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Design of an Axial-Radial Flux Permanent Magnet Synchronous Motor with Folding Windings

Shahram Khodabakhshi
Electrical Engineering Department,
Pooyesh Institute of Higher Education,
Qom, Iran
Shahram.khodabakhshi@gmail.com

Javad Rahmani Fard
Electrical Engineering Department,
Pooyesh Institute of Higher Education,
Qom, Iran
Javad.rahmani.fard@gmail.com

Abstract— **This paper proposes a design of axial radial flux permanent magnet synchronous motor with folding windings. The basic electromagnetic relations of the compound machine and a design rule of this type of machine are achieved. The calculation results show that the motor with this structure can greatly increase the power density of the motor under the larger outer diameter and power demand.**

Keywords- axial motor; radial motor; permanent magnet motor; folding winding; power density.

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1. Introduction

At present, the structure of commonly used permanent magnet (PM) motors is divided into radial and axial flux permanent magnet motors according to the direction of the magnetic flux when passing through the air gap [1-3]. However, in some cases, the structure of the motor is not compact enough to increase the power density more effectively. For example, for a radial flux permanent magnet motor, when the length of the motor is relatively small, the length of the end windings is a large proportion of the axial length of the motor. Moreover, a large part of the space between the bottom of slot and the shaft is not used. For the axial flux PM motor, a large part of the inner diameter and outer diameter are wasted on the end windings.

Although many researchers have taken various measures to shorten the end length, such as concentrated winding, short-distance winding, and improved wire embedding process and etc., but the effect is not very satisfactory. Ref. [4] proposed a new type PM motor with bearing-less. This motor consists of two half-conical air gaps on shaft and provides active magnetic bearing without any bearing component. Ref. [5] investigated on flux permanent magnet motor with two rotors in terms of radial and axial. In [6] a new magnetic bearing for small structure was proposed. The radial magnetic bearing and radial–axial magnetic bearing were investigated. In [7] the axial and radial flux motor permanent magnet motors for a bicycle are designed and compared them with conventional radial flux motor. In [8] a new hybrid hysteresis motor with axial and radial flux is designed and analyzed in order to increase output torque.

This paper proposes a new type of axial-radial-flux permanent magnet synchronous motor. The motor adopts a folding winding and combines two axial PM motor and radial PM motor. This kind of structure motor has the advantages of short end and convenient front, and makes full use of space and improves the power density. The finite element method (FEM) results verify the feasibility of the structure and its design scheme.

2. Structural principle

The axial-radial flux PM synchronous motor with folding windings can be regarded as a radial PM synchronous motor with a section taken from both ends of the axial direction and folding winding along the circumference to the axis. The schematic diagram of the structure is shown in Figure 1. The stator consists of a set of three-phase symmetrical folding windings, three sets of silicon steel sheets, sleeves and baffles, as shown in Figure 2.

The radial sub-motor core is formed by superimposing silicon steel sheets in the axial direction on the sleeve, and its outer circular surface has multiple axial slots. The axial sub-motor cores on both sides are wound from silicon steel sheets. One side of the iron core is fixed on two circular baffles with screws. In addition, there are multiple radial slots at the ends on both sides. The center lines of the openings are evenly arranged radially around the shaft.

The axial slots of the motor are in one-to-one correspondence with the radial slots on both sides of the stator core, and each corresponding slot is provided with an element side of the folding winding.

The sleeve and the two baffles on both sides are connected together by six bolts and fixed on the immovable shaft. The rotor consists of a rotor core, axial PMs and radial PMs.

