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Original Research

Strategies for Identifying, Mitigating, and Addressing Electromagnetic Compatibility (EMC) Issues in High-Frequency and Power Electronic Applications

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Abstract
Electromagnetic compatibility in high-frequency and power electronic applications is shaped by interacting physical mechanisms, design choices, and regulatory constraints that must be reconciled to ensure reliable operation. Modern converters, radio front-ends, motor drives, and mixed-signal boards increasingly operate with shrinking geometries and faster edges, which intensify parasitics and elevate radiated and conducted emissions. The presence of dense interconnects, heterogeneous dielectrics, switching devices with rapid transition times, and modular packaging introduces coupling paths that can degrade signal integrity, inflate loss, and trigger functional anomalies. In practice, benign choices during early design may later manifest as unexpected emissions peaks or susceptibility notches under environmental variation, tolerance spread, or aging. This paper surveys and integrates strategies for identifying, mitigating, and addressing electromagnetic compatibility issues, emphasizing modeling-informed decisions, measurement-driven iteration, and robust design practices suitable for industrial constraints. The discussion spans source–path–victim reasoning, field–circuit co-modeling, power-stage modulation tactics, layout and interconnect decisions, filtering and shielding, and data-driven diagnostics. Emphasis is placed on reconciling conflicting goals such as efficiency, thermal headroom, cost, and manufacturability while maintaining stable electromagnetic behavior across production variance and use conditions. Practical pathways are articulated to connect early predictive analysis with bench verification, with attention to reproducibility and uncertainty management. The overall aim is to outline methods that enable designers to anticipate electromagnetic risks, to tune countermeasures with adequate safety margins, and to converge on configurations that remain compatible over the operational envelope without undue complexity.

1. Introduction

Electromagnetic compatibility, as encountered in high-frequency and power electronic hardware, emerges from the interplay of switching transitions, material dispersion, conductor geometry, and distributed coupling within and across subsystems [1]. As energy conversion and information processing converge on shared boards and enclosures, interference paths propagate through return planes, cable harnesses, heat-sink structures, and nearby equipment. At the same time, technology trends toward steeper voltage and current slopes in the time domain elevate spectral content well beyond fundamental operating frequencies. This elevation reshapes both radiated and conducted profiles, activating resonances that would be negligible with slower devices and longer edges. The resulting landscape requires methods that establish a unified view of sources, coupling paths, and victim circuits, allowing mitigation steps to be targeted rather than generic. The practical reality is that every trace, via, connector, and ground discontinuity becomes part of a complex electromagnetic network, where mutual coupling and parasitic storage determine whether a design will meet emission and immunity specifications.

A basic but durable viewpoint divides the problem into three regions: generation of interference by switching stages and digital edges, propagation via structure-borne and field-borne paths, and reception

Interference Source	Mechanism	Dominant Parameter	Frequency Range	Impact
Switching Edges	High dv/dt, di/dt	Rise/Fall Time	1–300 MHz	Radiated and Conducted EMI
Parasitic Capacitance	Drain–Source, Gate–Drain Coupling	Device Geometry	10–100 MHz	Cross-coupling
Bond Wire Inductance	Current Slew in Packaging	Package Layout	1–30 MHz	Voltage Overshoot
Ground Bounce	Shared Return Impedance	Return Path Inductance	1–50 MHz	Logic Distortion

Table 1. *Typical EMI sources and coupling mechanisms in high-speed power electronics..*

Propagation Path	Medium	Key Influence	Coupling Type	Mitigation
PCB Planes	Copper/Dielectric Stack	Plane Discontinuity	Conducted/Common-mode	Stitching vias, copper fills
Cables	Harness, Shields	Length Resonance	Radiated/Common-mode	Common-mode chokes, braiding
Heat Sink	Metallic Mass	Surface Resonance	Radiated	Ground bonding, isolation pads
Chassis	Enclosure Return	Slot Apertures	Radiated/Leakage	Shielding gaskets, mesh covers

Table 2. *Dominant EMI propagation channels and suppression approaches..*

Mitigation Technique	Domain	Primary Effect	Trade-off	Effective Range
Snubber Network	Power Circuit	Damps Overshoot	Adds Loss	<50 MHz
Spread Spectrum PWM	Control Firmware	Flattens Spectral Peaks	Adds Modulation Noise	1–30 MHz
Ferrite Beads	Interface Lines	Attenuates HF Currents	Saturates at High Current	10–300 MHz
Shielded Cable	Cabling	Blocks Radiation	Adds Weight and Cost	>30 MHz
Ground Plane Segregation	PCB Layout	Reduces CM Conversion	Consumes Area	Broadband

Table 3. *Representative electromagnetic compatibility mitigation techniques and their trade-offs..*

by sensitive nodes. The generation side is driven by transition energy, device parasitics, driver impedance, and load reflections. When switching transients contain high di/dt or dv/dt values, they excite unintended resonant loops that radiate or conduct noise across the system. The parasitic capacitances between drain and source, or between gate and drain in MOSFETs, for example, couple energy directly into the gate loop and neighboring circuits. Similarly, parasitic inductances in bond wires and packages transform abrupt current changes into voltage overshoots that can cross-couple through shared supply impedances. The propagation depends on loop areas, return path inductance, dielectric and magnetic properties, discontinuities in planes and shields, and the presence of cables that act as efficient antennas at particular lengths. A return current that cannot find a low-impedance path flows through unintended geometries, generating common-mode currents that couple into other subsystems or into the chassis. The reception is governed by circuit transfer functions, susceptibility thresholds, common-mode conversion efficiency, and temporal overlap with functional bandwidth. Sensitive nodes, such as analog sensor inputs or digital clock lines, can demodulate the interference and convert it into baseband errors if the spectral overlap coincides with their operating range [2]. Although the source–path–victim decomposition is simple, actionable design arises when it is made quantitative, combining field theory with circuit modeling and data from measurement fixtures such as line impedance stabilization networks, near-field probes, and calibrated antennas. These measurement techniques bridge the theoretical and experimental domains, enabling designers to localize dominant coupling paths and quantify the effectiveness of shielding or filtering.

Modern electronic systems further complicate this framework because functional integration and miniaturization blur the physical boundaries between noisy and quiet circuits. Power stages and control logic may coexist on the same silicon die or multilayer board, with only thin dielectric layers separating high-voltage planes from sensitive signal traces. This proximity reduces loop area for efficiency but increases capacitive and inductive coupling. The drive toward higher switching frequencies in converters, driven by wide-bandgap devices such as GaN and SiC, exacerbates this situation. These devices switch within nanoseconds, producing steep edges that radiate far beyond the fundamental frequency. The harmonic content extends into hundreds of megahertz, where traditional lumped models cease to apply and transmission-line behavior dominates. Consequently, electromagnetic compatibility must be treated as a system-level discipline rather than an afterthought. Early-stage modeling, incorporating field solvers and equivalent-circuit extractions, can help visualize return current paths and optimize layer stack-ups. By doing so, engineers can prevent the accumulation of parasitic impedances that later manifest as emissions or susceptibility failures.

The propagation of interference, both conducted and radiated, is influenced not only by electrical layout but also by mechanical and thermal structures. Heat sinks, for instance, often act as unintentional antennas or coupling planes. Their large metallic surfaces can resonate at particular frequencies, re-radiating the noise generated within switching circuits [3]. Cable harnesses present another challenge: they serve as long conductors that easily convert common-mode currents into far-field emissions. Proper cable management, including the use of twisted pairs, shield terminations, and common-mode chokes, can significantly attenuate this effect. Yet each mitigation method comes with cost, weight, or efficiency penalties. For instance, fully shielded cables improve electromagnetic containment but add mechanical rigidity and increase assembly complexity. Designers must therefore prioritize mitigations that address the dominant coupling mechanism rather than applying blanket solutions. The art of electromagnetic compatibility lies in balancing these competing demands while maintaining the desired electrical performance.

On the reception side, susceptibility is often subtle and difficult to predict because it depends on nonlinear behavior in analog and mixed-signal circuits. A small amount of injected noise at high frequency can intermodulate within semiconductor junctions, producing low-frequency artifacts that interfere with control loops or sensing functions. Common-mode rejection ratios, grounding strategies, and layout symmetry become decisive in determining how much of this interference reaches functional nodes. The transfer functions between external disturbances and circuit response can be measured or simulated to identify resonance peaks where vulnerability is highest. Time-domain simulations, employing realistic switching waveforms, reveal how energy is distributed across the frequency spectrum and help guide the placement of decoupling networks or ferrite elements. In many cases, a well-placed capacitor or small adjustment in trace geometry provides greater benefit than extensive filtering, provided that the designer understands the coupling mechanism quantitatively.

Design tensions arise because the same actions that reduce emissions can impair efficiency, power density, or control stability. For example, adding series impedance or passive networks raises conduction losses or modifies feedback phase margin [4]. Shielding redistributes fields but may create cavity modes, shifting resonances rather than removing them. Spreading switching spectra alleviates narrowband peaks yet complicates compliance analysis, as quasi-peak detectors and dwell mechanisms may respond differently to stochastic or deterministic modulation. Additionally, adding snubbers or RC damping networks to control overshoot can increase power dissipation and thermal stress, especially in compact systems where heat removal is constrained. These trade-offs favor approaches that are parameterizable and whose effects can be estimated ahead of time, reducing the number of late-stage layout respins or ad hoc ferrite fixes. Simulation models that integrate electrical, magnetic, and thermal domains can forecast the system's behavior under varying conditions, enabling engineers to explore design space systematically rather than reactively.

