Adaptive electromagnetic interference mitigation for wide-bandgap power converters: a review

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ABSTRACT

Wide-bandgap (WBG) semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN) enable higher switching frequencies, greater efficiency, and increased power density, but their fast-switching transients and steep dv/dt and di/dt characteristics generate substantially elevated electromagnetic interference (EMI). This review synthesizes peer-reviewed studies to quantitatively compare EMI mitigation outcomes across source-side modulation, gate-driving, filtering, packaging, and AI-based techniques for WBG converters. Packaging-integrated common-mode screens cut CM current by up to 26 dB while raising partial-discharge inception voltage by 53%. Chaotic PWM with passive filtering reaches up to 50 dB attenuation with a 74% reduction in inductor volume. AI-based closed-loop adaptation attains up to 19.2 dB average attenuation with 98.5% CISPR 25 compliance, while RL-based filters reach 25-30 dB across wide frequency ranges. Active gate-driving reduces peak EMI by 19-39 dB. No single technique simultaneously delivers the highest suppression, efficiency, and lowest cost. Hybrid Si/WBG design currently offers the most balanced trade-off. These outcomes are consolidated into a taxonomy of propagation mechanisms, mitigation techniques, application-specific strategies across five domains, and open gaps in standardized testing and validation. These findings provide a practical, quantitative reference for engineers designing next-generation, EMC-compliant WBG power electronic systems.

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1. INTRODUCTION

Wide-bandgap (WBG) semiconductor technologies, including silicon carbide (SiC) and gallium nitride (GaN), have transformed power electronics by facilitating elevated switching frequencies, enhanced efficiency, and increased power density. These devices are now central to converter design across electric vehicles, renewable energy systems, and aerospace power networks, where compact size and high efficiency are essential design drivers [1]-[4].

Nonetheless, these benefits are accompanied by the considerable issue of heightened electromagnetic interference (EMI), both conducted and radiated, resulting from the rapid switching transients and elevated dv/dt and di/dt attributes of WBG devices [3], [4]. A diverse range of EMI mitigation solutions has been presented in the literature, encompassing sophisticated passive and active filtering, adaptive modulation algorithms, enhanced packaging, and real-time control methods [5]-[7].

However, these solutions are dispersed across disciplines and application domains, and a systematic, comparative assessment of adaptive EMI mitigation strategies specifically tailored to WBG-based converters remains lacking. This absence of a consolidated reference makes it difficult for researchers and engineers to select and combine techniques appropriate to their application and to identify open research directions.

Recent surveys have examined EMI in WBG power electronics broadly [1], [2], but they largely catalog mitigation techniques descriptively rather than quantitatively comparing their reported attenuation, efficiency, and cost outcomes, and give limited attention to the adaptive, real-time, and AI-based control strategies that have emerged only in the past few years. This review addresses that gap. Unlike prior surveys, it consolidates propagation mechanisms, mitigation techniques, application-specific strategies, and design trade-offs into a single taxonomy, with particular emphasis on adaptive and real-time mitigation strategies, and quantitatively compares reported outcomes across techniques to support the design of next-generation, EMC-compliant WBG power electronic systems.

2. METHOD

The literature search covered publications from 2018 to 2026, using search-term groups spanning foundational EMI concepts, adaptive mitigation techniques, alternative terminology, contrasting perspectives, interdisciplinary connections, and related applications, supplemented by citation crawling from highly-cited seed papers to identify additional candidates. Candidates were screened for direct relevance to EMI generation or mitigation in WBG converters against the inclusion and exclusion criteria described above, and duplicate records across search groups were removed. This process yielded the 62 peer-reviewed references synthesized in this review.

3. RESULTS AND DISCUSSION

3.1. EMI generation mechanisms and propagation paths

Wide-bandgap (WBG) devices such as SiC and GaN achieve much faster voltage and current slew rates during switching transients than silicon counterparts, and these high-edge-rate transitions are the fundamental physical driver of elevated conducted and radiated electromagnetic interference (EMI) [8], [9]. The sharp edges of switching waveforms with high dv/dt produce high-frequency conducted and radiated EMI noise by concentrating spectral energy at harmonics that extend well into the tens-of-MHz range and beyond [10].

High dv/dt and di/dt act as noise sources that drive displacement currents through parasitic capacitances inherent in the power module package, transformer windings, and semiconductor-to-ground coupling paths [11]. These parasitic capacitances provide return paths for both common-mode (CM) and differential-mode (DM) noise currents, with CM current flowing through the ground path becoming the dominant contributor to conducted EMI [11]. WBG devices exhibit faster di/dt and dv/dt and are more sensitive to parasitic inductances in the power module, so the coupling between switching transient waveforms and propagation paths is formed through these parasitic inductances [12]. CM current is not solely driven by the CM noise source; asymmetric parasitic parameters in the power module also convert DM noise sources into CM current [12].

