

Research Report

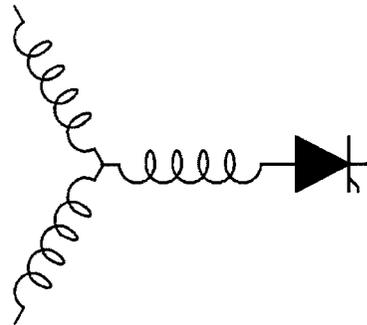
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**Performance Comparison of Dual-Rotor Radial-Flux and  
Axial-Flux Permanent-Magnet BLDC Machines**

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# Performance Comparison of Dual-Rotor Radial-Flux and Axial-Flux Permanent-Magnet BLDC Machines

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**Abstract** - A novel machine family – dual-rotor, Radial-Flux, Permanent-Magnet (RFPM) machines – has demonstrated that it can substantially improve machine torque density and efficiency. The objective of this paper is to provide a performance comparison between two major alternatives of this technology: Surface-mounted dual-rotor RFPM machines and Axial-Flux Permanent-Magnet (AFPM) machines. The comparison is accomplished at four power levels ranging from 3 to 50 HP at a constant speed of 1800 RPM. The comparison includes material weights and costs, copper and iron losses, torque and power per unit active volume, torque per unit active material weight, magnet material effect, losses per unit airgap area, and machine efficiency. Pole number effects on both machine types are investigated as well. The results reveal an indication of the machine best suited with respect to performance criterion for a particular design requirement.

## I. INTRODUCTION

A novel machine family (dual-rotor, Radial-Flux, Permanent-Magnet (RFPM) Machines) [1] has been proposed in previous studies and the findings demonstrated that members of this machine family can substantially improve machine torque density and efficiency. Meanwhile, Axial Flux Permanent Magnet (AFPM) machines [2-4] have recently found a growing interest by researchers since they are proven to be reliable and efficient in a number of applications where high torque density is required and space constraints exist.

The performance of AFPM machines was compared with conventional radial flux PM machines previously in the literature. The machine output torque is proportional to airgap area for the constant electrical and magnetic loadings. AFPM machines normally have two airgaps, but conventional PM machines have only one. Thus, higher torque density and higher torque/mass ratio have been reported for AFPM machines than conventional PM machines in earlier comparison studies [5-7].

Since the RFPM machines have topological dual structures of the AFPM machines and they both have two airgaps, it will be very interesting to compare the performance of the two types of machines. The slotted RFPM machine with toroidal windings and the slotted AFPM machine with toroidal windings are chosen for comparison.

Furthermore, both rare earth and ferrite magnets are employed in these two configurations. The comparison between the two types of machines is accomplished at four power levels ranging from 3 to 50 horsepower at a constant rated speed of 1800RPM. The comparison procedure is based on the same output power and same electrical and magnetic loadings for each power level. This comparison consists of material weights and costs, copper and iron losses, torque per unit volume, torque and power per unit weight, magnet material effect (both rare earth and ferrite magnets), power losses per unit airgap, and machine efficiency. Pole number effects on both machine types are investigated as well.

## II. RADIAL AND AXIAL FLUX PM MACHINE STRUCTURES

The features and structures of the two types of machines are discussed in this section. Both rare earth and ferrite magnets are used in each configuration. Thus, a total of four dual-rotor structures are analyzed in the paper.

### A. Dual-rotor, Toroidally-wound, Slotted, RFPM Machines

A 3-dimensional slotted configuration of dual rotor RFPM machine shown in Fig. 1 is accomplished by positioning the toroidally wound stator between two rotor cups carrying radially polarized surface mounted permanent magnets on the inner side. Back-to-back connected or gramme type stator windings are employed in this structure. The windings on both surfaces of the stator are used for torque production, which is similar to dual-rotor single-stator axial flux machines. The machine cross section is shown in Fig. 2.

