

Multiphase and Axial Flux Machine Topologies for Elevated Power Density

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ABSTRACT

The growing demand for compact and high-performance electric machines, particularly in electric vehicles (EVs) and aerospace applications, has stimulated research into multiphase and axial flux topologies. These machines offer elevated power density, enhanced fault tolerance, and reduced torque ripple compared to conventional three-phase radial flux machines. This paper reviews the latest advancements in multiphase and axial flux machine topologies, focusing on design principles, performance characteristics, and trade-offs. Comparative analysis using 2D illustrations and tabulated performance metrics demonstrates how these machines achieve higher torque density and efficiency. Challenges related to manufacturing, cooling, and control strategies are also discussed, along with emerging trends for next-generation high-power-density applications.

KEYWORDS: - *Multiphase machines, Axial flux motors, Power density, Electric vehicles, Torque density, High-performance electric machines*

INTRODUCTION

High-power-density electric machines are critical for modern EVs, hybrid systems, and aerospace applications. Conventional three-phase radial flux machines are limited by copper fill factor, cooling constraints, and torque density. To overcome these limitations, multiphase and axial flux topologies have emerged as promising alternatives.

Multiphase machines use more than three phases (typically 5, 6, or 9), providing increased fault tolerance, reduced phase current per conductor, and smoother torque profiles. Axial flux machines, by contrast, have a disc-shaped rotor-stator geometry with flux path parallel to the rotor shaft, offering short magnetic path lengths, high torque per unit volume, and low iron losses.

This paper explores the design, performance, and trade-offs of multiphase and axial flux machines for high-power-density applications.

MULTIPHASE MACHINE TOPOLOGIES

1. General Characteristics

- Typically 5–9 phases
- Lower per-phase current, reducing conductor and thermal losses
- Enhanced fault tolerance: machine can operate even with a phase open

2. Topology Variants

- Distributed winding multiphase machines
- Fractional-slot concentrated winding machines
- Open-end winding dual-inverter-fed multiphase systems

Figure 1: 5-Phase Stator Winding Layout

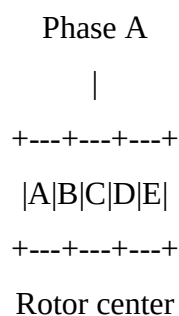


Table 1: Performance Comparison of 3-Phase vs 5-Phase Machines

Parameter	3-Phase	5-Phase
Torque Ripple (%)	12	5
Fault Tolerance	Low	High
Current per Phase (A)	50	30
Efficiency (%)	94	95.5

AXIAL FLUX MACHINE TOPOLOGIES

1. Key Features

- Rotor and stator discs with axial flux path
- High torque-to-weight ratio
- Reduced iron length → lower core losses
- Compact design ideal for EV hub motors

2. Variants

- Single-sided rotor (one rotor, one stator)
- Double-sided rotor (rotor–stator–rotor)
- Halbach array rotor magnets for improved flux density

Figure 2: Axial Flux Motor Cross-Section (Double Rotor)

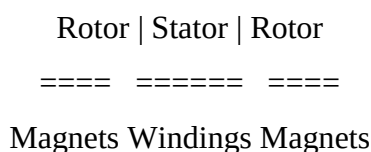


Table 2: Radial vs Axial Flux Motor Performance

Parameter	Radial Flux	Axial Flux
Torque Density (Nm/kg)	3.2	5.0
Power Density (kW/L)	2.5	4.1
Efficiency (%)	94	96
Stator Volume	Large	Compact

COMBINED MULTIPHASE AXIAL FLUX MACHINES

By integrating multiphase windings with axial flux topology, it is possible to maximize fault tolerance while achieving ultra-high torque density.

Figure 3: Conceptual Multiphase Axial Flux Machine

Rotor1 | Stator | Rotor2
 $\wedge \quad \wedge \quad \wedge$

A B C D E phases

- Advantages: reduced torque ripple, high reliability, high volumetric efficiency
- Challenges: end-turn management, complex cooling, and precise assembly

CONTROL STRATEGIES

Advanced modulation strategies for multiphase and axial flux machines include:

- Space Vector Modulation (SVM) for multiphase systems
- Decoupled control for dual-inverter-fed open-end windings
- Direct Torque Control (DTC) for axial flux motors to exploit high torque density
- Fault-tolerant control using redundant subspaces

Table 3: Modulation Techniques for Multiphase and Axial Flux Machines

Topology	Modulation Type	Benefit
Multiphase	SVM	Smooth torque, harmonic reduction
Axial Flux	DTC	High dynamic performance
Multiphase + Axial	Hybrid SVM + DTC	Fault tolerance + torque density

THERMAL AND MECHANICAL CONSIDERATIONS

- High power density increases heat flux → advanced cooling required
- Air or liquid cooling channels integrated in stator for axial flux motors
- Multipath flux in multiphase machines reduces localized heating

Figure 4: Stator Cooling Channel Layout (Axial Flux)

+-----+-----+
 | Liquid cooling channels embedded in stator disc
 +-----+-----+

Table 4: Thermal Performance of Axial Flux vs Radial Flux

Parameter	Radial Flux	Axial Flux
Max Temp (°C)	85	70
Continuous Power (kW)	100	135
Cooling Requirement	Moderate	Efficient with integrated channels

APPLICATIONS

- Electric vehicle hub motors
- Aerospace actuation and propulsion
- Renewable energy generators with compact footprint
- High-performance robotics and industrial drives

CHALLENGES

- Manufacturing complexity for axial flux and multiphase machines
- Cost of precision winding and rotor assembly
- Advanced cooling required for high power density
- Control strategy design and inverter compatibility

FUTURE TRENDS

- AI-based design optimization for multiphase axial flux machines
- Integration with wide-bandgap inverters for higher switching frequency
- Modular axial flux machines for scalable EV applications
- Additive manufacturing of stator and rotor structures for compact design

CONCLUSION

Multiphase and axial flux machine topologies present a pathway toward elevated power density, improved fault tolerance, and reduced torque ripple for modern EVs, aerospace, and industrial applications. Integration of multiphase windings with axial flux geometries can maximize efficiency, torque, and reliability. Advances in manufacturing, cooling, and control strategies are essential to fully exploit the potential of these high-performance machine topologies.

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