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Preprint

I. P. Girsang and J. Dhupia
Nanyang Technological University

M. Singh, V. Gevorgian, E. Muljadi, and J. Jonkman
National Renewable Energy Laboratory

To be presented at the IEEE Energy Conversion Congress and Exposition
Pittsburgh, Pennsylvania
September 14–18, 2014

Conference Paper
NREL/CP-5D00-62310
September 2014

Contract No. DE-AC36-08GO28308

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Impacts of Providing Inertial Response on Dynamic Loads of Wind Turbine Drivetrains

Irving P. Girsang* and Jaspreet S. Dhupia
School of Mechanical and Aerospace Engineering
Nanyang Technological University
Singapore
*Corresponding author: irving1@e.ntu.edu.sg

Mohit Singh, Vahan Gevorgian, Eduard Muljadi, and Jason Jonkman
National Renewable Energy Laboratory
Golden, Colorado

Abstract—**There has been a growing demand from the power industry for wind power plants to support the power system operation. One of such requirement is for wind turbine to provide ancillary service in the form of inertial response. Such service requires wind turbine generators (WTGs) to inject additional energy to the grid when the grid frequency drops to help arrest the frequency decline. Inertial response will understandably impose additional dynamic loads on the wind turbine drivetrain, which have not been given much attention so far. To bridge this gap, this paper utilizes holistic models of both fixed-speed and variable-speed WTGs that integrate the aero-elastic wind turbine model in FAST, developed by the National Renewable Energy Laboratory, with a detailed electro-mechanical drivetrain model developed in SimDriveline and SimPowerSystems. These models allow quantification of drivetrain loads at the gear-level in the midst of realistic turbulent wind and varying grid frequency conditions.**

I. INTRODUCTION

Wind energy industry has grown substantially, as reflected by the increasing size and rating of the manufactured turbines as well as the increasing number of operating wind power plants (WPPs). Not only do these developments increase the contribution of wind energy to meet overall energy demand, but they also bring forward discussions about the role of wind energy in maintaining the stability and reliability of the power system. There is a growing demand within the power industry for WPPs to support power system operations, which is evident from the continuing revisions to the existing grid codes developed by system operators all over the world. Such revisions require wind turbine generators (WTGs) to improve their immunity to line disturbances (e.g., fault ride-through) and provide ancillary services to the power system (e.g., inertial response, power reserve, and governor capability). Advancements in state-of-the-art technologies in the forms of high-efficiency generators, power electronics, and modern control have enabled WTGs to provide ancillary services. Many modern WPPs have the ability to control their output power in response to grid frequency in ways that are important to support the overall grid performance [1].

This work was supported in part by the U.S. Department of Energy under Contract DE-AC36-08-GO28308 with the National Renewable Energy Laboratory, in part by the Energy Innovation Programme Office of the Singapore Economic Development Board, and in part by the Energy Research Institute at Nanyang Technological University.

In the United States, the grid frequency is maintained at 60 Hz, with normal variation of 0.05 Hz [2]. Further deviations are undesirable because they can trigger generation trip and equipment damages. However, when the energy demand suddenly exceeds the supply because of a loss of a power plant or sudden increase in the load, the grid frequency starts to drop. The initial frequency dynamics are dominated by the inertial response of the generators that remain online, supplying power to the grid. The synchronous generators, which are normally utilized in conventional power plants (e.g., hydro, steam, and gas turbines), release their stored kinetic energy into the grid, reducing the initial rate of change of frequency and allowing the slower governor actions to catch up and contribute to frequency stabilization.

Many power system operators in different countries have begun recognizing the value of inertial response provided by WPPs and its importance for the system reliability. In particular, operators in Spain, Canada, Texas, Ireland, and Denmark have been in certain stages of implementing WTG inertial response requirements in their system operations [3]–[4]. Turbine manufacturers have also been offering inertial response capabilities [5]–[6]. However, the impacts of inertial response on the loads of the WTG drivetrain have not been given much attention. Deeper investigations by considering a holistic approach on the WTG models will give insights into the pros and cons of a variety of technologies and designs that provide the capabilities to support the power system.