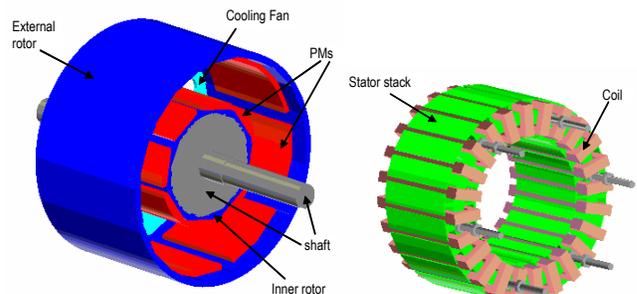


Fig. 1. Dual-rotor, toroidally-wound, slotted, RFPM machine structure

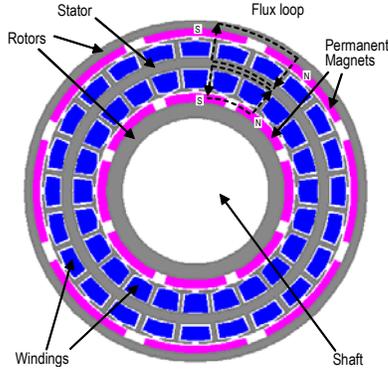


Fig. 2. Cross-section and flux distribution of the RFPM machine

### B. Dual-rotor, Toroidally-wound, Slotted, AFPM Machines

The dual rotor axial flux surface mounted PM machine structure is illustrated in Fig. 3 and the flux distribution is depicted in Fig. 4. The two disc shaped rotors carrying axially magnetized magnets mounted on the inner surfaces of the rotors are assembled on both sides of the stator structure with toroidal or gramme type windings. Similar to toroidally wound RFPM machine, the North-North (NN) type magnet arrangement required by the toroidal windings is used in this configuration.

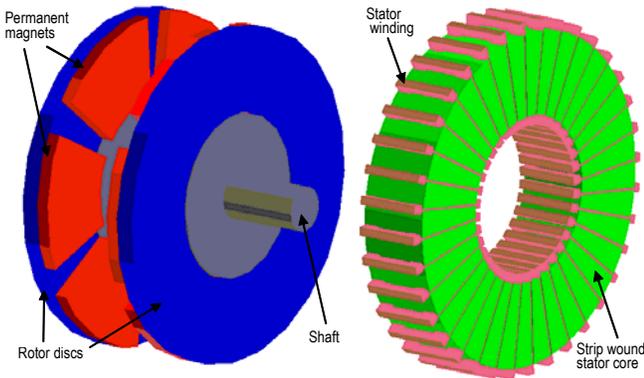


Fig. 3. Dual-rotor, toroidally-wound, slotted, AFPM machine structure

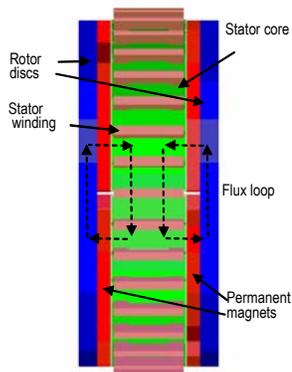


Fig. 4. Cross-section and flux distribution of the AFPM machine

The common advantages of both machines are those features caused by the dual-airgap, toroidal windings. The end windings of a toroidal type winding are quite short and it leads to lower copper loss and higher efficiency. Compared to conventional lap or wave windings, the machine volumes and material costs are reduced as well by employing the toroidal windings. Although cogging torque is introduced by slotting, it reduces the effective air-gap and improves torque density. Therefore, it could be possible to use low energy ferrite magnets to provide the field excitation while the machine overall torque density is still kept high.

### III. DESIGN CONDITION AND ASSUMPTIONS

The comparison between two types of machines is achieved at a constant speed of 1800 RPM and four different power levels of 3, 10, 25 and 50 HP. Both ferrite and rare earth magnets are used in each type of the configurations. Pole number effect on the torque density and efficiency is also included by comprising motors with 4, 8, 12, 16, 20, 24, and 28 poles for each configuration. The comparison consists of six aspects of the machine performance which are:

- Material weights and costs,
- Copper and iron losses,
- Torque and power per unit volume,
- Torque and power per unit weight,
- Power losses per unit airgap, and
- Machine efficiency.

Since this paper focuses on the performance comparison, the machine design procedures and equations that are easily obtained from the literature are omitted in this paper. In order to simplify the design process and make the comparison, several parameters are held constant for each type of the configurations. These constants as shown in Table I include electrical load, current density, flux densities in the airgap, slot filling factor, and stack factor.

