

Axial Flux In-wheel-motors for Vehicle Electrification

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Abstract

In-wheel-motors have emerged as a transformative technology in vehicle electrification, offering superior efficiency, compactness, and design flexibility over traditional off-wheel-motors. This study focuses on the advanced axial flux permanent magnet synchronous motors used as in-wheel-motors, which are critical for electric vehicle applications due to their high power and torque densities and minimized axial length. Automotive manufacturers increasingly adopt axial flux motors for their in-wheel-motors due to numerous advantages. The most appropriate configuration of axial flux motors is the single-stator double-rotor which supports a higher number of Neodymium permanent magnets, resulting in significantly improved power and torque densities, reduced iron losses, and enhanced efficiency compared to radial flux machines. This paper examines the state-of-the-art axial flux in-wheel-motors specifically designed for electric vehicles, highlighting the design considerations and engineering methodologies that contribute to their superior performance. By analyzing key performance metrics, including power and torque densities, efficiency, magnetic circuit topology, stator/rotor topology, winding configuration, drivetrain integration, and target applications, this paper demonstrates the potential of axial flux IWMs to drive a substantial transition into electric vehicles with allocated wheel torque control.

Keywords

in-wheel-motor, axial flux, vehicle electrification, power density, torque density

1 Introduction

As the vehicle industry embraces electrification, the demand for advanced motor technologies that meet these needs and offer high efficiency, reliability, and integration simplicity has surged. Traditional EVs with centralized propulsion systems using off-wheel motors (OWMs) fall short of these requirements (Said Jneid et al., 2020; Terzi et al., 2020). In this context, in-wheel motors (IWMs) have emerged as a groundbreaking technology for vehicle electrification, offering solutions that align with future demands (Setlak, 2005; Zaaaraoui and Mansouri, 2023). IWMs with direct drive features allow shifting the propulsion system from the vehicle chassis to inside the wheels' rim. This way, several drivetrain elements can be avoided such as transmission, differential, and shafts, which simplifies the vehicle structure, reduces the end cost, and improves the efficiency.

With the independent control of the wheels' torque, IWMs transport the centralized drive in OWM EVs into an allocated drive allowing the implementation and integration of various active safety systems simultaneously using minimum hardware elements. Therefore, advanced chassis

active-safety systems (ACASs) can be realized based on an electronic version, namely by-wire (Said Jneid and Harth, 2023a). For instance, controlling wheel acceleration individually allows for the implementation of a drive-by-wire traction control system (TCS). On the other hand, independent control of wheel deceleration through the regenerative braking feature of IWMs enables anti-lock braking system (ABS) functionalities based on brake-by-wire. Frictional brakes such as electronic wedge brakes (EWB) can also be integrated with regenerative braking providing a blending brake through seamless activation/deactivation of both systems (Said Jneid and Joukhadar, 2019; Said Jneid and Harth, 2023b; Said Jneid et al., 2023).

Furthermore, the differential driving and braking features of IWMs help assist the driver's steering through a steer-by-wire control. In addition, the differential driving and/or braking wheels' torque control enables the application of advanced electronic stability control (ESC) and torque vectoring (TV) essential for EVs. On the vehicle control system level, IWMs enable harmonious integration and activation of different ACASs including ABS,

TCS, ESC, and TV. For instance, in our previous works (Said Jneid and Harth 2023a, 2023c, 2023d, 2024a) TV is implemented based on ABS and TCS integration.

Several leading automotive and tire manufacturers have introduced conceptual and advanced designs of IWMs, each distinguished by unique design, specifications, and target applications. Permanent magnet synchronous motors (PMSMs) are the ideal option for IWMs due to their high torque density attributed to the utilization of Neodymium permanent magnets (PMs). Initial models of IWMs such as Protean IWM have utilized radial flux motors (Said Jneid and Harth, 2024b). The Protean IWM is a specialized propulsion system developed by Protean Electric for direct-drive electric vehicle applications. The Protean IWM boasts high fault tolerance, crucial for EV applications, by dividing the stator into eight independent sub-motors. (Said Jneid and Harth, 2025). However, recent advancements have seen a shift towards axial flux topologies, which offer impressive power and torque densities essential for EV applications (Bolam et al., 2020). Axial flux technology significantly increases the integration potential of IWMs due to its compact length-to-diameter ratio, allowing for more efficient and streamlined designs (Credo et al., 2021). The high power density, high energy efficiency, and compact design of axial flux motors make them particularly suitable for applications in the automotive field, especially for IWM electric vehicles (Hao et al., 2022; Gadiyar et al., 2023). In addition, axial flux motors have the following advantages:

- High power and torque densities.
- High torque-to-mass ratio.
- Lightweight and compact design with minimized axial length.
- Adjustable air gap.
- Low cogging torque, vibration and noise.
- Large diameter-to-length ratio essential for torque multiplication.
- High number of pole pairs essential for direct drive low-speed applications.
- High efficiency close to 98%.