The inertial response of a WTG varies depending on how it is connected to the grid. Fixed-speed (i.e., Type-1) WTGs are directly connected to the grid, because of which they behave similarly to conventional power plant generators and their inertial response is a physical characteristic that cannot be altered. On the other hand, the use of power converters in variable-speed (i.e., Type-3) WTGs offers a degree of decoupling from the grid, which makes the WTGs have little or no inertial response. Thus, to support the power system through injection of additional energy when the grid frequency starts to drop, an inertial control strategy has to be implemented on Type 3 WTGs. It is important to note that

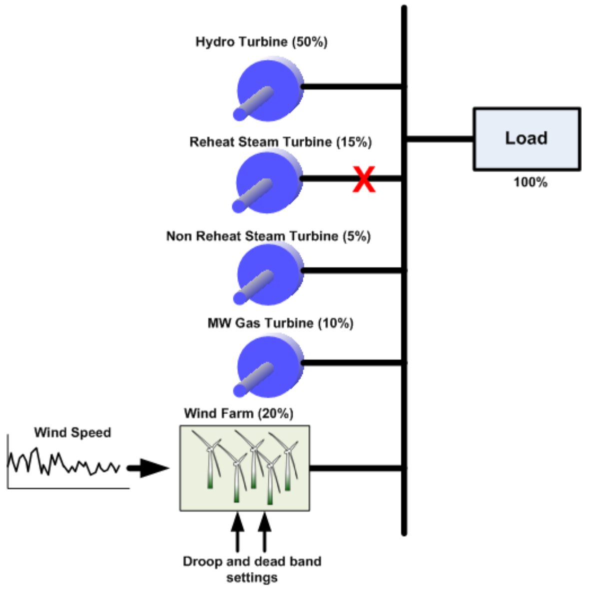

Figure 1. Interconnected system with multiple generators connected to the same grid.

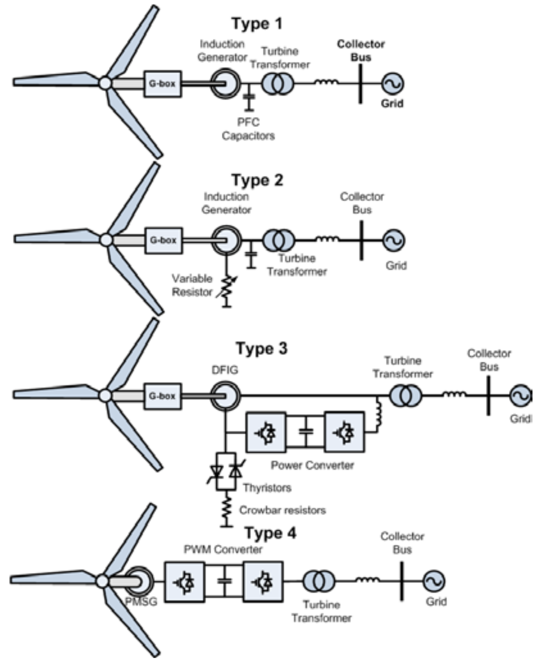

Figure 2. Various types of wind turbine generators.

inertial control takes place for only a few seconds to help arrest the frequency drop. Different from the primary frequency control, inertial control does not require the WTGs to have power reserve by yielding less than the maximum potential output power. Excellent state-of-the-art reviews of inertia control provided by WTGs have been conducted in [7]–[8].

This paper investigates the impacts of providing inertial response on the mechanical loads of both fixed-speed and variable-speed WTG drivetrains. Detailed dynamic time domain simulation models have been built by integrating the aero-elastic wind turbine model in FAST, developed by the National Renewable Energy Laboratory (NREL) [9] with the electro-mechanical drivetrain model in SimDriveline [10] and SimPowerSystems [11]. Simulations on these models were performed in the MATLAB/Simulink environment to investigate the dynamic loads experienced by the drivetrain components during the inertial response. The detailed wind turbine and controller models described in this paper have allowed investigation of drivetrain loads at a gear-level resolution in the midst of realistic turbulent wind and varying grid frequency conditions.

II. Inertial Response of WTGs

A simple representation of an interconnected power system is shown in Fig. 1, in which generators from conventional power plants, a WPP, and the load are connected to the grid. Any loss of large power generation (e.g., from the reheat steam turbine) develops an imbalance, in which the size of the load becomes larger than that of the generation. If no action is taken, this imbalance will create a drop in the grid system frequency, which governs the rotational speed of the synchronous generators. The ability of the generators remaining connected to the grid to deliver more power will determine how low the frequency will drop. The lowest frequency point reached during such event is known as the frequency nadir. In a power system consisting of only conventional power plants, the total inertia of the rotating mass of the synchronized generators connected to the grid is very large. This contributes to a large kinetic energy that can be transferred to the grid so that the frequency nadir is not too low.

WPPs can provide inertial response by having short-term capabilities to inject additional power to the grid. The inertial response of conventional generators depends on the inherent inertia and physics of the synchronous machine, which cannot be changed. This characteristic is also inherent to Type 1 WTGs, which have induction generators directly connected to the grid. However, for Type 3 WTGs, the amount of power transferred to the grid during the inertial response can be controlled to improve power system performance during the initial decline of the frequency after a loss of generation. The main limitations of controlled inertial response are extra heat and stress on both electrical and mechanical components due to the demand for sudden additional power generation. In particular, this paper employs a detailed model to study the impacts of inertial response on the dynamic loadings (i.e., mechanical stresses) of the drivetrains of both fixed- and variable-speed WTGs.

