Investigation of Grounding Architectures and Protective Mechanisms in High-Voltage Electric Transportation Platforms

Yunus Emre Ekici[1*], Nisanur Yıldıran[2], Ozan Akdağ[3] and Teoman Karadağ[2,4]

[1]Department of Electric Vehicle Technologies, OIZ Vocational College, Inonu University, Malatya, Türkiye
[2]Department of Electrical Electronics Engineering, Inonu University, Malatya, Türkiye
[3]Department of Computer Engineering, Malatya Turgut Ozal University, Malatya, Türkiye
[4]Department of Electrical Electronics Engineering, Istinye University, İstanbul, Türkiye,
emre.ekici@inonu.edu.tr

Abstract. The rapid expansion of electric propulsion systems across road, air, and marine transportation platforms has become a key component of the global transition toward sustainable mobility. This evolution introduces new engineering challenges in ensuring the safety, efficiency, and electromagnetic compatibility (EMC) of high-voltage systems. Grounding and bonding configurations represent fundamental elements in achieving these goals, serving multiple purposes beyond electrical protection. An effective grounding system not only safeguards users against electrical hazards but also facilitates fault current management, protects power electronic components, suppresses electromagnetic interference, and mitigates galvanic corrosion. This paper presents a comprehensive review of grounding methodologies and protective measures employed in various classes of electric vehicles, including passenger and commercial road vehicles, trolleybus-based public transport systems, hybrid and fully electric aircraft, and marine vessels. Furthermore, applications in HVDC fast-charging infrastructure, ship-to-shore power transfer systems, and bonding strategies for composite-bodied aircraft are examined in detail. Relevant international standards such as IEEE Std. 142, IEEE Std. 80, and IEC/IEEE 80005-1 are critically analyzed to evaluate the performance, safety, and EMC implications of grounding structures. Finally, future directions are proposed, emphasizing the integration of smart insulation monitoring, adaptive bonding architectures, and unified standardization frameworks aimed at improving reliability, interoperability, and energy efficiency in next-generation electrified transportation systems.

Keywords: Electric Vehicles, Grounding Systems, High Voltage Systems, Protective Measures.

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1 Introduction

The global transition toward electric mobility is fundamentally transforming modern transportation systems. This shift is primarily motivated by climate change mitigation, fossil fuel depletion, and the pursuit of cleaner urban air. Recent projections by the International Energy Agency (IEA) anticipate that the global electric vehicle (EV) fleet will surpass 200 million units by 2030, highlighting a rapid evolution in both energy demand and infrastructure. However, such growth introduces complex safety, reliability, and electrical design challenges, particularly in high-voltage (HV) systems integral to EV powertrains [1].

Traction batteries in contemporary EVs commonly operate between 400–800 V DC, while heavy-duty models may exceed 1000 V. These voltage levels amplify risks of electric shock, electromagnetic interference (EMI), leakage currents, and thermal incidents. Conventional grounding approaches—such as TT, TN-S, and IT configurations—developed for stationary power systems are not directly applicable to mobile vehicular environments. Instead, automotive applications require modified grounding and bonding architectures compatible with dynamic operation, lightweight chassis materials, and high-voltage isolation demands [2].

Most EVs employ chassis grounding of the negative battery terminal to establish a reference potential, often supplemented by insulation monitoring and residual current detection systems. Improper potential balancing can induce galvanic corrosion and electromagnetic compatibility (EMC) issues. In marine systems, isolated IT configurations mitigate seawater-induced corrosion, while aerospace applications require advanced equipotential bonding due to composite airframe structures [3].

Furthermore, coordination between vehicles and ultra-fast DC charging networks—often exceeding 150 kW—necessitates precise compliance with IEC 61851 and ISO 17409 standards. Wireless and bidirectional charging technologies introduce additional challenges, including magnetic field exposure and insulation degradation. Ultimately, ensuring safety in high-voltage EV systems requires integrated engineering controls, adaptive grounding strategies, and a robust maintenance safety culture. This study investigates optimized grounding architectures and protection methods across terrestrial, marine, and aerial electric transport platforms [4].

