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Genetic algorithm based design optimization of a permanent magnet brushless dc motor

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Genetic algorithm (GA) based design optimization of a permanent magnet brushless dc motor is presented in this paper. A 70 W, 350 rpm, ceiling fan motor with radial-filed configuration is designed by considering the efficiency as the objective function. Temperature-rise and motor weight are the constraints and the slot electric loading, magnet-fraction, slot-fraction, airgap, and airgap flux density are the design variables. The efficiency and the phase-inductance of the motor designed using the developed CAD program are improved by using the GA based optimization technique; from 84.75% and 5.55 mH to 86.06% and 2.4 mH, respectively. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1860891]

I. INTRODUCTION

Design of a permanent magnet brushless dc (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 computer-aided design (CAD) procedure results in best designs. In this paper, a detailed procedure for the CAD of a PM BLDC motor is given. A 70 W, 350 rpm, ceiling fan motor is initially designed using the developed CAD program. Then, the genetic algorithm (GA) based optimization technique is incorporated in the CAD program and the optimized design is achieved. Finite element (FE) analyses of the designs obtained as above are carried out to confirm the correctness of the design procedures. The following sections give the details of this work and the results of the above two design procedures.

II. CAD OF PM BLDC MOTOR

The CAD program of PM BLDC motor is a two-loop MATLAB-program with different function call. Motor specifications, type of configuration, material types, and other assumed data for the design are the input. The outer loop is to set and correct the assumed efficiency. Initially, the efficiency of the motor is assumed as η_0. The CAD program designs the motor and calculates the actual efficiency. The correction loop is active till the error between the assumed efficiency and the actual efficiency is within the given limit, a_2. The inner loop is for reducing the difference between the assumed and actual airgap flux densities by changing the length of the magnet (ℓm) in a similar way. The magnet length is increased till the error between the two is less than given limit, a_1. As given in the flow chart of the developed CAD program in Fig. 1, the calculation of the main dimensions, stator design, permanent magnet rotor design and the performance calculations[1] are the main four stages of the design.

Selection of standard wire gauge (SWG), material data for selected material number, specific iron loss data for a given material flux density and the frequency, etc. are also part of the developed program. Number of magnet poles (N_m), number of slots/pole/phase (N_{spp}), type of permanent

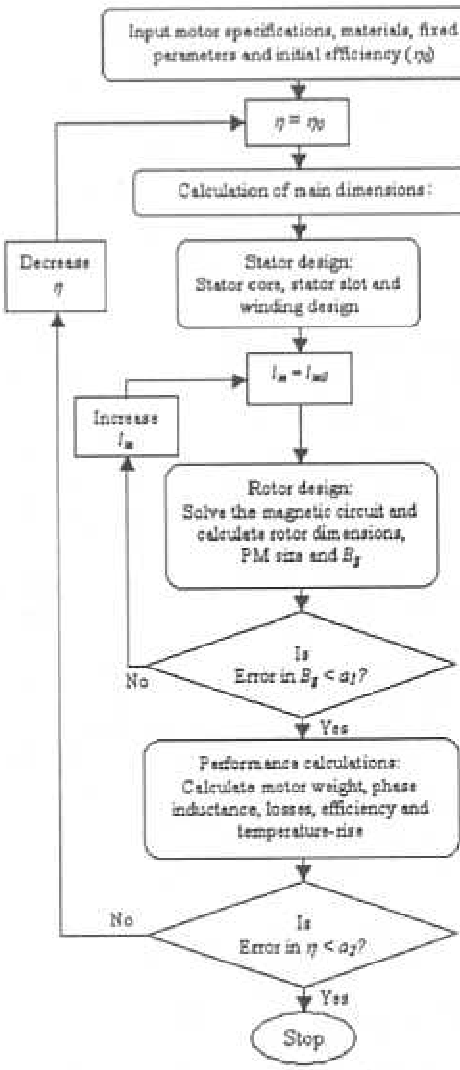

FIG. 1. Flowchart of the CAD program for the PM BLDC motor.

