Design and Analysis of High Speed Slotless PM Machine with Halbach Array

Seok-Myeong Jang, *Member, IEEE*, Sang-Sub Jeong, Dong-Wan Ryu, and Sang-Kyu Choi

***Abstract*—Slotless machines have been applied for a very high rotational speed and/or the ripple-free torque. In this paper, slotless machines equipped with external 4-pole field Halbach and radially magnetized PM array for electro-mechanical battery. This paper describes the comparison of the design guidelines, magnetic field characteristics, required magnet volume and optimal thickness of windings for two types of PM rotors.**

***Index Terms*—Halbach array, high speed, radial magnetization, slotless.**

I. Introduction

THE MOST important design consideration in the choice of high speed brushless PM machine type is the need to minimize eddy current losses in the retained sleeve and rotor due to slotting harmonics [1]. Therefore, slotless machines have been applied for a very high rotational speed and/or the ripple-free torque. Unfortunately, slotless PM machines have a lower open-circuit field than slotted types, which cause to reduce the advantage of high speed machine, such as high power density, small size and low weight. Fortunately, Halbach array can generate the strong and uniform magnetic field without additional magnetic materials [2]. Furthermore, their inherent self-shielding property and sinusoidal air-gap field distribution has been highlighted for high speed machine without recourse to conventional design features, such as distributed stator windings and/or skewing of the stator/rotor.

Slotted and slotless PM motors with external and internal field Halbach magnetization distributions have already been investigated, respectively [3], [4]. Therefore, this paper considers high speed slotless machines equipped with external 4-pole field Halbach and radially magnetized PM array for electro-mechanical battery. In particular, the paper describes the comparison of the design guidelines and analysis of two types, such as magnetic field, required magnet volume, optimal thickness of windings, and so on.

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S. M. Jang, S. S. Jeong, and D. W. Ryu are with the Electrical Engineering Department, Chungnam National University, Taejeon, Korea (e-mail: smjang@ee.chungnam.ac.kr).

S. K. Choi is with the Korea Institute of Machinery & Materials, Taejeon, Korea (e-mail: skchoi@mailgw.kimm.re.kr).

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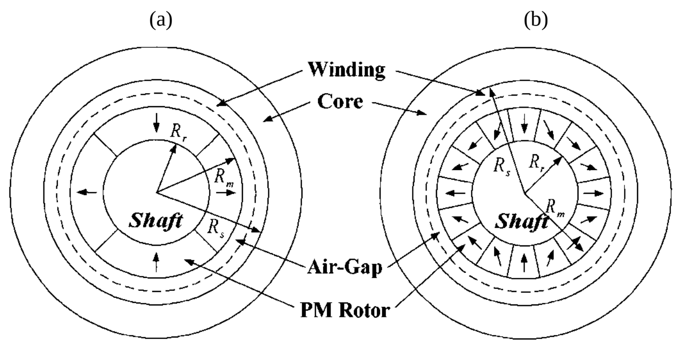

Fig. 1. 4-pole, 3 phase slotless motor: (a) Radially magnetized rotor (b) Halbach magnetized rotor.

II. Slotless PM Machine with Halbach Array Rotor

A. Analytical Model

Fig. 1 compares a 4-pole, 3-phase slotelss brushless motor, with (a) conventional radially magnetized permanent magnets, and (b) a multipole Halbach magnetized magnets. The stator is in the form of a ring and the windings have a toroidal configuration or slotless windings about the ring. These methods of winding have very short end-windings. The space available for windings is virtually doubled by the absence of the stator teeth, and this helps to achieve low copper losses.

The number of poles should be inversely proportional to the maximum speed of rotation. The reason, of course, is to limit the commutation frequency to avoid excessive switching losses in the transistors and iron losses in the stator. For very high speeds, two- and four-pole motors are preferred [5].

For conventional radially magnetized rotor, shaft must be made of iron to make flux path. For Halbach array field system, its inherent self-shielding property makes it easy to select shaft materials. Fig. 2 shows the open-circuit magneto-static field distribution of each rotor topologies.