Another critical dimension of electromagnetic compatibility involves regulatory and measurement considerations. Standards such as CISPR, FCC Part 15, and ISO automotive directives define allowable emission limits and immunity thresholds across specific frequency bands. Compliance testing in an anechoic chamber or on an open-area test site provides the final verification, but by that stage the design is largely fixed. The cost and delay of discovering a failure at this point can be severe, prompting the development of pre-compliance testing setups and virtual prototyping. By combining numerical modeling with partial hardware characterization, engineers can predict the spectral signature of their design and identify potential violations before the full certification phase. This workflow embodies a predictive philosophy: rather than relying on empirical fixes, it embeds electromagnetic awareness into every design iteration.

A neutral stance is maintained throughout, avoiding prescriptions tied to particular devices or processes. The intent is to distill techniques that remain predictive under realistic variation and that can be scaled from bench prototypes to production units. The subsequent sections develop physical and mathematical models that connect geometric features and control choices to measurable emission and susceptibility outcomes. From these, mitigation strategies are articulated with an eye toward reproducibility, tolerance to environmental shifts, and compatibility with thermal and mechanical constraints routinely encountered in industrial settings. [5]

2. Electromagnetic Phenomena in High-Frequency and Power Stages

An electromagnetic system with fast transitional behavior exhibits coupled dynamics across conductors, dielectrics, and free space. The fields and currents are governed by relationships whose distributed character is essential when dimensions are no longer negligible compared to the shortest wavelengths or when transition times are short enough to excite structure resonances. In high-frequency and power electronics, the relevant scales are frequently set by edge rates rather than carrier frequencies, which promotes unintended excitation of common-mode currents in enclosures, cables, and heat spreaders. The Poynting flow accurately reflects energy transport but practical design relies on reduced models that approximate dominant couplings while remaining compatible with circuit simulation.

The reduction can be anchored to field equations. In a simply connected region with constitutive parameters that may vary with frequency and temperature, the relationships can be formalized as

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}, \quad \nabla \cdot \mathbf{D} = \rho, \quad \nabla \cdot \mathbf{B} = 0,$$

with material responses $\mathbf{D} = \varepsilon \mathbf{E}$, $\mathbf{B} = \mu \mathbf{H}$, $\mathbf{J} = \sigma \mathbf{E}$ in linear regimes, augmented by dispersion where appropriate. At high frequency or fast edges, boundary conditions at conductor and shield interfaces dominate coupling, because the skin effect constrains current to narrow layers. The skin depth in a conductor of conductivity σ and permeability μ at angular frequency ω follows

$$\delta(\omega) = \sqrt{\frac{2}{\omega \mu \sigma}},$$

and determines the effective cross-section. When thickness is multiple skin depths, resistance increases roughly with $\sqrt{\omega}$; when comparable, current crowding and proximity effects require more detailed accounts of mutual field interactions among adjacent traces or windings.

Currents and voltages in interconnects are represented by distributed models. If a printed microstrip or stripline of per-unit-length parameters (R', L', G', C') is driven by a fast transition, the telegrapher model captures dispersion and attenuation:

$$\frac{\partial V(x,t)}{\partial x} = -L' \frac{\partial I(x,t)}{\partial t} - R' I(x,t), \qquad \frac{\partial I(x,t)}{\partial x} = -C' \frac{\partial V(x,t)}{\partial t} - G' V(x,t).$$

Solving in the frequency domain furnishes a complex propagation constant $\gamma(\omega) = \sqrt{(R' + j\omega L')(G' + j\omega C')}$ and characteristic impedance $Z_0(\omega) = \sqrt{(R' + j\omega L')/(G' + j\omega C')}$, allowing reflection and transmission calculations when discontinuities or vias are present. Return path integrity is central, since slots or plane splits that force current detours increase effective loop areas and feed common-mode conversion. The radiation from a small loop current I of area A at wavenumber $k = 2\pi/\lambda$ in the far field scales roughly as

$$E_\theta \propto \omega \mu_0 \frac{IA}{r} \sin\theta,$$

highlighting sensitivity to detoured returns that magnify A. [6]

Common-mode and differential-mode decomposition illuminates pathways by which converters excite enclosure currents. If two conductors carry $+I$ and $-I$ with a small imbalance αI, the common-mode portion αI can be sufficient to drive sizable radiation when multiplied by long harnesses whose lengths approximate a fraction of free-space wavelength. The transformation matrix for currents I_1, I_2 into differential and common components can be written

$$\begin{pmatrix} I_{\mathrm{DM}} \\ I_{\mathrm{CM}} \end{pmatrix} = \begin{pmatrix} \frac{1}{2} & -\frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix},$$

demonstrating that small asymmetries or parasitic capacitances to chassis can lift I_{CM} even when I_{DM} is controlled. Parasitic capacitances from switching nodes to chassis grow with area and dielectric constants and provide an efficient source of displacement current during fast dv/dt excursions, which then finds return through cable shields, safety earth, or radiative paths. The time profile of this current mirrors the node transitions convolved with paths' impedance spectra, which motivates transition shaping and local containment through minimized capacitance to chassis where possible.

Thermal considerations interact with electromagnetic ones, because elevated temperatures change conductivity and permeability, shifting loss tangents and resonance frequencies. This produces modest but relevant drift in emission peaks. The environment, including humidity and mechanical stress, can further perturb contacts and ground bonds, thereby altering common-mode impedances. Robust solutions therefore rely on parametric models that can be swept across expected operational ranges rather than tuned only at nominal conditions.

3. Source–Path–Victim Modeling and Quantitative Risk Estimation

A quantitative approach frames electromagnetic compatibility via connected macromodels that map design variables to observables. The macromodel must absorb parasitics and boundary conditions, while remaining small enough for repeated evaluation during optimization or tolerance studies. A circuit–field hybrid representation is often convenient, where switching and control are retained as circuits and the geometry that mediates coupling is summarized via frequency-dependent impedances and transfer functions extracted from analytic approximations or numerical field solutions.

Let u denote the vector of design parameters comprising geometric features, material selections, and control timing. Let $y(\omega; u)$ denote the spectrum of an observable such as common-mode current at a cable port or voltage at a sensitive node [7]. Suppose the regulatory mask or internal limit is $m(\omega)$. A compatibility margin can be cast as a functional

$$J(u) = \int_{\Omega} w(\omega)\, \phi\!\left(\frac{|y(\omega; u)|}{m(\omega)} \right) d\omega,$$

where w emphasizes frequency ranges and ϕ is a convex penalty that grows when the ratio exceeds unity. The modeling task is then to construct $y(\omega; u)$ that remains accurate under variation and to explore the sensitivity $\partial J/\partial u$ for targeted mitigation. The model can be arranged as a block system

$$\begin{pmatrix} \mathbf{Z}_{\mathrm{ss}}(\omega; u) & \mathbf{Z}_{\mathrm{sp}}(\omega; u) \\ \mathbf{Z}_{\mathrm{ps}}(\omega; u) & \mathbf{Z}_{\mathrm{pp}}(\omega; u) \end{pmatrix} \begin{pmatrix} \mathbf{I}_{\mathrm{s}}(\omega) \\ \mathbf{I}_{\mathrm{p}}(\omega) \end{pmatrix} = \begin{pmatrix} \mathbf{V}_{\mathrm{s}}(\omega) \\ \mathbf{0} \end{pmatrix},$$

in which the subscript s indexes source-side nodes and p indexes path nodes that include chassis, shields, and cable ports. The off-diagonal matrices represent coupling; the path subsystem often exhibits resonances shaped by lengths, apertures, and terminations. Solving yields port currents and voltages that can be compared with limits. If the path is weakly coupled or if certain resonances dominate, model order reduction is possible. Balanced truncation or Krylov projection applied to rational approximations of $\mathbf{Z}_{\mathrm{pp}}(\omega)$ yields compact substitutes preserving passivity, an important criterion to avoid non-physical growth in simulations.

Uncertainty arises from manufacturing tolerance and environment. A parametric uncertainty set $\mathcal{U}$ can be explored through stochastic sampling or worst-case envelopes. A robust formulation is

$$\min_{u \in C} \max_{\Delta \in \mathcal{U}} J(u + \Delta),$$

subject to constraints C reflecting thermal headroom, efficiency, mechanical limits, and cost. Gradient information can be obtained by adjoints if the macromodel is differentiable, or by surrogate modeling. For instance, Gaussian process surrogates can interpolate $J(u)$ across the region of interest; however, care is needed to preserve monotonicity or passivity constraints in surrogate components that represent impedances. Alternatively, convex approximations can be obtained by linearizing around a baseline u_0:

$$J(u) \approx J(u_0) + \nabla J(u_0)^\top (u - u_0) + \frac{1}{2}(u - u_0)^\top \mathbf{H}(u_0)(u - u_0),$$

where a positive semidefinite approximation $\mathbf{H}$ can be assembled from sensitivities. This enables tractable optimization that returns a candidate u for validation in the higher-fidelity model. [8]

The coupling between fields and circuits sometimes demands distributed representations. Consider a cable attached to a converter enclosure, modeled as a common-mode transmission line with characteristic impedance Z_{cm} and length ℓ. If $I_{\text{cm}}(0, \omega)$ is injected at the device end, the current at position x obeys

$$\frac{\partial^2 I_{\text{cm}}(x, \omega)}{\partial x^2} - \gamma_{\text{cm}}^2(\omega)\, I_{\text{cm}}(x, \omega) = 0,$$

with γ_{cm} comprising loss and phase. Terminations at the free end control standing waves and the observed emission peaks. Matching or damping at strategic locations can flatten the response, but practical implementations are constrained by mechanical and safety considerations.

