Journal of Sound and Vibration 331 (2012) 2070–2079

Contents lists available at SciVerse ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Design sensitivity analysis of dynamic responses for a BLDC motor with mechanical and electromagnetic interactions

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ARTICLE INFO

Article history:
Received 20 July 2011
Received in revised form
3 December 2011
Accepted 30 December 2011
Handling Editor: H. Ouyang
Available online 24 January 2012

ABSTRACT

This paper presents a design sensitivity analysis of dynamic responses of a BLDC motor with mechanical and electromagnetic interactions. Based on the equations of motion which consider mechanical and electromagnetic interactions of the motor, the sensitivity equations for the dynamic responses were derived by applying the direct differential method. From the sensitivity equation along with the equations of motion, the time responses for the sensitivity analysis were obtained by using the Newmark time integration method. The sensitivities of the motor performances such as the electromagnetic torque, rotating speed, and vibration level were analyzed for the six design parameters of rotor mass, shaft/bearing stiffness, rotor eccentricity, winding resistance, coil turn number, and residual magnetic flux density. Furthermore, to achieve a higher torque, higher speed, and lower vibration level, a new BLDC motor was designed by applying the multi-objective function method. It was found that all three performances are sensitive to the design parameters in the order of the coil turn number, magnetic flux density, rotor mass, winding resistance, rotor eccentricity, and stiffness. It was also found that the torque and vibration level are more sensitive to the parameters than the rotating speed. Finally, by applying the sensitivity analysis results, a new optimized design of the motor resulted in better performances. The newly designed motor showed an improved torque, rotating speed, and vibration level.

1. Introduction

A type of electrical motor widely used in many industrial applications is a brushless DC (BLDC) motor. BLDC motors have many advantages including low noise, high rotating speed, and high reliability. Therefore, these motors are used in many applications such as driving motors in robots, electrical vehicles, and home appliances. A recent trend is that motors require more accurate control of the electrical torque and rotating speed as well as low noise and vibration. To improve motor performances including torque, speed, and vibration, many researchers have developed efficient tools to design electrical motors such as sensitivity analysis. However, sensitivity analysis is mainly used for mechanical designs rather than in the design of electrical motors. Recently, as higher motor performances are required, sensitivity analysis is often used for the design of BLDC motors.

Most researchers put more focus on the electromagnetic behavior rather than mechanical behavior in the design of electrical motors. For this reason, their governing equations consider the electromagnetic behavior including the current,

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2011.12.034

electromagnetic torque, and rotating speed but exclude the translational motion. Therefore, the parameters evaluated for motor design have often been resistance, inductance, and magnetic flux density. Pillay and Krishnan [1] proposed circuit equations for a BLDC motor in the *abc* frame as well as the rotational equation and investigated the stator current and electromagnetic torque. A synchronous machine model which can be readily implemented in circuit-based simulation programs was reported by Pekarek et al. [2]. Since the equations of this model are only circuit equations, they can be used for parametric study of the resistance and inductance. Han et al. [3] described the average-value modeling of BLDC motor–inverter systems, which is more accurate for control of the logic circuit. Related to the sensitivity analysis for motor design, Ansuj et al. [4] presented a mathematical method for estimating the equivalent circuit parameters of induction machines from the most readily available performance characteristics. Through this method, they predicted the torque, speed, and performance of the induction motor. Zhang and Zhan [5] analyzed the sensitivity of pulse width modulation (PWM) speed control for a DC permanent magnetic motor with respect to motor control system parameters. In their analysis, the system parameters evaluated were the resistance, inductance and input voltage. For the parameter sensitivity analysis of induction motor drives, an improved open-loop speed estimation algorithm was introduced by Bolognani et al. [6]. All of the studies mentioned above did not consider interactions between electrical and mechanical behaviors. As a result, mechanical and electromagnetic parameters were not analyzed simultaneously.

Even though only the electromagnetic parameters were analyzed in the previous research for the sensitivity analysis of electrical motors, mechanical parameters as well as electromagnetic parameters should also be included. In fact, the motor performances such as torque, speed, and vibration level are also influenced by mechanical parameters such as the rotor mass, shaft/bearing stiffness, and rotor eccentricity. Most of the previous sensitivity studies of electrical motors analyzed the sensitivity of a motor control. Therefore, the previous studies have generally only investigated the electromagnetic characteristics for variations of the resistance and inductance. However, since a practical motor system is composed of mechanical and electromagnetic components, the mechanical and electromagnetic parameters should be simultaneously considered. Related to this topic, Im et al. [7] presented nonlinear equations of motion for a BLDC motor, which considers mechanical and electromagnetic interaction due to an air gap variation between the stator and rotor. Based on Ref. [7], design sensitivity needs to be analyzed for dynamic responses of a BLDC motor with mechanical and electromagnetic interactions.

In this study, a design sensitivity analysis was performed for the dynamic responses of a BLDC motor with mechanical and electromagnetic interactions. In order to consider the mechanical and electromagnetic interactions of the BLDC motor, we utilized the governing equations of motion presented by Im et al. [7]. These equations of motion are totally coupled nonlinear equations between the mechanical displacements and the electrical currents. From these equations, the sensitivity equations for the dynamic responses were derived by using the direct differential method. By solving both the governing equations and sensitivity equations with the Newmark time integration method, the sensitivity responses of motor performances for design parameters were obtained. For the sensitivity analysis, electromagnetic torque, rotating motor speed and the radial rotor displacement were selected as the motor performances while the rotor mass, equivalent stiffness, rotor eccentricity, winding resistance, coil turn number, and residual magnetic flux density were selected as the design parameters. In addition, based on the sensitivity analysis, an improved BLDC motor with a higher torque, higher speed, and lower vibration level was newly designed by applying the multi-objective function method.

2. Derivation of the sensitivity equations

We derived the sensitivity equations for the dynamic responses of an eight-pole, 12-slot, three-phase BLDC motor presented in Fig. 1, which consists of a rotor and stator. As shown in Fig. 1, the rotor with permanent magnets undergoes rotational motion and is supported by bearings mounted on a base plate. The stator has many poles holding stator coils with wire windings. The mass and the mass moment of inertia of the rotor are m and J, respectively. The eccentricity

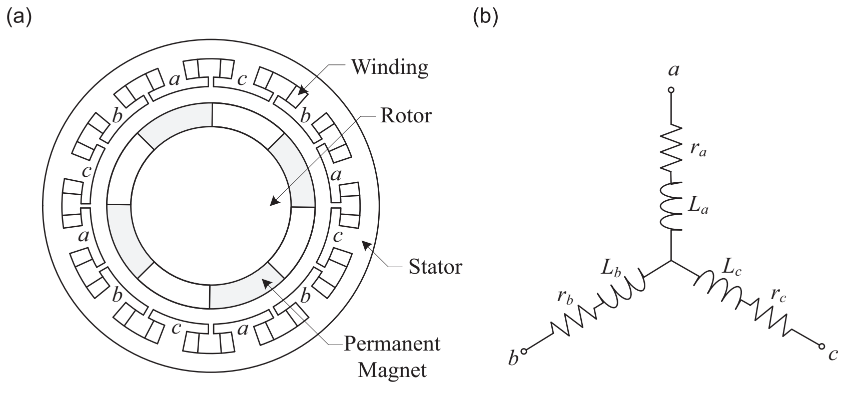

Fig. 1. Eight-pole, 12-slot, three-phase BLDC motor: (a) the mechanical structure, and (b) the Y-connection.