B. Air-Gap Flux Density

Assuming the relative recoil permeability of the permanent magnet to be 1.0, the flux density at the stator bore of the Halbach machine can be shown to be given by [3];

$$\begin{aligned} B_g(\theta) &= B_m \sin(p\theta) \\ &= \frac{2B_r p}{(p+1)}\left[1-\left(\frac{R_r}{R_m}\right)^{(p+1)}\right] \\ &\quad \times K\left(\frac{R_m}{R_s}\right)^{(p+1)} \sin(p\theta) \end{aligned}$$

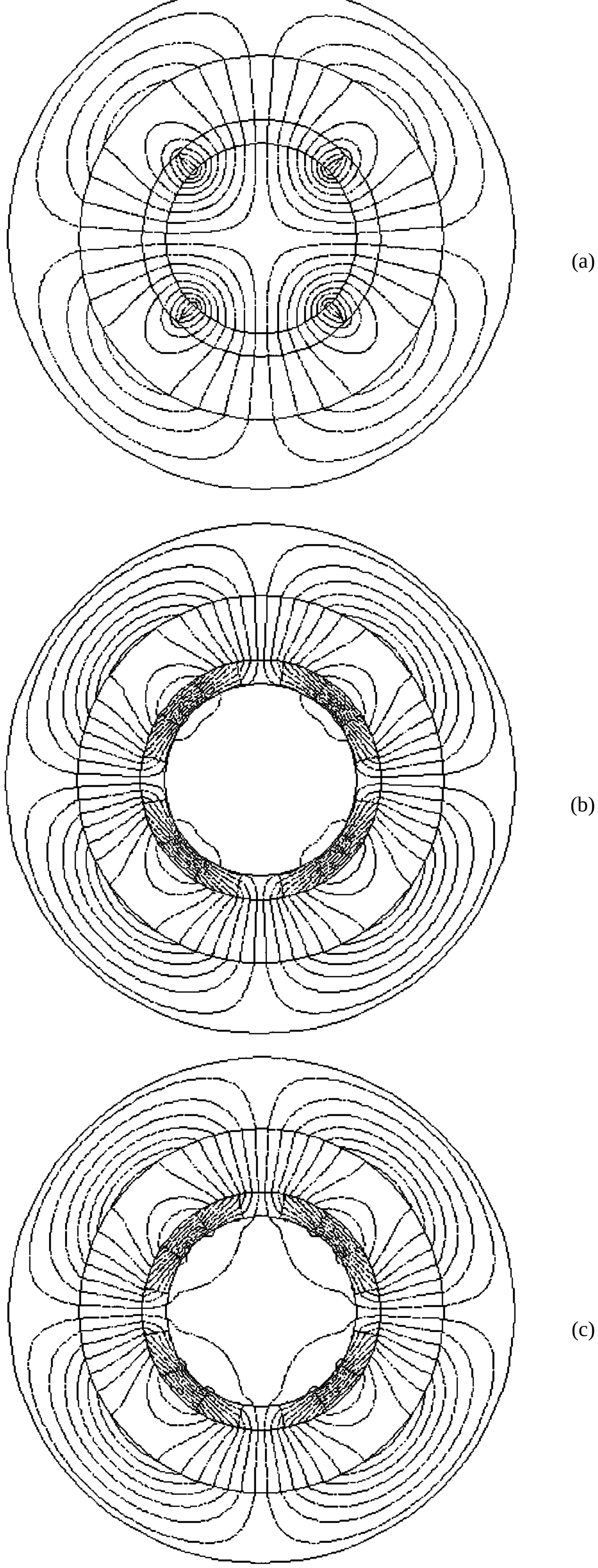

Fig. 2. Open-circuit magneto-static field: (a) Radial magnetization, (b) Halbach magnetization with air-cored shaft, (c) Halbach magnetization with iron-cored shaft.

where

B_m	is the peak air-gap flux density,
B_r	is the remanence,
R_s	is the stator bore radius,