TABLE I DESIGN CONDITIONS AND ASSUMPTIONS

Current density ( $A/mm^2$ ) <sup>a</sup>	5.5/5.6/5.7/6.0
Electrical loading ( $kA/m$ ) <sup>a</sup>	24.5/28/32.5/45
Friction & wind losses (%) <sup>a</sup>	3 /2/0.9/0.7
Air gap (mm)	1
Speed (RPM)	1800
Phase #	3
Magnet temperature rise ( $^{\circ}C$ )	80
Stator stack factor	0.95
Bare copper fill	~0.45
Residual flux density $B_r$ at $120^{\circ}C$ (T) <sup>a</sup>	0.32/1.0
Magnet relative permeability <sup>a</sup>	1.07/1.03
Airgap flux density (T) <sup>a</sup>	~0.25/0.65

a: for 3, 10, 25, and 50 HP, respectively

b: for ferrite and rare earth magnets, respectively

The ratio of the machine length to diameter for the RFPM configurations and the ratio of the stator inner diameter to outer diameter for the AFPM machines are optimized to give

the maximum power density or torque density and the highest efficiency.

#### IV. COMPARISON OF RADIAL- AND AXIAL-FLUX MACHINES

Under the conditions listed in Table I, the AFPM and RFPM machines are designed and optimized using Matlab-based programs, the effectiveness of which has been proven by the commercially available finite element analysis software – Maxwell. In this section, a set of design results including several plots and tables are provided, compared and discussed.

##### A. Ratio Effect of Length to Diameter & Stator Inner to Outer Diameter

Figs. 5, 7, and 9 show the plots of the ratio of torque to machine mass, torque density and efficiency versus the ratio of machine length to diameter for the RFPM machines while Figs. 6, 8, and 10 show the same machine performances of the AFPM machines as a function of the ratio of stator inner diameter to outer diameter. Four curves in each plot represent four different machine power levels. The pole numbers are selected based on the results in section E and practical limitations to maintain both high torque density and high efficiency.

Figs. 5 through 10 illustrate that the main aspect ratio of length to diameter for RFPMs and the ratio of stator inner diameter to outer diameter of the AFPMS are the main parameters to be optimized. Torque density, the ratio of torque to active material mass including iron, magnet, and copper, and efficiency are strongly a function of the aspect ratio. Since the highest torque density is achieved around 0.5 of the ratio and both efficiency and torque-mass decrease as the ratio increases beyond 0.5, the aspect ratio of 0.5 is selected to be used in the late design. For AFPMS, the highest torque densities are achieved when the inner-outer diameter ratio is between 0.5 and 0.6. Beyond this area, torque density decreases quickly while the ratio of torque to machine active material mass increases due to the higher diameter ratio. In other words, for higher diameter ratios, machine dimensions go up and the ratio of torque to machine volume goes down while torque to mass ratio increases.

Comparing Fig. 5 and 6, one can find that as the machine power rating increases from 3 to 50 horsepower, the torque to active material ratio increases more quickly for the RFPMS than for AFPMS for lower aspect ratios or diameter ratios. This indicates a potential that the RFPMS may achieve higher torque-to-mass ratio than AFPMS for higher power levels under the condition of same torque density. It should also be mentioned that torque to active material ratio is higher for lower values of aspect ratio in RFPM machines than for lower values of diameter ratio in AFPM machines. However, for higher aspect and diameter ratios, the AFPM machines have slightly higher torque to mass ratio compared to RFPM machines.

Since the axial length of the AFPM machines is almost constant, the diameter increases as the power rating increases. Therefore, large diameter should be expected for large power ratings. For the RFPM machines, the ratio of length to diameter can be optimized to meet the special machine shape requirements. In addition, the machine torque density is not very sensitive to the ratio, as illustrated in Fig. 7. This is an advantage for the RFPMS.

##### B. Effect of Ferrites & Rare Earth Magnets

As ferrite magnets are used, the torque-to-mass ratio, torque density, and efficiency, as illustrated in Figs. 11 through 16, all are lower than those of the rare earth magnet machines due to the lower airgap flux density. Although the ratio of torque to active material mass is almost the same for both AFPMS and RFPMS, RFPMS provide somewhat higher torque density than AFPMS. This is simply because of the fact that the optimum diameter ratio for AFPM machines is around 0.65 which results in higher machine diameters. As the machine diameters get bigger, entire machine volume increases and machine torque density (or torque to entire volume ratio) go down. However, as can be seen from Figs. 11 and 12, machine torque to active mass ratio stays high and it is comparable with the torque to mass ratio of the RFPMS.

