A disc-type motor with co-axial flux in the stator; – influence of magnetic circuit parameters on the torque

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Abstract This paper presents a three-dimensional analysis of the magnetic field distribution for a three-phase, disc-type, permanent-magnet, brushless DC motor with co-axial flux in the stator. Calculations are carried out using the 3-D finite element method (FEM). The electromagnetic torque is determined from the Maxwell stress tensor. For comparison, various dimensions of permanent magnets, pole shoes and air gap are analysed. It is shown that the ripple-cogging torque can be effectively reduced by an appropriate permanent magnet width and air-gap length. The simulation results are in good agreement with experimental data obtained from the prototype motor.

Keywords Disc-type brushless motor, Permanent magnets, Magnetic field analysis, Electromagnetic torque

1 Introduction
In the last two decades, disc-type permanent-magnet (DTPM) motors have been rapidly developed and widely used in various small-size, low-cost drives [1–3], including pumps, disc drives, electric vehicles and motor boats. In such applications, DTPM motors appear to be more efficient than induction motors of comparable size because they can be designed with higher torque-to-weight ratios.

A review of papers addressing the problem of magnetic field analysis in disc-type motors has been provided in detail by the authors [4]. There are numerous variants and magnet topologies for disc-type machines. The maximization of the average torque and minimization of the ripple-cogging torque are the most challenging problems in the design and performance of electrical machines [5].

In previous papers by the authors [4, 6], an effective three-dimensional analysis of the magnetic field distribution for a disc-type permanent-magnet brushless DC motor with a specific toroidal stator and the Gramme-type winding has been presented. The simulation results were in good agreement with experimental data obtained from the prototype torus motor, which confirmed the usefulness of the computational approach.

In this paper, the 3-D approach is used to comparatively analyze the magnetic field distribution in the air gap of a newly designed DTPM DC motor with co-axial magnetic flux in the stator, with the purpose of empirically optimizing the construction procedure. It is the authors’ experience that the motor construction with co-axial flux in the stator is more efficient than the torus-like one, and it offers a better motor performance. Various features of axial-field motors have been compared in [7], where it has been shown that of all axial-field machines, motors with N-to-S polarization offer the best performance characteristics as potential candidates for wheel-motor drives. Specifically, those motors have the highest “utilization factor”, defined as a ratio of torque to motor weight [7].

The torque ripple in permanent-magnet machines can be separated into three components [5, 8]:

1. Cogging torque, caused by the interaction of the permanent magnets’ field and stator slotting, which produces reluctance variations with the rotor position. This component is independent of stator current;
2. PM torque ripple, caused by interaction of the PM field with the stator magnetomotive force (mmsf) distribution harmonics;
3. Reluctance torque ripple, caused by the interaction between the stator mmsf and the angular variation in the rotor magnetic reluctance.

The cogging torque is the main component of the parasitic torques in the motor considered. The main purpose of this study is to reduce the disadvantageous effect of the ripple-cogging torque. For the calculations, professional 3-D FEM software is applied [11]. Specifically, the influence of permanent magnet dimensions, pole shoe widths as well as air-gap length on the torque is comparatively examined. Two integral quantities calculated from the 3-D model of the real-life prototype motor compare well with the corresponding figures obtained from experimental data.

2 Construction of the motor prototype
The prototype motor structure is shown schematically in Fig. 1. The stator consists of elements made of ferromagnetic cores (preferably laminated iron) and coils with trapezoidal cross sections wound on them. The elements...
are placed axially and distributed uniformly on the stator circumference and glued together by means of synthetic resin. The rotors are placed at both sides of the stator, which are made of steel discs with permanent magnets glued to their surfaces. In the torus disc motor [4], the two magnetic polarities in one pole pitch were the same (N-to-N or S-to-S) and the two main fluxes in the stator core had a symmetric distribution. However, in the considered co-axial flux disc-type motor, the two magnetic polarities in one pole pitch are different (N-to-S or S-to-N). The disc-like structures of the stator and rotor cause the magnetic field to be non-uniformly distributed within the volume of the motor, particularly in the motor stator core. This is the main reason why the magnetic field should be calculated in the 3-D space [4, 9].

The magnetic flux passes from one rotor disc to the other through the air gaps and stator core, with its winding in the axial direction. The coils can be connected to each other in different ways. Here, the three-phase star connection is considered. The distribution of the magnets on the rotor disc and the principles of motor operation are illustrated in Fig. 2.

The motor considered operates as a three-phase brushless DC machine in the auto-piloted mode; thus the rotor speed depends on the value of the load torque. The motor is supplied from a DC source through the six-pulse electronic inverter shown in Fig. 3. The variable frequency of the supply voltage results from the signals coming from Hall sensors, which indicate the positions of the rotor magnets with regard to the approaching stator poles. The windings are fed with a rectangular current waveform, thus only two phases can be simultaneously supplied (Fig. 2). The full cycle of the switch-overs of converter transistors, corresponding to six consecutive rotor positions, is given in Table 1. When the windings are fed with the supply voltage, a force is produced which causes the rotor to move in the clockwise direction. Three consecutive positions of the rotor (half period of the operation) are shown in Fig. 2.

In the motor version considered, the number of stator poles is higher than that for the rotor and their ratio is equal to 3/2. A similar effect can be obtained for the ratio 3/4, where there are more rotor poles than stator poles. In our high-rotational-speed motor, the 3/2 ratio is exploited. The number of transistor switch-overs and the current frequency in the stator winding in this case are both higher than those in the second case (with a ratio of 3/4).

The motor under consideration (Fig. 4) was manufactured by the AQUA-SZUT company of Wrocław. Its design parameters are shown in Table 2. The laminated stator core was made of iron sheet type ET 41–30 and the rotor disc was made of solid iron.

The second quadrant of the $B-H$ characteristic of the permanent magnet type Nd$_2$Fe$_{14}$B, employed as the flux source for the disc motor, is linear with a residual flux density $B_r$ of 1.21 T and a coercive magnetizing intensity $H_c$ of $950$ kA/m.

3 Computational method

The motor design requires an accurate knowledge of the magnetic field distribution. The magnetic field derived in the 3-D space allows the determination of the electromagnetic torque, taking into account the 3-D machine structure and the materials the motor is made of. The application of numerical methods enables us to account for non-linearities in the stator and iron cores, demagnetization characteristics of permanent magnets and possible non-uniform distribution of the magnetic field in the machine air gap.