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Comparison of performance of the axial-field and radial-field permanent magnet brushless direct current motors using computer aided design and finite element methods

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In this article, performance of 70 W, 350 rpm, axial-field and radial-field permanent magnet brushless dc motors is compared using computer aided design (CAD) and finite element (FE) methods. The design variables like number of poles, slots per pole per phase, airgap length, airgap flux density, slot electric loading, stator flux density, and the permanent magnet material are changed one at a time and the performances are calculated using the developed CAD program. The CAD results are validated by carrying out two-dimensional and three-dimensional FE analyses. It is observed that the axial-field motor gives higher efficiency, whereas the radial-field motor has less weight. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1853239]

I. INTRODUCTION

This article compares the performance of two main configurations of PM BLDC motors viz. surface-mounted radial-field type and stator sandwiched dual air gap axial-field type, designed for a fan application having 70 W, 350 rpm rating. Initially, the output equations for the two configurations of the motor are derived and based on this, a computer aided design (CAD) program is developed for the design and analysis of the motors. Number of phases, winding factor, stacking factor, slot space factor, and current density are considered the same for both the motors. Parametric analyses are carried out for both the motors and all the performances are compared. So as to compare the correctness of the CAD method, one finite element (FE) model each of both the configurations is implemented. For these two FE models, optimum values of the variables obtained from the parametric analyses are used for both the motors. Figure 1 shows the FE models of the two motors analyzed.

II. OUTPUT EQUATIONS OF PM BLDC MOTORS

Using the torque expressions,[1,2] the output equations for the motors are derived. For the radial-field motor

$$P=T\omega_m=N_C E_{\mathrm{ph}} I_{\mathrm{ph}} \Rightarrow T=\frac{P}{\omega_m}=\frac{N_C E_{\mathrm{ph}} I_{\mathrm{ph}}}{\omega_m}$$
$$=\frac{N_C(N_m N_{\mathrm{spp}} K_w B_g L D_{\mathrm{ro}} n_s \omega_m/2) I_{\mathrm{ph}}}{\omega_m}$$
$$=\frac{N_C N_m N_{\mathrm{spp}} K_w B_g L D_{\mathrm{ro}} I_s}{2} \Rightarrow L D_{\mathrm{ro}}=\frac{2T}{N_C N_m N_{\mathrm{spp}} K_w B_g I_s}.$$

The rotor outer diameter and the length of the motor can be separated out using proper D/L ratio.

Similarly, for the axial-field motor

$$P=T\omega_m=N_C E_{\mathrm{ph}} I_{\mathrm{ph}} \Rightarrow T=\frac{P}{\omega_m}=\frac{N_C E_{\mathrm{ph}} I_{\mathrm{ph}}}{\omega_m}$$
$$=N_C N_m N_{\mathrm{spp}} K_w B_g n_s I_{\mathrm{ph}}(R_o^2-R_i^2)$$
$$=N_C N_m N_{\mathrm{spp}} K_w B_g I_s(R_o^2-R_i^2).$$

The optimum ratio of outer radius to the inner radius reported by Chan[3] is $\sqrt{3}$, and using this value, we get the output equation as

$$T=N_C N_m N_{\mathrm{spp}} K_w B_g I_s(R_o^2-R_o^2/3)$$
$$=2N_C N_m N_{\mathrm{spp}} K_w B_g I_s R_o^2/3 \Rightarrow R_o=\sqrt{\frac{3T}{2N_C N_m N_{\mathrm{spp}} K_w B_g I_s}}.$$

By knowing the outer radius, R_o, the inner radius can be calculated. Rather than taking the specific electric loading, in PM BLDC motors, a specific slot loading I_s can be considered in the design with advantage.[1] Then, the product "$N_m N_{\mathrm{spp}} N_g I_s$" is constant. N_m is the number of poles, N_g is the number of air gaps, N_{spp} is the number of slots/pole/phase and K_w is the winding factor.