##### C. Weight, Cost and Torque Density

Based on Fig. 5 through Fig. 16, the aspect ratio of 0.5 for RFPMS, the diameter ratio of 0.55 for NdFeB AFPMS, and the diameter ratio of 0.65 for ferrite AFPMS are selected for the further design to compare the weight and cost. The pole numbers for each power level are optimized to be 8, 12, 16, and 16 for 3, 10, 25, and 50 horsepower respectively. The results shown in Table II illustrate that the iron mass is almost the same for two type machines, while RFPMS use more copper and AFPMS use more magnets. Since the magnet cost per unit is much higher than the other two materials, the total active material cost is higher for AFPMS than for RFPMS. This is easily understood by considering the fact that the equivalent air gap diameter of the RFPMS is larger than that of the AFPMS. This is achieved by placing all the magnets close to the machine outside diameter.

##### D. Losses and Efficiency

Losses, losses per unit airgap area, and efficiencies of the same designs shown in Table II are summarized in Table III. Iron losses were characterized by the Steinmetz equation based on the steel supplier's loss data for sinusoidal waveforms. In terms of the losses and efficiency, no significant difference is observed between two machine types while the loss per airgap area of the RFPMS is higher than that of the AFPMS due to smaller airgap. In other words, the RFPM machines need better cooling condition. Given that the airgap for the RFPMS is in the axial direction, it can provide stronger cooling wind than the radial direction airgap of the AFPMS to meet this better cooling requirement.

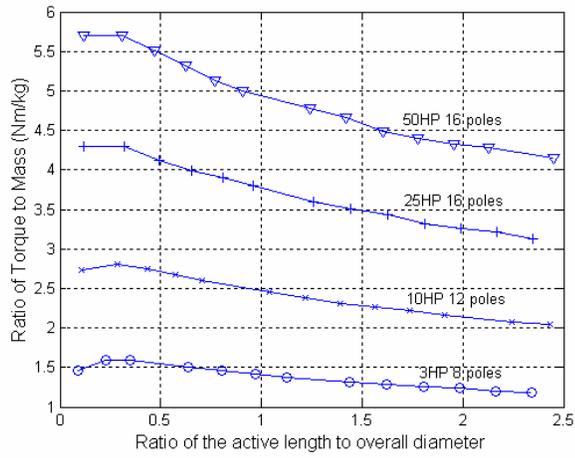


Fig. 5. Ratio of torque to active material mass versus the main aspect ratio of length to diameter for NdFeB RFPMs

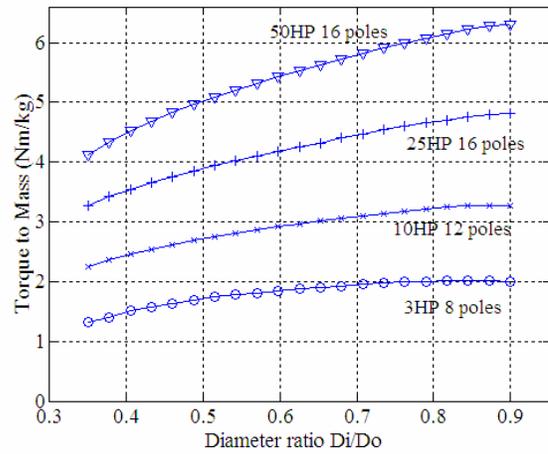


Fig. 6. Ratio of torque to active material mass versus the ratio of stator inner to outer diameter for NdFeB AFPMs

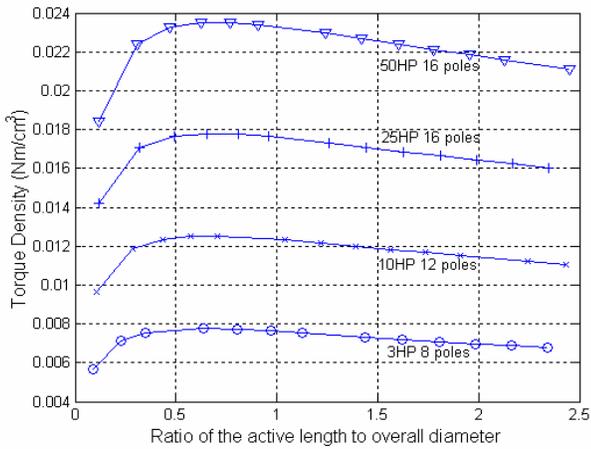


Fig. 7. Torque density versus the main aspect ratio of length to diameter for NdFeB RFPMs

