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EMI FILTER MAGNETICS · TECHNICAL ARTICLE

Two-Stage Integrated Common Mode Choke

Advanced EMI Suppression for EV On-Board Chargers, AI Server Power Supplies, and Power Inverters

Applications: EV OBC · AI Server PSU · Solar Inverter · Energy Storage Converter

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AUDIENCE	Power Electronics Engineers · EMC Engineers · Hardware R&D
WEBSITE	www.promagtech.com
EMAIL	zyong@promagtech.cn

Abstract

Modern high-power conversion systems — EV on-board chargers, AI server power supplies, solar inverters, and energy storage converters — operate at increasingly higher switching frequencies and power densities. This creates stronger conducted electromagnetic interference (EMI) that must be suppressed before it corrupts control circuits, communication buses, or adjacent power stages.

The two-stage integrated common mode choke addresses this challenge by combining low-frequency and high-frequency EMI suppression within a single magnetic component. This article explains the structural rationale, winding design trade-offs, core material selection, manufacturing considerations, and application requirements that engineering teams need to evaluate before specifying or designing such a component.

Key Finding: Two-stage integrated common mode chokes provide broadband EMI suppression in one package when PCB area is constrained and a single-stage choke cannot cover the full frequency range required by the EMI standard.

1. Background: The EMI Problem in High-Power Conversion

Every switching power converter generates conducted noise. When a power switch opens or closes, it produces voltage and current edges that propagate both differentially between the power lines and in common mode between the power lines and ground. Common mode (CM) noise is particularly difficult to control because it couples through stray capacitances to chassis, enclosure, and cable shields.

Regulatory standards — CISPR 25, CISPR 32, IEC 61000-6-4, FCC Part 15, and automotive standards such as CISPR 12 and CISPR 36 — define conducted emission limits that must be met before a product can be sold in most markets. Meeting these limits typically requires both differential mode (DM) and common mode filter stages in the power entry path.

1.1 Why a Single Common Mode Choke Is Often Insufficient

A conventional single-stage common mode choke provides an impedance peak in a limited frequency band. Its useful attenuation range depends on the core material, the number of turns, the winding geometry, and the coupling between windings. When conducted emission limits span from 150 kHz to 108 MHz — as they do in many automotive and industrial specifications — a single-stage choke cannot simultaneously provide the required attenuation at both the low and high ends of this range without growing physically large.

The low-frequency end requires high inductance, which favors a high-permeability core with many turns. The high-frequency end requires low parasitic capacitance, which favors fewer turns and a geometry that minimizes inter-winding capacitance. These requirements pull in opposite directions.

1.2 The Two-Stage Integration Concept

Rather than placing two separate common mode chokes on the PCB, the two-stage integrated approach combines both filtering functions on a single magnetic core or within a single mechanical package. This reduces:

- Total component count and PCB footprint
- Wiring parasitic inductance between filter stages
- Assembly time and mechanical complexity
- Total height in space-constrained enclosures

The integration does not eliminate the filter physics — both stages must still be designed correctly. It relocates the engineering challenge from PCB layout to magnetic component design.

2. Component Structure and Design Elements

2.1 Core Material: Amorphous and Nanocrystalline

The choice of core material determines the permeability profile, core loss, saturation behaviour, and operating temperature range. Two-stage integrated common mode chokes for high-performance applications most commonly use amorphous or nanocrystalline alloys wound or cut into closed-core geometries.

Property	Amorphous Core	Nanocrystalline Core	Notes
Initial Permeability	~10,000–80,000 μ	~20,000–150,000 μ	Higher μ → more CM impedance per turn
Core Loss @ 100 kHz	Low	Very low	Nanocrystalline preferred above 100 kHz
Saturation Flux Density	~1.2–1.56 T	~1.2–1.25 T	Similar range; check operating point
Curie Temperature	~350–400°C	~570°C	Nanocrystalline better for harsh thermal
High-Freq. CM Impedance	Good	Excellent	Nanocrystalline sustains impedance to MHz
Relative Cost	Lower	Moderate–Higher	Amorphous acceptable for many OBC designs

The closed-core (toroidal or rectangular closed-loop) geometry is preferred because it minimises the air gap reluctance path, concentrates flux inside the core, and reduces radiated EMI from the component itself. This is particularly important in automotive and data centre applications where internal EMI budgets are tight.

