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Nonlinear dynamic behaviors of permanent magnet synchronous motors in electric vehicles caused by unbalanced magnetic pull

Changle Xiang, Feng Liu*, Hui Liu, Lijin Han, Xun Zhang

School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

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ABSTRACT

Unbalanced magnetic pull (UMP) plays a key role in nonlinear dynamic behaviors of permanent magnet synchronous motors (PMSM) in electric vehicles. Based on Jeffcott rotor model, the stiffness characteristics of the rotor system of the PMSM are analyzed and the nonlinear dynamic behaviors influenced by UMP are investigated. In free vibration study, eigenvalue-based stability analysis for multiple equilibrium points is performed which offers an insight in system stiffness. Amplitude modulation effects are discovered of which the mechanism is explained and the period of modulating signal is carried out by phase analysis and averaging method. The analysis indicates that the effects are caused by the interaction of the initial phases of forward and backward whirling motions. In forced vibration study, considering dynamic eccentricity, frequency characteristics revealing softening type are obtained by harmonic balance method, and the stability of periodic solution is investigated by Routh–Hurwitz criterion. The frequency characteristics analysis indicates that the response amplitude is limited in the range between the amplitudes of the two kinds of equilibrium points. In the vicinity of the continuum of equilibrium points, the system hardly provides resistance to bending, and hence external disturbances easily cause loss of stability. It is useful for the design of the PMSM with high stability and low vibration and acoustic noise.

1. Introduction

Permanent magnet synchronous motors (PMSM) have been widely used in hybrid electric vehicles (HEV) and electric vehicles (EV) because of their fast response, high efficiency, high power density and high precision [1–3]. PMSM are required to have a smooth and quiet operation when used in HEV and EV. Therefore, noise and vibration of PMSM are considered a critical issue [4].

In rotating electric machines, electromagnetic radial forces acting on rotor and stator surfaces are much larger than tangential forces that produce torque. However, the radial forces cancel out each other when the air-gap distribution between rotor and stator is uniform in a cross section [5,6]. In fact, because of some reasons that are mentioned in following statement, rotor-stator eccentricity is inevitable, which may result in excessive acoustic noise and vibration [7]. In general terms, rotor-stator eccentricity can be principally classified into static eccentricity, dynamic eccentricity and mixed

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* Corresponding author.
E-mail address: lflhj2009@163.com (F. Liu).

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eccentricity [8,9]. Static eccentricity is caused by the axis of the rotor not being aligned with that of the stator although it still rotates about its own axis [10]. This can occur for example simply due to manufacturing tolerances, assembly errors, bearings wear, and so forth [5,10,11]. Dynamic eccentricity is caused by the center of rotation of the rotor not being aligned with the rotor axis. The usual causes are also manufacturing tolerances, bearings wear and incorrect manufacture. Rotor whirl near a critical speed is another source of dynamic eccentricity and is an important consideration in larger, flexible-shaft machines [10,11]. Mixed eccentricity is that static eccentricity and dynamic eccentricity exist simultaneously. When the rotor is eccentric with respect to the stator, the air-gap distribution is not uniform and causes the unbalance of the electromagnetic forces. Consequently a net radial force is generated, known as unbalanced magnetic pull (UMP), which pulls the rotor towards the stator in the direction of the minimum air-gap. UMP tends to further increase the eccentricity magnitude and acts as a source of vibration and acoustic noise [10,11].

According to the above statement, calculation of UMP is essential for vibration analysis. During the past several decades, many papers have been published on the subject of UMP. In general, the studies present in literature can be roughly classified in two methods: analytical method and finite element method. Finite element method [12] can now offer more accurate solutions to this problem, but this approach is very computationally expensive and often cannot provide an insight into the origins and key factors in the production of UMP [10]. Therefore, more scholars devoted to analytical method and an extensive approach for calculation of UMP was applied. Using the method based on the idea of modulating the harmonic magnetic motive force (MMF) waves by the air-gap permeance expressed as a Fourier series, the analytical expression of the air-gap flux density is obtained, which carries information about eccentricities [13–16]. Then the expressions of UMP with different pole pairs are developed by using Maxwell tensor method [15].