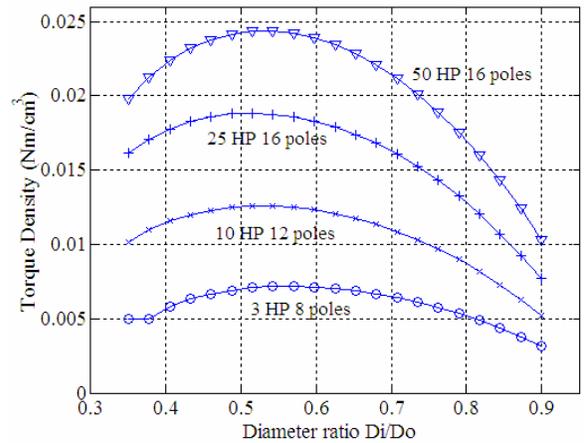


Fig. 8. Torque density versus the ratio of stator inner to outer diameter for NdFeB AFPMs

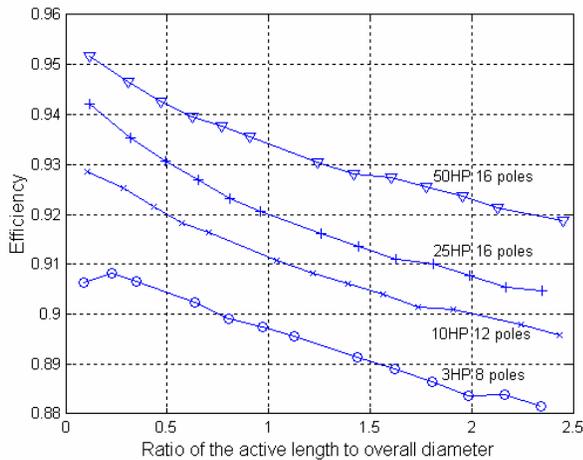


Fig. 9. Efficiency versus the main aspect ratio of length to diameter for NdFeB RFPMs

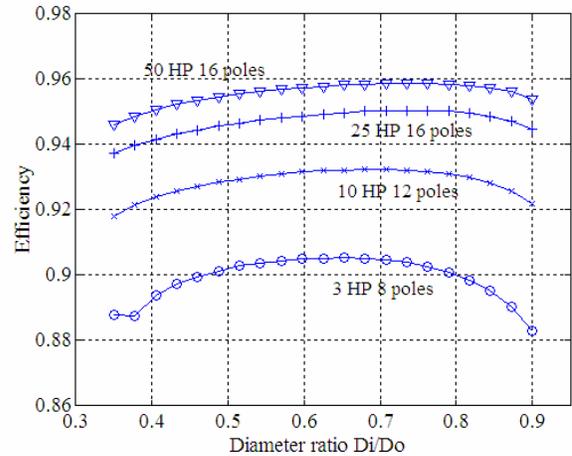


Fig. 10. Efficiency versus the ratio of stator inner to outer diameter for NdFeB AFPMs

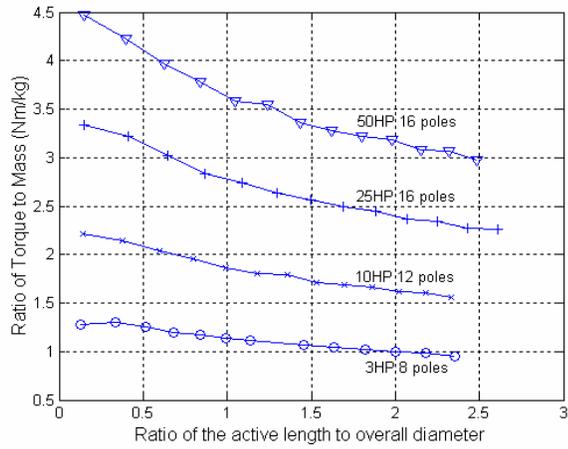


Fig. 11. Ratio of torque to mass versus the main aspect ratio of length to diameter for ferrite RFPMs

