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Design and Implementation of Radax Motor

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ABSTRACT: Typically, integrated electric propulsion plants are sized to accommodate peak loads at rated speeds. This paper evaluates a non-conventional radial-axial electric propulsion motor configuration to enhance efficiency in low speed, low power operating modes typical in a patrol scenario. Secondary benefits to the proposed radial-axial configuration are improved mission capability, fault tolerance and the ability to provide propulsion derived ship service from the integrated axial flux motors. Design and analysis studies of an asynchronous motor with a tapered geometry for a two-person electric vehicle were carried out. The goal of this study is to analyse change in the taper angle for this asynchronous motor in terms of the power factor, efficiency, starting torque, breakdown torque, and rated torque. First, the vehicle dynamics and the asynchronous motor structure were analysed. Then, axial, radial, and hybrid (Radi axial) flux electric motor models and the purpose of these models were investigated. Literature studies have shown that there is no work related to angle optimization for a Radi axial flux with a conical geometry hybrid structure for an asynchronous motor. The torque characteristics and other electromagnetic characteristics of the Radi axial , the traditional surface mounted PMSM, and the spoke-type PMSM are compared and analysed using the finite element method. The research results show that the proposed motor has high torque density, which provides a new design idea in the form of a high-torque-density PMSM for use in elevator-traction machines.

KEYWORDS: Radial-Axial, efficiency, torque, axial, radial. Low power, finite element analysis, PMSM

I. INTRODUCTION

To increase the power and torque of the motor within the restricted space of the system, various studies on material, structure, and control strategy have been conducted. Regarding the structure, interior permanent-magnet (PM) machines using the additional reluctance torque are applied to increase the total torque. However, their structures are suitable for the extension of the constant-power region using
flux-weakening control rather than a power increase. Axial flux PM machines (AFPMMs) can enhance the torque density by increasing the number of poles and the flux from the PM because the surface area of the air gap is bigger than that in radial flux machines.

Energy saving is an important topic in the current times, since most electricity is still generated with non-renewable resources, which also contaminate the environment. Moreover, industries like transportation are highly dependent on fossil fuels. One way to reduce this problem is the use of electric vehicles. For this reason, in recent years, electric vehicles have become very popular in many countries, therefore, the investigation and the interest of many people in electric motors and especially permanent magnet motors have increased as a consequence. However, transportation is not the only field where electric motors are important, since they also take approximately 70% of the total energy in the industry in general, this means that the efficiency of electric motors is one of the parameters that needs to be improved by investigating new design and manufacturing methods. For this reason, it is important that more people are involved in these themes.

However, Axial Flux PM machine (AFPMM) is suitable for a slim shape with a relatively short axial length and have a limitation on the increase in power for a given outer diameter of the machine. In this, a novel hybrid flux permanent-magnet machine (HFPMM) that combines radial and axial flux machines is proposed. The main advantage of the proposed configuration is the enhancement in the power density by increasing the air-gap flux in a constant volume of the motor. Based on the proposed structure, initial and improved models are presented. For this stage, Finite Element analysis approaches are proposed to effectively account for the 3-D structure. The validity of the design and analysis method is verified by experimental results using manufactured motors.

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A. PROBLEM IDENTIFICATION

The Radax motor, widely used in industrial applications for its reliability and performance, occasionally experiences operational challenges that can impact its efficiency and lifespan. Common issues associated with the Radax motor include power supply irregularities, bearing wear, overheating, and mechanical misalignments. Power supply inconsistencies, such as voltage fluctuations or inadequate current, can lead to poor motor performance or even failure. Bearing wear, often caused by improper lubrication or overuse, results in increased friction, noise, and vibration, ultimately affecting the motor's smooth operation. Overheating, typically due to inefficient ventilation or overload conditions, further exacerbates these issues, potentially leading to thermal damage of internal components. Mechanical misalignments or imbalances in the motor shaft can cause excessive vibration, noise, and uneven load distribution, all of which contribute to wear and tear. Identifying and addressing these issues early through proper diagnostics and maintenance is crucial to ensuring the long-term reliability and efficiency of Radax motors in demanding industrial environments.

