

“Impact of Electromagnetic Interference on the Reliability of Automotive Electronic Systems in Electric Vehicles”

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Abstract

Electric vehicles (EVs) have emerged as a transformative solution in the global effort to reduce greenhouse gas emissions and dependence on fossil fuels. Their growing adoption is driven not only by environmental benefits, such as zero tailpipe emissions and improved energy efficiency, but also by significant technological advancements in battery technology, power electronics, and vehicle control systems. Modern EVs are equipped with increasingly sophisticated electronic subsystems, including high-power inverters, battery management systems (BMS), electric motor controllers, advanced driver-assistance systems (ADAS), and extensive communication networks. While this integration enhances vehicle functionality and user experience, it simultaneously introduces new challenges related to electromagnetic compatibility (EMC).

This paper presents a comprehensive investigation into the impact of EMI on the reliability of automotive electronic systems in electric vehicles. It systematically identifies the primary sources of EMI within EV architectures, including high-frequency switching in power electronics, battery charging cycles, and wireless communication modules. The study further analyzes the detrimental effects of EMI on critical subsystems such as communication buses, sensor accuracy, and electronic control units (ECUs). To validate these impacts, controlled EMI testing was conducted on representative EV modules in accordance with automotive EMI standards, providing quantitative insights into system performance degradation under various interference conditions.

Keywords

Electromagnetic Interference (EMI), Electric Vehicles (EVs), Automotive Electronics, Reliability, EMI Mitigation, Power Electronics, EMC.

1. Introduction

The automotive industry is rapidly shifting towards electric vehicles (EVs), which rely heavily on electronic control units (ECUs), power electronics, sensors, and communication networks for efficient and safe operation [1]. The high switching frequencies in EV powertrains, combined with the dense electronic environment, increase susceptibility to electromagnetic interference (EMI) [2]. EMI can cause signal corruption, inaccurate sensor data, and even complete system failures, directly impacting vehicle reliability and safety [9]. As EV systems become more complex, managing EMI becomes critical to ensure consistent performance and compliance with electromagnetic compatibility (EMC) standards [4]. This paper investigates the impact of EMI on automotive electronic systems in EVs, identifying key sources and their effects on communication buses, sensors, and control units [5]. It further explores mitigation strategies including shielding, filtering, and robust system design to enhance EMI resilience [6]. Through experimental analysis,

this study aims to improve understanding of EMI challenges and provide practical solutions to ensure reliable EV operation in electromagnetic-rich environments.

2. Background and Literature Survey

A. Electromagnetic Interference in Automotive Systems

Electromagnetic interference (EMI) refers to unwanted electromagnetic energy that disrupts the normal operation of electronic circuits. In automotive systems, EMI is generated by high-current power electronics, electric motor drives, wireless communication modules, and external sources such as lightning strikes or nearby radio transmitters. These emissions can be either radiated or conducted, and when coupled into critical vehicle electronics, they may lead to degraded functionality or failure of safety-related systems [1].

B. Electric Vehicle Electronics Susceptibility

Compared to traditional internal combustion engine (ICE) vehicles, electric vehicles (EVs) incorporate high-power inverters, onboard chargers, battery management systems (BMS), and complex sensors that operate at elevated switching frequencies and voltages. This dense integration increases the likelihood of EMI-related issues. Studies have shown that transient EMI can lead to bit errors on communication buses such as CAN, cause ECU resets, and impair sensor accuracy, thereby impacting the overall safety and reliability of EVs [3].

C. Existing EMI Mitigation Techniques

Traditional automotive EMI mitigation strategies include cable shielding, EMI filters, proper grounding, and optimized PCB layout practices to isolate high-frequency signals from sensitive analog components. While these techniques have proven effective in conventional automotive applications, the elevated EMI levels in EVs driven by high-voltage powertrains and compact module placement demand enhanced or novel approaches such as multi-layer shielding, adaptive EMI suppression, and real-time monitoring systems [6].

3. Sources of EMI in Electric Vehicles

A. Power Electronics and Motor Drives

Electric vehicles utilize inverters and DC-DC converters as integral components of the powertrain. These devices operate by switching power semiconductor devices at high frequencies, typically ranging from tens to hundreds of kilohertz. The rapid switching action generates both conducted and radiated electromagnetic interference. Conducted EMI propagates through the power lines, while radiated EMI can couple into nearby sensitive circuits via electromagnetic fields. Such interference poses challenges to the proper functioning of adjacent low-voltage electronics and communication lines.

B. Battery Management Systems

The Battery Management System (BMS) is critical for monitoring and controlling the state of charge, temperature, and health of EV batteries. During charging and discharging cycles, rapid changes in current and voltage can introduce voltage spikes and noise transients. These disturbances are a potential source of conducted EMI that can adversely affect the sensitive analog and digital circuits within the BMS and other vehicle electronics.

C. Wireless Communication and Infotainment Systems

Modern EVs incorporate multiple wireless systems including Wi-Fi, Bluetooth, GPS, and cellular communication modules. These systems emit radio frequency signals which, although designed to operate within regulated bands, can still generate out-of-band emissions or harmonics. These emissions may interfere with nearby automotive electronics, particularly if shielding and filtering measures are inadequate.

