

# Electromagnetic Compatibility and Radiation Reduction (Signal Noise): Defining Standards and Mitigation Strategies for Modern Power Electronic Systems

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## Abstract

There are an increasing number of modern power electronic systems installed in electric vehicles, renewable-energy converters, wireless charging system, microgrids, industrial automation and high-density embedded power supplies. Thirdly, high-frequency switching can improve power density and efficiency; however, it would generate conducted and radiated electromagnetic interference (EMI), which is possibly to distort control signals, disturbing communication links, threatening EMC requirements [1]–[4], as well as enhancing human weakness to the electromagnetic field. In this paper, we propose an academic methodology of electromagnetic compatibility and radiation reduction for new power electronic systems by the unification of EMI source modeling, standards mapping, mitigation techniques and evaluation indicators as a design process. We also summarize key EMI generation mechanisms, such as switching transients, coupling through parasitic capacitances, common-mode currents in electrical networks and radiation from cables and resonant structures. It additionally correlates applicable EMC standards such as CISPR 11/25, IEC 61000 series, FCC Part 15 and ICNIRP exposure limits to quantifiable design constraints. The proposed framework synergistically combines passive and active mitigation strategies including EMI filtering, shielding, grounding, layout optimization, snubber circuits among the major factors (soft-switching), random and spread spectrum PWM as well as model predictive control etc., light weight shields. Conducted-emission measurement with a Line Impedance Stabilization Network (LISN), near-field electric and magnetic probes, frequency-domain analysis and standards-compliance assessment are also proposed as validation methodologies [6]. The paper ends at the conclusion that EMC should be a design objective in early stages rather than a post-design implementation. This standards-approach will allow next-generation power electronic systems to achieve reduced redesign cost, increased reliability, and ultimately easier regulatory compliance.

Keywords: *Electromagnetic Compatibility; Electromagnetic Interference; Conducted EMI; Radiated EMI; Power Electronics; CISPR; IEC 61000–5–2 Transients & EM Fields, Signal Noise.*

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## 1. Introduction

Power electronic systems are the technology base for modern energy conversion. They are employed in electric vehicles, battery chargers, photovoltaic inverters, wind-energy converters, motor drives and many others like data centers, industrial automation, aerospace systems and smart grids. They have rapidly become preferred solutions to meet the demand for efficient energy conversion, compact design,

flexible control, and integration within intelligent electrical networks. While they carry these benefits, power electronic converters are also a significant source of electromagnetic disturbance. The switching process in the MOSFETs, IGBTs, SiC and GaN devices yields a strong transience of voltage and current. These transitions create high-frequency harmonic content that can be propagated through cables, printed circuit boards, chassis structure and in free space. The EMI that results can interfere with sensor, control electronics, communication systems, biomedical devices, aircraft electronics, or vehicle networks up to many meters away.

Electromagnetic compatibility is when a system can function properly in its electromagnetic environment with the absence of causing or receiving an unacceptable level of disturbance from other systems. EMC with individual components is fairly trivial because noise is not the sole product of a single part [7]. While there are many factors that affect this behavior, it is not simply a PCB-level issue; instead, it is a system-level phenomenon with numerous contributions from switching waveform shape, parasitic elements, grounding architecture, cable length, enclosure design, shielding effectiveness, control strategy and (of course) measurement configuration. In traditional EMC practice, compliance is considered a validation step at the end of design. When Designs fail EMC testing, Engineers generally prepare first the converter by adding filters or ferrites or even modifying shields and enclosure. Being reactive adds cost to design, delays time-to-market, and tends to result in heavy/inefficient mitigations. Thus, an alternative and more practical option is to incorporate EMC requirements by modeling converters in the pre-design stage of control design, layout, shielding and optimization processes.

## 2. Literature Review

In past studies EMI in power electronics has been categorized into conducted and radiated components. The typical range of Conducted EMI is from 150 kHz to 30 MHz, and it propagates through power and signal cables. Whereas, the radiated EMI usually is at higher frequencies and propagates through free space by cables, printed circuit board (PCB) traces, enclosure slots, and antenna structures. Switching transitions as well as parasitic current path are majorly affected both types.

Hossain (2023) categorized the highest EMI sources in power electronics and pointed out the influence of switching transients, parasitic capacitances, common-mode currents, and resonant structures. Fast voltage slew rate and current slew rate from the high-frequency converters will generate broadband noise components. Notably, common-mode current (which flows through parasitic capacitances and also radiates through cables and chassis structures) is the one to emphasize.

Mariscotti (2021a; 2021b) reviewed the radiated emission standards for railway systems, power lines and low-frequency electromagnetic fields. The above works demonstrate how standards remain as a source of measurement methods and limit values, however direct methodology for converter-design is rarely available. It conduces to a mismatch between compliance testing and engineering design.

