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Design methodology and self-turning velocity control for high-speed slim sensorless brushless direct current motors with self-lubricated bearings

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ABSTRACT

This study presents the motor design methodology and adaptive fuzzy self-tuning proportional–integral–derivative (PID) velocity closed-loop control of slim sensorless brushless direct current (BLDC) motors with self-lubricated bearings that operate at a high speed of 14,000 rpm. Moreover, the novel sensorless commutation method includes a mask-based phase shift detector to detect precise optimal commutation points. A prototype of the slim sensorless radial-flux BLDC motor with a self-lubricated bearing for use in the blowers of vacuum cleaners was manufactured and the motor design methodology was verified. The damping interaction caused by the self-lubricating hydrodynamic bearings, shafts, and blades of blowers was also considered, together with a multi-physics analysis. The velocity control experiment used a adaptive fuzzy self-tuning PID control algorithm that has been proven to improve the dynamic performance of the slim sensorless BLDC motors in the blowers of vacuum cleaners. The settling time converged within 1 s, that is, the vacuum cleaners rapidly switched to different speeds, and the control approach exhibited robustness and precision in a steady state.

1. Introduction

Direct-drive slim sensorless brushless direct current (BLDC) motors have become increasingly popular and cost-competitive choices for industrial and military applications. The power electrical drives of high-performance electrical machines have been used to develop essential techniques for motion control systems. High-speed BLDC motors have become increasingly attractive in many applications, such as electrical vehicles, aircraft, pumps, compressors, fans, machine tools, robots, and industrial equipment [1–7]. Several BLDC applications require the following characteristics: high torque density, high power density, and efficiency over a wide range of speeds and torques. In addition, motor speed limitations associated with bearing types and resonant and self-excited vibrations often occur in bearing systems, limiting the rotational speed of motors. Resonant vibrations occur when motor speeds coincide with their resonant frequencies. Self-excited vibrations cause unstable rotation, and they start after a certain threshold speed [8]. Various lubricants used on self-lubricated bearings cause shear stress diversity; however, self-lubricated bearings are velocity-sensitive bearing components. The fluidic film mechanism design, supporting pressure, and dominant frictional losses of self-lubricated bearings are essential indexes, especially for high-speed motors [9]. Magnetic Hall-effect sensors and commutation circuits of blowers are unsuitable for harsh operating conditions that are characterized by high temperatures, high levels of humidity, and restricted space. These features mean that controlling slim sensorless BLDC motors at 14,000 rpm is challenging. These challenges will increase in the future. Since the 1970s, many sensorless commutation methods for detecting motor rotor positions have been developed. Investigators have designed

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controllers using linear matrix inequality algorithms, but the disadvantage of the algorithm is that it cannot be fully optimized [10–12]. In addition, researchers have used control approaches as observer controllers, such as an extended Kalman filter, for motor applications [13–15]. A phase-locked loop circuit was proposed to monitor the back electromotive force (back-EMF) of motors to obtain the rotor angular position estimation [16]. Furthermore, many researchers have presented methods to detect zero-crossing points (ZCPs) by using the back-EMF from a stationary state to the desired speed [17–21]. To develop a high-performance sensorless motor drive system, this study presents a rotor position detection method for the sensorless control of BLDC motors. The precise ZCPs of the back-EMF can be accurately detected over a wide speed range. A traditional phase shift detector (PSD) that included two counter/timers was used to estimate the phase delay time required for the motor to rotate a 30° electrical angle [22]. A PSD that included six counter/timers achieved a 90° phase delay [23]. In this study, a novel sensorless commutation applies a mask-based PSD (MPSD) to identify the optimal commutation points (OCPs) by using the terminal voltage and central voltage of slim sensorless BLDC motors without a Hall-effect sensor [24]. To improve the transient response and decay steady-state error of systems, conventional proportional–integral–differential (PID) controllers are the most popular control rules used in industrial applications. They exhibit simple architecture and conceivable physical intuition of PID parameters [25]. However, the gain parameters of conventional PID controllers are always fixed during operation; thus PID controllers are inefficient at controlling systems with high levels of lag, parameter variations, or model uncertainty. Because of these problems, many researchers have integrated fuzzy logic control methods [26–28] to tune the gain parameters of PID controllers to improve system performance. The PID parameters are tuned by adopting fuzzy inferences, which map the speed error and the speed error change rate to correct the original fixed PID parameters. High-performance vacuum cleaners can operate and clean dust at a wide range of speed regulations and high-precision speeds to adapt to different operating environments. However, many environmental disturbances occur in different operational conditions, therefore an adaptive control law aimed at counteracting inaccurate system modeling and load variation can be used to overcome various external loads of vacuum cleaner blowers [29,30]. High-performance vacuum cleaners can rapidly switch speeds to avoid always operating at the maximal speed, extending their lifetimes. This study presents the design methodology and self-tuning velocity control of high-speed slim sensorless BLDC motors with self-lubricated bearings, which exhibit an output power of 35 W at a rated speed of 14,000 rpm. Self-tuning velocity control of adaptive fuzzy PID control algorithms applied to slim sensorless BLDC motors in vacuum cleaner blowers was efficiently and successfully demonstrated.

