EMI DESIGN GUIDE · TECHNICAL ARTICLE

Common Mode Inductor Design Guide:

Improving EMI Performance

Core material selection, impedance matching, winding structure, grounding design, and EMI standard compliance for common mode chokes in switching power systems

Applications: EV OBC · Energy Storage PCS · PV Inverters · AI Server PSU · Industrial Power

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1. Key Finding

Key Finding: Common mode choke effectiveness depends on impedance across the actual conducted noise frequency band — not just at one spot frequency. Engineers should measure the system's noise spectrum first, then select core material and winding structure to match the dominant noise band. A choke that works at 150 kHz may provide negligible attenuation at 5 MHz, and vice versa.

2. Common Mode Noise: Source and Path

Every switching power converter generates common mode (CM) noise. When a power switch opens or closes, the voltage transitions on the switching node create displacement currents that flow through parasitic capacitances to ground — from the switch drain/collector to the heatsink, from the PCB copper to chassis, and from the transformer winding to its core. These currents return through the ground conductor, forming a conducted common mode interference path.

Unlike differential mode (DM) noise — which flows between the two power lines and is primarily a function of inductor ripple current — common mode noise is driven by the rate of voltage change (dV/dt) at the switching node, multiplied by the parasitic capacitance to ground. As switching frequencies increase with SiC and GaN devices, and as power densities increase, common mode noise levels rise.

2.1 Common Mode vs. Differential Mode: Key Distinction

Parameter	Common Mode (CM) Noise	Differential Mode (DM) Noise
Current path	Both lines carry current in the same direction; returns via ground	Current flows between the two power lines; net return is zero
Primary source	dV/dt at switching node × parasitic capacitance to ground	Inductor current ripple; converter topology
Suppression method	Common mode choke (flux adds in core)	DM filter inductor + X-capacitors (flux cancels in CM choke)
Dominant frequency	Often 150 kHz – 30 MHz	Often 150 kHz – 2 MHz (lower frequency)
EMI standard limit	CISPR 25/32/11 — conducted limits apply to both	Same standards; CM and DM contribute independently

3. How a Common Mode Choke Works

A common mode choke consists of two (or more) windings wound on a shared magnetic core. The key operating principle relies on flux cancellation and flux addition:

- Differential mode current: the two line currents flow in opposite directions through the two windings. The magnetic fluxes they produce in the shared core cancel each other. The core sees (almost) zero net flux from DM current, so DM inductance is very low — the choke presents negligible impedance to the differential power current.

- Common mode current: both line currents flow in the same direction through their respective windings. The magnetic fluxes add in the shared core, producing high inductance. The choke presents high impedance to common mode noise current.

$$Z_{CM} = j\omega L_{CM} \quad \text{(high — attenuates CM noise)}$$

$$Z_{DM} = j\omega L_{leakage} \quad \text{(very low — passes DM power current)}$$

The ratio of CM inductance to DM leakage inductance is a key quality indicator for a common mode choke. A well-designed choke has $L_{CM} / L_{leakage} > 100$, meaning CM impedance is at least 100× higher than DM impedance at the same frequency.

> **Self-Resonance Warning:** Every common mode choke has a self-resonant frequency (SRF) above which its inter-winding capacitance dominates and impedance falls. Above the SRF, the choke is capacitive and provides little attenuation. Engineers must verify the SRF is above the highest noise frequency that needs to be suppressed.

4. Core Material Selection

The choice of core material determines the frequency range over which the common mode choke provides useful impedance, the peak impedance achievable, and the temperature stability of that impedance over the operating temperature range.

