

Design and Optimization of EMC Filtering Strategies for DC-DC Converters in Electric Vehicles Applications

Soufiane Lghazi¹, Zakaria M'barki¹, Youssef Mejdoub¹, Kaoutar Senhaji Rhazi¹, Ali Ait Salih¹

¹Laboratory of Networks, Computing Science, Telecommunication, and Multimedia (RITM), CED Engineering Sciences, Higher School of Technology, Hassan II University, Casablanca, Morocco

Article Info

Article history:

Received Oct 19, 2025

Revised Jan 7, 2026

Accepted Jan 31, 2026

Keywords:

Electric vehicles

DC-DC converter

Electromagnetic compatibility

Electromagnetic interference

Common-mode and differential-mode noise

ABSTRACT

The rapid electrification of vehicles intensifies electromagnetic interference (EMI) challenges in DC–DC converters, particularly isolated topologies used for high-voltage to low-voltage energy transfer. High-frequency switching generates common-mode (CM) and differential-mode (DM) conducted noise that threatens compliance with stringent CISPR 25 Class 5 standards. This paper proposes the design, modeling, and evaluation of a compact electromagnetic compatibility (EMC) filter capable of simultaneously suppressing CM and DM emissions in an isolated DC–DC converter for electric vehicle applications. The proposed passive filter combines a CM choke with Y-capacitors, a DM π -filter using X-capacitors and series inductors, and an RC damping branch to avoid resonances. The converter and filter were modeled in LTspice, and conducted emission spectra were evaluated using a Line Impedance Stabilization Network (LISN) with Fast Fourier Transform (FFT) analysis. Simulation results demonstrate that conducted emissions are reduced by about 40 dB μ V, ensuring full compliance with CISPR 25 Class 5 limits. The proposed solution offers a cost-effective and practical approach to improve EMC margins and reliability in automotive DC–DC converters. The results presented in this study are based on circuit-level simulations, and experimental validation will be addressed in future work.

Copyright © 2026 Institute of Advanced Engineering and Science.
All rights reserved.

Corresponding Author:

Soufiane Lghazi,
RITM Laboratory, Higher School of Technology, Hassan II University of Casablanca,
Km 7 El Jadida Road-r.p.8, B.P. 20000, Casablanca-Morocco.
Email: lghazisf@gmail.com

1. INTRODUCTION

The rapid development of electric vehicles (EVs) has accelerated the integration of power electronic converters, especially isolated DC–DC converters that transfer energy from high-voltage batteries to low-voltage auxiliary systems. Operating at high switching frequencies improves efficiency and compactness, but it also generates significant electromagnetic interference (EMI) [1-3]. These disturbances propagate through power lines and affect the performance of sensitive on-board electronics. Ensuring electromagnetic compatibility (EMC) has therefore become a critical requirement, with CISPR 25 Class 5 defining the strictest limits for conducted emissions in automotive applications.

Conducted EMI in DC–DC converters typically appears in the 100 kHz–10 MHz range and includes both common-mode (CM) and differential-mode (DM) components [4-6]. Without effective filtering, these emissions exceed regulatory thresholds, leading to communication disturbances, malfunctions, and reduced system reliability. Numerous EMI mitigation techniques have been proposed, including passive filters, active filters, spread spectrum modulation, and modified converter topologies [7-9]. Passive filtering remains the most widely adopted due to its simplicity, robustness, and cost-effectiveness.

In recent years, Active EMI Filters (AEF) have emerged as a promising solution for conducted EMI mitigation in high-power-density applications, including electric vehicles and high-frequency power converters. By actively sensing and canceling noise currents, AEFs can reduce the required size of passive

components and improve low-frequency attenuation. However, their implementation requires additional control circuitry, sensors, power consumption, and careful stability design, which significantly increases system complexity and cost. In automotive DC–DC converters, where reliability, simplicity, and cost-effectiveness are critical constraints, passive filtering solutions remain widely adopted for industrial implementation. Therefore, this work focuses on an optimized passive EMC filter, while acknowledging AEFs as a complementary and promising research direction [10–12].

However, most existing studies address CM and DM noise separately, often requiring bulky or complex designs that are difficult to integrate into automotive platforms. Very few works explicitly target full compliance with CISPR 25 Class 5 limits while also considering practical constraints such as size, cost, and thermal performance [13],[14]. This gap highlights the need for a compact and efficient filtering strategy that simultaneously suppresses CM and DM noise, prevents resonances, and remains compatible with automotive requirements.

This paper proposes the design, modeling, and evaluation of a compact EMC filter integrated into an isolated DC–DC converter for EV applications. The originality of this work lies in the co-optimization of three functional branches: a CM choke with Y-capacitors, a DM π -filter with X-capacitors and inductors, and an RC damping network. Simulation results based on LTspice and LISN analysis demonstrate that the proposed filter achieves around 40 dB μ V attenuation of conducted EMI, ensuring compliance with CISPR 25 Class 5 standards [19], [24]. The proposed solution provides a practical and cost-effective approach to improve EMC margins and system reliability in automotive power electronics.

Unlike many existing works that treat common-mode and differential-mode filtering separately, this study focuses on the co-optimization of CM, DM, and damping branches under CISPR 25 Class 5 constraints for an isolated automotive DC–DC converter. The contribution of this paper lies not in proposing a new topology, but in a systematic design methodology and performance-oriented integration of passive filtering stages, targeting high attenuation, stability, and compactness for EV applications.

2. RESEARCH METHOD

This section presents the objective of this study, which is to design, model, and evaluate an optimized EMC filter for an isolated DC–DC converter used in EV applications as illustrated in Figure 1, simultaneously suppressing both CM and DM conducted EMI to ensure full compliance with CISPR 25 Class 5 limits. The proposed filter architecture integrates three functional stages: a CM choke with Y-capacitors, a DM π -filter using X-capacitors and series inductors, and a damping branch based on a series RC network. The design process includes frequency-domain simulation in LTspice, and conducted EMI evaluation is performed through FFT analysis using a LISN model. This approach targets a compact, passive, and cost-effective EMI mitigation solution suitable for integration into automotive-grade power converters.

