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Development and Validation of WECC Variable Speed Wind Turbine Dynamic Models for Grid Integration Studies

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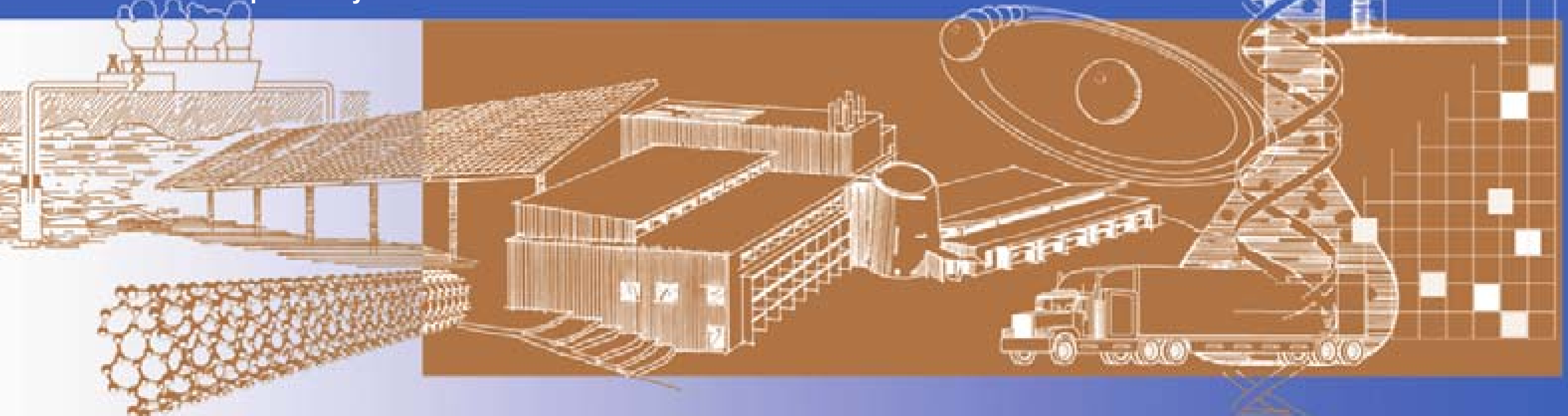

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DEVELOPMENT AND VALIDATION OF WECC VARIABLE SPEED WIND TURBINE DYNAMIC MODELS FOR GRID INTEGRATION STUDIES

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Abstract-- With high wind penetration levels being planned in North America, the need for grid operators to quickly assess the impacts of wind generation on system stability has become critical. In the planning phase, this assessment is normally done with positive sequence phasor time-domain analysis tools such PSS/E or PSLF, which allow for simulation of the dynamic response of a power system to major disturbances (e.g., short circuits). The lack of suitable dynamic models for the wide variety of wind turbines available in the marketplace has been an obstacle in performing accurate analyses of this type, though efforts led by the Western Electricity Coordinating Council (WECC) to develop industry-standard wind turbine models are addressing this issue. Still, the level of model complexity that is appropriate and necessary for these studies, particularly with regard to the wind turbine rotor and electromechanical drivetrain dynamics, is a subject of debate.

This paper describes reduced-order, simplified wind turbine models developed under the leadership of the WECC Modeling & Validation Working Group. These models were developed for analyzing the stability impact of large arrays of wind turbines with a single point of network interconnection. Dynamic simulations have been performed with these models, and comparisons made with results derived from higher-order models used in manufacturer-specific representations of aero conversion and drivetrain dynamics. The paper concludes with an assessment of whether the simplified models impact the accuracy of the electrical model outputs when viewed from the point of interconnection.