III. COMPUTER AIDED DESIGN

The CAD program of PM BLDC motor is a two-loop MATLAB program with a different function call. The outer loop is to set and correct the assumed efficiency. The inner

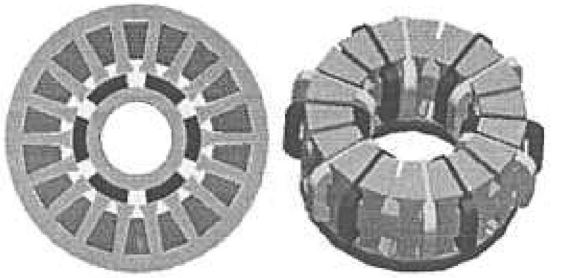
(a) (b)

FIG. 1. FE models of (a) radial-field and (b) axial-field PM BLDC motor.

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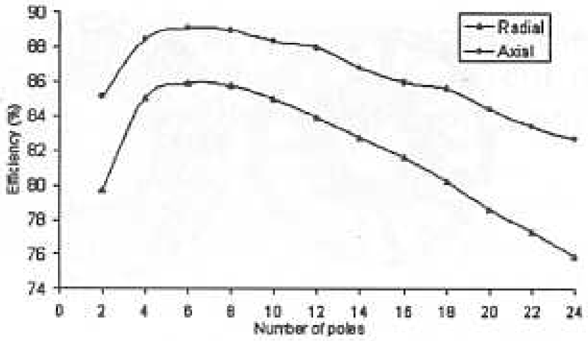

FIG. 2. Variation in efficiency with number of poles for axial and radial-field PM BLDC motors.

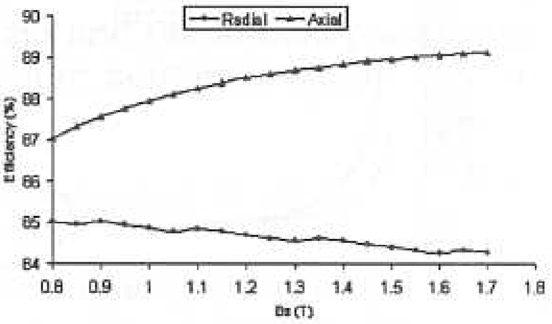

FIG. 3. Variation in efficiency with stator flux density for axial and radial-field PM BLDC motors.

loop is for reducing the difference between the assumed and actual flux densities by changing the length of the magnet. Motor specifications, type of configuration, material types, and other assumed data for the design based on selection tips are provided as the input. Calculation of the main dimensions, stator design, permanent magnet rotor design, performance calculations, and the data sheet generation are the main five stages of the CAD program. Selection of standard wire gauge, 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.

IV. PARAMETRIC ANALYSIS

Number of magnet poles N_m, number of slots/pole/phase N_{spp}, permanent magnet properties, airgap l_g, stator flux density B_{st}, airgap flux density B_g, current density J_s, and slot electric loading I_s are changed one at a time from a minimum to maximum value in steps and all performances are calculated using the CAD program.

Figure 2 gives the comparison of efficiencies at the rated load for the motors with the number of poles. The efficiency is always more for axial-field motor. This is because of better utilization of the conductor length in axial-field motor. The maximum efficiency in both the motors occurs for six numbers of poles. For lower pole-numbers, weight of iron and weight of overhang winding are high which increase the losses in the motor. For higher pole numbers, however, the frequency will be higher, and hence, the iron losses will increase drastically. The optimum number of poles thus falls within 4, 6, and 8. This is true for both the motors.

The slots/pole/phase does not affect the efficiency of the radial-field motor, whereas in case of axial-field motor, the efficiency increases marginally with the slots/pole/phase ratio. An increase in this ratio, however, results in decrease in the phase-inductance and vice versa in both the motors.

Parametric analysis with various PM materials indicated that for the same output power form the motor, the volume of the PM material for axial-field motor is lower than the radial-field motor; also with this less PM material, the axial-field motor gives higher efficiency of 89.07% compared to 84.25% of the radial-field motor. And if we consider the same volume of PM material, then naturally the axial-field motor gives higher efficiency.