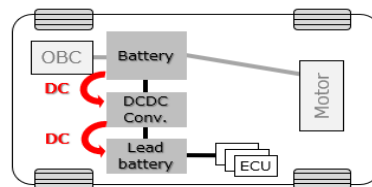


Figure 1. Power electronics in EV

2.1. DC-DC Converter Design and Operation

The DC-DC converter used in this study is based on an isolated topology, which is essential for galvanic isolation and safety in EV architectures [16–20]. The converter steps down a HV input (400–600 V) from the main battery or HV network to a stable LV output (12–14 V) required by standard batteries and the auxiliary systems such as lighting, infotainment, and control units [17], [18].

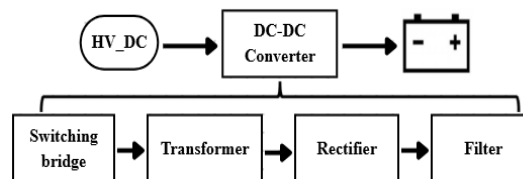


Figure 2. Blocks diagram for DC-DC converter

The converter consists of four main blocks: a full-bridge inverter stage with MOSFET switches, a high-frequency isolation transformer, a full-wave rectifier using Schottky diodes, and a low-pass RC filter, as illustrated in Figure 2 and 3.

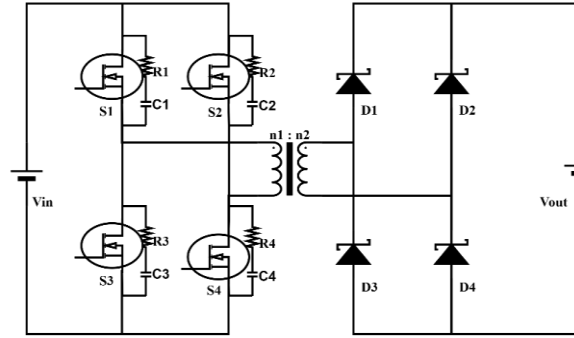


Fig. 3. Equivalent circuit for DC-DC Converter

2.1.1. Power Switching Stage (Inverter Bridge).

The switching bridge, is the first and most critical block of the isolated DC-DC converter. Its primary function is to convert the DC voltage from the high-voltage battery into a high-frequency AC signal suitable for transformer operation. High-frequency operation allows the transformer and passive components to be compact while maintaining high conversion efficiency [16].

In this design, the switching bridge consists of MOSFET power switches arranged in a full-bridge configuration. This topology provides high power handling, and precise output voltage control through pulse-width modulation (PWM). The MOSFETs are driven by a high-speed gate signal, which can be modeled in LTspice using a pulse voltage source [19], as illustrated in Table 1.

Table 1. Mosfet control for DC-DC converter

Parameter	Value
Initial voltage V_{off} , V	0
Peak voltage V_{on} , V	1
Delay before the first pulse T_d , s	0
Rise time T_r , ns	1
Fall time T_f , ns	1
Pulse width T_{on}	D/f_s
Period of the pulse, s	$1/f_s$

The pulse width is determined by the duty cycle ($D = 0.5$) and the switching frequency ($f_s = 400$ kHz), with rise/fall times of 1 ns. This configuration enables fast switching for high efficiency while minimizing conduction losses.

2.1.2. High-Frequency Isolation Transformer

The transformer is the second key block in the isolated DC-DC converter and serves multiple critical functions. Its primary role is to provide galvanic isolation between the high-voltage input and the low-voltage output, ensuring safety for both the vehicle and its occupants. Additionally, the transformer adapts the voltage level from the high-voltage battery (up to 600 V) to the low-voltage range of 12–14V required for auxiliary systems.

The AC signal generated by the switching bridge is applied to the primary winding of the transformer. In this study, the transformer is modeled with a primary inductance $L_1 \approx 2$ mH, a secondary inductance $L_2 \approx 2$ μ H, and a coupling coefficient $K=1$, representing ideal magnetic coupling [20]. The mutual inductance is therefore:

$$M = K\sqrt{L_1 L_2} = 1 \cdot \sqrt{2\text{mH} \cdot 2\mu\text{H}} \approx 63.2\mu\text{H} \quad (1)$$

Where:

- M: Mutual inductance between primary and secondary [H]
- K: Magnetic coupling coefficient ($0 \leq K \leq 1$), 1 for ideal coupling
- L_1 : Primary inductance [H]
- L_2 : Secondary inductance [H]

➤ Determination of L_1 and L_2 :

The values of L_1 and L_2 are determined based on energy storage requirements and the desired current ripple.

Primary inductance L_1 is calculated to limit the peak current in the switching bridge:

$$L_1 = \frac{V_{in} \cdot D}{\Delta I_p \cdot f_s} \quad (2)$$

Where:

- L_1 : Primary inductance of the transformer [H]
- V_{in} : Input voltage (400 – 600 V)
- D : Duty cycle (0.5 for 50%)
- ΔI_p : Maximum allowed primary current ripple [A]
- f_s : Switching frequency (400KHz)

$$L_2 = \frac{V_{out}(1-D)}{\Delta I_p \cdot f_s} \quad (3)$$

Where:

- L_2 : Secondary inductance [H]
- V_{out} : Output voltage (12 - 14 V)
- ΔI_p : Maximum allowed primary current ripple [A]
- f_s : Switching frequency (400KHz)

These equations ensure that the converter meets efficiency and ripple constraints while minimizing transformer size. The turns ratio $n = N_p/N_s$ defines the voltage conversion:

$$V_s = \frac{N_s}{N_p} \cdot V_p \quad (4)$$

Where:

- N_p : Number of primary turns
- N_s : Number of secondary turns
- V_{in} : Input voltage
- V_{out} : Output voltage

2.1.3. Rectifier Circuit.

The rectifier is the third critical block in the isolated DC-DC converter, responsible for converting the high-frequency AC voltage from the transformer secondary into a regulated DC output [17], [21]. In this design, a full-wave rectifier using diodes is employed to maximize efficiency and minimize voltage ripple at the output.