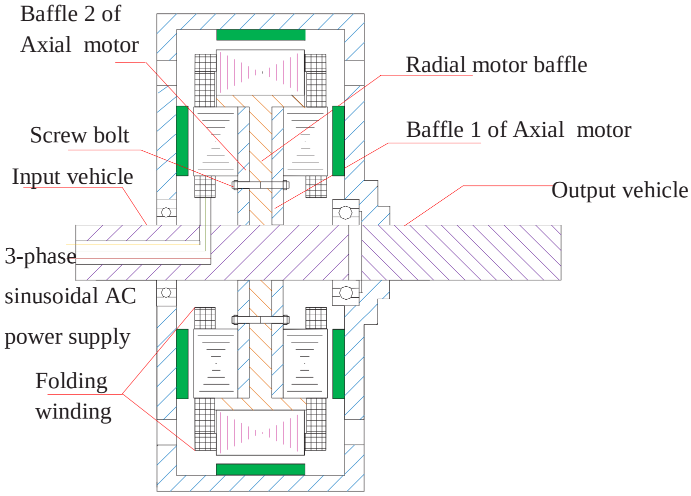


Figure 1: Schematic diagram of the axial radial flux PM motor structure

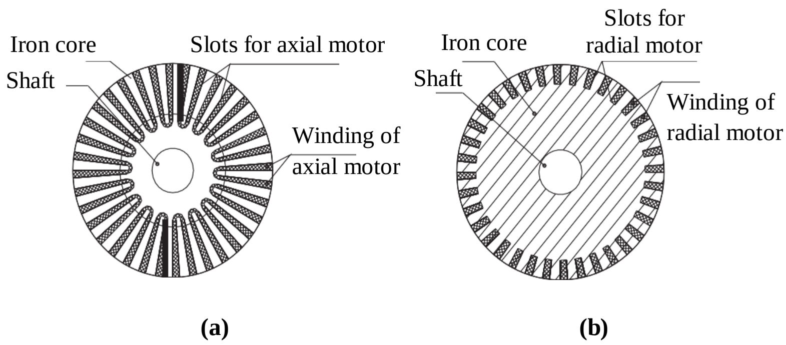


Figure 2: View of stator core and winding (a) Right view of stator core, (b) A cross-sectional view of the core shaft

A number of radially magnetized PMs are evenly distributed on the inner circular wall of the rotor core and the PMs on the two inner end surfaces of the rotor core are magnetized axially, and they are evenly arranged radially around the shaft.

In order to coordinate the operation of the axial and radial parts, it is necessary to ensure that the center lines of each group of axial and radial slots are aligned, and that the center lines of each group of axial and radial PMs are also consistent. Since this axial-radial motor evolved from a radial motor, it still outputs power through an independent drive unit. After the stator winding is connected in star connection, it is connected to the external three-phase sinusoidal AC power supply through the outlet hole of the shaft.

When the stator winding is energized with three-phase alternating current, a rotating magnetic field with the same speed is generated in the radial air gap of the motor and the axial air gap at both ends, respectively, and the three fields together drive the rotor to rotate in the same direction and the same speed, and the core shell of the rotor is a rotary power output terminal.

3. Determination of the design plan

In order to simplify the motor analysis, the axial-radial motor can be decomposed into three motors that are completely independent in structure and magnetic circuit. These three motors have the same current, the same speed and winding distribution. Since the two disc motors are exactly the same and only one need to be analyzed. The design flowchart is shown in Figure 3.

Since we don't know how the axial sub-motor and the radial sub-motor carry out power distribution, at first design a radial flux outer rotor motor that meets the power requirements (folding winding is more suitable for outer rotor structure). After the radial motor size is obtained, the basic size of the axial motor is determined according to the minimum thickness of the sleeve.

Equation (1) expresses the electromagnetic power equation of the radial flux PM synchronous motor.

$$P_{emR} = P' \cos\psi = \frac{\alpha'_p K_{Nm} K_{dp} \cos\psi n A_R B_\delta}{6.1} D_{iR}^2 l_{ef} \tag{1}$$

According to Equation (1), when the armature diameter and electromagnetic loading are constant, the electromagnetic power is proportional to the axial length of the motor, so that the core length of the radial sub-motor can be determined.