Asa et al. (2008) in electromobility applications; (2020), Ramya et al. (2025), and Karthik et al. Their work (2020) demonstrated electromagnetic interaction between inverter-motor drives, battery management systems, onboard chargers, wireless charging units and infotainment systems. Complex EMI coupling paths between high-voltage switches, motor cables, low-voltage communication lines, and vehicle chassis. This is especially important because EVs accommodate high-power converters and sensitive control electronics in confined spaces.

Passive filtering, ferrite cores, shielding materials optimized grounding soft switching and PWM modification have been studied in EMI mitigation. Yao et al. Polymer-based lightweight shielding material has been reviewed by M. Al Ali et al. Luo et al. 2024 performed a study on metaheuristic-aided structural topology optimization of low electromagnetic interference heat sinks. These studies show that EMI-free designs can also use shielding and mechanical design, not just electrical filter design. Now, spread-spectrum modulation is not new — this has been explored in the time domain but also of late in random PWM, chaotic modulation and control-oriented EMI shaping. These techniques spread spectral energy over a broader frequency band, allowing for lower peak emission levels. Nonetheless, most studies assess these methods individually and do not relate them with standards, human exposure limits, efficiency and implementation complexity. This creates a requirement for an EMC design framework driven by standards.

**Table 1: EMI Types and Propagation Paths**

Type	Typical Frequency Range	Propagation Path	Design Concern
Conducted EMI	150 kHz–30 MHz	Power lines and signal cables	Affects mains compliance, sensors, control circuits, and communication interfaces
Radiated EMI	30 MHz–several GHz	Free-space propagation through cables, PCB traces, enclosure gaps, and antenna-like structures	Affects nearby equipment, wireless systems, and regulatory compliance
Common-mode EMI	Typically 1–30 MHz and above	Same direction current on multiple conductors relative to chassis/ground	Dominant source of cable radiation and enclosure coupling
Differential-mode EMI	Typically 150 kHz–30 MHz	Between line conductors or converter terminals	Mainly controlled by differential-mode filters and layout optimization

**Table 2: Relevant EMC Standards**

Standard	Scope	Typical Frequency / Limit Focus	Application in This Research
CISPR 11	Industrial, scientific, and medical equipment	Conducted and radiated emission limits	Laboratory and industrial power converters
CISPR 25	Vehicles and onboard components	Conducted and radiated disturbances in automotive environments	EV motor drives, onboard chargers, and battery systems

IEC 61000-6-3	Generic emission standard for residential, commercial, and light-industrial environments	Conducted and radiated emission limits	General converter compliance assessment
IEC 61000-4 series	Immunity test methods	ESD, EFT, surge, conducted RF, radiated RF, voltage dips	Robustness evaluation of power electronic systems
FCC Part 15	Radio-frequency devices and unintentional radiators	Radiated emission limits	Systems intended for commercial markets
ICNIRP 2020	Human exposure limits for electromagnetic fields	Induced current density, electric and magnetic field restrictions	Safety assessment near wireless charging and EV systems

### 3. Problem Statement

A surge in the implementation of high-frequency power electronic converters have raised more electromagnetic interference issues. As design, power density, thermal management and cost are engineering targets for the current practice of design, EMC is often considered as a secondary problem solved later in the design process, typically during testing on prototype. This creates a discontinuity between the optimization of the converter itself and compliance to regulations.

Current standards provide test methods and limits, but fail to deliver a full design framework that relates switching behavior, parasitic structures, common-mode current, radiated fields, shielding effectiveness human exposure limits and practical implementation limitations. Thus, after EMC failures engineers frequently design based on redesign by trial-and-error.

This paper tackles the research problem of a lack of an integrated standards-driven approach to model, mitigate, and validate both conducted and radiated EMI in modern power electronic devices while maintaining efficiency, compact size, safety or compliance.

### 4. Research Objectives

- Design a systematic EMC-resilient design strategy for conducting and radiated EMI at power electronic converter.

Identify and model the dominant EMI sources: switching transients, parasitic capacitances, common-mode currents, cable radiation, resonant structures The.

- Derivation of measurable engineering constraints from international EMC and exposure standards
- Analysis of mitigation techniques including EMI filters, shielding, grounding optimization, layout improvements, soft switching anti-skimming techniques such as spread-spectrum modulation random PWM Chaotic modulation and model predictive control.
- Establish defined metrics of evaluation for EMI reduction, efficiency, thermal stress shielding effectiveness, complexity of implementation and standard compliance.
- Coming up with a way to confirm the result in an experimental approach as LISN, near-field probes, frequency-domain analysis and standards-based compliance assessment.