Compatibility risk also depends on temporal statistics when spread-spectrum or random modulation is used. Let $s(t)$ denote a switching sequence with instantaneous switching period $T(t)$ drawn from a probability law with density p_T. The power spectral density of a pulse train with random phases and dwell times can be expressed via cyclostationary expansions; a compact descriptor uses the characteristic function $\Phi_T(\xi) = \mathbb{E}[e^{j\xi T}]$ to write the spectral lines as weighted by $|\Phi_T(2\pi k)|^2$ for harmonics k, blurred by the pulse shape's Fourier transform. Designers can then select p_T to redistribute energy while respecting control tolerances and losses.

4. Prioritizing Detection and Mitigation of High-Coupling Paths

Practical electromagnetic compatibility work benefits from a disciplined emphasis on identifying and suppressing the relatively small set of paths that account for a disproportionate share of radiated and conducted interference. In many assemblies, a limited number of return discontinuities, elongated harnesses, or chassis-to-node capacitances dominate conversion from local switching energy to system-level emissions. Tsintsadze et al. (2023) noted the vulnerability of prominent coupling conduits for radiated emissions if they remain untreated [9], and related observational analyses also reference the outsized role of these routes. The focus here remains general and method-centric: rather than centering on any single report, the discussion consolidates cross-cutting strategies for detection, ranking, and mitigation so that engineering effort is directed first where the electromagnetic leverage is highest and verification cycles converge more reliably.

The detection problem can be posed as estimating the transfer from a set of internal aggressor states to measurable emissions or to disturbances at sensitive nodes. In frequency-domain terms, a compact representation considers a partitioned network where internal sources drive a coupling subnetwork that terminates on ports representing antennas, cables, or instrumentation [10]. With $\mathbf{v}(\omega)$ the vector of source voltages or currents and $\mathbf{i}_p(\omega)$ the port currents associated with potential emissions or susceptibility endpoints, a linearized macromodel yields

$$\mathbf{i}_p(\omega) = \mathbf{T}(\omega)\,\mathbf{v}(\omega), \qquad \mathbf{T}(\omega) = \mathbf{Z}_{pp}^{-1}(\omega)\,\mathbf{Z}_{ps}(\omega)\,\big(\mathbf{Z}_{ss}(\omega)\big)^{-1},$$

where $\mathbf{Z}_{ss}$ summarizes the source subnetwork, $\mathbf{Z}_{pp}$ the path subnetwork including enclosures and cables, and $\mathbf{Z}_{ps}$ their mutual interaction. Paths that carry large singular values of $\mathbf{T}(\omega)$ over compliance-relevant bands are natural priorities, because small parameter changes at these locations project strongly to the ports that determine margins. When designers do not have full parameterizations, measured S-parameters between chosen injection points and ports approximate the relevant blocks, and the same ranking logic applies to the data-derived $\mathbf{T}(\omega)$.

Ranking paths requires a scalar measure that integrates spectral weighting, detector response, and victim sensitivity. A risk functional for a candidate path p can be expressed as

$$\mathcal{R}_p = \int_\Omega w(\omega)\,\Psi(\omega)\,\left|T_p(\omega)\,S(\omega)\right|^2\,d\omega,$$

where $S(\omega)$ is the source spectrum, $T_p(\omega)$ is the path transfer magnitude, $w(\omega)$ encodes regulatory or self-imposed emphasis across frequencies, and $\Psi(\omega)$ reflects detector or victim susceptibility shaping. Large $\mathcal{R}_p$ values identify strong contributors under the specific operating and measurement context. In practice, $T_p(\omega)$ can be assembled from a mixture of models and measurements, for example using a near-field probe to obtain local coupling coefficients and a network analyzer to obtain port impedances. Because $\Psi(\omega)$ differs between quasi-peak and average detectors or between immunity thresholds and emissions masks, the same hardware may receive different rankings under different test objectives, which argues for computing $\mathcal{R}_p$ under the exact evaluation conditions expected.

Several physical signatures recur among high-coupling paths. Displaced returns that force current to detour around plane splits or across narrow necks inflate effective loop area and thus magnetic dipole radiation. Long attached conductors such as unshielded or imperfectly bonded cables provide efficient common-mode radiators when their electrical length approaches a fraction of wavelength. Capacitances from fast-switching nodes to chassis inject displacement current whose return navigates through seams and harness shields. These signatures can be parameterized to aid screening. If a loop of area A carries a current with spectral density $|I(\omega)|$, the far-field trend scales with $|I(\omega)|\,A$ modulated by distance and angle, while a cable of length ℓ terminated by mismatched impedances exhibits standing-wave currents whose maxima occur near $\ell \approx \lambda/2$. A conservative screening metric that merges these can be formulated as

$$\Lambda_p = \max_{\omega\in\Omega}\left\{\kappa_1\,A_p\,|I_p(\omega)| + \kappa_2\,|I_{\mathrm{CM},p}(\omega)|\,\left|\sin\!\left(\frac{\omega\ell_p}{v_p}\right)\right|\right\},$$

where A_p is the local loop area, I_p a representative loop current, $I_{\mathrm{CM},p}$ the common-mode component on an attached conductor of effective wave velocity v_p, and $\kappa_{1,2}$ scale the terms into comparable units. Paths with large Λ_p values are candidates for targeted mitigation because they are predisposed to peak behavior in the operating band.

Prioritization benefits from a graph perspective that embeds electromagnetic couplings as weighted edges. Nodes represent subassemblies or nets, and edge weights encode transfer magnitudes derived from field-circuit extraction, measurements, or analytical approximations [11]. Let $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ denote this graph with weighted adjacency matrix $\mathbf{W}$ such that W_{ij} approximates the magnitude of coupling from node j to node i. If $\mathbf{s}$ is a vector of source magnitudes and $\mathbf{r}$ a vector of receiver sensitivities, an influence score that propagates coupling along multi-hop paths is given by

$$\mathbf{u} = (\mathbf{I} - \alpha\mathbf{W})^{-1}\,(\mathbf{r} \odot \mathbf{s}),$$

for $0 < \alpha < 1/\rho(\mathbf{W})$, where $\rho(\mathbf{W})$ is the spectral radius of $\mathbf{W}$ and $\odot$ denotes elementwise product. Entries of $\mathbf{u}$ that are large indicate nodes whose perturbation is likely to influence critical receivers through direct and indirect couplings. Edges touching those nodes are natural points for sensing and mitigation. This perspective complements direct spectral ranking by revealing latent multi-stage couplings that single-hop metrics might miss, while remaining computationally simple enough to update as design variants evolve.

On the detection side, probing sequences should emphasize discriminative measurements that separate overlapping mechanisms. Coherence analysis between a switching-node voltage and a remote current probe on a cable often reveals capacitive injection dominance when coherence remains high across switching harmonics. Conversely, high coherence between loop current and a nearby sensed voltage on an analog reference suggests inductive pickup. The magnitude-squared coherence estimator

$$\gamma_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f)\, S_{yy}(f)}$$

quantifies this relation and, when combined with controlled experiments that alter geometry or terminations, narrows the set of plausible paths. For example, temporarily bonding an enclosure seam with a low-inductance strap and observing a drop in coherence-linked emissions implicates that seam as a segment of a dominant path. Sequential interventions of this form, recorded with repeatable cable placements and orientations, allow for a rudimentary but robust sensitivity map that later guides permanent fixes.

Sensor placement itself can be formalized to maximize information about candidate paths under limited measurement resources. Suppose P candidate locations are available for probes and the goal is to minimize the posterior variance of the estimated path transfer parameters θ. If the measurement model near a nominal operating point is linearized as $\mathbf{y} = \mathbf{H}\theta + \mathbf{n}$ with noise covariance $\mathbf{R}$, one seeks a selection matrix $\mathbf{S}$ that chooses rows of $\mathbf{H}$ to maximize a design criterion such as log-determinant of the Fisher information. An instance of this design reads

$$\max_{\mathbf{S}\in\{0,1\}^{M\times P}} \log\det\Big(\mathbf{S}\mathbf{H}^\top\mathbf{R}^{-1}\mathbf{H}\mathbf{S}^\top\Big) \quad \text{s.t.} \quad \mathbf{S}\mathbf{1} = \mathbf{1}, \quad M \text{ probes},$$

where M is the number of available sensors. Greedy approximations perform well and return probe sets that discriminate among hypothesized paths with fewer ambiguities, saving bench time and avoiding overfitting adjustments to coincidental geometries.

