

A Review of Ring Motors with Integrated Loads

Adonay A. Asgodom* *Student Member, IEEE*, Takahiro Noguchi* *Member, IEEE*,

FNU Nishanth† *Senior Member, IEEE*, Eric L. Severson* *Senior Member, IEEE*

*Department of Mechanical Engineering, University of Minnesota-Twin Cities, Minneapolis, MN 55455 USA

†Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, WI 53706 USA

Abstract—Ring motors are electric machines that are typically characterized by having a hollow rotor / stator, a small difference between the inner and outer radii, and a large outer diameter relative to the axial length. The hollow portion of the ring motor allows integrating loads, such as an aerial or marine propeller, enabling power-dense systems. This paper reviews integrated ring motor designs from literature across different applications. Based on this review, first, design trends and performance parameters are identified and compared with conventional radial flux machines. Next, the bearing challenges posed by the unique form-factors of these machines are identified and approaches to realize bearings are presented. Finally, a research outlook is presented that identifies the benefits of applying multi-physics optimization, additive manufacturing, and bearingless machine technology to realize improved integrated ring motor designs.

Index Terms—Ring motors, gearless drives, marine thrusters, bearingless motors, machine design, windings, torque density, power density, efficiency.

I. INTRODUCTION

Ring motors are electric machines with a hollow rotor and nearly always a large diameter-to-axial-length ratio. The hollow structure of these machines allows placing the loads and / or power electronic drives in the cavity to realize a highly integrated drive system, with highly desirable benefits of increased power-density and torque-density.

Ring motors with integrated loads have been developed for applications such as marine thrusters, e.g. [1]–[3], electro-hydraulic machines, e.g. [4], aerial propulsion, e.g. [5], [6], and flywheel energy storage, e.g. [7]. In [8], [9], rim driven propulsors in the maritime and aviation industries have been comprehensively reviewed. However, literature lacks a review of the associated electric machine design and performance across different applications.

The main contribution of this paper is a review of literature on load-integrating ring motors that emphasizes the electric machine aspects. This review includes an overview of the application spaces, classification of the types of electric machines used, key electric machine sizing parameters (airgap length, current density, and magnetic shear stress), and electric machine performance metrics (power, efficiency, torque, and power density) along with a research outlook of the technology. The presented literature review spans all energy conversion applications and places priority on publications with experimental results.

This work was supported in part by the USA National Science Foundation under grant #1942099.

This paper is organized into five sections. First, ring motor designs from different application domains are reviewed in Section II. Next, the design and performance aspects of these designs are presented and compared with conventional radial flux electric machines in Sections III and IV respectively. Since the form factors of ring motors can introduce unique challenges with bearings, Section V reviews the bearing type and placement in ring motors and their performance impact. Finally, this paper concludes by providing a research outlook for ring motor technology by identifying emerging research directions to realize high-performance integrated ring motors.

II. APPLICATIONS

This section reviews ring motor designs with integrated loads across different application scenarios, see Fig. 1. The primary incentives for integrating the load with the machine include eliminating redundant components and improved thermal management to achieve a compact form-factor, resulting in net power density improvements.

A. Marine Applications

The earliest load-integrating ring motors were developed for maritime rim driven thrusters (RDTs), e.g., [1]–[3], [10], [13]–[44]. In [25], an induction motor was designed for marine applications, such as steering large vessels. This machine used metallic cans to insulate the stator and rotor from seawater, which resulted in low efficiencies due to increased eddy current losses. In [2], a rim driven thruster was developed, that uses epoxy to seal the stator and rotor of a permanent magnet motor. The use of epoxy sealant reduced the eddy current losses relative to the metallic can designs. However, epoxies are susceptible to damage from water debris, exposing the electrical components to seawater. In [43], a 30 kW machine was developed for a tidal stream turbine (tidal energy converter). This machine replaced a hydraulic thruster and was used to align the turbine with the direction of the waves. Experimental results demonstrated efficiencies under 80 %, which is acceptable for the intermittent application. In [44], a 750 kW scaled down prototype of a projected 18 MW commercial RDT was developed. The prototype recorded an improved efficiency compared to conventional propulsor of the time. Currently, rim driven thrusters with power ranging from 0.5 kW to 650 kW are commercially available [45], [46].

B. Aerial Applications

Ring motors with integrated propellers have been developed for aerial propulsion, e.g., [5], [6], [47]–[52]. In [5], a

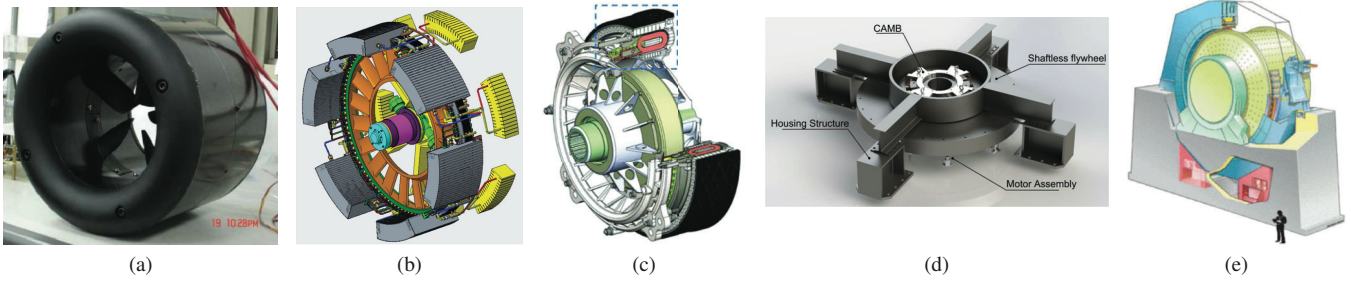


Fig. 1. Examples of ring motors integrated with loads: (a) shaftless marine propulsor [10], (b) aerial ring motor with integrated propulsor and drive electronics [5], (c) triple rotor gearbox integrating aerial ring motor [11], (d) IESS utilizing ring motor [7], and (e) gearless drive grinding mill [12].

permanent magnet ring motor that integrates a propeller into the rotor with a current density of more than 55 A/mm^2 was reported, Fig. 1b. The stator uses hollow conductors, cooled using super-critical CO_2 and has integrated power-electronic modules, resulting in a 12 kW/kg overall power density. In [47], a triple rotor permanent magnet ring motor was integrated with a gearbox, Fig. 1c. This motor used in-slot refrigerant circulation to attain current densities up to of 35 A/mm^2 [11]. This design achieved a 12 kW/kg overall power density, which makes it a promising candidate to replace turbofan engines for electric aircraft.