4.1 Core Material Comparison

Core Material	Initial Permeability μi	Effective Freq. Range	Loss Character	Best Application
Ferrite (MnZn)	2,000–10,000	100 kHz – 10 MHz	Low high-freq. loss; cost-effective	SMPS, EV OBC, general EMI filter (CISPR 32)
Nanocrystalline alloy	20,000–80,000	30 kHz – 1 MHz	Very low loss; high CM impedance/turn	High CM impedance needs; broadband filter
Amorphous alloy	10,000–50,000	1 kHz – 500 kHz	Low loss; good at lower frequency	SiC/GaN modules, ultra-thin design, compact
Iron powder / Sendust	26–200	10 kHz – 500 kHz	Higher loss; soft saturation	DM filter — not suitable for CM choke primary

4.2 Frequency Band Matching

The most common selection mistake is choosing core material based only on cost or availability, without verifying that the material provides useful impedance in the actual noise band. The following approach is recommended:

- Step 1: Measure the conducted emission spectrum on the actual converter, or obtain from simulation. Identify the dominant CM noise frequencies.
- Step 2: Match core material to the dominant noise band — ferrite for 1–10 MHz; nanocrystalline for 30 kHz–1 MHz; amorphous for 1 kHz–500 kHz.
- Step 3: Request or measure CM impedance vs. frequency curve (Z_{CM} vs. f) from the supplier over the full CISPR test range. A single inductance value at 100 kHz is insufficient.
- Step 4: Verify self-resonant frequency (SRF) is above the highest noise frequency requiring attenuation.

Noise Source / Application	Dominant CM Noise Band	Recommended Core
SMPS (IGBT, 20–100 kHz)	150 kHz – 5 MHz	Ferrite MnZn
EV OBC / PFC (65–200 kHz)	150 kHz – 10 MHz	Ferrite or Nanocrystalline
SiC inverter (100–300 kHz)	1 MHz – 30 MHz	Ferrite or Amorphous
GaN server PSU (300 kHz–2 MHz)	5 MHz – 30 MHz	Ferrite (high-frequency grade)
Energy storage PCS (8–50 kHz)	150 kHz – 5 MHz	Nanocrystalline or Ferrite
PV string inverter (16–50 kHz)	150 kHz – 5 MHz	Nanocrystalline or Ferrite

5. Magnetic Circuit and Winding Design

5.1 Core Geometry: Closed vs. Open

Closed-core geometries (toroidal or rectangular closed loop) concentrate magnetic flux entirely within the core material. This maximises the effective permeability seen by the winding, minimises leakage field radiation from the component, and provides the highest CM impedance per unit of core volume.

Open-core geometries (E-I, U-I cores with gaps) allow flux to escape through the gap and surrounding air. This reduces effective permeability and CM impedance, but is sometimes used when the gap is needed to handle DC bias — which is not a typical requirement for CM chokes.

> **Design Rule:** Always use closed-core geometry for common mode chokes. Toroidal cores are standard for single-phase designs; rectangular closed-loop cores (nanocrystalline or amorphous) are standard for high-current flat-wire two-stage integrated designs. Avoid E-I or U-I core geometries for CM chokes.

5.2 Winding Structure Design

The winding configuration directly affects both the CM impedance magnitude and the inter-winding capacitance that limits the usable frequency range (SRF).

Winding Design Rules for Optimal CMC Performance:

- Winding symmetry: the two windings must be wound with identical turns, identical conductor cross-section, and (where possible) symmetric physical placement on the core. Asymmetry produces DM leakage inductance and unequal phase impedance.
- Tight coupling: the two windings should be wound in close proximity to maximise magnetic coupling coefficient k. In a well-designed CMC, $k > 0.99$, giving $L_{leakage} / L_{CM} < 1\%$.
- Minimal inter-winding capacitance: the capacitance between the two windings creates a bypass path for high-frequency CM noise. Keep the two windings separated by the minimum insulation required for the hi-pot voltage, and avoid overlapping winding regions where possible.

