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Published in:
Proceedings of The European Wind Energy Conference and Exhibition 2012

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Barahona Garzon, B., Hansen, A. D., Cutululis, N. A., & Sørensen, P. E. (2012). Inertial response from wind turbines: the impact on structural loads. In *Proceedings of The European Wind Energy Conference and Exhibition 2012* (Vol. 3, pp. 1485-1492). European Wind Energy Association (EWEA).

Inertial response from wind turbines: the impact on structural loads

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Abstract

This works evaluates the impact on structural loads of DFIG wind turbines providing inertial response while operating at rated power. The approach is to use an integrated simulation environment to model the most important electrical, structural, and control dynamics. Estimation of the impact is done in terms of 1-Hz equivalent loads, and maximum-minimum loads. It is observed that some structural loads are significantly affected. Therefore the trade off between the amount of inertial response and the cost of loads imposed should be assess from an statistical perspective.

Introduction

Inertial response from wind turbines can contribute to maintain short-term stability of the power system. In power systems with large amount of power produce by wind power plants, such feature will be relevant. Since the work in [1] there are a number of proposed control strategies in the literature. Nowadays many manufacturers already offer wind turbines with the capability of providing inertial response [2,3]. However, grid codes to rule this requirement are not yet in place. Furthermore, practical implementation of inertial response in variable speed wind turbines may be impose considerable loading on wind turbine components. This works evaluates the impact on structural loads of DFIG wind turbines providing inertial response. The approach is to use an integrated simulation environment. Namely, the objectives of this work are

- to estimate the impact on wind turbine structural loads providing inertial response,
- to compare the response of the power system with, and without inertial response from wind turbines and
- to demonstrate the capabilities of an integrated simulation approach.

The most important dynamics of power system, electrical machine, control, structure, and aerodynamics are modeled in an integrated simulation environment. The software tools integrated in this environment are (1) aeroelastic software (HAWC2) and (2) Matlab/Simulink. Technical details of the interfacing of these software can be found in other publications of the authors.

The following section, describes the integrated analysis model that consists of a power system model for frequency control and a wind power plant model as indicated in Figure 1. The wind power plant is modeled by the aggregated response of a wind turbine model. The power system, wind turbine controls, wind turbine generator and wind turbine aggregation are modeled in Matlab/Simulink while the wind turbine structure and aerodynamics are modeled in HAWC2. The Results section describes the numerical simulation results, such as the response of the power system frequency, blade angle and generator torque, as well as some of the structural loads that are significantly affected. A table of normalized equivalent and maximum-minimum loads gives a picture of the impact on all structural loads that are are normally used for design verification (blade root, low-speed shaft, tower top and tower bottom moments). Finally the conclusions of this work are gathered in the Conclusions section.

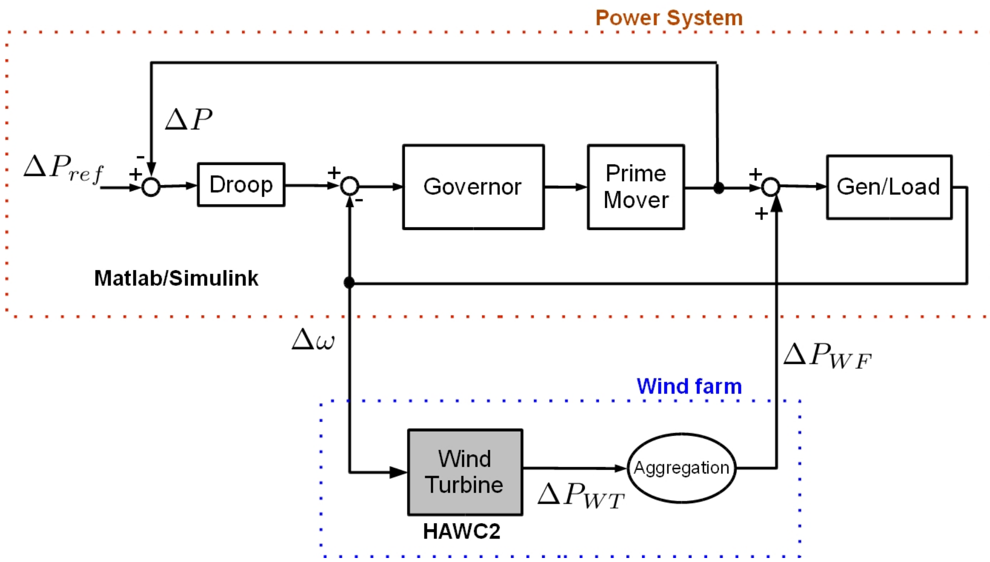

Figure 1: Integrated analysis model that couples a power system for frequency control model with a wind turbine aeroelastic model.

