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Article

Optimization Method for Minimum Mass of Permanent Magnet Excited HIA with Air-Gap Winding

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Abstract: This paper proposes the optimization method for the minimum mass of permanent magnet (PM) excited homopolar inductor alternator (HIA) with air-gap winding used for high-speed driving system. The calculation results show that there is an optimal value for shell diameter and unit number of HIA to make the mass to be smallest. A 1 MW at 22000 rpm PM excited HIA is designed. The analytical results are verified by the FEM simulations. The losses, temperature rise, rotor stress and modal of the PM excited HIA are also analyzed. The calculation results show that the solid rotor eddy-current losses and the temperature rise of PM excited HIA are acceptable. Also the rotor strength is adequate, and the rotor system is a stiffness rotor, and it can safely operate. Finally, the comparison between PM excited HIA and permanent magnet rotor machine is discussed.

Keywords: permanent magnet excited homopolar inductor alternator; optimization method for minimum mass; air-gap winding; unit number

I. Introduction

The permanent magnet rotor machines (PMRMs) have the advantage of high power density and efficiency, and they can be classified into permanent magnet synchronous motor (PMSM) and permanent magnet brushless DC motor (PM BLDC), and the single rotor or dual rotor machine [1-3]. But the reliability of it is not so high, due to the complex rotor structure, especially in the high-speed driven system. Also the rotor magnet has the risk of demagnetization on the condition of very high temperature rising cause by eddy-current losses.

The homopolar inductor alternator (HIA) has a very simple rotor, and it has the advantage of high power density and reliability, and was successfully used in the field of high power-density pulsed power supply [4-8], flywheel energy storage [9-12], airborne applications [13], propulsion system of ship [14] and so on.

The HIA can be classified into copper conductor excited HIA [4-9, 15-17], high-temperature superconductor excited HIA [13-14] and permanent magnet (PM) excited HIA [10-12] according to the exciting modes. For the PM excited HIA, because the magnet is placed between the two half shells, the magnetic flux density is almost invariable, the eddy currents losses are very small, what's more the heat dissipation condition for magnet is much better than the PMRM, so the temperature rise of magnet for PM excited HIA is very low, and there is no risk of magnet demagnetization. So the PM excited HIA has much higher reliability than the PMRM.

For the high-speed HIA with slot stator core, the squeezing effects of winding are extremely serious, and the fundamental air-gap magnetic flux density is relative lower than PMRMs. In this paper, we propose a PM excited HIA with air-gap winding, which has much lower winding copper losses compared with conventional PM excited HIA. And also the air-gap magnetic flux density is very high which can address the issue of relative low fundamental air-gap magnetic flux density for

HIA with slot stator core. And in order to enlarge the power capacity, the multistage stator-cores HIAs proposed in [15-17] are adopted. The optimal design of PM excited HIA has been studied in [10-12], but there are no literatures discussing about the optimization of unit number of HIA for the minimum mass of this machine.

The structure of this paper is as follows. First, a brief introduction for the structure of the PM excited HIA with air-gap winding is presented. Then the optimization method for the minimum mass is proposed.

Finally, a 1 MW at 22000 rpm PM excited HIA is designed. The analytical results are verified by the FEM simulations, and the losses, temperature rise, rotor stress and modal of the PM excited HIA are analyzed by simulation. Finally, the comparison between PM excited HIA and PMRM is discussed.

II. Structure of PM excited HIA with air-gap winding

The structure of conventional PM excited HIA can be found in [11-12], and the permanent magnet is placed between the left shell and right shell as shown in 0 (a). And in this paper, the air-gap winding is adopted. The winding supporting structure is shown in 0 (b). The windings are placed in the hole of a cylinder which is made from epoxy resin. The epoxy resin cylinder is fixed on the inner surface of the stator core. The single-layer windings are chosen for the PM excited HIA.

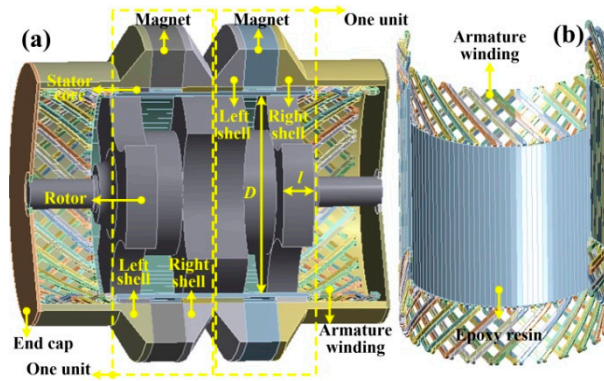


Figure 1. (a) The structures of multi-unit PM excited HIA; (b) The air-gap winding.