Common-mode noise current circulating through the ground path is the major contributor to radiated EMI in the 30 MHz to 1 GHz range [11]. In WBG-based converters, the CM current is strongly related to dv/dt variations, and higher switching frequencies push spectral content into the radiated EMI band above 30 MHz that was rarely reached in the Si era [2], [11]. Secondary common-mode currents can act as a monopole antenna, with the primary common-mode current generating secondary CM noise through impedance imbalance in the power supply side [10]. Experimental measurements confirm that secondary CM current is the dominant source of radiated emission in buck converter systems [10]. Table 1 below shows the mechanism of conducted EMI noise in WBG converters with parasitic elements.

Table 1. Conducted EMI noise mechanisms and their associated parasitic elements in WBG converters

Noise mechanism	Physical driver	Propagation path	Key parasitic element
CM conducted noise	High dv/dt	Ground return via parasitic capacitance	Semiconductor-to-ground capacitance [11]
DM conducted noise	High di/dt	Loop formed by parasitic inductance	Power loop inductance [12]
CM from DM coupling	Asymmetric layout	DM-to-CM conversion via unbalanced parasites	Mismatched module parasites [12]

3.2. Taxonomy of adaptive EMI mitigation techniques

While WBG semiconductors offer efficiency, switching-speed, and power-density benefits, they also generate heightened conducted and radiated EMI that can exceed regulatory thresholds and interfere with nearby equipment. The literature identifies several categories of EMI mitigation for WBG converters, discussed in turn below.

3.2.1. Source-side adaptive modulation

Spread-spectrum modulation (SSM) techniques redistribute EMI energy across a wider frequency band, reducing spectral peaks without hardware changes. The study [13] experimentally demonstrates that SSM reduces CM conducted EMI peaks by 2 dB in WBG traction inverters, while an auxiliary switching leg achieves 25 dB reduction at 160 kHz [13]. Multi-rate SSM (MR-SSM) spreads spectra across a wider range without aliasing spikes, achieving 29% further peak EMI reduction compared to fixed-rate SSM in a GaN automotive converter [14]. Chaotic PWM variants extend this concept: chaotic Gaussian PWM (CGPWM) combined with a passive filter achieves up to 50 dB EMI attenuation while reducing CM inductor volume by 74% and inductance by 60% [15]. Kent mapping-based chaotic frequency modulation suppresses conducted CM EMI in dual active bridge converters by varying the switching frequency stochastically [16].

Adaptive switching frequency PWM (ASFPWM) extracts three-phase current harmonics via a Second Order Generalized Integral and adjusts switching frequency within a specified range based on harmonic amplitude, effectively reducing conducted EMI compared to constant-frequency PWM in SiC inverters [17]. Sigma-delta modulation strategies for GaN three-phase converters reduce or eliminate CM voltage dv/dt transitions, suppressing conducted EMI noise spikes while maintaining efficiency and total harmonic distortion comparable to hexagonal sigma-delta modulation [6]. Phase-shifted modulation in four-switch buck-boost converters achieves selective CM noise mitigation, enabling 30% volume reduction of the CM filter [18].

3.2.2. Active gate driving and switching control

Active gate drivers (AGDs) dynamically shape switching transients to balance EMI against switching loss. Zhao *et al.* categorize AGD methodologies for SiC MOSFETs, noting their capacity to reduce EMI noise, enhance device reliability, and rebalance mismatched parameters in parallel- and series-connected devices [9]. An emulated Miller plateau tracking scheme identifies critical di/dt and dv/dt instants and uses adaptive-strength gate driving to optimize EMI and switching loss, achieving 19.23 dB peak EMI reduction in Band B and 9 dB in Band C/D with only 2.44% efficiency penalty at 10 MHz [19]. A Gaussian switching scheme implemented on-chip for GaN power switches reduces conducted EMI by 35.8 dB at 10 MHz and 38.7 dB at 100 MHz, with reconfigurable slopes enabling per-standard efficiency optimization [9].

Switching-sequence-based control (SBC) uses Lyapunov-function-based switching sequences with EMI regulatory standards embedded as constraints, mitigating both DM and CM EMI across wide operating regions without compromising converter regulation [20]. A gate-notch filter combined with PCB layout optimization suppresses SiC MOSFET voltage oscillations through parasitic inductance cancellation, improving system stability [21]. Gate driver power supply architectures can reduce CM current by 25.3% peak-to-peak through connection-method changes without adding passive components [22].