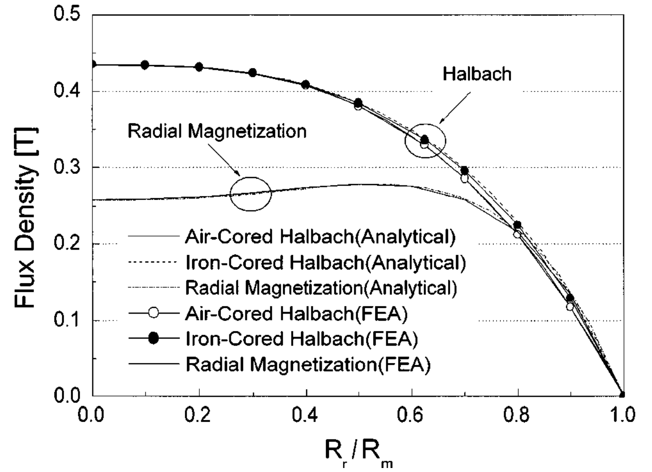

Fig. 3. Variation of peak flux density at stator surface with magnet thickness.

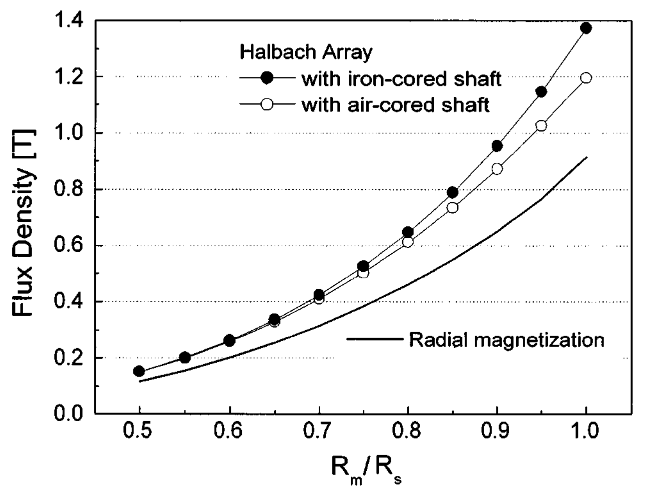

Fig. 4. Variation of peak flux density at stator surface with magnetic air-gap.

R_r and R_m	are the inner and outer radius of the permanent magnet, respectively, and
p	is the number of pole-pairs.

For an air-cored rotor, $K = 1$, whilst for an iron-cored rotor K is given by;

$$K = \left[1 - \left(\frac{R_r}{R_m}\right)^{2p} \left(\frac{R_m}{R_s}\right)^{2p}\right]^{(-1)}.$$

The flux density at the stator bore of the radially magnetized rotor can be shown in reference [2].

For a fixed value of the ratio R_m/R_s, Fig. 3 shows how the peak air-gap flux density varies with the ratio R_r/R_m, for each types magnetized rotor topologies. It can be seen that, for R_r/R_m is small, Halbach array has superior flux property. For a fixed ratio of R_r/R_m, Fig. 4 shows the peak flux density variation with R_m/R_s, which is relative to variation of magnetic air-gap.

C. Induced Voltage and Torque

The open-circuit rms phase EMF is calculated as [6];

$$E = \sqrt{2} r_e l_a B_m K N_{ph} \omega_s / p$$

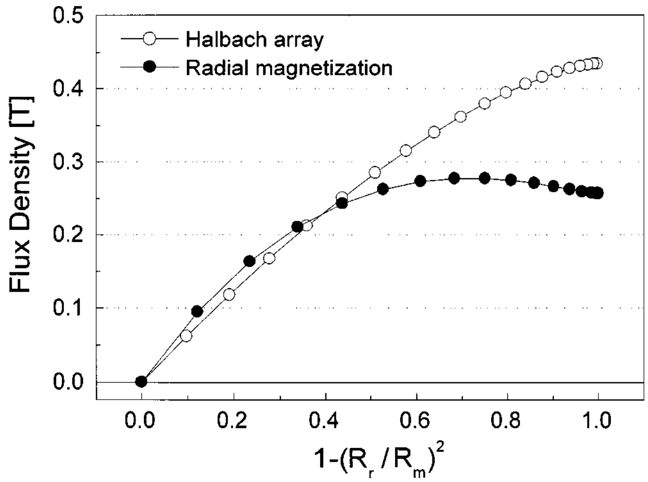

Fig. 5. Variation of peak flux density at stator surface with $1 - (R_r/R_m)^2$.