III. Calculation of mass

A. The main dimensions

The rotor diameter is determined by:

$$D = \frac{v_{cr}}{n_r} \frac{\pi}{60} \quad (1)$$

v_{cr} is the tip speed of rotor, n_r is the rotating speed. The RMS value of no-load phase induced voltage can be calculated by:

$$E_{ph} = \frac{P_o}{3I_{ph} \cos \phi} \quad (2)$$

P_o is the output power, and I_{ph} is the RMS value of phase current, $\cos \phi$ is the power factor of machine.

The amplitude of no-load flux per pole for one unit of HIA can be calculated by:

$$\Phi_{ph} = \frac{E_{ph}}{4.44 K_{mu} K_{n1} N f} \quad (3)$$

K_{mu} is the unit number of HIA, K_{n1} is the winding coefficient, N is number of series turns per phase, and f is the electrical frequency of machine.

Then the length of one stator core can be calculated by:

$$l = \frac{p\Phi_{ph}}{2(D+2\delta)B_{\delta}\lambda_1^*} - \delta \quad (4)$$

Here, p is pole pair number, δ is the air-gap length, and B_{δ} is maximum value of air-gap magnetic flux density, λ_1^* is the per-unit value of fundamental air-gap permeance.

B. The mass of permanent magnet

In the derivation of the dimension parameters of the permanent magnet, the leakage fluxes of magnetic path are also been taken into consideration, which are ignored in [10-12].

The magnetic circuit is shown in 0. Here, F_c is the magneto motive force produced by the permanent magnet, R_m is the magnetic reluctance of permanent magnet, and R_{ms} and R_{δ} are the magnetic reluctance of leakage and main magnetic path respectively. From the magnetic circuit, the formulas of length of magnet can be obtained that, to be:

$$l_m = \frac{2B_{\delta}\delta\left(\frac{A_{ms}}{A_{shell}} + \mu_r\right)}{B_m - \frac{\pi B_{\delta}\lambda_0^* D(l+\delta)}{A_{shell}}} \quad (5)$$

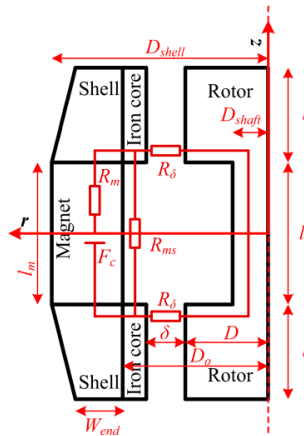


Figure 2. The magnetic circuit of one unit of the PM excited HIA.

The derivation of l_m and the definitions of symbols in (5) are presented in appendix A. And the length of magnet l_m is the same as the length of rotor shaft l_b .

In order to make the value of l_m to be positive, the value of A_{shell} must satisfy that:

$$A_{shell} > \frac{\pi B_{\delta}\lambda_0^* D(l+\delta)}{B_m} \quad (6)$$

The mass of permanent magnet can be calculated by:

$$\begin{aligned} M_{PM} &= K_{mu}\rho_{PM}A_{shell}l_m \\ &= 2K_{mu}\frac{\rho_{PM}B_{\delta}\delta(A_{ms} + \mu_r A_{shell})}{B_m - \frac{\pi B_{\delta}\lambda_0^* D(l+\delta)}{A_{shell}}} \end{aligned} \quad (7)$$

Here, ρ_{PM} is the mass density of permanent magnet.

C. The total mass of machine

The diameter of rotor shaft is:

$$D_{shaft} = \sqrt{\frac{4D(l+\delta)B_{\delta}\lambda_0^*}{B_{shaft}}} \quad (8)$$

Here, the B_{shaft} is the average value of magnetic flux density in rotor shaft. Then, the mass of rotor can be calculated as follows.

$$M_{rotor} = \rho_r \pi \left(\left(\frac{D}{2} \right)^2 l + \left(\frac{D-2h}{2} \right)^2 l + \left(\frac{D_{sh}}{2} \right)^2 l_m \right) \quad (9)$$

$$h = K_h \delta \quad (10)$$

Here, the K_h is defined as ratio of rotor slot depth to air-gap length, and ρ_r is the mass density of alloy steel.

The mass of armature winding can be calculated by:

$$M_{coil} = 1.15 m l_{coil} N S_{cu} \rho_{cu} \quad (11)$$

Here, m is the phase number of winding, S_{cu} is cross-section area of conductors, ρ_{cu} is the mass density of the copper. The calculation of length of armature winding l_{coil} for one turn is presented in appendix B.