In contrast to radial flux motors in which the magnetic lines follow a radial direction to the shaft, axial flux motors refer to the axial direction in which magnetic lines travel across the air gap axially parallel to the shaft (Ifedi et al., 2012). Fig. 1 shows the direction of magnetic lines in axial flux motors compared to radial and transverse motors.

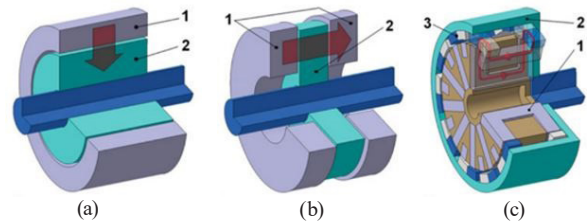


Fig. 1 Direction magnetic lines travel in the (a) radial flux machines, (b) axial flux machines, and (c) transverse flux machines (1: stator, 2: rotor, 3: permanent magnet) (Trzesniowski, 2023)

However, axial flux motors have some drawbacks such as (Edmondson, 2022; Gobbi et al., 2024):

- High-cost manufacturing process.
- Heat and integration issues connected to the magnets.
- Long manufacturing time.
- Long optimization time due to the need for 3D simulation.

Mainly, there are three topologies for axial flux machines as shown in Fig. 2:

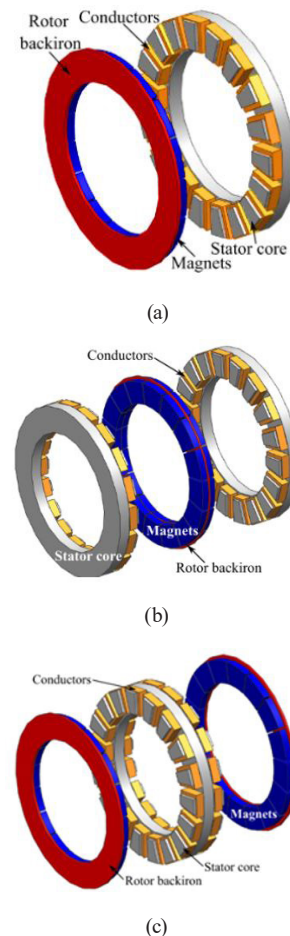


Fig. 2 Main configurations of axial flux machines: (a) single-stator single-rotor, (b) double-stator single-rotor, and (c) single-stator double-rotor (Jenkins et al., 2023)

- Single-stator single-rotor.
- Double-stator single-rotor.
- Single-stator double-rotor.

2 State-of-the-art of axial flux in-wheel-motors

As radial flux IWMs, axial flux IWMs employ PMSM architecture utilizing the high torque and power densities of the Neodymium PMs for applications that require high torque density such as EVs. However, with the recent increase in the price of rare-earth permanent magnets (PMs), the trend is shifting towards magnet-less motors, such as switched reluctance motors (SRMs). Axial flux IWMs have further preferred features compared to radial ones including compact design, short axial length, reduced iron and copper mass, and high efficiency making them preferable for EV applications. Axial IWMs can have flexible design topologies depending on the number of rotors and stators and can be classified into types such as single-stator/single-rotor, single-stator/double-rotor, double-stator/single rotor, and double-stator/double-rotor. However, axial IWMs suffer from non-uniform air gaps due to the strong axial interaction between the stator and rotor magnetic fields. Various manufacturers have engineered several axial flux IWMs, each with distinctive features and functionalities customized to fulfil specific application needs.

2.1 NTN IWM drive unit

In response to the growing global demand for high-performance and eco-friendly electric drivetrains for next-generation EVs, NTN has developed a highly integrated drive system, tailored for geared drive EV applications (Hao et al., 2022; Isobe et al., 2011). This innovative system integrates an axial flux IWM, a reducer (speed/torque converter unit), and a sensor-based control system within the wheel rim size of 15 inches, as shown in Fig. 3 NTN



Fig. 3 NTN axial flux IWM (NTN, 2011)

