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Dynamic characteristics of motor-gear system under load saltations and voltage transients

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ABSTRACT

In this paper, a dynamic model of a motor-gear system is proposed. The model combines a nonlinear permeance network model (PNM) of a squirrel-cage induction motor and a coupled lateral-torsional dynamic model of a planetary geared rotor system. The external excitations including voltage transients and load saltations, as well as the internal excitations such as spatial effects, magnetic circuits topology and material nonlinearity in the motor, and time-varying mesh stiffness and damping in the planetary gear system are considered in the proposed model. Then, the simulation results are compared with those predicted by the electromechanical model containing a dynamic motor model with constant inductances. The comparison showed that the electromechanical system model with the PNM motor model yields more reasonable results than the electromechanical system model with the lumped-parameter electric machine. It is observed that electromechanical coupling effect can induce additional and severe gear vibrations. In addition, the external conditions, especially the voltage transients, will dramatically affect the dynamic characteristics of the electromechanical system. Finally, some suggestions are offered based on this analysis for improving the performance and reliability of the electromechanical system.

1. Introduction

An electrical machine connected to a planetary gearbox composes an electromechanical power-train that can be found in various heavy-duty applications such as wind turbines, coal mining machines, helicopters and automobiles. The planetary gear system has a number of advantages including high power-to-weight ratio, reduced cost, high energy efficiency, balanced motion, coaxial arrangement and high degree of reliability [1–3]. However, besides the internal excitations such as time-varying mesh stiffness, the electromechanical system often operates under severe external working conditions such as large fluctuations of the external load or voltage transients due to faults in the power supply system [4–6]. A failure in the planetary gearbox can cause catastrophic accidents and extended downtimes, and require expensive maintenance. Therefore, it is crucial to conduct the electromechanical dynamic analysis for the motor-gear system under different working conditions in order to improve the dynamic performance and system reliability.

Much of the research in the area of electromechanical dynamic analysis focuses on the accurate and efficient modeling of electronic power machine for the realistic simulation of power transmission systems. Conventional lumped models (d-q models) of electric machines are incapable of including the spatial and nonlinear effects inside a machine. These models

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usually use estimated parameters based on experimental data. The detailed geometry of the machine cannot be taken into account directly from these lumped parameters [7].

Finite element analysis (FEA) is another common method for modeling the electronic machines. It is usually employed in the study of spatial harmonics in electric machinery considering the geometry inside the motors. This method has excellent accuracy, but requires much more computational time. One alternative approach that can include spatial effects is the Permeance Network Model (PNM). The PNM has the advantage of close association with the physical field distributions in the machine similar to FEA, but is less computationally intensive. Therefore it can be implemented in more advanced studies in which the interaction of gear system and electric machine is important. In a word, the PNM can provide a compromise between finite element model and d-q type model with sufficient accuracy [8–10], and is adopted in this study.

One of the major concerns for the electronic machines is power quality, because severe problems may occur if the power supply has a failure [4]. As one of the most common electrical equipments used in industrial application, induction motor is sensitive to voltage transients as they are connected directly to power supply or through a converter. For instance, when the motor is subject to voltage sag, high current peaks and torque peak emerge at the beginning and at the end of voltage sags (voltage recover) instants and the speed loss occurs. The values of current peaks, torque peak and speed loss depend on the sag characteristics, such as the magnitude and duration. Many experimental and analytical studies have been carried out to investigate the effects of voltage transients on the induction motors [11,12]. However, few studies can be found for the dynamic characteristics analysis of the motor-gear electromechanical system under voltage transients, which is addressed in this study.

As for the gear system, many dynamic models of planetary sets have been proposed in the literatures. Kahraman [1] proposed a simplified pure torsional model of a single-stage planetary gear set and compared the torsional natural frequencies with those predicted by a more sophisticated transverse-torsional model. Lin and Parker [13] proposed an analytical model of planetary gears which includes key factors that affects the gear vibration such as the gyroscopic effects and time-varying stiffness. Kim et al. [14] proposed a dynamic model of planetary gear set in which the pressure angles and contact ratios are time-varying. These models are proposed mainly to investigate the vibration properties of gear transmission systems. They can only be used in vibration analysis of transmission systems at a mean or constant rotational angular velocity, and therefore not suitable for transient analysis of variable speed process. Some dynamic models [15,16] of planetary gear set in nonstationary operations have been proposed based on these models [13,17] by modifying the meshing stiffness according to the rotational angle with a mean or constant rotational speed. These gear system dynamic models usually use gear mesh vibratory displacements as generalized coordinates, or consider rotating speed of gear transmission as a given information [15,16]. However in reality, the rotational speed of an electromechanical system is always changing. As a result, these models cannot be directly used to connect with the electric motor model. A translational-torsional dynamic model of the herringbone planetary gear set for variable speed process has been proposed by Liu et al. [2,18], in which the translational and rotational displacements are chosen as the generalized coordinates. In this paper, a lateral-torsional dynamic model for variable speed process of the spur planetary gear set is proposed based on Liu's work, which can connect with the electric motor model for the electromechanical dynamic analysis. In addition, the mesh stiffness is calculated based on potential energy method, which can be further used to study the effect of gear faults and gear ring elasticity.

So far, none of the aforementioned studies above considered electromechanical coupling effect such as the interactions among the internal excitations of the motor and the planetary gear system. However, in practice, these internal factors such as spatial harmonics and magnetic saturation, as well as the external excitation such as voltage transients can significantly affect the dynamic behavior of the system. Therefore, the primary goal of this study is to investigate the effects of the various internal and external excitations on the dynamic characteristics of the coupled electromechanical system.

This paper proposes a method to formulate a more comprehensive model of the electromechanical system including a nonlinear permeance network model of electric motors with a lateral-torsional dynamic planetary gear system. The nonlinear PNM method makes it possible to consider winding distribution, stator and rotor slotting, nonlinearity of the materials in electric machine. The lateral-torsional dynamic planetary gear system takes into account the time-varying gear mesh stiffness calculated from an analytical method based on the potential energy principle. The external load saltations, which is common for electromechanical systems, and the effect of power faults are also considered in the model. An example has been given to simulate the dynamic behavior of the electromechanical system when the supply three-phase voltage suffers a disconnection for 10 ms and a sudden 40% reduction from line-line 230 V (RMS) separately. The dynamic characteristics of the electromechanical including the transient stator and rotor currents, varying rotor rotational speed, electromagnetic torque of the electric motor and dynamic gear mesh forces of the planetary gear system are obtained.

The rest of the paper is structured as follows: Section 2 presents nonlinear PNM induction machine model; Section 3 presents dynamic models of the planetary gear system and lumped-parameter induction machine; and Section 4 presents dynamic characteristics simulation and analysis for the electromechanical system under startup, normal load, load saltations, voltage interruption and voltage sags. Finally, some conclusions and suggestions for design improvements based on the analysis are presented in Section 5.

2. Nonlinear PNM induction machine model

Permeance network models (PNM), also known as reluctance network models or magnetic equivalent circuits (MEC), can be used to study steady-state and transient performance of electrical machines. This method was first introduced by Lwith-