A. Fixed-speed (Type 1) WTGs

Fig. 2 shows the schematic of Type 1, Type 2, Type 3, and Type 4 WTGs. Because Type 1 WTGs are directly connected to the grid, they are capable of releasing kinetic energy stored in their rotating parts (e.g., rotor blades, gearbox, and generator). Consider the characteristic curve of a Type 1 WTG operating at rated wind speed of 10.8 m/s as

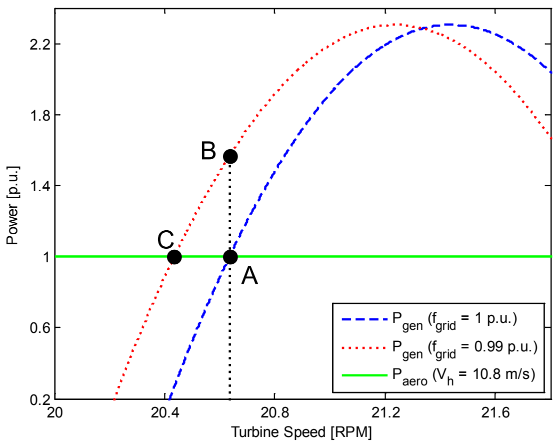

Figure 3. Kinetic energy transfer to grid during a frequency decline for Type 1 WTG.

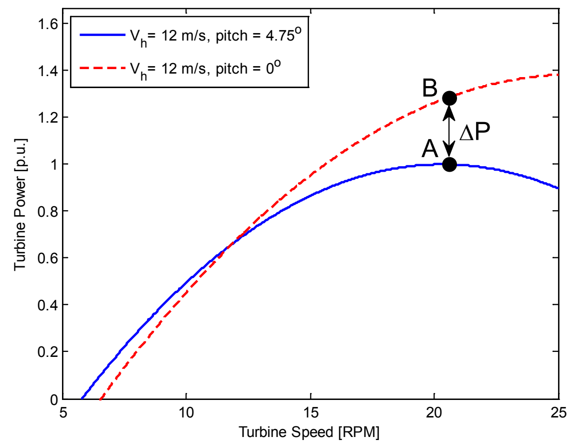

Figure 4. Kinetic energy transfer to grid during a frequency decline for Type 3 WTG.

shown in Fig. 3. For normal grid frequency of 60 Hz (i.e., 1 p.u.), the WTG operates at its rated operating point **A**, which is the intersection between the available aerodynamic power and generator output power. When there is a sudden drop in the frequency by 1%, the rotor speed does not change instantaneously because of the inertia of the turbines. However, the generator power-speed characteristic moves to the left, instantaneously shifting the operating point from **A** to **B**. As a result, there is an increase in the generated power at the same operating speed, which comes with a spike in the generator torque. The rotational speed then decreases along the shifted operating curve to reach a new balanced operating point **C**, during of which the kinetic energy stored in the turbine is transferred to the grid to help arrest the frequency decline.

B. Variable-speed (Type 3)WTGs

A schematic of a Type 3 WTG is also shown in Fig. 2. The use of power converters, which decouple these WTGs from the grid disturbances, requires the implementation of an inertial control. Consider the characteristic curve of a Type 3 WTG as shown in Fig. 4. When the wind speed increases higher than the rated wind speed of 10.8 m/s, the generator output power must be maintained at its rated power, achieved by controlling the blade pitch angles to curtail the aerodynamic power. For example, at the wind speed of 12 m/s, the turbine operates at **A**. At this point, the pitch angle is set to 4.75° to deliver the rated power. If the blade is pitched to 0° at **B**, the available aerodynamic wind power is 27% higher than the rated output. During normal operation, this excess power can bring the turbine into an undesired runaway (i.e., overloading and overspeeding) condition. However, when the grid frequency drops, Type 3 WTG can inject this excess power to the grid to help arrest the frequency decline. The maximum power boost that can be provided depends on the available aerodynamic power as well as the capacity of electrical and mechanical components of the turbine to carry the stresses. In particular, the designed rated torque should not be exceeded throughout the turbine operations to maintain the integrity of the WTG drivetrain.

III. Model Descriptions

The WTGs modeled in this paper are based on the Gearbox Research Collaborative (GRC) turbine [12] at NREL. The drivetrain of this turbine has been modeled in various levels of fidelity and validated for dynamic load calculations [13] and condition monitoring [14]. Further, this turbine model has been applied to simulate turbine loads under various conditions, including the unconventional ones [15]. This model has also been used to verify several controllers specifically designed to mitigate drivetrain loads [16]–[17]. Fig. 5 shows a schematic of the integrated wind turbine, drivetrain, and generator models in the MATLAB/Simulink environment.

