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Electromagnetic Compatibility Design for Automotive Electronics: Challenges and Solutions for EMI Reduction

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ABSTRACT: The rapid advancement of automotive electronics, fueled by the rise of electric vehicles (EVs), autonomous driving, and connected car technologies, has intensified the challenges of electromagnetic interference (EMI) and electromagnetic compatibility (EMC). High-frequency switching in power converters, complex wiring harnesses, and sensitive communication systems generate and are susceptible to EMI, posing risks to vehicle safety, reliability, and performance. This paper presents a comprehensive EMC design framework for automotive electronics, addressing conducted and radiated EMI through advanced modeling and innovative mitigation strategies. A high-frequency equivalent circuit model predicts EMI in a 500W EV DC-DC converter, validated via MATLAB/Simulink simulations and experimental measurements. Proposed solutions include a fuzzy logic-based pulse width modulation (PWM) controller to stabilize switching, a hybrid EMI filter combining passive and active elements, and optimized printed circuit board (PCB) layout techniques to minimize parasitic effects. Simulations demonstrate a 32 dBµV reduction in conducted EMI and a 28 dBµV/m reduction in radiated EMI, with experimental results confirming compliance with CISPR 25 and ISO 11452 standards. These techniques are cost-effective, scalable, and adaptable to applications such as EV powertrains and advanced driver-assistance systems (ADAS). This work enhances the EMC of automotive electronics, ensuring robust performance in the electrified and connected automotive ecosystem.

KEYWORDS: Electromagnetic Interference, Electromagnetic Compatibility, Automotive Electronics, Electric Vehicles, Fuzzy Logic PWM, Hybrid EMI Filter, PCB Layout, CISPR 25, ISO 11452.

I. INTRODUCTION

The automotive industry is undergoing a transformative evolution, driven by the proliferation of electric vehicles (EVs), autonomous driving technologies, and connected car systems, all of which rely on sophisticated automotive electronics. These systems, including power converters, sensors, communication modules, and advanced driver-assistance systems (ADAS), enhance vehicle efficiency, safety, and connectivity, enabling features such as regenerative braking, lane-keeping assistance, and real-time navigation. However, the integration of high-frequency, high-power electronics introduces significant challenges related to electromagnetic interference (EMI) and electromagnetic compatibility (EMC). EMI, generated by rapid switching in power converters, complex wiring harnesses, and wireless communication systems, can degrade system performance, disrupt critical functions, and pose safety risks. For instance, EMI from a DC-DC converter in an EV may interfere with Controller Area Network (CAN) buses or radar-based ADAS, potentially causing malfunctions that compromise vehicle safety. EMC, defined as the ability of electronic systems to operate reliably in their electromagnetic environment without causing or suffering intolerable disturbances, is a critical requirement for modern vehicles. Automotive EMC standards, such as CISPR 25 for emissions and ISO 11452 for immunity, impose stringent limits on conducted and radiated EMI to ensure functionality and safety.

Traditional EMI mitigation techniques, such as passive filters, shielding, and soft switching, face significant limitations in the automotive context. Passive filters are bulky and less effective at low frequencies, shielding increases vehicle weight, undermining EV efficiency, and soft switching may not consistently reduce EMI across diverse operating conditions. The compact, densely packed nature of automotive electronics amplifies parasitic effects, such as stray capacitances and inductances, complicating EMC design. While extensive research has addressed EMI in other

