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WIND ENERGY SCIENCE DISCUSSIONS

WESD

Interactive comment

Interactive comment on "Optimal Output Feedback H_∞ Torque Control of a Wind Turbine Rotor using a Parametrically Scheduled Model" *by* Dana Martin et al.

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Response to referee 2 comments

Thank you to the reviewers and editors for the comments and the opportunity to revise and improve our paper. We have made substantial revisions to the paper to address the comments from both reviewers. In this document, we explain how we addressed specific comments in our revision.

Abstract 1. "For such applications, Linear Parameter Varying (LPV) control provides a state-space approach to designing nonlinear controllers with robust performance" you also synthesis an LPV controller. Why is this a nonlinear controller? i. The abstract has been fully revised to address this and other comments as “Wind turbine fatigue damage can be greatly reduced through the application of Linear Parameter Varying (LPV) control architectures as compared to traditional control methodologies. LPV control theory facilitates optimal controller synthesis considering various objectives; in this work, we apply LPV control theory to a MIMO LPV model of a nonlinear turbine plant using Linear Matrix Inequalities (LMIs) and convex optimization solvers to produce the LPV controller. The application of the torque controller to a down-wind, two bladed, scaled, Segmented Ultra-light Morphing Rotor (SUMR) results in improved turbine performance and reduced damage equivalent load (DEL) accumulation during turbulent inflow. The reduction in DEL is attributed to the limit placed on the exogenous disturbances' effect on performance channels stemming from H_∞ LMI formulation.” ii. The controller is nonlinear because of the relationship between rotor angular velocity Ω_r and aerodynamic torque τ_a. Details describing this relationship are presented in (Johnson et al., 2006, Martin et al., 2017). 2. “LPV uses multi-input multi-output (MIMO) model with a..” please check grammar (e.g Linear Parameter Varying uses . . . what does it mean?) i. We have addressed the comment. Please see revised abstract given in Response1i. Introduction 1. “robustness of H control” what do you mean? i. The paragraph has been revised as “LPV control theory provides guarantees of stability despite the presence of plant parameter uncertainty and/or uncertainties in the measured scheduling parameter (Shamma, 1988; Zhao and Nagamune, 2017; Sato and Peaucelle, 2013; Sato et al., 2010). It utilizes robust control theory (Levine, 2011) during the construction of the LMI constraints for the optimization problem, providing guarantees of stability in the presence of deviations from model parameters used during control synthesis, and similar guarantees of stability in the presence of exogenous disturbances the plant may be exposed to during operation. Conservative performance can be an issue, given significant deviations from the design operating point which can be addressed through LPV control theory's potential to create less conservative controller response by appropriate scheduling of the plant's dynamics. However, given the degree of nonlinearity for variable speed, variable pitch (VSVP) wind turbines, solving the optimization problem is non-trivial given a system with a large number of states to be considered during the MIMO controller synthesis. To deal with the complexity of the LPV optimization process, the gridding (Wang and Seiler, 2018) technique is utilized, allowing existing conic solvers (Sturm, 1999) to find globally optimal solutions within a highly nonlinear domain and ill-conditioned problem (Ostergaard et al., 2009), in addition to creating finite dimensional LMI's from an originally infinite dimensional LPV model." (pg. 2) 2. P2, line 21, "a LPV" should be "an LPV" i. Edit has been addressed in this section as well as throughout the paper. Controller Derivation 1. P6, quality of the figure should be improved Quality of all figures has been addressed. Specifically, Figure 1 on pg. 6 has been updated and is shown below in Figure 1