A. Wind Turbine and Pitch Controller Model

The GRC turbine is rated at 750 kW. Table I summarizes the important properties of this turbine. The turbine model is loaded into the FAST S-Function block, which is connected to the pitch controller block. Above the rated wind speed, the blade pitch angles are controlled to achieve the desired output power. Traditionally, the blades are collectively pitched (i.e., the pitch angle is equal for all blades) to maintain rated output power. As discussed earlier, a Type 3 WTG can be pitched to capture more aerodynamic power. To do so in this paper, a pitch controller [18] with a first-order pitch actuator model as shown in Fig. 6 is used. The relationship between the measured grid frequency and the power reference is described after the following subsection.

B. Drivetrain Model

FAST inherently employs a two-mass drivetrain model. Due to its low degree of freedom, the drivetrain model of FAST is limited in describing various drivetrain configurations and their complex dynamics. A higher fidelity torsional model is adopted in this paper to model the drivetrain. In this model, each shaft is modeled as an ideal

TABLE I. MODEL PARAMETERS OF GRC WIND TURBINE

Configuration, Rating	3 Blades, 750 kW
Gearbox, Overall Ratio	3 Stages, 81.49
Rotor, Hub Radius	24.1 m, 0.3 m
Hub Height	54.8 m

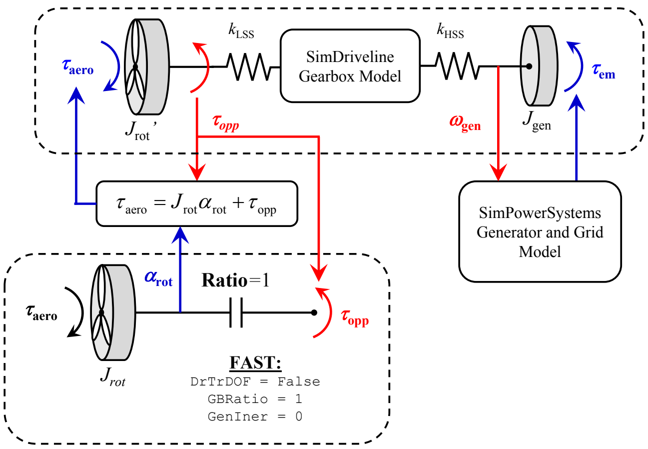

Figure 5. Schematic of integrated wind turbine, drivetrain, and generator models in MATLAB/Simulink environment.

massless torsional spring and each gear is modeled as an inertial body. This model considers constant gear meshing stiffness, which plays an important part in the dynamics of the meshing gear pairs [14]. This model is built using SimDriveline, available in the MATLAB/Simulink library. The GRC drivetrain model is shown in Fig. 7. The multi-stage gearbox consists of a planetary gear stage and two parallel gear stages, with two intermediate shafts. The development and simulations of this drivetrain model are discussed in detail in [19].

C. Generator Model

The GRC WTG originally employs a fixed-speed squirrel-cage induction generator (SCIG). A doubly-fed induction generator (DFIG) model is also considered in this paper because it aims to investigate the inertial responses of both fixed-speed (Type 1) and variable-speed (Type 3) WTGs. The same induction generator model, which is based on a commercial WTG of the same rating available in the market, is used for both Type 1 and 3 WTGs. The key parameters of the generator and converter (for Type 3 WTG) are summarized in Table II. Detailed models of SCIG and DFIG were built in SimPowerSystems, coupled to the drivetrain model.

To simulate the frequency dips, measured grid frequency of an interconnection was taken as input to the generator model. NREL has developed a custom monitoring system and software to autonomously and continuously monitor and capture grid frequency events [1]. One such system was installed at the National Wind Technology Center (NWTC) in June 2011 and has since been monitoring the frequency of the Western Interconnection. This frequency measurement is

TABLE II. PARAMETERS OF THE 750-kW INDUCTION GENERATOR

Generator	
Line-Line Voltage (RMS)	690 V
Nominal Frequency, No. of Pole Pairs	60 Hz, 2
Stator Resistance, Leakage Inductance (pu)	0.016, 0.06
Rotor Resistance, Leakage Inductance, both referred to Stator (pu)	0.016, 0.06
Magnetizing Inductance (pu)	2.56
Inertia Constant (s)	2
Converter	
Converter Maximum Power (pu)	0.5
Grid Side Coupling Inductance, Reactance (pu)	0.15, 0.0015
Nominal DC Bus Voltage	1200 V
DC Bus Capacitor	0.01 F

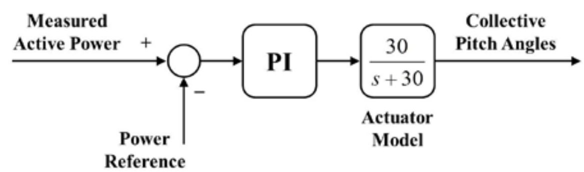

Figure 6. Collective pitch controller to achieve desired output power.