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domains, such as photovoltaic systems, the automotive environment—characterized by high power density, stringent safety requirements, and dynamic operating conditions—remains underexplored. The unique constraints of automotive systems, including space limitations, weight restrictions, and exposure to harsh conditions like temperature extremes and vibrations, necessitate tailored EMC solutions. This research proposes a comprehensive EMC design framework for automotive electronics, focusing on EMI reduction in power electronic systems critical to EVs and ADAS.
The objectives are to develop a high-frequency equivalent circuit model for predicting conducted and radiated EMI, to introduce novel mitigation strategies including a fuzzy logic-based PWM controller, a hybrid EMI filter, and optimized PCB layout techniques, and to validate these solutions through simulations and experimental measurements on a 500W EV DC-DC converter prototype. By providing scalable, cost-effective, and robust solutions, this work enhances the reliability and safety of automotive electronics, contributing to the advancement of electrified and autonomous vehicles in an increasingly connected automotive landscape. The framework addresses both conducted EMI, prevalent in the 150 kHz–108 MHz range, and radiated EMI, critical in the 30 MHz–1 GHz range, ensuring compliance with international standards and supporting the industry's transition to smarter, greener vehicles.

II. BACKGROUND AND FUNDAMENTALS OF EMI IN AUTOMOTIVE ELECTRONICS

Electromagnetic interference (EMI) in automotive electronics encompasses unwanted electromagnetic noise that disrupts system operation, classified into conducted EMI, which propagates through physical connections in the 150 kHz to 108 MHz frequency range, and radiated EMI, which propagates through air in the 30 MHz to 1 GHz range. Conducted EMI is further divided into common mode (CM) noise, flowing in the same direction through power lines and returning via the vehicle chassis ground, and differential mode (DM) noise, flowing in opposite directions through power lines. CM noise, driven by capacitive coupling between components and the chassis, dominates at higher frequencies above 5 MHz and is a primary concern due to its ability to couple with external circuits, such as communication systems. DM noise, caused by rapid current transients during switching, is prevalent at lower frequencies below 5 MHz, affecting power line stability and converter efficiency. In automotive electronics, EMI originates from multiple sources, including high-frequency switching in power converters, such as DC-DC converters and inverters, digital circuits in microcontrollers, and RF communication modules operating in protocols like CAN, LIN, Ethernet, or 5G.

Parasitic elements, such as stray capacitances in semiconductors, inductances in wiring harnesses, and non-ideal behaviors of passive components, amplify these disturbances by forming resonant circuits that exacerbate noise propagation. The automotive environment presents unique challenges, including compact packaging to meet space constraints, high power density to support efficient power delivery, and exposure to harsh conditions, such as temperature variations from -40°C to 85°C, mechanical vibrations, and electrical load fluctuations. For instance, a 500W DC-DC converter in an EV, switching at 100 kHz, can generate CM noise that couples with long wiring harnesses, acting as antennas to produce radiated emissions that interfere with radar sensors operating in the 76–81 GHz band or GPS receivers critical for navigation. These disturbances can lead to signal degradation, reduced system reliability, and safety hazards, such as erroneous ADAS responses or communication failures in vehicle-to-everything (V2X) systems. Automotive EMC standards, such as CISPR 25, specify conducted EMI limits ranging from 66 to 90 dBμV for broadband emissions in the 150 kHz–108 MHz range and radiated EMI limits from 24 to 54 dBμV/m in the 30 MHz–1 GHz range, while ISO 11452 defines immunity requirements against external disturbances, such as radiated fields up to 100 V/m.

EMI measurements utilize a Line Impedance Stabilization Network (LISN) for conducted emissions and anechoic chambers for radiated emissions, with frequency-domain analysis using spectrum analyzers preferred for assessing compliance. Time-domain measurements, leveraging digital signal processing techniques like Fast Fourier Transform (FFT), are employed for transient analysis, capturing intermittent disturbances common in automotive systems due to dynamic load changes or switching events. A thorough understanding of these EMI fundamentals, including noise sources, propagation paths, and measurement techniques, is essential for developing targeted modeling and mitigation strategies that address the unique EMC challenges in automotive electronics. This background provides the foundation for analyzing EMI generation and susceptibility in complex vehicle systems, guiding the design of robust solutions that ensure reliable operation under diverse conditions.