The rectified output voltage V_{out} is related to the secondary AC voltage by:

$$V_{out} = \frac{2 \cdot N_s}{\pi \cdot N_p} \cdot V_p \quad (5)$$

Where:

- V_{out} : Rectified DC output voltage [V]
- V_p : AC voltage applied to the transformer primary [V]
- N_p : Number of primary turns
- N_s : Number of secondary turns
- $\frac{2}{\pi}$: Average/DC conversion factor of a full-wave rectified

The output current ripple ΔI_s depends on the rectifier and the following filter:

$$\Delta I_s = \frac{V_L(1-D)}{L_2 \cdot f_s} \quad (6)$$

Where:

- ΔI_s : Peak-to-peak secondary inductor current ripple [A]
- V_L : Magnitude of the inductor voltage during the OFF interval [V]
- L_2 : Output inductor (smoothing choke) [H]
- D : Duty cycle (0-1)
- f_s : Switching frequency (400KHz)

This equation ensures that the current ripple is within acceptable limits for low-voltage loads and contributes to minimizing stress on passive components.

2.1.4. Damping Filter

In this DC-DC converter, the series RC filter is designed to suppress high-frequency noise and damp resonances caused by the switching bridge and transformer leakage [21]. The capacitor and resistor values are selected based on the converter's voltage ripple, switching frequency, and desired damping.

The capacitor value is primarily determined by the energy storage requirement and the acceptable voltage ripple at the output. For a given voltage ripple ΔV and load current I_{load} , the capacitor can be estimated as:

$$C_{out} = \frac{I_{load}}{\Delta V \cdot f_s} \quad (7)$$

Where:

- C_{out} : Output capacitor value [F]
- I_{load} : Maximum output current [A]
- ΔV : Maximum allowed output voltage ripple [V]
- f_s : Switching frequency (400KHz)

Based on the converter's operating conditions, the calculation leads to $C_{out} = 1.5$ mF, which ensures that voltage fluctuations remain within safe limits for the low-voltage system.

The resistor is chosen to provide adequate damping of high-frequency resonances without excessively reducing efficiency. The damping ratio for a series RC filter is:

$$\gamma = \frac{R_{out}}{2} \cdot \sqrt{\frac{C_{out}}{L_{eq}}} \quad (8)$$

Where:

- γ : Damping ratio (dimensionless) of the RC damping network
- R_{out} : series resistance in the damping branch [Ω]
- C_{out} : Damping capacitor value [F]
- L_{eq} : Equivalent inductance seen by the damping capacitor (includes transformer leakage and line inductances) [H]

For critical or slightly underdamped behavior, $R_{out} = 1\Omega$ provides sufficient damping to suppress oscillations while maintaining efficiency.

2.2. DC-DC Converter Design Overview

The converter was modeled and simulated using LTspice, confirming stable performance under nominal operating conditions with minimal voltage overshoot and rapid dynamic response, as illustrated in Figure 4. The input voltage was set to 400 V, and the output was regulated within the 12–14 V range, delivering up to 160W.

Table 1. Specification of the DC-DC Converter

Parameter	Value
Input Voltage V_{in} , V	400
Output Voltage V_{out} , V	[12 to 14]
Output Power P_{out} , W	160
Switching Frequency f_{sw} , KHz	400
Transformer primary inductance L_1 , mH	2
Transformer secondary inductance L_2 , μ H	2
Duty Cycle D_{cy}	0.5
Coupling coefficient K	1
Output Resistor R_{out} , Ω	1
Output Capacitor C_{out} , mF	1.5

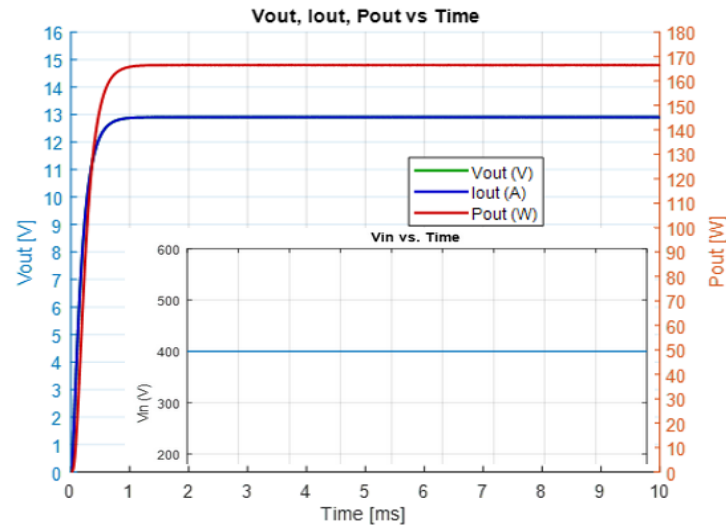


Figure 4. Vout vs. Vin 400V-to-13V DC-DC converter

The switching stage operates at 400 kHz to minimize passive component size and enhance efficiency. The transformer ensures electrical isolation and voltage adaptation, while the output filter smooths the voltage and reduces ripple. Table 1 illustrates the design parameters.

2.3. EMI Characterization Using FFT and LISN

The electromagnetic emission behavior of the converter was assessed through conducted EMI analysis using a Line LISN model. The LISN emulates a standardized impedance (typically $50\ \Omega$) at the power input terminals and isolates the converter's noise from the external power source. Its purpose is to provide a stable reference for EMI measurements and ensure repeatable conditions during testing. The equivalent circuit used in the simulation is shown in Figure 5, which includes $250\ \mu\text{H}$ series inductors and decoupling capacitors of $0.2\ \mu\text{F}$. Two resistive branches ($5\ \Omega$ each) are used to replicate the load effect and measurement ports. This configuration helps to accurately capture the conducted noise in both CM and DM paths. The output noise voltage is measured across the LISN's ports and is analyzed using a FFT algorithm over a frequency range of 100 kHz to 10 MHz, allowing identification of dominant harmonic components and verification of compliance with CISPR 25 Class 5 limits [22].