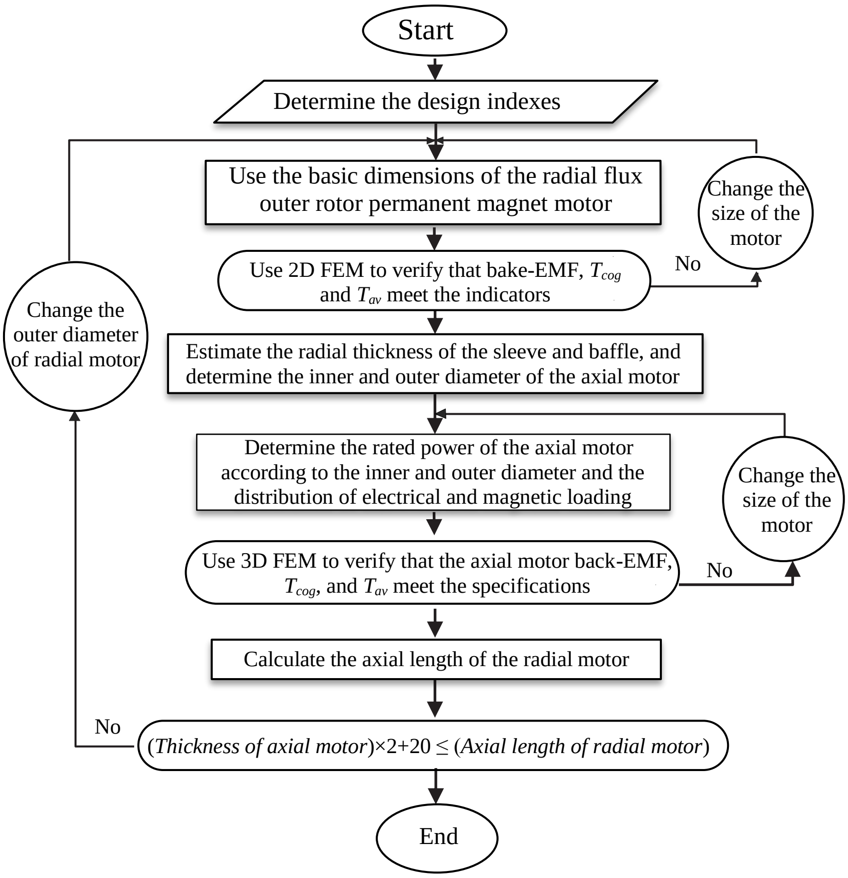


Figure 3: Design flowchart of axial-radial motor

Where D_{iR} is radial motor armature diameter, l_{ef} is the effective length of the radial motor, K_{Nm} is the waveform factor of air gap magnetic field, K_{dp} is winding coefficient, $cos\psi$ is the power factor, B_δ is air gap magnetic density (T), n is the motor speed (rpm), α'_p is the pole arc coefficient, A_s is the electrical loading of outer rotor motor (A/m). According to the above process, an axial-radial flux permanent magnet synchronous motor is designed, and the main parameters are shown in Table 1.

Table 1. The main parameters of the axial-radial motor

Parameters	Radial motor	Axial motor
Number of poles	10	10
Number of stator slots	12	12
Stator thickness (mm)	68	18
Air gap length (mm)	1	1
Stator inner diameter (mm)	142	90
Stator outer diameter (mm)	176	126
Rotor outer diameter (mm)	200	126
Axial width of the whole machine (mm)	116	116
Rated speed (r/min)	4000	4000
Rated voltage (V)	190	190
Rated power (kW)	10	10

4. Finite element analysis

The three-dimensional model of the axial-radial motor and the finite element calculation results are shown in Figure 4.

