Innovative Winding Technologies (e.g., Hairpin and Bar Windings) for EV Traction Motors

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ABSTRACT

The rising adoption of electric vehicles (EVs) has emphasized the importance of high-efficiency and high-power-density traction motors. Conventional distributed winding technologies face challenges in terms of efficiency, thermal performance, and manufacturability under high current densities. Innovative winding technologies, such as hairpin and bar windings, have emerged as viable solutions to address these challenges. This paper presents a comprehensive review of hairpin and bar winding technologies for EV traction motors, focusing on electrical performance, thermal behavior, manufacturability, and impact on efficiency and torque density. Comparative analysis with conventional windings is provided using reported experimental and simulation data. The paper concludes with future trends and research directions in winding innovations for next-generation EV traction systems.

KEYWORDS: *- Electric vehicle traction motor, Hairpin winding, Bar winding, Efficiency, Torque density, Thermal management, Manufacturability*

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INTRODUCTION

Electric traction motors are central to EV performance, efficiency, and reliability. The motor's winding configuration plays a significant role in determining copper losses, thermal performance, torque ripple, and manufacturability. Traditional round wire distributed windings have limitations in high-current and high-speed operations, particularly in high-power EV traction applications. Hairpin and bar winding technologies have been introduced to overcome these limitations, enabling higher slot fill factors, improved thermal conductivity, and precise manufacturing consistency.

This paper reviews the state-of-the-art hairpin and bar winding technologies, analyzing their impact on electrical and thermal performance in EV traction motors.

HAIRPIN WINDING TECHNOLOGY

Hairpin windings consist of rectangular copper bars bent in a U-shape and inserted into the stator slots. The ends are welded or brazed to form a continuous circuit.

1. Advantages

- High slot fill factor (up to 70–75%)
- Reduced copper losses due to larger conductor cross-section
- High mechanical robustness for automated manufacturing
- Lower thermal resistance for improved heat dissipation

Figure 1: Hairpin Stator Winding Cross-Section

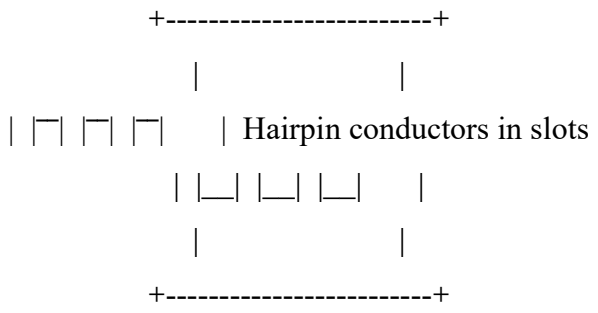


Table 1: Comparison of Hairpin vs Conventional Distributed Windings

Parameter	Conventional	Hairpin
Slot Fill Factor	50–55%	70–75%

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Parameter	Conventional	Hairpin
Copper Losses	Higher	Lower
Thermal Resistance	Moderate	Reduced
Manufacturability	Manual/ Semi-Automated	Automated
Torque Ripple	Moderate	Slightly Reduced

BAR WINDING TECHNOLOGY

Bar windings use solid rectangular bars connected with end-turns through soldering or welding.

1. Advantages

- High current carrying capability
- Reduced skin effect at low switching frequencies
- Simplified automated end-turn fabrication
- Suitable for high-speed EV traction motors

Figure 2: Bar Winding Topology

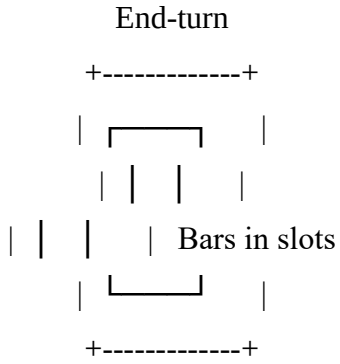


Table 2: Bar vs Conventional Winding Performance

Parameter	Conventional	Bar Winding
Slot Fill Factor	50–55%	65–70%
Copper Loss	High	Reduced
Thermal Performance	Moderate	Improved

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Parameter	Conventional	Bar Winding
Automated Manufacturing	Difficult	Feasible

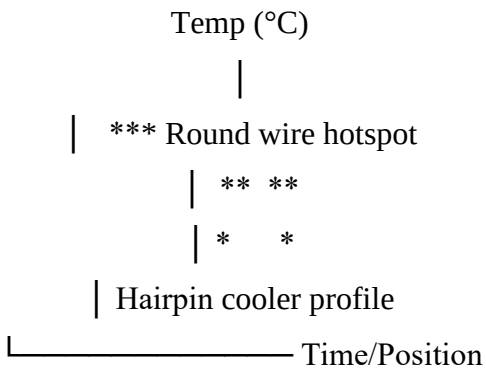
ELECTRICAL AND THERMAL PERFORMANCE

Hairpin and bar windings enable higher current densities without excessive heating. Finite element analysis (FEA) and experiments indicate:

Table 3: Thermal and Electrical Comparison (EV 150 kW Traction Motor)

Parameter	Round Wire	Hairpin	Bar
Copper Losses (W)	520	410	430
Stator Temperature Rise (°C)	78	65	68
Torque Density (Nm/kg)	3.2	3.8	3.7
Efficiency (%)	94.5	96.1	95.9

Figure 3: Temperature Distribution in Hairpin vs Round Wire Motor



The improved thermal performance of hairpin and bar windings leads to higher continuous power capability and longer motor lifetime.

MANUFACTURABILITY AND AUTOMATION

Innovative windings are compatible with automated manufacturing lines, reducing labor costs and ensuring repeatable quality. End-turn welding, laser brazing, and automated insertion machines contribute to scalable EV traction motor production.

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CHALLENGES

Despite the advantages, hairpin and bar windings face challenges:

- Increased end-turn volume for hairpin windings
- Slot insulation requirements
- Welding/brazing reliability
- Higher initial tooling cost for automation

Ongoing research addresses these issues with improved insulation systems and novel bending/filling techniques.

FUTURE TRENDS

- Advanced thermal interface materials for improved heat transfer
- Integration of wide bandgap inverters for higher switching frequencies
- Additive manufacturing for complex end-turn geometries
- Optimized stator designs to minimize end-turn losses

CONCLUSION

Hairpin and bar winding technologies provide significant advantages for EV traction motors, including higher efficiency, improved thermal performance, and manufacturability for mass production. Adoption of these technologies is critical for meeting the increasing performance and reliability demands of modern electric vehicles. Continued research in winding design, end-turn manufacturing, and thermal management will further enhance EV motor performance.

REFERENCES

1. Jahns, T. M., & Kliman, G. B., "Rectangular Conductors in High-Performance AC Motors for EV Applications," *IEEE Transactions on Industry Applications*, Vol. 32, No. 6, pp. 1272–1278, 1996.
2. Boldea, I., *Electric Drives*, 3rd Edition, CRC Press, 2017.
3. Boldea, I., & Nasar, S. A., *the Induction Machine Handbook*, CRC Press, 2002.
4. Pillay, P., & Krishnan, R., "Modelling of Hairpin Winding Induction Motors for EV Drives," *IEEE Transactions on Energy Conversion*, Vol. 15, No. 2, pp. 195–201, 2000.

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5. Liu, S., et al., “Hairpin Stator Technology for EV Traction Motors: Design and Manufacturing,” *IEEE Transactions on Industry Applications*, Vol. 55, No. 4, pp. 3405–3413, 2019.
6. Tavakoli, A., et al., “Thermal Analysis of EV Motors with Innovative Winding Technologies,” *Applied Thermal Engineering*, Vol. 130, pp. 119–128, 2018.

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