The total mass of machine can be calculated by:

$$M_t = M_{rotor} + M_{coil} + M_{sta} + M_{shell} + M_o \quad (12)$$

M_{sta} is the mass of stator, M_{shell} is the mass of shell, and M_o is the mass of other parts, such as end cap, bearings and so on. The calculations of M_{sta} , M_{shell} are presented in appendix C.

IV. Optimization method for minimum mass of PM excited HIA

A. The design input parameters and constraint condition

The design input parameters of the PM excited HIA are shown in table I. The constraint conditions are as follows.

- 1) Comprehensive considering reducing the electrical frequency and the weight of HIA, the poles pair number is chosen to be 3.
- 2) The rotor slot depth is chosen to be about 11 times of air-gap length.
- 3) The ratio of rotor slot width to the tooth pitch is chosen to be about 0.55 in order to obtain the as large fundamental component of air-gap magnetic field as possible.

TABLE I. THE DESIGN INPUT PARAMETERS OF PM EXCITED HIA

Parameters	Value
Maximum rotating speed (rpm)	22000
Maximum electrical frequency (Hz)	≤ 1200
Maximum output power (MW)	1
Total weight of machine (kg)	≤ 250

Efficiency at rated output power	$\geq 96\%$
Continuous working time (s)	≤ 100

B. Optimization method

The optimization parameters are listed in table II. The variations of B_δ are 1.0 T, 1.25 T and 1.5 T, the variations of K_{mu} are 1, 2 and 3. The calculated mass of permanent magnet is presented in 0, and the total mass of machine is presented in 0. It can be found that the larger the B_δ is, the larger the mass of magnet is; the larger the B_δ is, the smaller the total mass of machine is. It can be also found that there is an optimal value for D_{shell} and K_{mu} to make the mass to be smallest. Taking the mass of the magnet and the machine into comprehensive consideration, the optimal value of K_{mu} , B_δ and D_{shell} can be found from the Figure 3 and Figure 4, to be 2, 1.5 T and 0.45 m, respectively.

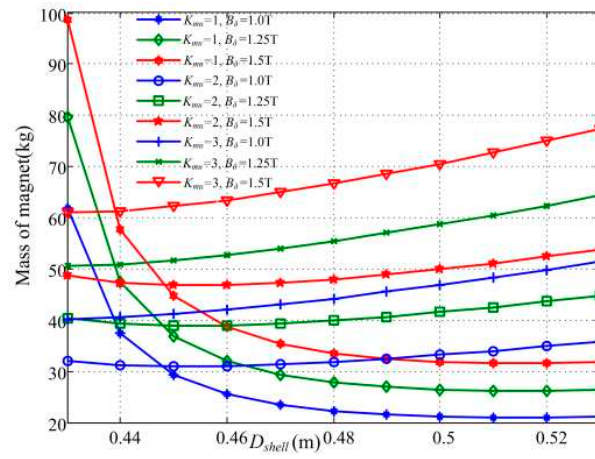


Figure 3. The mass of permanent magnet.

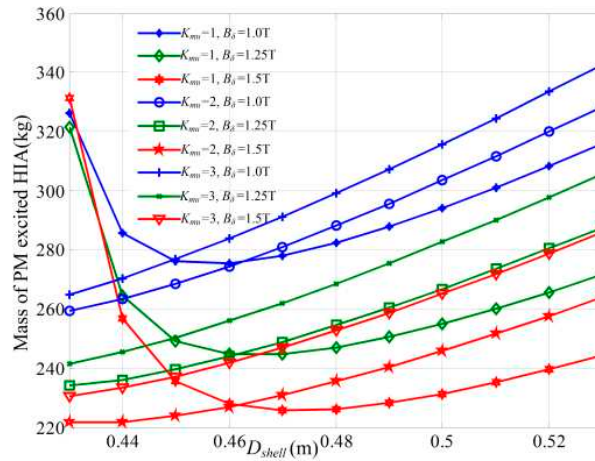


Figure 4. The total mass of PM excited HIA.

TABLE II. THE OPTIMIZATION PARAMETERS OF PM EXCITED HIA

Parameters	Variation
Maximum value of air-gap magnetic flux density B_δ	1.0-1.5 T
Unit number of stator core K_{mu}	1-3
Maximum outer diameter of shell D_{shell}	0.43-0.53 m

V. Design results

The designed parameters of PM excited HIA are shown in table III. The analytical calculated parameters of electromagnetic properties are shown in table IV, and the air-gap permeance used in the analytical methods is obtained by look-up table. The look-up table is obtained by the two-dimensional FEM simulation model which is presented in [18-19].

