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Optimization of brushless direct current motor design using an intelligent technique

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ABSTRACT

This paper presents a method for the optimal design of a slotless permanent magnet brushless DC (BLDC) motor with surface mounted magnets using an improved bee algorithm (IBA). The characteristics of the motor are expressed as functions of motor geometries. The objective function is a combination of losses, volume and cost to be minimized simultaneously. This method is based on the capability of swarm-based algorithms in finding the optimal solution. One sample case is used to illustrate the performance of the design approach and optimization technique. The IBA has a better performance and speed of convergence compared with bee algorithm (BA). Simulation results show that the proposed method has a very high/efficient performance.

1. Introduction

The permanent magnet brushless DC (BLDC) motor is increasingly being used for industrial, domestic and medical applications, especially in fractional horse power range due to its excellent features, such as small size and weight, high torque density, large power to volume ratio, high efficiency, low noise, low vibration, simple maintenance, high dynamic response, longevity, improved reliability and good control characteristics in a wide range of speeds. The stator of a BLDC motor is like that of a conventional DC motor and the rotor has permanent magnets. The BLDC motor is also referred to as an electronically commutated motor as the commutation is performed electronically at certain rotor positions and this is the main difference of this motor with conventional DC motors that uses brushes and mechanical commutators. Applications of BLDC motors include electromagnetic actuators, electric vehicle propulsion systems, electric power steering of small and medium-size vehicles, extruders, printing presses, roll formers, pump's motive part, CD-ROMs, robotic, propulsion system for aircraft and underwater vehicles [1–9] but not limited to them.

The modern BLDC motors have been designed with slotless configuration in their stator, in spite of preliminary ones that have slotted stator. The slotless machine design advantages over slotted structure include reduction in manufacturing costs, simplicity in production, zero cogging torque, reduction in slot harmonic effect, smooth running, low winding inductance, high speed capability, lower vibration, lower audible noise, fast current response, high reliability, low electrical resistance, low static friction, operates in hostile environment and no sparking, and high thermal efficiency. The slotless BLDC motor mainly is used as a medical device and factory automation, such as high speed medical drills, surgical robot systems, prosthetic limb drive systems, high speed miniature spindles, etc. [1,9–11].

In [11], a simplified analytical method has been presented to design a slotless BLDC motor. This method consists of a system of equations with many approximations and beside that, this method is limited and just can be applied to small and two-pole BLDC motors. In [12], electromagnetic field analysis based on the finite element

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method has been used to design a high power density and high efficiency outer rotor BLDC motor for the applications of electric vehicles. In [13], detailed and comprehensive formulations which are necessary and needed in the design of slotless BLDC motors with surface mounted magnet configuration have been presented considering both torque and speed as mechanical requirements. Then, GA has been used to find the optimal geometries of the motor. An objective function has been proposed covering the losses, cost and volume of the motor besides the mechanical and electrical requirements and constraints. In [14], a GA based optimal design of a permanent magnet BLDC motor has been proposed considering efficiency as the objective function and motor weight and temperature rise as the constraints. A computational study of a brushless DC motor is presented in [15], to determine the thermo-flow characteristics in the windings and bearings under the effects of heat generation. Thermal characteristics under the effects of heat generation in a BLDC motor using 3D finite element analysis in order to evaluate the motor cooling performance that has been done. The impact and the effect of various design parameters, including the inlet location, geometry, and bearing groove geometry, on the performance of a BLDC motor are considered and optimized. What is optimized? It is something to improve the motor's cooling performance based on optimal design. In [16], a design method for a small-sized slotless BLDC motor with distributed hexagonal windings has been employed and the objective is maximizing torque density. This new design method is semi-analytical whereas, numerical approaches based on finite element analysis with an analytic model are used to analyze the magnetic and output characteristics of the motor. The designed motor is fabricated, and the experimental results are compared with the results of the simulation. In [17], a simulation method for BLDC motors has been presented. The purpose is to provide a solution for the initial design process, where the simulation speed is important due to the numerous variables that have to be considered. The method requires a reduced number of parameters in order to simplify and facilitate the design process. The experimental results from a 7-phase BLDC motor with one uncontrolled phase validate the modeling method. The precision and efficiency of the simulation method have been validated by the experimental tests on several prototypes, so it can be readily used as a design tool for this kind of motor. In [18], optimal design of a BLDC wheel motor has been done. For this purpose, an analytical model for the optimal design is detailed and each equation that was used for the sizing is explained. A specific procedure has been presented to order all equations in order to ease their resolution. Then, three optimization problems with an increasing number of parameters and constraints have been proposed. Also, a multimodalway has been introduced to promote the development of hybrid methods and special heuristics.