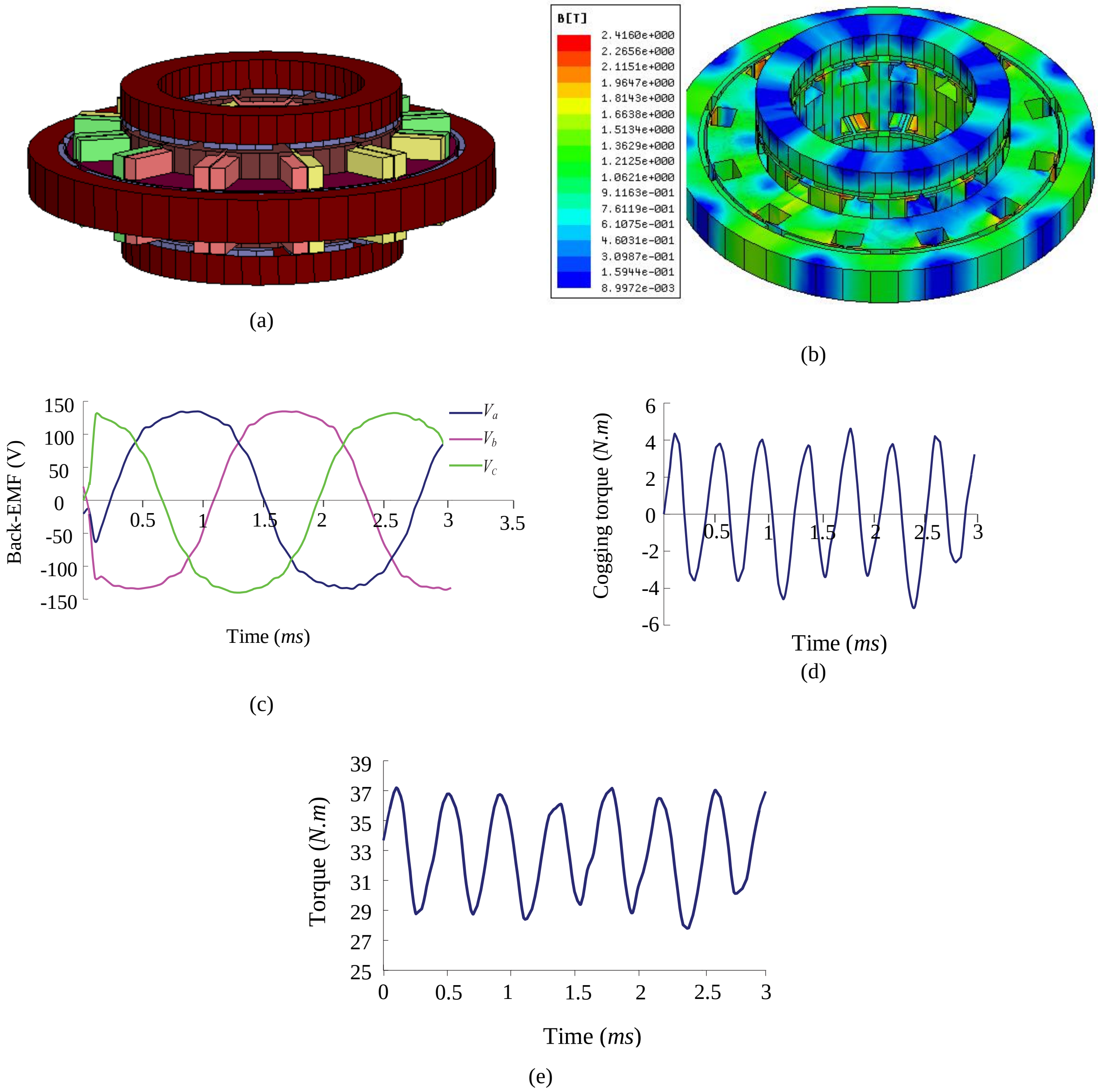


Figure 4: Simulation model and results of axial-radial motor. (a) 3D model (b) Flux density distribution (c) Back-EMF, (d) Cogging torque, (e) Torque

It can be seen from the figure 3 that the 3D finite element software takes a long time to simulate the axial-radial motor as a whole, and the mesh division cannot be very fine, so the calculation result is not very accurate. The axial motor has a simpler structure and smaller volume than the axial radial motor. The radial motor uses two-dimensional finite element software for separate analysis. The axial motor uses 3-dimensional FEM for analysis, so the calculation results are relatively accurate. The FEM model and calculation results are shown in Figure 5 and Figure 6**.**