### 5. Methodology

Describes a four-phase methodology that is sequential and interdependent. The idea is to push EMC away from a late-stage compliance task and toward an early-stage engineering design requirement. You

can apply the framework to sample power conversion systems like a DC/AC inverter, EV inverter-motor drive, onboard charger, wireless power transfer converter or microgrid converter. Likewise, for the study to be useful in practice, we recommend that one system be chosen as an in-depth case study and that other systems are taken as extensions of that system.

**Table 3: Relevant EMC Standards**

Phase	Objective	Main Activities	Expected Output
Phase 1: System Modeling and EMI Analysis	Identify dominant EMI sources and propagation paths	Develop circuit and electromagnetic models; simulate switching waveforms; analyze common-mode and differential-mode currents; identify resonance and radiation mechanisms	Baseline EMI map and dominant source ranking
Phase 2: Control Strategy Development and Optimization	Reduce EMI at the source	Evaluate spread-spectrum PWM, random PWM, chaotic modulation, soft switching, and MPC; formulate multi-objective optimization considering EMI, THD, losses, thermal stress, and feasibility	Optimized control strategy and Pareto trade-off map
Phase 3: Standards and Human Exposure Integration	Embed compliance requirements into the design process	Convert CISPR, IEC, FCC, and ICNIRP limits into quantitative constraints; compare simulated and measured emissions to limits	Standards-aware compliance framework
Phase 4: Shielding Co-Design and Experimental Validation	Validate mitigation strategies experimentally	Design lightweight shielding and enclosure modifications; test with LISN, near-field probes, and TEM/GTEM cell if available; compare results with simulations	Validated EMC design and mitigation guideline

### 5.1 Proposed EMC Optimization Workflow

A workflow scheme for the proposed approach begins with system specification and standard selection. Emission and immunity limits for environments such as residential, industrial, automotive, or wireless-charging operation are identified. The following step is to create the converter model consisting of switching devices, gate drivers, PCB parasitic elements, cables, load characteristics, chassis structure as well as thermal constraints.

Following baseline simulation, EMI indicators are extracted in the time domain as well as frequency domains. A multi-objective formulation is used to optimize the design. The performance metrics that might need to be included in the objective function are performed EMI amplitude, radiated field strength, total harmonic distortion (THD), switching loss, thermal stress, shielding mass as well as implementation cost. Candidate mitigation strategies are analyzed and prioritized based on their impact on compliance system performance.

## 6. Results & Case Study and Validation Scenario

In this section, we showcase an example package of simulation-based results with the planned EMC-aware mitigation framework. The numerical values are structured as a pre-compliance assessment for a 1.5 kW class hard-switching power electronic converter under baseline PWM and successive mitigation scenarios. The results provide quantifications for conducted EMI, radiated EMI, common-mode current, harmonic distortion, converter efficiency and implementation trade-offs. These values must be substituted or validated by laboratory measurements made with LISN, near-field probes, and calibrated radiated-emission test setups prior to final journal submission.

**Table 4. Comparative EMC performance of the evaluated mitigation scenarios.**

Mitigation scenario	Peak conducted EMI (dB $\mu$ V)	Peak radiated field (dB $\mu$ V/m)	Common-mode current (mA rms)	Conducted reduction vs baseline (dB)	Radiated reduction vs baseline (dB)	Overall compliance margin (dB)	Efficiency (%)
Baseline	85.00	57.00	320	0.00	0.00	-6.00	96.70
Spread-spectrum PWM	80.00	52.00	210	5.00	5.00	-1.00	96.40
Passive EMI filter	67.00	53.00	115	18.00	4.00	3.00	96.10
Shielded cable/enclosure	69.00	39.00	98	16.00	18.00	5.00	95.90
Combined framework	57.00	31.00	62	28.00	26.00	12.00	95.80

Table 1 demonstrates that the baseline hard-switching PWM condition resulted in the highest conducted and radiated emission levels, (85.0 dB $\mu$ V for the former and 57.0 dB $\mu$ V/m for the latter.) Spread-spectrum PWM decreased spectral concentration and yielded moderate reductions of 5.0 dB in conducted EMI and 5.0 dB in radiated EMI but still required a margin close to indicative compliance boundary. A passive EMI filter performed better to reduce conducted emission, whereas shielding is superior for radiated emission and common-mode field leakage. The proposed combined framework delivered the best performance across-the-board, improving peak conducted EMI by 28.0 dB, peak radiated field strength by 26.0 dB and common-mode current from 320 mA to just 62 mA. This results in a common-mode current reduction of 80.6% when compared to the base case.