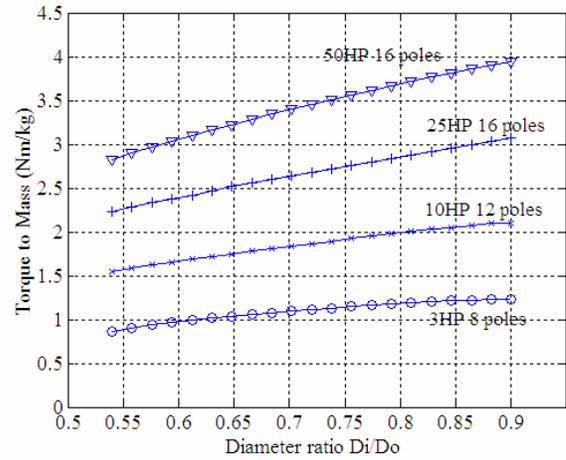


Fig. 12. Ratio of torque to mass versus the ratio of stator inner to outer diameter for ferrite AFPMs

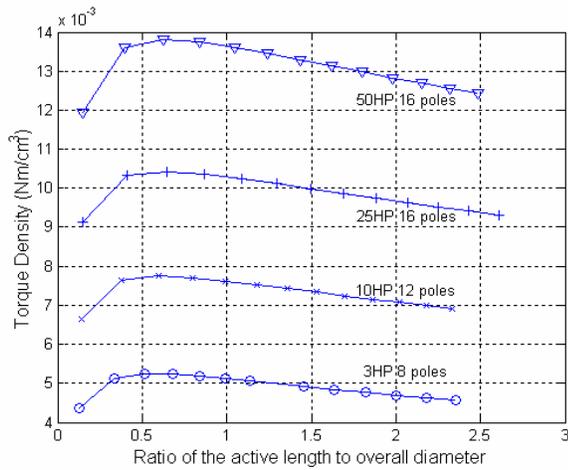


Fig. 13. Torque density versus the main aspect ratio of length to diameter for ferrite RFPMs

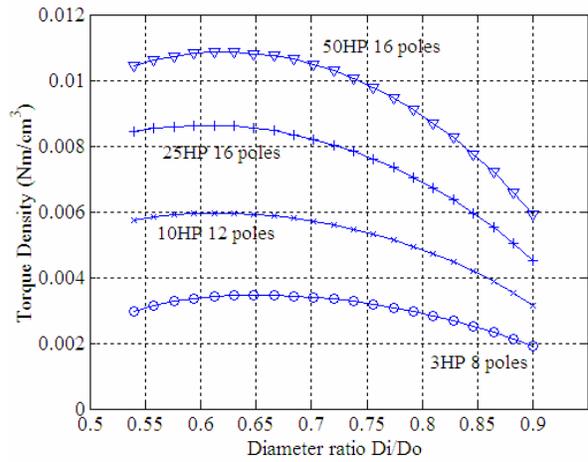


Fig. 14. Torque density versus the ratio of stator inner to outer diameter for ferrite AFPMs

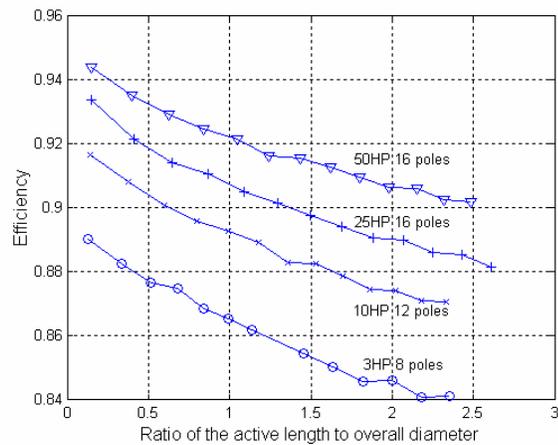


Fig. 15. Efficiency versus the main aspect ratio of length to diameter for ferrite RFPMs

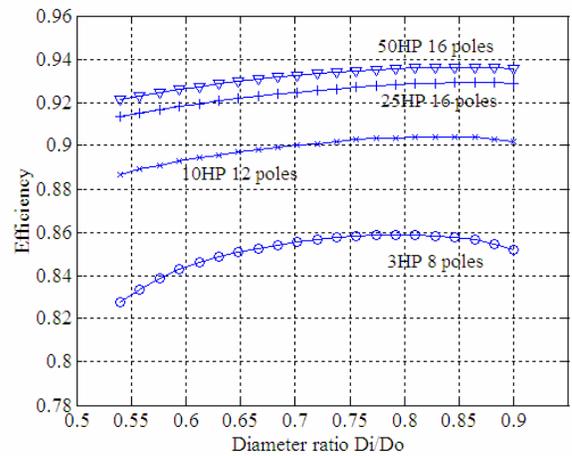


Fig. 16. Efficiency versus the ratio of stator inner to outer diameter for ferrite AFPMs