IWM is designed with concentrated winding (shortening the axial length), an inner rotor, boasting a peak power of up to 20 kW, and a peak torque of 490 Nm at a max DC voltage of 400 V. The total mass of the unit is around 25 kg, making it lighter than comparable systems while achieving the same power limits. This weight reduction is attributed to the efficient gearbox that maximizes the motor torque (reduction ratio is 1/11), allowing for the application of a lighter motor (Suzuki and Kayo, 2007). To enhance torque density, the motor employs a mixed forced oil/air cooling system for cooling the reducer and the motor including internal parts of the rotor, stator, and coils. In contrast, a water-cooling system is used to cool down the inverter, boosting current density and delivering greater power within the same volume unit. The maximum efficiency achieved for the speed/torque converter is 98% in the forward direction and 97.5% in the reverse direction. However, the motor's maximum efficiency reaches 94.7%, while the total maximum efficiency of the whole unit is 90%. For small and medium-sized vehicles, optimal performance can be achieved by installing two NTN drive units. However, the installation of four units ensures exceptional performance across diverse operating environments (NTN, 2011). Table 1 provides the electrical and mechanical specifications of the NTN IWM drive unit.

Table 1 Electrical and mechanical specifications of NTN IWM drive unit

IWM Unit	NTN
Power (Peak/ continuous) [kW]	20/14
Torque (Peak/continuous) [Nm]	490/350
Max Speed [rpm]	15,000
Voltage [VDC]	400-450
Peak Efficiency [%]	Motor: 75, Reducer: 95 System: 85
Mass [kg]	25
Wheel Size [inch]	17
Peak Power Density [kW/kg]	0.8
Peak Torque Density [Nm/kg]	19.6
Winding Topology	-
Motor Topology	Axial-Flux
Rotor Topology / Poles	Inner-Rotor / 9
Stator Topology / Slots	Outer / 12
Drivetrain Topology	Geared-Drive
Reducer /Gear-Ratio	Cycloid Reducing System 1/11
Cooling system	Water + Air
Integration level	IWM+ Reducer
Ingress Protection Level	IP66
Dimensions	-
Ref	(Suzuki and Kayo, 2007)

2.2 YASA IWM drive unit

YASA produces unique axial flux motors with exceptional performance and 2-3 times higher power density compared to radial flux motors of the same size. Unlike traditional motors, YASA removed the stator yoke and adopted shorter concentrated windings leading to iron and copper mass reduction, minimized loss, and improved efficiency. Furthermore, they are cost-effective and environmentally sustainable due to using simple designs with fewer materials. Thus, a 50% reduction in size and weight is achieved compared to radial flux motors, making them flexible and light, fitting EV requirements. By utilizing an oil cooling system, YASA motors further deliver consistently high performance, even under demanding conditions. YASA introduced different motor versions such as P400 HC, P400 C, P400 S, and 750R fitting a wide range of applications. The YASA 750 R motor shown in Fig. 4 sets a new standard in torque and power density within its category, making it the ideal choice for traction and generation applications. With a focus on lower speed and higher torque, this motor delivers a peak power of 200 kW and, a peak torque of 700 Nm, and offers a speed range of 0-3,250 rpm, (YASA, 2024). Table 2 provides the electrical and mechanical specifications of YASA IWM drive unit products.



Fig. 4 YASA 750R axial flux IWM (YASA, 2024)

2.3 MagnaX IWM drive unit

MagnaX specializes in designing high-performance axial flux electric motors aimed at driving the electrification of the e-mobility. MagnaX motor is designed uniquely as compact and lightweight facilitating seamless integration into next-generation powertrain configurations, freeing up space for enhanced battery storage capacity. Key features include full integration into the electric drivetrain and eAxle, an effective electromagnetic design minimizing material usage per kilowatt, a dual rotor permanent magnet

Table 2 Electrical and mechanical specifications of YASA IWM drive unit products

IWM unit	YASA 750R	YASA P400
Power (peak/continuous) [kW]	200 (@ 700 VDC-100 (@ 400 VDC) /70	160 (@ 700 VDC-100@ 700VDC) /60
Torque (peak/continuous) [Nm]	790/400	370/200
Max speed [rpm]	3,250	8,000
Voltage [VDC]	400-700	400-700
Peak efficiency [%]	Motor: >95	Motor: >95; system: 90
Mass [kg]	37	27
Peak power density [kW/kg]	5.4	5.92
Peak torque density [Nm/kg]	21.4	13.7
Winding topology	Concentrated	Concentrated
Motor topology	Axial-flux	Axial-flux
Rotor topology/poles	Inner double rotor/12	Inner double rotor/12
Stator topology/slots	Single-stator/18	Single-stator/18
Drivetrain topology	Direct-drive	Direct-drive
Reducer/gear-ratio	-	-
Cooling system	Oil	Oil
Integration level	IWM only	IWM only
Ingress protection level	-	-
Dimensions	Ø 368 x 92 mm	Ø 305 x 106.7 mm
Ref	(Jenkins et al., 2023; YASA, 2024)	(Jenkins et al., 2023; YASA, 2024)