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III. CHALLENGES IN AUTOMOTIVE EMC DESIGN

Achieving electromagnetic compatibility in automotive electronics is a formidable task due to the intricate interplay of advanced technologies and stringent operational constraints. The widespread adoption of power electronic systems, such as DC-DC converters and inverters in EVs, introduces high-frequency switching noise, with frequencies ranging from 20 kHz to several MHz, generating significant CM and DM noise. These noise components couple with wiring harnesses, which can extend several meters across a vehicle, transforming conducted EMI into radiated emissions that interfere with sensitive systems like ADAS radar, operating in the 76–81 GHz band, or infotainment modules relying on GPS and 5G connectivity. The compact design of automotive electronics, driven by the need to minimize space and weight, exacerbates parasitic effects, as components are densely packed, increasing stray capacitances and inductances. For example, an EV powertrain module integrates multiple converters within a confined space, amplifying electromagnetic coupling between components and creating resonant circuits that amplify noise at specific frequencies, typically 1–10 MHz for conducted EMI and 30–100 MHz for radiated EMI. The extensive wiring harnesses, often comprising hundreds of wires with lengths up to 5 meters, act as unintentional antennas, particularly in the 30 MHz–1 GHz range critical for automotive communication systems, making radiated EMI a significant concern. The diverse operating conditions in vehicles—ranging from high-load urban driving with frequent load changes to low-load highway cruising with stable loads, temperature extremes from -40°C to 85°C, and mechanical vibrations—further complicate EMC design, as EMI characteristics vary dynamically. A DC-DC converter may exhibit higher noise levels under heavy load conditions due to increased switching transients, requiring adaptive mitigation strategies that perform consistently across scenarios. The coexistence of analog, digital, and RF systems, such as CAN buses operating at 1 Mbps, 5G modems at 6 GHz, and radar sensors at 77 GHz, increases EMI susceptibility, necessitating robust immunity against both internal and external disturbances, such as radiated fields from nearby vehicles or infrastructure. Compliance with stringent EMC standards, such as CISPR 25 and ISO 11452, adds further complexity, as manufacturers must balance performance with cost, weight, and production scalability.

Traditional mitigation techniques face significant limitations: passive EMI filters are bulky, occupying up to 10% of module volume, and less effective at low frequencies below 1 MHz, where CM noise from communication systems is prevalent; shielding adds weight, potentially increasing vehicle mass by 5–10 kg, undermining EV efficiency; and soft switching techniques, while reducing switching losses, may not consistently suppress broadband EMI, particularly in the 30–108 MHz range. The lack of standardized models for predicting EMI across diverse automotive systems hinders proactive design, often leading to costly redesigns after prototype testing, with rework costs estimated at 20–30% of development budgets. Emerging technologies, such as vehicle-to-grid (V2G) systems operating at 50–100 kHz and wireless power transfer at 85 kHz, introduce additional EMI challenges due to their high-power, high-frequency operations, further underscoring the need for innovative EMC solutions. These challenges highlight the urgency of developing advanced modeling and mitigation strategies that address both conducted and radiated EMI while meeting the automotive industry's stringent requirements for safety, efficiency, and scalability in an increasingly electrified and connected vehicle landscape.

IV. MODELING OF CONDUCTED AND RADIATED EMI

Accurate prediction of electromagnetic interference is a cornerstone of effective EMC design in automotive electronics, enabling designers to identify and mitigate noise sources early in the development process. This research develops a high-frequency equivalent circuit model for a 500W DC-DC converter, representative of EV auxiliary power systems, to predict both conducted and radiated EMI. The model incorporates critical parasitic elements to capture the complex electromagnetic interactions within the system. The switch capacitance (C_{sw}), typically 100–500 pF, represents the parasitic capacitance between MOSFETs and the vehicle chassis ground, facilitating CM noise coupling. The wiring harness inductance ($L_{harness}$), modeled as 1–10 µH for a 1–5 m cable, accounts for the inductive effects of long cables connecting the converter to other vehicle systems. The output filter capacitance (C_f), set at 10 µF, and inductance (L_f), set at 500 µH, are included to simulate noise attenuation, while the chassis ground capacitance ($C_{chassis}$), approximately 1–10 nF, models coupling between the converter and the vehicle body. For conducted EMI, the CM noise current is modeled as $I_{CM} = V_{CM} / [j\omega L_{eq} + 1 / j\omega C_{eq}]$, where V_{CM} is the common mode voltage derived from the switching node voltage, typically 50–100 V at 100 kHz, L_{eq} is the equivalent inductance combining $L_{harness}$ and L_f, and C_{eq} is the equivalent capacitance including C_{sw} and $C_{chassis}$.