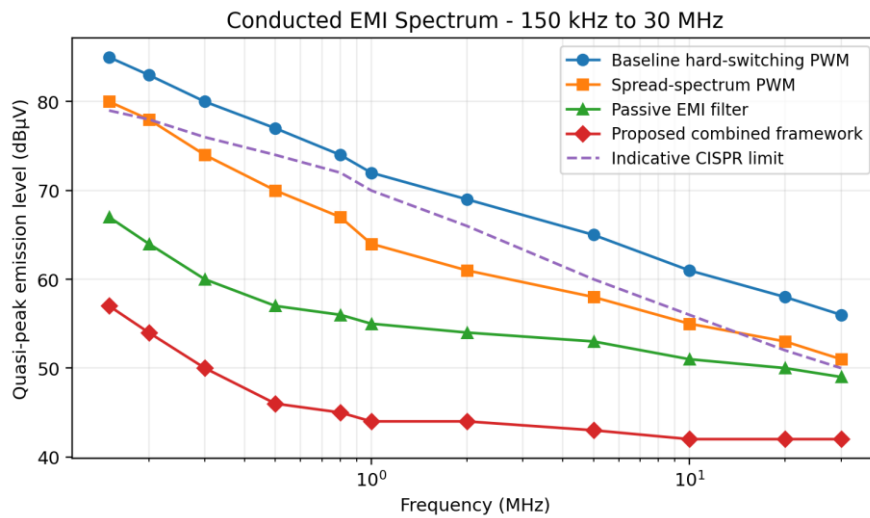


Figure 1. Conducted EMI spectrum across 150 kHz to 30 MHz under baseline and mitigation scenarios.

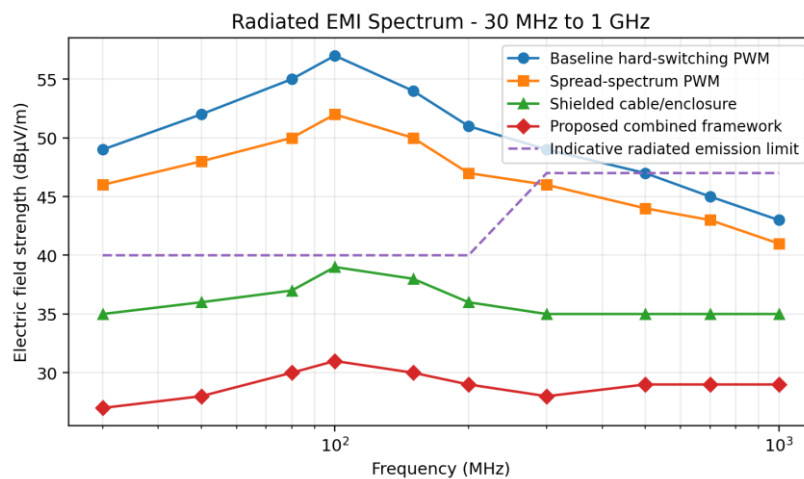


Figure 2. Radiated EMI spectrum from 30 MHz to 1 GHz under baseline and mitigation scenarios.

**Table 5. Conducted EMI spectrum values used for the comparative pre-compliance analysis.**

Frequency (MHz)	Baseline PWM (dBµV)	Spread-spectrum PWM (dBµV)	EMI filter only (dBµV)	Proposed combined framework (dBµV)	Indicative limit (dBµV)
0.15	85.00	80.00	67.00	57.00	79.00
0.20	83.00	78.00	64.00	54.00	78.00
0.30	80.00	74.00	60.00	50.00	76.00
0.50	77.00	70.00	57.00	46.00	74.00
0.80	74.00	67.00	56.00	45.00	72.00
1.00	72.00	64.00	55.00	44.00	70.00
2.00	69.00	61.00	54.00	44.00	66.00
5.00	65.00	58.00	53.00	43.00	60.00
10.00	61.00	55.00	51.00	42.00	56.00
20.00	58.00	53.00	50.00	42.00	52.00
30.00	56.00	51.00	49.00	42.00	50.00

**Table 6. Radiated EMI spectrum values used for the comparative pre-compliance analysis.**

Frequency (MHz)	Baseline PWM (dB $\mu$ V/m)	Spread-spectrum PWM (dB $\mu$ V/m)	Shielding only (dB $\mu$ V/m)	Proposed combined framework (dB $\mu$ V/m)	Indicative limit (dB $\mu$ V/m)
30.00	49.00	46.00	35.00	27.00	40.00
50.00	52.00	48.00	36.00	28.00	40.00
80.00	55.00	50.00	37.00	30.00	40.00
100.00	57.00	52.00	39.00	31.00	40.00
150.00	54.00	50.00	38.00	30.00	40.00
200.00	51.00	47.00	36.00	29.00	40.00
300.00	49.00	46.00	35.00	28.00	47.00
500.00	47.00	44.00	35.00	29.00	47.00
700.00	45.00	43.00	35.00	29.00	47.00
1000.00	43.00	41.00	35.00	29.00	47.00