TABLE III. DESIGNED PARAMETERS OF PM EXCITED HIA

Symbol	Parameter	Value
D	Rotor diameter (mm)	304
p	Pole pair number	3
h	Rotor slot depth (mm)	68
l	Length of one stator core (mm)	41
l_b	Length of shaft	44
δ	Air-gap length (mm)	6
D_i	Stator-core inner diameter (mm)	316
D_o	Stator-core outer diameter (mm)	332
z_1	Stator slot number	54
L_m	Length of permanent magnet (mm)	44
D_{shell}	Shell maximum outer diameter (mm)	450
a	Parallel branches	1
q	Stator slot number per pole per phase	3
N_l	Winding layers	1
n_c	Number of conductors per slot	1
N	Number of series turns per phase	9
β	Short pitch coefficient of armature winding	1
B_δ	Maximum air-gap magnetic field (T)	1.5
n_r	Rotating speed (rpm)	0-22000
K_{mu}	Unit number of HIA	2

TABLE IV. PARAMETERS OF ELECTROMAGNETIC PROPERTIES OF PM EXCITED HIA

Symbol	Parameter	Value
E_{rms}	RMS value of phase EMF (V)	560
f_{max}	Maximum fundamental electrical frequency (Hz)	1100
I_n	RMS value of rated phase current (A)	625
P_n	Rated output power (kW)	1000

A. The calculation of electromagnetic parameter

The calculations of RMS value of phase no-load back electromotive force (EMF) for PM excited HIA are like the conventional machine. The calculations of synchronous inductance of dq axis for PM excited HIA can consult the salient pole synchronous machine, the detailed derivation can be found in reference [19]. The analytical calculation is presented Table V. And the three-dimensional FEM simulations are used to verify the calculation. The simulation conditions are as follows:

- 1) For d axis: When the axis of A phase align with d axis, the currents in three phase windings are as follows:

$$\begin{cases} I_A = I_m \cos(2\pi f_1 t) \\ I_B = -\frac{1}{2} I_m \cos(2\pi f_1 t) \\ I_C = -\frac{1}{2} I_m \cos(2\pi f_1 t) \end{cases} \quad (13)$$

2) For q axis: When the axis of A phase align with d axis, the currents in the three phase windings are as follows:

$$\begin{cases} I_A = 0 \\ I_B = \frac{\sqrt{3}}{2} I_m \cos(2\pi f_1 t) \\ I_C = -\frac{\sqrt{3}}{2} I_m \cos(2\pi f_1 t) \end{cases} \quad (14)$$

The simulation has considered the saturation of magnetic circuit, and the winding current of A phase is the rated value. The synchronous reactance of dq axis is calculated by the ratio of EMF and current of A phase, and the synchronous inductance can be calculated from the synchronous reactance. The comparisons of analytical calculation and FEM simulation for synchronous inductances are presented in table V. The analytical results coincide with the FEM simulation results.

TABLE V. COMPARISONS OF ANALYTICAL CALCULATION AND FEM SIMULATION FOR SYNCHRONOUS REACTANCE

Parameters	Analytical	FEM simulation
Synchronous inductance of d axis L_d (uH)	44	44
Synchronous inductance of q axis L_q (uH)	57	60

VI. Simulation results

A. The no-load simulation results

The 3D FEM simulations are used to verify the calculation results in analytical methods. The air-gap magnetic induction distribution is shown in 0, and the maximum value is about 1.5 T. The simulated waveforms of induced no-load phase voltage and line-to-line voltage are shown in 0, and the RMS value of phase induced voltage is 565 V. The simulation results are coincided with the analytical calculation results.

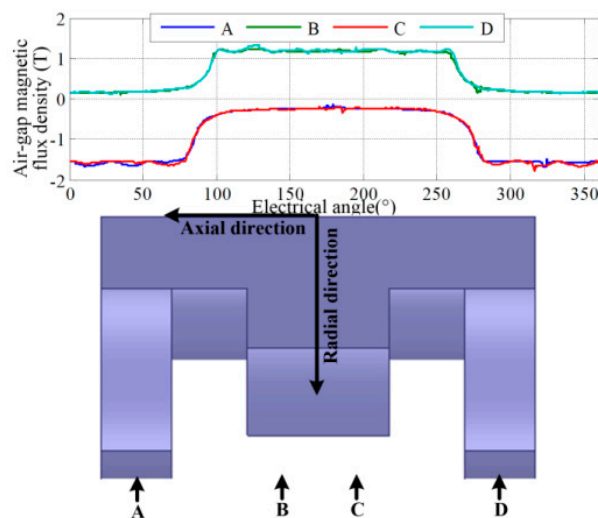


Figure 5. The air-gap magnetic induction distribution.