In [48], an out-runner induction ring motor was developed for hybrid electric propulsion. This machine was designed to fit into the existing space of a turbofan engine without affecting the streamlined design of the nacelle. The authors claimed that this machine can achieve a power density of 13 kW/kg at 10 MW output power, without using rare-earth materials. In [49], an out-runner permanent magnet ring motor was developed. This machine used self-pumped air to cool the stator via heat-sinks integrated into the stator [53].

In [50], an axial flux permanent magnet (PM) motor was integrated with a propeller for an electric vertical takeoff and landing (eVTOL) aircraft. A current density of 18.8 A/mm^2 was achieved using the air flow generated by the propeller as the coolant.

C. Other Applications

Ring motors have also been integrated with loads such as hydraulic pumps, flywheels, gearboxes, and grinding mills, e.g., [4], [7], [54]–[58]. In [4], an axial flux PM motor was integrated with a radial piston hydraulic pump for electrified off-high way vehicles. This integration allowed cooling using hydraulic fluid, resulting in current densities up to 20 A/mm^2 . In [54], an internal gear pump was integrated with a radial flux PM ring motor to drive off high-way vehicles. The hydraulic fluid was used as the coolant to achieve a maximum current density of 20 A/mm^2 .

In [7], an out-runner permanent magnet ring motor/generator was integrated with a flywheel to realize an inertial energy storage system (IESS), Fig. 1d. A coreless stator was used to minimize the iron losses and achieve high efficiencies (crucial for IESS), and fixed to the ground via movable base.

In [18], [59], a gearbox integrating permanent magnet ring motor was developed for off high-way vehicle traction applications. The gearbox lubricating oil was used to directly cool the stator and achieve a maximum current density of 14.5 A/mm^2 . It was found that metallic debris chipped of the gearbox and carried by the lubricant caused minimal insulation degradation [59].

In the mining industry, gearless ring motors with diameters up to 12 meters, see Fig. 1e, are used to grind rocks containing mineral ores [60]. These gearless machines have relatively low maintenance cost compared to traditional grinding mills with geared drives. In [56]–[58] gearless motor drives (GMDs) with ring motors rated for $7\text{--}20 \text{ MW}$ power levels are reported. These machines operate at rotational speeds under 15 r/min . Owing to the massive size, torque, and power levels, these machines are usually close-circuit forced air cooled with air-to-water heat exchangers [12], [58], [60].

III. CLASSIFICATION AND DESIGN ASPECTS

This section first presents a classification of integrated ring motor variants. Next, the different design parameters of the ring motor designs are reviewed and compared with conventional electric machines.

A. Classification

Ring motors can be radial or axial flux machines. Axial flux machines are generally known for their high torque density, and thus have been the preferred topology for high torque density application [50], [61]. Ring motors can also be classified based on the rotor design as permanent magnet (PM), induction (IM), reluctance (Rel), or wound field synchronous (WFSM) machines. PM ring motors are capable of sustaining larger magnetic loading that ultimately leads to large torque and power densities [2]. On the other hand, induction ring motors benefit from rotor design free of rare earth materials rendering them less expensive as compared to PM motors [48]. Ring motors can also be classified as in-runner and out-runner motors. Table I summarizes the authors' classification of ring motor variants and cites relevant design examples from literature.

TABLE I
CLASSIFICATION OF LOAD-INTEGRATING RING MOTOR TOPOLOGIES

Radial Flux						Axial Flux
PM		IM		Rel	WFSM	PM
In-runner	Out-runner	In-runner	Out-runner	In-runner	In-runner	
· Marine [2], [3], [10], [13]–[17], [19]–[23], [35]–[42], [44], [62], [63] · Aerial [5], [51], [66]–[70] · Traction [18], [59] · Pump: hydraulic [54], [71], [72], water [62], [73]	· Aerial [49], [53] · Hydraulic [55]	· Marine [1], [24], [25], [43] · Aerial [64]	· Aerial [48], [65]	· Marine [26], [27]	· Grinding mills [56]–[58]	· Marine [28]–[34] · Aerial [50] · Hydraulic [4]

TABLE II
DESIGN AND PERFORMANCE PARAMETERS DISTRIBUTION OF
LOAD-INTEGRATING RING MOTORS.

Application	Marine	Aerial	Traction
D/L ratio	1 - 25	1.5 - 30.7	2.95 - 4.25
Current density [A/mm ²]	2.7 - 10	13 - 55	14.5
Torque density [kNm/m ³]	2 - 21	15 - 76	13 - 25
Power density [kW/L]	0.08 - 150	40 - 75	4.2 - 4.4
Power [kW]	0.007 - 2500	0.044 - 10000	40 - 294

B. Diameter to Length Ratio

In-runner ring motors integrate the load at the center of the machine, this leads to large overall diameter. For a given torque density (or magnetic shear stress), the electrical torque is dependent on the volume of the rotor. Consequently, increased diameter leads to reduced axial length. This effect is characterized by the diameter to length (D/L) ratio. The D/L ratio of surveyed ring motor designs is provided in Table II and plotted Fig. 2a. For ring motors reported in the literature, this ratio is found to be predominantly larger than 2 with designs reaching 25 for marine applications and 30 for aerial applications. This is higher than conventional synchronous machines, which have D/L ratios in the range of 2 to 7.5 as shown in Fig. 2a [74].

C. Airgap Length

Airgap length is a critical design parameter affecting several key electric motor performance metrics. Increased airgap length leads to decreased magnetic flux density and increased flux leakage, decreasing the power and torque capabilities of a machine. In induction motors, increased airgap leads to increased magnetization currents [1], [25]. On the other hand, permanent magnet ring motors are found to be more tolerant of larger airgap, a property useful in marine RDTs because it allows space for stator/rotor epoxy sealer and minimizes windage loss [2].

Based on the application, ring motors can have liquids in the airgap, e.g., [1], [2], [4], [71] to achieve improved thermal management and increase the power-density of the system. However, using a liquid in the airgap can increase the windage losses, necessitating a multi-physics analysis/optimization of the system. Furthermore, if the liquid is conductive and

corrosive (e.g., sea water in [1], [2]), there is also a risk of insulation breakdown and short circuit.