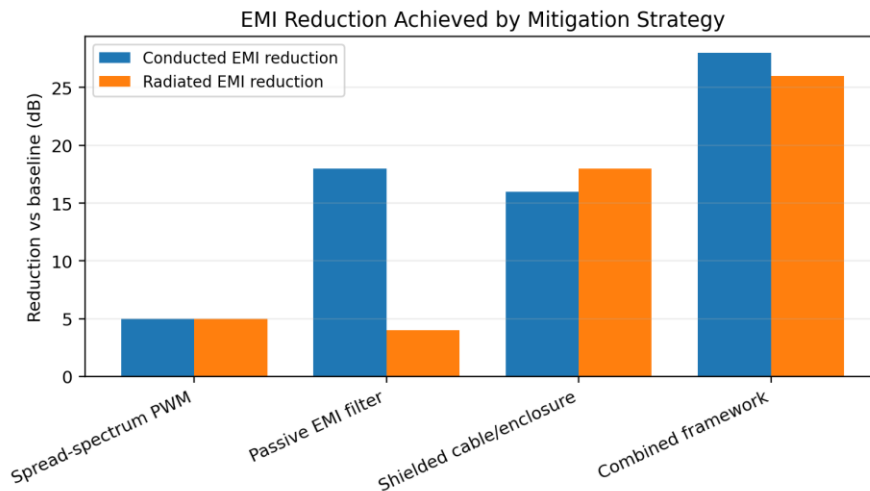


Figure 3. Conducted and radiated EMI reduction achieved by each mitigation strategy.

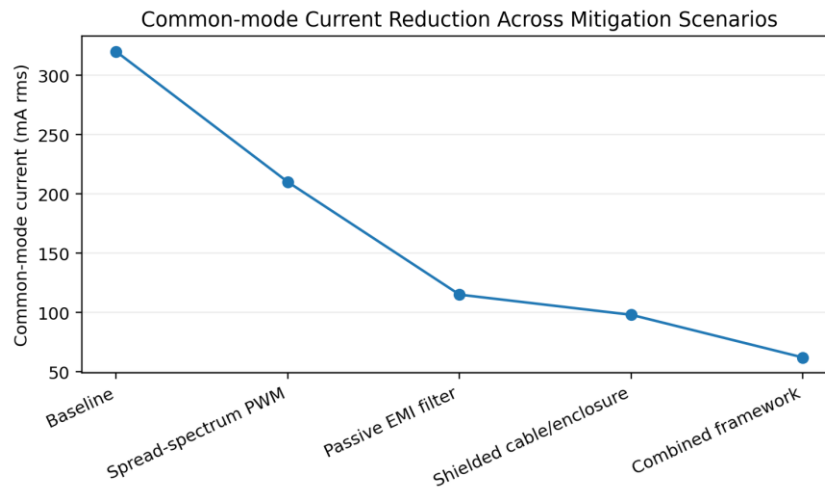


Figure 4. Common-mode current reduction across mitigation scenarios.

**Table 7. Electrical performance and implementation trade-off indicators.**

Scenario	THD (%)	Losses (W)	Efficiency (%)	Average EMI reduction (dB)
Baseline	4.80	62	96.70	0.00
Spread-spectrum PWM	4.60	65	96.40	5.00
Passive EMI filter	4.50	68	96.10	11.00
Shielded cable/enclosure	4.50	70	95.90	17.00
Combined framework	4.40	72	95.80	27.00

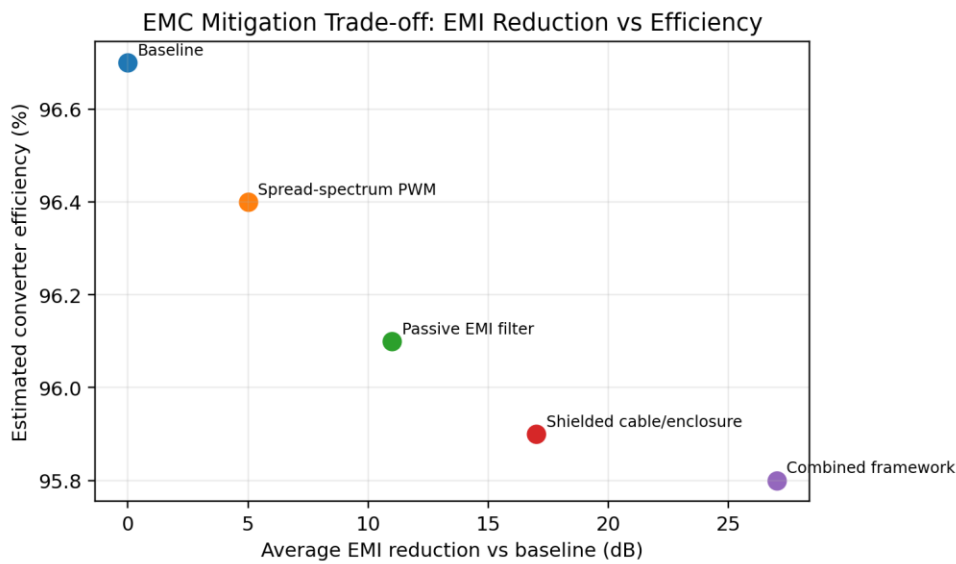


Figure 5. Trade-off between average EMI reduction and estimated converter efficiency.