### E. Pole Number Effect

Pole number effects on torque density and efficiency are shown in Fig. 17 through Fig. 20, in which the aspect ratio of 0.5 was employed for the RFPMs and 0.55 as the diameter ratio for the AFPMs based on the analyses in Section A and B. Those plots show the similar effect of pole number on the RFPMs and AFPMs. As a result of increased frequency, efficiency decreases as the pole number increases. It should

be mentioned that the machine efficiency for AFPMs is less sensitive to increased poles than that of RFPMs as seen in Figs 19 and 20. In addition, although the pole numbers shown in these plots are in a wide range from 4 to 28 poles, certain high numbers can not be employed in practice limited by the stator tooth stiffness. For example, the tooth width of the 12 pole 3 HP motors is as thin as 1 mm, which is insufficient to provide enough mechanical stiffness.

TABLE II ACTIVE MATERIAL MASS AND COST

Magnet	Power	RFPM machines				AFPM machines			
		Copper Wt (kg)	Iron Wt (kg)	Magnet Wt (kg)	Cost <sup>a</sup> (\$)	Copper Wt (kg)	Iron Wt (kg)	Magnet Wt (kg)	Cost <sup>a</sup> (\$)
NdFeb	3	1.87	5.86	0.55	58	1.10	4.60	1.10	96
	10	4.10	10.45	1.10	116	2.16	9.72	2.00	176
	25	7.23	16.55	1.75	188	3.86	17.71	3.59	317
	50	12.41	24.36	2.23	259	6.49	26.00	5.54	489
Ferrite	3	3.17	5.91	1.10	28	2.70	6.10	1.79	30
	10	6.59	11.32	2.15	56	4.91	13.36	4.02	61
	25	12.05	18.41	3.54	97	8.36	23.64	7.30	108
	50	20.50	26.27	4.51	150	15.01	35.68	9.58	166

a: 5.5\$/kg for ferrites; 77\$/kg for NdFeb; 4.4\$/kg for copper; 1.32\$/kg for laminations.

TABLE III LOSSES AND EFFICIENCY FOR RFPM AND AFPM MACHINES

Magnet	Power	RFPM machines				AFPM machines			
		Copper Loss (W)	Iron Losses (W)	Losses/airgap <sup>a</sup> (W/cm <sup>2</sup> )	Eff	Copper Loss (W)	Iron Losses (W)	Losses/airgap <sup>a</sup> (W/cm <sup>2</sup> )	Eff
NdFeb	3	92.2	57.1	0.456	0.911	91.4	60	0.37	0.911
	10	205	270	0.734	0.922	186.4	189.8	0.42	0.934
	25	395	837	1.197	0.930	345.5	480.1	0.55	0.949
	50	729	1300	1.546	0.942	643.6	713.5	0.73	0.958
Ferrite	3	156	54.8	0.370	0.889	225.2	82	0.43	0.857
	10	353	243	0.548	0.909	423.8	272.6	0.44	0.898
	25	661	733	0.792	0.923	747.8	666.3	0.52	0.922
	50	1218	1110	1.032	0.935	1487.5	1027.6	0.76	0.931

