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Research paper

Investigation of electromechanical coupling vibration characteristics of an electric drive multistage gear system

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ABSTRACT

In order to investigate the electromechanical interaction mechanism, a dynamic model of an electric drive multistage gear system is established, wherein the electromagnetic characteristics of the induction machine and the translational-rotational vibration of the gearbox are considered. The influence of the electromagnetic effect on the natural vibration characteristics of the gearbox is studied. An integrated method using Campbell diagram, modal energy and speed sweep analysis is presented to identify the resonances of the electromechanical system. The spectrum characteristics of the mechanical signals and the electrical signals are also compared. The results demonstrate that the magnetic field introduces a new vibration mode to the gearbox and changes the low-frequency torsional vibration characteristics of each component. The system investigated in this study exhibits resonance risk when the rotor speed approaches 989 r/min, and it requires special attention during actual operation. When mechanical resonance occurs, recognizable shape features appear in the spectrum of the current and electromagnetic torque. This study supplies some guidance to the design, speed adjustment, and monitoring of electric drive gear systems.

1. Introduction

Electric drive gear systems are a typical electromechanical system that is widely used in electric vehicles, wind turbines, coal-mining machines, and other mechanical equipments. With the development of electric drive systems directed toward large-power and high-integration, the problems due to the mechanical vibration caused by the electromechanical interaction effect gradually appear and intensify [1,2]. Excessive vibration is generally accompanied by severe dynamic load, which accelerates the failure of components and endangers the stability of system operation. Therefore, it is critical to study the vibration characteristics of electric drive systems and understand the interaction mechanism that aids enhancement of the dynamic performance of the systems, and ensures reliable operation of the mechanical equipments.

An electric drive gear system generally comprises four fundamental functional modules: electric machine, gearbox, power grid/power supply, and load device, as illustrated in Fig. 1. The electric machine converts the electrical energy from the power supply into mechanical energy when operating as a motor, and converts mechanical energy from the load device into electrical energy when operating as a generator.

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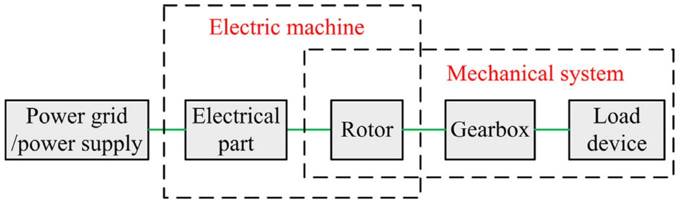

Fig. 1. Constituent parts of an electric drive gear system.

At present, a majority of the authors treat an electromechanical coupling system as uncoupled, and study the vibration characteristics of electric machine and mechanical drive system separately. Among them, a few authors considered the electric machine shown in Fig. 1 as the main object, and adopted an electromechanical rotor model without considering the rest of the drivetrain [1,2] or with the rest of the drivetrain simplified as a spring vibrator connecting to the rotor [3–5]. The above-simplified model exhibits few degrees of freedom and can be used for the vibration analysis of the rotor under electromechanical interaction. However, dynamic excitations from gear meshes and shaft deformations are neglected. Neither the natural vibration characteristics of the entire drive system nor the dynamic performance of each component can be completely presented. Meanwhile, the other section of authors were mainly concerned with the mechanical system shown in Fig. 1, and studied the free and forced vibration characteristics of the gearbox. Helsen et al. [6] established the multibody dynamics model of a wind turbine gearbox, and analyzed the influence of structural flexibility on the modal behavior of the system. Qin et al. [7] derived the vibration differential equations of a wind turbine drivetrain by using the Lagrangian formula, and investigated dynamic characteristics such as mesh force and transmission error. Yu et al. [8] adopted a new load-sharing index based on the Floquet-Lyapunov theory to evaluate the influence of various structural parameters on the load sharing performance of multiple-mesh gear pairs of a tunnel-boring machine. Chen et al. [9] integrated a dynamic model of an electric traction gearbox with the locomotive-track coupled vertical dynamic model, and studied the vibration responses of the components on the locomotive under the combined effect of gear mesh excitation and wheel-rail excitation. Khabou et al. [10] studied the nonstationary vibration characteristics of a single-stage gear during start-up of the motor. The above-mentioned studies have considered various types of configuration of electric drive gear systems as study objects, and the detailed vibration models of the gear systems were established. However, the electrical part is not considered, and the rotor speed and electromagnetic torque of the machine are set as known conditions. Although this method is straightforward to implement, it is not capable of reflecting the effect of the electrical system on the mechanical system, thus the magnetic field-induced mechanical vibration cannot be presented.

Many translational-rotational vibration models using the lumped parameter method have been developed to simulate the behavior of planetary gears. Kahraman [11] derived a nonlinear dynamic model of a planetary gear set and investigated the sensitivity of load sharing characteristics to design, manufacturing and assembly related variations. Lin and Parker [12] modified the model of Ref. [11] by adopting a different coordinate system and investigated the natural frequency spectra and vibration modes of general planetary gears. Guo and Parker [13] extended the model of Ref. [12] and introduced tooth wedging, bearing clearance, mesh stiffness variation and gravity into the model. Kim et al. [14] proposed a dynamic model of a planetary gear set with the pressure angles and contact ratios regarded as time-varying variables. In these models, one of the standard assumptions is that the gears and carrier rotate with the prespecified speeds. However, in reality, the rotation speed of a gear system is determined by the external loads, and usually unknown before the simulation especially when operating in a nonstationary condition. In addition, only the elastic vibration of the gears is taken into account in these models, whereas the rotation of the rotor in an electric machine model generally contains rigid-body motion component, therefore the above models cannot be directly used to connect with the model of electric machine. Liu et al. [15] proposed a dynamic model of the herringbone planetary gear set for variable speed process with the position of the contact lines determined by the gear angular displacements. Based on Liu's work, a translational-rotational dynamic model of the spur planetary gear set is proposed using a different coordinate system in this paper. In the model, both the rigid rotation and elastic vibration of the gears are considered, and the gear mesh stiffness and mesh error are expressed in a different manner. The essential new feature of this model is that the dynamics of the gears is determined by the external loads, rather than the prespecified rotation speed, which was done in earlier related studies.

An electric machine exhibits the characteristics of sensors, and machine current signature analysis (MCSA) has been considered as an alternative to conventional vibration signature analysis for electromechanical system monitoring. A few researchers have attempted to use electrical signals such as stator phase current and electromagnetic torque of the electric machine to diagnose faults in the gearbox. In the studies conducted in Refs. [16–19], the response characteristics of electrical signals from the electric drive gearboxes having faults such as spalling, tooth cracking, pitting, and eccentricity were analyzed separately, using fixed-shaft or simplified planetary gear models. However, the above-mentioned studies focus mainly on single-stage gearboxes; furthermore, research on the effect of mechanical resonances on the responses of the electrical signals is rarely mentioned in the existing literatures.

In this study, an electromechanical dynamic model for an electric drive gear system is established, by integrating the lumped parameter model of the multistage gearbox and the equivalent circuit model of the induction machine through the