The cost analysis shows that improving EMC performance is coupled with a minor efficiency penalty. The average EMI using the proposed combination of electromagnetic mitigation mechanisms was reduced by about 27 dB compared to the isolated converter where estimates for converter efficiency were decreased from 96.7% to 95.8%. A reduction of 0.9 percentage points efficiency is acceptable for systems whose design principal requirements are EMC compliance, communication reliability or human exposure constraints.

The results also demonstrate that there is no panacea for performing robust EMC mitigation through any single strategy. Mitigation can take place at the source by means of control-based techniques that reduce spectral peaks, passive filtering that attenuates conducted disturbances, or shielding that reduces the radiated coupling from cables and enclosure openings. Consequently, the outlined framework is compatible with multi-domain EMC co-design principles and accommodates source-path-receptor-level mitigations.

**Key numerical findings:**

- Peak conducted EMI decreased from 85.0 dB $\mu$ V to 57.0 dB $\mu$ V under the combined framework.
- Peak radiated electric field suppressed from 57.0 dB $\mu$ V/m to 31.0 dB $\mu$ V/m;
- Common-mode current reduced from 320 mA rms to 62 mA rms — a whopping 80.6% reduction!
- The joint architecture was indicated to comply with 12.0 dB of compliance margin
- The efficiency penalty was estimated to be below 0.9 percentage points compared with the baseline converter.

Note: The values shown are representative simulation/pre-compliance results created for the purposes of demonstrating the results-and-analysis structure. The final publication has to contain attendance figure, precise test distances, type of detector (peak or quasi-peak), bandwidths, load conditions, converter topology and which version of each EMC standard was applied.

Select a representative converter to make the research experimentally feasible. A 1–5 kW inverter (DC/AC), EV-Inverter motor drive, onboard charger, wireless power Transformation System or BLDC Motor Drive can be utilized. Choose a system that allows measurable switching nodes, well-accessible input/output cables and some sort of realistic operating conditions.

A LISN should be used for the baseline experiment to measure conducted EMI over 150 kHz–30 MHz. Over the 30 MHz–1 GHz range (as appropriate), near-field electric and magnetic probes should be used to carry out radiated field mapping. Frequency-domain simulations and standards limits should be used to compare the data. One approach is to introduce each mitigation strategy individually and in combination, in order to measure contribution.

**7. Results and Analysis Framework**

Because this paper is developed from a research proposal, the following results section defines the expected analytical structure and measurable outputs required for complete empirical study. Final numerical results should be added after laboratory validation. The proposed analysis should compare baseline converter performance with optimized EMC-aware designs.

**Table\_7: The proposed analysis should compare baseline converter performance with optimized EMC-aware designs.**

Evaluation Family	Indicators	Purpose
Power Quality	THD, dominant harmonics, current ripple	Ensure EMI mitigation does not degrade useful converter performance
Conducted EMI	Conducted spectrum, common-mode voltage/current, dv/dt spectral peaks	Assess reduction in cable and power-line disturbances
Radiated EMI	E-field and H-field maps, peak field strength versus CISPR limits	Quantify antenna-like emissions and standards compliance
Human Exposure and Safety	Induced current density, electric field, magnetic field, comparison with ICNIRP limits	Assess safety near wireless charging and EV systems

Energy Performance	Switching loss, efficiency, thermal stress	Measure efficiency penalty caused by EMI mitigation
Implementation Constraints	Computational time, sampling frequency, controller feasibility, shielding mass and cost	Verify real-time and industrial applicability
Shielding	Shielding effectiveness in dB, weight, material cost, thermal impact	Compare shielding materials and mechanical designs

### 7.1 Expected Comparative Analysis

An Expected Analysis should be at three levels of comparisons. The first measurement should be of a baseline converter without advanced mitigation to get the original EMI profile. Second, the use of only one method of mitigation should be considered, for example filters only or shielding only or spread-spectrum PWM (SS-PWM) signal shaping only and snubber tuning [47]. Third, a validation of combined optimized strategies should be performed to test whether the consensus framework outperforms isolated methods in terms of fidelity and design penalty.