Approach

The approach followed in this work is to use an integrated simulation environment. This section describes the integrated analysis model illustrated in Figure 1, the power system model couples to the wind power plant and wind turbine model with the variable $\Delta\omega$, that represents the deviation of the power system frequency from its nominal value. The wind power plant model consists of aggregating the response of a single wind turbine model to represent the total output of the wind power plant. Since the power system model is in Δ variables, the variations in the output of the wind turbine ΔP_{WT} are aggregated to produce the variations in the wind power plant output ΔP_{WF} that are fed back to the power system model. The simulation cases presented in this work considers constant wind speed and a synchronized response of wind turbines to power system frequency deviations, therefore the aggregation is linear. The power system model is a text book model for frequency control, that represents the lumped response of prime movers, generation, load, speed-control (governor) and droop control.

As illustrated in Figure 1, some of the models are built in Matlab/Simulink and others in HAWC2. The models developed in Matlab/Simulink are the lumped model of a power system for frequency control (Figure 2), a classical dynamic model of asynchronous machine in dq-frame, its rotor converter control (Figure 3) and a generic blade angle control (Figure 4). These models are coupled to a wind turbine structure, and aerodynamics models in HAWC2 (Figure 3).

The power system model for frequency control is described in Figure 2, where the transfer function H_{gl} represents the lumped response of generation and load in the power system. The control of the generation units is modeled as a typical speed PI control (i.e. governor) H_g and turbine transfer function H_t. A droop control (i.e. proportional control) sets the speed reference $\Delta\omega_s$* to the speed governor.

The HAWC2 structural wind turbine model is illustrated in Figure 3. The structural formulation in the aeroelastic code HAWC2 is a multibody formulation in a floating reference frame allowing a realistic representation of large deflections [4].

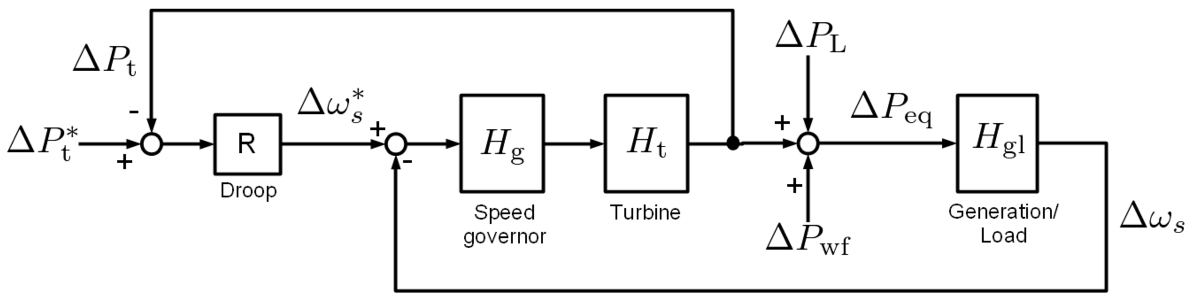

Figure 2: Power system model for frequency control.

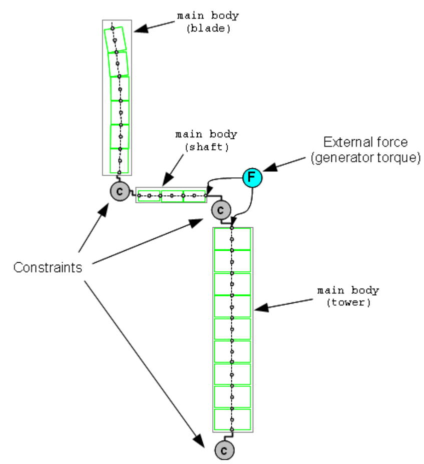

Figure 3: Wind turbine model in HAWC2.

Blade angle control and generator control are illustrated in Figure 4 and 5 respectively. The blade angle control is a generic control with gain schedule that considers the pitch actuator as a first order system [5]. The generator rotor side control is a generic PI cascade control in dq-frame [6], where the q-axis controls active power and the d-axis controls reactive power. Rotor side and grid side converters, as well as grid side converter control are considered ideal. These simplifications are considered valid to study the impact on structural loads.

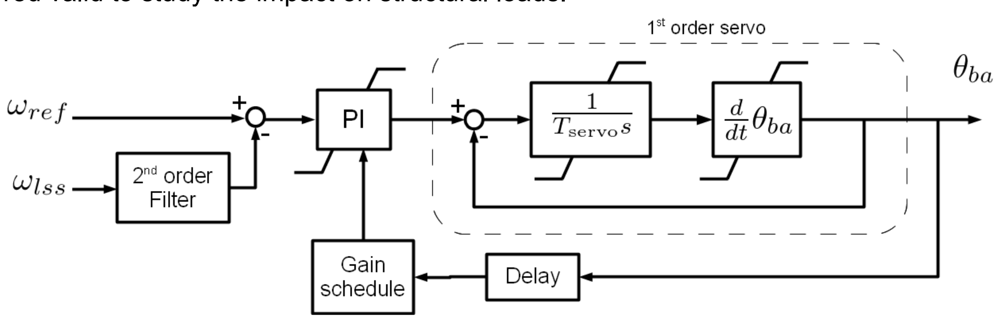

Figure 4: Generic blade angle control.