configuration enabling the highest torque-to-weight ratio, a yokeless stator design for shorter flux paths and reduced weight (26.5 kg), a concentrated winding with a rectangle cross-section, minimizing copper loss, and oil cooling for optimal thermal management. MagnaX produces a series of IWMs tailored for diverse applications, including the AXF185, AXF225, AXF275, and AXF350. Standing out among all the MagnaX models is the AXF275 shown in Fig. 5 which has a peak power of 300 kW and a peak torque of 500 Nm while offering a maximum speed of 8,000 rpm (Leijnen and Moreels, 2018; Magnax, 2024; Sigler, 2024; Traxial, 2024). Table 3 provides the electrical and mechanical specifications of Magnax IWM drive unit products.



Fig. 5 MagnaX AXF275 axial flux IWM (Leijnen and Moreels, 2018)

2.4 Phi-Power AG IWM drive unit

Phi-Power AG manufactures high-performance axial flux motors distinguished by their high power and torque densities at minimum torque ripple for automotive applications. These motors are designed to be lightweight yet powerful, offering high efficiency and torque for improved

performance. With a simple liquid cooling system using water-glycol, without the need for oil, making maintenance is easy. The low rotor inertia ensures quick and responsive acceleration, while compatibility with standard inverters ensures seamless integration into existing systems.

Table 3 Electrical and mechanical specifications of Magnax IWM drive unit products

IWM Unit	Magnax AXF 185	Magnax AXF 225	Magnax AXF 275	Magnax AXF 300-85S	Magnax AXF 350
Power (peak/continuous) [kW]	100/50	170/85	300/150	266/200	480/240
Torque (peak/continuous) [Nm]	100/50	250/133	520/267	600/410	1,000/500
Max speed [rpm]	12,000	10,000	8,000	12,000	4,000
Voltage [VDC]	400-900	400-900	400-900		400-900
Peak efficiency [%]	Motor: 96-97 system: 91-92	Motor: 96-97 system: 91-92	Motor: 96-97 system: 91-92	Motor: 96-97 system: 91-92	Motor: 96-97 system: 91-92
Mass [kg]	8	14	26.5	32.8	42
Peak power density [kW/kg]	12.5	12.1	11.3	8.1	11.4
Peak torque density [Nm/kg]	12.5	17.9	18.9	18.7	23.8
Winding topology	Concentrated	Concentrated	Concentrated	Concentrated	Concentrated
Motor topology	Axial-flux	Axial-flux	Axial-flux	Axial-flux	Axial-flux
Rotor topology/poles	Inner double-rotor/12	Inner double-rotor/12	Inner double-rotor/12	Inner double-rotor/12	Inner double-rotor/12
Stator topology/slots	Single-stator/18	Single-stator/18	Single-stator/18	Single-stator/18	Single-stator/18
Drivetrain topology	Direct-drive	Direct-drive	Direct-drive	Direct-drive	Direct-drive
Reducer/gear-ratio	Gearbox can be integrated	Gearbox can be integrated	Gearbox can be integrated	Gearbox can be integrated	Gearbox can be integrated
Cooling system	Oil	Oil	Oil	Oil	Oil
Integration level	IWM only	IWM only	IWM only	IWM only	IWM only
Ingress protection level	IP65	IP65	IP65	IP65	IP65
Dimensions	Ø 185 × 75 mm	Ø 225 × 86 mm	Ø 275 × 86 mm	Ø 300 × 131 mm	Ø 350 × 131 mm
Ref	(Juschus et al., 2018; Leijnen and Moreels, 2018; Traxial, 2024)	(Juschus et al., 2018; Leijnen and Moreels, 2018; Traxial, 2024)	(Juschus et al., 2018; Leijnen and Moreels, 2018; Traxial, 2024)	(Juschus et al., 2018; Leijnen and Moreels, 2018; Traxial, 2024)	(Juschus et al., 2018; Leijnen and Moreels, 2018; Traxial, 2024)

Additionally, integrated resolver feedback and stator temperature sensors provide precise control and monitoring. With a flexible concentrated winding configuration various operating voltages are applicable. Phi-Power AG IWMs offer versatility and reliability for a wide range of applications. The company introduced several models including Phi271, Phi275, Phi301, Phi381, and Phi382. The Phi382 motor shown in Fig. 6 is distinguished as a powerhouse of performance tailored for demanding applications. With a peak power of 400 kW (up to 20 s) and a continuous power of 180 kW, it delivers a peak torque of 1,280 Nm (up to 60 s)