B. KEY FEATURES OF THE SYSTEM

The Radax motor system is renowned for its advanced design and versatility, making it suitable for a wide range of industrial applications. Several key features distinguish this motor system, ensuring optimal performance, efficiency, and durability under various operating conditions.

1. **High Efficiency and Performance**: Radax motors are designed to offer high energy efficiency, minimizing power consumption while delivering optimal torque and speed. The motors are engineered to operate with low electrical losses, making them ideal for energy-conscious applications where operational costs need to be minimized.
2. **Robust Construction**: Built with durable materials, Radax motors are designed to withstand harsh environments and demanding workloads. The motors are resistant to wear and tear, with advanced sealing technologies that protect against dust, moisture, and corrosive elements, making them suitable for use in industrial plants and outdoor settings.
3. **Flexible Motor Sizing and Configurations**: One of the key features of Radax motors is their customizable sizing and configurations. Depending on the specific requirements of the application, Radax motors can be tailored in terms of power output, speed, and torque, providing solutions for a wide array of industries, from manufacturing to renewable energy.
4. **Integrated Safety Features**: The motor system includes built-in safety features such as thermal overload protection, which prevents the motor from overheating and suffering damage in the event of a fault. Additionally, Radax motors are designed with features to prevent mechanical failure, enhancing their reliability and minimizing downtime.
5. **Low Maintenance and Longevity**: Designed for minimal maintenance, the Radax motor system incorporates self-lubricating bearings, efficient cooling systems, and vibration reduction technologies, which significantly extend the lifespan of the motor. The durability of these motors reduces the need for frequent service interventions, providing a cost-effective long-term solution.
6. **Noise and Vibration Reduction**: Radax motors are equipped with advanced noise and vibration dampening features that ensure quiet and smooth operation. These features are critical in applications where excessive noise can be disruptive, such as in hospitals or high-precision manufacturing environments.

MOTOR DESIGN AND WORKING PRINCIPLE

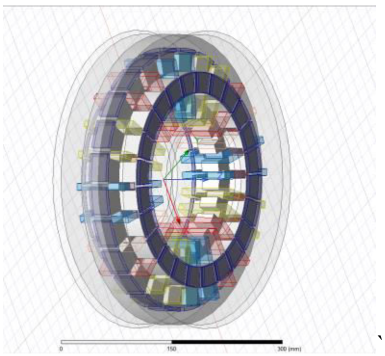

Fig. 1: - Magnets and Winding of RADAX motor

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The system setup of the depicted Radax Motor consists of a unique hybrid configuration combining both radial and axial flux paths to enhance power density and efficiency. The stator and rotor are structured in a way that leverages the advantages of both flux orientations, ensuring optimal torque production and compact design. The stator comprises multiple coil windings arranged strategically to interact with permanent magnets or electromagnets in the rotor. The rotor itself is designed with layered magnetic segments to facilitate smooth flux transition between radial and axial directions. The transparent outer casing in the visualization suggests an emphasis on thermal management, mechanical integrity, and electromagnetic efficiency. This architecture is particularly suitable for applications requiring high torque-to-weight ratios, such as electric vehicles, aerospace propulsion, and industrial automation systems.

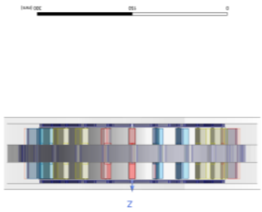

Fig 3: - Top View of RADAX motor

The stator comprises multiple sets of coil windings strategically positioned to interact with both radial and axial magnetic fields, enhancing flux linkage while minimizing eddy current losses. The rotor incorporates permanent magnets (PMs) or electromagnets arranged in a layered configuration to ensure smooth flux transitions and uniform distribution. This hybrid magnetic circuit leads to higher torque density, reduced core losses, and improved thermal management, making the motor highly efficient. The mechanical housing, often made from lightweight yet durable materials such as aluminum or composite alloys, ensures structural stability and vibration resistance. Integrated cooling mechanisms, such as liquid cooling channels or forced air convection, contribute to enhanced thermal performance, reducing hotspots and extending the motor's lifespan. The Radax motor's unique hybrid topology allows for superior power-to-weight ratio, making it particularly suitable for **e**lectric vehicles, aerospace propulsion, renewable energy systems, and industrial automation. By combining the advantages of radial and axial flux motors, this design offers enhanced torque efficiency, compactness, and operational stability,