2. "only the portion of the sensitivities falling between the cut-in (2 m/s) and rated (5 m/s) wind speeds will be used in the construction of the parameter varying functions" a rated speed of 5 m/s sounds strange. Is that for the novel rotor? If yes, this rotor model should be introduced. i. In order to reduce the confusion these low wind speeds may cause the reader, they have been normalized as presented in Table 1 (pg. 7) and Figure 2 (pg. 8). Additionally, further clarification has been added to reduce confusion about the turbine model used in this paper in the form of "Control design utilizes simplified plant models describing the dynamics of interest for feedback gain synthesis. In this section, a generalized three DOF plant model will be derived in the form of (1) using physics based principles and simple force balance calculations. The end goal is to obtain a below-rated torque controller with drivetrain damping and energy capture objectives which will be applied to the SUMR-D turbine. The SUMR is a novel rotor design concept which aims to utilize morphing rotor technology in order to accomplish load alignment (Loth et al., 2017) such that structural design requirements are reduced. The SUMR-D design is a scaled version of the SUMR-13i design (Ananda et al., 2018), which will be used to validate the design process as a proof of concept field prototype. Specific details of the turbine model we use in the research follow in Section 3. While the application of the controller will be applied to the down-wind, two

bladed SUMR-D rotor, the modeling and controller synthesis procedure is valid for any VSVP wind turbine model.” (pg. 5) ii. “This paper is focused on partial load operation (region 2) (Johnson et al., 2006) of the SUMR-D turbine, therefore, only the portion of the sensitivities falling between the cut-in 2 m/s and rated 5 m/s wind speeds are used in the construction of the parameter varying functions corresponding to the novel rotor design and gravi-aero elastic scaled operating points, to be used in a research field test. These properties are scaled values of the SUMR-13i (Ananda et al., 2018) turbine, and applied to the structural, aerodynamic, and operational properties resulting in lower than normal operational set points. See Section 3.1 for more information.” (pg. 8) 1. P13, figure 7 not clear i. All Figure quality has been addressed. ii. Updated Figure shown in Figure 2 below

2. For performance channels it doesn’t make sense to present the phase i. Performance system phase has been removed from Figure 6. Performance Vector Design 1. Eq 15 with the previous S, really doesn’t make sense. I stopped reading the paper after this point. While the ACC paper from the same authors was easy to read, correct and well organized this paper seems to be the opposite. i. Additional clarification for the sensitivity function has been added in the form “This shaping procedure is accomplished by multiplying the transfer function of the weighting function W_{z1} (Bossanyi and Hassan, 2000) with the sensitivity function (13). The weighting function is centered at the drivetrain first eigenfrequency $\Xi_{DT_{1P}}$, and shown in Figure 4. This provides the desired frequency response.” (pg. 10)

Aborted Review We have thoroughly revised the paper and hope this reviewer and other readers find the revised version easier to read, correct, and better organized.