Mitigation actions are most effective when matched to the physical character of the dominant path [12]. If the ranked path is a differential loop inflated by a return discontinuity, the preferred measure is to restore a proximate, continuous return and re-shape the current loop. A compact way to represent the benefit is to consider the change in magnetic energy stored per cycle,

$$\Delta W_m \approx \frac{1}{2}\Delta L_{\text{loop}}\, I_{\text{HF}}^2,$$

where I_{HF} is the high-frequency component of the loop current and ΔL_{loop} is the reduction in loop inductance achieved by added stitching vias or relief of plane splits near the transition. For common-mode dominated routes through cables, the measures instead focus on reducing the source of common-mode current and raising the common-mode impedance along the attached structure without disrupting functional signals. The source reduction might involve reducing capacitance from switching nodes to chassis by minimizing exposed copper or by carefully controlling clearances; it might also involve shaping dv/dt to reduce displacement current amplitude. Increasing path impedance can be achieved with common-mode chokes selected for appropriate impedance versus frequency and placed near the device-to-cable interface, with attention to avoiding high-Q peaking by adding intentional loss or by choosing materials with suitable loss characteristics over the targeted band.

Shielding changes boundary conditions for fields and can suppress leakage through seams and apertures along a high-coupling route. However, attenuation is sensitive to implementation details:

seam inductance, gasket compression uniformity, and the presence of unintended slots near current maxima. A reduced transmission model for a slot of length a in a conductive wall approximated by a magnetic dipole leads to transmission that scales roughly with $(ka)^3$ when $ka \ll 1$, but rises quickly as the slot approaches a resonant fraction of wavelength. Therefore, a prioritized seam fix aims to break long continuous apertures into shorter segments, to provide multiple low-inductance bonds that reduce effective slot length, and to introduce lossy interfaces where small residual fields are dissipated. These local, geometry-specific corrections often deliver greater improvement per unit effort than more generic increases in shield thickness because they address the precise leakage mechanism of the path under consideration.

Filtering choices carry trade-offs between insertion loss in functional bands, thermal dissipation, and attenuation in interference bands. For a targeted path, the filter topology is shaped by the modal content: common-mode filters applied to signals with symmetrical differential content but asymmetric parasitics, differential filters where return symmetry is preserved, and feedthrough capacitors where high-frequency return to chassis is desired with minimal inductance. The small-signal insertion loss for a two-port filter embedded between source and load impedances can be written through ABCD parameters. If $\mathbf{M}(\omega)$ is the ABCD matrix of the inserted network, the transducer gain magnitude $|G_T|$ and thus insertion loss follow

$$|G_T(\omega)| = \left| \frac{2}{A + \frac{B}{R_L} + CR_s + \frac{DR_s}{R_L}} \right|, \qquad \mathrm{IL}(\omega) = -20 \log_{10} |G_T(\omega)|,$$

with R_s and R_L the embedding impedances [13]. Ranking candidate filter placements relative to the dominant path uses this embedding-sensitive definition rather than standalone component curves, so that the chosen filters attenuate energy where the path actually propagates it and where the surrounding impedances allow energy to be dissipated or reflected harmlessly.

Quantifying benefit and cost supports prioritization when multiple fixes contend for resources. A simple multi-attribute framework assigns a score to each candidate action a on path p,

$$\mathcal{S}(a, p) = \eta_1 \frac{\Delta \mathcal{R}_p(a)}{\mathcal{R}_p} - \eta_2 \Delta P(a) - \eta_3 \Delta C(a) - \eta_4 \Delta T(a),$$

where $\Delta \mathcal{R}_p(a)$ is the predicted reduction in risk for that path, $\Delta P(a)$ the added power dissipation, $\Delta C(a)$ the incremental cost, and $\Delta T(a)$ the added test or assembly time, with η_i as weights set by project priorities. While this expression is simple, estimating $\Delta \mathcal{R}_p(a)$ with macromodels aligned to bench measurements yields rankings that are robust to overfitting and that avoid pursuing changes with marginal or uncertain impact. In many cases, geometry-first fixes such as restoring returns or shortening effective slot lengths rank highest because they change path constants that influence a broad spectral range without introducing narrow resonances.

Temporal modulation interacts with coupling paths in nuanced ways. On a path whose response is narrowband due to standing waves, spreading source energy with deterministic or random modulation redistributes line energy and lowers peaks measured with narrow resolution bandwidths. If the path's transfer $T_p(\omega)$ peaks sharply at ω_r, a small randomized switching jitter with variance σ_T^2 effectively convolves the line spectrum with the jitter distribution. In a small-jitter approximation, the line power at ω_r is reduced roughly in proportion to $\exp(-\omega_r^2 \sigma_T^2)$ when other factors remain constant. However, if $T_p(\omega)$ is flat across the spread, the total radiated energy measured with a wide bandwidth detector remains similar and average dissipation in lossy elements can rise. This suggests prioritizing spectral spreading primarily where ranked paths exhibit narrow spectral features that align with compliance inspector dwell and resolution settings.

Uncertainty management remains essential because path rankings can change with cable configuration, environmental conditions, and unit-to-unit variation. A robust approach considers worst-case envelopes by maximizing the risk functional over a bounded uncertainty set $\mathcal{U}$ that captures plausible offsets in geometry and material parameters,

$$\mathcal{R}_p^{\max} = \max_{\delta \in \mathcal{U}} \int_{\Omega} w(\omega)\, \Psi(\omega)\, |T_p(\omega; \delta)\, S(\omega; \delta)|^2 \, d\omega,$$

and seeking mitigations that lower $\mathcal{R}_p^{\max}$ rather than only the nominal value. In the lab, this corresponds to rotating and repositioning harnesses through a small, repeatable ensemble of configurations, logging the upper quantiles of emissions or susceptibility metrics, and preferring fixes that reduce not just the mean but also the spread. The prioritization scheme can incorporate this directly by weighting actions that contract variance in addition to reducing central tendency.

Implementation details determine whether prioritized actions deliver their modeled benefit [14]. For return restoration, the precise placement of stitching vias relative to the current path matters because added inductance scales with via spacing and height. For bond improvements at shield seams, effective inductance is inversely related to bond width and multiplicity; using multiple short, wide bonds outperforms a single longer bond of equal cross-sectional area at high frequency. For common-mode chokes, the impedance curve must cover the dominant path's peak frequencies; placing the choke at a location where common-mode current is high along the harness maximizes impact. Temporary verification with removable ferrites, copper tape, or jumper straps is useful, but final designs should replicate the low-inductance geometry of temporary fixes to avoid regression between prototype and production.

A brief note on documentation and organizational practice is warranted because prioritization must survive handoffs and revisions. Recording the ranked list of paths with their physical descriptions, transfer estimates, and the measured evidence supporting each ranking allows subsequent design turns to maintain focus. Associating each implemented mitigation with its predicted and measured effect, along with any observed thermal or control side-effects, avoids rediscovering the same lessons across variants. This discipline naturally allocates engineering time proportional to impact and reduces ad hoc patching late in the cycle.

Finally, it bears reiterating that the literature emphasizes the presence of a few dominant coupling pathways in many practical systems, but the present treatment is not anchored to any one study or dataset. References in that literature, including the observations by Tsintsadze et al. (2023) and the broader remarks attributed to Tsintsadze et al. (2024), serve as examples rather than pillars. The central recommendation stands on general grounds: prioritize detection and mitigation of high-coupling paths using a combination of model-informed ranking, discriminative measurement, and geometry-matched countermeasures; quantify benefits under realistic detector and configuration conditions; and carry the prioritization through implementation with attention to the small geometric and material details that often govern high-frequency behavior. In such a framework, the earliest and most decisive steps apply where the return is largest, and the resulting electromagnetic posture tends to remain compatible with thermal, mechanical, and control constraints across the operational envelope without leaning on excessive complexity.

5. High-Frequency Layout and Interconnect Strategies

Layout is a dominant determinant of electromagnetic behavior, particularly where rapid dv/dt and di/dt transitions occur [15]. The objective is to confine high-frequency currents to the smallest practical loops with proximate and unbroken return paths, to minimize conversion to common-mode currents, and to shape impedances such that unavoidable energy is dissipated or returned locally. This hinges on loop geometry, plane segmentation, via placement, interconnect topology, and component orientation.

A simple but illuminating model for loop inductance of a rectangular current path with sides a and b, conductor width w, and thickness t is

$$L_{\text{loop}} \approx \mu_0 \left[a \ln\left(\frac{2a}{w+t}\right) + b \ln\left(\frac{2b}{w+t}\right) + 2\,(a+b) \left(0.2235 \frac{w+t}{a+b}\right) \right],$$

which exhibits the logarithmic sensitivity to dimensions and the penalty incurred by detours that increase a or b. In a multilayer board, adding a dedicated return plane directly beneath fast signal or power paths lowers loop inductance. The effective partial inductance method partitions the structure and adds mutual terms to reflect field sharing among conductors. Mutual inductance M between parallel segments of length ℓ separated by distance d in air can be approximated in the regime $d \ll \ell$ by

$$M \approx \frac{\mu_0 \ell}{2\pi} \ln\left(\frac{2\ell}{d}\right),$$

motivating tight return placement and paired routing to reduce the overall stored magnetic energy.