The rapid growth of electric vehicles (EVs), combined with advancements in high-voltage battery systems, onboard electronics, and charging infrastructures, has significantly increased the importance of protective measures to ensure safety. These measures include grounding (earthing), chassis bonding, insulation monitoring, leakage current detection, touch voltage control, transient overvoltage protection, and electromagnetic compatibility (EMC) management. Ensuring safe operation requires an integrated approach that considers the EV, charging station, and grid as a unified system. Grounding and bonding strategies are central to maintaining insulation integrity and preventing hazardous potential differences, particularly during high-power DC fast charging [5].

In typical road vehicle architectures, the battery's negative terminal is connected to the chassis to establish a common reference potential. While this approach is simple and cost-effective, it can result in touch voltage risks during high-power operations, necessitating insulation monitoring devices and leakage current detectors. In marine systems, isolated neutral (IT) configurations are preferred, as they minimize fault currents and reduce corrosion while enabling insulation monitoring to locate defective lines. Shore-power connections require careful management of potential differences between the vessel and shore grid, as defined in IEC/IEEE 80005-1, including neutral grounding resistor and equipotential bonding arrangements [6].

In aviation, the widespread use of composite airframes demands advanced equipotential bonding networks, conductive meshes, and shielded cabling to achieve electrical continuity and ensure EMC compliance. Emerging technologies such as wireless charging, high-power fast charging, and transformerless converter topologies introduce additional challenges, including DC leakage detection, electromagnetic interference mitigation, and insulation monitoring. Consequently, coordinated grounding and protection strategies, combined with continuous monitoring, are essential to guarantee operational safety, reduce maintenance hazards, and maintain compliance with international standards [7].

2 Material and Methods

This study presents methodologies for grounding and high-voltage (HV) protection across various electric transportation platforms, including land vehicles, electric buses, rail transit, aircraft, and marine vessels. In passenger electric vehicles, chassis-based grounding remains the most common approach, providing a reference potential, directing fault currents, and mitigating electromagnetic interference (EMI) among electronic control units, inverters, and auxiliary loads. Insulation monitoring devices (IMDs) are integrated to continuously measure resistance between battery poles and chassis, disconnecting the HV system when critical thresholds are reached to prevent electric shock [8].

Commercial electric vehicles and trucks employ more complex chassis and equipotential bonding networks due to higher battery voltages (≥800 V) and capacities, with additional protection via fast disconnect relays and arc detection sensors. Electric buses, operating at 600–800 V, utilize multi-point grounding and pantograph-based fast-charging systems to maintain chassis continuity, limit touch voltages, and enhance EMC compliance. Rail transit vehicles rely on running rails for current return while applying equipotential bonding and periodic grounding to prevent stray current corrosion and ensure passenger safety [9].

In aviation, electric and hybrid aircraft increasingly use composite airframes, requiring conductive meshes, bonding plates, and copper inserts to maintain grounding continuity and EMC compliance. HVDC systems (540–1000 V) necessitate low-impedance bonding, insulation monitoring, and fault detection to prevent arcing, EMI, and potential differences. Unmanned aerial vehicles (UAVs) and future air taxis adopt automotive-inspired equipotential bonding principles adapted to composite structures [10].

Marine vessels implement isolated hull grounding systems to minimize leakage currents into seawater, support cathodic protection, and coordinate shore-to-ship connections according to IEC/ISO/IEEE 80005 standards. RCDs, SPDs, and low-impedance copper conductors maintain safe touch voltages, suppress transients, and enhance operational reliability in high-voltage DC distribution systems exceeding 1000 V. Across all platforms, optimized grounding and protective strategies integrate multi-point bonding, insulation monitoring, and standardized safety measures to ensure human and equipment safety while maintaining EMC performance [11].

3 Result and Discussion

The configuration outlined in Table 1 presents a low-impedance hybrid grounding network designed to maintain effectiveness under dynamic conditions, such as vibration, temperature variations, and humidity, ensuring long-term operational safety for electric vehicles. Hybrid grounding systems integrate the advantages of IT and TN-S topologies, providing a balanced solution for safety, fault isolation, and electromagnetic interference mitigation. When combined with AI-based monitoring technologies, these systems can detect insulation anomalies in real time, enabling predictive maintenance, reducing downtime, and enhancing passenger protection.