It is observed that by changing the soft magnetic material used in the stator from M47 to M15, the efficiency increases from 86.93% to 89.41% in the case of the axial-field motor, whereas the increase is from 81.31% to 84.66% in case of the radial-field motor. But it can be observed again that for the same soft magnetic material, the axial-field motor performs better.

Analysis with varying the airgap in both the motors revealed that the rated power and full load efficiency can be achieved in by having a penalty of increase in the volume of permanent magnet material. For example, if the airgap is increased from 0.3 to 1 mm, the weight of the selected permanent magnet material NdFeB-35, goes up from 0.083 to 0.255 kg in the case of the axial-field motor, whereas the magnet weights for the radial-field motor are correspondingly 0.048 and 0.144 kg. The significant information here is that, the magnet required in radial-field motor is less compared to the axial-field motor. But it is worth to mention here that the copper weight in the radial-field motor is 1.24 kg against the corresponding value of 0.94 kg in axial-field motor. The requirement of high magnet volume in case of the axial-field motor is because of the selected doubly sandwiched geometry, necessitating double the number of magnets than that required in the radial-field motor. The variation in the phase inductance for the earlier change in airgap is from 6.4 to 2.62 mH for the axial-field motor and from 7.2 to 3.83 mH for the radial-field motor. This reinstates the advantageous fact that the axial-field motor has less phase inductance than the radial one.

The increase in stator current density does give the advantage of reduction in the weight of copper and also the iron. But the penalty is reduction in efficiency in both the motors. For example, the increase in current density from 1.5 to 3 A/mm^2 resulted reduction in weight of copper from 1.33 to 0.64 kg and 1.65 to 0.86 kg in axial-field and radial-field motors, respectively. Similarly the weight of iron has decreased from 1.56 to 1.35 kg and 1.25 to 0.99 kg in these motors, respectively. The penalty has been reduction in efficiency from 90.03% to 87.25% and 86.25% to 80.4%, respectively, in axial-field and radial-field motors. This is happening obviously because of the increase in copper loss. The higher value of current density necessitates smaller outer diameter for the radial-field motor, and axial length for the axial-field motor. The phase-inductance of the axial-field mo-

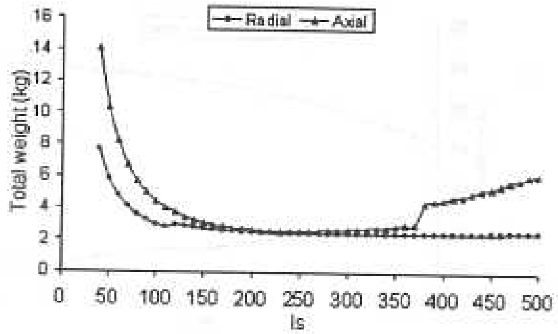

FIG. 4. Variation in motor weight with slot electric loading for axial and radial-field PM BLDC motors.

tor remained nearly constant for such a change in current density, whereas for the radial-field motor, the phase-inductance decreased form 5.76 to 4.78 mH.

As shown in Fig. 3, increase in the stator teeth and core flux density results in improvement in efficiency in axial-field motor. Even though the iron loss is increasing marginally because of the increase in flux density, the copper loss decreases to a bigger extent owing to substantial reduction in mean length of turn. In case of the radial-field motor, the efficiency decreases marginally with the increase in stator flux density; in this case the copper loss is nearly the same and the iron loss is increasing. Further, the phase inductance in radial-field motor is decreasing with the increase in stator flux density, whereas it is nearly constant in axial-field motor.