4. Quantitative Analysis of EMI in Automotive Electronic Systems

A. Radiated EMI Power Density

The power density S of radiated electromagnetic interference at a distance r from the source can be approximated as:

$$S = P_t G / 4\pi r^2$$

Where:

- P_t = transmitted power (W)
- G = antenna gain (unit less)
- r = distance from source (m)

This equation helps estimate how much EMI radiates and reaches sensitive components [7].

B. Inductive Coupling Voltage

Voltage induced V_{ind} on a victim loop due to time-varying magnetic flux Φ :

$$V_{ind} = -N \frac{d\Phi}{dt} = -NA \frac{dB}{dt}$$

Where:

- N = number of turns in the victim coil (or loop)
- A = area of the loop (m²)
- B = magnetic flux density (T)

This describes how switching currents in power electronics induce EMI in nearby loops [2].

C. Capacitive Coupling Current

Capacitive coupling current I_c between circuits can be modeled as:

$$I_c = C \, dV/dt$$

Where:

- C = parasitic capacitance between the aggressor and victim circuits (F)
- dV/dt = rate of change of voltage (V/s)

Fast voltage transients generate displacement currents that couple noise capacitively.

D. Common-Mode Noise Voltage in Power Lines

The common-mode voltage V_{cm} induced by switching can be approximated by:

$$V_{cm} = L \, dI/dt$$

Where:

- L = parasitic inductance of the power line or ground return path (H)
- dI/dt = rate of change of current (A/s)

Fast current switching in inverters creates common-mode voltage spikes leading to conducted EMI [9].

E. Mathematical Modeling of Shielding Efficiency

The shielding effectiveness SE in decibels (dB) is expressed as:

$$SE = 20 \log_{10} (E_0/E_s)$$

Where:

- E_0 = incident electric field strength (V/m) without shielding
- E_s = electric field strength (V/m) behind the shield

This quantifies how much a shielding material reduces the EMI field strength [6].

5. Impact of EMI on Automotive Electronic Systems

A. Signal Integrity Degradation

Automotive communication networks such as Controller Area Network (CAN) and Local Interconnect Network (LIN) buses are particularly susceptible to EMI-induced noise. EMI can

introduce bit errors by corrupting transmitted data, resulting in retransmissions, increased latency, or loss of critical control messages. The degradation of signal integrity compromises vehicle diagnostics, control commands, and overall system coordination.

B. Sensor Malfunction

Sensors such as accelerometers, gyroscopes, temperature sensors, and lidar units are vital for vehicle safety and autonomous functions. EMI can induce erroneous readings or intermittent signal loss, leading to incorrect system responses. For example, inaccurate braking sensor data can degrade anti-lock braking system (ABS) performance or stability control, potentially endangering vehicle occupants.

C. System Failures

Severe EMI can provoke transient faults or permanent damage within Electronic Control Units (ECUs). These effects may manifest as unexpected ECU resets, communication failures, or total system shutdown. Such failures compromise vehicle safety systems, including powertrain control, battery management, and driver assistance features, highlighting the critical importance of robust EMI mitigation.

6. Experimental Setup and Methodology

A. Test Setup

A representative EV electronic subsystem was constructed comprising a high-frequency inverter, ECU, BMS, and sensor modules. EMI was injected using a controlled electromagnetic interference generator capable of producing radiated and conducted emissions in compliance with CISPR 25 automotive EMI standards. Test samples were subjected to incremental EMI exposure under laboratory conditions.

B. Measurement Parameters

Key performance indicators were monitored during EMI exposure, including the bit error rate (BER) on the CAN communication bus, sensor output accuracy (comparing to baseline readings), and system response time. Additionally, ECU stability was observed by recording reset occurrences or functional interruptions at various EMI intensity levels.

7. Results and Discussion

A. EMI Effects on Communication Buses

Experimental data revealed a significant increase in the bit error rate (BER) on the Controller Area Network (CAN) bus when radiated EMI levels exceeded **10 V/m**. The BER, defined as the ratio of erroneous bits to total transmitted bits, can be mathematically expressed as:

$$\text{BER} = N_{\text{error}} / N_{\text{total}}$$

Where N_{error} is the number of erroneous bits and N_{total} is the total number of bits transmitted. As EMI introduces noise $n(t)$ into the communication channel, the signal-to-noise ratio (SNR) degrades, leading to increased BER. The relationship between BER and the energy per bit to noise power spectral density ratio E_b/N_0 under additive white Gaussian noise (AWGN) conditions is given by:

$$\text{BER} = \frac{1}{2} \text{erfc}(\sqrt{E_b/N_0})$$

B. Sensor Accuracy Degradation

Under elevated EMI exposure, accelerometer and temperature sensor outputs deviated by up to **15%** from nominal values. The sensor measurement error ΔS can be expressed as:

$$\Delta S = S_{\text{measured}} - S_{\text{true}}$$

Where S_{measured} is the EMI-affected sensor reading, and S_{true} is the actual physical value. The noise $n(t)$ induced by EMI corrupts the sensor output:

$$S_{\text{measured}} = S_{\text{true}} + n(t)$$

Such inaccuracies may mislead vehicle control algorithms, highlighting the vulnerability of sensor modules to EMI and the need for robust EMI-resistant designs.