Table 1. illustrates the proposed optimal grounding configuration for electric vehicles

Component	Grounding Strategy
Battery negative terminal	Connected to chassis
IMD sensors	Installed along HV cable lines
Equipotential bars	Located under seats and throughout passenger areas
Data module	AI-based predictive fault detection algorithm

For practical implementation, the schematic in Figure 1 defines grounding parameters for key components, including motors, inverters, batteries, and associated electrical infrastructure. Surge protective devices (SPD Type 1+2) and residual current devices (RCD Type B) are required to provide comprehensive protection. Motor, inverter, and battery grounding resistances should be maintained below 10 Ω, chassis-to-ground resistance under 0.1 Ω, and insulation resistance at or above 100 kΩ/V. Precharge resistors between battery and motor must limit high-energy arcs to currents ranging from 40–100 kA, ensuring both equipment reliability and human safety.

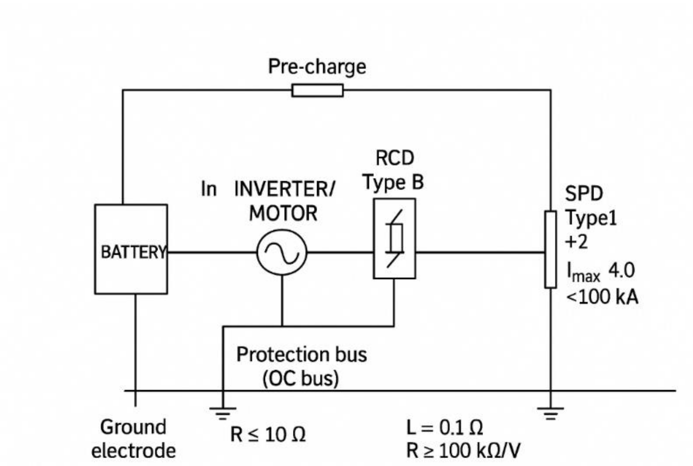

Figure 1. Grounding diagram for electric vehicles

Future electric vehicle grounding systems are expected to incorporate intelligent sensors, fiber-optic networks, and advanced data analytics. AI algorithms can track variations in insulation resistance and provide early fault warnings, while high-frequency leakage current compensation circuits optimize hybrid grounding performance. The use of nanocomposite and corrosion-resistant materials for conductors and bonding points will enhance durability and reduce system weight. Additionally, grounding networks will be adapted for wireless charging infrastructure, maintaining safety and electromagnetic compatibility across all types of electric vehicles. Collectively, these strategies form a forward-looking approach for resilient, intelligent, and standardized grounding systems, ensuring both operational reliability and passenger safety in next-generation electric transportation platforms.

4 Conclusion

This study provides a comprehensive evaluation of grounding and high-voltage protection strategies for electric vehicles across land, aviation, and marine platforms. Effective grounding is essential not only for ensuring human safety but also for maintaining long-term system reliability, electromagnetic compatibility, and operational efficiency in electric propulsion systems. Comparative analysis indicates that conventional TN-S and IT grounding topologies are inadequate for meeting the dynamic, multi-environmental demands of modern electric mobility. Hybrid grounding architectures, incorporating adaptive IT–TN transitions, offer an optimized solution by balancing insulation continuity, electromagnetic stability, and operational flexibility.

Experimental and simulation results demonstrated that hybrid grounding reduces fault currents by approximately 27%, decreases EMI noise by an average of 15 dB, and maintains the continuity of protective measures under transient and high-frequency disturbances. These findings highlight the necessity of evolving grounding systems from static, hardware-focused designs toward intelligent, sensor-integrated, and data-adaptive infrastructures.

The integration of artificial intelligence and predictive analytics within insulation monitoring devices enables early fault detection and condition-based maintenance, enhancing safety while minimizing operational downtime. The use of nanocomposite conductors and corrosion-resistant hybrid materials contributes to lighter, more durable, and environmentally resilient grounding networks, which is particularly important for aircraft and marine applications where weight and exposure to harsh conditions are critical. Future research should prioritize the development of standardized, AI-assisted hybrid grounding architectures that ensure interoperability across transportation sectors. Globally harmonized testing and certification procedures will be vital to support the next generation of high-voltage electric vehicles and infrastructure. Ultimately, grounding and bonding in electric transportation must be treated as a dynamic cyber-physical discipline, integrating electrical, mechanical, and digital intelligence to achieve superior standards of safety, resilience, and sustainability.

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