D. Current Density

Nearly all applications benefit from power-dense and torque-dense electric machines. Increasing the current density in the windings can enable achieving power-dense and torque-dense designs. However, this requires considering the thermal management potential of the machine to ensure safe and reliable operation.

Designers of high performance ring motors have devised effective thermal management methods that achieved current densities in the range 2.7-10 A/mm² for marine, 13-55 A/mm² for aerial and up to 14.5 A/mm² for traction applications, Table II. One of these methods is direct coil cooling by flooding the airgap with a process fluid actuated by the load [2], [4], [50], [54], [59], [72]. In [54], [71], Zappaterra et al. compared a hydraulic fluid and an air cooled electric hydraulic units (EHUs). In [54], a current density of 20 A/mm² was reported for the hydraulic fluid cooled variant, while in [71] a current density of 2.76 A/mm² was reported for the air cooled variant which is an order of magnitude less from the liquid cooled variant. Flooded airgaps greatly minimize the conduction distance improving cooling, however to achieve extreme current densities, in-slot cooling and hollow windings with coolant passages are utilized [11], [47], [68]–[70], [75]. Table II shows current density of load-integrating motors reported in the literature.

To put the reported current densities in perspective, it is useful to review the conventional range of current densities reported in the literature. In [74], Pyrhonen et al. recommend current densities in the range 13-18 A/mm² for direct water cooled machines. In [76], Polikarpova reports current densities in the range 7-30 A/mm² for direct oil immersion cooling. In light of these upper bound limits, it can be seen that modern ring motors are pushing the boundaries of current density through direct coil cooling and slot invasive cooling.

E. Magnetic Shear Stress

Average magnetic shear stress is frequently used to size electric motors. It is also an important metric to compare electric motors with wide range of construction and principle of operation. The magnetic shear stress of load-integrating ring motors reported in the literature is plotted in Fig. 2b.

Note that most of the designs reported are within or below the range for conventional PM motors, which seems to imply that ring motors are at a disadvantage. However, nearly all of the surveyed ring motors with high current density did not report sufficient data to compute the involved magnetic shear stress. Several of these designs did report an associated performance metric, torque density, from which it can be deduced that the magnetic shear stress of these designs is quite high, see Section IV-A.

F. Winding Design

As seen from Section III-B, in-runner ring motors tend to have large diameter to length ratio. The D/L ratios of ring motors lead to lower active winding to end winding length ratios. Since the end windings do not contribute to useful power conversion but add additional resistance, it reduces the efficiency of the machine [2]. High pole-count and fractional-slot concentrated windings result in shorter end-winding length, and are often utilized to minimize copper loss in ring motors. In Fig. 2c, the variation of number of poles against rotational speed is shown, revealing the expected inversely proportional relationship. Furthermore, increasing the number of poles decreases the flux per pole, which minimizes the yoke weight and maximizes the torque density. However, there are limits to these benefits, as increasing the number of poles also increases iron losses and increases the electrical frequencies, that can pose current regulation challenges.

G. Rotor Tip Speed and Rotational Speed

The rotor tip speed and rotational speed of ring motors are dependent on the load requirements. Certain applications require lower peripheral speeds for optimum operation. For instance, hydraulic machines and marine propellers tend to revolve slowly to minimize cavitation. Moreover, ring motors are typically used for direct-drive applications that benefit from high torque-density at relatively modest speeds compared to modern high speed motors [78]. The rotational speed of the ring motors surveyed in this paper range from 10 r/min to 20,000 r/min while the rotor tip speeds are usually below 200 m/s, Fig. 2d. In contrast, high performance state-of-the-art motors with greater than 100,000 r/min and nearly 400 m/s tip speed have been reported in [78].

IV. PERFORMANCE PARAMETERS

This section reviews the performance parameters of ring motors. The form-factor of ring motors introduces opportunities and challenges in regard to the design aspects as reviewed in Section III. Industry operation requirements have driven the design of ring motors, leading to improved motoring performance that will be reviewed in the following four subsections. In the first subsection, torque density of ring motors reported in the literature is reviewed. In the following two sub-sections, power density and power output of ring motors is reviewed. In the last sub-section, the efficiency of ring motors against the IE4 standard is reviewed.

A. Torque Density

Torque densities reported in the literature are in the range of 2-21 kNm/m³ for marine, 15-76 kNm/m³ for aerial, and 13-25 kNm/m³ for traction applications, Table II. Figure 3a shows several load-integrating ring motors that have torque density above 30 kNm/m³, the upper bound for conventional radial flux PMSMs. These designs correspond to machines with rated current density in the range of 10-55 A/mm², which is above the potential of motors with conventional thermal management systems, as reviewed in Section III-D. Many of these high current density motors did not provide sufficient data to populate the magnetic shear stress plot, Fig. 2b, as discussed in Section III-E. However, high torque density stems from high magnetic shear stress, which is a function of high current density. This indicates that designers have been able to exploit the unique aspects of load-integrating ring motors to achieve magnetic shear stress values above the range of conventional radial flux PMSMs.

B. Power Density

Load-integrating ring motors have large potential in terms of power density. The volumetric power density of experimental ring motors reported in the literature reaches 40 kW/L while simulation results reach 150 kW/L, see Table II and Fig. 3b. Most surveyed ring motors have power density that fall close or below the upper limit for radial flux PMSMs (10 kW/L). As ring motors integrate the load, it is often difficult to draw a line identifying the rotor and load apart. For instance, the rotor back iron can be the rim of an integrated propeller. A key advantage of the seamless integration of load and motor is high overall power density. In [5], Jahns and Yagielski report a power density of 29 kW/kg for the motor only. When the load, motor drive, and thermal management systems required to run the machine are included, the overall power density is 12 kW/kg, showcasing improved system level power density of load-integrating ring motors and their importance in electrifying the aviation industry where power density is a crucial parameter.

C. Power Output

Ring motors have been designed for power ratings from a few watts to tens of mega-watts (MW). Table II summarizes the power ratings of ring motors reported in the literature based on application. Currently the most powerful ring motors are GMD grinding mills installed at mining sites [56]–[58] and turboelectric motors under development for electric aircraft propulsion [5], [47], [48].