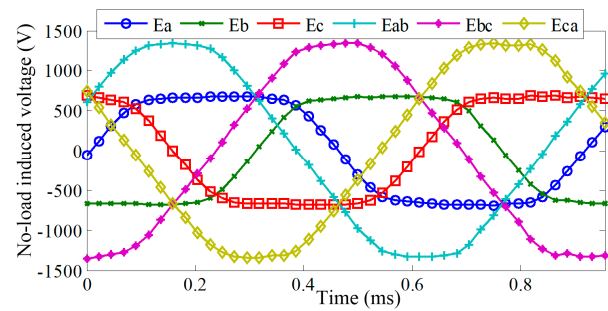


Figure 6. The simulated waveforms of no-load induced voltage.

B. The simulation results at rated load

A 3D FEM model combined with external circuit is used to verify the performance at rated load condition. For the external circuit, the square wave control is adopted. The simulated phase current and the torque waveforms are presented in 0. The simulation results show that the RMS values of phase currents are about 630 A and the average torque is about 434 N. m, which are coincided with the analytical calculation results.

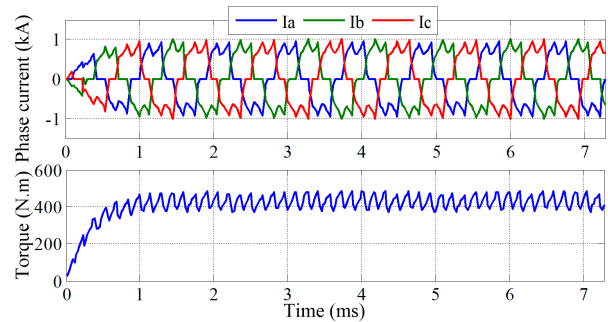


Figure 7. The simulated waveforms of phase currents and torque at rated load.

C. Losses and efficiency

The losses of electrical machine are composed of air friction and mechanical losses, iron core losses, rotor eddy-current losses and armature winding copper losses. The air friction losses are calculated by empirical formulas in [7], and it is verified by the experiment result. The iron losses are calculated by the FEM simulations.

The different kinds of losses for PM excited HIA at rated load are shown in table VI.

TABLE VI. DIFFERENT KINDS OF LOSSES FOR PM EXCITED HIA AND PMRM AT RATED LOAD		
	PM excited HIA	PMRM
Winding copper losses (kW)	5	10.4
Stator iron losses (kW)	2.5	14.2
Rotor eddy-current losses (kW)	6	0.35
Mechanical and air friction losses (kW)	6.4	1.7
Total losses (kW)	19.9	26.65
Efficiency	98%	97.4%

For the PM excited HIA, due to the slotless stator core structure, the extremely serious squeezing effects of armature winding are relieved, so the armature winding copper losses of PM excited HIA are much less than the conventional PM excited HIA.

The simulated results of iron losses for PM excited HIA are shown in table VI and 0. It can be found that the rotor and stator iron losses are 6 kW and 2.5 kW, respectively.

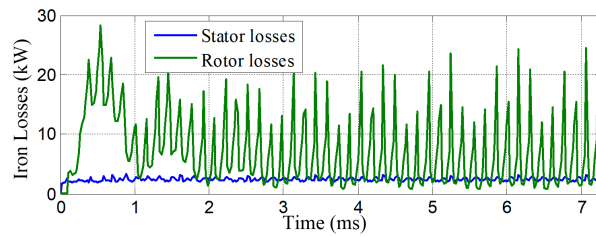


Figure 8. The simulated stator and rotor losses waveforms for PM excited HIA at rated load.

In order to reduce the air friction losses, pumping vacuum is used. The vacuum degree is set to be 0.95, considering the difficulty of pumping vacuum and rotating seal. The calculated air friction losses for the PM excited HIA are presented in 0. And at 22000 rpm, the air friction losses are about 6.3 kW.

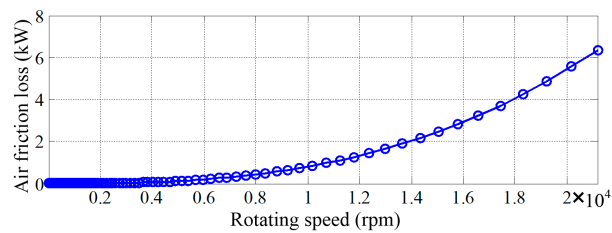


Figure 9. The calculated air friction losses for PM excited HIA.

D. Temperature rising

The temperature rising is simulated by the 3D FEM simulation. The temperature rising curve is shown in 0 (a), and at 100 s, the 3D temperature distribution is shown in. The maximum temperature is 149.39 °C, which is at the face of rotor, and maximum temperature for armature winding is 123 °C, which is at the end of the winding. So, the machine can operate safely.