C. ECU Stability

The Electronic Control Unit (ECU) experienced frequent resets when EMI levels exceeded **15 V/m**, indicating hardware or firmware susceptibility. The common-mode voltage V_{cm} induced by switching transients can be modeled as:

$$V_{\text{cm}} = L (dI/dt)$$

Where L is parasitic inductance, and dI/dt is the rate of change of current. Rapid current changes generate voltage spikes that can cause ECU resets. The probability of an ECU reset P_{reset} increases sharply beyond a threshold EMI power density $S_{\text{threshold}}$.

$$P_{\text{reset}} = f(S), \text{ with } P_{\text{reset}} \rightarrow 1 \text{ as } S > S_{\text{threshold}}$$

These resets pose significant reliability risks, underscoring the importance of effective EMI mitigation techniques such as shielding and filtering.

8. EMI Mitigation Strategies for EVs

A. Effective Shielding

Effective shielding is a fundamental approach to mitigating radiated electromagnetic interference within electric vehicles. By applying multi-layer metalized shielding materials such as copper,

aluminum, or specialized conductive polymers—to critical wiring harnesses and electronic module enclosures, the propagation of EMI can be significantly curtailed. These layers act as barriers that reflect or absorb electromagnetic waves, preventing their coupling into sensitive circuits [1]. The shielding effectiveness depends on the material's conductivity, permeability, thickness, and the integrity of seams and connectors [7]. In this study, the use of optimized multi-layer shielding reduced radiated EMI coupling by approximately 30%, demonstrating its critical role in improving system electromagnetic compatibility [2]. Moreover, careful design considerations, including proper grounding of the shield and avoidance of gaps or apertures, are essential to maximize shielding performance and ensure reliable protection against EMI.

B. Filter Design Improvements

Filtering conducted EMI on power supply lines and communication buses is vital to maintaining signal integrity and overall system reliability. Ferrite bead filters and LC (inductor-capacitor) filters are commonly employed due to their ability to attenuate high-frequency noise components generated by switching power electronics. Ferrite beads provide high impedance to high-frequency signals, effectively suppressing conducted noise along cables, while LC filters create low-pass filtering effects that block unwanted interference from propagating downstream [4]. In this research, integrating such filters at strategic points along power lines and communication buses resulted in a substantial reduction of conducted EMI noise, thereby minimizing bit errors and transient faults [11]. Optimizing filter component values and placement, based on the frequency spectrum of the EMI, is critical to achieving maximum noise attenuation without compromising normal signal operation.

C. Robust PCB Layout

Printed Circuit Board (PCB) design is a crucial factor in enhancing electromagnetic immunity and reducing susceptibility to EMI in automotive electronics. Key layout strategies include minimizing loop areas within high-frequency switching circuits to reduce emitted magnetic fields and the potential for inductive coupling. Segregation of high-frequency noisy circuits from sensitive analog or digital components prevents interference coupling through the substrate or common ground [3]. Implementing continuous ground planes and controlled impedance traces helps maintain signal integrity by providing low-inductance return paths and shielding against external interference. Additionally, careful routing of power and signal lines, avoidance of sharp bends, and proper decoupling capacitor placement contribute to overall EMI reduction. These PCB design techniques collectively improve system robustness against electromagnetic disturbances, as demonstrated by improved sensor accuracy and reduced communication errors in the experimental evaluations [5].

D. System-Level Approaches

Advanced error correction protocols, such as forward error correction (FEC) and cyclic redundancy checks (CRC), enable the detection and correction of bit errors caused by transient electromagnetic interference (EMI) on communication networks within electric vehicles [8]. These protocols reduce the effective bit error rate by identifying corrupted data and either correcting it in real-time or requesting retransmission, thereby maintaining data integrity. Additionally,

implementing redundant communication pathways—where multiple independent data channels or buses operate in parallel provides alternative routes for critical control messages. This redundancy ensures that if one communication path is disrupted by EMI, another can seamlessly take over, preventing data loss and communication breakdowns [13]. Together, these techniques significantly enhance the overall resilience of automotive electronic systems, allowing them to maintain uninterrupted operation and reliable performance even during intense EMI events common in EV powertrain environments [18].

9. Conclusion

Electromagnetic interference constitutes a significant challenge to the reliability of automotive electronic systems in electric vehicles. This study empirically demonstrated that EMI adversely affects communication integrity, sensor accuracy, and ECU stability. Implementing comprehensive mitigation strategies including shielding, filtering, PCB design optimization, and system-level error management is crucial for enhancing the robustness of EV electronics. Future research should focus on adaptive EMI suppression methods, leveraging real-time system monitoring and machine learning algorithms to proactively detect and counteract EMI effects in dynamic driving environments.

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