D. Efficiency

The efficiency of ring motors reported in the literature is provided in Fig. 3c. Most surveyed ring motors exhibit more than 90 % efficiency. In [47], 95.7 % efficiency is recorded for a turboelectric motor operating under take-off loading condition, the most demanding phase of flight in terms of power consumption [68]. In [5], 94 % take-off and climb efficiency is reported for a similar application motor with 93 % cruise efficiency.

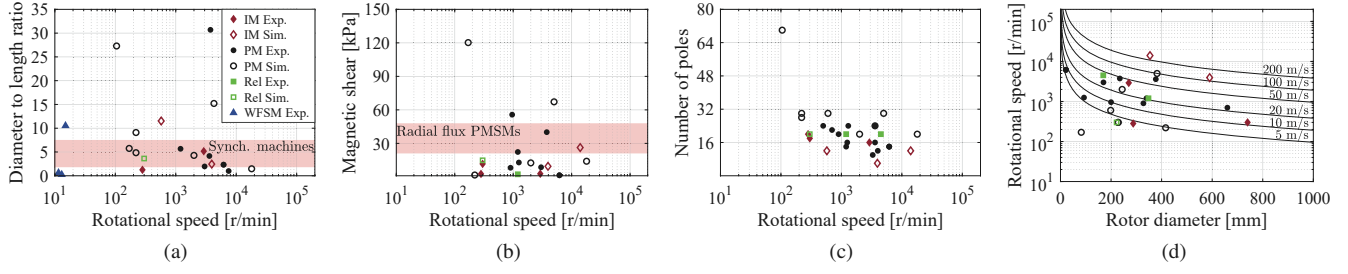


Fig. 2. Design aspects for published ring motor designs: (a) diameter to axial length ratio, (b) average magnetic shear stress, (c) number of poles, and (d) rotor diameter. Shaded regions indicate typical range of D/L ratio in sub-figure (a) and shear stress in sub-figure (b) based on [74, Ch. 6]. **Note:** IM, PM, Rel, and WFSM denote induction, permanent magnet, reluctance, and wound flux synchronous machines respectively. Exp. and Sim. denote experimental and simulation results respectively.

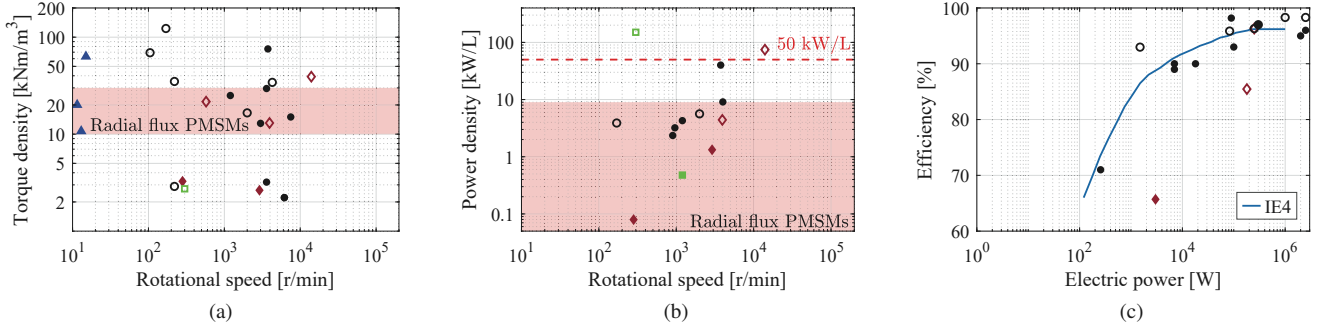


Fig. 3. Ring motor performance parameters: (a) torque density; shaded region indicate typical range for radial flux PMSMs [61], (b) power density; shaded region indicates typical range for radial flux PMSMs; the red dashed line indicates DoE's 50 kW/L target [77], and (c) efficiency along with the IE4 standard.

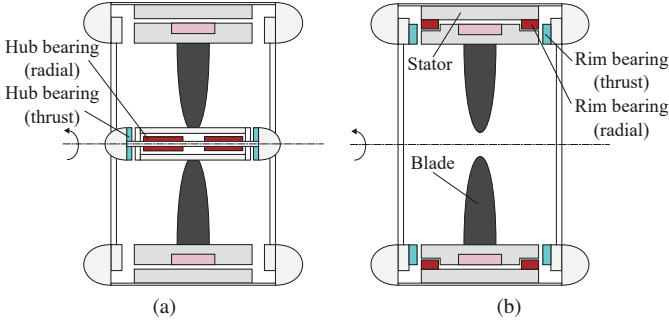


Fig. 4. Technical differences in bearings for ring motors (a) hub bearing, located at the center, and (b) rim bearing, located at the rim of the machine.

V. APPROACH TO BEARINGS

This section reviews the configuration and types of bearings in load-integrating ring motors. Ring motors present a unique challenge for bearings due to their rotors requiring supporting forces at larger diameters than standard motors. Bearing approaches to address this challenge can be categorized based on the location of the bearing, as hub and rim bearings. They can also be broadly classified based on mode of operation as mechanical, hydrodynamic, and magnetic bearings. This section is subdivided into three subsections, with the first two subsections reviewing hub and rim bearings, and last subsection reviewing the bearing mode of operation.

A. Hub Bearings

Hub bearings are installed at the hub/center of the motor, Fig. 4a. They require a set of evenly distributed supporting ribs and connecting members to ground the bearing to the housing. The resulting structure is complicated, increases the overall weight of the machine, and creates additional drag if the load moves process fluid. In propulsion applications, the axial forces on the rotating blade gradually increase toward the tip. This creates undue bending moments on the involved structure. On the other hand, because hub bearings have a small diameter, a longer life is granted through relatively low DN values (diameter $\times$ r/min) compared to rim bearings.

B. Rim Bearings

Rim bearings are installed at the rim of the motor, Fig. 4b. They connect the rotor and stator at the airgap removing the need for complex supporting structure and resulting additional drag. The diametrically large bearing can be heavy neutralizing improved specific power and torque densities [50]. Moreover, rim bearings have a short life due to the relatively large DN values (diameter $\times$ r/min) compared to hub bearings. In rim bearings, frictional forces operate at a larger lever arm, creating larger frictional torque [50]. Despite these, rim bearings are crucial components of modern RDTs.