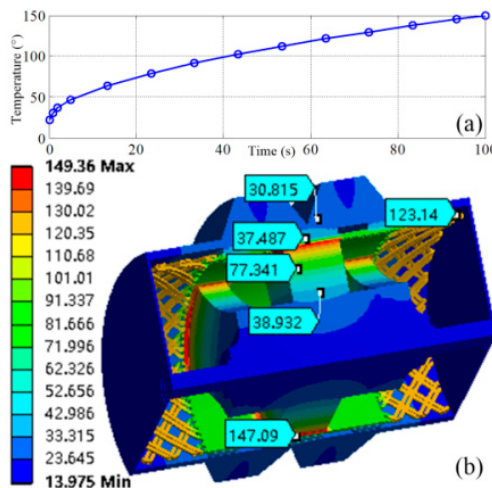


Figure 10. (a) The temperature rising curve, (b) 3D temperature distribution calculated by FEA.

E. Rotor stress and modal

The rotor stress and rotor modal are simulated by the 3D FEM simulation. The von misses stress of rotor is shown in 0 (a), and the radial deformation is shown in 0 (b). The maximum stress is 558 Mpa which is much less than tensile strength of rotor material. The maximum radial deformation is 0.165 mm, which is much less than physical air-gap length. The first critical speed of the rotor is 86610 rpm, which is much larger than the operation speed 22000 rpm. So the rotor system can safely operate.

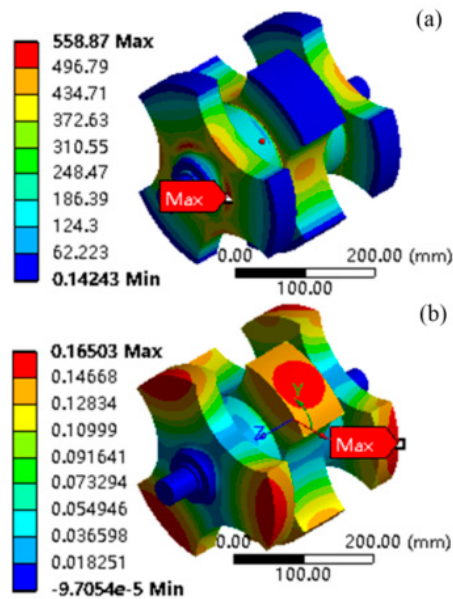


Figure 11. (a) The Von misses stress of rotor (MPa); (b) The radial deformation (mm).

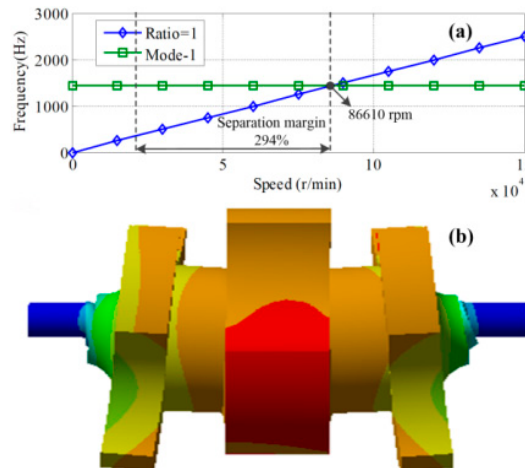


Figure 12. The simulated (a) Campbell chart; (b) first band modal of rotor.

VII. Comparisons between PM excited HIA and PMRM

In order to compare the PM excited HIA and the PMRM; the PMRM is designed on the condition that the rotating speed, pole pair number, the stator slot number and the winding pitch are the same with the PM excited HIA. The designed parameters of PMRM are presented in table VII. The stator core of PMRM is slot-core structure. The parallel branches of PMRM winding are 3, while for the PM excited HIA the parallel branches are 1. The conductor per slot for PMRM is 2, while for the PM excited HIA the conductor per slot is 1.

TABLE VII. DESIGNED PARAMETERS OF PMRM

Symbol	Parameter	Value
D_{ro}	Rotor outer diameter (mm)	132
P	Pole pair number	3
h_M	Thickness of magnet (mm)	20
n_{Ms}	Number of slices for magnet in axial direction	20
L	Length of rotor or stator (mm)	480
D_{ri}	Rotor inner diameter (mm)	60
δ	Air-gap length (mm)	10
D_i	Stator-core inner diameter (mm)	152
D_o	Stator-core outer diameter (mm)	255
z_1	Stator slot number	54
z_{sk}	Skew width in slot number	1
α_p	Mechanical pole embrace	0.6

D_{shell}	Shell maximum outer diameter (mm)	315
a	Parallel branches	3
q	Stator slot number per pole per phase	3
N_l	Winding layers	2
n_c	Number of conductors per slot	2
N	Number of series turns per phase	6
β	Short pitch coefficient of armature winding	1
B_δ	Maximum air-gap magnetic field (T)	0.7
n_r	Rotating speed (rpm)	0-22000

The three-dimension model of the PMRM is presented in Figure 13. It can be seen that, the axial length of PMRM are much large than the PM excited HIA. This is because that, for the PM excited HIA, the rotor tip speed can be very large, while for the PMRM due to the complex rotor structure, the rotor tip speed cannot be too large, and the rotor diameter is small relatively. The comparisons of the PM excited HIA and PMRM are presented in table VIII. It can be seen that, the PM excited HIA has the equivalent power density and larger efficiency compared with the PMRM.