Fig. 6 MagnaX AXF275 axial flux IWM (Leijnen and Moreels, 2018)

and a continuous torque of 550 Nm, ensuring consistent and reliable performance under varying conditions. At a maximum speed of 6,000 rpm, the Phi382 motor offers direct drive eliminating the need for a reduction gear set. The maximum efficiency achieved is 95.5%. This motor fits a rim diameter of 0.38 m weighing 83 kg with a low rotor inertia of 0.11 kgm², making it a versatile and efficient solution suitable for heavy-duty vehicles, (Phi-Power AG, 2024). Table 4 provides the electrical and mechanical specifications of Phi Power AG IWM drive unit products.

2.5 Turntide IWM drive unit

Turntide produces high-performance axial flux IWMs. Turntide IWMs are suitable for supply voltages up to 850 VDC, offering versatility and adaptability. With a peak efficiency exceeding 95%, they deliver maximum performance while minimizing energy consumption, ensuring optimal operation and cost-effectiveness. The Turntide axial flux motor series presents a lineup of compact electric motors renowned for their power and torque density. High torque at low speeds enables system simplification through the removal of gearbox, shafts and mounting interfaces. Specifically engineered for high performance, these motors are ideal for hybrid and retrofit applications, offering versatility across various industries. Featuring advanced liquid cooling using water/

Table 4 Electrical and mechanical specifications of Phi Power AG IWM drive unit products

IWM unit	Phi 301	Phi 301	Phi 271S
Power (peak/ continuous) [kW]	160 /85	150/90	75/45
Torque (peak/continuous) [Nm]	520/190	240/140	120/92
Max speed [rpm]	9,000	12,000	12,000
Voltage [VDC]	250-800	250-800	250-800
Peak efficiency [%]	>95.5	>95.5	>95.5
Mass [kg]	29	20	12
Peak power density [kW/kg]	5.5	7.5	6.3
Peak torque density [Nm/kg]	19.3	12	10
Winding topology	Distributed	Distributed	Distributed
Motor topology	Axial-flux	Axial-flux	Axial-flux
Rotor topology/poles	Inner-single rotor/10	Inner-single rotor/10	Inner-single rotor/10
Stator topology/slots	Double stator/14	Double stator/14	Double stator/14
Drivetrain topology	Direct drive	Direct drive	Direct drive
Reducer/gear-ratio	-	-	-
Cooling system	Water- glycol	Water- glycol	Water- glycol
Integration level	IWM only	IWM only	IWM only
Ingress protection level	IP69	IP69	IP69
Dimensions	Ø 300 × 120 mm	Ø 270 × 106 mm	Ø 270 × 77 mm
Ref	(Phi-Power AG, 2024; E-Mobility Engineering, 2024)	(Phi-Power AG, 2024; E-Mobility Engineering, 2024)	(Phi-Power AG, 2024; E-Mobility Engineering, 2024)

ethylene-glycol, they ensure consistent and enhanced performance even under demanding conditions. Turntide produces a series of IWMs AF125-AF440, each motor is tailored to meet specific power and torque requirements. AF125-AF440 have a continuous power range of 59-376 kW, a continuous torque range of 100-1,040 Nm, a maximum speed range of 5,000-12,000 rpm, and a weight range of 22-160 kg. The Turntide AF140 shown in Fig. 7 has a peak/continuous power of up to 220/94 kW (up to 20 s), peak/continuous torque of 600/260 Nm, and a maximum speed of 5,000 rpm weighing only 43 kg making it suitable for high demands EVs (Turntide, 2024). Table 5



Fig. 7 Turntide AF140 axial flux IWM (Turntide, 2024)

provides the electrical and mechanical specifications of Turntide IWM drive unit products.

2.6 Emrax IWM drive unit

The Emrax electric motors/generators represent a collection of lightweight, compact, and high power-density (10 kW/kg) axial flux IWMs. Designed with high torque-low speed and high efficiency (92% to 98%), fitting for a wide range of direct drive applications including electric bikes, electric buses, marine, and airplanes. Emrax application examples cover main traction motors, hybrid powertrains, range extenders, wind/water turbine generators, integrated starter generators, hydraulic motor replacements, and robotics. Furthermore, the Emrax TWIN configuration allows for stacking two motors, effectively doubling both power and torque capabilities. The company introduced five models: Emrax188, Emrax208, Emrax228, Emrax268, and Emrax348. Each is available with three optional voltage levels (high, medium, and low), and three optional cooling types (air, liquid, and combined air/liquid). The Emrax348 shown in Fig. 8 has a peak/continuous power of 420/210 kW and a peak/continuous torque of 1,000/500 Nm with a max speed of 4,500 rpm, weighing only 42 kg, (EMRAX, 2024). Table 6 provides the electrical and mechanical specifications of Emrax IWM drive unit products.