I. INTRODUCTION

The WECC Modeling & Validation Working Group recently initiated an effort to develop and validate a series of generic dynamic models for wind turbine generators (WTG). The objectives of this effort are to 1) allow performance of transient stability studies in early stages of interconnection process when WTG manufacturer/model may be undetermined, 2) reduce WTG manufacturer confidentiality concerns with respect to proprietary aspects of dynamic models, and 3) improve the quality, portability (between simulation platforms), and usability of models, consistent with the level of accuracy expected in an initial system impact evaluation.

Generic models are being developed for four major WTG topologies. The first topology, referred to as a Type 1 WTG, is shown in Figure 1. This machine is pitch-regulated, and drives a squirrel cage induction generator which is directly coupled to the grid.

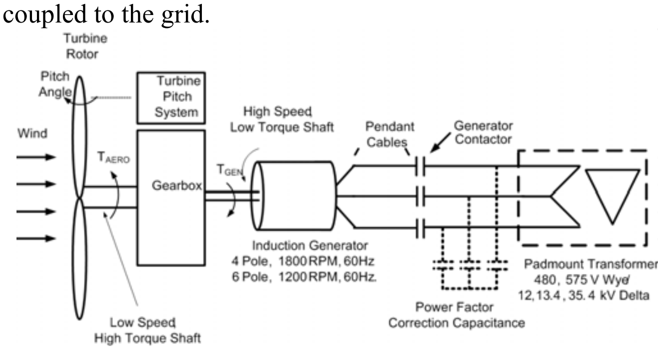

Fig. 1. Conceptual block diagram of WECC Type 1 WTG

The Type 2 WTG shown in Figure 2 is a variation on the Type 1, operating with variable slip. It utilizes a wound rotor induction generator whose rotor winding is brought out via slip rings and brushes. An external rotor resistance is electronically modulated to effect dynamic changes in the machine's torque-speed characteristics.

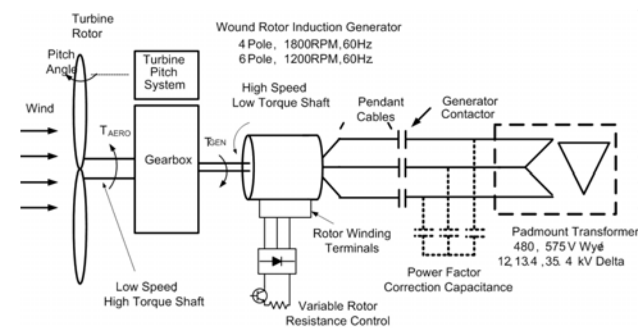

Fig. 2. Conceptual block diagram of WECC Type 2 WTG

The doubly fed induction generator (DFIG), or partial conversion, topology of Figure 3 is designated as WECC Type 3. The turbine is pitch-regulated and features a wound rotor induction generator with an AC/DC/AC power converter connected between the rotor terminals and grid. The generator stator winding is directly coupled to the grid. The power converter in the rotor circuit allows for independent control of generator torque and flux, providing fast active and reactive power control over a wide range of generator speeds.

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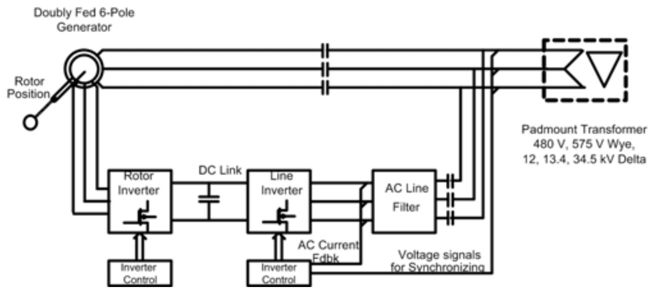

Fig. 3. Conceptual block diagram of WECC Type 3 WTG

Finally, the full conversion topology of Figure 4 is designated as WECC Type 4. The turbine is pitch-regulated and features an AC/DC/AC power converter through which the entire power of the generator is processed. The generator may be either induction or synchronous type. As with the Type 3 WTG, the power converter allows for independent control of quadrature and direct axis output currents at the grid interface, providing fast active and reactive power control over a wide range of generator speeds.