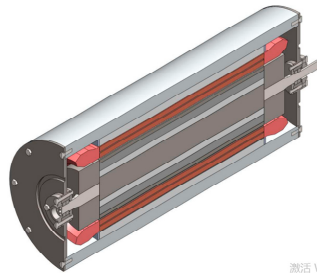


Figure 13. The three-dimension model of PMRM.

TABLE VIII. THE COMPARISON OF PMRM AND PM EXCITED HIA

Parameters	PMRM	PM excited HIA
Maximum rotating speed n_{max}	22000	22000
RMS value of phase EMF (V)@ n_{max}	494	560
Maximum electrical frequency (Hz)	1100	1100
Synchronous inductance of d axis (uH)	25.8	44
Synchronous inductance of q axis (uH)	25.8	57
Weight of permanent (kg)	18	46
Total weight of machine (kg)	240	240
Rotor initial (kg.m ²)	0.18	0.7
Efficiency at rated output power	97.4%	98%

A. The power factor

From table V, it can be found that the synchronous inductance of PMRM is much less than the PM excited HIA. This is because that the air-gap length between rotor and stator iron for PMRM is much larger than PM excited HIA. So, the power factor of PMRM is larger than the PM excited HIA.

B. Losses and Efficiency

The different kinds of losses for PMRM at rated load are shown in table VI. It can be found that, the armature copper losses and iron core losses of PM excited HIA are less than the PMRM, while the rotor eddy-current losses and air friction losses of PM excited HIA are much larger than the PMRM.

1) Winding copper losses

For the PM excited HIA, due to the slotless stator core structure, the extremely serious squeezing effects of armature winding are relieved, so the armature copper losses of PM excited HIA are much less than the PMRM.

2) Iron losses

The iron core losses of PM excited HIA are 2.5 kW, while for the PMRM the iron core losses are 14.2 kW. The reason is that the iron losses are proportional to the square of magnetic flux density, and the stator core of PMRM is slot-core structure, and the magnetic flux density in the tooth is large, while the stator core of PM excited HIA is slot-less, the magnetic flux density is uniform relatively.

What's more, the weight of stator core for PMRM is much larger than the PM excited HIA, which are 80 kg and 15 kg for PMRM and PM excited HIA respectively, and the reason is that the thickness of stator iron yoke for PM excited HIA is much smaller than the PMRM. The magnetic fluxes of PM excited HIA pass the shell and then the other half stator core, so there is no requirement for stator iron yoke to pass the magnetic fluxes between two poles.

3) Rotor eddy-current losses

The rotor eddy-current losses of PMRM are 0.35 kW; while the rotor eddy-current losses of PM excited HIA are 6 kW. The reason is that the magnet segmentation of PMRM in axial direction, which can reduce eddy current dramatically.

4) Air friction losses

The air friction losses of PM excited HIA are much larger than the PMRM. And at the rotating speed of 22000 rpm, the losses are 6.4 kW and 1.2 kW for the PM excited HIA and PMRM respectively. The reason is that the rotor tip speed of PM excited HIA is much larger than the PMRM, and the rotor structure of PM excited HIA is salient while the rotor outer face of PMRM is smooth.

C. The reliability

The rotor structure of PMRM is complex, while the rotor of PM excited HIA is very simple and it has very high reliability. On the other hand, the magnet of PMRM has eddy current losses, and in some worse condition of heat dissipation, the temperature rise of magnet could be very high, and this can cause the magnet loss of magnetism. But, for the PM excited HIA, because the magnet is placed between the two half shells, the magnetic flux density is almost invariable, the eddy currents losses are very small, what's more the heat dissipation condition for magnet is much better than the PMRM, so the temperature of magnet for PM excited HIA is very low, and there is no risk of magnet demagnetization. So, it can be concluded that the PM excited HIA has much higher reliability than the PMRM.

VIII. Conclusions

This paper proposes a permanent magnet excited HIA with air-gap winding used for the high-speed driving system. The optimization method for the minimum mass is proposed. The calculation results show that the larger the air-gap magnetic flux density is, the lighter the machine is, but the larger the mass of magnet is. The relationship between the unit number, shell diameter and the mass is studied, and calculation results show that there is an optimal value for shell diameter and unit number to make the mass to be smallest.