Table 5 Electrical and mechanical specifications of Turntide IWM drive unit products

IWM Unit	Turntide AF125	Turntide AF130	Turntide AF140
Power (peak/continuous) [kW]	100/59	140/64	220/94
Torque (peak/continuous) [Nm]	220/100	350/145	600/260
Max speed [rpm]	12,000	8,000	5,000
Voltage [VDC]	600-800	600-800	600-800
Peak efficiency [%]	> 95	> 95	> 95
Mass [kg]	22	30	43
Peak power density [kW/kg]	4.5	4.6	4.6
Peak torque density [Nm/kg]	10	11.6	14
Winding topology	-	-	-
Motor topology	Axial-flux	Axial-flux	Axial-flux
Rotor topology/poles	Inner/-	Inner/-	Inner/-
Stator topology/slots	-	-	-
Drivetrain topology	Direct-drive	Direct-drive	Direct-drive
Reducer/gear-ratio	-	-	-
Cooling system	Water/glycol	Water/glycol	Water/glycol
Integration level	IWM only	IWM only	IWM only
Ingress protection level	IP67	IP67	IP67
Dimensions	Ø 285 × 110 mm	Ø 300 × 110 mm	Ø 380 × 115 mm
Ref	(Turntide, 2024)	(Turntide, 2024)	(Turntide, 2024)



Fig. 8 Emrax348 axial flux IWM (EMRAX, 2024)

2.7 Evolito IWM drive unit

Evolito offers a range of axial flux motors that redefine compactness and efficiency in their class by eliminating the yoke and incorporating a segmented magnet layout, allowing for weight reduction yet enhancing performance. The stator is provided with options for both 1×3 and 2 × 3 phase configurations based on power density and fault tolerance demands. The company introduced three models, D250 with low torque/high speed, D500 with mid torque/speed, and D1500 with high Torque/low Speed. The Evolito D500 shown in Fig. 9 has a peak/continuous

power of 350/320 kW and a peak/continuous torque of 560/500 Nm. Despite its impressive capabilities, this motor remains lightweight, weighing approximately 30 kg, and compact, measuring 375 × 128 mm. With a maximum speed of 9,000 rpm (for up to 30 seconds), the Evolito D500 offers high-speed performance in a small package, making it ideal for a wide range of electric vehicle applications (Evolito, 2024; Alcock, 2023; Risen, 2024). Table 7 provides the electrical and mechanical specifications of Evolito IWM drive unit products.



Fig. 9 Evolito D1500 axial flux IWM (Evolito, 2024)

Table 6 Electrical and mechanical specifications of Emrax IWM drive unit products

IWM unit	Emrax 188	Emrax 208	Emrax 228	Emrax 268	Emrax 348
Power (peak/continuous) [kW]	60/37	86/56	124/75	210/117	400/210
Torque (peak/continuous) [Nm]	100/56	150/90	230/130	500/250	1,000/500
Max speed [rpm]	8,000	7,000	6,500	4,500	4,000
Voltage [VDC]	50-660	50-690	50-830	100-830	100-830
Peak efficiency [%]	96	96	96	96	96
Mass [Kg]	7.1-7.9	9.4-10.3	12.9-13.5	21.4-22.3	43.1-43.9
Peak power density [kW/kg]	7.6	8.3	9.2	9.4	9.1
Peak torque density [Nm/Kg]	12.7	14.6	17	22.4	22.8
Winding topology	Concentrated	Concentrated	Concentrated	Concentrated	Concentrated
Motor topology	Axial-flux	Axial-flux	Axial-flux	Axial-flux	Axial-flux
Rotor topology/poles	Inner double-rotor/20	Inner double-rotor/20	Inner double-rotor/20	Inner double-rotor/20	Inner double-rotor/20
Stator topology/slots	Single-stator/18	Single-stator/18	Single-stator/18	Single-stator/18	Single-stator/18
Drivetrain topology	Direct-drive	Direct-drive	Direct-drive	Direct-drive	Direct-drive
Reducer/gear-ratio	-	-	-	-	-
Cooling system	Air/water/combined	Air/water/combined	Air/water/combined	Air/water/combined	Air/water/combined
Integration level	IWM only	IWM only	IWM only	IWM only	IWM only
Ingress protection level	IP66	IP66	IP66	IP66	IP66
Dimensions	Ø 188 × 79 mm	Ø 208 × 85 mm	Ø 228 × 86 mm	Ø 268 × 94 mm	Ø 348 × 112 mm
Ref	(EMRAX, 2024)	(EMRAX, 2024)	(EMRAX, 2024)	(EMRAX, 2024)	(EMRAX, 2024)

