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Dynamic characteristic of electromechanical coupling effects in motor-gear system

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ABSTRACT

Dynamic characteristics of an electromechanical model which 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 is analyzed in this study. The simulations reveal the effects of internal excitations or parameters like machine slotting, magnetic saturation, time-varying mesh stiffness and shaft stiffness on the system dynamics. The responses of the electromechanical system with PNM motor model are compared with those responses of the system with dynamic motor model. The electromechanical coupling due to the interactions between the motor and gear system are studied. Furthermore, the frequency analysis of the electromechanical system dynamic characteristics predicts an efficient way to detect work condition of unsymmetrical voltage sag.

1. Introduction

The electromechanical power-train system such as an induction machine combined with a planetary gear set is used in many types of machinery due to its manifold advantages such as high reliability, high power-to-weight ratio, low cost, etc. [1,2]. However, the electromechanical system is often subjected to the electric abnormalities and its mechanical failures [3–5]. Its wide applications in modem industries make it crucial to conduct an electromechanical dynamic analysis for the motor-gear system in order to improve the dynamic performance and system reliability.

Much of the current research in this area focuses on the machine current signature analysis [6–8] or the accurate and efficient modeling of electronic power machine [9–11]. The most common methods for electronic power machine modeling are the lumped-parameter model and finite element (FE) model. However, the conventional lumped-parameter model is incapable of including the spatial and nonlinear effects inside a machine [12] and the finite element model requires massive computational time when allowing for spatial harmonics and nonlinear effects with excellent accuracy [13]. In this study, the permeance network model (PNM) is applied to simulate the dynamic motions of the electric induction machine. The PNM or the magnetic equivalent circuits (MEC) of the electric machine is formally introduced by E. R. Laithwaite [14] in 1967 and V. Ostovic [15] developed it by building a series of sophisticated PNMs of induction machine and permanent magnet synchronous machine. P. Sewell et al. [16] applied the PNM approach to simulate the dynamic performance of induction machine by incorporating the permeance values from the FE method. S. D. Sudhoff et al. [17] proposed a PNM based state-variable

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model of induction machine with the permeance parameters directly calculated from geometrical data. X. Han et al. [18] proposed a coupled PNM motor model calculating both the radial and tangential motor eccentric forces for mechanical vibration stability and nonlinear behavior analysis. The advantage of the PNM motor model is that it can achieve a good balance between accuracy and efficiency. It is similar to the FE model that it is able to model the physical field distributions in the machine, but with much less computations. In addition, it can be implemented in further studies in which the dynamic interactions of gear system and electric machine are important.

There are various kinds of dynamic gear system models proposed by scholars for different research objects and purposes. For example, J. Lin and R. G. Parker [19] proposed an analytical model of planetary gears for natural frequencies and vibration modes sensitivities analysis in which the carrier angular speed is restricted to constant or mean values as the carrier acceleration is ignored. A. Kahraman et al. [20] put forward a vibration model of a multi-mesh gear train with the vibrational displacements as variables which cannot be used to connect with the motor model directly by rotational angular variables. Ph. Velex et al. [21] set up a torsional gear model with time-varying mesh stiffness and unsteady input rotational speed due to live reciprocating engine combustion and inertial effects. M. T. Khabou et al. [22] proposed an eight degree-of-freedom gear dynamic model in transient regime such as machine start up process and engine acyclic condition. These two models modified the mesh stiffness according to the rotational angle or speed of gears. However, the input engine rotational speed was given or a simple relation function between torque and speed was assumed instead of using a sophisticated motor model. To address this issue, G. Clerc et al. [23] proposed a combined PNM motor model with a dynamic model of spur or helical gears for motor defects and gear faults analysis. Unlike the single stage gear model used in Ref. [23], a lateral-torsional dynamic model for variable speed process of the spur planetary gear set [24] based on Liu's model [25] is used in this paper. The applied model can connect with the electric motor model for the electromechanical dynamic analysis.

Power quality is of great importance to electromechanical system because severe problems may occur if the power supply has a failure [3,26]. As one of the most common electrical equipment used in industrial application, induction motor is sensitive to voltage unbalance. J. Pedra et al. [27] found that the unsymmetrical voltage sags can cause torque and current peaks, and speed loss to the three-phase squirrel-cage induction motor behavior. A. S. Nautiyal et al. [28] proposed a competent approach to explain torque-speed, torque-time and speed-time characteristic of an induction motor operating under different degree and conditions of voltage unbalance. L. Guasch et al. [29] analyzed different consequences brought by the unsymmetrical voltage sag magnitude and duration, type of sag, and initial point-on-wave on the induction machines behavior. Experimental study has also been carried out to investigate the effects of unsymmetrical voltage sag on the induction motor by F. Babaa et al. [30]. However, very few studies can be found for the dynamic characteristics analysis of the motor-gear electromechanical system under unsymmetrical voltage sags. The primary goal of this study is to further investigate the electromechanical coupling effects of the motor-gear electromechanical system with emphasis on the slots effect and saturation effect of the motor coupling with effects of the time-varying stiffness and different shaft stiffness on the dynamic characteristics for the electromechanical system. Meanwhile, operation conditions monitoring of the system under unsymmetrical voltage sags and variable input loads is also investigated here. It is different from our previous studies e.g., the dynamic behavior analysis of the electromechanical system focuses on the effects of the different external conditions like load saltations and three-phase voltage transients in Ref. [24] or the effects of the electromagnetic stiffness and damping from the induction machine on the nature vibration characteristics of the multistage gear system in Ref. [31].

This study uses a comprehensive dynamic model of the electromechanical system based on previous study [24]. The model contains a nonlinear permeance network model of electric motors with a lateral-torsional dynamic planetary gear system. Some simulation examples have been given to show the dynamic behavior of the electromechanical system. The dynamic characteristics including spectra of stator and rotor currents, varying rotor rotational speed, electromagnetic torque, dynamic mesh forces and accelerations of the ring gear are obtained.

The rest of the study is structured as follows: Section 2 presents the PNM motor model. Section 3 presents dynamic models of the planetary geared rotor system and the induction machine. Section 4 presents dynamic characteristics simulation and analysis for the electromechanical system with or without load and unsymmetrical voltage sags separately. Finally, several conclusions are presented.

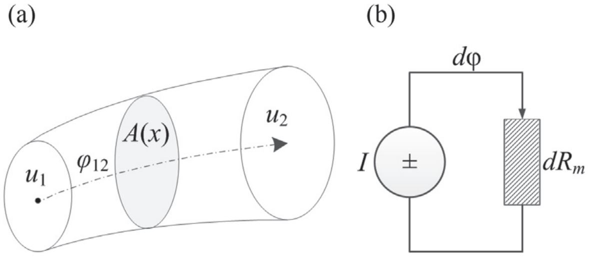

Fig. 1. Geometric definition of (a) a flux tube and (b) a magnetic equivalent circuit.