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The DM noise is driven by the differential voltage across the converter's input, expressed as V_DM = V_in - V_out, where V_in is 400V and V_out is 48V in the modeled system. Radiated EMI is modeled by treating the wiring harness as a dipole antenna, with the radiated electric field strength given by E = (I_harness · l · ω · μ_0) / (4π · r), where I_harness is the harness current (1–10 mA), l is the harness length (1–5 m), μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ H/m), and r is the distance from the harness (1–10 m). The model accounts for resonant frequencies, typically 1–10 MHz for conducted EMI and 30–100 MHz for radiated EMI, where parasitic elements amplify noise, creating peaks that challenge compliance with CISPR 25 limits. The model was implemented in MATLAB/Simulink, simulating a 500W DC-DC converter operating at 100 kHz with a 400V input and 48V output, typical of EV battery management or auxiliary systems. The simulation included a LISN to measure conducted EMI in the 150 kHz–108 MHz range and an antenna model for radiated EMI in the 30 MHz–1 GHz range. Without mitigation, the simulated conducted EMI spectra showed a peak CM noise of 88 dBμV at 10 MHz, exceeding CISPR 25 limits of 66–90 dBμV, while radiated EMI reached 62 dBμV/m at 100 MHz, above the 24–54 dBμV/m limit.

The model was further refined to include secondary parasitic effects, such as PCB trace capacitances (10–50 pF) and connector impedances (0.1–1 Ω), improving prediction accuracy. Experimental validation was conducted on a 500W prototype at an EMC test facility, using a LISN for conducted measurements and an anechoic chamber for radiated measurements. The prototype featured a realistic wiring harness of 3 m length and chassis grounding, replicating automotive conditions. The model accurately predicted peak EMI levels, with deviations of less than 5 dBμV attributed to unmodeled parasitic effects, such as PCB trace capacitances and connector impedances. Validation tests included dynamic scenarios, such as load transients from 50% to 100% and input voltage variations of ±10%, confirming the model's robustness across operating conditions. The validated model provides a powerful tool for predicting EMI in automotive power electronics, enabling designers to identify noise sources and optimize mitigation strategies early in the design phase, reducing development costs and ensuring compliance with stringent EMC standards.

V. PROPOSED EMI MITIGATION TECHNIQUES

To address the multifaceted challenges of EMI in automotive electronics, this research proposes three synergistic mitigation strategies: a fuzzy logic-based pulse width modulation (PWM) controller, a hybrid EMI filter combining passive and active elements, and optimized printed circuit board (PCB) layout techniques. The fuzzy logic-based PWM controller is designed for the DC-DC converter to stabilize switching and reduce EMI at the source. Unlike conventional PWM, which uses fixed switching frequencies and generates broadband noise due to variable load conditions, the fuzzy controller dynamically adjusts the duty cycle based on real-time input voltage and load current variations. The controller employs two inputs: the error E(i) = [V_out(i) - V_ref] / V_ref, where V_out(i) is the instantaneous output voltage and V_ref is the reference voltage (48V), indicating the deviation from the desired output, and the change in error CE(i) = E(i) - E(i-1), which determines the adjustment direction. The output is the change in duty cycle (ΔD), computed using 49 fuzzy rules based on seven linguistic variables: Negative Large, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, and Positive Large. These rules are designed to minimize switching transients by adapting the duty cycle to load fluctuations, concentrating noise at predictable frequencies and reducing EMI. Mamdani's inference method and center-of-gravity defuzzification ensure precise control, achieving a 15 dBμV reduction in conducted EMI at 1 MHz in simulations, as the stabilized switching minimizes dv/dt and di/dt variations.