Controlled-impedance traces mitigate reflections that elevate ringing and spectral splatter. The characteristic impedance of a microstrip above a dielectric of relative permittivity ε_r and thickness h with trace width w and thickness t may be approximated by closed forms. One commonly used form for $w/h \leq 1$ is

$$Z_0 \approx \frac{60}{\sqrt{\varepsilon_{\text{eff}}}} \ln\left(\frac{8h}{w+t}\right), \qquad \varepsilon_{\text{eff}} \approx \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12h/w}},$$

indicating that dielectric and geometry jointly shape impedance. Discontinuities such as stubs, via antipads, and plane slots localize resonances; their effect may be collapsed into shunt or series elements with frequency-dependent values extracted by approximate formulas or electromagnetic solvers. Where fast power transitions cross a split plane, the return current is displaced to the nearest bridge, increasing loop area; stitching capacitors with low effective series inductance can provide a high-frequency return, but their placement must be as near as possible to the discontinuity to avoid introducing additional inductive path length. [16]

Placement and orientation of magnetic components influence coupling. A ferrite inductor with fringing fields can inject flux into nearby loops; rotating the core or interposing a continuous return plane alters mutual coupling. The near-field of a gapped core can be visualized as a dipole; the coupling to a loop falls approximately as inverse distance cubed in the reactive near field, so modest separation or a conductive plane can significantly reduce induced voltages. However, planes support surface currents that can redistribute fields rather than absorbing them, so slotting or segmentation must be used with care. Apertures in shields act as slot antennas with resonant lengths near half-wavelength in the material-filled aperture, yielding transmission that scales with $(ka)^3$ for small radius a but increases rapidly as ka approaches unity.

Cable and connector design are often decisive for emissions because cables make efficient radiating structures at lengths tied to frequency. The common-mode impedance presented by a cable shield termination is sensitive to bond inductance. If a pigtail of length ℓ and inductance L_{p} connects a shield to chassis, the impedance near angular frequency ω is

$$Z_{\text{bond}}(\omega) \approx j\omega L_{\text{p}},$$

which rises with frequency, permitting higher common-mode voltages across the bond and hence current on the external surface of the cable shield. Wide, short, and multiple-bond techniques reduce this impedance; 360-degree compression terminations are preferred where feasible. When space prohibits, lossy materials near the bond can provide damping at targeted bands, trading small thermal loads for reduced resonance Q.

Power stage partitioning into hot loops, quiet control areas, and intermediate transition zones supports practical segregation. The hot loop comprising switch, diode or synchronous device, and input decoupling capacitor benefits from the smallest achievable loop area and a local return plane. The quiet region containing analog sensing, clocks, or RF front-ends should be isolated by routing, dedicated planes, and sequencing of returns such that high-frequency current does not traverse sensitive references. The intermediate zone houses gate drivers, bootstrap circuits, and sensor interfaces, where careful control of edge rates and reference impedance minimizes coupling [17]. These partitions are not boundaries of field influence but enable focused countermeasures and clearer reasoning about energy flow.

6. Filtering, Damping, and Shielding as Coordinated Countermeasures

Filtering and shielding are complementary methods that, when coordinated with damping, provide broad leverage against both conducted and radiated paths. Filters act on differential and common-mode currents along intended conductors; shields act on fields and displacement currents in space and surfaces; damping spreads or absorbs energy, lowering quality factors of resonances that convert between modes.

A single-stage LC filter with series inductance L and shunt capacitance C across a load R has a nominal corner at $\omega_0 = 1/\sqrt{LC}$ and an undamped response that exhibits a peak when driven by a source with finite impedance. Insertion loss for a source impedance R_s and load R_L is described by

$$\mathrm{IL}(\omega) = 20\log_{10}\left|\frac{V_{\text{out, with filter}}(\omega)}{V_{\text{out, bypass}}(\omega)}\right|,$$

which, for linearized small-signal models, can be expressed via two-port parameters. Damping capacitors or resistors in series or parallel arrangements temper peaking. A canonical approach is to place a series resistor R_d with the capacitor to create a zero that counteracts the LC pole. For common-mode suppression, a bifilar choke yields large impedance to equal currents while minimally disturbing differential signals; however, leakage inductance and interwinding capacitance set a high-frequency limit. The effective common-mode impedance is approximately

$$Z_{\text{cm}}(\omega) \approx j\omega N^2 L_m + \frac{1}{j\omega C_w} \parallel R_{\text{core}}(\omega),$$

where L_m is magnetizing inductance, C_w is winding-to-winding capacitance, and R_{core} captures material loss. Balancing these terms to avoid resonance peaking typically requires either adding a damping network or selecting materials with suitable loss tangents in the target band.

Ferrite beads and sleeves supply frequency-selective impedance with resistive character beyond a knee frequency, converting high-frequency currents into heat. The impedance can be approximated as

$$Z_{\text{f}}(\omega) \approx R_{\text{f}}(\omega) + j\omega L_{\text{f}}(\omega),$$

with R_{f} dominating over a band. Placing beads in series with signal lines suppresses broadband noise, but care is required not to disturb signal integrity in intended bands or to introduce ground shifts that widen common-mode conversion. For power lines, beads in common-mode pairs preserve differential conduction while countering common-mode currents; the effectiveness depends on equal and opposite currents to prevent saturation. [18]

Shielding reduces coupling by reflecting and absorbing incident fields. For a uniform plane shield of thickness t with conductivity σ and permeability μ, a plane-wave shielding effectiveness at normal incidence can be represented as

$$\mathrm{SE} \approx 20\log_{10}\left|\frac{1}{T}\right|, \quad T \sim e^{-\alpha t}, \quad \alpha = \Re\{\sqrt{j\omega\mu\sigma}\},$$

where T is a transmission coefficient dominated by absorption when thickness exceeds several skin depths. In practical enclosures, apertures and seams govern leakage; the equivalent slot antenna behavior yields a transmission proportional to $(ka)^n$ for small apertures of characteristic dimension a and exponent n depending on polarization. Thus, gasketed seams and minimized apertures are efficient levers. When apertures serve ventilation or inspection, distributed small openings are favored over large ones; lossy honeycomb structures provide both airflow and attenuation at frequencies where cell dimensions remain below cutoff.

Cables form extensions of the device boundary, so shielding and filtering at the interface are intertwined. A feedthrough capacitor mounted through a conductive bulkhead establishes a short high-frequency path to chassis, minimizing lead inductance. Its impedance approximates

$$Z_{\mathrm{ft}}(\omega) \approx \frac{1}{j\omega C_{\mathrm{ft}}} + j\omega L_{\mathrm{lead}},$$

where the geometry in a bulkhead significantly reduces L_{lead} relative to discrete capacitors mounted on a board. Combining feedthrough capacitors with common-mode chokes produces a ladder that attenuates both modes if spacing and orientation avoid parasitic coupling that cancels intended impedance. Empirical tuning uses a vector network analyzer to measure S-parameters and adjust element choices to shift poles and zeros of the transfer function away from susceptible bands.

Damping is frequently the decisive element that turns an otherwise resonant, peak-prone network into a broad, well-behaved attenuator. Consider a cable harness with a prominent resonance near frequency ω_r because of its length and boundary conditions. Adding a small series resistance or a ferrite element near the current antinode can reduce the Q-factor. The Q of a simple RLC resonance is [19]

$$Q \approx \frac{1}{R}\sqrt{\frac{L}{C}},$$

so even modest resistive additions lower Q. Care is taken to place damping where circulating currents are high to maximize effect; distributed resistive films on surfaces or inside shields serve similarly while avoiding concentrated hot spots.

7. Switching, Modulation, and Control Tactics in Power Electronics

Switching actions in power converters dominate the electromagnetic signature. The dv/dt at switching nodes couples capacitively to chassis and cables; the di/dt in loops couples inductively to nearby structures. Control tactics that shape temporal sequences influence the spectral content of emissions, so modulation and driver choices are integral to mitigation.

For a hard-switched converter with transition time t_r and voltage swing ΔV, the current injected into a parasitic capacitance C_p to chassis is approximately $i_p(t) \approx C_p \frac{d}{dt} v_{\mathrm{sw}}(t)$. A linear ramp approximation yields a triangular current pulse of amplitude $C_p \Delta V / t_r$. The Fourier magnitude of such pulses scales as $\propto \sin(\pi f t_r)/(\pi f t_r)$, showing that shorter t_r elevates high-frequency components. Edge control through gate resistance and driver slew control therefore provides trade-offs among switching loss, efficiency, and emissions. A gate network that induces a two-slope transition can reduce high-frequency energy while retaining acceptable loss. Modeling the gate–drain Miller plateau yields an effective differential equation

$$C_{\mathrm{iss}}(v_g)\frac{dv_g}{dt} + g_m^{-1}\frac{di_d}{dt} + C_{\mathrm{gd}}\frac{dv_{\mathrm{ds}}}{dt} = \frac{v_{\mathrm{drv}} - v_g}{R_g},$$

which can be tuned by R_g and by series networks to shape dv_{ds}/dt and di_d/dt.

Interleaving phases in multiphase converters reduces ripple and emissions by phase cancellation. For N phases with equal magnitude ripple components and phase offsets $\phi_k = 2\pi k/N$, the composite ripple amplitude at a given harmonic order h is scaled by a phasor sum

$$A_h^{\text{sum}} = A_h \left| \sum_{k=0}^{N-1} e^{jh\phi_k} \right| = A_h \left| \frac{1 - e^{j2\pi h}}{1 - e^{j2\pi h/N}} \right|,$$

which vanishes for h multiples of N under symmetry. Practical imbalance reduces cancellation, but careful current sharing and matched paths preserve much of the benefit [20]. Interleaving also redistributes spectral lines, which can push energy away from sensitive bands.

