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Analytical framework of gearbox monitoring based on the electro-mechanical coupling mechanism

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Abstract

Along with the development of the Hybrid Electric Vehicles (HEVs), the permanent magnetic synchronous motor (PMSM) and the planetary gearbox is widely used because of its high power density. There is much significant electro-mechanical coupling phenomenon in the mechanical installations. The aim of this paper is the analytical study of a planetary gearbox by using the stator current signature analysis in the PMSM based on the electro-mechanical coupling mechanism. This paper proposes a mathematical framework based on the electro-mechanical coupling model of the PMSM-planetary gearbox system, considering the load torque oscillation and the time-varying mesh stiffness. The model simulation result shows that from the mathematical framework, the load torque oscillation frequency and the time-varying mesh stiffness frequency can be predicted through the current frequency. The proposed mathematical model is verified by the model simulation. And a test-bed based on a 60kW three-phase PMSM connected to a planetary gearbox has been used. Fourier transform is applied to the demodulated torque signal and current signal for denoising and removing the intervening neighbouring features.

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Keywords: PMSM, motor current signal analysis, fault diagnosis, planetary gearbox, Fourier transform

1. Introduction

Planetary gearboxes and permanent magnet synchronous machines (PMSM) are preferred in many drive-trains applications, such as wind turbines, maritime and automobiles, as they allow for a larger transmitted torque to weight ratio, easily control, high reliability and efficiency, and reduced maintenance costs. However, failures in these components can often result in catastrophic accidents, large down-times and expensive maintenance. Therefore, detecting such failures at early stage can significantly reduce the associated capital losses and down-time. The study of the gearboxes fault detection in electromechanical systems has been mainly performed using vibration and acoustic based methods [1-5]. Vibration signals have numerous disadvantages like signal background noise due to external perturbations, sensitivity to the censor location, and their invasive installation environment [6]. Motor current signal analysis(MCSA) can present an alternative for mechanical analysis based on the electrical signatures of electric motors.

The potential of stator current analysis is mentioned in [7-9]. It has been shown that the mechanical faults can be reflected on the motor current. Some cases are studied where load torque oscillations cause

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changes in the stator current spectrum, showing the feasibility of the MCSA monitoring of mechanical perturbations. Mechanical faults such as static and dynamic air-gap eccentricities and the bearing faults have been successfully detected through AC motor stator current [10-12].

Publications related fixed-axis gearbox monitoring using MCSA in induction machine-based electromechanical systems are presented in [13-17]. Primarily, a multistage gearbox for a mechanical fault case is studied in [14] and [15]. It is shown that the rotating as well as the mesh frequency components can be detected in the stator current spectrum. However, the monitoring of the planetary gearbox using MCSA in PMSM-based electromechanical systems has been challenging so far because of the difficulties in modeling the planetary gear-set such as a large number of degrees of freedom and nonlinearity in the PMSM model.

The electro-mechanical drive-train consisting of a PMSM connected to a load through a planetary gearbox is modeled by Jaspreet [18]. Then the PMSM stator current response under healthy and faulty gear tooth conditions can be evaluated. Nevertheless, Jaspreet show the result without any proposed explicit theoretical development for the analyzed frequency components.

Fourier transform(FT) is used to decompose a signal into many levels with different frequency bandwidth. This will demodulate the signal for denoising and removing the intervening neighbouring features.

In this paper, the electro-mechanical drive-train consisting of a PMSM connected to a load through a planetary gearbox is modeled. The PMSM is modeled by Park's equation [19]. The planetary gearbox is modeled by a lumped multi-body dynamic model [20]. If a fault exists in one of the gears, such as spalled tooth, it results in a reduced gear meshing stiffness as the faulty tooth passes through the gear meshing [6]. Then a theoretical framework based on the observation of the torque spectrum is developed for a PMSM connected to a planetary gearbox without any faults for the purpose of mechanical analysis. It is shown that due to the torsional vibration induced by the load oscillation in the output wheels and the stiffness variation of the gear teeth contact, the gearbox adds the rotation and mesh frequency components into the torque signature. This effect makes the stator current multicomponent phase modulated. Then the Fourier transform(FT) is used to decompose the stator current signal in the test-bed to verify the theoretical framework.

2. Dynamic model of the electro-mechanical drive-train

2.1. PMSM model

A PMSM model and the electromagnetic torque can be represented in a representation as [21]

$$\begin{aligned}\dot{\mathbf{\Lambda}} &= \mathbf{A}(\omega_r)\cdot\mathbf{\Lambda} + \mathbf{V} + \mathbf{R}\cdot\mathbf{L}^{-1}\cdot\mathbf{G}\cdot\lambda_f' \\ T_e &= (3/2)(P/2)\left(\mathbf{\Lambda}^T - \mathbf{G}^T\cdot\lambda'\right)\left(\mathbf{L}^{-1}\right)^T\cdot\mathbf{W}\cdot\mathbf{\Lambda}\end{aligned} \tag{1}$$

Where, $\mathbf{\Lambda}$ is the magnetic flux vector and $\mathbf{V}$ is the terminal voltage vector, $\mathbf{I}$ is the current vector, vector $\mathbf{G}$ is a constant matrix, $\mathbf{R}$ is the resistance matrix, P is the number of the poles and $\mathbf{L}$ is the inductance matrix, $\mathbf{A}(\omega_r)$ is a function of electrical rotor speed ω_r, and are described as

$$\begin{aligned}&\mathbf{\Lambda} = \begin{bmatrix}\lambda_{qs} & \lambda_{ds}\end{bmatrix}^T,\ \mathbf{V} = \begin{bmatrix}v_{qs} & v_{ds}\end{bmatrix}^T,\ \mathbf{I} = \mathbf{L}^{-1}\cdot\left(\mathbf{\Lambda} - \mathbf{G}\cdot\lambda_f'\right),\ \mathbf{R} = diag\begin{bmatrix}r_s & r_s\end{bmatrix} \\ &\mathbf{G} = \begin{bmatrix}0 & 1\end{bmatrix}^T,\ \mathbf{A}(\omega_r) = -\left(\mathbf{R}\cdot\mathbf{L}^{-1} + \omega_r\cdot\mathbf{W}\right),\ \mathbf{L} = \begin{bmatrix}L_q & 0\\ 0 & L_d\end{bmatrix},\ \mathbf{W} = \begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix}\end{aligned} \tag{2}$$

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