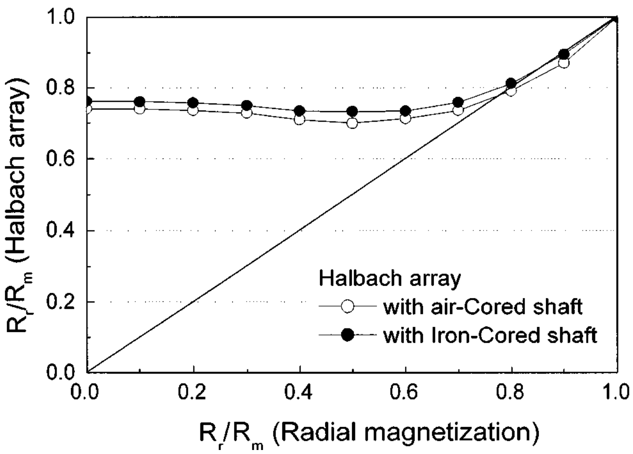

Fig. 6. Variation of R_r/R_m for Halbach magnetized rotor with R_r/R_m of iron-cored radially magnetized rotor.

where

l_a is the stack length,
r_e is the radius of effective air-gap,
ω_s is the electrical angular velocity,
K is the fundamental winding factor, and
N_{ph} is the number of turns per phase.

The electromagnetic torque of a 3-phase ac machine is given as;

$$T = \frac{3}{\omega_m} EI \sin\delta$$

in [Nm]. ω_m is the mechanical angular velocity and I is the rms phase current, and δ is the load angle.

D. Magnet Volume Requirements

For a fixed rotor outer radius R_m and magnet length along axial direction l_m, magnet volume varies with $1 - (R_r/R_m)^2$ and given by;

$$V_{pm} = \pi R_m^2 l_m \left[1 - \left(\frac{R_r}{R_m}\right)^2\right].$$

Fig. 5 shows the peak flux density variation with the $1 - (R_r/R_m)^2$. For a fixed ratio of R_m/R_s, Fig. 6 shows the variation of the required ratio of R_r/R_m for air- and iron-cored Halbach magnetized rotors, with the ratio R_r/R_m of an equivalent radially magnetized iron-cored rotor. It can be seen that below a certain ratio of R_r/R_m, the Halbach rotor requires a lower volume of magnet material.

TABLE I
HARMONIC OF AIR-GAP FLUX DENSITY WAVEFORM

Harmonic Order	1	3	5
Air-cored Halbach	0.212	-	-
Iron-cored Halbach	0.225	-	-
Radial Magnetization	0.235	0.023	0.003

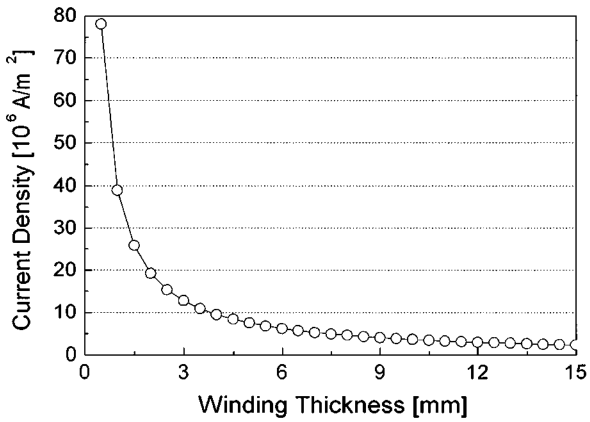

Fig. 7. Variation of current density in windings under constant power dissipation.