Table 7 Electrical and mechanical specifications of Evolito IWM drive unit products

IWM Unit	Evolito D250	Evolito D500	Evolito D1500
Power (peak/continuous) [kW]	230/207	300/230	150/100
Torque (peak/continuous) [Nm]	230/208	500/280	1,450/1,200
Max speed [rpm]	10,000	9,000	2,500
Voltage [VDC]	400-800	400-800	400-800
Max efficiency [%]	97	97	97
Mass [kg]	8.3	28	35
Max power density [kW/kg]	28	12	4.3
Max torque density [Nm/kg]	> 26	> 18	> 40
Winding topology	Concentrated	Concentrated	Concentrated
Motor topology	Axial-flux	Axial-flux	Axial-flux
Rotor topology/poles	Inner double-rotor/12	Inner double-rotor/12	Inner double-rotor/12
Stator topology/slots	Single-stator/18	Single-stator/18	Single-stator/18
Drivetrain topology	Direct-drive	Direct-drive	Direct-drive
Cooling system	Oil	Oil	Oil
Integration level	IWM only	IWM only	IWM only
Ingress protection level	-	-	-
Dimensions	Ø 315 × 126 mm	Ø 345 × 123 mm	Ø 440 × 110 mm
Ref	(Evolito, 2024)	(Evolito, 2024)	(Evolito, 2024)

2.8 Beyond Motors IWM drive unit

Beyond Motors leads the charge in advancing electric vehicles by delivering unrivalled continuous power and torque density through cutting-edge axial flux motors. These lightweight yet robust motors represent ideal propulsion solutions for EVs. The company offers a range of models and the flexibility of customizable designs. The AXM2, AXM3, and AXM4 models excel in a power-to-weight ratio higher than 12 kW/kg and torque-to-weight ratio more than 18 Nm/kg, featuring two winding configurations (1 × 3 and 2 × 3 phases) and three DC voltage levels ranging from 300 to 850 V. Equipped with a water/glycol cooling system, Beyond Motors' products achieve unmatched continuous power and torque density at impressive efficiency levels of up to 96%. For applications requiring increased power and torque, these motors can be stacked, allowing for the combination of up to three motors to meet the demands of heavy-duty vehicles. Each stacked motor necessitates a dedicated controller (inverter) for operation. Among the lineup, the AXM4 model shown in Fig. 10 stands out for its exceptional performance, boasting peak/continuous power of 300/230 kW, peak/continuous torque of 950/600 Nm, and a maximum speed of 4,500 rpm – all while maintaining a lightweight design of just 48 kg, making it ideal for direct-drive applications (Beyond, 2024). Table 8 provides the electrical and mechanical specifications of Beyond Motors IWM drive unit products.



Fig. 10 Beyond Motors AXM4 IWM (Beyond, 2024)

3 Conclusion

The transition to electric vehicles (EVs) represents a significant shift in the automotive industry, aimed at reducing greenhouse gas emissions, improving energy efficiency, and decreasing reliance on fossil fuels. The electrification of vehicles involves integrating advanced electric powertrains that deliver superior performance, lower maintenance costs, and greater sustainability compared to traditional internal combustion engine vehicles. In-wheel motors (IWMs) play a crucial role in advancing vehicle electrification. These motors are integrated directly into the

Table 8 Electrical and mechanical specifications of Beyond Motors IWM drive unit products

IWM unit	Beyond Motors AXM2	Beyond Motors AXM3	Beyond Motors AXM4
Power (peak/continuous) [kW]	130/75	220/130 (@ 400-800V) 135/80 (@ 850 V)	300/230 (@ 850 VDC) 400/230 (@ 550-750 VDC)
Torque (peak/continuous) [Nm]	180/120	525/310	950/600
Max speed [rpm]	7,500/6,000 (continuous)	- 5,800 (Max @ 400-800V) - 3,200 (Max @ 850 V) - 4,000 (continuous @ 400-800 V) - 2,500 (continuous @ 400-800 V)	4,500/3,600
DC voltage [VDC]	300/550/850	400/550/800/850	550/750/850
Max efficiency [%]	96	96	96
Mass [kg]	14.5	27	48
Max power density [kW/kg]	9	8.1	8.3
Max torque density [Nm/kg]	12.4	19.4	19.8
Winding topology	Concentrated	Concentrated	Concentrated
Motor topology	Axial-flux	Axial-flux	Axial-flux
Rotor topology	Inner-rotor	Inner-rotor	Inner-rotor
Stator topology (slots/poles)	-	-	-
Drivetrain topology	Direct drive	Direct drive	Direct drive
Cooling system	Water/glycol	Water/glycol	Water/glycol
Integration level	IWM only	IWM only	IWM only
Protection level	IP55	IP55	IP55
Dimensions	Ø 241 × 117 mm	Ø 320 × 134.8 mm	Ø 400 × 146.6 mm
Ref	(Beyond, 2024)	(Beyond, 2024)	(Beyond, 2024)