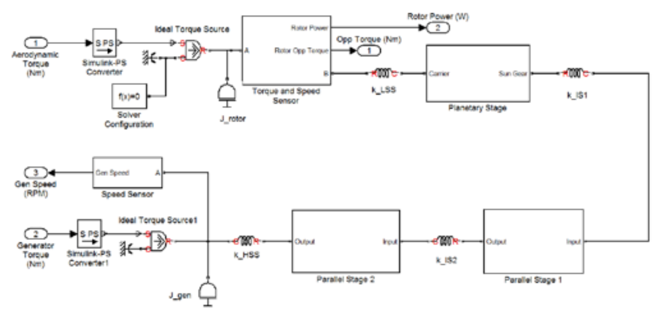

Figure 7. Collective pitch controller to achieve desired output power.

conducted to gather a collection of disturbance events, which can help in dynamic modelling of frequency behavior, understanding the loading impacts on the WTGs, and assisting control engineer to determine how WPPs can support the grid within safe limits. Three measured frequency dip events caused by large losses of generation in the Western Interconnection were implemented in this study, which are shown in Fig. 8. Event A represents the event with the lowest measured frequency nadir; Event B represents that with the double dips; and Event C represents that with a low frequency nadir along with a fast recovery. The detailed DFIG model built in SimPowerSystems to take the measured grid frequency as an input is shown in Fig. 9.

At above-rated operations, because Type 3 WTGs can be pitched to capture and deliver more power to the grid, the power reference shown in Fig. 6 is set to be 10 % higher than the rated power when the grid frequency drops below 59.95 Hz. To avoid overheating of the generator windings and power converters in realistic condition, the reference power is returned to the rated power after 15 seconds as presented in [20].

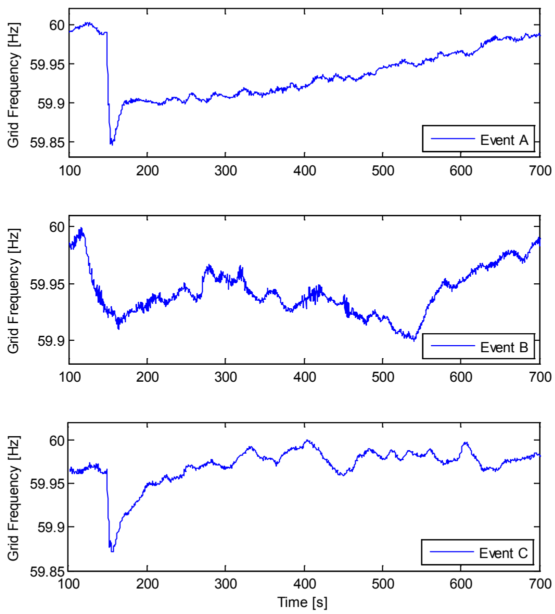

Figure 8. Frequency dips measured at NWTC.

IV. SIMULATION RESULTS AND DISCUSSIONS

Simulations were performed using both constant and turbulent wind conditions. The former helps to isolate the effects of inertial responses and grid frequency variations on the mechanical loads of WTG drivetrain without any aerodynamic variations. The latter simulates the more realistic operating conditions of the WTGs providing inertial response amidst varying wind and grid frequency.

A. Deterministic Wind Condition (No Turbulence)

At the wind speed of 15 m/s, the responses of the Type 1 GRC WTG for Event A are shown in Fig. 11. As discussed in Section II, in the event of a frequency dip, this WTG yields power higher than its rated power injected to the grid. The operation then returns to the rated power at a lower speed. Because this WTG is directly connected to the grid, its speed profile follows the profile of the grid frequency. The instantaneous deliverance of power to the grid introduces torque spikes into the drivetrain. The bottom plot of Fig. 11 shows the transmitted torque between the sun gear and one of the three planet gears. This torque indicates the amount of stress experienced by the gear teeth. The inertial response of this WTG comes in the cost of increased stresses on the gear. Depending on how low the frequency nadir is, the transmitted torque may reach a value beyond the gear rating. Further, lower grid frequency increases the average load experienced by the gears. Over the years, the accumulated effects caused by frequency decline and/or other type of line disturbances may shorten the life of gearbox and other turbine components.

For the same wind speed and frequency event, the responses of Type 3 GRC WTG are shown in Fig. 12.

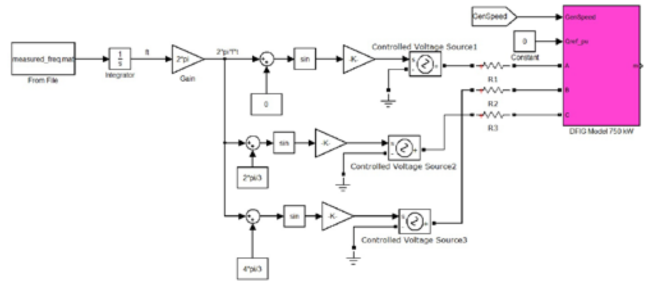

Figure 9. Detailed DFIG model taking measured grid frequency input.