E. Harmonic of Air-Gap Flux Density Waveform

Harmonic of air-gap flux density cause to generate losses of rotor and stator. Table I shows a harmonic of air-gap flux density waveform of Halbach and radially magnetized rotor with the ratio $R_r/R_m = 0.8$. Halbach magnetized rotor has a pure sinusoidal air-gap flux density distribution. These results are identically obtained at different magnet thickness and/or magnetic air-gap. It makes them eminently appropriate for electromechanical battery, for which a low core loss is achieved in order to maximize efficiency at the motoring and generating modes.

F. Optimal Thickness of Windings

One of the characteristics of slotless motor is the existence of an optimal thickness of armature windings to produce maximum torque per ohmic power dissipated in the armature windings [4]. For a comparison of the torque production capability of Halbach and radial magnetization, the ohmic power is fixed to 7.7 W and the volume of the magnets and the mechanical air-gap are fixed, while volume of motor varies with winding thickness.

Fig. 7 shows the variation of the current density in the armature winding which has the thickness of the windings under the constraint of constant ohmic power dissipation in the armature. Fig. 8 indicates that there is an optimal thickness of armature windings for highest motor torque. It was obtained by product of two elements which are the radial component of the no-load

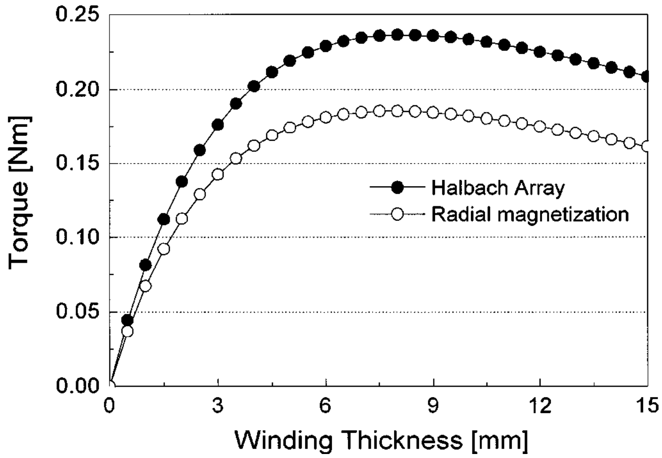

Fig. 8. Optimal thickness of stator winding with winding thickness.

air-gap magnetic flux density and the current of the armature conductors.

III. Comparison of Halbach Rotor and Radially Magnetized Rotor

From the foregoing results, we designed the motor/generator aimed at electro-mechanical battery. It was designed as 1 kW PM motor/generator with the rated speed of 40 000 rpm. It is accelerated to rated speed during 1800 sec. Table II compares the design and predicted results of Halbach magnetized and radially magnetized rotors for same specification. It can be seen that the Halbach motor has a lower motor volume about 15% than radial magnetization motor. Also motor losses reduce about 16.1%.

TABLE II
Comparison of Design and Predicted Results

Items	Radial	Halbach	A note
Power[W]	1000		
Torque[Nm]	0.512		
R_r/R_m	0.55		
R_m/R_s	0.677	0.686	
Peak Flux Density[T]	0.326	0.42	+28.8%
Flux/PM Volume [Wb/m^3]	12.1	15.8	+30.6%
Length/Diameter[mm]	69/60	58/61	
Turns per Phase	26	24	
Power/Volume [Wb/cm^3]	5.13	5.9	+15%
Copper + Core Loss[W]	31	26	-16.1%

IV. Conclusions

Magnetic field, required magnet volume, optimal thickness of winding of 4-pole, slotless brushless motor with Halbach magnetized rotor and radially magnetized rotor has been discussed. It has been shown that the Halbach magnetized rotor has the strong and the sinusoidal air-gap flux density. The Halbach magnetized rotor with the slotless stator core is applied to a high speed motor/alternator for an electro-mechanical battery to eliminate the eddy current loss and to increase the air-gap flux density.

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