- Insulation between windings: must withstand the specified hi-pot test voltage. For 800V systems, inter-winding insulation must sustain AC 3000 V / 1 min without breakdown.
- Conductor sizing: the conductor cross-section must handle the full rated current with acceptable DCR. For high-current (>20A) designs, flat wire is typically required to meet the DCR target within the available window area.
- Number of turns: more turns increase CM inductance but also increase inter-winding capacitance, lowering SRF. There is an engineering trade-off between low-frequency impedance (more turns) and high-frequency range (fewer turns).

5.3 Two-Stage Integrated Design

When a single-stage common mode choke cannot provide adequate attenuation across the full conducted emission frequency range, a two-stage integrated design places two CM choke stages on a single core or within a single mechanical package.

- Stage 1 (low-frequency stage): uses a thick conductor (low DCR, handles rated current) with more turns — optimised for 150 kHz to ~1 MHz.
- Stage 2 (high-frequency stage): uses a thin conductor (low capacitance, low skin-effect AC resistance) with fewer turns — optimised for 1 MHz to 30 MHz.
- Integration advantage: eliminates the PCB trace inductance between two separate discrete chokes, reduces footprint, and improves the high-frequency performance of the first stage by removing its parasitic series inductance path.

6. Impedance Calculation and Attenuation Estimation

6.1 CM Impedance Model

The CM impedance of a common mode choke is not simply jωL at all frequencies. The full equivalent circuit includes:

- Series inductance L_CM: the CM inductance determined by core permeability, turns count, and core cross-section area
- Series resistance R_core: the core loss resistance, which accounts for energy absorbed by the core material at each frequency
- Shunt capacitance C_winding: the inter-winding and inter-turn capacitance, which bypasses the inductance at high frequency

The combined impedance Z_CM(f) peaks at the frequency where inductive and capacitive reactances are equal (the SRF), and falls above that frequency. The impedance below the SRF is dominated by the inductive branch; above the SRF, by the capacitive branch.

6.2 CISPR Design Targets

The following impedance targets are engineering references for common mode choke design when targeting specific CISPR emission limits. Actual required impedance depends on the CM noise source level and the Y-capacitor network in the system.

CISPR Standard	Frequency Range	Typical CM Impedance Target	Insulation / Hi-Pot Req.
CISPR 32 Class B (IT equipment)	150 kHz – 30 MHz	≥ 200 Ω at 150 kHz; sustained to 10 MHz	AC 1500 V / 1 min winding-to-winding; IR ≥ 10 MΩ
CISPR 25 Class 5 (automotive)	150 kHz – 108 MHz	≥ 300 Ω at 150 kHz; high impedance to 30 MHz	AC 500 V (12V system); AC 2000 V+ (800V EV)

CISPR Standard	Frequency Range	Typical CM Impedance Target	Insulation / Hi-Pot Req.
CISPR 11 Class A (industrial)	150 kHz – 30 MHz	≥ 200 Ω at 150 kHz	AC 1500 V / 1 min
IEC 61000-3-2 (harmonics)	50 Hz fundamental	Not applicable — harmonic current filter	N/A for CM choke

> **Important:** These impedance targets are starting points for design, not guaranteed pass criteria. Whether the system passes the CISPR limit depends on the CM noise source level, Y-capacitor values, cable routing, and ground connection impedance — not on the CM choke impedance alone. Always verify with pre-compliance measurement on the assembled system before submitting for formal test.

7. Grounding Design and Y-Capacitors

The common mode choke works in combination with Y-capacitors (line-to-ground capacitors) to form a low-pass filter for CM noise. The choke provides series impedance in the CM path; the Y-capacitors provide a low-impedance shunt path that diverts CM noise current before it reaches the line terminal.

7.1 Y-Capacitor Placement

- Y-capacitors are placed between each power line and the safety earth (PE) ground, both on the mains input side and (sometimes) on the converter output side.
- The capacitance value is limited by the maximum allowable leakage current: I_leakage = 2πf × C_Y × V_line. For household equipment (CISPR 32), leakage ≤ 3.5 mA is typically required, limiting total Y-capacitance to ≤ 33 nF at 230V/50Hz.
- For industrial equipment or equipment where a PE ground connection is verified, larger Y-capacitance is allowed, giving more attenuation.