2.2 Asymmetric Winding Gauges — Why Two Different Wire Sizes

On many two-stage integrated common mode chokes, the two windings wound onto the core use different wire cross-sections. This design choice is intentional and serves distinct engineering purposes rather than being a cost reduction measure.

The Thicker Winding — Low-Frequency Stage

The low-frequency stage winding handles the dominant power current and must provide sufficient impedance to attenuate CM noise in the lower conducted emission band, typically 150 kHz to 1 MHz. The thicker flat copper wire reduces:

- DC resistance (DCR), which directly reduces I^2R copper loss and temperature rise under rated current
- Current density in the conductor cross-section, improving long-term reliability in thermally demanding environments
- Winding resistance at power frequency, keeping efficiency loss acceptable in high-current OBC and inverter designs

Flat copper wire is preferred over round wire in this stage because it achieves a higher copper fill factor within the available window area, allows controlled winding geometry that is repeatable in production, and provides better thermal contact to the core surface or heatsink interface.

The Thinner Winding — High-Frequency Stage

The high-frequency stage targets noise in the range from approximately 1 MHz to 30 MHz or above. At these frequencies, two phenomena become critical: skin effect and inter-winding parasitic capacitance.

Skin effect concentrates current in a thin surface layer of the conductor. The skin depth δ in copper at frequency f is given by:

$$\delta\ (\mathrm{mm}) = 66.1 / \sqrt{f(\mathrm{Hz})} \quad \rightarrow \quad \delta \approx 0.066\ \mathrm{mm\ at\ 1\ MHz}, \quad \delta \approx 0.021\ \mathrm{mm\ at\ 10\ MHz}$$

A thinner conductor whose cross-section is on the order of one to two skin depths contributes nearly all of its copper area to conducting current, while a thick conductor wastes the interior copper area. Using a thinner winding in the high-frequency stage therefore improves high-frequency attenuation efficiency without unnecessarily increasing DCR in the high-current path.

Parasitic capacitance between turns and between the two windings creates a bypass path for high-frequency noise. This capacitance is proportional to the conductor surface area facing the opposing winding. A smaller-gauge conductor reduces this facing area, lowering the parasitic capacitance and extending the frequency range over which the choke provides effective attenuation.

2.3 Flat Copper Wire and Fill Factor

Flat copper wire (also called rectangular or foil wire) contributes to the two-stage integrated design in the following ways:

Flat Copper Wire Advantages in CM Choke Design
• Higher fill factor: rectangular conductors pack more tightly than round wire, increasing copper cross-section per unit window area
• Lower DCR: increased copper cross-section reduces winding resistance at the same number of turns
• Controlled geometry: winding pitch and layer position are repeatable, giving consistent parasitic capacitance from part to part
• Improved thermal contact: flat conductors have a larger surface area in contact with adjacent materials, supporting better heat dissipation
• Reduced winding height variation: flatter profile keeps the component within dimensional tolerances for automated PCB assembly

2.4 Magnetic Circuit Optimization

The magnetic circuit of a common mode choke must raise common mode impedance while minimising differential mode inductance. In common mode, both line currents flow in the same direction through the winding, and their fluxes add inside the core, producing high inductance. In differential mode, the line currents are equal and opposite, and their fluxes cancel, leaving only leakage inductance as the DM component.

The two-stage integrated design must preserve this flux cancellation principle across both winding sections. If winding symmetry is compromised — for example, by unequal turn counts or unequal coupling coefficients — unintended DM inductance is introduced. This can distort the current waveform and cause current ripple in power conversion stages that are downstream of the filter.

> **Design Rule:** Common mode impedance should be maximised at the target noise frequency, while differential mode inductance should remain below 1–3% of CM inductance. Deviating from this balance degrades either filtering effectiveness or converter efficiency.

3. Application Scenarios

3.1 EV On-Board Charger (OBC)

An on-board charger converts AC grid power to regulated DC for the traction battery. The power stage typically uses a PFC front-end followed by a DC-DC stage. Both stages generate conducted EMI that must be suppressed before the AC line interface.