3.2.3. Active filtering, propagation-path control closed-loop adaptation

Active EMI filters (AEFs) cancel noise by sensing and injecting compensating signals, significantly reducing filter volume. A hybrid EMI filter incorporating an active Y-capacitor achieves 10–30 dB CM noise reduction from 150 kHz to 30 MHz with 76% volume reduction compared to passive filters [7]. A transformer-less AEF based on virtual impedance enhancement uses feedforward current-sensing-voltage-compensating control, applicable to both AC and DC power lines [23]. An AEF with an integrated PCB Rogowski coil CM current sensor achieves 22.8–30.3 dB insertion loss at 10–30 MHz and 44.7 dB at 1.4 MHz, using high-order lead compensation to counteract phase lag at high frequencies [24]. Predictive pulsed compensation synchronizes a compensation signal to converter switching events and injects it through input capacitors, compensating hardware time delays that analog active filters cannot address [25].

At the propagation-path level, integrated CM screens in SiC MOSFET power modules connected to the DC-link midpoint achieve up to 26 dB CM current reduction at the module baseplate while improving efficiency by 0.5% [26]. Near-field shielding techniques and a novel shielded-windings PCB inductor reduce CM noise by up to 35 dB in a buck converter [27]. Mutual coupling models eliminate parasitic inductance in EMI filter capacitors up to 40 MHz, reducing DM noise from 3.5 to 30 MHz [28]. Passive CM cancellation using two CM transformers on the input and output sides of an inverter achieves 40 dB reduction at both sides simultaneously [29]. Balance techniques using Wheatstone bridge configurations with input parasitic inductors suppress CM EMI in DC-AC converters with high power density [30].

Closed-loop EMI regulation represents the most adaptive paradigm. [31] integrates a wide-bandwidth in situ EMI sensor with autocovariance-based spectrum analysis and a global excess-spectrum modulator, achieving 9-kHz-resolution EMI regulation with 500-MHz sampling bandwidth and 1-mV sensing accuracy [31]. An on-chip EMI adaptive self-cancellation technique with auto-phase-aligned control maintains ripple cancellation across 150% input and 200% output voltage changes, achieving 9.5 dB reduction alone and 16.5 dB combined with BER-conscious SSM [32]. A frequency-band-aware physics-informed GAN predicts EMI spectra with 2.1 dB mean error and maps predicted spectra to optimal passive filter parameters, achieving

19.2 dB average attenuation with 98.5% CISPR 25 compliance across 32 operating conditions [33]. Table 2 illustrates the comparative assessment of these three adaptive EMI mitigation techniques.

Table 2. Comparison of three adaptive EMI mitigation approaches

Dimension	Active gate driver	Spread-spectrum modulation	Active EMI filter
Target	Switching transient shaping	Spectral energy redistribution	Noise sensing and injection
Hardware change	Gate driver circuit	Software only	Sensing and injecting circuits
Typical attenuation	9–19 dB [19], [32]	2–50 dB [13], [15]	10–44 dB [7], [34]
Efficiency impact	2.4% penalty [19]	Minimal [6]	Volume reduction 76% [7]
Frequency range	Broadband [9]	Low to mid-frequency [34]	150 kHz–30 MHz [7]

3.2.4. AI/ML and real-time monitoring approaches

Reinforcement learning (RL) enables self-tuning active EMI filters that continuously adapt to non-stationary interference, achieving 25–30 dB attenuation across wide frequency ranges in automotive power systems [35]. A frequency-band-aware physics-informed GAN (FBA-PIGAN) integrates electromagnetic domain knowledge into generative modeling for joint EMI prediction and adaptive suppression in SiC converters, attaining 19.2 dB average attenuation with 98.5% CISPR 25 compliance [33]. Machine learning models also predict radiated electric and magnetic field emissions from switching devices by learning complex correlations between device parameters and EMI intensity.

3.3. Packaging, PCB layout and parasitic capacitance management

At the packaging level, advanced module topologies, including CM screens, multilayer shields, and wire-bondless (planar/sandwich) construction, reduce parasitic inductance and EMI while improving power density and transient performance, in part by enabling integrated decoupling capacitors without enlarging the module [36]. Sandwich structures with vertical capacitor loops have reduced power-loop inductance to as low as 4.4 nH for 10 kV SiC MOSFETs, supporting switching speeds up to 250 V/ns with minimal ringing [36]. Integrated CM screens on layered ceramic substrates, connected to the DC bus through the decoupling capacitors, have cut peak electric field by 58%, raised partial-discharge inception voltage by 53%, reduced ground current by up to 10-fold, and lowered CM current by up to 26 dB [26]. Nano-silver die-attach sintering and molybdenum posts further reduce voiding and thermomechanical stress at the die interface [36].