7.2 CM Filter Insertion Loss

The insertion loss of a CM filter consisting of a choke and Y-capacitors can be estimated as:

$$IL\_CM(dB) \approx 20 \times \log_{10}(Z\_CM / (2 \times Z\_source + Z\_CM)) \quad + \quad \text{attenuation of Y-cap}$$

Where Z_source is the source impedance of the CM noise (typically 50–150 Ω in CISPR measurement setup). Maximising Z_CM relative to Z_source is the design goal for the choke stage.

8. Temperature and Reliability Considerations

8.1 Impedance vs. Temperature

The permeability of core materials changes with temperature, and this directly affects CM inductance and impedance. Ferrite MnZn permeability typically peaks near 70–100°C and falls above that; nanocrystalline permeability is more stable across the -40°C to +125°C automotive temperature range. Always request or measure CM impedance at the maximum operating temperature, not only at room temperature.

8.2 Saturation from Inrush and Fault Current

Common mode chokes are designed to pass rated load current without saturation. However, inrush currents at power-on or fault currents during overload can momentarily exceed the rated current by 5–20×. If the core saturates during inrush, CM inductance temporarily collapses, and the filter provides no attenuation precisely when large transient noise is generated.

- Select cores with adequate saturation flux density (B_sat) and verify that the peak current × turns product does not exceed the core's amp-turn saturation limit
- Nanocrystalline and ferrite cores saturate "hard" (sudden collapse); iron silicon aluminium and amorphous cores saturate "soft" (gradual reduction). Soft saturation is more forgiving for transient overload.
- For energy storage PCS applications with bidirectional current, verify saturation in both charge and discharge directions separately.

8.3 Long-Term Reliability

- Winding insulation: specify insulation class matched to maximum operating temperature (Class F for 155°C, Class H for 180°C in automotive/industrial)
- Core material ageing: nanocrystalline and amorphous cores are stable over temperature cycling; ferrite cores can develop micro-cracks under thermal shock — ensure mounting design does not impose mechanical stress on the core
- Moisture and contamination: potting or conformal coating is recommended for outdoor (PV, storage) and automotive applications

9. Application-Specific Design Guidance

9.1 EV On-Board Charger (OBC)

The OBC PFC input is one of the most demanding applications for common mode chokes: high current (15–60A), wide frequency noise spectrum (CISPR 25 Class 5 covers 150 kHz to 108 MHz), automotive temperature cycling (-40°C to +105°C), and tight package height constraints.

OBC CM Choke Specification Priorities:

- Core material: nanocrystalline for low-frequency CM (150 kHz–1 MHz); ferrite for high-frequency (1–30 MHz). Two-stage integrated design recommended when single-stage cannot cover full CISPR 25 Class 5 range.
- Conductor: flat wire winding above 30A to achieve adequate cross-section within package height limit
- Insulation: AC 3000 V hi-pot for 800V OBC (winding-to-winding and winding-to-core); Class H temperature rating
- SRF: must be above 30 MHz to cover CISPR 25 Class 5 upper frequency limit
- Package height: often the binding constraint — flat wire and closed rectangular core minimise height
- AEC-Q200 qualification: required for automotive-grade supply; request qualification test records from supplier

9.2 Energy Storage PCS

Energy storage converters typically switch at 8–50 kHz. The dominant CM noise is in the 150 kHz – 5 MHz range. Nanocrystalline or ferrite cores both work; the choice depends on the current level and

cost target. For large PCS with currents of 100–500A, three-phase common mode chokes with nanocrystalline closed cores are the standard solution.

9.3 AI Server Power Supply

GaN-based AI server PSUs switch at 300 kHz to 2 MHz. The conducted emission spectrum extends to 30 MHz (CISPR 32 Class B). The critical design challenge is achieving sufficient CM impedance above 5 MHz while keeping inter-winding capacitance low enough to avoid early SRF. High-frequency ferrite cores with minimal winding turns and carefully controlled winding geometry are the standard approach for this application.