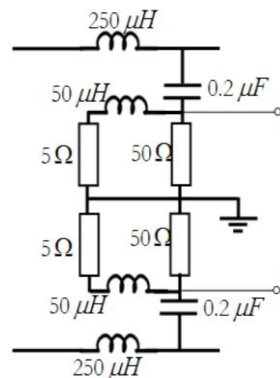


Figure 5. Equivalent circuit for LISN device

Simulation results show that the unfiltered converter generates high levels of conducted EMI, with spectral peaks reaching up to 122 dB μV , as illustrated in Figure 6. These emissions are primarily caused by fast switching transitions, transformer leakage inductance, and parasitic capacitances in the circuit layout [22].

The identified EMI spectrum indicates the presence of both common-mode and differential-mode noise components, which exceed the CISPR 25 Class 5 limits, thus confirming the need for an effective filtering strategy [20].

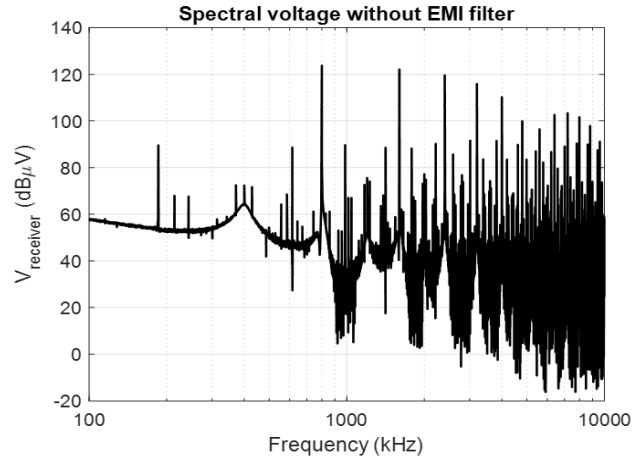


Figure 6. Conducted EMI Spectrum Without Filtering

2.4. EMC Filter Architecture and Design

Based on the conducted EMI spectrum obtained in last section, a dedicated EMC filter was designed to suppress both CM and DM noise components. The proposed filter integrates three distinct branches: a CM filter, a DM π -filter, and a damping network. Each branch targets a specific noise path and is optimized for the relevant frequency band [24-26]. The overall architecture is illustrated in Figures 7 and 8.

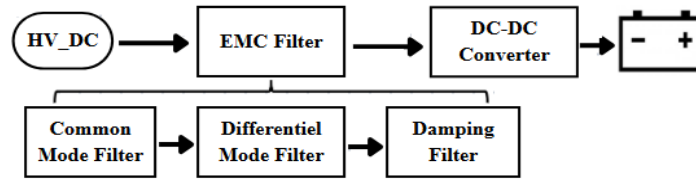


Figure 7. Blocks diagram for EMC filter

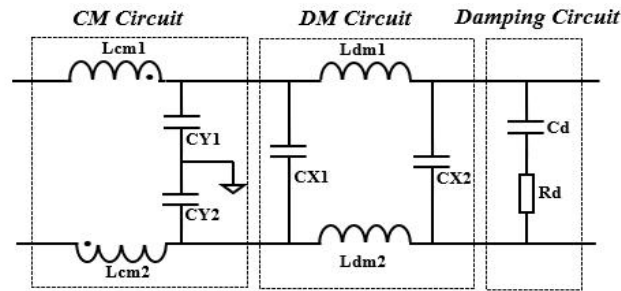


Figure 8. Equivalent circuit for EMC filter

The design goals include the effective attenuation of CM and DM emissions between 100 kHz and 10 MHz, compliance with CISPR 25 Class 5 emission limits, compact implementation suitable for automotive converters, and stability through resonance damping [24].

2.4.1. Common-Mode Filter Design

CM noise originates from parasitic capacitance between switching nodes and ground, typically flowing simultaneously in both positive and negative supply lines relative to the chassis [24]. To suppress this noise, a CM choke and Y-capacitors are used.

The CM choke presents high impedance to CM currents while minimally affecting DM currents due to its symmetrical winding. Two Y-capacitors (10nF each) are placed from each supply line to ground to provide a low-impedance path for high-frequency CM currents.

The resonance frequency of the common-mode filtering branch is estimated using standard LC resonance relationships widely reported in the EMC literature.

2.4.2. Differential-Mode Filter Design

DM noise appears between the positive and negative supply lines due to high di/dt switching currents [22]. A π -filter is used to attenuate these disturbances, consisting of two series inductors (DM chokes) and two X-capacitors placed between the lines.

The resonance frequency for each leg is calculated as:

$$f_{DM} = \frac{1}{2\pi\sqrt{L_{DM}C_X}} \quad (9)$$

$$L_{DM} = \frac{1}{(2\pi f_{DM})^2 C_X} \approx 419 \mu\text{H} \quad (10)$$

Where,

- L_{DM} : Inductance of the differential-mode filter[H]
- C_X : X-capacitor value [F]; (1nF)
- f_{DM} : Resonance frequency of the differential-mode filtering branch [Hz]

The filter is designed to attenuate switching noise centered around 246 kHz. The π -filter topology offers symmetrical noise suppression and helps decouple CM and DM interference paths, improving the overall filtering efficiency and EMI performance of the system [25].

2.4.3. RC Damping Network

To prevent resonances between filter stages and parasitic elements, a damping circuit is added. It consists of a series resistor and capacitor tuned to attenuate low-frequency oscillations and overshoot [25].

The damping frequency is selected as:

$$f_d = \frac{1}{2\pi R_d C_d} \quad (11)$$

$$R_d = \frac{1}{2\pi f_d C_d} \approx 4.70 \text{ k}\Omega \quad (12)$$

Where

- f_d : Cutoff frequency of branch [Hz]
- R_d : Series resistance of the damping branch [Ω]
- C_d : Damping capacitor [F]

The resulting damping frequency is approximately 338 Hz, which effectively suppresses low-frequency resonance phenomena between filter components and parasitic elements, without affecting the converter's nominal operation [25].