The controller's adaptability was tested under dynamic conditions, such as load changes from 250W to 500W and input voltage fluctuations from 360V to 440V, maintaining stable output and reducing EMI peaks by 10 dBμV at 5 MHz compared to conventional PWM. The second strategy is a hybrid EMI filter, integrating passive and active components to attenuate both CM and DM noise across the 150 kHz–108 MHz range. The passive component includes a common mode inductance of 2 mH to suppress high-frequency CM noise, Y-capacitors of 33 nF to provide a low-impedance path for CM noise to ground, and an X-capacitor of 1.5 μF to attenuate DM noise. The corner frequencies are calculated as f_c,CM = 1 / (2π √(L_CM C_y)) ≈ 200 kHz and f_c,DM = 1 / (2π √(L_DM C_x)) ≈ 300 kHz, optimizing attenuation for automotive EMI spectra. The active component uses a current transformer to sense CM noise currents, typically 1–10 mA, and an operational amplifier circuit to inject compensatory currents, enhancing low-frequency attenuation (150 kHz–1 MHz) where passive filters are less effective, achieving a 20 dBμV reduction at 200 kHz. The hybrid filter's compact design, occupying 30% less volume than traditional passive filters, is critical for automotive space constraints, with simulations showing a 32 dBμV reduction in conducted EMI at 10 MHz. The third strategy involves optimized PCB layout techniques to minimize parasitic effects and radiated EMI.

These include reducing loop areas for high-current traces to lower inductive coupling, separating analog and digital ground planes to prevent crosstalk, and incorporating ferrite beads (500 Ω at 100 MHz) in series with power lines to suppress high-frequency transients. The PCB design employs a four-layer board with dedicated ground and power planes to enhance shielding, reducing radiated EMI by 28 dBμV/m at 100 MHz in simulations. Additional techniques include shortening trace lengths to 5–10 mm, using via stitching for low-impedance grounding, and placing decoupling capacitors (0.1 μF) near high-speed components to mitigate voltage transients, achieving a 23 dBμV/m margin in radiated EMI compliance.

The integration of these strategies—fuzzy PWM for source noise reduction, hybrid filtering for propagation path attenuation, and PCB optimization for parasitic minimization—creates a robust EMC solution. The fuzzy controller enhances filter performance by stabilizing switching frequencies, while the hybrid filter and PCB optimizations address both conducted and radiated EMI, ensuring compliance with CISPR 25 and ISO 11452 standards. This approach is cost-effective, requiring minimal hardware modifications, and scalable for applications like EV battery management systems, where stable power delivery is critical, and ADAS radar modules, where low radiated EMI prevents interference with 77 GHz signals. Case studies demonstrate practical applicability: in a battery management system, the hybrid filter reduced conducted EMI by 30 dBμV at 5 MHz, ensuring reliable CAN bus communication, while in a radar module, PCB optimizations lowered radiated EMI by 25 dBμV/m at 300 MHz, maintaining signal integrity.

VI. SIMULATION AND EXPERIMENTAL RESULTS

The effectiveness of the proposed EMI mitigation techniques was rigorously evaluated through simulations in MATLAB/Simulink and experimental measurements on a 500W DC-DC converter prototype, designed to emulate EV auxiliary power systems. The simulation modeled a converter with a 400V input, 48V output, and 100 kHz switching frequency, incorporating the fuzzy logic-based PWM controller, hybrid EMI filter, and optimized PCB layout. The system was tested under diverse operating conditions, including load variations from 50% to 100% (250W–500W), input voltage fluctuations of ±10% (360V–440V), and temperature ranges from -20°C to 60°C, reflecting real-world automotive scenarios such as urban driving with frequent load changes and highway cruising with stable loads. The fuzzy PWM controller achieved a voltage regulation accuracy of 98.7%, maintaining the output within ±0.4V of the 48V reference, compared to 95.5% for conventional PWM under similar conditions. This stability reduced switching transients, lowering conducted EMI by 15 dBμV at 1 MHz, 12 dBμV at 5 MHz, and 10 dBμV at 10 MHz without additional filtering, as the adaptive duty cycle minimized dv/dt and di/dt variations. The hybrid EMI filter further attenuated conducted EMI, achieving a peak CM noise of 53 dBμV at 10 MHz, a 32 dBμV reduction from the unmitigated case of 85 dBμV, well within CISPR 25 limits of 66–90 dBμV.

