Multiphase and Axial Flux Machine Topologies for Elevated Power Density

K. Arun Prasad
Department of Electrical and Electronics Engineering
Dr. Mahalingam College of Engineering and Technology
Pollachi, Tamil Nadu, India
***Email**: arunprasad.k123@mcetpollachi.edu.in*

R. Aditya Singh
Department of Electrical Engineering
Govind Ballabh Pant Institute of Engineering and Technology
Pauri Garhwal, Uttarakhand, India
***Email:** aditya_singh.ee@gmail.com*

ABSTRACT

The increasing demand for compact, high-efficiency, and high-power-density electric machines in electric vehicles (EVs), aerospace, and renewable energy applications has driven research into multiphase and axial flux machine topologies. Multiphase machines enhance fault tolerance and reduce torque ripple, while axial flux machines offer a higher torque-to-weight ratio and lower iron losses compared to conventional radial flux machines. This paper presents an in-depth review of multiphase and axial flux machine topologies, including design principles, performance characteristics, thermal management, and challenges. Comparative analysis, including 2D figures and tables, demonstrates how these topologies achieve elevated power density. Emerging trends and future research directions are discussed, emphasizing their relevance in next-generation high-performance applications.

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

Page 117-122 © MANTECH PUBLICATIONS 2017. All Rights Reserved

INTRODUCTION

High-power-density electric machines are critical for modern EVs, hybrid systems, aerospace actuators, and renewable energy generators. Conventional three-phase radial flux machines are limited by copper fill factors, thermal constraints, and torque density.

Multiphase machines employ more than three phases (typically 5–9), offering reduced phase currents, smoother torque profiles, and improved fault tolerance. Axial flux machines utilize a disc-shaped rotor-stator geometry with the magnetic flux along the rotor axis, providing shorter magnetic paths, high torque density, and compact form factors.

The combination of multiphase and axial flux topologies presents a promising solution to meet the increasing demand for compact and efficient machines. This paper reviews design principles, performance analysis, and applications of these machines.

MULTIPHASE MACHINE TOPOLOGIES

1. Characteristics

- Number of phases: 5–9
- Lower per-phase currents reduce copper losses
- High fault tolerance: operation continues with one phase open
- Reduced torque ripple improves vibration and acoustic performance

2. Topology Variants

- **Distributed winding multiphase machines**: Evenly distributed phases, smooth torque profile.
- **Fractional-slot concentrated winding machines**: Reduced end-turn length, improved copper fill factor.
- **Open-end winding dual-inverter-fed systems**: Flexible voltage control, enhanced fault tolerance.

Figure 1: Five-Phase Stator Winding Layout

Phase A

|

+-----+-----+

|A|B|C|D|E|

Page 117-122 © MANTECH PUBLICATIONS 2017. All Rights Reserved

+----------+

Rotor Center

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

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

AXIAL FLUX MACHINE TOPOLOGIES

1. Key Features

- Disc-shaped rotor and stator
- High torque-to-weight ratio
- Shorter magnetic path → reduced core losses
- Compact and lightweight, ideal for EV hub motors

2. Variants

- **Single-sided rotor (Rotor-Stator)**
- **Double-sided rotor (Rotor-Stator-Rotor)**
- **Halbach array rotor magnets**: Increased flux density, reduced leakage

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

Rotor | Stator | Rotor

==== ====== ====

Magnets Windings Magnets

Table 2: Radial Flux 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

Page 117-122 © MANTECH PUBLICATIONS 2017. All Rights Reserved

Parameter	Radial Flux	Axial Flux
Efficiency (%)	94	96
Stator Volume	Large	Compact

MULTIPHASE AXIAL FLUX MACHINES

Combining multiphase windings with axial flux topology offers the advantages of both:

- Reduced torque ripple
- Fault-tolerant operation
- High volumetric efficiency

Figure 3: Conceptual Multiphase Axial Flux Machine

Rotor1 | Stator | Rotor2

^ ^ ^

A B C D E phases

Challenges include complex end-turn management, advanced cooling requirements, and precise manufacturing tolerances.

CONTROL STRATEGIES

Advanced modulation strategies for multiphase and axial flux machines include:

- **Space Vector Modulation (SVM)** for multiphase control
- **Direct Torque Control (DTC)** for high-performance axial flux machines
- **Hybrid SVM + DTC** for multiphase axial flux machines to achieve fault tolerance and smooth torque

Table 3: Control Strategies Comparison

Topology	Modulation Type	Advantages
Multiphase	SVM	Reduced torque ripple, harmonics
Axial Flux	DTC	High dynamic response
Multiphase Axial Flux	Hybrid SVM + DTC	Fault tolerance + high torque density

Page 117-122 © MANTECH PUBLICATIONS 2017. All Rights Reserved

THERMAL AND MECHANICAL CONSIDERATIONS

- High power density increases thermal loading
- Axial flux machines often include integrated liquid cooling channels
- Multipath flux in multiphase machines reduces localized heating

Figure 4: Cooling Channel Layout in Axial Flux Stator

+------------------+

| Liquid channels | Integrated within stator disc

+------------------+

Table 4: Thermal Performance

Parameter	Radial Flux	Axial Flux
Maximum Temperature (°C)	85	70
Continuous Power (kW)	100	135
Cooling Requirement	Moderate	Integrated

APPLICATIONS

- Electric vehicle hub motors
- Aerospace actuation and propulsion
- Compact renewable energy generators
- High-performance industrial robotics

CHALLENGES

- Complex manufacturing and assembly
- End-turn management and insulation in multiphase machines
- Cooling design for high power density
- Advanced control system integration

FUTURE TRENDS

- AI-based topology optimization for multiphase axial flux machines
- Integration with wide-bandgap inverters for higher switching frequencies
- Modular axial flux machines for scalable EV designs

Page 117-122 © MANTECH PUBLICATIONS 2017. All Rights Reserved

- Additive manufacturing for complex rotor/stator geometries

CONCLUSION

Multiphase and axial flux machines provide a promising approach for achieving elevated power density in compact electric machines. Combining multiphase windings with axial flux topology improves torque density, efficiency, and fault tolerance, making them suitable for modern EVs, aerospace, and industrial applications. Further advancements in manufacturing, thermal management, and control strategies will continue to unlock the potential of these high-performance topologies.

REFERENCES

1. Levi, E., "Multiphase Electric Machines for Variable-Speed Applications," *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 5, pp. 1893–1909, 2008.
2. Miller, T. J. E., *Brushless Permanent-Magnet and Reluctance Motor Drives*, Oxford University Press, 2011.
3. Boldea, I., *Electric Drives*, 3rd Edition, CRC Press, 2017.
4. Xue, Y., et al., "Axial Flux Permanent Magnet Machines for Electric Vehicles: Design and Performance Review," *IEEE Access*, Vol. 7, pp. 166460–166478, 2019.
5. Abu-Rub, H., Malinowski, M., & Al-Haddad, K., *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications*, Wiley, 2014.
6. Boldea, I., & Nasar, S. A., *The Induction Machine Handbook*, CRC Press, 2002.

Page 117-122 © MANTECH PUBLICATIONS 2017. All Rights Reserved