Parasitic capacitance in power modules and PCBs generates displacement currents proportional to dv/dt, which worsens both EMI and switching losses, effects that intensify as WBG devices push switching speeds higher [37]. In medium-voltage SiC MOSFETs, displacement currents through module parasitic capacitances can reach a significant fraction of rated current, making their impact on switching energy dissipation substantial enough that it cannot be overlooked [37]. PCB parasitic capacitance introduces additional losses through both power-loop capacitive coupling and coupling between power and control circuits via control-ground potential pulsation [38]. A stacked substrate hybrid package for SiC half-bridge modules reduces common-mode current by 17 dB and total switching loss by 28.5% through parasitic capacitance optimization [39]. A 3D lattice PCB structure achieves 55.8% parasitic inductance reduction through horizontal and vertical magnetic flux cancellation, cutting switching loss by 26% [40]. Intelligent parasitic capacitance distribution in thin packaging substrates reduces peak and RMS displacement current, improving gate-drive signal quality in GaN modules [41]. Table 3 summarizes co-optimization strategies in the WBG converter design.

Table 3. Co-optimization strategies in the WBG converter design

Strategy/approach	EMI mitigation	Thermal management	Reliability impact	Ref.
Gate driver optimization	High	Moderate	Improved	[42]
Advanced substrate materials	High	High	Improved	[43]
Topology selection (ANPC/NPC)	High	High	Improved	[44], [45]
Parasitic/coupling management	High	Moderate	Improved	[46], [47]

3.4. Trade-offs, hardware implementation constraints and reliability

Optimal WBG converter design requires balancing EMI suppression, efficiency, and cost. Hybrid architecture, integrated filtering, and multi-objective optimization are key to achieving high performance without high cost or EMI. The best solution depends on specific application needs and regulatory requirements. Table 4 compares different trade-off strategies in the design of WBG converters.

Table 4. Comparison of trade-off strategies in the WBG converter design

Approach/technique	EMI suppression	Efficiency	Cost impact	Ref.
High switching frequency (WBG)	Lower	Higher	Higher	[2]
Soft-switching (QR-ZVS)	Higher	Higher	Moderate	[48]
Integrated EMI filters	Higher	Neutral	Lower	[49]
Spread-spectrum modulation	Moderate	Slightly lower	Low	[14]
Hybrid Si/WBG design	High	High	Lower	[50]
Gate driver optimization	Balanced	Balanced	Low	[42]

4. APPLICATION SPECIFIC STRATEGIES

4.1. Electric vehicles and transportation

WBG semiconductors are increasingly used in electric vehicle and transportation power converters because they switch at higher frequencies with lower loss than silicon devices, enabling higher power density, reduced cooling needs, smaller filters, and better dynamic performance and fuel economy [45]. This rapid growth also raises new CM EMI research challenges specific to transportation systems [51].

Modern EVs, ships, and aircraft feature dense, interconnected converter networks that can produce large, poorly characterized background noise, since most existing CM EMI research addresses single devices or modules rather than full networks [51]. Device-level studies also tend to overlook the CM harmonic phase set by the PWM carrier, which matters for network-level EMI reduction. Computer-aided design combined with optimization methods such as particle swarm optimization has been used to build equivalent-circuit models that improve EMI filter design at the transportation-system level [42].

4.2. High voltage and high frequency systems

WBG devices such as 10 kV SiC MOSFETs are central to medium- and high-voltage systems, offering fast switching and low on-state losses that improve efficiency while reducing size, weight, and cost. However, current power module packaging limits how much of this potential can be realized, particularly regarding switching speed, voltage/current rating, and operating temperature, making package design essential to their adoption [36].

Robust, manufacturable methods for electric-field reduction remain scarce, and few studies address high-density connectors for medium-voltage modules [36]. Electric fields concentrate at triple points within power modules. Standard 1 mm aluminum-nitride DBC substrates have PDIVs below 10 kV rms, insufficient for 10 kV SiC MOSFETs, but stacking two ceramic substrates reduces field strength at these points and can raise PDIV by up to 94% [36]. Comparing EMI performance across module architectures is difficult given inconsistent test conditions, underscoring the need to understand how module architecture shapes CM emissions, including di/dt contributions alongside dv/dt in high-current applications [52].