3. RESULTS AND DISCUSSION

3.1. Simulation Results and EMI Attenuation

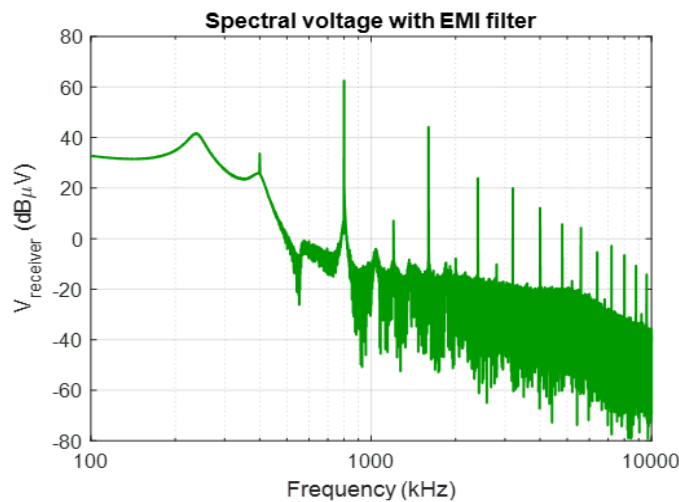


Figure 9. Conducted EMI with filtering (FFT, 100 kHz–10 MHz); Class-5 limit shown

The proposed DC-DC converter and its integrated EMC filter were simulated using LTspice to evaluate their performance under realistic operating conditions. The simulation environment included a LISN and FFT analysis to extract conducted EMI levels before and after filtering.

The unfiltered converter exhibited multiple EMI peaks between 100 kHz and 10 MHz, with amplitudes reaching up to 122 dB μ V. These emissions exceeded the CISPR 25 Class 5 conducted emission limits and were primarily due to rapid switching transitions and parasitic elements in the converter layout. The most prominent peaks were observed around 126 kHz and 246 kHz, corresponding to CM and DM interference.

After integrating the EMC filter, the FFT analysis showed a significant reduction in EMI amplitudes, conducted emissions were reduced by approximately 40 dB μ V across the targeted frequency range, as illustrated in figure 9. The filter effectively attenuated both CM and DM components, bringing the overall spectrum below the CISPR 25 Class 5 limits.

3.1.1. Impact of Parasitic Elements

It should be noted that at high frequencies, particularly above 10 MHz, the conducted EMI behavior is strongly influenced by parasitic effects such as the equivalent series resistance (ESR) and equivalent series inductance (ESL) of capacitors, as well as stray inductances associated with PCB traces and interconnections. In the present study, ideal component models were primarily used to focus on the fundamental EMI attenuation mechanisms of the proposed filter. In practical implementations, particularly above 10 MHz, parasitic elements may shift resonance frequencies, reduce attenuation effectiveness, and introduce additional high-frequency ringing. Therefore, incorporating detailed parasitic models and PCB layout effects constitutes an important extension of this work and will be addressed in future experimental validation.

3.1.2. Impact of MOSFET Switching Dynamics

In practical DC-DC converters, MOSFETs exhibit non-ideal switching behavior with finite $\frac{dv}{dt}$ and $\frac{di}{dt}$, as well as package- and gate-drive-related parasitics, which can cause voltage overshoot and high-frequency ringing. In this study, manufacturer-based MOSFET models were used in the LTspice simulations, including finite switching times, nonlinear output capacitance, body diode behavior, and switching losses, enabling realistic representation of the main semiconductor-related conducted EMI mechanisms. However, PCB layout and detailed gate-drive parasitics were not explicitly modeled, which may lead to some underestimation of high-frequency EMI. Nevertheless, the results remain valid for conducted EMC analysis and for evaluating the relative effectiveness of the proposed filter, while full layout modeling and experimental validation are left for future work.

3.1.3. Insertion Loss Analysis

To quantitatively assess the effectiveness of the proposed EMC filter, the insertion loss (IL) was calculated as the difference between the conducted EMI spectra measured with and without the filter. The insertion loss is defined as:

$$IL(f) = V_{Unfiltered}(f) - V_{Filtered}(f) \quad (13)$$

Where $V(f)$ is the noise voltage magnitude expressed in dB μ V at frequency f . Based on the FFT results, the proposed filter provides an insertion loss of approximately 30–45 dB over the dominant frequency range between 150 kHz and 10 MHz, with maximum attenuation observed around the main CM and DM resonance frequencies. These results confirm the strong attenuation capability of the filter and provide a clearer quantitative evaluation of its EMI suppression performance.

3.1.4. High-Frequency Effects of Cables, LISN, and Y-Capacitors

At high frequencies, conducted EMI measurements are influenced not only by the converter and filter, but also by the interconnecting cables, the measurement setup, and safety-related components. Power cables can exhibit antenna-like behavior above several tens of megahertz, leading to additional radiation and coupling effects that are not captured in simplified circuit-level simulations. In addition, the high-frequency behavior of the LISN may deviate from its ideal impedance due to parasitic elements, which can affect the measured EMI spectrum. Furthermore, the selection of Y-capacitors in automotive applications is constrained by safety standards and leakage current limits, which may restrict the achievable common-mode attenuation. In the present study, simplified cable and LISN models were used to focus on conducted EMI behavior. A more comprehensive high-frequency modeling of cables, LISN, and safety constraints will be addressed through experimental measurements in future work.

The final EMI spectrum confirms the effectiveness of the proposed filtering strategy in achieving regulatory compliance without compromising converter performance. The simulation results validate the design approach and demonstrate the practical viability of the filter in automotive applications.