2. Design methodology

The design methodology of the high-speed slim sensorless radial-flux BLDC motors with self-lubricated bearings used in the blowers of vacuum cleaners is based on the following principal considerations:

I. Various physical parameters and rotor dynamical properties of the mechanical system (e.g., damping factors, self-excited and resonant frequencies, stress, and temperature) limit the speed of slim BLDC motors. Hence, they should be considered with a multi-physics analysis.
II. The relationship between torque and speed (i.e., the *T–N* characteristic curve) and the friction between the blades and shafts should be considered. The intersection points must approach the corner or resonant frequencies of motors.
III. The diameter proportions of the shafts to blades, and the ratio between active and total rotor length are crucial indexes that affect the accelerated motion, air resistance, maximal speed, and stability of motors.
IV. The bending and thrust loading caused by unbalanced force or excitation should be considered to account for the self-lubricating hydrodynamic bearing and blower fluidic effect.
V. The loading coupling from the blower dynamics and the high-speed slim sensorless radial-flux BLDC motors should be carefully manipulated. The overall efficiencies must satisfy the design specification.

Based on these considerations, the motor electromagnetic finite element analysis (FEA), self-lubricating hydrodynamic bearing operating point, blower characteristics, and closed-loop velocity control algorithms are comprehensively and conscientiously addressed in this study.

2.1. Architecture of slim sensorless radial-flux BLDC motors

The mechanical computer-aided design (CAD) and computer-aided manufacturing (CAM) design of the whole architecture of the production process and experimental prototype for the three phase high-speed slim sensorless radial-flux BLDC motors with self-lubricated bearings for blowers in vacuum cleaners are shown in Fig. 1. The cross-sectional view and all the component nomenclature of the designed high-speed slim sensorless radial-flux BLDC motors with self-lubricated bearings are shown in Fig. 2. The mechanical structure of the slim sensorless radial-flux BLDC motors primarily consists of three phases, nine-slot stators with their coil windings placed in slots using a wye connection, and rotors with 12-pole NdFeB circular permanent magnets (PMs). The cogging torque was reduced by the nine arc-shaped teeth. The blades of blowers were assembled on the top of the motor shafts for the blowers in vacuum cleaners. The total outer diameter and thickness of the designed slim sensorless radial-flux BLDC motors with a printed circuit board (PCB) were 40 mm and 18.2 mm, respectively. The designed slim sensorless radial-flux BLDC motors satisfied the requirements of vacuum cleaner blowers, such as high torque and high power densities, small dimensions, low material quantities, and compact construction. The normal mechanical and electrical parameter values of the slim sensorless radial-flux BLDC motor prototype used in vacuum cleaner blowers are shown in Table 1. The motor resistance and inductance of a single phase can be measured by an LCR meter that is set up at a suitable operational rated voltage and current. The moment of inertia (with a rotor mass of 18 g and a radius of 15.5 mm) can be calculated using CAD and CAM software. SI units are used to ensure that the motor torque constant is