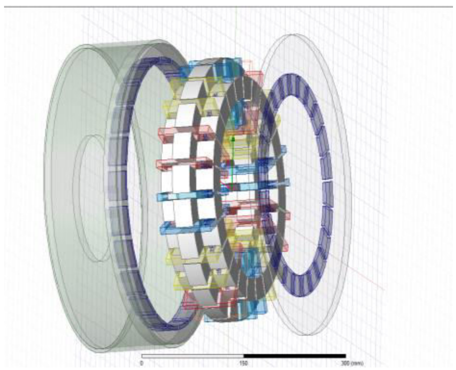

Fig. 2: - Bisectional view of RADAX motor

RADIAL FLUX MOTOR MODELING

We first describe the analytical model for a radial-flux motor's torque generation. In a motor, the fundamental harmonic of MMF generated by the PMs on the rotor is

$$F_{pm}(\theta_s) \approx F_{pm1}\cos(Z_r\theta_s - Z_r\omega_{rt}) \quad (1)$$

$$\text{Where } F_{pm1} = \frac{\frac{4}{\pi}B_r h_m}{\mu_0}$$

Zr is the magnet array's number of pole-pairs, θs is the angular coordinate in the stator fixed frame, θm is the rotor's angular position, μ0 is the vacuum permeability, hm is the magnet thickness, and Br is the remanence of the permanent magnet. Considering the average and fundamental-harmonic air gap permeance, the air gap permeance can be approximated by

$$P_g(\theta_s) \approx P_0 + P_1\cos(Z_s\theta_s) \tag{2}$$

Where,

$$P_0 = \frac{\mu_0}{g'}\left(\frac{1 - 1.6\,\beta b_0}{t}\right)$$

$$P_1 = \frac{\mu 0}{g'}\,\frac{4}{\pi}\beta\left(\frac{1}{2} + \frac{(b0/t)^2}{0.78125 - 2(b0/t)^2}\right)\sin\left(\frac{1.6\pi b0}{t}\right)$$

$$\beta = 0.5 - \frac{1}{2\left(1 + \left(\frac{b_0}{2g'}\right)^{-\frac{1}{2}}\right)}$$

Zs is the stator teeth number, b0 is the slot opening, t is the slot pitch, g is the mechanical airgap length, and g′=g+hm is the magnetic airgap length. Then the air gap flux density generated by the PMs is

$$B_{pm} = F_{pm}(\theta_s)P_g(\theta_s)$$

$$\approx F_{pm1}\cos(Z_r(\theta_s - \theta_m)P_0 + P_1\cos(Z_s\theta_s)) \quad (3)$$

$$= B_{pm1}\cos\big((Z_r \pm Z_s)\theta_s - Z_r\theta_m\big)$$
$$+B_{pmh}\cos\big(Z_r(\theta_s - \theta_s)\big).$$

$$\text{Where } B_{pm1} = \frac{F_{pm1}P_1}{2} \quad (4)$$

$$\text{and } B_{pmh} = F_{pm1}P_0$$

Considering only the fundamental and slot harmonics, the stator winding distribution in one phase is

$$N_s(\theta_s) \approx \frac{4}{\pi}k_\omega(N\cos(p\theta_s))$$
$$+N_{h1}\cos\big((Z_s - p)\theta_s\big) - N_{h2}\cos\big((Z_s + p)\theta_s\big) \quad (5)$$

where N is the number of turns of stator windings per phase per pole, and kw is the winding factor, Zs is the number of stator teeth, Nh1 and Nh2 are the magnitude of the teeth harmonics in the stator winding distribution. For concentrated full-pitch windings.

B. AXIAL-FLUX MOTOR MODELING

Next, we present the modelling for torque generation of an axial-flux motor, and discuss the difference between the radial flux and axial flux motor. This derivation is based on the reference [2].