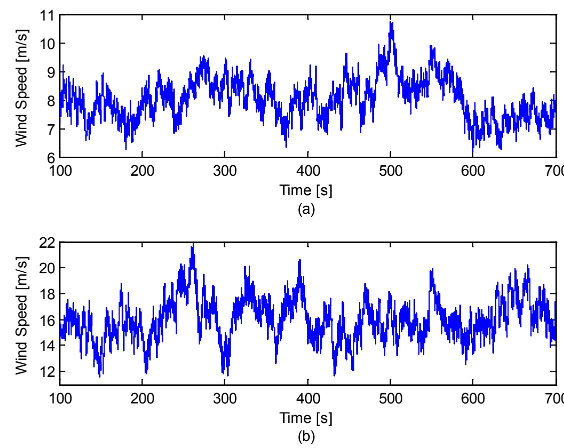

Figure 10. Turbulent wind speed for (a) Type 1 and (b) Type 3 WTGs.

Because a Type 3 WTG inherits a certain degree of decoupling from the grid through its power converters, this type of WTG can operate normally despite disturbances occurring at the grid. Thus, it inherently does not contribute to the inertial response. However, as discussed in Section II, this WTG can contribute by pitching the blade to allow for the transfer of additional power from incoming wind to the grid. As shown in the bottom of Fig. 12, the blades are pitched 1.25^{o} less from the nominal value for 15 seconds before being pitched back to normal. As soon as the blade pitch decreases to capture more aerodynamic power, the WTG speeds up and when the blade pitch increases, the WTG slows down and then accelerates back to its rated speed. In terms of the drivetrain load, the injection of extra power, as shown in the top of Fig. 12, significantly escalates the stresses experienced by the gears. The more power delivered to the grid, the higher the stresses the gears have to be designed to sustain. Further, each time the blade pitch angle changes, the gears experience transient vibrations that impose higher fatigue loads and reduced lifetime.

B. Turbulent Wind Conditions

TurbSim was used to generate realistic hub-referenced turbulent wind fields following the Kaimal spectrum [21], as shown in Fig. 10. Fig. 10 (a) shows a mean speed of 8 m/s with 10 % turbulent intensity to investigate the inertial responses of the Type 1 GRC WTG at below-rated operation. On the other hand, Fig. 10 (b) shows a mean

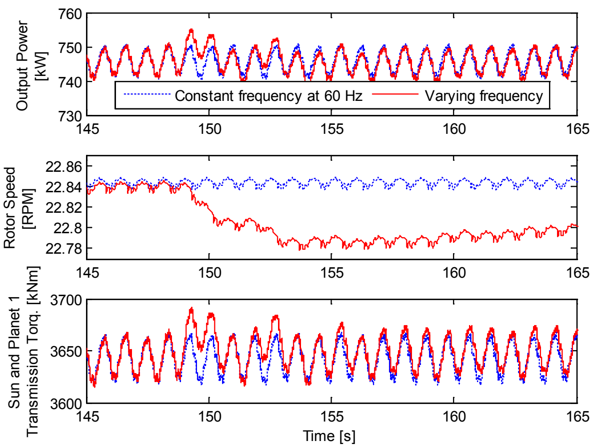

Figure 11. Type 1 WTG drivetrain response comparisons for normal frequency event and during a frequency dip.

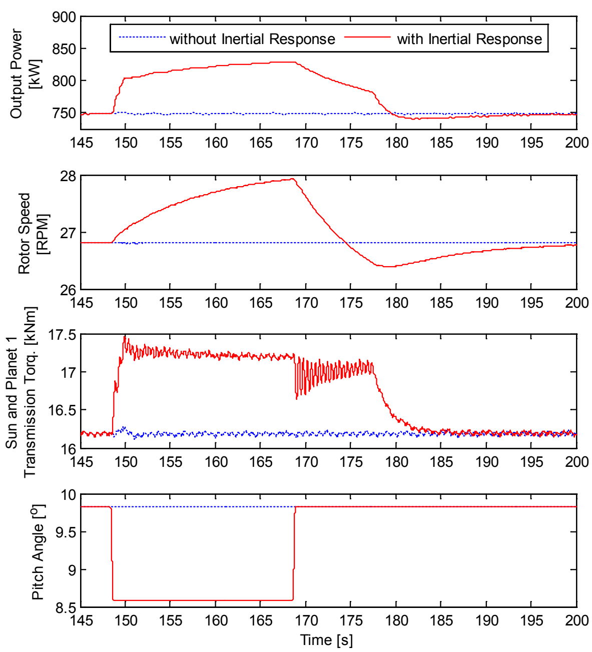

Figure 12. Type 3 WTG response comparisons with and without inertial response.

speed of 16 m/s with 10 % turbulent intensity to investigate the responses of its Type 3 counterpart at above-rated operation. Each condition simulated a 600-second event, as recommended by the International Electrotechnical Commission 61400-12 standard [22]. To isolate the effects of inertial response and grid frequency variations, the turbulent wind speed and pitch controllers are maintained for each WTG, whereas the frequency case varies.