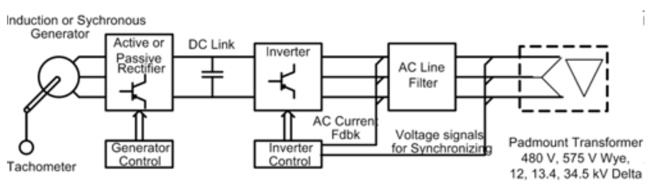

Fig. 4. Conceptual block diagram of WECC Type 4 WTG

In this paper, specific subsystem model development and validation exercises for two particular WTG types are described. Section II details the scope of the investigation. In section III, existing models are examined and validated against higher order models. Finally, conclusions are summarized in Section IV.

II. SCOPE OF INVESTIGATION

The objective of this study was to determine if simplified and generic aerodynamic and mechanical drive train models could be applied to a range a commercially available Type 3 and Type 4 WTGs. These topologies have the highest priority to the WECC TSO membership based on the present state of interconnection queues. Due to the fast dynamics of the power electronics, it is relatively straightforward to generalize the generator/converter models in these machine types. However, in the currently available manufacturer-specific models, the WTG aerodynamic and mechanical drive train representations are quite diverse.

The applicability of the models is limited to positive sequence transient stability studies related to normally cleared transmission system faults. These faults have durations of 150 to 200 ms, with stable events recovering to new steady states in 20 to 30 seconds. Constant wind speed during the transient is assumed.

It is recognized that generalization and simplification of the representation of the WTG dynamics has a cost with respect to accuracy. However, it is WECC's objective that the level of complexity for the generic models be appropriate to the level of accuracy needed in an initial System Impact Study. Sensitivity analysis with manufacturer-specific models can follow later in the interconnection process, if necessary.

III. MODEL DEVELOPMENT AND VALIDATION

A. Generic WTG Aerodynamic Model

The primary motivations for developing generic aerodynamic models are that: a) WTG airfoil characteristics are manufacturer-specific and proprietary, and b) the coefficients of aero power and torque are highly non-linear functions of pitch angle and rotor tip speed ratio. Current practices on modeling WTG aerodynamics for transient stability studies generally involve the use of $C_p(\lambda,\theta)$ curves such as those shown in Figure 5. The coefficient of power, C_p, on the vertical axis represents the fraction of mechanical power that may be extracted from the available power in the free stream wind velocity by the WTG rotor. The horizontal axis is the rotor tip speed ratio, λ, the ratio of the speed of the tip of the rotor to the wind speed. As the pitch angle, θ, increases, the fraction of power transferred from the wind to the rotor decreases. For initial conditions with wind speeds producing less than rated power, θ will be close to zero degrees, and the turbine operates at a constant tip speed corresponding to peak C_p. Above rated wind speed, θ is increased to shed mechanical power.

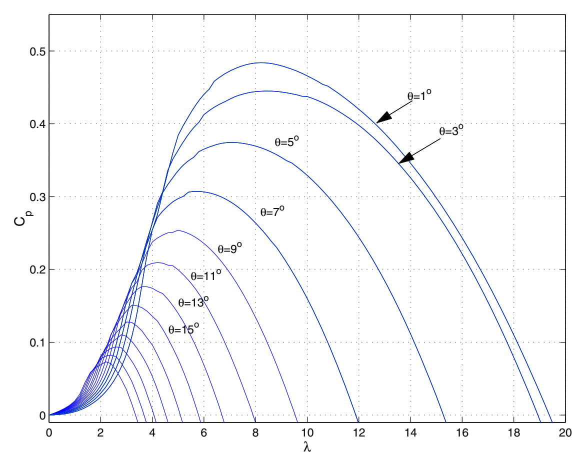

Fig. 5. Typical Cp curves for variable-speed, variable-pitch WTG

Under current industry practices, these manufacturer-specific C_p curves are typically fitted to high-order polynomial approximations which require dozens of coefficients to characterize due to their extreme non-linearity. This modeling process is overly burdensome to the transmission planner who is unfamiliar with wind turbine technology and accustomed to simulating traditional turbine-generators. Thus, it is desirable to find a replacement for these $C_p(\lambda,\theta)$ curves in the form of a traditional (linear) turbine-governor model.