3.2. Compliance with CISPR 25 Class 5 Standards

CISPR 25 Class 5 defines the strictest limits for conducted electromagnetic emissions in automotive electronic systems, particularly those related to safety and communication. These limits are applied over the 150 kHz to 108 MHz range and must be met to ensure homologation and electromagnetic compatibility in production vehicles.

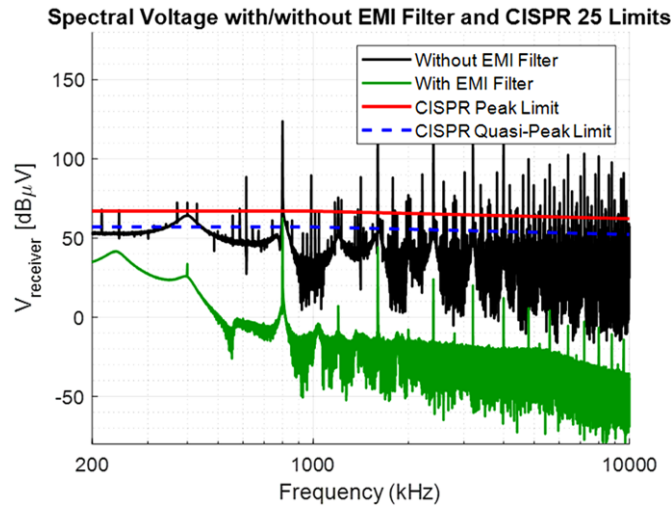


Figure 10. Compliance plot: unfiltered vs. filtered spectra vs. CISPR 25 Class 5

Based on the simulation illustrated in Figure 10, the results presented in this figure confirm that the proposed EMC filter reduces both CM and DM EMI levels to values well below the Class 5 limits in the 100 kHz to 10 MHz frequency band, which includes the dominant emission peaks of the converter. By achieving attenuation levels of approximately 40 dBμV, the designed filter ensures full compliance with the regulatory thresholds [19], [24]. This demonstrates the effectiveness of the co-optimized filter architecture and validates its applicability for integration into automotive DC-DC converters intended for use in high-EMC-demand environments.

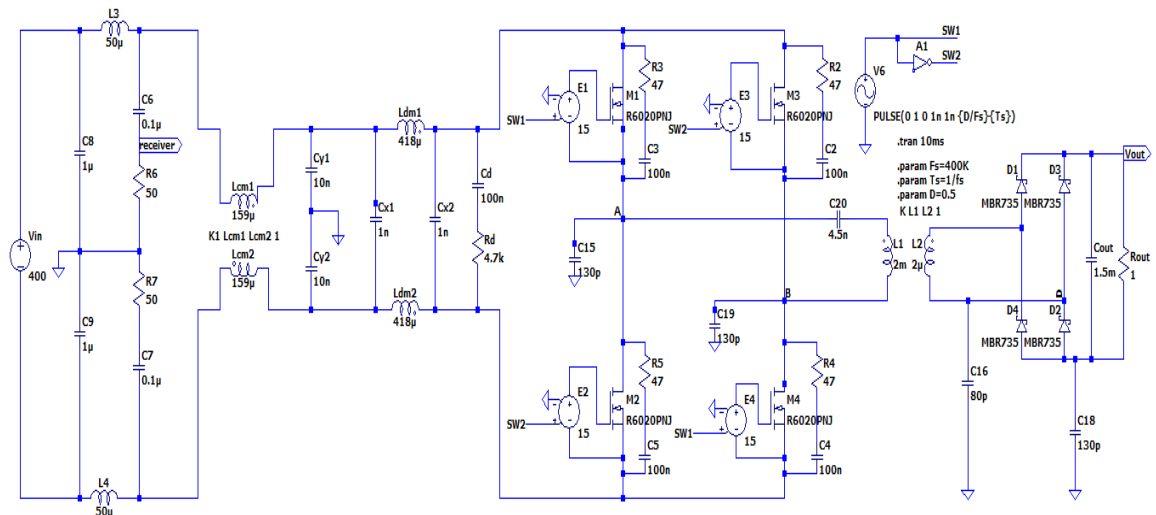


Figure 11. LTspice Simulation of DC-DC Converter with integrated EMI Filter

Figure 11 illustrates the complete LTspice simulation schematic of the isolated DC-DC converter with the integrated EMC filter, highlighting the implementation of the CM, DM, and damping branches used in the conducted EMI analysis.

4. CONCLUSION

This paper presented the design, modeling, and evaluation of a compact electromagnetic compatibility (EMC) filter for an isolated DC–DC converter in electric vehicle (EV) applications. The proposed solution combines three co-optimized branches: a common-mode filter with a choke and Y-capacitors, a differential-mode π -filter with X-capacitors and inductors, and an RC damping network.

Simulation results based on LTspice and FFT analysis with a LISN model demonstrated that the filter suppresses both common-mode and differential-mode conducted noise by approximately 40 dB μ V in the 100 kHz–10 MHz band. This ensures full compliance with CISPR 25 Class 5 standards, representing the strictest requirements for automotive EMC.

Although the individual filter components are based on classical passive structures, the originality of this work lies in the coordinated design and optimization of the common-mode filter, differential-mode π -filter, and RC damping network under stringent CISPR 25 Class 5 constraints for isolated DC–DC converters in electric vehicle applications. This systematic co-design approach enables high EMI attenuation, stability against resonances, and compact implementation, which are critical requirements for automotive power electronics.

Future work will focus on the implementation of a hardware prototype and experimental conducted EMI measurements in a certified EMC laboratory to validate the simulation results and assess the impact of real components, parasitic effects, and PCB layout constraints.

The proposed EMC filtering strategy can be directly applied to isolated DC–DC converters used in electric vehicle auxiliary power modules, on-board chargers, and power distribution units. Its compact and fully passive structure makes it suitable for integration into automotive power electronics systems where space, reliability, and compliance with CISPR 25 Class 5 standards are critical requirements.