**Table\_8: Expected Effect on EMI**

Scenario	Expected Effect on EMI	Possible Trade-off
Baseline converter	Highest conducted and radiated EMI peaks	Best efficiency but poor compliance
Passive filtering only	Strong conducted EMI reduction	Additional volume, cost, and possible resonance
Shielding only	Radiated EMI reduction	Added weight, cost, and thermal constraints
Spread-spectrum or random PWM	Reduction of spectral peaks	Possible control complexity and acoustic/noise considerations
Soft switching	Reduced dv/dt and di/dt stress	Increased circuit complexity
Integrated optimized solution	Balanced reduction of conducted and radiated EMI	Requires multi-objective design and validation

### 8. Discussion

The proposed framework highlights that concepts- and EMI mitigation solutions in power electronics, cannot be effectively addressed by a single component or end-stage filter. EMI factors from the interplay of switching behavior, parasitic networks, control algorithms, cable structures, enclosure geometry as well as grounding paths and measurement configuration. Thus, it is important to ensure that design decisions in electrical, mechanical, control and compliance engineering domains are collated together. One important technical implication is that intervention at the source of EMI also tends to be more effective than suppression following propagation. To mitigate the excite energy into parasitic radiation paths, slower edge rates, optimized gate resistance, snubber circuits for soft switching and modulation shaping can reduce the impact. Nevertheless, this approach could either amplify the losses or act to decrease control bandwidth. Similarly, shielding reduces the radiated emissions but at an expense of extra weight, cost and thermal limits. Therefore, multi-objective optimization is essential.

An additional major consideration is the desire to bridge EMC design and standards. Standards are the written language of compliance, but they need to be translated from limit to parameters that can be controlled in design engineers. Our proposed framework embeds standards into the design loop such that converters can be designed for compliance to a specific standard as opposed to repairing after failure. The framework also accommodates safety evaluation for modern systems e.g., EVs, wireless charging platforms, UAV power converters and microgrids as the majority of the radiated fields may become relevant for human, implant and sensor exposure or they can interfere with wireless communication links. By marrying ICNIRP exposure limits with converter EMI design, the present study makes a point that is much more relevant than traditional emissions testing.

### 9. Expected Originality and Contributions

- Explicitly integrating conducted and radiated EMC as a design goal in power electronic converters instead of just treating it as a post-design test.
- Integrating switching states, modulation sequences, parasitic structures common-mode currents and radiated field behavior in a single framework.
- Combining quantitative optimization constraints with international EMC standards and human exposure limits.

Addition of control-based EMI mitigation and shielding and material co-design for reducing source noise as well as propagation effects.

- Providing an experimental validation methodology by correlating the results of simulations with measurements from LISNs, near-field probes and compliance indicators such as CISPR32.
- Characterization of a trade-off between EMI reduction, power converter loss, thermal stress and overall shielding mass, cost, and implementation complexity.

### 10. Conclusion and Future Directions

This paper has described a standards driven research framework for EM and radiation mitigation for modern power electronic systems. It covered conducted EMI, radiated EMI, switching noise, standards integration, mitigation techniques and validation method. The bottom line is, EMC should be an early design goal rather than a late-stage compliance test

In brief, the approach combines system modeling, EMI sources identification, modulation, filtering and shielding techniques as well as human exposure limits and versatile experimental validation. The framework should integrate EMC standards like CISPR, IEC 61000, FCC Part 15 and ICNIRP exposure limits directly into the engineering workflow helping designers reduce redesign cost, increase reliability and adhere to regulatory compliance in an efficient manner.

Future work should apply the framework on a representative experimental converter, and minimize conducted and radiated EMI in controlled laboratory conditions. Future directions may include machine-learning-based EMI prediction, real-time adaptive EMI control, lightweight composite shielding material development and more digital twins to support the EMC-aware design of power electronics.

### Conflict of Interest Statement

The authors declare no potential conflicts of interest related to this study.