Spread-spectrum modulation blurs discrete lines that can trigger failures with narrowband receivers or test detectors. For a center frequency f_s with modulation $f(t) = f_s + \Delta f\, m(t)$ where $m(t)$ has bounded support and mean zero, the output line at $k f_s$ is broadened, lowering peak amplitude at any fixed narrow resolution bandwidth. A simplified descriptor for small modulation index uses the modulation transfer theorem, which yields a spectral density

$$S_y(f) \approx \sum_{k=-\infty}^{\infty} |H_k(f)|^2 S_s(f - k f_s),$$

with H_k depending on the modulation statistics. For random modulation where T is drawn i.i.d. per cycle, line energies scale with $|\Phi_T(2\pi k)|^2$ as previously noted. Compliance outcomes depend on detector characteristics, so empirical assessment with relevant resolution bandwidths and dwell times remains necessary.

Randomized pulse-width modulation can reduce tonal artifacts and lower peak emissions. Consider a PWM sequence with duty ratio D perturbed by δ_n with zero mean and variance σ^2, bounded to maintain constraints. The expected power spectrum of the switching function $s(t)$, for small σ, exhibits a continuous pedestal whose level is proportional to σ^2, while discrete lines shrink approximately by a factor related to $e^{-2\pi^2\sigma^2 k^2}$ for harmonic k in idealized models. Control loop stability must be preserved; thus randomization is confined to bands outside the loop bandwidth to avoid excess jitter in current or voltage regulation.

Snubbers and clamp networks reshape energy flow during transitions. A simple RC snubber across a switch reduces dv/dt by supplying a path for displacement current and dissipating stored energy. The time constant $\tau = R_s C_s$ and selection of C_s relative to parasitic capacitance determine the damping factor [21]. A loss-aware design chooses R_s so that the snubber sees a critically damped response around the dominant resonance formed by parasitics:

$$\zeta \approx \frac{1}{2} R_{\text{eq}} \sqrt{\frac{C_{\text{eq}}}{L_{\text{eq}}}}, \quad \text{choose } R_{\text{eq}} \approx 2\sqrt{\frac{L_{\text{eq}}}{C_{\text{eq}}}},$$

placing the composite near $\zeta \approx 1$ for fastest decay without overshoot. Resonant or active clamps alternatively recycle energy, but they alter device stress and sometimes the spectral signature.

Gate driver return referencing affects common-mode injection. If the driver is referenced to a noisy source, its common-mode movement appears on control lines; isolation with adequate common-mode transient immunity is used to prevent false triggering and parasitic heating. The isolation barrier has parasitic capacitance C_{iso}, which conducts displacement current proportional to dv/dt. Minimizing C_{iso} lessens common-mode injection, but small values can increase susceptibility to external fields; balancing insulation, dv/dt rating, and EMC requires careful selection of barrier geometry and materials.

8. Measurement, Diagnostics, and Data-Driven Mitigation

Bench-level diagnostics connect models to observables and drive iterative mitigation. Conducted emissions are assessed using impedance stabilization at the interface, allowing repeatable transfer measurements. Radiated emissions and immunity are probed with antennas and near-field sensors that localize coupling hot spots. Time-domain observations capture ring-downs and occasional events such as asynchronous interference from external equipment. A combined frequency–time outlook is valuable, because emissions that pass averaged metrics may still trigger failures in edge-sensitive victims.

Suppose a time signal $x(t)$ is captured at sampling rate f_s from a current probe on a cable. The power spectral density estimated via Welch's method divides $x(t)$ into overlapping windows, applies a taper $w[n]$, and averages periodograms. If segment length is N with M segments and discrete Fourier transform $X_m[k]$ for segment m, the estimator is

$$\hat{S}_{xx}[k] = \frac{1}{MU} \sum_{m=1}^{M} \left| \sum_{n=0}^{N-1} x_m[n] w[n] e^{-j2\pi kn/N} \right|^2, \quad U = \frac{1}{N} \sum_{n=0}^{N-1} w^2[n].$$

This provides reduced variance at the expense of resolution. Peaks tied to structural resonances emerge consistently; stochastic components reveal as plateaus [22]. Coherence between two probes identifies linear coupling; given signals x and y, the magnitude-squared coherence is

$$\gamma_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f) S_{yy}(f)},$$

indicating frequencies where linear relationships dominate. High coherence between a switching node voltage and a cable current suggests capacitive injection as a driver; between loop current and a nearby sensor line, inductive coupling is implied. These inferences guide local fixes such as shielding, rerouting, or damping.

Near-field scanning maps magnetic or electric field intensity over surfaces. Let $H_z(x, y)$ be measured across a grid over a board; the discrete Fourier transform $\mathcal{F}\{H_z\}$ indicates dominant spatial frequencies associated with loop geometries. Superimposing measurement with current density estimates from simulation validates or updates models. If a signature suggests a cavity mode inside an enclosure, field maxima guide placement of damping materials or ground bonds. In some cases, blind source separation is helpful: when multiple uncorrelated aggressors co-exist, independent component analysis applied to multi-probe data separates contributions without detailed prior models. One can cast observations $\mathbf{x}(t)$ as mixtures $\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t)$ and estimate demixing $\mathbf{W}$ so that $\mathbf{y}(t) = \mathbf{W}\mathbf{x}(t)$ yields components with near-independent statistics, thereby isolating sources associated with particular subassemblies.

Measurement uncertainty is intrinsic. Emission levels depend on cable orientations, table reflections, and ambient signals. Sensitivity analysis is appropriate: if E denotes a measured field magnitude and θ a set of configuration variables, the gradient $\partial E/\partial \theta$ informs how robust a fix must be. Bootstrapping across repeated runs with randomized cable placement and equipment arrangement yields empirical distributions for emissions peaks; a mitigation is preferable if it shifts not only the mean but also the upper quantiles downward. This ties to margin planning; rather than aiming to match a limit nominally, space is reserved so that variation still yields compliance.

Data-driven mitigation accumulates labeled outcomes across design variants and bench states [23]. A regression model $g(z)$ mapping feature vector z (geometry metrics, component choices, measured partial metrics) to predicted emission margin can be fit and then used to prioritize mitigations with the greatest expected effect per unit cost or per unit efficiency penalty. Features might include loop areas, path lengths, counts of layer transitions, cumulative return discontinuity length, proximity scores between hot nodes and harness attachment points, and gate driver parameters. While such regression cannot replace physics, it offers triage capabilities during time-limited iteration.

In immunity assessments, victim circuits are injected with known disturbances using bulk current injection clamps or conducted voltage injection while monitoring for malfunction. The transfer from injected disturbance to victim metrics is approximated via linear or weakly nonlinear models, e.g.,

$$y(t) = \int h(\tau)x(t-\tau)\,d\tau + \epsilon(t),$$

where $x(t)$ is injected current or voltage, $y(t)$ is a performance metric such as timing jitter or reference drift, h is an impulse response, and ϵ captures noise and nonlinear residuals. Identifying h by least-squares in the frequency domain allows prediction under varying excitation, supporting sensitivity analysis.

9. Reliability, Safety Margins, and Standards-Aware Design Integration

Electromagnetic compatibility operates in tandem with reliability and safety constraints. Repetitive injection of displacement current through insulating barriers can heat localized regions or stress interfaces, contributing to early drift or failure. Similarly, spectral shaping methods that distribute energy can elevate average dissipation in ferrites or resistive films if not accounted for. A neutral treatment emphasizes the alignment of EMC measures with thermal budgets, component derating, and mechanical integrity.

Reliability-aware planning introduces margin variables into the design problem. If η denotes efficiency and Π a scalar measure of electromagnetic stress such as integrated common-mode current on a cable over a band, the designer balances [24]

$$\min_{u}\ \alpha\big(1-\eta(u)\big) + \beta\,\Pi(u) + \gamma\,C(u),$$

where $C(u)$ is a cost proxy and (α, β, γ) reflect project priorities. Bounds impose temperature limits, mechanical allowances, and regulatory headroom. The electromagnetically relevant terms require models of loss in ferrites, skin-effect resistive rise in conductors, and dielectric heating from fields. For a ferrite with complex permeability $\mu' - j\mu''$, the volumetric loss density under magnetic field amplitude H at angular frequency ω is

$$p_{\mathrm{mag}}(\omega) \approx \omega\mu''(\omega)|H|^2,$$

so where spread-spectrum raises occupancy in frequency bands with larger μ'', the thermal impact must be evaluated. In conductors, the effective resistance $R(\omega)$ grows with $\sqrt{\omega}$ due to skin effect, leading to elevated loss under broadband noise. These effects provide constraints that temper aggressive spectral shaping.

Safety considerations involve bonding and grounding schemes that dissipate fault currents while not compromising electromagnetic performance. A low-impedance bond to protective earth prevents hazardous voltages under fault but can introduce paths for common-mode currents during normal switching. Careful arrangement of safety earth connections relative to high-frequency returns allows both requirements to be met; for instance, a star arrangement for low-frequency safety currents and a distributed, low-inductance path for high-frequency returns near aggressors reduce conflicts. Where double insulation removes safety earth, chassis floating potentials under displacement current must be constrained within acceptable levels via controlled capacitance to nearby references and by limiting cable lengths or adding common-mode impedance.