ACKNOWLEDGMENTS

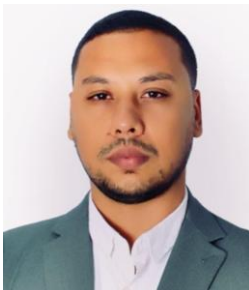
The authors would like to express their sincere gratitude to all members of the RITM laboratory at ESTC for their valuable support and guidance throughout the development of this research.

REFERENCES

- [1] L. Yuan, J. Zhang, Z. Liang, M. Hu, G. Chen, and W. Lu, "EMI challenges in modern power electronic-based converters: recent advances and mitigation techniques," *Frontiers in Electronics*, vol. 4, Nov. 2023, doi: <https://doi.org/10.3389/felec.2023.1274258>.
- [2] H. Tekin, S. Vatansever, and D. Ertekin, "Evaluation and Implementation of EMI/EMC Compliance for a Proposed Power Electronics-Based Converter Topology for Electric Vehicles," *Elektronika ir Elektrotechnika*, vol. 30, no. 5, pp. 22–30, Oct. 2024, doi: <https://doi.org/10.5755/j02.eic.38216>.
- [3] L. Zhai, G. Hu, M. Lv, T. Zhang, and R. Hou, "Comparison of Two Design Methods of EMI Filter for High Voltage Power Supply in DC-DC Converter of Electric Vehicle," *IEEE Access*, vol. 8, pp. 66564–66577, 2020, doi: <https://doi.org/10.1109/access.2020.2985528>.
- [4] A. Zeghoudi, H. Slimani, A. Bendaoud, B. Benazza, S. Bechekir, and H. Miloudi, "Measurement and analysis of common and differential modes conducted emissions generated by an AC/DC converter," *Electrical Engineering & Electromechanics*, no. 4, pp. 63–67, Jul. 2022, doi: <https://doi.org/10.20998/2074-272x.2022.4.09>.
- [5] B. Benazza, A. Bendaoud, H. Slimani, M. Benaissa, M. Flitti, and A. Zeghoudi, "Experimental study of electromagnetic disturbances in common and differential modes in a circuit based on two DC/DC boost static converter in parallel," *Electrical Engineering & Electromechanics*, no. 4, pp. 35–39, Jun. 2023, doi: <https://doi.org/10.20998/2074-272x.2023.4.05>.
- [6] S. Bechekir, A. Zeghoudi, D. Ould-Abdeslam, M. Brahmi, H. Slimani, and A. Bendaoud, "Development of a boost-inverter converter under electromagnetic compatibility stress equipping a photovoltaic generator," *Electrical Engineering & Electromechanics*, no. 5, pp. 14–19, Aug. 2023, doi: <https://doi.org/10.20998/2074-272x.2023.5.02>.
- [7] A. Ouhammam, H. Mahmoudi, Y. El Hachimi, and A. Daghour, "Simulation and optimization of EMI filter of conducted emission for high voltage gain DC-DC converter," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 2, p. 902, Jun. 2024, doi: <https://doi.org/10.11591/ijpeds.v15.i2.pp902-912>.
- [8] Z. M'barki, A. A. Salih, Y. Mejdoub, and K. S. Rhazi, "Digital pseudo-random modulation: a key to EMI reduction in EVs boost converters," *International Journal of Applied Power Engineering (IJAPE)*, vol. 13, no. 3, p. 594, Sep. 2024, doi: <https://doi.org/10.11591/ijape.v13.i3.pp594-602>.
- [9] S. Chaudhuri, I. Mukherjee, and S. Hemamalini, "Mitigation of Electromagnetic Interference from DC-DC Converters for Electric Vehicle Application," *Artificial Intelligence for Sustainable Energy*, pp. 195–208, 2024, doi: https://doi.org/10.1007/978-981-99-9833-3_14.
- [10] S. Kalaiarasu and S. Natarajan, "Multi-level active EMI filter for conducted EMI noise mitigation for TSCB converter in EV applications," *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, vol. 47, 2023, doi: <https://doi.org/10.1007/s40998-023-00607-8>.
- [11] M. Darisi, T. Caldognetto, D. Biadene, and M. Stellini, "Digital active EMI filter for smart electronic power converters," *Electronics*, vol. 13, no. 19, 2024, doi: <https://doi.org/10.3390/electronics13193889>.

