COMPUTER AIDED DESIGN AND ANALYSIS OF PERMANENT MAGNET BRUSHLESS DC MOTORS

By

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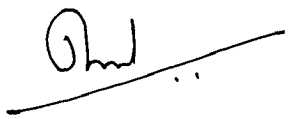
CERTIFICATE

This is to certify that the thesis entitled, **"Computer Aided Design and Analyses of Permanent Magnet Brushless DC Motors,"** being submitted by **Mr. Parag Ramakrishna Upadhyay** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Electrical Engineering Department of Indian Institute of Technology, Delhi.

Mr. Parag Upadhyay worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted in part or in full to any other University or Institute for the award of any degree.



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ABSTRACT

Permanent magnet brushless dc (PM BLDC) motors have advantages such as high efficiency, high torque density, high power density, and high reliability. These motors are inherently maintenance free because of the absence of a mechanical commutator. Since the high-energy magnets such as samarium cobalt and neodymium iron boron (Nd-Fe-B) have very low permeability, the effect of armature reaction is very less in these motors. Therefore, these motors are increasingly being used in various domestic and industrial applications.

In this research work, the design and analysis equations in full for the radial-flux as well as the axial-flux PMBLDC motors of selected topologies such as surface mounted PM type, interior PM type, stator sandwiched type, etc., are developed and utilized to develop a full fledged CAD program for the accurate design of PM BLDC motors.

Three PM BLDC motors of ratings, (i) 24 V, 70 W, 350 rpm, (ii) 230 V, 2.2 kW, 1450 rpm and (iii) 230 V, 20 kW, 1500 rpm, in each category of the radial-flux surface mounted type, redial-flux interior PM type and axial-flux stator sandwiched type are designed using the developed CAD program. From the design results, it is observed that in all the categories, the efficiency increases with the rating; the phase inductance is more when the voltage is more; and for the same voltage, the phase inductance decreases with increase in power rating. The efficiency and weight of the designed surface mounted radial-flux 70 W motor are 85.14% and 2.726 kg respectively. For the interior PM and axial-flux motors, the corresponding values are 82.51%, 3.49 and 89.14%, 2.69 kg. A genuine comparison is made between the radial-flux and axial-flux PM BLDC motors. It is observed that in all counts, the axial-flux motor is superior. Its efficiency is about 4% higher and phase inductance is lower than the equivalent radial-flux motor.

Design of a PM BLDC motor using conventional design techniques generally does not lead to cost effective and efficient designs. Computerization of the conventional design procedure and arriving at the optimum design, based on some correction loops will lead to somewhat better designs. The application of optimization techniques in the CAD procedure results in further improvements in best designs. The direct use of a coding, search from a population, blindness to auxiliary information, and robustness due to randomized operators are the advantages of GA over other more commonly used optimization techniques. GA is more effective method for optimization of electric motor because the variable parameters are having fixed upper bounds and lower bounds, there are only few constraints and the objective function can be defined easily depending on the design criterion.

In this work, GA based design optimization with the efficiency of the motor as the objective function is carried out. The permissible temperature rise and the weight of the motor are the design constraints. Since the airgap, airgap flux density, slot electric loading, magnet-fraction and the slot-fraction are significantly affecting the efficiency, these five design variables are considered in the optimization routine. It is observed that the efficiency increases with the number of design variables, and therefore, all the five design variables are considered in the optimization routine. It is observed that the unconstraint optimization gives the highest efficiency, 88.14 % for the 70 W radial-flux surface mounted motor, but with a heavy penalty of increased volume, weight and thereby definitely the cost; whereas the constraint optimization gives improved efficiency of 86.06 % as against the optimum CAD based motor efficiency of 84.75 %. It is observed that the phase-resistance, phase inductance, weight of copper, copper loss, temperature rise, outer diameter and number of turns/slot are less in the constraint GA based optimized motor compared to the optimum CAD based motor, but with a marginal increase of the weight of

iron, weight of permanent magnet and thereby the motor weight. The increase in efficiency, reduction in phase-resistance, and the reduction in the temperature rise are the significant improvements obtained because of the GA based optimization.

Generally, an axial-flux PM BLDC motor, owing to its special construction, necessitates 3-D FE analysis for accurately calculating its performance such as developed torque, etc. The 3-D FE analysis necessitates large number of elements and hence the problem size will be huge needing large processing time. Also the requirement of a 3-D FE analysis module becomes mandatory for the designer. A new simpler technique namely the integral force technique to calculate the developed torque of this motor from the 2-D FE analysis results is formulated. The design data of the 70 W axial-flux PM BLDC motor designed using the developed CAD program have been used for modeling this motor for the 2-D and 3-D FE analyses. The peak torque calculated by the 3-D FE analysis is 2.2608 Nm as against the 2.2705 Nm obtained from the integral force technique. The CPU time taken by the 3-D analysis is 3 hours 11 minutes as compared to 19 minutes 50 seconds taken by the integral force technique. In addition to that, the pre-processing time required is very less in this method compared to the 3-D FE method.

After a thorough investigation using the 2-D FE analysis, the torque developed by the interior PM motor is improved by shifting all the rotor magnets with respect to the axis of the corresponding pole shoes in a direction opposite to the rotation of the motor. The shape of the torque profile is not affected much by these shifts. By this method, for the same input power, mass and volume of the motor, the average torque increases, typically by 23.5% for 0.8 mm shift. Two methods namely, skewing of stator slots for surface mounted radial-flux motor and rotor pole shaping for interior PM motor are investigated using the FE analyses to reduce the toque ripples. It is observed that by employing these techniques the torque ripple comes down from the original value of 23 % to less than 7%

in the first case and 32.4% to 10.95% in the second case, respectively.

FE analysis is carried out on the designed 70 W surface mounted radial-flux PM BLDC motor at no load and full load conditions to study the effects of armature reaction. It is observed that the magnetic neutral axis is shifted at full load from the geometric neutral axis by 1.8°. In a typical 3 hp, 3-phase, 48 V, 16 pole, 800 rpm axial-flux PM BLDC motor designed for the direct drive of an electric two-wheeler, the flux density in the airgap at full load reduces to 0.120 T from the no load value of 0.135 T. The reduction in airgap flux density is not linear with the armature current but increases drastically with the current.

Contents