C. Mode of Operation

Depending on the application of the motor, ring motors can employ mechanical bearings, hydrodynamic bearings or

magnetic bearings [3], [4], [63]. Mechanical bearings have unyielding stiffness and load carrying capacity per unit surface area. They are ideal for applications that generate tremendous radial and/or axial forces at any operating speed. Instance of such applications include hydraulic pump and planetary gearbox integrating ring motors [4], [59]. However, mechanical bearings can be bulky with complex housing requirements. Furthermore, they are susceptible to corrosion.

To minimize component count, pollution, and complexity, RDTs use seawater lubricated hydrodynamic bearings [79]. Polymer-metal friction pairs are used to create the necessary supporting forces cutting the bearing's life short [79]. Moreover seawater has low viscosity, leaving the bearings with low load carrying capacity [79], [80].

VI. RESEARCH OUTLOOK

Ring motors with integrated loads have been developed across various applications, as reviewed in Section II. To further improve the power-density, efficiency, and manufacturability of these machines and realize high-performance designs, three key technologies are identified in this section and a research outlook is presented.

A. Multi-Physics Modeling and Optimization

Ring motors with integrated loads often have multiple physics (e.g., electrical, thermal, structural, fluid flow) that need to be simultaneously optimized to meet the system requirements on metrics such as power density, efficiency, and cost. Literature, e.g., [4], [81], [82] shows that multi-physics optimization, often using population based optimization algorithms coupled with FEA is a key tool to identify electric machine designs that meet or exceed the performance requirements. However, these optimizations are often time consuming and have significant computational requirements. Furthermore, several analytical approximations used in conventional electric machine analysis may not be applicable to ring motors due to their axially short form factor, necessitating the development of computationally efficient multi-physics modeling and optimization techniques specifically for ring motors.

B. Additive Manufacturing

Seamless integration of loads with ring motors often requires parts with complex geometries that may not be manufacturable using conventional techniques. Additive manufacturing has been shown to provide a promising pathway to realize complex-shaped electric machine components, e.g., [83]–[85]. Several high performance ring motor designs in literature have features produced using AM that would be impossible to fabricate otherwise [11], [68], [70], [75]. In [11], intricate in-slot cooling channels and a portion of triple rotor structure were additively manufactured. Similarly in [70], [75], additively manufactured hollow windings were used to improve cooling. AM can be used to produce other components that have complex form-factors stemming from overarching requirements of motor-load optimization [69], [83], [85]. Even

though the technology is at its infancy with high cost per mass and low production rate, it is expected to mature in the future.

C. Magnetic Levitation

As described in Section V, the large diameter of ring motor rotors poses challenges for conventional bearings. Integrated ring motors often have further unique bearing requirements to meet the application and load specifications. For example, the ring motors for aerial propulsion desire extreme reliability and the ring motors where the airgap is flooded with the process fluid (e.g. [4]), desire oil-free bearings. One potential solution pathway for these challenges is to support the rotor through magnetic levitation forces produced by the motor's stator. This concept is referred to as a bearingless motor and is an active research area for levitating rotors in conventional motors [86]. Bearingless motors have been shown to achieve compact, long-life drives and oil-free operation without mechanical friction or wear.

The application of bearingless motor technology to RDTs was explored in [3]. It was shown that the limited load carrying capacity of today's bearingless motor technology requires using hydrodynamic thrust bearings to overcome the axial forces for this application. As reviewed in [86], industrial bearingless motors have been successful at reaching significant power levels (up to 60 kW) and are expected to play a significant role in the future to realize frictionless and oil-free load-integrating ring motors.

VII. CONCLUSION

This paper reviewed the state-of-the-art in ring motor technology with an emphasis on load-integrating designs. Several integrated ring motors designed for energy conversion applications such as marine and aerial propulsion, hydraulic power and traction were reviewed to identify their design aspects and performance parameters. These parameters were compared to conventional radial flux machines to show the capability of ring motor technology to integrate a variety of loads across a wide range of power levels. In addition, the review also showed that in certain fluid handling applications, the process fluid can be used as a coolant for integrated ring motors, further improving their power density. This paper further finds that multi-physics modelling, additive manufacturing, and bearingless motor technology provide promising future research pathways to improve the torque and power density, manufacturability, and lifetime of integrated ring motor designs.

REFERENCES

- [1] P. M. Tuohy, A. C. Smith, M. Husband, and P. Hopewell, "Rim-drive marine thruster using a multiple-can induction motor," *IET Electric Power Applications*, vol. 7, no. 7, pp. 557–565, 2013.
- [2] S. Abu Sharkh, S. Turnock, and A. Hughes, "Design and performance of an electric tip-driven thruster," *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 217, no. 3, pp. 133–147, 2003.
- [3] W. Manenschijn, N. Kuipers, and B. Kalma, "Design and control of bearingless drive for rim driven thruster," in *The 18th International Symposium for Magnetic Bearings*. ISMB, 2023.