The effect of the required speed has been neglected in the optimization procedure in most of the published papers, and therefore the strength of the BLDC motor is not well defined. In this paper, a method for the optimal design of a slotless permanent magnet BLDC motor with surface mounted magnets using IBA [19] has been proposed by considering torque, maximum speed, voltage, losses and cost. An objective function has been proposed covering the power losses, material cost and volume of the motor simultaneously, in addition to the mechanical and electrical requirements. All of the effective parameters and constraints have been considered in the optimization problem. IBA has been used to find the optimal geometries of the assumed motor. Electrical and mechanical requirements such as voltage, torque and speed and other limitations e.g. upper and lower limitations of the motor geometries constraints of the optimization problem were considered. The results have been examined using sensitivity analysis which has shown the efficacy/effectiveness of the proposed technique.

2. Formulations

In this paper, a new method for the optimal design of a slotless permanent magnet BLDC motor with surface mounted magnets using IBA has been presented by considering torque, power, maximum speed, voltage, losses and cost. An objective function has been proposed covering the power losses, material cost and volume of the motor simultaneously, besides the mechanical and electrical requirements. In addition to these criterions, other objectives may be considered such as cogging torque minimization, vibration reduction, magnetic flux leakage and leakage inductance minimization. Generally, the inclusion of some of these criterions into formulas is not regarded and thus a structural modification of the motor is required. For instance, cogging torque is almost eliminated in the slotless configuration against slotted structure of BLDC motors; or increase in the accuracy of fabrication procedure reduces vibration. So, the most important and common criterions are loss, cost and mass which were considered in this paper.

The cross-section area of a typical slotless BLDC motor and its geometric parameters are shown in Fig. 1. Three main regions are depicted in this figure as stator/rotor yoke, winding, and surface mounted permanent magnets (poles).

The proposed objective function is formed by a set of geometrical variables such as, number of pole pairs (p), cross sectional area of the winding (A_c), pole-arc per pole-pitch ratio (β), magnet thickness (l_m), stator/rotor core thickness (l_y), winding thickness (l_w), mechanical air gap (l_g), rotor radius (r_r), current density (J_{cu}), wire gauge and stator/rotor axial length (l_s), which is usually represented by the machine form factor (λ)

$$\lambda = d_b / l_s \tag{1}$$

$$d_b = 2(r_r + l_g) \tag{2}$$

where d_b is the bore diameter.

Specifications that depend on materials such as winding filling factor (k_f), permanent magnet remanence (B_r) and stator/rotor core flux density at knee point of B–H curve (B_{sy}^{knee}) should be given. Requirements of the motor consist of the rated value of electromagnetic torque (T_{em}) and the rated rotor rotational velocity (ω_r).

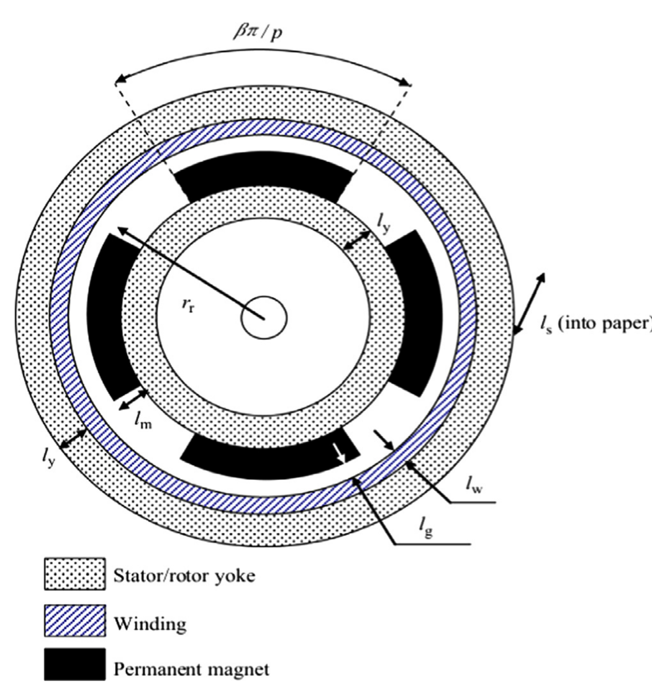

Fig. 1. The cross-sectional area of a slotless BLDC motor.