^{-1})$
B_g	generator external stiffness $(\mathrm{Nm}\cdot\mathrm{rad}^{-1})$
B_t	turbine total external stiffness $(\mathrm{Nm}\cdot\mathrm{rad}^{-1})$

ACKNOWLEDGMENT

The authors would like to thank M. Hand and E. Muljadi from NREL for their great help in providing the simulator, thus giving us the opportunity to validate our theoretical results.

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