9.4 Solar PV and Industrial Converters

Solar string inverters (CISPR 11 Class A) and industrial drives typically have their dominant CM noise in the 150 kHz – 5 MHz band. Nanocrystalline cores with flat wire winding are well-suited: they provide high CM impedance at low frequencies (good for MPPT inductor ripple noise) and the flat wire winding efficiently uses the core window at high current.

10. Specification Checklist for Custom CM Choke

Parameters Required for Engineering Review:

- Converter topology and application (OBC / PFC / PCS / inverter / PSU)
- Rated current (RMS per conductor) and peak current (including inrush)
- EMI standard to comply with (CISPR 25 Class 5 / CISPR 32 Class B / CISPR 11 / other)
- Dominant noise frequency range requiring attenuation (measured or estimated)
- Target CM impedance at key frequencies (e.g. ≥ 200 Ω at 150 kHz; ≥ 100 Ω at 5 MHz)
- Y-capacitor values and placement in the filter circuit
- System voltage and winding-to-winding / winding-to-core hi-pot requirement
- Operating temperature range (min and max; under-hood, trunk, outdoor, indoor)
- Package envelope: maximum L × W × H mm; PCB footprint; pin pitch
- Cooling method: natural convection / forced air / baseplate
- Certification: AEC-Q200 / UL / TUV / CE / RoHS; annual quantity
- Number of phases: single-phase, split-phase, or three-phase

11. FAQ

Q1: Why does my CM choke stop working above a certain frequency?

Above the self-resonant frequency (SRF), the inter-winding capacitance of the choke bypasses the inductance. The component becomes capacitive, and CM noise current passes through it rather than being blocked. To extend the usable frequency range: (1) reduce the number of turns (lowers capacitance but also lowers LF impedance), (2) use a core with lower permeability (fewer turns needed for same CM inductance), (3) separate winding layers to reduce inter-winding capacitance, or (4) use a two-stage design with a high-frequency stage optimised for low capacitance.

Q2: Can I use the same core for CM and DM filtering?

In a CM choke, the DM current produces no net flux in the core, so the core does not contribute to DM inductance. DM filtering must be done separately, either with a dedicated DM inductor, or through the leakage inductance of the CM choke (which is typically much smaller than needed for DM filtering alone). For most applications, a CM choke and a separate DM filter inductor or X-capacitor are both required.

Q3: Why is my CM choke warm even though it passes the rated current?

CM choke heating comes from two sources: (1) conductor copper loss (I^2R, from DCR and AC resistance at the harmonic frequencies of the converter current), and (2) core loss from the CM noise current circulating in the core. If the core material is poorly matched to the noise frequency, core loss can be significant. Verify that the core material loss factor ($\tan\delta = \mu''/\mu'$) is low at the dominant noise frequency. Flat wire winding reduces DCR and the associated copper loss.

Q4: Can the values in this guide be used directly in production?

No. All values in this guide are engineering references. Production values must be confirmed through approved samples, CM impedance measurement across the full noise frequency range, DCR measurement at operating temperature, hi-pot testing, and thermal validation at rated current before production release.

12. Contact and Related Resources

Resource	URL
Two-Stage Integrated CMC Article	promagtech.com/technical-resources/two-stage-integrated-common-mode-choke.html
Common Mode Choke Selection Guide 2026	promagtech.com/technical-resources/common-mode-choke-selection-impedance-core-materials.html
Three-Phase Common Mode Inductor Product	promagtech.com/products/three-phase-common-mode.html
High-Freq. Amorphous CM Inductor Product	promagtech.com/products/high-freq-amorphous.html
Flat Wire vs Round Wire Selection Guide	promagtech.com/technical-resources/flat-wire-vs-round-wire-inductors.html

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