MW-class WTG have rotor inertia constants on the order of several seconds. Thus, the rotor speed change, and hence $\Delta\lambda$, is relatively small for the disturbances of interest in a typical transient stability study. This suggest a possibility of linearization of the power coefficient around initial operating points. This approach has been shown to be practical with one manufacturer's C_p curves in a previous paper [1].

In this study, the power coefficients for rotors from three commercially available variable speed turbines and one paper design were analyzed by taking the partial derivatives of P_{mech} with respect to θ_{pitch} and ω_{rotor}. The relationship between $dP_{mech}/d\theta_{pitch}$ and θ_{pitch} for each rotor is shown in Figure 6. The resulting approximately linear relationship of $dP_{mech}/d\theta_{pitch}$ to θ_{pitch} for each rotor is consistent with that of Reference 1.

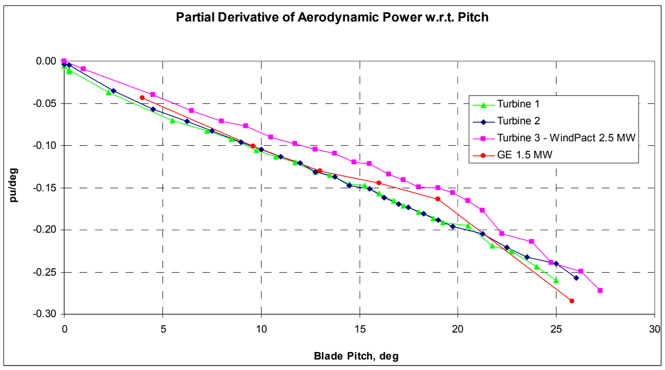

Fig. 6. $dP_{mech}/d\theta_{pitch}$ as a function of θ_{pitch} for example Type 3 and 4 WTGs

Next, the partial derivatives of P_{mech} with respect to ω_{rotor} were taken. The relationships between $dP_{mech}/d\,\omega_{rotor}$ and θ_{pitch} for three of the rotors are shown in Figure 7. Over most of the pitch range, small changes in ω_{rotor} result in even smaller changes in P_{mech}.

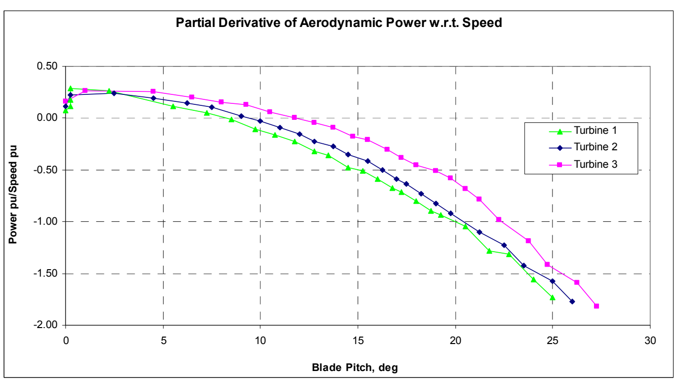

Fig. 7. $dP_{mech}/d\omega_{rotor}$ as a function of θ_{pitch} for example Type 3 and 4 WTGs

