

Recent Advances and Applications of Ferrite Materials in Electric Vehicle

Power Electronics and Energy Systems: A Review

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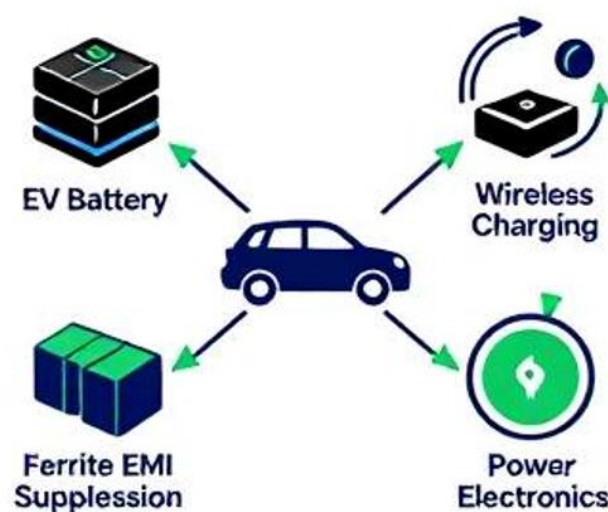
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Abstract

The global transition toward sustainable transportation depends heavily on the advancement of electric vehicles (EVs), which require efficient energy conversion, storage, and management systems. Ferrites, a class of ceramic magnetic materials, play a crucial yet often overlooked role in enabling modern EV technologies. This review examines the significant contributions of ferrites to the electric vehicle industry, with particular emphasis on their applications in power electronics, electromagnetic interference (EMI) suppression, electric motors, charging systems, and advanced battery technologies. Recent studies published since 2020 are analyzed to highlight material innovations, improved magnetic performance, thermal stability, reduced energy losses, and enhanced operational efficiency achieved through ferrite-based components. Emerging trends in nanostructured ferrites, soft magnetic composites, and high-frequency applications are also discussed. The review demonstrates that ferrites are essential for improving the reliability, efficiency, durability, and sustainability of EV technologies, thereby supporting the future development of clean, intelligent, and energy-efficient transportation systems worldwide in both industrialized and developing countries.

Graphical Abstract



1. Introduction

The transportation sector is undergoing a paradigm shift, driven by the urgent need to reduce greenhouse gas emissions and combat climate change. Electric vehicles (EVs) stand at the forefront of this revolution, promising a cleaner and more sustainable alternative to internal combustion engine vehicles. The core of an EV lies in its sophisticated electrical systems, which demand high efficiency, reliability, and compact design.

Key components such as electric motors, on-board chargers, DC-DC converters, and battery management systems (BMS) are central to EV performance and energy efficiency. The materials used in these components are paramount to achieving these goals. Among these, magnetic materials, particularly ferrites, have emerged as indispensable enablers due to their unique electromagnetic properties. This review focuses on the critical role of ferrites in advancing EV technology, examining their applications and the recent progress made in optimizing their performance for the demanding automotive environment.

2. The Crucial Role of Ferrites in EV Energy Systems

Ferrites are transition metal oxides with a specific crystal structure that imparts remarkable magnetic properties, including high magnetic permeability, high electrical resistivity, and low core losses at high frequencies. These characteristics make them ideally suited for a wide range of applications within EVs, primarily in power electronics and electromagnetic compatibility (EMC).

2.1. Power Electronics: The Heartbeat of EV Efficiency

Power electronic converters are essential for efficiently managing the flow of electrical energy within an EV. They are responsible for converting and regulating voltages from the battery pack to the motor, the onboard charger, and auxiliary systems. The magnetic components within these converters, such as inductors and transformers, are critical for their functionality and efficiency.

Inductors and Transformers in On-Board Chargers (OBCs): On-board chargers facilitate the charging of the EV battery from AC power sources. High-frequency transformers and inductors are core components of these chargers, enabling efficient power conversion. Ferrites, with their high permeability and low loss at high frequencies (typically >100 kHz), allow for smaller, lighter, and more efficient magnetic components. This miniaturization is crucial for integrating OBCs into the increasingly space-constrained designs of EVs. Recent advancements have focused on developing ferrite materials with even lower losses and higher saturation magnetic flux density to enable higher power densities and charging speeds [1].

DC-DC Converters: EVs utilize multiple DC voltage levels. High-voltage battery packs (e.g., $400V$ or $800V$) need to be stepped down to lower voltages (e.g., $12V$ or $48V$) for powering auxiliary systems like lighting, infotainment, and power steering. High-frequency DC-DC converters, often employing ferrite cores, are essential for this voltage conversion. The efficiency of these converters directly impacts the overall energy economy of the vehicle. Research since 2020 has emphasized the development of advanced ferrite compositions and core geometries to minimize eddy current losses and hysteresis losses, thereby boosting converter efficiency and thermal performance [2].