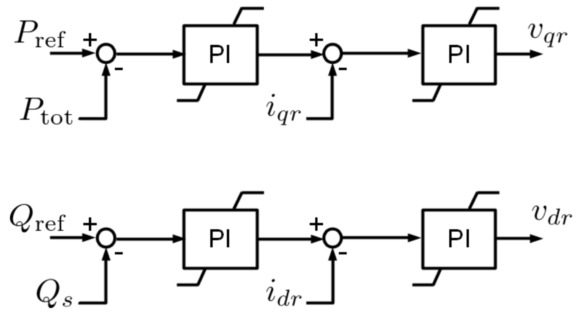

Figure 5: Generic rotor side converter control.

The inertial response control [7] is shown in Figure 6, it changes the power set point of the generator rotor control P_{ref} by adding a power reference P_{ir} to the optimal power reference P_{ref}^{*}. P_{ir} is proportional to the power system frequency deviation $\Delta\omega$. PLL controls consider ideal and therefore represented as time delay.

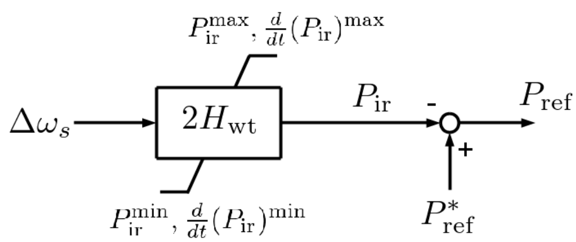

Figure 6: Generic inertial response control.

Results

This section presents the results of two simulation cases with the models described in the previous section. The power system has a total capacity of 60 MW, a 12 MW wind power plant is modeled by aggregating a single 2 MW DFIG wind turbine model. Two cases of a sudden loss of generation are simulated one with the wind power plant with inertial response capability producing rated power. The second case without the wind power plant. The objective is to compare the response of the power system with, and without inertial response from wind turbines (Figure 7). A common inertia emulation control law from the literature is used. The first case, is used to evaluate the impact on structural loads compared to that of normal operation. The estimation of the impact is done in terms of 1-Hz equivalent loads, and maximum-minimum loads (Figure 8-10 and Table I).

Figure 7 shows the response of the power system due to loss of generation, as expected it can be observed by comparing the two cases, that the wind power plant with inertial response will positively contribute, reducing the minimum value of the frequency drop. The blue line represents the response of the power system with the wind power plant providing inertial response, and the red circles represent the response without the wind power plant.

In order to illustrate the dynamic behavior of the wind turbine proving inertial response a phase plot of torque-speed is shown in Figure 8. It can be observe that the response is practically linear at the beginning of the event when the turbine is require to boost the power production suddenly. The torque reaches a maximum and then as the frequency recovers the torque reduces swinging back to rated operation. The minimum speed is reach when the torque is already reducing. The speed then increases as the torque reduces and swings back to normal operation.

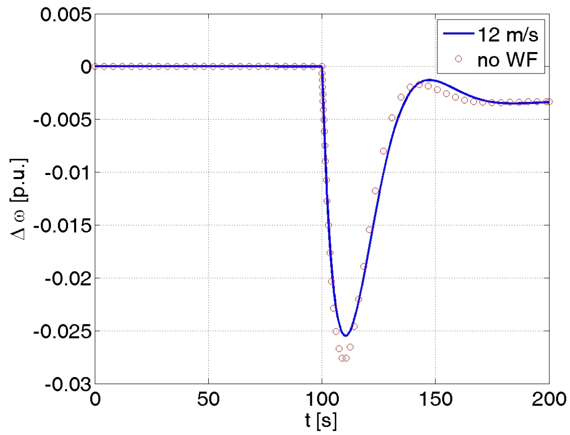

Figure 7: Power system frequency response with wind power plant providing inertial response (blue line) and without wind power plant (red circles).

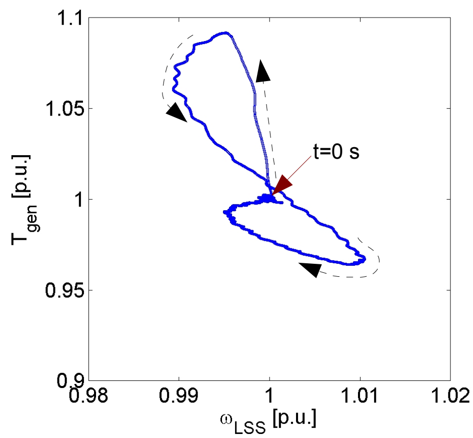

Figure 8: Wind turbine torque-speed plane during inertial response.

