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Topology Optimization and Additive Manufacturing for High-Efficiency Machines

V. Harikrishnan
Department of Electrical and Electronics Engineering
Government College of Engineering, Salem
Salem, Tamil Nadu, India
Email: *harikrishnan.v.eee@gcesalem.edu.in*

A. Rishabh Singh
Department of Electrical Engineering
Baba Saheb Ambedkar College of Engineering
Agra, Uttar Pradesh, India
Email: *rishabh.singh.ee@gmail.com*

ABSTRACT

The demand for high-efficiency and high-performance electrical machines has motivated the integration of advanced design and manufacturing techniques. Topology optimization enables the systematic design of machine cores and magnetic structures to minimize losses, reduce weight, and improve flux distribution. Additive manufacturing (AM), particularly 3D printing, allows realization of complex geometries that were previously unachievable through conventional manufacturing methods. This paper presents a comprehensive review of topology optimization and additive manufacturing applications in electrical machines, focusing on high-efficiency motors and generators. Various case studies, including optimization of stator and rotor structures and the realization of intricate cooling channels, are discussed. Comparative tables and 2D illustrations are provided to highlight performance improvements, demonstrating the potential of these technologies to revolutionize machine design.

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KEYWORDS: *- Topology optimization, Additive manufacturing, High-efficiency machines, Electrical machine design, 3D printing, Motor cores*

INTRODUCTION

High-efficiency electrical machines are critical for applications ranging from electric vehicles to renewable energy systems. Traditional design methodologies rely heavily on iterative prototyping and simplified geometries, often resulting in suboptimal efficiency and weight. Topology optimization offers a computational approach to distribute material optimally within a given design space, considering constraints such as flux density, thermal limits, and structural stiffness.

Additive manufacturing (AM) complements topology optimization by enabling the fabrication of complex geometries, including internal cooling channels, lightweight rotor and stator structures, and intricate laminations. The combination of these techniques allows the realization of high-efficiency machines that are lighter, more compact, and thermally superior compared to conventionally manufactured counterparts.

TOPOLOGY OPTIMIZATION IN ELECTRICAL MACHINES

Topology optimization uses numerical methods, such as the finite element method (FEM), to optimize material distribution. In electrical machines, this is primarily applied to:

- Stator core laminations
- Rotor cores and poles
- Flux barriers and magnetic paths

1. Optimization Objectives

- Minimize iron and copper losses
- Maximize torque-to-weight ratio
- Improve thermal dissipation
- Reduce cogging torque

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Figure 1: Example of Stator Topology Optimization

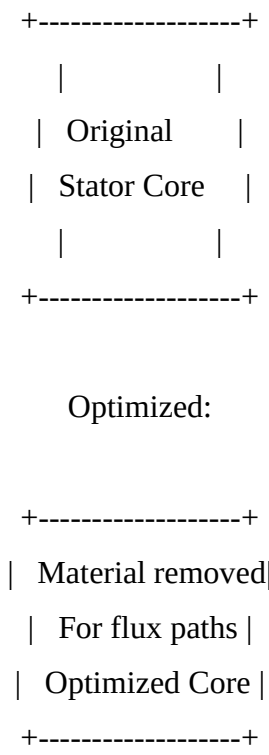


Table 1: Performance Comparison (Stator Core Design)

Parameter	**Conventional Stator**	**Optimized Stator**
Copper Loss (W)	120	105
Iron Loss (W)	90	72
Torque Density (Nm/kg)	3.5	4.2
Efficiency (%)	94.2	96.1

ADDITIVE MANUFACTURING FOR HIGH-EFFICIENCY MACHINES

Additive manufacturing enables the realization of complex geometries dictated by topology optimization and novel thermal management schemes.