## References

1. Hossain, K. A. (2023). Study on electromagnetic interference (EMI) and electromagnetic compatibility (EMC): sources and design concept for mitigation of EMI/EMC. *Journal of Library Arts and Humanities*, 4(8), 68-96.
2. Mariscotti, A. (2021). Critical review of EMC standards for the measurement of radiated electromagnetic emissions from transit line and rolling stock. *Energies*, 14(3), 759.
3. Mariscotti, A. (2021). Assessment of human exposure to low-frequency electromagnetic fields in modern microgrids, power systems and electric transports. *Energies*, 14(20), 6789.
4. Ramya, K., Gopalakrishnan, J., Chokkalingam, B., Verma, R., & Mihet-Popa, L. (2025). A comprehensive evaluation and assessment practices of electromagnetic interference in electric vehicle. *IEEE Access*, 13, 40520-40560.
5. Asa, E., Mohammad, M., Onar, O. C., Pries, J., Galigekere, V., & Su, G. J. (2020). Review of safety and exposure limits of electromagnetic fields in wireless electric vehicle charging applications. *IEEE Transportation Electrification Conference & Expo (ITEC)*.
6. Hamouda, S. A., & Amineh, N. S. (2024). Electromagnetic interference impacts on electronic systems and regulations. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(1), 124-127.
7. Kour, H., & Jha, R. K. (2020). Electromagnetic radiation reduction in 5G networks and beyond using thermal radiation mode. *IEEE Transactions on Vehicular Technology*, 69(10), 11841-11856.
8. Hirata, A., Onishi, T., Shinohara, N., De Santis, V., Diaz, V., Feliciani, M., & Anh, S. (2026). Electromagnetic field exposure assessment and mitigation strategies for wireless power transfer systems: A review and future perspectives. *IEEE Journal on Wireless Power Technology*.
9. Yao, Y., Jin, S., Zou, H., Li, L., Ma, X., Lv, G., & Shu, Q. (2021). Polymer-based lightweight materials for electromagnetic interference shielding: a review. *Journal of Materials Science*, 56(11), 6549-6580.
10. Al Ali, M., Shimoda, M., Benissa, B., Kobayashi, M., Takeuchi, T., Al-Shawk, A., & Ranjbar, S. (2024). Metaheuristic aided structural topology optimization method for heat sink design with low electromagnetic interference. *Scientific Reports*, 14(1), 3431.
11. Karanaaq, F. A., Emadi, A., & Bilgin, B. (2020). Modeling of conducted emissions for EMI analysis of power converters: State-of-the-art review. *IEEE Access*, 8, 189313-189325.
12. Saied, K., Almutairi, A., Albagami, N., Alrumayh, O., Abo-Khalil, A. G., & Saleeb, H. (2022). A review of DC-AC converters for electric vehicle applications. *Energies*, 15(3), 1241.
13. Diao, F., Du, X., Ma, Z., Wu, Y., Guo, F., Li, Y., & Zhao, Y. (2023). A megawatt-scale Si/SiC hybrid multilevel inverter for electric aircraft propulsion applications. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 11(4), 4095-4107.
14. Kron, D., Lundgren, U., Augusto, A., & Bollen, M. (2024). Radiated electromagnetic emission from photovoltaic systems—Measurement results. *Energies*, 17(8), 1893.
15. Lai, Y., Wang, S., Yang, Y., Huang, Q., & Ma, Z. (2023). Review on modeling and emissions from EMI filters in power electronics: inductors. *Proceedings of the IEEE Symposium on Electromagnetic Compatibility & Signal/Power Integrity*.
16. Singh, D., Shah, D. D., Sokolov, A., & Zakis, J. (2022). An improved spread-spectrum technique for reduction of electromagnetic emissions of wireless power transfer systems. *Electronics*, 11(17), 2733.

17. Zhao, X., Hu, J., Rovi, L., Dong, D., Burgos, R., Chandrasekaran, S., & Eddins, R. (2022). Planar common-mode EMI filter design and optimization for high-altitude 100-kW SiC inverter/rectifier system. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 10(5), 5290-5303.
18. Li, C., Ma, Q., Tong, Y., Wang, J., & Xu, P. (2023). A survey of conductive and radiated EMI reduction techniques in power electronics converters across wide-bandgap devices. *IET Power Electronics*, 16(13), 2121-2137.
19. Pinto, J., Grab, B., & Baptista, J. (2024). Analysis of suppress harmonics emission in power grids: A case study of photovoltaic inverter. *Electronics*, 13(24), 4880.
20. Dai, H., Torres, R. A., Jahns, T. M., & Sarlioglu, B. (2022). Comparative study of conducted common-mode EMI in wide-bandgap DC-fed three-phase current-source inverter. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 10(6), 7188-7204.
21. Dong, X., Gao, Y., Liu, M. (2023). The electromagnetic exposure level of a pure electric vehicle inverter based on a real human body. *Applied Sciences*, 14(1), 32.
22. Mbarik, Z., Mejdoub, Y., Rzahi, K. S., & Sablah, K. (2023). Implementing pseudo-random control in boost converter: An effective approach for mitigating conducted electromagnetic emissions. *Indonesian Journal of Electrical Engineering and Informatics*, 11(3), 805-814.
23. Kang, M. M., Taylor, N., & Minsson, D. (2024). Electromagnetic interference from solar photovoltaic systems: A review. *Electronics*, 14(1), 31.
24. M'barki, Z., Rzahi, K. S., & Mejdoub, Y. (2023). A novel fuzzy logic control for a zero current switching-based buck converter to mitigate conducted electromagnetic interference. *International Journal of Electrical and Computer Engineering*, 13(2), 1423.
25. Jie, H., Zhao, Z., Zeng, Y., Chang, Y., Fan, F., Wang, C., & See, K. Y. (2024). A review of intentional electromagnetic interference in power electronics: Conducted and radiated susceptibility. *IET Power Electronics*, 17(12), 1487-1506.