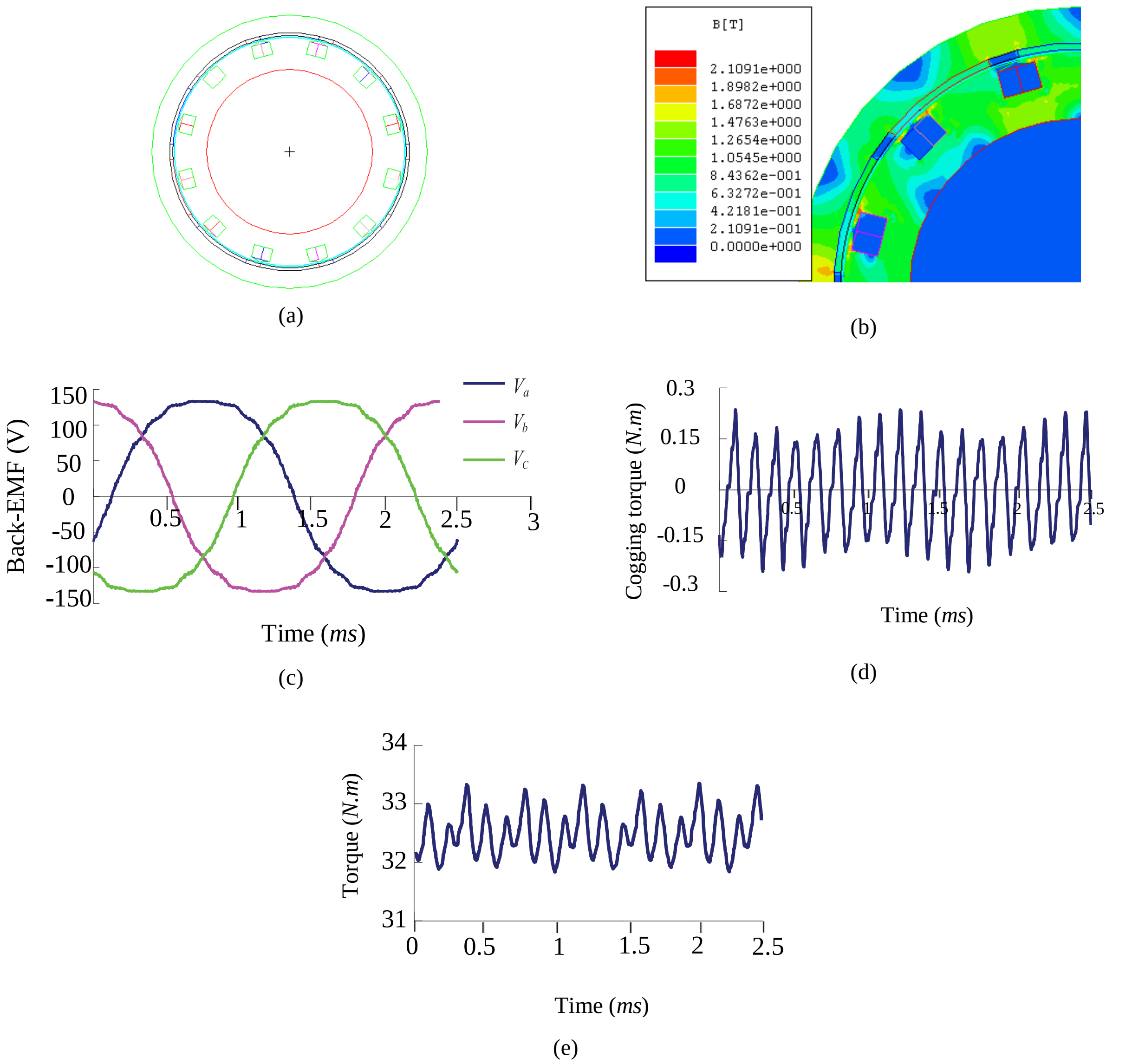
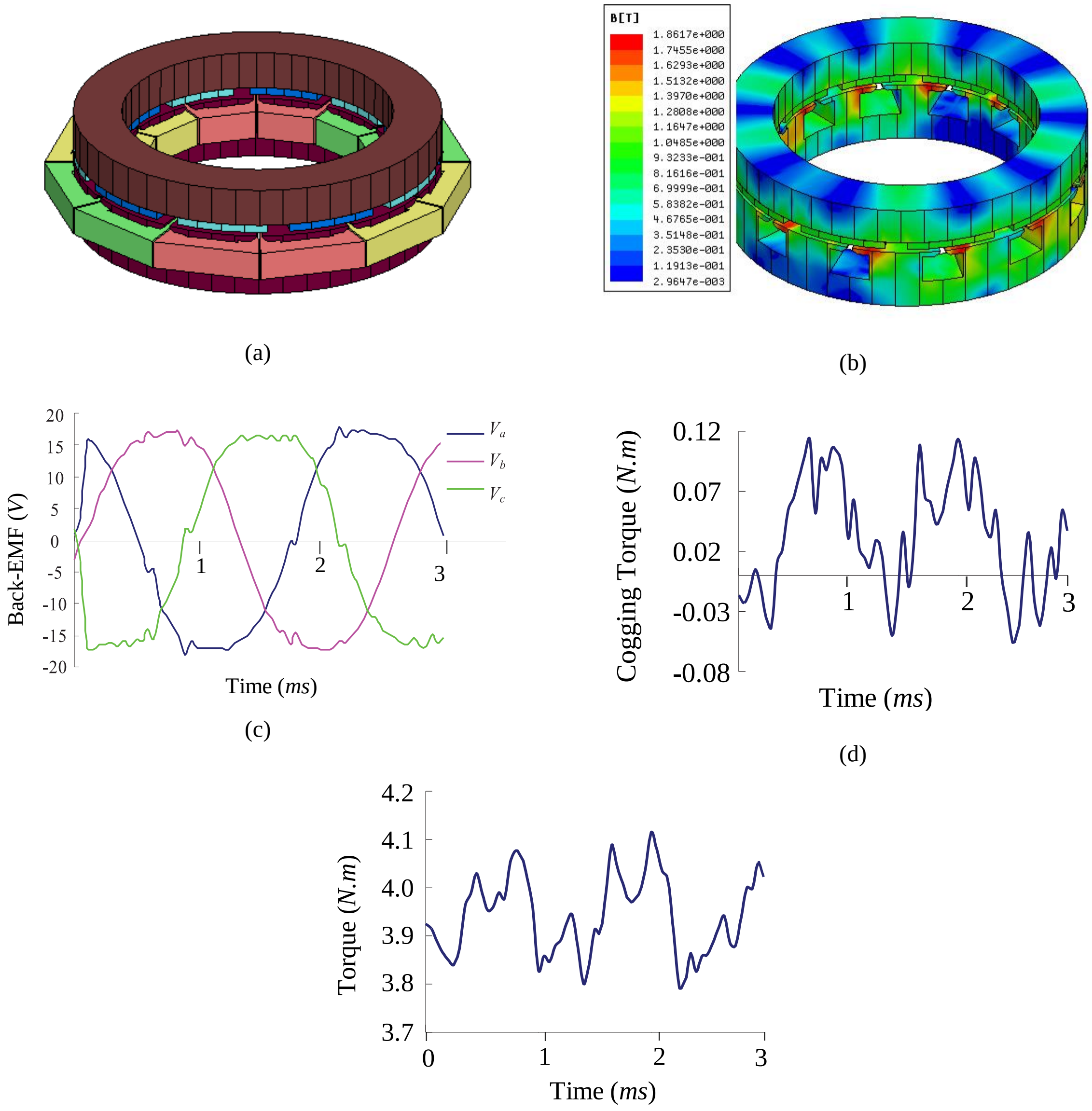