Electric Motor Drives: The electric motor is the powertrain of an EV. While the primary magnetic fields are generated by permanent magnets or windings, magnetic components within the motor drive electronics (inverters) also rely on ferrite materials for filtering and energy storage, contributing to the overall efficiency and smooth operation of the motor.

2.2. Electromagnetic Interference (EMI) Suppression

Modern EVs are complex systems with numerous electronic components operating at high frequencies. This can lead to electromagnetic interference (EMI), which can disrupt the functionality of sensitive electronic circuits and potentially pose safety risks. Ferrite beads and cores are widely used as passive EMI filters. They are clamped around cables carrying high-frequency signals, effectively absorbing and dissipating unwanted electromagnetic noise. The high resistivity of ferrites minimizes eddy current losses at high frequencies, making them highly effective in suppressing conducted EMI. Research continues to explore new ferrite formulations that offer broader frequency range suppression and higher attenuation capabilities, crucial for meeting stringent automotive EMC standards [3].

2.3. Battery Management Systems (BMS)

While ferrites are not directly part of the battery cells, they play a role in the sophisticated Battery Management Systems (BMS) that monitor and control battery pack performance. Ferrite components can be found in current sensors and communication circuits within the BMS, ensuring accurate data acquisition and reliable operation of the battery pack, which is critical for safety, longevity, and optimal performance of the EV.

2.4. Ferrite Compositions, Crystal Structures, and Magnetic Characteristics

Ferrites are ferrimagnetic ceramic materials generally represented by the formula MFe_2O_4 , where M denotes a divalent metal ion such as Mn, Ni, Zn, Co, or Mg. Depending on their crystal structure, ferrites are commonly classified into spinel ferrites and hexagonal ferrites. In electric vehicle applications, spinel ferrites are by far the most widely utilized owing to their excellent soft magnetic properties, high electrical resistivity, and low power losses at high frequencies.

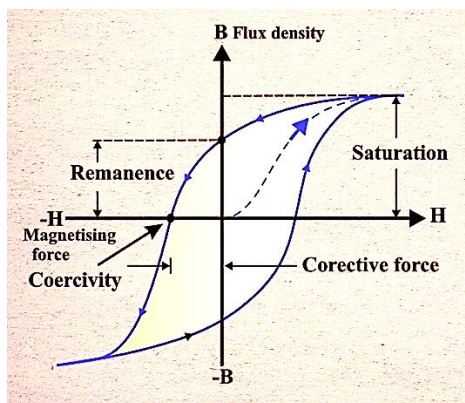


Fig. 1. Hysteresis loop of the ferrimagnetic materials.

Among the commercially available ferrites, manganese-zinc (MnZn) ferrites and nickel-zinc (NiZn) ferrites are the dominant materials employed in EV power electronic systems. MnZn ferrites exhibit high magnetic permeability and relatively high saturation flux density, making them suitable for transformers and inductors used in on-board chargers and DC–DC converters. In contrast, Ni-Zn ferrites possess significantly higher electrical resistivity, which minimizes eddy-current losses at high frequencies and makes them ideal for EMI suppression components and high-frequency filtering applications.

Table 1. Primary applications of Ferrites in electric vehicle architectures.

Ferrite	Key EV applications
MnZn Ferrites	Power inductors, transformers, and common mode chokes
NiZn Ferrites	EMI suppression, high-frequency components
Hexaferrites	Antenna materials, microwave components, and specialized shielding

The magnetic performance of ferrites is commonly evaluated through their hysteresis loop. Soft ferrites exhibit narrow hysteresis loops characterized by low coercivity and low hysteresis losses. Consequently, less energy is dissipated during repeated magnetization cycles, resulting in improved efficiency for high-frequency power conversion systems. The area enclosed by the hysteresis loop is directly proportional to the magnetic energy loss per cycle. Therefore, minimizing hysteresis losses remains a primary objective in ferrite material development for EV applications.

The selection of magnetic materials is critical for optimizing the performance of electric vehicle (EV) power electronics. As illustrated in **Table 1**, ferrites are categorized into three primary groups based on their composition: Mn-Zn, Ni-Zn, and Hexaferrites. Each type serves a distinct role within the EV architecture. While MnZn ferrites are indispensable for high-power applications such as transformers and common mode chokes, NiZn ferrites are preferred for high-frequency tasks, particularly in EMI suppression. Additionally, Hexaferrites offer unique properties for specialized microwave and antenna-related components.