Figure 9 shows (from top to bottom) the time response of generator torque, shaft speed and blade angle. It can be observe that the blade angle control responds to change the angle on attach and increase the thrust as the generator is requested to boost its power. During this event many of the structural loads are affected. The time response of the torsion on the shaft, the tower bottom tilt moment and the tower top yaw moment are significantly affected as shown in Figure 10. However other loads are also affected, Table I shows 1-Hz equivalent loads [8], maximum-minimum values and standard deviation of structural loads time series during the inertial response event, all of them normalized to the value in normal operation.

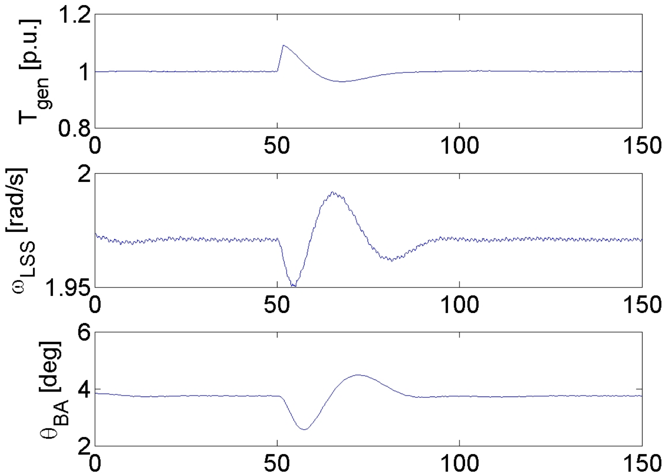

Figure 9: Time response of generator torque, shaft speed and blade angle.

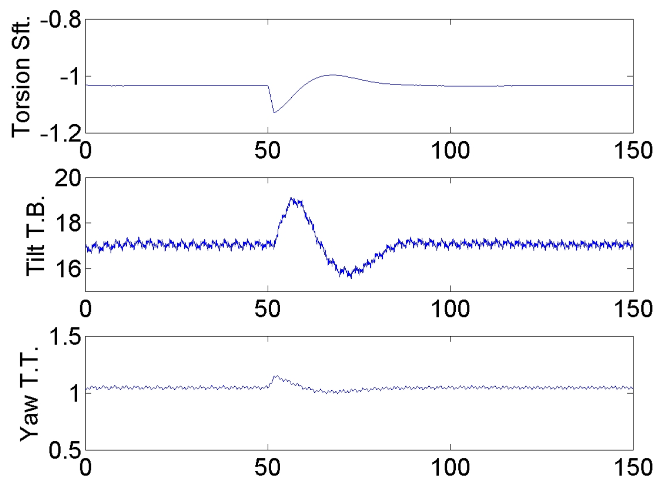

Figure 10: Shaft torsion, tower bottom tilt and tower top yaw moment (all in MNm).

Table I: Normalized equivalent and extreme loads.

	Shaft			Blade			Tower bottom			Tower top		
	Mx	**My**	**Mz**	**Mx**	**My**	**Mz**	**Mx**	**My**	**Mz**	**Mx**	**My**	**Mz**
1-Hz Eq. Load	1.00	1.00	36.85	1.12	1.00	1.08	2.43	1.23	1.00	1.08	2.78	1.01
Max. Load	1.01	1.01	1.09	1.08	1.03	1.10	1.10	1.09	1.12	1.03	1.08	1.12
Min. Load	1.00	0.18	0.96	0.92	0.25	0.90	0.93	0.80	0.7	0.96	0.96	0.02
Std. Dev.	1.0	1.00	19.79	1.05	1.0	1.02	4.87	1.24	1.01	1.02	2.6	1.01

Conclusions

The integrated simulation environment and models presented make it possible to assess (1) the impact of wind turbine inertial response on power system frequency; while at the same time being able to study (2) the impact on wind turbine structural loads.

Simulations showed that in terms of 1-Hz equivalent loads and maximum-minimum loads shaft torsion (shown in the top plot of Figure 10 and as “Shaft Mz” in Table I), tower bottom tilt moment (shown in the middle plot of Figure 10 and as “Tower bottom Mx” in Table I) and tower top yaw moment (shown in the bottom plot Figure 10 and as “Tower top My” in Table I) are significantly affected. Therefore it is relevant to further study the influence of control parameters and different control schemes, considering also different wind turbine operating points and taking into account the frequency of the event to fully assess the impact on life-time.

Therefore, the trade off between the amount of inertial response that wind turbines can provide, and the cost of the loads imposed on them should be assess from an statistical perspective, and perhaps considered when defining regulations in grid codes.

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