- [4] F. Nishanth, G. Bohach, M. M. Nahin, J. Van de Ven, and E. L. Severson, "Development of an integrated electro-hydraulic machine to electrify off-highway vehicles," *IEEE Transactions on Industry Applications*, vol. 58, no. 5, pp. 6163–6174, 2022.
- [5] T. M. Jahns and J. R. Yagielski, "Electric flightworthy lightweight integrated thermally-enhanced powertrain system (eflites)," *Presented at the Special Session on ASCEND program, 2023 IEEE Energy Conversion Congress and Expo (ECCE)*, 2023.
- [6] T. Balachandran and X. Peter, "Cryogen-free ultra-high field superconducting electric (cruise) motor," https://arpa-e.energy.gov/sites/default/files/2024-05/12_Hinetics_ARPA-E_ASCEND_2024_Presentation_final.pdf, 2024.
- [7] X. Li, B. Anvari, A. Palazzolo, Z. Wang, and H. Toliyat, "A utility-scale flywheel energy storage system with a shaftless, hubless, high-strength steel rotor," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 8, pp. 6667–6675, 2017.
- [8] X. Yan, X. Liang, W. Ouyang, Z. Liu, B. Liu, and J. Lan, "A review of progress and applications of ship shaft-less rim-driven thrusters," *Ocean engineering*, vol. 144, pp. 142–156, 2017.
- [9] A. Kasaei, W. Yang, Z. Wang, and J. Yan, "Advancements and applications of rim-driven fans in aerial vehicles: A comprehensive review," *Applied Sciences*, vol. 13, no. 22, p. 12502, 2023.
- [10] M.-F. Hsieh, J.-H. Chen, Y.-H. Yeh, C.-L. Lee, P.-H. Chen, Y.-C. Hsu, and Y.-H. Chen, "Integrated design and realization of a hubless rim-driven thruster," in *IECON 2007-33rd Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2007, pp. 3033–3038.
- [11] K. Saviers, R. Regan, W. Zhao, A. Kuczek, A. Alahyari, Z. S. Du, J. A. Weibel, and J. Tangudu, "Stator prototype for a high current density electric motor: Assembly, evaluation, and testing," in *2023 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, 2023, pp. 1802–1808.
- [12] S. B. Andersen, I. F. Santos, and A. Fuerst, "Investigation of model simplification and its influence on the accuracy in fem magnetic calculations of gearless drives," *IEEE transactions on magnetics*, vol. 48, no. 7, pp. 2166–2177, 2012.
- [13] S. Sharkh and S. Lai, "Slotless pm brushless motor with helical edge-wound laminations," *IEEE Transactions on Energy Conversion*, vol. 24, no. 3, pp. 594–598, 2009.
- [14] S. Abu Sharkh, S. Turnock, and G. Draper, "Performance of a tip-driven electric thruster for unmanned underwater vehicles," in *ISOPE International Ocean and Polar Engineering Conference*. ISOPE, 2001, pp. ISOPE-I.
- [15] S. A. Sharkh, M. Harris, and R. Stoll, "Design and performance of an integrated thruster motor," 1995.
- [16] S. A. Sharkh, S. H. Lai, and S. Turnock, "Structurally integrated brushless pm motor for miniature propeller thrusters," *IEE Proceedings-Electric Power Applications*, vol. 151, no. 5, pp. 513–519, 2004.
- [17] S. Sharkh and S. Lai, "Design optimization of a slotless pm brushless motor with helical edge wound laminations for rim driven thrusters," *High Technology Letters*, vol. 16, no. 1, pp. 70–79, 2010.
- [18] S. Sinkko, J. Montonen, M. G. Tehrani, J. Pyrhönen, J. Sopanen, and T. Nummelin, "Integrated hub-motor drive train for off-road vehicles," in *2014 16th European Conference on Power Electronics and Applications*. IEEE, 2014, pp. 1–11.
- [19] Ø. Krøvel, "Design of large permanent magnetized synchronous electric machines: Low speed, high torque machines-generator for direct driven wind turbine-motor for rim driven thruster," 2011.
- [20] Z. Liu, K. Wang, Y. Guo, J. Li, and F. Li, "Design and optimization of a halfbach consequent-pole permanent magnet machine for rim-driven thruster," in *2023 26th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, 2023, pp. 5203–5208.
- [21] X. Wang, J. Zhu, and T. Qiao, "Design and analysis of a double-layer fault tolerant permanent magnet rim driven motor," in *2020 5th International Conference on Automation, Control and Robotics Engineering (CACRE)*. IEEE, 2020, pp. 483–487.
- [22] H. Cao and W. Chen, "Structural optimization of the halfbach array pm rim thrust motor," in *AIP Conference Proceedings*, vol. 1967, no. 1. AIP Publishing, 2018.
- [23] M.-S. Kim and S.-A. Kim, "Design and experimental verification of hubless rim-driven propulsor consisting of bearingless propeller for an unmanned underwater drone," *Energies*, vol. 16, no. 21, p. 7458, 2023.
- [24] H. Zhao, H. H. Eldeeb, Y. Zhan, Z. Ren, G. Xu, and O. A. Mohammed, "Robust electromagnetic design of double-canned im for submergible rim driven thrusters to reduce losses and vibration," *IEEE Transactions on Energy Conversion*, vol. 35, no. 4, pp. 2045–2055, 2020.