The active compensation circuit was particularly effective at low frequencies, reducing CM noise by 20 dBμV at 200 kHz and 18 dBμV at 500 kHz, addressing the limitations of passive filters in this range. Radiated EMI was assessed using an antenna model simulating a 3m wiring harness, with the optimized PCB layout reducing peak emissions to 34 dBμV/m at 100 MHz, a 28 dBμV/m improvement from 62 dBμV/m, and 30 dBμV/m at 300 MHz, compliant with CISPR 25 radiated limits of 24–54 dBμV/m. The PCB's reduced loop areas, ferrite beads, and multilayer grounding were critical in suppressing high-frequency transients and minimizing crosstalk, achieving a 23 dBμV/m margin at 100 MHz and 21 dBμV/m at 300 MHz. The experimental setup validated these findings using a 500W prototype tested at an EMC test facility. The converter featured a fuzzy PWM controller implemented on a digital signal processor (DSP), a hybrid EMI filter with a 2 mH inductance, 33 nF Y-capacitors, 1.5 μF X-capacitor, and an active compensation circuit, and a four-layer PCB with optimized trace routing, via stitching, and decoupling capacitors.

Conducted EMI measurements were conducted using a LISN, and radiated EMI was measured in an anechoic chamber, following CISPR 25 procedures. The experimental conducted EMI spectra showed a peak CM noise of 51 dBμV at 10 MHz, with a 35 dBμV margin below the CISPR 25 limit, average noise levels of 38 dBμV at 1 MHz (28 dBμV margin), 42 dBμV at 5 MHz (24 dBμV margin), and 40 dBμV at 200 kHz (26 dBμV margin). Radiated EMI measurements confirmed a peak of 31 dBμV/m at 100 MHz, with a 23 dBμV/m margin, 28 dBμV/m at 300 MHz (21

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dBμV/m margin), and 25 dBμV/m at 500 MHz (19 dBμV/m margin), ensuring compliance across the 30 MHz–1 GHz range. Immunity tests per ISO 11452 demonstrated robust performance, with no degradation in converter output under 100 V/m radiated fields at 400 MHz and 800 MHz, critical for coexistence with external RF sources like 5G base stations. The prototype was also tested under dynamic conditions, simulating urban driving with load transients every 10 seconds and highway cruising with stable loads for 30 minutes, achieving consistent EMI suppression with a 30 dBμV margin in conducted EMI under high-load conditions and a 25 dBμV/m margin in radiated EMI under low-load conditions. Additional tests under temperature extremes (-20°C and 60°C) confirmed stable performance, with conducted EMI margins reduced by only 2–3 dBμV at 60°C due to slight increases in parasitic capacitances. Minor discrepancies between simulation and experimental results, typically 3–5 dBμV, were attributed to unmodeled parasitic effects, such as connector capacitances (0.1–1 pF) and PCB manufacturing tolerances (±0.1 mm trace width). These results underscore the robustness of the proposed techniques in achieving EMC compliance across diverse automotive scenarios, maintaining high efficiency and reliability while addressing both conducted and radiated EMI effectively.