A 1 MW at 22000 rpm PM excited HIA is designed. The analytical results are verified by the FEM simulations, and the losses, temperature rise, rotor stress and modal of the PM excited HIA are analyzed by FEM simulation. The FEM simulation results show that the solid rotor eddy-current losses and the temperature rise of PM excited HIA are acceptable. Also the rotor strength is adequate, and the rotor system is a stiffness rotor, and it can safely operate. The PM excited HIA has equal power density and larger efficiency than the PMRM.

The prototype machine is to be made in the future, and the plan of test experiment is ongoing used to examine the theory and design methods of this paper.

IX. Appendix

A. Calculation of length of magnet l_m

From the ohm's law for magnetic circuit, the magneto motive force produced by the permanent magnet is calculated by:

$$F_c = R_m B_{shell} A_{shell} + \frac{2B_\delta \delta}{\mu_0} \quad (A1)$$

Here, F_c is the MMF produced by the permanent magnet, and μ_0 is permeability of vacuum. B_{shell} is the average flux density in the permanent magnet, and A_{shell} is the cross-section area of permanent magnet. R_m is the magnetic reluctance of permanent magnet, to be:

$$R_m = \frac{l_m}{\mu_0 \mu_r A_{shell}} \quad (A2)$$

Here, μ_r is the relative permeability of permanent magnet. Substituting (A2) to (A1), it can be obtained that:

$$F_c = \frac{l_m B_{shell}}{\mu_0 \mu_r} + \frac{2B_\delta \delta}{\mu_0} \quad (A3)$$

The magneto-motive force produced by the permanent magnet is:

$$F_c = \frac{l_m B_m}{\mu_0 \mu_r} \quad (A4)$$

Combining (A3) and (A4), it can be obtained that:

$$l_m = \frac{2B_\delta \delta \mu_r}{B_m - B_{shell}} \quad (A5)$$

The average flux density in the permanent magnet B_{shell} can be calculated by:

$$B_{shell} = \frac{\pi B_\delta \lambda_0^* D(l + \delta) + \Phi_{ms}}{A_{shell}} \quad (A6)$$

Here, λ_0^* is the per-unit value of DC component of air-gap permeance. The cross-section area of permanent magnet A_{shell} is:

$$A_{shell} = \frac{\pi}{4} (D_{shell}^2 - D_o^2) \quad (A7)$$

Here, D_{shell} is the maximum diameter of shell, which is also equal to the outer diameter of permanent magnet; D_o is the outer diameter of stator core.

Φ_{ms} is the magnetic flux leakage of permanent magnet, and it can be calculated by:

$$\frac{2B_\delta \delta}{\mu_0} = R_{ms} \Phi_{ms} \quad (A8)$$

R_{ms} is the magnetic reluctance of leakage magnetic path, and it can be calculated by:

$$R_{ms} = \frac{l_m}{A_{ms} \mu_0} \quad (A9)$$

A_{ms} is the cross section area of leakage magnetic path, and it can be calculated by:

$$A_{ms} = \frac{\pi}{4} (D_o^2 - D_{shaft}^2) \quad (A10)$$

Here, D_{shaft} is the diameter of rotor shaft. Combining (A6), (A8) and (A9), it can be obtained that:

$$B_{shell} = \frac{\pi B_\delta \lambda_0^* D(l + \delta) + \frac{2B_\delta \delta}{l_m} A_{ms}}{A_{shell}} \quad (A11)$$

Combining (A5) and (A11), the length of magnet can be obtained.

B. Calculation of length of armature winding

The calculation of length of the armature winding for one turn is:

$$l_{coil} = 2(2l_{en} + 2l_{K_{mu}} + l_m K_{mu}) \quad (B1)$$

Here, l_{en} is the length of one-side end windings for one half turn.

C. Calculation of mass

The calculation of mass of stator is:

$$M_{sta} = K_{mu} \frac{\rho_s l \pi}{2} [D_o^2 - (D + 2\delta)^2] \quad (C1)$$

Here, ρ_s is the mass density of silicon steel sheet.

The calculation of mass of shell is:

$$M_{shell} = 2\rho l \pi \left[\left(\frac{D_o}{2} + W_{end} \right)^2 - \frac{D_o^2}{4} \right] [l_{endp} + l_0] \\ + K_{mu} \rho l \pi \left[\left(\frac{D_o}{2} + W_{end} \right)^2 + \frac{D_{shell}^2}{4} - \frac{D_o^2}{2} \right] \quad (C2)$$

Here, l_{endp} is the axial length of end winding, and l_0 is the one-side end extended length of end winding. W_{end} is the thickness of shell end.

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