a: (Copper loss + Iron Losses)/ total airgap area

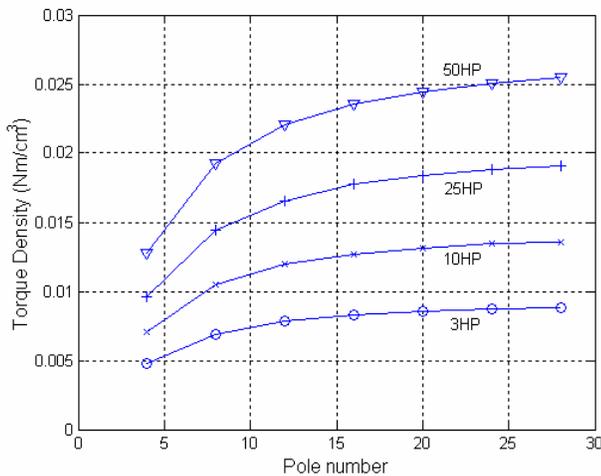


Fig. 17. Torque density versus pole number for NdFeB RFPMs

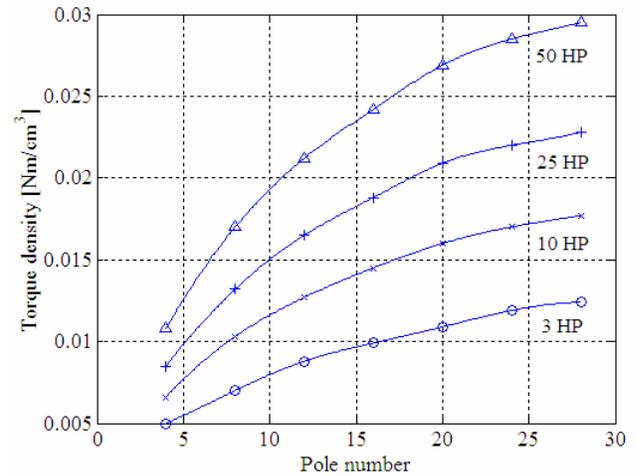


Fig. 18. Torque density versus pole number for NdFeB AFPMs

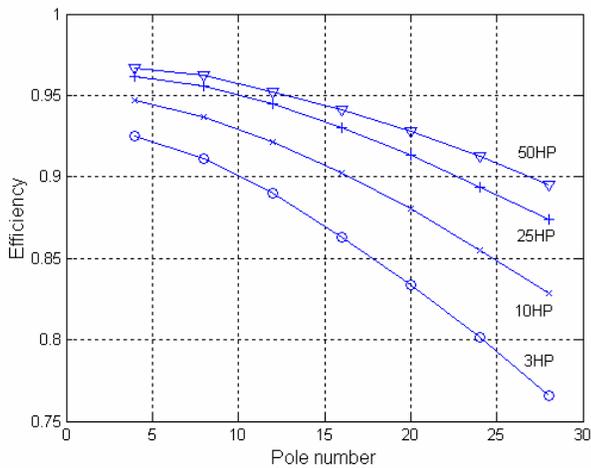


Fig. 19. Efficiency versus pole number for NdFeB RFPMs

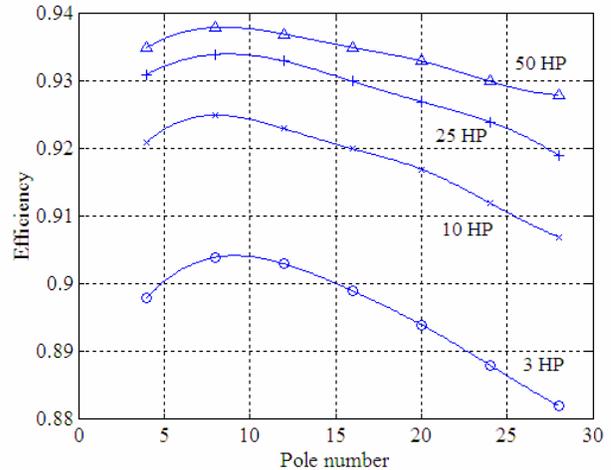


Fig. 20. Efficiency versus pole number for NdFeB AFPMs

## V. CONCLUSIONS

A comparison between the dual-rotor toroidal-wound RFPM and AFPM machines has been carried out. The comparison was conducted at four power levels ranging from 3 to 50 horsepower at a constant rated speed of 1800RPM.

In general, the RFPM and AFPM machines have the similar performance in terms of torque density, torque-to-mass ratio, losses, and efficiency. However, the material cost of AFPM machines is much higher than that of the RFPM machines due to more magnets needed for the AFPMs. For the same efficiency, power loss per unit airgap area is higher for the RFPM than AFPM machines. It also indicates that the RFPMs need and can provide stronger cooling capability than the AFPMs.

The effects of the machine pole number, the main aspect ratio of length to diameter for RFPMs, and the ratio of stator inner to outer diameter for AFPMs on machine features are investigated as well. The results yield an indication of the machine best suited with respect to performance for particular design requirements.

The ratio of length to diameter is almost constant for an AFPM machine, which may limit its applications, while this ratio can be chosen or optimized for a RFPM machine to meet the application requirement. Meanwhile, the outside rotor may limit the applications of both RFPM and AFPM machines.

The comparison made above is based on a concept design. No effort was made to build prototypes. Ten percent error between these designs and experimental results, if there were

any, should be expected. Other machine aspects, such as mechanical structure, cogging torque, should be stressed as important as well, but not included in this paper.

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