Recent studies have focused on optimizing grain size, dopant concentration, and sintering conditions to reduce coercivity while maintaining adequate saturation magnetization. Such improvements contribute directly to higher converter efficiencies, lower thermal generation, and increased reliability in electric vehicle power electronics.

2.5. Comparison of Ferrites with Alternative Magnetic Materials

Various magnetic materials are employed in electric vehicle systems, including ferrites, silicon steel, amorphous alloys, nanocrystalline alloys, and powdered iron cores. However, ferrites possess several advantages that make them particularly attractive for high-frequency applications. **Table 2** presents a qualitative comparison of ferrites with other magnetic materials commonly employed in electric vehicle applications, including silicon steel, amorphous alloys, and nanocrystalline materials. As shown, ferrites exhibit significantly higher electrical resistivity, resulting in substantially lower eddy-current losses during high-frequency operation. This characteristic makes them particularly attractive for onboard chargers, DC–DC converters, EMI filters, and other high-frequency power electronic devices. While nanocrystalline materials generally offer higher saturation flux density and superior magnetic performance under certain operating conditions, their higher cost and more complex manufacturing processes may limit widespread adoption. Silicon steel remains highly effective in low-frequency applications such as traction motors but suffers from increased losses at elevated switching frequencies. Consequently, ferrites provide a favorable balance between cost, efficiency, electromagnetic compatibility, and manufacturability, making them one of the most widely utilized magnetic materials in modern electric vehicle systems. The comparison further highlights that the selection of magnetic materials in EV systems is application-dependent; however, ferrites remain the preferred choice whenever high-frequency operation, EMI mitigation, and compact component design are the primary design objectives [4–9].

Table 2. Comparison of Magnetic Materials Used in EVs.

Property	Ferrite	Silicon Steel	Amorphous Alloy	Nanocrystalline
Resistivity	Very High	Low	Medium	Medium
High-Frequency Performance	Excellent	Poor	Good	Excellent
EMI Suppression	Excellent	Poor	Moderate	Moderate
Cost	Low	Low	High	Very High
EV Electronics	Excellent	Limited	Good	Excellent

First, ferrites exhibit electrical resistivities several orders of magnitude greater than metallic magnetic materials. This significantly reduces eddy-current losses during high-frequency operation. Second, ferrites offer excellent electromagnetic interference suppression capabilities, which are essential in modern EV architectures containing numerous electronic subsystems. Third, ferrites are relatively inexpensive and can be manufactured in complex geometries using established ceramic-processing technologies.

Although nanocrystalline alloys may provide higher saturation flux density, they are generally more expensive and require more complex manufacturing procedures. Silicon steel remains highly suitable for low-frequency traction motors but becomes less efficient at the switching frequencies commonly used in modern power converters. Consequently, ferrites continue to dominate applications such as onboard chargers, DC–DC converters, EMI filters, communication modules, and battery management electronics.

2.6. Major Electric Vehicle Devices Utilizing Ferrite Components

Ferrite materials are employed throughout modern electric vehicles in a wide variety of devices and subsystems:

- On-board chargers (OBCs): High-frequency transformers and inductors.
- DC–DC converters: Energy-storage inductors and isolation transformers.
- Traction inverter systems: Output filters and electromagnetic compatibility components.
- Battery management systems (BMS): Current sensors and communication circuits.
- Electromagnetic interference (EMI) filters: Ferrite beads, sleeves, and common-mode chokes.
- Wireless charging systems: Magnetic flux guidance and shielding structures.
- Vehicle communication modules: Noise suppression and signal integrity enhancement.

The widespread integration of ferrite components highlights their critical role in improving energy efficiency, reliability, electromagnetic compatibility, and charging performance in next-generation electric vehicles.

As illustrated in **Fig. 2**, the integration of advanced power electronics is fundamental to the efficiency and reliability of modern Electric Vehicles (EVs). Ferrite materials play a pivotal role in this architecture due to their excellent high-frequency magnetic properties. Specifically, ferrites are utilized in critical subsystems to manage electromagnetic interference (EMI) through suppression beads and common mode chokes, ensuring signal integrity in sensitive control units. Furthermore, the high permeability and low core loss of ferrites make them indispensable for high-frequency transformers and inductors within the onboard charging systems and DC-DC converters, which are essential for efficient power management between the high-voltage battery and the vehicle's auxiliary systems.

