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Wind turbine drive train dynamic characterization using vibration and torque signals

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ABSTRACT

Dynamic analysis of wind turbine drive train subjected to stochastic aerodynamic loads is carried out in the present study. The longitudinal wind speed at the turbine site normally consists of a mean value superimposed with ramp, gust and turbulence components. In the present study, the aerodynamic torque is obtained by considering wind speed parameters of a typical wind turbine site. The dynamic model accounts for time varying gear mesh stiffness, bearing elasticity and torsional shaft stiffness. The dynamic analysis is done with stochastic aerodynamic loads and the vibration responses are obtained in time and frequency domains. It is observed that the entire spectral content of the vibration signals is confined to low frequency region, whereas higher frequencies are hidden. In order to capture the hidden frequency information from vibration signals, the wavelet decomposition technique is used. The dynamic analysis using torque signals is also discussed. The present study shows that, from the internal resistive torque all the characteristic frequencies can be clearly observed.

1. Introduction

The installation capacity of wind turbines is increasing significantly year by year. A wind turbine drive train is a typical case of rotating equipment operating at slow speeds and subjected to severe stochastic loads. The wind turbine components are always affected by uncertain loads. Such kind of load spectrum always leads to vibration signals which are nonlinear and non-stationary in nature [1]. The dynamic analysis and condition monitoring of most of the rotating machinery focus on rotating components that are subjected to constant, periodic or transient load spectra. These are relatively easier for modeling and analysis, compared to the wind turbine drive trains. Wind turbines are subjected to wind loads which are stochastic in nature. Due to these loads, the chances of failures are higher for critical components, such as gearbox. The downtime and cost associated with the gearbox is more, as handling of this component is difficult. Hence, detailed predictive condition monitoring strategies have to be developed for such components. A huge step-up speed in the range of 40:1 to 135:1 can be achieved from rotor to generator in wind turbine using epicyclic gearbox [2]. Qin et al. [3] carried out wind turbine gearbox dynamic analysis with flexible multi-body modeling technique, taking into account the elastic strain energy due to gears and bearings. Abboudi and Walha [4] carried out dynamic analysis of a two stage external gearbox of wind turbine using an empirical approach based on aerodynamic torque. Guo et al. [5] modeled gravity effect on the vibration response of wind turbine planetary gears and it is concluded that the gravity plays a vital role when compared to gear tooth meshing excitation alone. These results compared well with those of mathematical and experimental models. Rigid multibody modeling with discrete flexibility approach is used by Todorov et al. [6] to assess the torsional dynamic behavior of wind turbine drive train. The dynamic behavior of wind turbine gearbox is evaluated using

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three techniques namely pure torsional, rigid multi-body modeling and flexible multi-body modeling [7,8]. Here, finite element approach and test rig experiments are used. By taking variable gear mesh stiffness into account, Shi et al. [9] studied the torsional dynamic behavior of the entire wind turbine drive train subjected to constant aerodynamic torque excitation using Lagrange's approach.