Figure 5: Simulation model and results of radial motor. (a) 3D model (b) Flux density distribution (c) Back-EMF, (d) Cogging torque, (e) Torque



(e)

Figure 6: Simulation model and results of axial motor. (a) 3D model (b) Flux density distribution (c) Back-EMF, (d) Cogging torque, (e) Torque

The calculation results of the separate design of the sub-motors and the overall design of the axial-radial motor are compared in Table 2.

Table 2. Comparison of simulation results

Parameters	Radial motor	Axial motor	Sum of effects	Axial-radial motor	Error (%)
No-load back EMF amplitude (V)	145.6817×68/ 90=110.75	18.635	148.02	148	0.01
Cogging torque (N.m)	0.48	0.0353	0.556	9.63352	94.2
Average torque (N.m)	33.01849×68/ 90= 24.94731	3.946841	32.84	32.95683	0.35
Peak-to-peak electromagnetic torque (N.m)	1.5112	0.32063	2.15	9.1765	76.57
Axial magnetic pull (KN.m)	0	1	0	0	0

It can be seen from Table 2 that compared with the overall design, the no-load back EMF and the average torque error are very small, and the cogging torque and electromagnetic torque peak-to-peak error are very large. This is due to the complex structure of the axial-radial motor, and the calculation of the 3-dimensional field with relatively coarse mesh division, which brings a large error to the calculation result. Therefore, a separate design method can be used in the optimization design process, which can save calculation time and obtain more accurate simulation results.

5. Motor performance analysis

5.1. Performance comparison with conventional motor

This paper uses the radial motor that meets the technical requirements for comprising with axial-radial motor as the object. The power and outer diameter of the two motors are the same. Table 3 shows the comparison of main dimensional parameters of axial radial motors and conventional radial outer rotor motor. The calculation shows that the power density of the axial radial motor is 1.38 times that of the conventional radial outer rotor motor. Therefore, it can be said that the axial radial motor fully embodies the advantage of large power density.