VII. DISCUSSION

The proposed EMC design framework for automotive electronics represents a significant advancement in addressing the complex challenges of EMI reduction, offering a robust and versatile solution for modern vehicles. The fuzzy logic-based PWM controller outperforms conventional PWM by achieving a 98.7% voltage regulation accuracy, a 3.2% improvement, and reducing conducted EMI by 15 dBμV at 1 MHz, 12 dBμV at 5 MHz, and 10 dBμV at 10 MHz through stabilized switching. This contrasts with randomized PWM techniques, which may introduce audible noise in the 20–20 kHz range, potentially affecting passenger comfort, or soft switching, which increases circuit complexity by 10–15% and may fail to suppress broadband EMI, particularly in the 30–108 MHz range. The adaptive nature of the fuzzy controller, leveraging 49 fuzzy rules to dynamically adjust the duty cycle, ensures consistent performance under varying load and voltage conditions, making it ideal for dynamic automotive environments like urban driving with frequent load changes or highway cruising with stable loads. The controller's ability to concentrate noise at predictable frequencies enhances the performance of downstream filtering, reducing the filter's size and cost by 20–30% compared to traditional designs.

The hybrid EMI filter, integrating a 2 mH passive inductance with 33 nF Y-capacitors, 1.5 μF X-capacitor, and an active compensation circuit, achieves a 32 dBμV reduction in conducted EMI at 10 MHz, surpassing passive filters' limited low-frequency performance (typically <10 dBμV below 1 MHz) and active filters' high cost, which can increase system expenses by 15–20%. The active component's ability to inject compensatory currents enhances attenuation at 150 kHz–1 MHz, critical for automotive communication systems like CAN buses operating at 1 Mbps, achieving a 20 dBμV reduction at 200 kHz and 18 dBμV at 500 kHz. The hybrid filter's compact design, occupying 30% less volume than traditional passive filters, addresses automotive space constraints, making it suitable for densely packed modules like EV powertrains. The optimized PCB layout, with reduced loop areas, separated ground planes, ferrite beads, and multilayer grounding, lowers radiated EMI by 28 dBμV/m at 100 MHz, 25 dBμV/m at 300 MHz, and 22 dBμV/m at 500 MHz, offering a lightweight alternative to traditional shielding, which can add 5–10 kg to vehicle weight, reducing EV range by 1–2%. The four-layer PCB design, incorporating via stitching and decoupling capacitors, minimizes crosstalk and high-frequency transients, achieving a 23 dBμV/m margin at 100 MHz and 21 dBμV/m at 300 MHz in radiated EMI compliance. Compared to state-of-the-art methods, such as chaotic PWM, which may reduce EMI by 10–15 dBμV but introduces control complexity, or advanced shielding, which increases costs by 10–20%, the proposed approach is cost-effective, requiring minimal hardware modifications, and scalable across automotive applications, from EV battery management systems to ADAS radar modules. Compliance with CISPR 25 and ISO 11452 standards ensures applicability to stringent automotive requirements, while the high-frequency equivalent circuit model enables proactive EMI prediction, reducing redesign costs by up to 30% compared to iterative prototype testing.
The model's accuracy, with deviations of less than 5 dBμV from experimental results, supports its use in complex systems, such as vehicle-to-grid (V2G) interfaces operating at 50–100 kHz or wireless power transfer at 85 kHz, where high-power switching introduces additional EMI challenges. Practical case studies demonstrate the framework's versatility: in an EV battery management system, the hybrid filter reduced conducted EMI by 30 dBμV at 5 MHz, ensuring reliable CAN bus communication under high-load conditions, while in an ADAS radar module, PCB optimizations lowered radiated EMI by 25 dBμV/m at 300 MHz, maintaining signal integrity for 77 GHz radar signals critical for collision avoidance. In a V2G system, the fuzzy PWM controller reduced conducted EMI by 18 dBμV at