To evaluate the gear loads at turbulent wind conditions, the transmitted torque between the sun gear and one of the planet gears are imported to the MLife code [23] to calculate the 1-Hz damage equivalent load (DEL). The slope of the cyclic stress to cycles-to-failure (i.e. the SN curve) is chosen to be 10, which is typical for the wind turbine gears made from case-hardened cast iron.

TABLE III. GEAR DELS OF TYPE 1 WTG

Frequency Cases	DEL [Nm]	Difference
Fixed Nominal Frequency	5685	-
Event A	5710	0.44 %
Event B	5709	0.42 %
Event C	5708	0.40 %

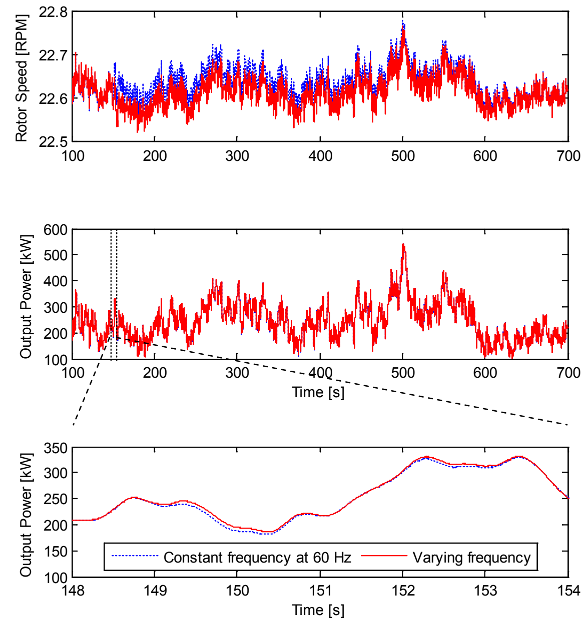

Figure 13. Type 1 WTG response under turbulent wind condition and grid frequency for Event A.

Because the wind speeds shown in Fig. 10 (a) are below the rated wind speed, the pitch angles for the Type 1 GRC WTG are fixed at 0^{o}. Fig. 13 shows the responses of the Type 1 GRC WTG for Event A. As the frequency drops, the WTG delivers slightly higher power to the grid. It is important to note that this additional power comes from the rotating inertias of the WTG drivetrain as the captured aerodynamic power remains constant. The speed of the WTG is very much affected by the frequency variations. This results in higher gear loads as summarized in Table III. As expected, the highest load is attributed to Event A, which suffers from the lowest grid frequency.

The wind speeds in Fig. 10 (b) are always above the rated wind speed to allow implementation of controlled inertial response on the Type 3 GRC WTG using the pitch controller of Fig. 6. Figs. 14, 15, and 16 show the responses of the Type 3 GRC WTG with inertial responses for Events A, B, and C, respectively. The output powers of the WTG are able to follow the reference power by correspondingly reducing the blade pitch angles. However, as expected, the additional power yields some overspeedings.

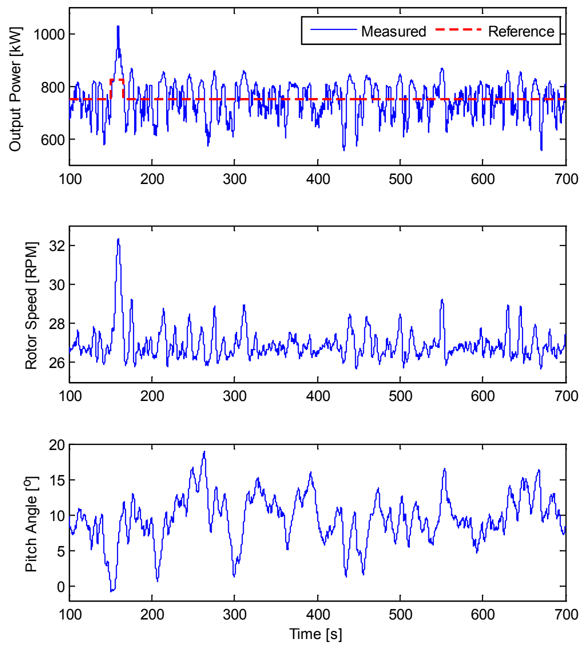

Figure 14. Type 3 WTG response under turbulent wind condition and grid frequency for Event A.