Finally, a MATLAB® simulation of a grid fault using a two-mass drive train model and complete pitch system model for one of the WTGs was performed. The change in mechanical power applied to the low speed shaft of the drive train with respect to the initial power was the sum of the partial derivatives with respect to pitch angle and rotor speed derived in Figures 6 and 7. Time domain plots of mechanical power and rotor speed for this disturbance are shown in Figures 8 and 9. In each plot, two cases are considered: 1) $dP_{mech}/d\omega_{rotor}$ corresponding to Figure 7, and 2) $dP_{mech}/d\omega_{rotor} = 0$. It can be seen that very little accuracy is sacrificed by ignoring the $dP_{mech}/d\omega_{rotor}$ term. This may be attributed to the small change in tip speed that occurs during the disturbance due to the long inertia constant (several seconds) of the WTG rotor.

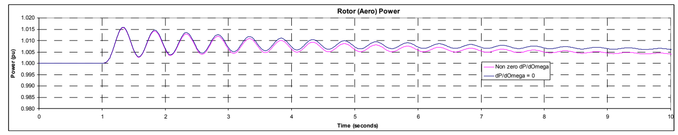

Fig. 8. Time response of P_{mech} with and without $dP_{mech}/d\omega_{rotor}$ term

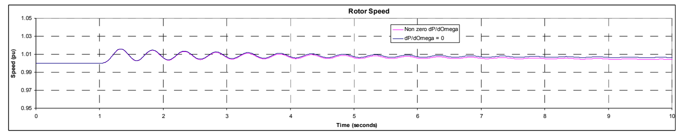

Fig. 9. Time response of ω_{rotor} with and without $dP_{mech}/d\omega_{rotor}$ term

B. Generic WTG Drivetrain Model

The motivations for the development of generic WTG drivetrain models are similar to those for the generic aerodynamic models. A wide variance exists in the level of detail provided by individual WTG manufacturers (e.g., rigid-mass versus multi-mass representations) in current models. The fast torque response of the power electronics in Type 3 and Type 4 machines allows for damping of various natural frequencies present in the drivetrain to prevent WTG damage, but these damping algorithms are highly manufacturer-specific and proprietary. None of this bodes well for the transmission planner unfamiliar with wind turbine technology.

One mode present in all MW-class WTGs is the torsional mode of the low speed shaft connecting the rotor to the gearbox (or to the generator in a direct-drive machine). The two-mass representation of the drivetrain shown in Figure 10 captures these dynamics. Mechanical torque T_{mech} is applied to the rotor inertia to produce rotor acceleration. Likewise, electrical torque T_{elec} is applied to the generator inertia to resist generator acceleration. The resulting difference in rotor and generator speed causes wind-up of the mainshaft in proportion to torsion coefficient K. The natural frequency is a function of this torsion coefficient and the rotor and generator inertias.

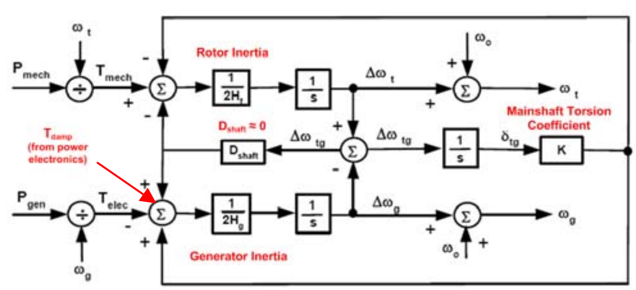

Fig. 10. Two-mass, compliant-shaft drivetrain representation

Some natural damping (D_{shaft}) acts to resist this speed difference, but design of an efficient drivetrain causes this damping to be negligible in MW-class variable speed WTGs. Instead, this mode (and possibly others) are damped via a component of torque (T_{damp}) produced by the power electronics. It is desirable to find a way to replace the manufacturer-specific damping algorithm with a generic damping function, or to eliminate it altogether by replacement of the multi-mass model with a single-mass model.