- [12] B. Narayanasamy and F. Luo, "A Survey of Active EMI Filters for Conducted EMI Noise Reduction in Power Electronic Converters," *IEEE Transactions on Electromagnetic Compatibility*, vol. 61, no. 6, pp. 2040–2049, Dec. 2019, doi: <https://doi.org/10.1109/TEM.2019.2953055>.
- [13] Z. M'barki, K. S. Rhazi, and Y. Mejdoub, "A proposal of structure and control overcoming conducted electromagnetic interference in a buck converter," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 1, p. 380, Mar. 2022, doi: <https://doi.org/10.11591/ijpeds.v13.i1.pp380-389>.
- [14] Z. M'barki, A. Ait Salih, Y. Mejdoub, and K. Senhaji Rhazi, "Strategic electromagnetic interferences suppression in boost converters: zero-switch techniques," *International Journal of Advances in Applied Sciences*, vol. 13, no. 2, p. 340, Jun. 2024, doi: <https://doi.org/10.11591/ijaas.v13.i2.pp340-350>.
- [15] Y. Li et al., "Analysis and Design of a High-Frequency Isolated Dual-Transformer DC-DC Resonant Converter," *Electronics*, vol. 12, no. 1, p. 103, Dec. 2022, doi: <https://doi.org/10.3390/electronics12010103>.
- [16] M. Forouzesh, X. Yu, Y.-F. Liu, et al., "4 kW Auxiliary Power Module for Electric Vehicles Utilizing a Dual-Phase LLC DC–DC Converter," in *Proc. IEEE Applied Power Electronics Conf. (APEC)*, 2025, pp. 1892–1898, doi: <https://doi.org/10.1109/APEC20253219.2025.10497236>.
- [17] S. B. Sudarshan and G. Arunkumar, "Isolated DC–DC power converters for simultaneous charging of electric vehicle batteries: research review, design, high-frequency transformer testing, power quality concerns, and future," *Sustainability*, vol. 15, no. 3, p. 2813, 2023, doi: <https://doi.org/10.3390/su15032813>.
- [18] S. Coelho, V. Monteiro, and J. L. Afonso, "Topological advances in isolated DC–DC converters: High-efficiency design for renewable energy integration," *Sustainability*, vol. 17, no. 6, p. 2336, 2025, doi: <https://doi.org/10.3390/su17062336>.
- [19] P.-C. Chen, W.-C. Lin, M.-C. Tsai, G.-C. Hsieh, and H.-I. Hsieh, "Analysis, Simulation and Design of Soft-Switching Mechanisms in DC to DC Step-Down Converter," *2019 IEEE 4th International Future Energy Electronics Conference (IFEEEC)*, pp. 1–5, Nov. 2019, doi: <https://doi.org/10.1109/ifeec47410.2019.9015023>.
- [20] Y. Shen, H. Wang, A. Al-Durra, Z. Qin, and F. Blaabjerg, "A Structure-Reconfigurable Series Resonant DC–DC Converter With Wide-Input and Configurable-Output Voltages," *IEEE Transactions on Industry Applications*, vol. 55, no. 2, pp. 1752–1764, Mar. 2019, doi: <https://doi.org/10.1109/tia.2018.2883263>.
- [21] G. Merlin Suba and M. Kumaresan, "Design of LLC resonant converter with silicon carbide MOSFET switches and nonlinear adaptive sliding controller for brushless DC motor system," *Electrical Engineering & Electromechanics*, no. 4, pp. 34–43, Jul. 2022, doi: <https://doi.org/10.20998/2074-272x.2022.4.05>.
- [22] R. Amjadifard, F. Bagheroskouei, and V. Talebzadeh, "Conducted EMI Noise Modelling for DC–DC Converters Based on the Time-Domain Measurements," *IET Power Electronics*, vol. 18, no. 1, Jan. 2025, doi: <https://doi.org/10.1049/pel2.70026>.
- [23] A. Ait Salih, Z. M'barki, Y. Mejdoub, and K. S. Rhazi, "Black-box modelling of electromagnetic compatibility in DC-DC converters for electric vehicles," *Acta IMEKO*, vol. 14, no. 2, pp. 1–8, Jun. 2025, doi: <https://doi.org/10.21014/actaimeko.v14i2.2035>.
- [24] Y. Kobori, Y. Sun, and H. Kobayashi, "Selective Notch Frequency Technology for EMI Noise Reduction in DC–DC Converters: A Review," *Sensors*, vol. 25, no. 10, p. 3196, May 2025, doi: <https://doi.org/10.3390/s25103196>.
- [25] K. Sabhi, M. Talea, H. Bahri, and S. Dani, "Integrating dual active bridge DC-DC converters: a novel energy management approach for hybrid renewable energy systems," *Electrical Engineering & Electromechanics*, no. 2, pp. 39–47, Mar. 2025, doi: <https://doi.org/10.20998/2074-272x.2025.2.06>.
- [26] V. Pandey, K. Hatua, and S. Bhattacharya, "Mitigation of Conducted Electromagnetic Noise of DC–DC Converter by a Novel Inductor–Diode Based Circuit Technology," *IEEE Transactions on Power Electronics*, vol. 40, no. 6, pp. 8125–8138, Jun. 2025, doi: <https://doi.org/10.1109/tpel.2025.3539848>.

BIOGRAPHY OF AUTHORS



Soufiane Lghazi was born in Morocco in 1997. He is a Ph.D. student at the Laboratory of Networks, Computing Science, Telecommunication, and Multimedia (RITM), ESTC Casablanca, Hassan 2 University in Morocco. In 2021, he graduated from Morocco's National School of Computer Science and Systems Analysis with a master degree in embedded systems for automotive. His research activities include the development of a control structure capable of optimizing electromagnetic emissions in electrical vehicles. He can be contacted at email: lghazisf@gmail.com.



Zakaria M'barki was born in Morocco in 1990. He is a Ph. D researcher at the Laboratory of Networks, Computing Science, Telecommunication, and Multimedia (RITM), ESTC Casablanca, Hassan 2 University in Morocco. In 2014, he graduated with honors from Morocco's National School of Electricity and Mechanics with a degree in Electrical and Telecommunication Engineering. His research activities include the development of a control structure capable of optimizing electromagnetic emissions in power electronics converters. He also has research interests in renewable energy sources, FACTS, power systems, and control system applications. He can be contacted at email: mbarki.ensem@gmail.com.



Youssef Mejdoub was born in Morocco, in 1980. He received his Ph.D. Thesis on Modeling of Multiconductor Transmission Lines, in 2014 from Cadi Ayyad University, Marrakech Morocco. Since 2016, he has been a Professor at the Superior school of technology (EST), University of Hassan II of Casablanca. He currently works at the Electrical Engineering Department, Superior school of technology. His current research interests are antennas, electromagnetic compatibility, and MTL lines. He can be contacted at email: ymejdoub@yahoo.fr or youssef.mejdoub@univh2c.ma.



Kaoutar Senhaji Rhazi qualified professor in Electrical Engineering; at the School of Technology in Casablanca. Morocco. A graduate engineer in electrical engineering from the Mohammadia School of Engineers (EMI) in Rabat. Morocco (in 1991). Had the research preparation certificate (CPR) in telecommunications Ph.D. in July 2006 (in electromagnetic compatibility). Passed academic qualification in the same field in 2014. Became higher education teacher in 2020. Current research interests are: 'power electronics' and 'electromagnetic compatibility'. She can be contacted at email: ka.mhome.2024@gmail.com.



Ali Ait Salih is a Ph.D. student at the Laboratory of Networks, Computing Science, Telecommunication, and Multimedia (RITM), ESTC Casablanca, Hassan II University, Morocco. His current research interests include power electronics and electromagnetic compatibility. He can be contacted at email: alitsalihi@gmail.com.