The major difference between a radial- and axial-flux motor is that the axial motor's geometry, fields, and torques depend on the radius 'r'. In an axial-flux motor, the fundamental harmonic of the rotor MMF is

$$F^a_{pm}(\theta_s) = F^a_{pm1}\cos(Z_r\theta_r - Z_r\omega_r t) \quad (6)$$

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Where

$$F^{a}_{pmn} = \frac{4}{n\pi}\frac{B_r h_m}{\mu_0} \quad (7)$$

The axial flux motor's air gap permeance is

$$P^{a}_{g}(\theta_s) \approx P^{a}_{0}(r) + P^{a}_{1}(r)\cos(Z_s\theta_s) \quad (8)$$

Where

$$P^{a}_{0}(r) = \frac{\mu_0}{g'^a}\left(1 - 1.6\beta\,\frac{b0(r)}{t(r)}\right) \quad (9)$$

$$g'^a = g^a + h_{mag} \quad (10)$$

$$P^{a}_{1}(r) = \frac{\mu_0}{g'^a}\,\frac{4}{\pi}\beta\left(\frac{1}{2} + \frac{\left(\frac{b_0}{t(r)}\right)^2}{0.78 - 2\left(\frac{b_0}{t(r)}\right)}\right)\sin\left(1.6\pi\,\frac{b_0(r)}{t(r)}\right)$$

$$\beta = 0.5 - \frac{1}{2\left(1+\left(\frac{b_0}{2g'}\right)^{-\frac{1}{2}}\right)} \quad (11)$$

Note that in an axial-flux machine the slot opening b0 and slot pitch t are both functions of the radius r. Assume that the axial-flux motor has constant slot opening b0. Then the PM-generated air gap flux for the axial-flux PM motor is

$$B^{a}_{pm} = F^{a}_{pm}(\theta_s)P^{a}_{g}(\theta_s) \approx F_{pm1}\cos(Z_r(\theta_s - \theta_m)P^{a}_{0} + P^{a}_{1}\cos(Z_s\theta_s)) = F_{pm1}P^{a}_{0}\cos Z_r(\theta_s - \theta_m) + \frac{F_{pm1}P^{a}_{1}(r)}{2}\cos\big((Z_r - Z_s)\theta_s - Z_r\theta_m\big) \quad (12)$$

Considering the stator winding distribution

$$N^{a}_{s}(\theta_s) \approx \frac{1}{2}k^{a}_{\omega}\,\frac{4}{\pi}\left(N\cos(p\theta_s) + N_{h1}\cos\big((Z_s - p)\theta_s\big)\right) + N_{h2}\cos\big((Z_s + p)\theta s\big) \quad (13)$$

where N is the number of winding per phase per pole, Nh1 = N/(Zs/p − 1), Nh2 =N/(Zs/p +1)
Then the generated torque of the axial motor can be calculated as

$$T_{axial} = \frac{3}{\pi}F^{a}_{pm1}k^{a}_{\omega}NZ_rI_s\left(\frac{f_{p0}}{Zr/p} + f_{p1}\right) \quad (14)$$

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C. MATERIAL USED

Component	Material	Common alternatives	Flux density	Benefits of selected materials
Magnets	Alnico-5	NdFeB	1.3T	Durability
Stator inner part	FR4-EPoxy	G10	Non-magnetic	Good mechanical strength
Stator overall	Somaloy 700HT-5P	Iron powder	1.5T	Low eddy current loss
Outer rotor	Still 1008	Silicon s	1.6T	Cost effective

Table I :- Properties of electrical lamination and magnetic composite materials.

III. SIMULATIONS RESULTS.

The analytical models for radial- and axial-flux VPM motors are validated using numerical simulations. The graph shows the comparison between the analytically calculated combined VPM motor's torque generation and finite element simulation results as a function of several key design parameters. Note that this simulation is only for model validation, and the design choice of the parameters do not reflect the parameter selection for the proposed machine. The good agreement of the results validates the developed analytical model.