100 kHz, supporting stable power transfer to the grid, while the hybrid filter achieved a 22 dBμV margin at 500 kHz, preventing interference with smart grid communication. Limitations include the hybrid filter's dependency on accurate noise sensing, requiring calibration for different converter topologies, which may increase design time by 5–10%, and the need for precise PCB manufacturing, with tolerances of ±0.1 mm, potentially raising production costs by 5–10%. The framework's adaptability to diverse operating conditions, validated under load variations, voltage fluctuations, temperature extremes, and dynamic driving scenarios, supports its real-world applicability. Future enhancements could explore adaptive fuzzy controllers that self-tune based on real-time EMI measurements, potentially achieving an additional 5–10 dBμV EMI reduction by optimizing rule sets dynamically. Machine learning-based EMI prediction models could improve accuracy in systems with multiple converters, reducing prediction errors to 1–2 dBμV, while compact active EMI filters could reduce filter volume by 20–30%, addressing space constraints in next-generation vehicles. The proposed techniques provide a robust, scalable, and cost-effective solution for EMC compliance, critical for the reliability and safety of electrified and autonomous vehicles in an increasingly connected automotive ecosystem.

VIII. CONCLUSION AND FUTURE WORK

This research presents a comprehensive framework for electromagnetic compatibility design in automotive electronics, addressing the critical challenges of conducted and radiated EMI in power electronic systems essential for electric vehicles, autonomous driving, and connected car technologies. The high-frequency equivalent circuit model accurately predicts EMI in a 500W DC-DC converter, validated through MATLAB/Simulink simulations and experimental measurements, enabling proactive design optimization that reduces development costs by up to 30%.

The proposed mitigation strategies—a fuzzy logic-based PWM controller, a hybrid EMI filter, and optimized PCB layout techniques—achieve a 32 dBμV reduction in conducted EMI at 10 MHz, 20 dBμV at 200 kHz, and 28 dBμV/m reduction in radiated EMI at 100 MHz, ensuring compliance with CISPR 25 and ISO 11452 standards. The fuzzy PWM controller stabilizes switching, achieving 98.7% voltage regulation accuracy and reducing conducted EMI by 15 dBμV at 1 MHz, 12 dBμV at 5 MHz, and 10 dBμV at 10 MHz, outperforming conventional PWM by 3.2% and randomized PWM by avoiding audible noise. The hybrid filter, combining a 2 mH passive inductance with 33 nF Y-capacitors, 1.5 μF X-capacitor, and an active compensation circuit, enhances low-frequency attenuation critical for automotive communication systems, achieving a 20 dBμV reduction at 200 kHz and occupying 30% less volume than traditional passive filters. The optimized PCB layout, with reduced loop areas, separated ground planes, ferrite beads, and multilayer grounding, minimizes parasitic effects, offering a lightweight alternative to shielding and achieving a 23 dBμV/m margin in radiated EMI compliance at 100 MHz. These techniques are cost-effective, requiring minimal hardware modifications, and scalable for diverse applications, including EV battery management systems, ADAS radar modules, vehicle-to-grid interfaces, and wireless power transfer systems. The framework's validation under dynamic conditions—load variations from 250W to 500W, voltage fluctuations of ±10%, temperature extremes from -20°C to 60°C, and driving scenarios like urban and highway conditions—demonstrates its robustness for real-world automotive environments.

Case studies highlight practical applicability: in a battery management system, the hybrid filter ensured reliable CAN bus communication; in a radar module, PCB optimizations maintained 77 GHz signal integrity; and in a V2G system, the fuzzy PWM supported stable power transfer. Limitations include the need for hybrid filter calibration and precise PCB manufacturing, which may increase design and production costs marginally. Future research could explore adaptive fuzzy controllers that self-tune based on real-time EMI measurements, potentially achieving an additional 5–10 dBμV reduction. Machine learning-based EMI prediction models could enhance accuracy in multi-converter systems, while compact active EMI filters could reduce size and weight, addressing space constraints. Extending the framework to emerging technologies, such as vehicle-to-everything communication or high-frequency wireless charging, offers further opportunities for advancing EMC compliance and system efficiency. This work contributes significantly to the development of reliable, efficient, and EMC-compliant automotive electronics, paving the way for the next generation of electrified and autonomous vehicles in a connected and sustainable automotive future.

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