- [25] P. Tuohy, A. Smith, and M. Husband, "Induction rim-drive for a marine propulsor," 2010.
- [26] A. Hassannia and A. Darabi, "Design and performance analysis of superconducting rim-driven synchronous motors for marine propulsion," *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 1, pp. 40–46, 2013.
- [27] K. Richardson, C. Pollock, and J. Flower, "Design of a switched reluctance sector motor for an integrated motor/propeller unit," 1995.
- [28] H. Ouldhamrane, J.-F. Charpentier, F. Khoucha, A. Zaoui, Y. Achour, and M. Benbouzid, "Optimal design of axial flux permanent magnet motors for ship rim-driven thruster," *Machines*, vol. 10, no. 10, p. 932, 2022.
- [29] P. Ojaghlu and A. Vahedi, "Specification and design of ring winding axial flux motor for rim-driven thruster of ship electric propulsion," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 2, pp. 1318–1326, 2018.
- [30] P. Ojaghlu, A. Vahedi, and F. Tootoonchian, "Magnetic equivalent circuit modelling of ring winding axial flux machine," *IET Electric Power Applications*, vol. 12, no. 3, pp. 293–300, 2018.
- [31] P. Ojaghlu and A. Vahedi, "A new axial flux permanent magnet machine," *IEEE Transactions on Magnetics*, vol. 54, no. 1, pp. 1–6, 2017.
- [32] L. Drouen, J.-F. Charpentier, E. SEMAIL, F. HAUVILLE, and S. Clenet, "A coupled electromagnetic/hydrodynamic model for the design of an integrated rim-driven naval propulsion system," *ElectrIMACS*, 2008.
- [33] S. Djebarri, J. F. Charpentier, F. Scuiller, and M. Benbouzid, "Design and performance analysis of double stator axial flux pm generator for rim driven marine current turbines," *IEEE Journal of Oceanic Engineering*, vol. 41, no. 1, pp. 50–66, 2015.
- [34] S. Djebarri, J. F. Charpentier, F. Scuiller, M. Benbouzid, and S. Guemard, "Rough design of a double-stator axial flux permanent magnet generator for a rim-driven marine current turbine," in *2012 IEEE International Symposium on Industrial Electronics*. IEEE, 2012, pp. 1450–1455.
- [35] H. Cao and W. Chen, "A novel type of rim thrust motor with halfbach array permanent magnet rotor," in *AIP Conference Proceedings*, vol. 1967, no. 1. AIP Publishing, 2018.
- [36] Y. Li, B. Song, Z. Mao, and W. Tian, "Analysis and optimization of the electromagnetic performance of a novel stator modular ring drive thruster motor," *Energies*, vol. 11, no. 6, p. 1598, 2018.
- [37] B. Cheng, G. Pan, and Y. Cao, "Analytical design of the integrated motor used in a hubless rim-driven propulsor," *IET Electric Power Applications*, vol. 13, no. 9, pp. 1255–1262, 2019.
- [38] D. D. Kim, Y. Wu, A. Noel, and K. Youcef-Toumi, "Rim propeller for micro autonomous underwater vehicles," in *Dynamic Systems and Control Conference*, vol. 46209. American Society of Mechanical Engineers, 2014, p. V003T44A005.
- [39] J. Zhang, "Electromagnetic performance analysis of the rim electromagnetic direct-driven propeller," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 236, no. 2, pp. 752–762, 2022.
- [40] Y. Shen, P. Hu, S. Jin, Y. Wei, R. Lan, S. Zhuang, H. Zhu, S. Cheng, J. Chen, D. Wang *et al.*, "Design of novel shaftless pump-jet propulsor for multi-purpose long-range and high-speed autonomous underwater vehicle," *IEEE transactions on magnetics*, vol. 52, no. 7, pp. 1–4, 2016.
- [41] J. Liang, X. Zhang, M. Qiao, P. Zhu, W. Cai, Y. Xia, and G. Li, "Optimal design and multifield coupling analysis of propelling motor used in a novel integrated motor propeller," *IEEE transactions on magnetics*, vol. 49, no. 12, pp. 5742–5748, 2013.
- [42] D. Brown, "Submersible outboard electric motorpropulsor," *Naval engineers journal*, vol. 101, no. 5, pp. 44–52, 1989.
- [43] P. Tuohy, *Development of canned line-start Rim-driven electric machines*. The University of Manchester (United Kingdom), 2011.
- [44] B. Van Blarcom, J. Hanhinen, and F. Mewis, "The commercial rim-driven permanent magnet motor propulsor pod," in *Ship Production Symposium, Boston MA, USA*, 2002, pp. 25–26.
- [45] R. D. Technology, "Rim drive technology," <https://rimdrivetechology.nl/>, online; accessed on: 2024-7-17.
- [46] Voith, "Voith inline thruster and voith inline propulsor," <https://voith.com/corp-en/drives-transmissions/voith-inline-thruster-propulsor.html>, online; accessed on: 2024-7-17.
- [47] H. Zhang, Z. Chaudhry, A. Kuczek, T. Clydesdale, W. Zhao, and J. Tangudu, "Design and analysis of a triple-rotor integrated with a gearbox for a high power density motor," in *2023 IEEE International*