1. Applications in Electrical Machines

- Complex cooling channels within rotor/stator
- Lightweight rotors with flux barriers
- Geometrically optimized end-turns
- Integration of multi-material structures for insulation and conductivity

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Figure 2: Example of 3D-Printed Rotor with Cooling Channels

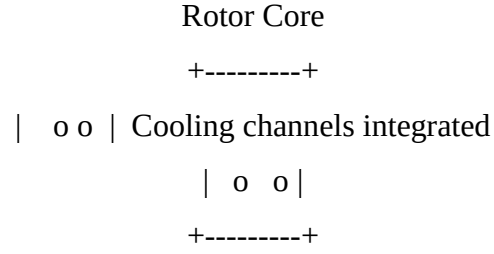


Table 2: Thermal Improvement with Additive Manufacturing

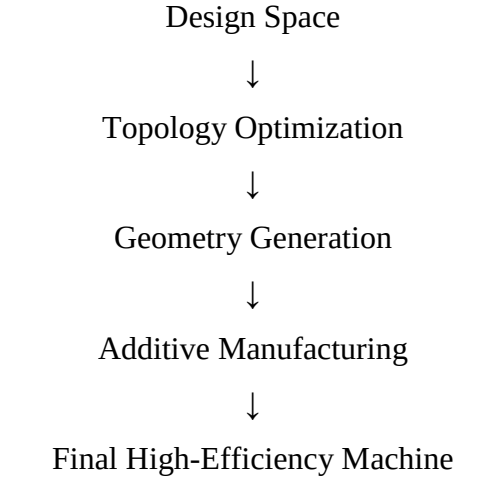
Design	Cooling Approach	Max Temperature (°C)	Efficiency (%)
Conventional	External fins	92	94.5
AM Optimized	Integrated channels	78	96.3

INTEGRATED DESIGN: TOPOLOGY OPTIMIZATION + AM

By combining topology optimization with additive manufacturing:

1. Material is removed from low flux density areas while maintaining structural integrity.
2. Complex geometries for cooling and flux barriers can be fabricated.
3. Machines achieve higher torque density, lower losses, and better thermal performance.

Figure 3: Integrated Design Workflow



CASE STUDIES

1. High-Efficiency PMSM for EV Application

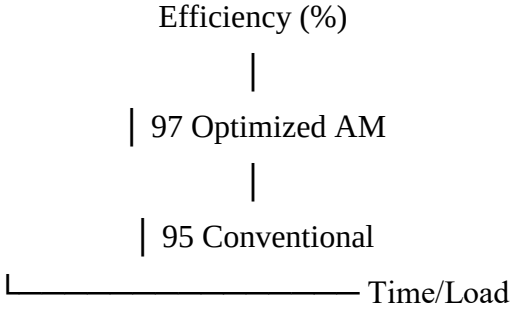
- Stator and rotor optimized for reduced iron and copper losses

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- AM employed to fabricate intricate rotor cooling channels
- Results:

Metric	Conventional PMSM	Optimized + AM
Torque (Nm)	150	165
Efficiency (%)	95	97
Weight (kg)	45	38
Temperature Rise (°C)	80	66

Figure 4: Efficiency Improvement with Optimized AM Motor



CHALLENGES

- Material properties of 3D-printed cores can differ from laminated steel
- Eddy current and saturation effects must be carefully analyzed
- Scaling to high-volume manufacturing
- Surface finish and insulation integration for stator windings

FUTURE TRENDS

- Multi-material additive manufacturing combining conductive and magnetic materials
- Integration with AI-driven topology optimization
- Lightweight machine designs for aerospace EV applications
- Hybrid metal and polymer structures for enhanced thermal and mechanical performance

CONCLUSION

Topology optimization combined with additive manufacturing presents a transformative approach to designing high-efficiency electrical machines. By enabling complex geometries, enhanced thermal management, and reduced losses, these technologies can significantly

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improve torque density and overall machine performance. Adoption of these methods in EVs, renewable energy, and industrial drives promises higher efficiency, lighter machines, and innovative designs that conventional methods cannot achieve.

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