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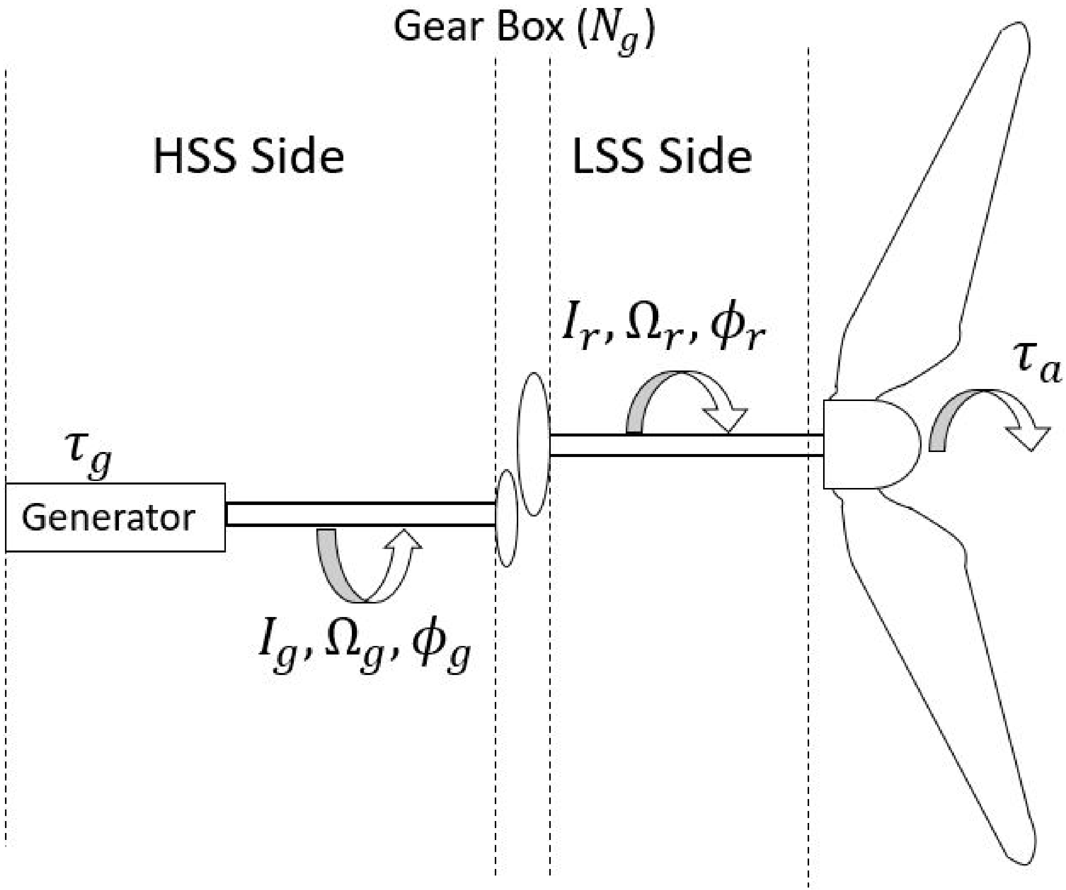

Fig. 1. Drive Train Model

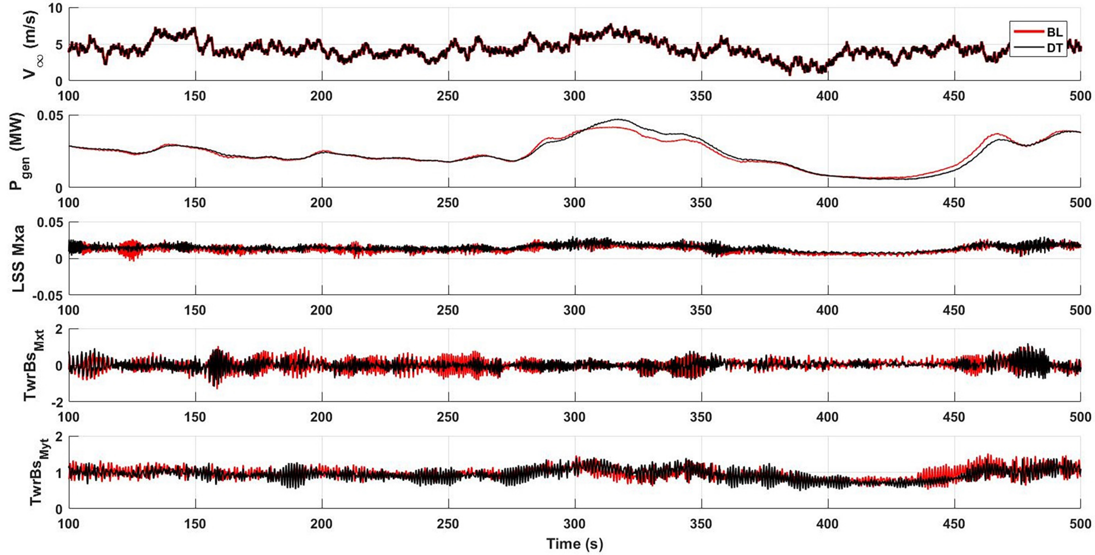

Fig. 2. Time Series

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Discussion paper