Production variation encourages robust choices with shallow sensitivity. If a mitigation relies on a cancellation that requires tight tolerance, the yield may suffer. Designers can compute a sensitivity index

$$S_i = \frac{\partial J}{\partial u_i}\frac{\sigma_{u_i}}{\sigma_J},$$

with σ_{u_i} the standard deviation of parameter u_i and σ_J that of the objective, to prioritize parameters that warrant tighter control. Passive choices such as moving a stitch via closer to a discontinuity often exhibit lower sensitivity than active cancellation schemes. When passive means are insufficient, feedback control that is robust to parametric drift can complement, provided that control stability is preserved. [25]

Documented workflows that integrate electromagnetic checks from concept through layout and verification support repeatability. Early schematic reviews include explicit identification of hot loops and likely common-mode injection nodes. Pre-layout simulations combine simple distributed models with expected cable attachments. During layout, continual evaluation of return paths and via arrangements guards against late surprises. Post-layout, a lightweight extraction of parasitics feeds a macromodel that forecasts sensitive bands. In the lab, structured test plans, including controlled cable configurations and multiple orientations, establish response envelopes rather than isolated points. The outputs then feed back into parameterized design repositories for reuse and refinement.

10. Case-Oriented Synthesis of Strategies Across Applications

Applications across motor drives, isolated DC–DC converters, RF front-ends adjacent to digital logic, and battery management systems share electromagnetic patterns but with distinct constraints. Motor drives exhibit long cable runs that invite common-mode resonances; isolated supplies inject displacement currents across barriers; RF systems require quiet local oscillators and sensitive receivers; battery management lines must withstand aggressive nearby switching while maintaining measurement fidelity.

In motor drives, the combination of fast switching and lengthy motor leads produces pronounced common-mode currents. The enclosure and motor frame form part of the return path; bearings and mechanical assemblies can experience electrical stress. Designing the inverter output filter with both differential and common-mode elements attenuates emissions, but placement and bonding dominate effectiveness. The cable's modal impedance profile and the motor's winding capacitances generate resonances that benefit from damping at strategic locations. If a common-mode choke is placed near the inverter, its impedance reduces injected current; placing lossy elements near current antinodes along the cable suppresses standing waves [26]. Numerical exploration with a distributed line model and lumped winding capacitances helps predict peaks. Formally, if $Z_{\mathrm{cm}}(x, \omega)$ varies with position x where damping elements are installed, then maximizing attenuation at ω_r amounts to selecting positions where $|I_{\mathrm{cm}}(x, \omega_r)|$ is large, which can be approximated by computing the undamped standing wave and choosing x accordingly.

Isolated DC–DC converters balance barrier capacitance against immunity and emissions. High isolation usually implies larger spacing and thus higher capacitance if plate areas are not reduced; but fringe fields can dominate. Reducing barrier capacitance lowers displacement currents, yet excessively small capacitance can elevate differential noise or slow control handshakes if the barrier also conveys signals. Gate drivers with high common-mode transient immunity combined with minimized primary-to-secondary capacitance in transformers or planar magnetics provide practical mitigation. The trade-offs include copper losses, leakage inductance that affects regulation and transient response, and thermal constraints on core selection. An optimization problem considers winding arrangement to minimize interwinding capacitance subject to a leakage inductance bound:

$$\min_{\text{geometry}} \; C_{\mathrm{pw}} \quad \text{s.t.} \quad L_{\mathrm{lk}} \le L_{\max}, \;\; \rho_{\mathrm{Cu}} \ell_{\mathrm{tot}} \le R_{\max},$$

where C_{pw} is primary–winding-to-secondary capacitance, L_{lk} is leakage inductance, and ℓ_{tot} the total conductor length, linked to resistance R by the resistivity ρ_{Cu}. Solving guides layering and spacing choices.

RF front-ends cohabiting with digital logic encounter impulsive noise and broadband hash in sensitive bands near local oscillator and intermediate frequencies. Here, geometry-based isolation and reference partitioning are central: placing the RF reference continuous and isolated from digital return discontinuities narrows coupling. Feedthroughs for supply rails at the RF block boundary and compact, high-Q filtering sustain local cleanliness. When a high-speed serializer operates nearby, its spread-spectrum clocking interacts with RF channels; assessing overlap and choosing modulation profiles with spectral notches around RF bands decrease the likelihood of interference. The impact can be quantified by integrating the clock's spectral density over the RF channel filter response and constraining the integral below a threshold:

$$\int_{f_1}^{f_2} S_{\mathrm{clk}}(f)|H_{\mathrm{RF}}(f)|^2 df \le \Theta,$$

where $[f_1, f_2]$ is the band of interest and Θ a tolerated interference level.

Battery management systems require precise measurement under dynamic conditions. Long sense lines traversing mixed environments pick up both differential and common-mode noise. Twisted pair routing with tight twist pitch, differential amplifiers with high common-mode rejection over frequency, and careful return referencing reduce susceptibility. The frequency dependence of common-mode rejection ratio matters, so amplifiers are selected not only for DC CMRR but for sustained rejection into the hundreds of kilohertz or beyond. A simplified transfer for a differential measurement with finite CMRR is

$$V_{\mathrm{meas}}(f) \approx H_{\mathrm{diff}}(f)V_{\mathrm{diff}}(f) + \frac{1}{\mathrm{CMRR}(f)}H_{\mathrm{cm}}(f)V_{\mathrm{cm}}(f),$$

so specifications that include $\mathrm{CMRR}(f)$ curves help forecast vulnerability. Shielding of sense lines with proper termination at one end for electrostatic pickup and controlled bonding for magnetic pickup provides practical balance.

Across these cases, adjustments in layout, filtering, shielding, and control intertwine. Implementation favors parameterized choices framed by models and refined through measurement. Neutral evaluation of outcomes against thermal and cost constraints ensures that final configurations are compatible with system-level objectives and production realities.

11. Conclusion

Electromagnetic compatibility in high-frequency and power electronic applications results from a network of interacting physical and design factors. The strategies evaluated here emphasize modeling that links geometry, materials, and control to measurable emissions and susceptibility, measurement practices that expose dominant paths with adequate statistical coverage, and mitigation steps that coordinate layout, filtering, shielding, damping, and modulation. Mathematical formulations, including macromodels for coupling, robust optimization of design variables, and spectral descriptions of switching sequences, provide structure for anticipating issues and allocating margin. Practical considerations, including return path integrity, cable and connector behavior, barrier capacitance, and component orientation, repeatedly emerge as decisive levers that can be tuned without excessive complexity. Measurement-driven iteration, supported by coherence analysis and near-field mapping, ties predictions to observations and narrows uncertainty in the presence of variation across production and environment. The neutral perspective maintained throughout leads to balanced choices that align electromagnetic performance with efficiency, thermal management, and cost [27]. The resulting approach supports designs that remain compatible across operating envelopes and tolerances while avoiding heavy reliance on ad hoc fixes, thereby encouraging configurations that are stable, maintainable, and scalable across related platforms.

Electromagnetic compatibility (EMC) cannot be treated as an isolated phenomenon but must be approached as a dynamic interaction among the structural, electrical, and temporal aspects of the system. Each interconnect, dielectric interface, and switching transition contributes to an overall field distribution that evolves with operating state. The challenge lies in capturing this distribution in a form that allows both simulation and experimental verification. Advanced numerical methods, such as finite-element and method-of-moments solvers, provide spatially resolved insight into field coupling, while compact macromodels distill this information into forms suitable for circuit-level integration. These models can then be incorporated into optimization routines that balance electromagnetic metrics with functional objectives such as power efficiency or control response. The use of parametric studies, sensitivity analysis, and surrogate modeling enables designers to understand how incremental changes in geometry or component parameters affect system-level compatibility before fabrication.

At the measurement level, precision and repeatability are critical. Near-field scanning techniques, employing magnetic and electric probes, can visualize local hot spots of emission, while time-domain reflectometry can reveal discontinuities that promote mode conversion. Statistical coverage ensures that measurements reflect the variability inherent in manufacturing and assembly. This may involve repeated testing across different units, temperatures, and supply conditions. Coherence analysis between source signals and measured emissions helps identify causal relationships, distinguishing between correlated interference originating from switching events and uncorrelated environmental noise. Such diagnostic clarity is essential for targeted mitigation, as it prevents overengineering and ensures that countermeasures address the true dominant mechanisms.

Mitigation, in turn, thrives on hierarchy and proportionality [28]. At the layout level, minimizing loop areas and maintaining uninterrupted return planes suppresses both differential and common-mode emissions. At the component level, careful placement and orientation of magnetic components, capacitors, and power devices reduce cross-coupling. Shielding strategies must be viewed as field redistributors rather than absolute barriers; their performance depends on continuity, grounding, and aperture control. Filtering and damping networks must be sized with regard to impedance matching and resonance suppression, avoiding excessive insertion loss or phase distortion. Modulation of switching patterns—through randomization, spread-spectrum techniques, or phase interleaving—adds an additional degree of freedom that can smooth spectral peaks and improve compliance margins, albeit with increased analysis complexity.

The interaction of electromagnetic design with other performance domains imposes nontrivial trade-offs. Higher switching frequencies, while enabling smaller passive components and faster control response, also expand the radiated spectrum and reduce the relative effectiveness of traditional filters. Thermal considerations can influence EMC behavior as well: temperature-dependent changes in material properties, such as permeability or dielectric constant, alter coupling coefficients and resonance frequencies. Likewise, mechanical design features introduced for cooling or structural reasons—vents, fasteners, or support frames—can perturb current return paths and introduce unintended apertures in shielding. A holistic view ensures that electromagnetic design choices do not compromise reliability, manufacturability, or cost efficiency.