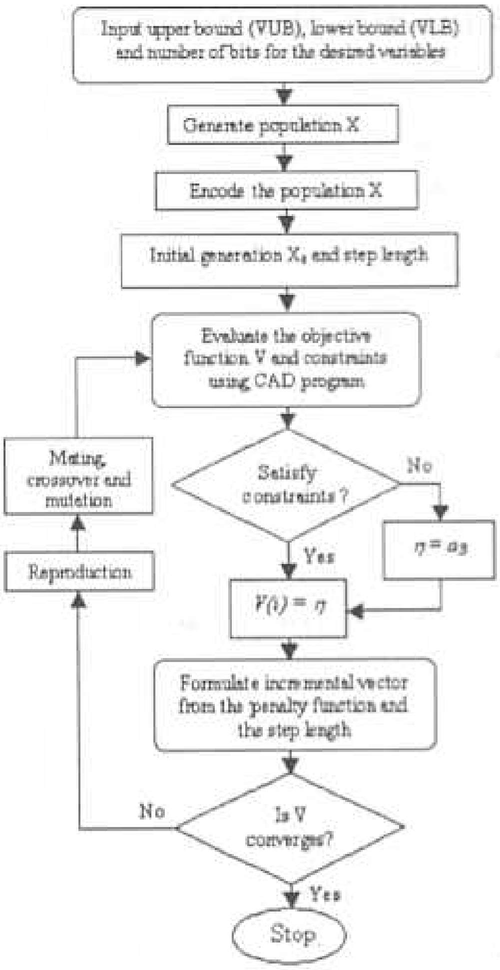

FIG. 2. Flowchart of the GA based optimized CAD program.

magnet material and its grade, type of soft magnetic material, length of airgap (l_g), current density (J_s), stator flux density (B_{st}), airgap flux density (B_g), slot electric loading (I_s), magnet fraction (α_m), slot fraction (α_s), stacking factor (K_s), slot space factor (K_{sf}), winding factor (K_w), flux density in the rotor core (B_{rc}) are the parameters required for the design.

III. GENETIC ALGORITHM BASED DESIGN OPTIMIZATION

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.[2] GA is the best 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. As shown in Fig. 2, the GA requires the population, an objective function, the constraints and the initial population. The population is the set of individual vectors for the parameters given in terms of upper bound (VUB), lower bound (VLB), and the increment step in the form of bits. The GA is associated with three genetic operations, namely reproduction, crossover, and mutation.[2]

In this work, the efficiency of the motor is taken as the objective function. The permissible temperature-rise and the weight of the motor are the design constraints. It is observed form the parametric analysis conducted using the developed CAD program, that among all the design parameters, a few only such as airgap, airgap flux density, slot electric loading, magnet-fraction and the slot-fraction are affecting the efficiency and hence these five design variables are considered in the optimization routine. Four analyses are carried out using this optimization routine, in which 2, 3, 4, and 5 of the above variables are actually declared as design variables. The following upper and lower bounds of these variables are used in this work:

Slot Electric loading, I_s : 100–400 A
Airgap flux density, B_g : 0.5–0.90 T
Length of airgap, l_g : 0.3–1.00 mm
Magnet-fraction, α_m : 0.5–0.95
Slot-fraction, α_s : 0.3–0.65

In the CAD based design carried out in the previous section, the values of these variables were selected after conducting parametric analyses as 220 A, 0.8 T, 0.5 mm, 0.7 and 0.5, respectively. The optimization program generates vector $K(i)$ which is a set of the above five variables. The objective

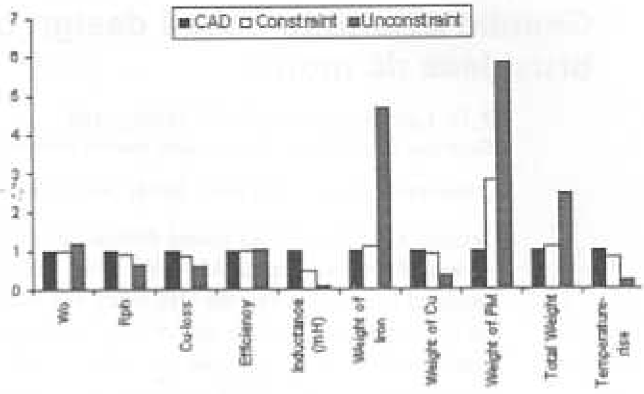

FIG. 3. Per unit relative performance of the designed PM BLDC motor.

TABLE I. Optimized efficiency of the PM BLDC motor for two to five design variables.

Design variables	Efficiency of the optimized motor
I_s, B_g	85.64%
I_s, B_g, l_g	85.93%
I_s, B_g, l_g, α_m	86.04%
$I_s, B_g, l_g, \alpha_m, \alpha_s$	86.06%

TABLE II. Comparison of the performance of the designed PM BLDC motors.

Parameters	CAD based design	GA based constraint optimization based design	GA based unconstraint optimization based design
Efficiency (%)	84.75	86.06	88.14
Number of turns/slot	65	53	15
Outer diameter (mm)	92	91	126
Axial length (mm)	45	48	91
Motor weight (kg)	2.40	2.65	5.92

TABLE III. Comparison of the results of the designed PM BLDC motors with the FE analysis results.