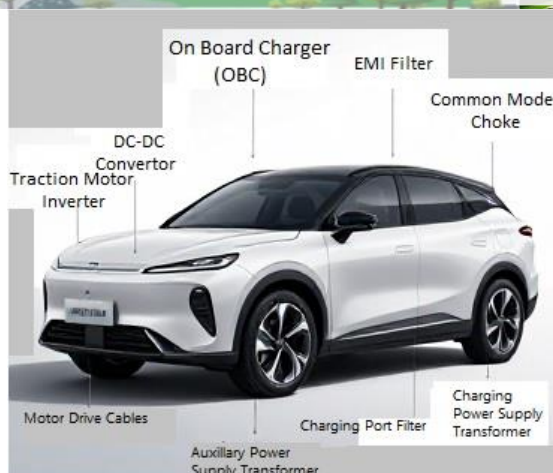


Fig. 2. Schematic illustration of a modern Electric Vehicle (EV) architecture highlighting the strategic integration points of ferrite-based components, including EMI suppression beads, transformers, inductors, and common-mode chokes.

3. Advanced Ferrite Materials and Innovations

The demanding requirements of the EV industry have spurred significant innovation in ferrite materials and manufacturing. Key areas of development include:

3.1. Soft Ferrites for High-Frequency Applications

Soft ferrites, such as Manganese-Zinc (MnZn) and Nickel-Zinc (NiZn) ferrites, are particularly important due to their high permeability and low core losses at high frequencies.

MnZn Ferrites: These offer very high permeability and low losses at lower frequencies (up to a few MHz), making them suitable for OBC transformers and inductors. Recent work has focused on improving their thermal stability and reducing hysteresis losses at higher operating temperatures found in automotive environments [10]. Nanocrystalline MnZn ferrites have shown promise in achieving higher energy densities in power converters.

NiZn Ferrites: These ferrites possess higher resistivity and lower eddy current losses at higher frequencies (tens of MHz), making them excellent candidates for high-frequency EMI suppression and high-frequency converters. Research has explored doping strategies and novel sintering techniques to enhance their magnetic properties and thermal conductivity [11].

3.2. Novel Processing and Manufacturing Techniques

Advanced manufacturing techniques are crucial for producing high-performance ferrite components.

Nano-structuring: The synthesis of ferrite nanoparticles and their assembly into bulk materials allows for controlled microstructure and enhanced magnetic properties. Nanocrystalline ferrites exhibit higher saturation magnetization and reduced coercivity, leading to lower power losses [12].

Additive Manufacturing (3D Printing): The ability to 3D print complex ferrite geometries offers unprecedented design freedom for magnetic components. This enables the creation of optimized shapes that improve thermal management, reduce size, and enhance performance, tailored specifically for EV applications [13].

3.3. Material Characterization and Performance Enhancement

Accurate characterization of ferrite properties under relevant operating conditions is essential. Researchers are employing advanced techniques to:

Analyze core losses: Understanding the contributions of hysteresis, eddy current, and residual losses is key to designing more efficient components [14].

Evaluate thermal management: High power densities in EV systems generate significant heat. Ferrite materials with improved thermal conductivity and stability are being developed to prevent overheating and ensure reliability [15].

Investigate high-temperature performance: Automotive components operate under wide temperature ranges. Ferrite formulations that maintain their magnetic properties at elevated temperatures are critical for robust EV systems [16].

4. Challenges and Future Outlook

Despite their crucial role, several challenges remain for the widespread adoption and optimization of ferrites in EVs:

Thermal Management: High power densities in EV systems generate significant heat, which can degrade ferrite performance and reliability. Developing ferrites with better thermal conductivity and stability at high temperatures is an ongoing challenge.

Brittleness: As ceramic materials, ferrites are inherently brittle, making them susceptible to mechanical shock and vibration, common in automotive environments. Research into composite materials or improved manufacturing to enhance mechanical robustness is needed.

Material Scarcity and Environmental Impact: Some ferrite compositions rely on rare earth elements or metals with supply chain concerns. Developing sustainable and readily available ferrite materials is an important future direction.

Integration and Miniaturization: Continued demand for smaller, lighter, and more powerful EV systems requires further advancements in ferrite materials and component design to achieve higher power densities.

The future outlook for ferrites in EVs remains exceptionally bright. As battery technologies improve, charging infrastructure expands, and vehicle electrification accelerates, the demand for efficient and reliable magnetic components will only grow. Continued research into novel ferrite compositions, advanced manufacturing techniques like additive manufacturing, and integrated material-system design will be essential to unlock the full potential of ferrites in powering the next generation of electric vehicles.

5. Conclusion

Ferrites are foundational materials that underpin the efficiency, reliability, and performance of electric vehicles. From enabling high-speed charging and efficient power conversion to ensuring electromagnetic compatibility, their unique magnetic properties are indispensable. The ongoing innovations in ferrite materials science and manufacturing, particularly those emerging from 2020 onwards, are paving the way for even more compact, efficient, and robust EV systems. As the automotive industry continues its rapid electrification, the role of ferrites will undoubtedly expand, solidifying their status as the unsung heroes powering the electric vehicle revolution.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data is used in this article.

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