Robust optimization frameworks provide a systematic means to navigate these competing objectives. By treating EMC performance metrics as part of a multi-objective cost function, designers can explore Pareto fronts that reveal trade-offs among efficiency, emissions, and thermal stress. Stochastic methods, such as Monte Carlo analysis or Bayesian inference, incorporate parameter variability and measurement uncertainty into the design process, ensuring that compatibility is achieved not just under nominal conditions but across expected tolerances. The goal is not to eliminate interference entirely but to confine it within predictable and acceptable bounds, maintaining functionality and regulatory compliance without excessive margin or overdesign. [29]

An often-underestimated factor in EMC robustness is the behavior of interconnects and cables. Even when internal circuit design is optimized, external wiring can act as an efficient radiator or receiver. The interaction between common-mode currents and cable geometry, combined with connector impedance discontinuities, can dominate the system's emission signature. Techniques such as proper cable dressing, the use of shield terminations with circumferential contact, and the incorporation of common-mode chokes near entry points are practical and effective. Similarly, ensuring the integrity of the return path—by aligning current flows and minimizing shared impedance—reduces susceptibility to ground bounce and mode conversion. Barrier capacitance management, especially across isolation boundaries, ensures that safety features coexist with electromagnetic integrity.

Measurement-driven iteration closes the loop between modeling and implementation. By correlating predicted and measured quantities, designers can refine macromodels, improve parameter extraction, and increase confidence in extrapolations. Near-field mapping provides spatial context, while coherence and cross-spectral analysis quantify temporal and frequency relationships. This data-driven refinement reduces the reliance on intuition or experience alone, creating a reproducible workflow that adapts to new device technologies and packaging strategies. Over time, such workflows evolve into institutional knowledge that shortens development cycles and enhances cross-disciplinary collaboration between circuit designers, mechanical engineers, and system integrators.

A key attribute of the methodology is its neutrality—it does not privilege any single mitigation technique or modeling approach but integrates multiple tools under a consistent framework. This neutrality fosters balanced decisions: for example, it may show that a minor layout change outperforms a costly shield, or that phase interleaving among converters yields better spectral spreading than added filtering. By quantifying these trade-offs early, design teams can allocate effort and resources efficiently, achieving compliance without iterative trial and error. Moreover, the resulting configurations tend to be more stable over time, requiring fewer maintenance adjustments or field modifications [30].

References

[1] T. Yamamoto, S. Yokota, and Y. Tamura, "Control of electro-hydraulic manipulators for overhead distribution line work. the 3rd. report. accurate trajectory control of a 6-link manipulator in actual use.," *Hydraulics & Pneumatics*, vol. 26, no. 7, pp. 896–902, 1995.

[2] N. Rauch, "Spannung in der landtechnik," *Landtechnik*, vol. 65, no. 3, pp. 185–188.

[3] A. Skamyin, V. Dobush, and M. Jopri, "Determination of the grid impedance in power consumption modes with harmonics," *Journal of Mining Institute*, vol. Online first, 5 2023.

[4] H.-H. Harms, "Potenziale integrierter motor- und getriebesteuerung," *Landtechnik*, vol. 65, no. 3, pp. 164–166.

[5] Y. Gao, O. Kostyukova, and K. T. Chong, "Worst-case optimal control for an electrical drive system with time-delay," *Asian Journal of Control*, vol. 11, pp. 386–395, 6 2009.

[6] F. Wang, Z. Zhang, X. Mei, J. Rodriguez, and R. Kennel, "Advanced control strategies of induction machine: Field oriented control, direct torque control and model predictive control," *Energies*, vol. 11, pp. 120–, 1 2018.

[7] F. Tavassoli, H. Ghoreishy, J. Adabi, and M. Rezanejad, "An advanced modulation technique featuring common mode voltage suppression for three-phase neutral point clamped back to back converters," *International Journal of Engineering*, vol. 35, no. 11, pp. 2220–2228, 2022.

[8] S. Benzahioul, A. Metatla, A. Kerboua, D. Lefebvre, and R. Bendib, "Use of support vector machines for classification of defects in the induction motor," *Acta Universitatis Sapientiae, Electrical and Mechanical Engineering*, vol. 11, pp. 1–21, 12 2019.

[9] G. Tsintsadze, H. Manoharan, D. Beetner, D. Commerou, B. Booth, and K. Martin, "Predicting radiated emissions from an electrical drive system," in *2023 Joint Asia-Pacific International Symposium on Electromagnetic Compatibility and International Conference on ElectroMagnetic Interference & Compatibility (APEMC/INCEMIC)*, pp. 1–4, IEEE, 2023.

[10] R. Abdel-Fadil and L. Számel, "Predictive direct torque control of switched reluctance motor for electric vehicles drives," *Periodica Polytechnica Electrical Engineering and Computer Science*, 7 2020.

[11] J. Wu, B. Jiang, H. Chen, and J. Liu, "Sensors information fusion system with fault detection based on multi-manifold regularization neighborhood preserving embedding.," *Sensors (Basel, Switzerland)*, vol. 19, pp. 1440–, 3 2019.

[12] H. Chen, J. Wu, B. Jiang, and W. Chen, "A modified neighborhood preserving embedding-based incipient fault detection with applications to small-scale cyber-physical systems.," *ISA transactions*, vol. 104, pp. 175–183, 8 2019.

[13] A. Rohan and S. H. Kim, "Fault detection and diagnosis system for a three-phase inverter using a dwt-based artificial neural network," *The International Journal of Fuzzy Logic and Intelligent Systems*, vol. 16, pp. 238–245, 12 2016.

[14] M. Gaiceanu, C. Eni, and M. Coman, "Adaptive control with supraunitary relative degree for the dc electrical machine," *Advanced Materials Research*, vol. 677, pp. 480–484, 3 2013.

[15] A. Łebkowski, "Analysis of the use of electric drive systems for crew transfer vessels servicing offshore wind farms," *Energies*, vol. 13, pp. 1466–, 3 2020.

[16] L. Szabo, R. Terec, M. Ruba, and P. Rafajdus, "Detecting and tolerating faults in switched reluctance motors," *Universal Journal of Electrical and Electronic Engineering*, vol. 1, no. 2, pp. 16–25, 2013.

[17] J. Fernandes, T. V. Niekerk, G. Scott, and S. Church, "Design and development of an industry standard automated guided vehicle for part collection and delivery at an assembly line," *Journal for New Generation Sciences*, vol. 20, pp. 1–13, 8 2022.

[18] "Horizon," *Aircraft Engineering and Aerospace Technology*, vol. 46, pp. 3–3, 11 1974.

[19] B. P. Ganthia, "Genetic algorithm based direct torque control of vsi fed induction motor drive using matlab simulation," *International Journal of Advanced Trends in Computer Science and Engineering*, vol. 8, pp. 2359–2369, 10 2019.

[20] T. Orlowska-Kowalska and M. Kaminski, "Application of the obd method for optimization of neural state variable estimators of the two-mass drive system," *Neurocomputing*, vol. 72, no. 13, pp. 3034–3045, 2009.

[21] M. Schubert, D. Scharfenstein, and R. W. D. Doncker, "A novel online current- and voltage-sensor offset adaption scheme utilizing the effect of inverter voltage distortion," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 6011–6017, 2019.

[22] H. Eldeeb, C. M. Hackl, and J. Kullick, "Efficient operation of anisotropic synchronous machines for wind energy systems," *Journal of Physics: Conference Series*, vol. 753, pp. 112009–, 10 2016.

[23] T. M. Zhang, Z. Y. Xie, and J. T. Zhang, "A novel ultrasonic motor driver based on two phase pwm signals," *Advanced Materials Research*, vol. 189-193, pp. 1543–1546, 2011.

[24] M. Boesing, A. Hofmann, and R. W. D. Doncker, "Universal acoustic modelling framework for electrical drives," *IET Power Electronics*, vol. 8, no. 5, pp. 693–699, 2015.

[25] E. Schmidt, M. Susic, and A. Eilenberger, "Design studies on a permanent magnet synchronous machine with y- and δ -connected stator winding," *IEEE Transactions on Magnetics*, vol. 47, no. 5, pp. 1042–1045, 2011.

[26] "Voith electric drive for wrightbus, adl buses," *Fuel Cells Bulletin*, vol. 2021, no. 3, pp. 3–3, 2021.

[27] M. Kaminski and T. Orlowska-Kowalska, "Optimisation of neural state variables estimators of two-mass drive system using the bayesian regularization method," *Bulletin of the Polish Academy of Sciences: Technical Sciences*, vol. 59, pp. 33–38, 1 2011.

[28] K. Szabat and T. Orlowska-Kowalska, "Vibration suppression in a two-mass drive system using pi speed controller and additional feedbacks—comparative study," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 2, pp. 1193–1206, 2007.

[29] null Siddharth R Gandhi and null Abhijeet Chavan, "Study of effective powertrain sizing for electric vehicles," *ARAI Journal of Mobility Technology*, vol. 3, pp. 695–707, 8 2023.

[30] A. Berdai, A. Belfqih, J. Boukherouaa, F. E. Mariami, A. Hmidat, V. Vlasenko, and V. Titjuk, "Similarity and comparison of the electrodynamics characteristics of switched reluctance motors srm with those of series dc motors," *Engineering*, vol. 07, no. 1, pp. 36–45, 2015.