Table 3. Comparison of dimensional parameters of axial radial motor and conventional radial outer rotor motor

10 kW motor	Axial radial motor	Conventional radial outer rotor motor
Motor outer diameter (mm)	200	200
Radial motor stator thickness (mm)	68	90
Axial motor stator thickness (mm)	18	—
Total axial length of the entire motor (counting the end) (mm)	116	160

5.2. Analysis and improvement of technical indicators

The prototype design parameters listed in Table 3 only meet the technical requirements. In fact, its output power has not been maximized. First of all, in the above parameters, the thickness of the sleeve and shaft connection part is 38mm, and this part is not need to be so thick. Secondly, according to the electromagnetic relationship of the axial permanent magnet motor, when the outer diameter and maximum electrical loading are fixed the power is the maximum at $\lambda=1/\sqrt{3}$ (λ is the ratio of the inner and outer diameter). Now, the ratio of the inner and outer diameter is 1:1.4 and obviously the optimal ratio is not reached. In order to make full use of the space in the radial motor, the power of the radial sub-motor can be reduced, i.e. the power of the axial sub-motor can be increased. From equation (2), the diameter of the shaft (d) can be preliminarily determined as:

$$d=\left(T_N / \tau_f\right)^{1/3} \tag{2}$$

where T_N is the rated torque and here is equal to 31.83N.m, τ_f is allowable stress of shaft material (N/mm2). For the #45 steel, τ_f=70.63N/mm2, so that the diameter of the shaft is about 38.33mm. In order to meet the requirements of the extension length and insulation distance of the stator coil end, there must be a sufficient distance between the stator inner diameter and the rotating shaft. So the inner diameter of the motor is not less than 90mm. According to the full utilization of the axial motor, when the inner diameter is 90mm, calculated the outer diameter is 156mm. Therefore, as long as the outer diameter is greater than 156mm, the axial sub-motor can get the maximum power density. Here, the inner and outer diameters of the axial sub-motor are 90mm and 156mm respectively.

Electromagnetic power of the axial flux permanent magnet synchronous motor can be expressed as:

$$P_{emA} = P' \cos\psi = \frac{\pi^2 n}{240} \alpha'_p K_{Nm} K_{dp} \cos\psi B_\delta A_{\max R} \left(D_{oA}^2 - D_{iA}^2 \right) D_{iA} \tag{3}$$

where D_{iA}, D_{oA} are the inner and outer diameter of the armature of the axial motor, respectively, A_{maxR} is electrical loading at the smallest radius in radial motor (*A/m*). According to Eq. (3), the electromagnetic power is only related to its inner and outer diameter when the electromagnetic loading is constant. In this way, substituting the inner and outer dimensions of 90 *mm*, 126 *mm* and 90 *mm*, 156 *mm* respectively, the power of the axial motor with an outer diameter of 156 mm can be calculated to be 7.888 *kW*. At this time, the radial motor power is 2.112*kW*. The inner and outer diameters of the radial motor are 172*mm* and 246*mm* respectively by using the above described method.

At this time, although the axial motor is optimally used, the axial length of the radial sub-motor is only 27.5*mm*, and the space for the baffle is insufficient. Since the power of the axial motor is proportional to the inner and outer diameters, the axial motor cannot be fully utilized if it is required by the original design index. If the index requires higher power, both the axial sub-motor and the radial sub-motor can be more fully utilized. When the outer diameter of the axial motor is 156*mm*, the axial length of the radial part is 40, which is an increase of 12.5*mm* from the original length. The calculation shows that the power is increased 2.27*kW*.

Therefore, when the total power demand of the motor is greater than 12.27*kW*, the advantage of the higher power density of the axial- radial motor can be fully utilized. At this time, if it is designed as an ordinary external rotor motor, the total axial length needs to be 12.5*mm*, and the total axial length of the axial-radial motor is 84*mm*. The calculation shows that the power density of the axial radial motor is 48.8% higher than that of the outer rotor radial motor. Therefore, the radial-axial flux permanent magnet synchronous motor studied in this paper can better exert its advantages of high power density in the occasions of larger outer diameter and higher power demand.

6. Conclusion

In this paper, according to the characteristics of the radial and axial permanent magnet motors, a new type of folded winding structure of axial and radial flux permanent magnet synchronous motors is proposed, which can further increase the power density of the motor. The finite element method is used to design the sub-motors separately, which saves calculation time and hardware resources, and can obtain more accurate simulation results. For the axial radial flux permanent magnet synchronous motor, the advantages of large power density can be exerted in the occasion of larger outer diameter and higher power demand.

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