Due to nonlinearity and negative stiffness effect, UMP plays a key role in the vibration of motor, such as orbit, stability. Rotor mass unbalance and external forces induce cylindrical and conical whirls of the rotor and then the whirls cause the variation of the air-gap, thus yielding UMP acting upon the rotor, which again adversely affects the whirls of the rotor system [10]. Then a coupled phenomenon occurs between mechanical characteristics and magnetic origins through the air-gap in rotor-stator vibration system [10,17,18]. Pennacchi et al. [5] presented the simulation of the dynamical behaviors of a 320 MVA generator, showing the harmonic content of UMP and the presence of nonlinearities. He et al. [19] built up numerical models to predict the vibration and noise behaviors of permanent-magnet direct current commutator motor with UMP. Shin et al. [4] analyzed the vibration characteristics of PMSM through investigation into its electromagnetic vibration sources of which the specific harmonic orders were studied by the fast Fourier transformation (FFT) analysis. Xu et al. [20] took advantage of an analytical method for UMP along with finite element model for the rotor system, and studied influences of UMP on the radial vibration of the rotor system. Kim et al. [21] used finite element transfer matrix (FETM) to investigate the transient whirl response of rotor-motor system and the result indicates that magnetically coupled origins enhance the system vibration by reducing the system stiffness of radial direction, comparing with purely mechanical origins. Therefore, some scholars began to focus on the stability of the system. Gustavsson et al. [22] investigated the influence of UMP on the rotor stability for a synchronous hydropower generator with the assumption of proportional damping. Calleecharan et al. [8] and Wu et al. [23] applied rotor model to study the dynamic consequences of UMP on generator. Furthermore, eigenvalue-based stability analysis was performed which offers insights in system design parameters. Chen et al. [24] investigated the stability and frequency characteristics of PMSM in HEV. Lundström et al. [25] analyzed the dynamic behavior of generator through the use of symmetries for certain cases. For different shape deviations the basin of attraction was studied for rotor-stator impact motions.

Most of these papers mentioned above paid attention to the electric machines within narrow speed range, especially for hydro-generators operating at rated speed. They mainly devoted to the precise calculation of UMP, and then calculated dynamic response by numerical method. These researches cannot present the vibration characteristics of the rotor system in detail, such as multiple equilibrium points, modulation phenomena, analytical solution, frequency characteristics [24], etc. It is noticeable that the study of the coupling mechanism caused by UMP of PMSM in HEV and EV from a mechanical and dynamic perspective is still lacking. Comparing with other electric machines, PMSM in HEV and EV operate over wide speed and load ranges, which make the vibration complex. As a part of the powertrain, the PMSM are connected to gearbox and the manufacturing errors, assembly errors and extra load influencing the bearing wear [17], lead to the rotor unbalance, so UMP occurs when vehicle is in motion. In addition, excitation deriving from road roughness can impact on the rotor through powertrain, whilst internal combustion engine also acts as an external excitation for HEV. The excitations further result in the increase of UMP. Usually, the excitation signals include high gear-meshing frequencies, especially, planetary gear sets widely used in HEV and EV powertrains and then the radial vibration becomes significant when one or more forcing frequencies of planetary gear sets match the rotor resonant frequencies. The factors mentioned above may severely degrade the performance of the PMSM, causing irreversible demagnetization of permanent magnets, wear of bearing, rubbing of rotor and stator, and so forth [11]. Therefore, the nonlinear dynamic behaviors caused by UMP of the PMSM require deeper investigation.

The purpose of this paper is to study nonlinear dynamic behaviors of the rotor system of PMSM in HEV and EV. In this paper, we only consider the common situation that the pole-pair number is larger than 3. Under this prerequisite, in Section 2, UMP model and the governing equations for the rotor system are presented. In Section 3, the system stiffness characteristics influenced by UMP are analyzed. In Section 4, the nonlinear dynamical behaviors of the free vibration and forced vibration are investigated, respectively. In free vibration study, eigenvalue-based stability for multiple equilibrium points is analyzed and hence the static bifurcation diagram is plotted. Amplitude modulation effects caused by UMP are discovered of which the