To determine the feasibility of generalizing the damping of the mainshaft mode, time-domain simulations of the response of a commercially available Type 4 WTG to a grid fault were performed. The WTG model included a two-mass representation of the drivetrain per Figure 10, as well as the manufacturer's actual algorithm for generating the damping torque T_{damp}. Time domain plots of rotor speed, generator speed, terminal voltage and electrical power for three cases are shown in Figure 11. In the top plot, there is no passive damping (i.e., $D_{shaft} = 0$), and the active damping term T_{damp} is driven to zero, as well. It can be seen that mainshaft mode continues ringing even 10 seconds after the fault has been cleared. In the center plot, D_{shaft} remains zero, but the manufacturer's damping algorithm is enabled, resulting in the mainshaft mode being damped within about four cycles of the natural frequency. Finally, in the lower plot, active damping has been disabled, and D_{shaft} is increased from zero to 0.5 pu. While far from exact, it can be seen an approximate response of manufacturer-specific active damping may be obtained through proper selection of a passive damping coefficient.

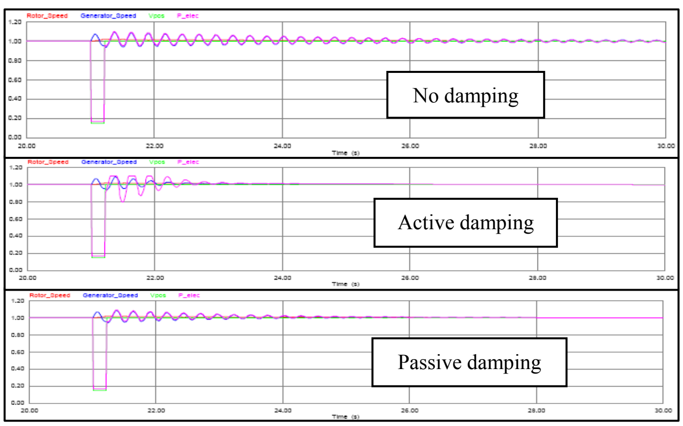

Fig. 11. Time domain response of two-mass, compliant-shaft drivetrain with three different mainshaft mode damping models

A further investigation undertaken as part of this study was to determine the diversity impact on mainshaft mode power oscillations when using an equivalent model of a plant consisting of many Type 3 or Type 4 WTGs and a single point of interconnection with the transmission network. It is generally accepted that power transients occurring at the individual WTG output terminals due to wind turbulence and tower shadow effects are effectively statistically filtered in a plant with a large number of spatially distributed WTGs [2]. Mainshaft wind-up due to these effects can be assumed to have poor correlation from WTG to WTG, thus the equivalent model of the plant approximates a single mass under these pseudo steady-state conditions.

To determine whether diversity of mainshaft wind-up due to these pseudo steady-state effects impacts the response of the plant at the point of interconnection for transmission system faults, a plant consisting of 12 individual WTGs was modeled using the WTG manufacturer's active damping algorithm. Rather than assuming constant wind speed, which would result in no mainshaft wind-up as an initial condition on each WTG, a series of sinusoidal wind speed disturbances of varying magnitude and frequency was superimposed on a 1.0 pu base (DC) wind speed. For each wind speed disturbance, power at the point of interconnection was monitored for two different cases: 1) with the same wind speed disturbance phase angle at each of the 12 WTGs, and 2) with the wind speed disturbance phase angle randomly distributed between zero and 360 degrees amongst the 12 machines.

Typical results are shown in Figures 12 and 13. In this case, the wind speed disturbance has a frequency of one hertz and a magnitude of 0.2 pu. This magnitude corresponds to a turbulence intensity of 0.14, classified as a "medium" level of turbulence for a WTG with a rated wind speed of 15 m/s according to IEC 61400-1.

In Figure 12, the upper plot shows generator speed, rotor speed and power output for one WTG. The lower plot shows the collective power output of all 12 machines. The phase angle of the wind speed disturbance is the same at all WTGs, so the one hertz power disturbance is reflected directly to the point of interconnection. Thus, the initial condition on mainshaft wind-up is identical on all 12 WTGs.