Parameter		CAD based design		GA based optimized (constraint) design	
		CAD	FE	GA	FE
Average torque (Nm)		1.91	2.02	1.91	2.09
Average airgap flux density (T)		0.80	0.79	0.850	0.852
Stator flux density (T)	Stator core	1.6	1.55	1.6	1.58
	Stator teeth	1.6	1.78	1.6	1.65
	Rotor core	1.8	1.79	1.8	1.86
Phase-inductance (mH)		5.55	5.83	2.4	2.46

function and the design constraints are evaluated using the developed CAD program. The optimization program is run for different conditions with 20 bits for each variable. The program converges on attaining the error between the two-generation peaks of the calculated efficiencies is within the given limit.

IV. RESULTS

Table I gives the efficiencies of the optimized motor with 2–5 design variables declared as actual variables in the optimization routine. It is observed that the efficiency increases when the number of design variables declared are more. Therefore, it is decided to consider all the five design variables in the optimization routine. Then, the GA based optimization is carried out with and without declaring the design constraints, namely the motor weight and the temperature-rise.

Figure 3 gives the per unit relative performance of the three motors designed; CAD based design with out any optimization, and with constraint as well as unconstraint GA based optimization routines. Table II gives a comparison of significant parameters of the three motors thus designed. It is observed that the unconstraint optimization gives the highest efficiency, 88.14%, 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 CAD based motor efficiency of 84.75%. More results of the CAD based and the constraint GA based designs with corresponding results obtained from the FE analyses are given in Table III. It may be observed form the Table III that the results obtained from the FE analyses are fairly matching with the results obtained from the developed CAD program for the motors with and without GA based optimization. However, the developed torques as per the FE analyses are more by 5.76% and 9.42% in the motors based on CAD and GA based optimization. These deviations can be attributed to the approximations or empirical formulas considered in the developed CAD program such as Carter's coefficient, etc for the slot leakage, fringing, and nonlinearities. The flux density plots of the designed PM BLDC motors for the CAD and GA based optimized designs are shown in Figs. 4 and 5, respectively. Apart from the flux densities, these figures give an idea about the overall geometry, the stator laminations, rotor laminations, permanent magnets, and the stator slotting, etc.

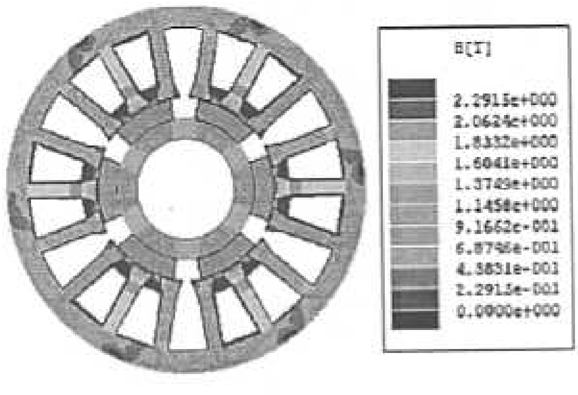

FIG. 4. Flux density plot of the CAD based PM BLDC motor.

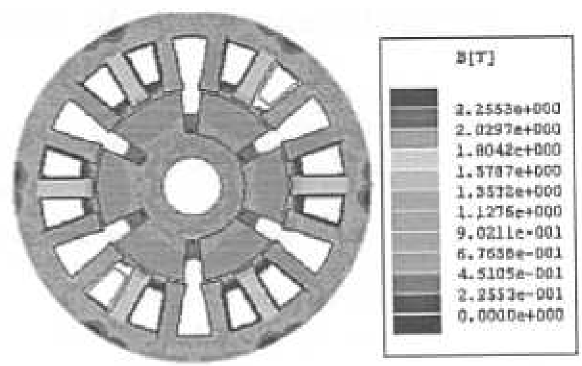

FIG. 5. Flux density plot of the GA based optimized (constraint) PM BLDC motor.

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 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.

V. CONCLUSIONS

GA based constraint optimization technique in the design of PM BLDC motor enhances the performance of the motor. The efficiency and the phase-inductance of a 70 W, 350 rpm ceiling fan motor designed using the above technique are 86.06% and 2.4 mH against 84.75% and 5.55 mH obtained from the CAD based program. Validity of the results of both the above design methods have been fairly established by carrying out FE analyses of the motors.

[1]Daune C. Hanselman, *Brushless Permanent-Magnet Motor Design* (McGraw Hill, New York, 1994).

[2]D. E. Goldberg, *Genetic Algorithms in search, optimization and machine learning* (Pearson Education, Singapore, 2002).