wheel hubs, providing direct drive to each wheel. This configuration enhances vehicle dynamics, improves efficiency, and allows for more flexible and innovative vehicle designs. IWMs contribute to better handling, faster acceleration, and the elimination of components such as drive shafts and differentials, which reduces vehicle weight and complexity.

Axial flux permanent magnet synchronous motors (PMSMs) are highly suitable for integration into IWMs due to their compact design, high power density, and superior efficiency. These motors generate torque through the interaction of magnetic fields that are parallel to the motor's axis, resulting in a thinner and lighter motor compared to traditional radial flux motors. The advantages of axial flux PMSMs include enhanced performance, reduced energy consumption, and the ability to fit into the limited space available in wheel hubs, making them an excellent choice for electric vehicle applications.

Despite the increasing cost of rare-earth permanent magnets, axial flux IWMs maintain a strong position in the market due to their adaptable design topologies and high performance. Among the leading products, several manufacturers have introduced innovative solutions:

3.1 NTN IWM drive unit

This unit integrates an axial flux IWM with a reducer and sensor-based control system. It is designed with concentrated winding and an inner rotor, achieving a peak power of 20 kW and peak torque of 490 Nm, with a total mass of 25 kg. The NTN unit uses a mixed forced oil/air cooling system and water cooling for the inverter, achieving a maximum efficiency of 94.7%.

3.2 YASA IWM drive unit

Known for removing the stator yoke and using shorter concentrated windings, YASA motors offer a significant reduction in size and weight while maintaining high performance. The YASA 750R motor, for example, delivers 200 kW peak power and 700 Nm peak torque, utilizing an oil cooling system for high performance under demanding conditions.

3.3 MagnaX IWM drive unit

Featuring a compact and lightweight design, the MagnaX motors, such as the AXF275, achieve a peak power of 300 kW and peak torque of 500 Nm. The design incorporates a dual rotor configuration and yokeless stator, enhancing the torque-to-weight ratio and reducing material usage.

3.4 Phi-Power AG IWM drive unit

These motors are designed for high power and torque densities with minimal torque ripple. The Phi382 model offers a peak power of 400 kW and a peak torque of 1,280 Nm, with a liquid cooling system for easy maintenance and high efficiency.

3.5 Turntide IWM drive unit

Turntide motors are notable for their high efficiency (over 95%) and adaptability to supply voltages up to 850 VDC. The AF140 model, for example, provides a peak power of 220 kW and peak torque of 600 Nm, using advanced liquid cooling for consistent performance.

3.6 Emrax IWM drive unit

Emrax motors are lightweight and compact, offering high power density and efficiency. The Emrax348 model achieves 420 kW peak power and 1,000 Nm peak torque, with multiple cooling options to fit various applications.

3.7 Evolito IWM drive unit

Evolito's motors eliminate the yoke and incorporate a segmented magnet layout, reducing weight and enhancing performance. The D500 model delivers 350 kW peak power and 560 Nm peak torque, suitable for a wide range of EV applications.

3.8 Beyond Motors IWM drive unit

Beyond Motors' AXM4 model excels in power-to-weight and torque-to-weight ratios, offering 300 kW peak power and 950 Nm peak torque. The modular design allows for stacking motors to meet heavy-duty vehicle demands.

The continuous advancements in axial flux IWM technology promise to address the electrification challenges of the automotive industry, pushing the boundaries of EV performance and efficiency.

Nomenclature

ABS	Anti-lock braking system
ACAS	Advanced chassis assistance systems
ESC	Electronic stability control
EV	Electric vehicle
EWB	Electronic wedge brake
IWM	In-wheel-motor
OWM	Off-Wheel-Motor
PM	Permanent magnet
PMSM	Permanent magnet synchronous motor
SRM	Switched reluctance motor
TCS	Traction control system
TV	Torque vectoring

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