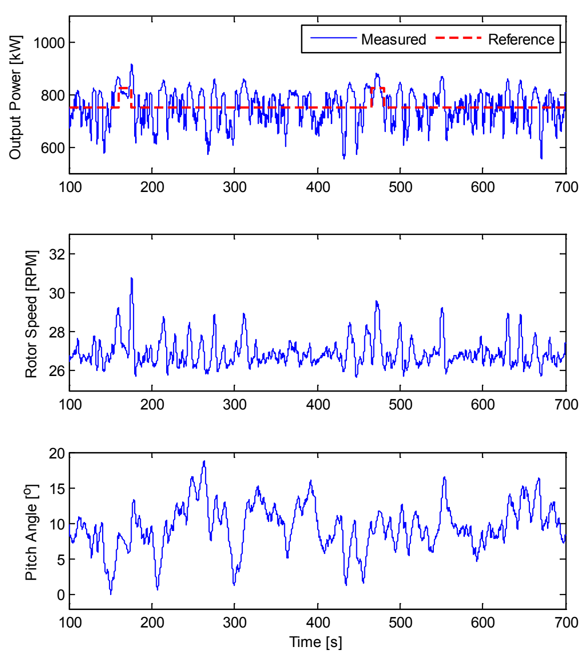

Figure 15. Type 3 WTG response under turbulent wind condition and grid frequency for Event B.

TABLE IV. GEAR DELS OF TYPE 3 WTG

Frequency Cases	**DEL**		
	without Inertial	with Inertial	difference
Case A	5231 Nm	5246 Nm	0.29 %
Case B	5233 Nm	5264 Nm	0.59 %
Case C	5232 Nm	5247 Nm	0.29 %

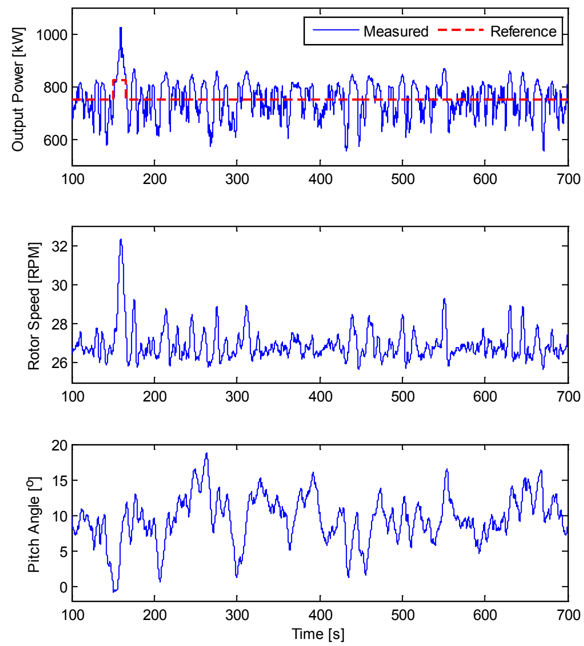

Figure 16. Type 3 WTG response under turbulent wind condition and grid frequency for Event C.

The comparisons of the gear DELs with and without inertial control are summarized in Table IV. As a Type 3 WTG has a certain degree of decoupling from the grid, the frequency variations do not impact the gear loads much. Additional loads are attributed to the transient vibrations each time the power reference, along with the average gear transmitted load, changes. Understandably, the highest load for Type 3 GRC WTG is attributed to the double-dip event of Event B, which yielded twice an increase in the gear load compared to other cases.

With the exception of the double-dip event, the inertial response of Type 3 WTG resulted in lower drivetrain load. Thus, it can be concluded that for general grid frequency events, which has a profile similar to Events A and C, Type 3 WTGs give better inertial response in terms of higher additional energy transferred to the grid and lower increase in the drivetrain loads.

V. CONCLUSIONS

The analysis presented in this paper attempts to provide additional contributions to the ongoing industry-wide discussions on the impacts of providing inertial responses to the grid on the reliability of WTGs. Distinctions in inertial responses between the fixed- (Type 1) and variable- (Type 3) speed WTGs have been discussed in term of the fatigue load experienced by the gears of the WTG drivetrain.

The inertial response of Type 1 WTG is a physical characteristic that cannot be altered. Thus, volatile frequency variations can deteriorate the drivetrain components. On the other hand, Type 3 WTG is quite decoupled from the grid. Thus, the drivetrain load is not much affected by the frequency variation. However, pitch control has to be implemented for variable-speed WTGs to provide the inertial response, which can only be done at above the rated wind speed. Additional loads on Type 3 WTG drivetrain during its inertial response are caused by the transient vibrations attributed to the change in output power.

ACKNOWLEDGMENT

The authors thank Katie Wensuc of National Renewable Energy Laboratory for the assistance in editing this paper.

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