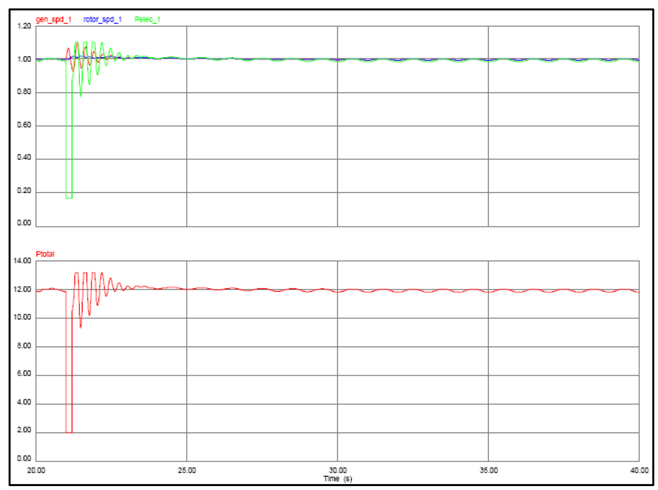

Fig. 12. Single and multiple WTG power output, same mainshaft wind-up

In Figure 13, the phase angle of the wind speed disturbance is randomly distributed amongst WTGs, so the one hertz power disturbance is nicely filtered from the plant output, both before and after the grid disturbance. In this case, however, the mainshaft wind-up from WTG to WTG has poor correlation. Despite this, there is practically no statistical filtering of the power oscillations associated with the mainshaft mode frequency (~ 4 hertz in this case). From these results, it may be concluded that the mainshaft windup variations associated with typical wind turbulence levels are insignificant with respect to the change in windup associated with grid fault. Thus, the diversity effect is negligible, and a two-mass model is necessary if the mainshaft mode is of interest in the particular transmission system under study.

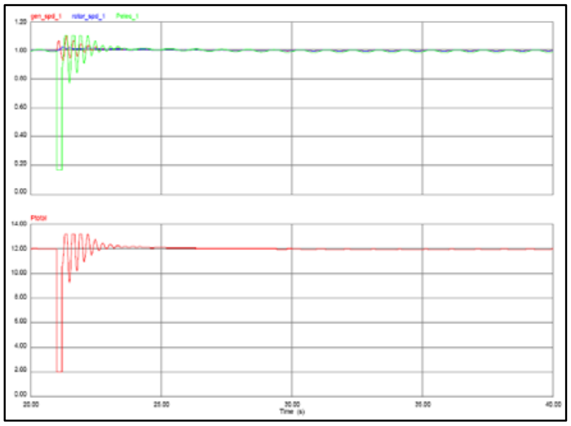

Fig. 13. Single and multiple WTG power output, random mainshaft wind-up

IV. CONCLUSIONS

A generic simplified aerodynamic model for WECC Type 3 and Type 4 WTGs, with sufficient accuracy for initial transient stability analysis, has been developed. The model has been validated against a MATLAB® state-space simulation. In a future task, WECC will investigate the applicability of these results to Types 1 and 2 WTGs.

A passive damping term for the two-mass drive train model has been verified to reasonably approximate the response of manufacturer-specific mainshaft mode damping controls in Types 3 and 4 WTGs.

The diversity effect of mainshaft windup has been demonstrated to be an insufficient filtering mechanism of the mainshaft mode in Types 3 and 4 WTGs. A two-mass representation (rather than single rigid mass) is necessary if modes in the 2-5 Hz range typical for MW-class WTGs are relevant to the system impact being evaluated in the simulation.

These conclusions are being incorporated in the documentation being produced by the WECC Modeling and Validation Working Group for the generic models of these variable speed WTGs [3, 4].

V. REFERENCES

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