Notations

A_r, A_g	ramp and gust amplitudes
C_1, C_2, C_3	low, intermediate and high speed shaft torsional stiffness.
$C_p(\lambda, \beta)$	power coefficient
$H_1(s), H_2(s)$	spatial and rotational sampling filter
I	turbulence intensity factor of wind
$J_i\ (i = 1 \ldots 8)$	inertias of rotor, carrier, planets, sun, gear1, gear2, gear3, and generator
k_{ri}, k_{si}, k_{pg}	time varying mesh stiffness of ring–planet, planet–sun and gear–pinion.
$K_{bj}\ (j = 1 \ldots 6)$	stiffness values of bearings
L_1, L_2	length scales of the Kaimal and von Karman spectra
$[M], [C(t)], [K(t)]$	mass, damping, and stiffness matrices
R	radius of rotor
$S(f)$	auto spectral density function
T_i, T_s	initial and stop times
$T_R(t), T_G(t)$	rotor and generator torque
$u(t), U, u_r(t), u_g(t), u_t(t)$	total, average, ramp, gust and turbulence components of wind speed
$y_i, z_i, y_s, z_s, y_1, z_1, y_2, z_2, y_3, z_3$	translational degrees of freedom in y & z directions of planets, sun, gear1, gear2, and gear3.
σ	wind speed standard deviation
γ	decay factor
λ	tip speed ratio
ϕ, θ, β	incident angle, angle of attack, and pitch angle
ω_r, ω_d	rotor speed and rotor damping factor
${\omega_M}^{(p)}, {\omega_M}^{(g12)}, {\omega_M}^{(g34)}$	gear mesh frequency of ring–planet and planet–sun, gear1–2, gear2–3
$\delta_{ri}, \delta_{si}, \delta_{pg}$	dynamic transmission errors of ring–planet, planet–sun, gear–pinion
$\phi_i\ (i = 1 \ldots 8)$	Absolute rotational angles of rotor, carrier, planets, sun, gear1, gear2, and gear3, and generator absolute rotational angles.

Coupled torsional bending dynamic analysis is carried out for fixed speed wind turbine using Lagrange's approach in [10]. Here, constant gear mesh stiffness, support bearing elasticity and strain energy associated with shafts are used in the formulation. Aerodynamic torque is modeled as a periodic signal based on the empirical relation. Harmonic balance method is used by Ji et al. [11] to obtain the dynamic responses of the wind turbine gearbox. Techniques like finite element analysis and experimental modal analysis are adopted by Haijun et al. [12] for estimating the natural frequencies and mode shapes. Lumped parameter dynamic model of the wind turbine gearbox is developed by Long Quan et al. [13] to estimate the vibration levels. Yongqian et al. [14] elaborated the effect of design parameters on the sensitivity of the natural frequency and dynamic characteristics with respect to gear mesh stiffness in epicyclic wind turbine gearbox.

The details of different wind components existing at wind turbine sites are revealed in [15]. Different wind speed models (Weibull, extreme value distribution of type 1 & type 2 and Rayleigh) are proposed by Jang and Lee [16] for the Taiwan area. The random nature of wind is normally represented by the Weibull distribution model, four component composite model, auto regressive and moving average model and power spectral model [17]. Near the wind turbine site, the best approximation to represent wind is the Weibull distribution; this has been concluded based on wind data, over a period of 44 years [18]. There always exist deterministic and stochastic components in wind loads [19]. The main reason for gearbox failures is the wind stochastic load that always creates uneven stochastic aerodynamic torque on the rotor. These loads are distributed unevenly between the bearings and gears [20].

Zhu et al. [21] using the commercial SIMPACK software carried out the dynamic analysis of the wind turbine drive train by considering external excitations due to load spectrum and internal excitations due to the time varying mesh stiffness and transmission errors. These results are compared with the experimentally measured vibration acceleration signals. A simplified method is proposed to estimate the long-term extreme value of the gear transmitted load. This value is estimated based on the cumulative Weibull distribution for one hour mean wind speed [22]. The need to consider the effects of mesh stiffness and impact stress on the dynamic transmission error evaluation of the wind turbine planetary gear system is revealed by Zhao et al. [23]. Wei et al. [24] analyzed the effects of uncertainty in the gearbox system parameters like mesh stiffness, damping and transmission error on the dynamic response of the system. In literature, dynamic analysis of the wind turbine drive train is performed by subjecting the drive train to constant or periodic load components only. Srikanth and Sekhar [25] modeled the wind turbine drive train by including the coupled torsional bending dynamics. Here, the wind turbine is subjected to stochastic loads which are estimated based on the Danish standard DS 472. In addition, time varying mesh stiffness of gear, stiffness of shaft and bearing are considered in the dynamic formulation. Although, the standard model is used, the obtained signals from this method are not close to realistic signals on site. Hence, the authors further improved the wind modeling and carried out the drive train analysis in the present study.