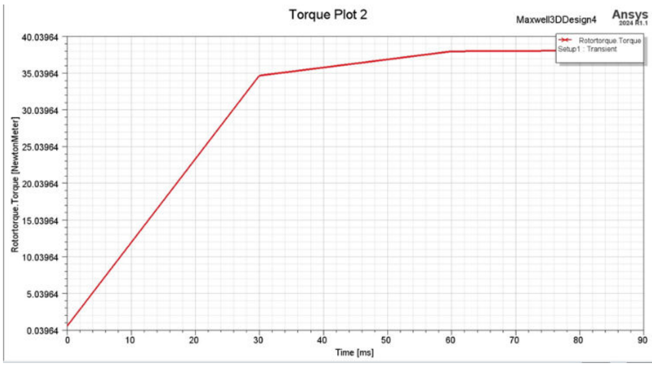

Fig.4: - Vector plot of Flux densities of proposed design

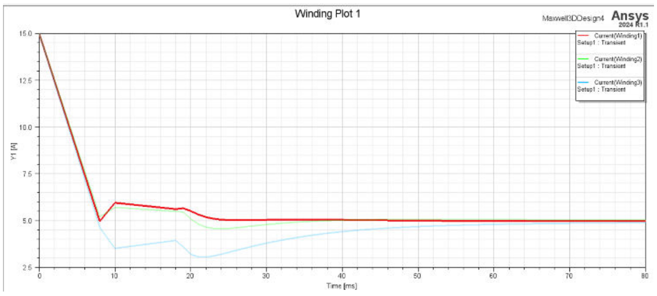

Fig. 5:- Vector plot of Flux densities of proposed design

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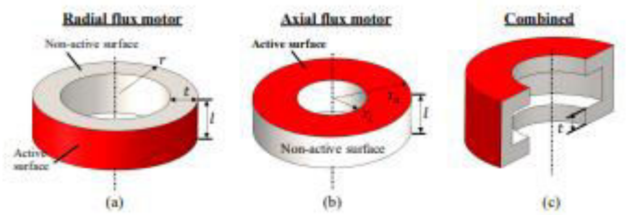

Fig. 6:- Diagrams of motor topology comparison. Red surfaces: active (torque-generation) surfaces. Grey surfaces: non-active surfaces. (a) Radial-flux machine. (b) Axial-flux machine. (c) Combined axial- and radial-flux machine.

We next discuss the overall motor sizing selection for the proposed motor topology. Figure 6 shows the diagram of rotors for radial-flux, axial-flux, and combined radial and axial-flux electric machines, where the red surfaces are the active torque-generating surfaces of the rotor. Assume a constant shear stress generation τe on the rotor's active surfaces. For the machine configurations shown in Fig. 5, the scaling of the motor's torque, mass, volume, specific torque, and torque density are shown in Table I, where l is the rotor's axial length, r is the air gap radius of the radial-flux motor, ro and ri are the outer and inner air gap radius of the axial-flux machine, respectively, ρ is the motor's density, and t is the thickness of the radial-flux motor ring with the stator thickness considered. Table I shows that the radial flux motor performs best when the machine has large radius and low motor ring thickness, while the axial motor performs best when the machine has small axial length. However, for general sized motors, radial or axial flux machine alone cannot provide good overall performance.

Table II:-
Scaling of performance with overall dimensions.

Spec	Radial Flux	Axial flux	Combined
Torque T	$2\pi r^2 l \tau_e$	$\frac{2\pi}{3}(r_o^3 - r_i^3)\tau_e$	$A_1 T_r + A_2 T_a$
Mass m	$2\pi \rho r t l$	$\pi \rho l (r_o^2 - r_i^2)$	$A_1 m_r + A_2 m_a$
Volume V	$\pi r^2 l$	$\pi r_o^2 l$	$A_1 V_r + A_2 V_a$
T/m	$r^2 l/t$	r_o^3	$A_1 r^2 l + A_2 r_o^3$
T/V	r	r_o/l	$A_1 + A_2 r/l$

IV. CONCLUSION AND FUTURE WORK

In this paper, we presented the design, modelling, and expected performance for a new type of high-torque direct drive motor using combined axial- and radial-flux motors. Analytical models for the motor's torque generation have been developed and validated by finite element simulations. The sizing and key parameter selection were conducted with the developed analytical model. New mechanical design was proposed for the stator assembly of the combined-flux motor. The simulated performance of the proposed motor demonstrated torque improvement compared with conventional machines. We are currently working on further optimization of the motor for reduced torque ripple and thermal design of the machine, and will work on the prototype construction and experimental evaluations in the future.

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