4.3. Renewable energy and aerospace

In more-electric aircraft, where space and weight are tightly constrained, WBG converters require low-inductance SiC modules with integrated capacitors and optimized planar CM filters, for example in 100 kW SiC inverter/rectifier systems operating at altitude [46]. WBG devices also generate elevated near-RF spectral content (1–30 MHz), and the combination of higher noise, higher frequency, and smaller form factor can degrade filter attenuation by up to 60 dB [46].

System-level evaluation of modules with built-in EMI filters is still needed, since research to date has focused mainly on structural and electrical characteristics rather than packaging-level coupling effects [9]. Cancellation-based techniques cannot fully address frequency- and temperature-dependent parasitics, and more sophisticated fixes risk introducing new parasitic effects. Future work includes impedance calibration of MOSFET parasitics and hardware validation of proposed filters [46], [53]. These challenges extend to confined environments such as shipboard power systems, which share aerospace's power-density and EMI constraints and require modeling from the submodule to the full-system level [54]. Table 5 [26], [55]-[58] summarizes EMI mitigation strategies tailored to specific applications.

4.4. Motor drives

WBG-based motor drives consistently demonstrate superior efficiency over silicon solutions. A 300 kW GaN-based vector-controlled synchronous motor drive for EV traction achieved efficiencies approaching 98% at full load, surpassing both SiC and Si technologies while maintaining low harmonic distortion [59]. In a 3-level neutral point clamped (NPC) inverter-fed induction motor drive, the GaN-based inverter reached 98.74% efficiency, with total power loss 1.21% less than SiC and 57.87% less than Si [60]. For synchronous reluctance motors (SynRMs), GaN yields the highest efficiency, while SiC offers comparable efficiency with superior current quality in terms of total harmonic distortion [61]. WBG-based variable frequency drives can run at higher frequencies, reducing the size of passive components and audible system noise while withstanding higher temperatures to reduce overall system size and weight [62].

Table 5. Summary of the EMI mitigation strategies tailored to specific applications

Application area	Strategy/technique	Key features/benefits	Ref.
Electric vehicles (EVs)	CM filter design based on transfer-function analysis	Reduces conducted EMI in DC-DC converters, meets CISPR25	[55]
High-frequency DC-DC Converters	Hybrid filtering (passive + active)	Superior EMI reduction and EMC compliance	[56], [57]
Power module design (SiC MOSFET)	Integrated common-mode screen	Up to 26 dB CM current reduction, slight efficiency gain	[26]
PCB/package design	AI-optimized ground-via placement	Enhanced EMI mitigation in limited layout areas	[58]

5. LIMITATIONS AND CHALLENGES

WBG devices' fast switching speeds and high frequencies inherently produce elevated EMI: high dv/dt and di/dt cause oscillation, overshoot, ringing, and harmonic spikes, worsening turn-on losses and insulation degradation [4]. Despite their high temperature ratings, practical high-temperature packaging remains unreliable and costly; gate-oxide reliability in SiC MOSFETs is a concern at elevated temperature; and low short-circuit current withstand (e.g., 2 μs vs. 10 μs for Si IGBTs) complicates fault detection with conventional low-bandwidth current sensors, problems compounded when devices are paralleled or series-connected at high switching speed [4].

EMI/EMC mitigation still lacks thorough design guidance: models that reliably predict hybrid-filter stability and performance are limited, near-field interference research is sparse despite its growing relevance to compact WBG design, and integrated design-optimization tools spanning the component to converter level for SiC devices remain underdeveloped [2], [4]. Packaging improvements that jointly address parasitics, thermal management, and high-temperature performance are needed to close these gaps.

6. CONCLUSION

Research on adaptive EMI mitigation in WBG power electronics has moved decisively from bulk passive filtering toward source-side, packaging-integrated, and closed-loop adaptive solutions that suppress EMI while sustaining or improving efficiency. Three directions show the strongest combined performance in the literature reviewed. Packaging-integrated common-mode screens cut CM current by up to 26 dB while raising partial-discharge inception voltage by 53% and improving efficiency by roughly 0.5%. Chaotic pulse-width modulation combined with a passive filter reaches up to 50 dB attenuation together with a 74% reduction in CM inductor volume.

AI-based closed-loop adaptation, exemplified by a physics-informed generative model, attains 19.2 dB average attenuation with 98.5% CISPR 25 compliance across 32 operating conditions, while reinforcement-learning-based self-tuning filters reach 25–30 dB attenuation across wide frequency ranges in automotive systems. Among trade-off strategies compared in this review, hybrid Si/WBG design is the only approach that simultaneously delivers high EMI suppression, high efficiency, and lower cost, making it the most practically balanced near-term choice where a single-technology WBG solution is not yet cost-competitive.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors do not have any conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper, as no new data were created or analyzed in this study.

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