- Electric Machines & Drives Conference (IEMDC)*. IEEE, 2023, pp. 1–7.
- [48] C. of Engineering, “Research scientist cg cantemir develops lightweight motor concept for nasa electric aircraft,” <https://car.osu.edu>, online; accessed on: 2024-3-29.
 - [49] D. Lee, T. Balachandran, S. Sirimanna, N. Salk, A. Yoon, P. Xiao, J. Macks, Y. Yu, S. Lin, J. Schuh *et al.*, “Detailed design and prototyping of a high power density slotless pmsm,” *IEEE Transactions on Industry Applications*, vol. 59, no. 2, pp. 1719–1727, 2022.
 - [50] M. Liben and D. C. Ludois, “Analytical design and experimental testing of a self-cooled, toroidally wound ring motor with integrated propeller for electric rotorcraft,” *IEEE Transactions on Industry Applications*, vol. 57, no. 3, pp. 2342–2353, 2021.
 - [51] C. Tschida, “large electric aircraft propulsion systems (aerialist),” https://arpa-e.energy.gov/sites/default/files/2024-05/3_Wright_%20ARPA-E_ASCEND_Pitch_Deck_4_9_24_0.pdf, 2024.
 - [52] M. Tomsic, “Cryo-thermal management of high power density motors and drives,” https://arpa-e.energy.gov/sites/default/files/2024-05/16_ARPA-E_ASCEND_Deck_for_Hyper_Tech_Talk_April_9_2024_Rev_2_0.pdf, 2024.
 - [53] T. Balachandran, S. Srimmana, A. Anderson, X. Yi, N. Renner, and K. S. Haran, “Assembly and qualification of a slotless stator assembly for a mw-class permanent magnet synchronous machine,” in *2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*. IEEE, 2020, pp. 1–10.
 - [54] F. Zappaterra, D. Pan, T. Ransegnola, A. Vacca, S. D. Sudhoff, and E. Busquets, “A novel electro-hydraulic unit design based on a shaftless integration of an internal gear machine and a permanent magnet electric machine,” *Energy Conversion and Management*, vol. 310, p. 118432, 2024.
 - [55] P. Lindh, J. Tiainen, A. Grönman, T. Turunen-Saaresti, C. Di, L. Laurila, E. Scherman, H. Handroos, and J. Pyrhönen, “Two cooling approaches of an electrohydraulic energy converter for non-road mobile machinery,” *IEEE Transactions on Industry Applications*, vol. 59, no. 1, pp. 736–744, 2022.
 - [56] H. U. Wurgler, “The world’s first gearless mill drive,” *IEEE Transactions on Industry and General Applications*, no. 5, pp. 524–527, 1970.
 - [57] R. A. Errath, “15000-hp gearless ball mill drive in cement-why not!” *IEEE Transactions on Industry Applications*, vol. 32, no. 3, pp. 663–669, 1996.
 - [58] L. Nieto and M. Ahrens, “Gearless mill drive protection improvements and its behaviour at minera escondida ltda.” in *2007 IEEE Industry Applications Annual Meeting*. IEEE, 2007, pp. 1766–1772.
 - [59] J. Montonen, J. Nerg, M. Polikarpova, and J. Pyrhönen, “Integration principles and thermal analysis of an oil-cooled and-lubricated permanent magnet motor planetary gearbox drive system,” *IEEE Access*, vol. 7, pp. 69 108–69 118, 2019.
 - [60] S. B. Andersen, *Design and optimization of gearless drives using multi-physics approach*. Technical University of Denmark, 2012.
 - [61] F. Nishanth, J. Van Verdegheem, and E. L. Severson, “A review of axial flux permanent magnet machine technology,” *IEEE Transactions on Industry Applications*, vol. 59, no. 4, pp. 3920–3933, 2023.
 - [62] C. Li, H. Cui, F. Bu, and J. Liu, “Multi objective optimization design of permanent magnet ring torque motor based on response surface method,” in *2021 24th International Conference on Electrical Machines and Systems (ICEMS)*. IEEE, 2021, pp. 1204–1208.
 - [63] L. Matuszewski and K. Falkowski, “Ring thruster with magnetic bearings,” in *Oceans 2003. Celebrating the Past... Teaming Toward the Future (IEEE Cat. No. 03CH37492)*, vol. 4. IEEE, 2003, pp. 2023–2031.
 - [64] A. C. Smith, M. F. Iacchetti, and P. M. Tuohy, “Feasibility study of an induction motor rim drive for an aircraft boundary-layer-ingestion fan,” *The Journal of Engineering*, vol. 2019, no. 17, pp. 4506–4510, 2019.
 - [65] L. Livadaru, A. Munteanu, A. Simion, and C.-G. Cantemir, “Design and finite element analysis of high-density torque induction motor for traction applications,” in *2015 9th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*. IEEE, 2015, pp. 211–214.
 - [66] R. C. Bolam and Y. Vagapov, “Implementation of electrical rim driven fan technology to small unmanned aircraft,” in *2017 Internet Technologies and Applications (ITA)*. IEEE, 2017, pp. 35–40.
 - [67] A. Saulin, R. C. Bolam, J. P. C. Roque, and Y. Vagapov, “The application of slotless skewed windings to a rim driven fan for aircraft electrical propulsion (aep),” in *2022 57th International Universities Power Engineering Conference (UPEC)*. IEEE, 2022, pp. 1–6.
 - [68] A. Al-Qarni, E.-R. Ayman, and F. Wu, “Impact of machine parameters on the design of high specific power permanent magnet machines for aerospace applications,” in *2021 IEEE International Electric Machines & Drives Conference (IEMDC)*. IEEE, 2021, pp. 1–8.
 - [69] F. Wu, A. M. EL-Refaie, and A. Al-Qarni, “Additively manufactured hollow conductors integrated with heat pipes: Design tradeoffs and hardware demonstration,” *IEEE Transactions on Industry Applications*, vol. 57, no. 4, pp. 3632–3642, 2021.
 - [70] A. Al-Qarni, E.-R. Ayman, and F. Wu, “Design and analysis of a high specific power outer rotor surface mounted permanent magnet machine equipped with additively manufactured windings,” in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, 2021, pp. 4578–4585.
 - [71] F. Zappaterra, A. Vacca, and S. D. Sudhoff, “A compact design for an electric driven hydraulic gear machine capable of multiple quadrant operation,” *Mechanism and Machine Theory*, vol. 177, p. 105024, 2022.
 - [72] S. Qu, F. Zappaterra, A. Vacca, and E. Busquets, “An electrified boom actuation system with energy regeneration capability driven by a novel electro-hydraulic unit,” *Energy Conversion and Management*, vol. 293, p. 117443, 2023.
 - [73] L. Amri, M. Kebdani, S. Zouggar, and J.-F. Charpentier, “Design and optimization of a rim driven motor for pump application,” *Materials Today: Proceedings*, vol. 72, pp. 3775–3779, 2023.
 - [74] J. Pyrhonen, T. Jokinen, and V. Hrabovcova, *Design of rotating electrical machines*. John Wiley & Sons, 2013.
 - [75] S. Vahid, T. Chowdhury, S. Koushan, and E.-R. Ayman, “Electrical characteristics of additively manufactured hollow conductor coils with integrated heat pipes for electric aircraft applications,” in *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE, 2022, pp. 1–8.
 - [76] M. Polikarpova, “Liquid cooling solutions for rotating permanent magnet synchronous machines,” Ph.D. dissertation, Lappeenranta University of Technology, 2014.
 - [77] “Electrical and electronics technical team roadmap,” *U.S Dept. of Energy - Office of Energy Efficiency and Renewable Energy (EERE)*, 2017.
 - [78] D. Gerada, A. Mebarki, N. L. Brown, C. Gerada, A. Cavagnino, and A. Boglietti, “High-speed electrical machines: Technologies, trends, and developments,” *IEEE transactions on industrial electronics*, vol. 61, no. 6, pp. 2946–2959, 2013.
 - [79] X. Liang, X. Yan, W. Ouyang, R. J. Wood, and Z. Liu, “Thermo-elasto-hydrodynamic analysis and optimization of rubber-supported water-lubricated thrust bearings with polymer coated pads,” *Tribology International*, vol. 138, pp. 365–379, 2019.
 - [80] C. Ning, W. Ouyang, F. Hu, X. Yan, and D. Xu, “A wear monitoring method and influencing factors of water-lubricated polymer bearings based on improved ultrasonic reflection coefficient amplitude spectrum and ultrasonic reconfiguration calculation,” *Wear*, vol. 522, p. 204689, 2023.
 - [81] G. Bramerdorfer, J. A. Tapia, J. J. Pyrhönen, and A. Cavagnino, “Modern electrical machine design optimization: Techniques, trends, and best practices,” *IEEE Transactions on Industrial Electronics*, vol. 65, no. 10, pp. 7672–7684, 2018.
 - [82] X. Yi, A. Yoon, and K. S. Haran, “Multi-physics optimization for high-frequency air-core permanent-magnet motor of aircraft application,” in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*. IEEE, 2017, pp. 1–8.
 - [83] R. Wrobel and B. Mecrow, “A comprehensive review of additive manufacturing in construction of electrical machines,” *IEEE Transactions on Energy Conversion*, vol. 35, no. 2, pp. 1054–1064, 2020.
 - [84] F. Nishanth, A. D. Goodall, I. Todd, and E. L. Severson, “Characterization of an axial flux machine with an additively manufactured stator,” *IEEE Transactions on Energy Conversion*, vol. 38, no. 4, pp. 2717–2729, 2023.
 - [85] F. Wu and A. M. EL-Refaie, “Toward additively manufactured electrical machines: Opportunities and challenges,” *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1306–1320, 2019.
 - [86] J. Chen, J. Zhu, and E. L. Severson, “Review of bearingless motor technology for significant power applications,” *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1377–1388, 2019.