Enhancement of the airgap flux density in radial field-motor results in increase in efficiency, reduction in weight of motor and phase-inductance, but it necessitates more magnet volume. Reduction in copper loss because of reduced copper requirement is the reason for the increase in efficiency. Typically, in a radial-field motor when the airgap flux density is increased from 0.5 to 0.8 T, the efficiency increases from 84.84% to 86.01%; also with a reduction in motor weight from 3.02 to 2.7 kg and phase inductance from 7.35 to 3.21 mH. In case of an axial-field motor, when the airgap flux density is changed from 0.5 to 0.8 T, the efficiency is marginally decreasing form 89.48% to 89.07%. Here, since there is no reduction in copper weight, there is no reduction in copper loss too, but the ironless is marginally increasing. For the axial-field motor, the phase inductance is decreasing from 8.38 to 4.32 mH for the earlier change in airgap flux density.

The variation in motor weight with the slot electric loading is shown in Fig. 4. Increasing the slot electric loading from 50 to 150 A, results in reduction in motor weight for both the motors, then from 150 to 300 A, the motor weight is more or less constant. Beyond this value, for the axial-filed motor, the weight goes up whereas for the radial-field motor, it remains nearly the same.

TABLE I. A comparison of CAD and FE results of radial-field and axial-field PM BLDC motors.

Parameter		Radial		Axial	
		CAD	FE	CAD	FE
Average torque (N m)		1.913	2.02	1.91	1.98
Average airgap flux density (T)		0.796	0.793	0.799	0.866
Stator flux density (T)	Stator core	1.6	1.55	1.557	1.537
	Stator teeth	1.6	1.778	1.55	1.537
	Rotor core	1.8	1.786	1.641	1.635
Phase-inductance (mH)		5.55	5.83	4.89	5.29

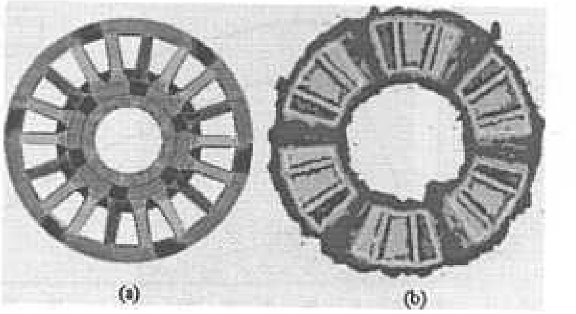
(a) (b)

FIG. 5. Flux density plots of (a) radial-field and (b) axial-field PM BLDC motors.

V. VALIDATION USING FE ANALYSIS

So as to validate the results of the developed CAD program used for the parametric analysis, two motor designs with the optimum values of all the variables are modeled using the FE method. In case of the radial-field motor, a two-dimensional FE model and in case of the axial-filed motor, a three-dimensional FE model is used. For the selected motors, the number of poles is 6, the slots per pole per phase is 1, the airgap is 0.5 mm, the airgap flux density is 0.8 T, the stator flux density is 1.6 T, the current density is 2.5 $\mathrm{A/mm^2}$, number of phases is 3, slot electric loading is 220 A, the PM material is NdFeB-35 and the soft magnet material is M19.

Figure 5(a), gives the flux density plot of the cross section of the radial-field motor and Fig. 5(b) gives the flux density plot at the magnet face of the axial-field motor. The significant results of the FE analysis in comparison with the results obtained form the CAD program are given in Table I. It is observed that the FE results are fairly matching with the computed values using the CAD program. The variations are of course the limitations of the CAD program, which is not based on any numerical techniques and also because of few empirical formulations and values used in it such as Carter's coefficient, etc.

VI. CONCLUSIONS

In this article, a genuine comparison is made between the axial-field and radial-field PM BLDEC motors. It is observed that in all counts, the axial-field motor is superior. Its efficiency is about 4% higher and phase inductance is lower than the equivalent radial-field motor. The effects of various design parameters on the performance of these motors are discussed in detail.

[1] D. C. Hanselman, *Brushless Permanent-Magnet Motor Design* (McGraw Hill, New York, 1994).
[2] J. R. Handershot and T. J. E. Miller, *Design of Permanent Magnet Brushless Motors* (Oxford Science, New York 1994).
[3] C. C. Chan, IEEE Trans. Energy Convers. EC-2, 294 (1987).