Parameter	Typical OBC Requirement
Rated AC Input Voltage	85–265 V AC (universal range)
Rated Input Current	8–32 A (3.3–22 kW range)
Switching Frequency	65–200 kHz (SiC designs reach 300 kHz+)
CM Attenuation Target	30–50 dB in CISPR 25 Class 5 limits
Operating Temperature	-40°C to +105°C (under-hood or trunk-mounted)
Insulation Requirement	Hi-Pot ≥ AC 3000 V (HV isolation class)
Package Constraint	Height-limited: many OBC assemblies ≤ 15–25 mm clearance

For OBC designs, the two-stage integrated choke must simultaneously handle high continuous current, survive automotive temperature cycling, and pass insulation tests at significantly higher voltages than typical industrial equipment. The use of flat copper wire becomes particularly valuable in this context because it allows the designer to meet DCR and temperature rise requirements without increasing the component footprint beyond the space envelope.

3.2 AI Server Power Supplies

AI training and inference systems draw extremely high peak and average power from rack-level power distribution. Server power supplies operating at 48 V bus or 400 V AC input must pass CISPR 32 conducted emission limits and maintain high efficiency to reduce data centre cooling costs.

At the high switching frequencies used in modern server PSUs — 300 kHz to 1 MHz is increasingly common with GaN devices — the high-frequency performance of the common mode choke becomes the binding constraint. A two-stage integrated design using nanocrystalline core material can sustain useful CM impedance from below 1 MHz to well above 30 MHz, covering the CISPR 32 range with one component.

> **AI Server Note:** GaN-based server PSUs switching at 500 kHz–1 MHz require CM choke designs where the high-frequency winding capacitance is aggressively minimised. A two-stage integrated structure with a thin HF winding and a nanocrystalline closed core offers one practical path to meeting CISPR 32 Class B limits in these designs.

3.3 Solar and Energy Storage Inverters

Grid-connected inverters inject AC current into the utility grid and are subject to conducted emission standards at the grid interface. High-frequency switching generates CM currents that flow through the stray capacitance between the PV array, battery stack, or DC bus and the protective earth conductor.

These leakage currents can trigger residual current protection devices (RCDs) on the AC side and increase shock risk in the DC circuit. The CM choke at the AC output or DC bus interface must suppress these currents effectively across the full emission standard frequency range.

Application	Primary EMI Concern	Key Choke Requirement
String Solar Inverter	CM current through PV-earth capacitance	High LF impedance, 50–60 Hz ground current limiting
Three-Phase Storage Inverter	CM noise across 150 kHz–30 MHz	Broadband suppression, high operating current
EV DC Fast Charger	Conducted and radiated EMI to grid	CISPR 11 Class A/B, insulation 3 kV+
Grid-Tied Industrial UPS	CISPR 11 Group 1 Class A	Low DM leakage, high CM attenuation

4. Performance Evaluation Parameters

Engineering teams evaluating or specifying a two-stage integrated common mode choke should request or measure the following parameters. Supplier datasheets that list only inductance at 100 kHz and DCR are insufficient for a rigorous design review.

4.1 Common Mode Impedance Curve

The CM impedance should be measured with a vector network analyser (VNA) or impedance analyser over the full frequency range of the applicable EMI standard. The curve reveals the frequency of peak impedance, the rate of roll-off above and below the peak, and the location of any self-resonance that creates a low-impedance window.

For a two-stage integrated design, the impedance curve should ideally show two distinct impedance peaks or a broad, relatively flat response that covers more of the frequency axis than a single-stage design would achieve.

4.2 DC Resistance (DCR)

DCR determines copper loss and temperature rise. Always request or measure DCR at the temperature where the component will operate, not only at 25°C. Copper resistivity increases with temperature:

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DCR(T) = DCR(25°C) × [1 + 0.00393 × (T − 25)]
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A component with DCR = 5 mΩ at 25°C will have DCR ≈ 6.4 mΩ at 85°C and ≈ 7.0 mΩ at 105°C. In a 30 A design, this difference is 3.15 W of additional heat at 105°C relative to the 25°C measurement.

4.3 Temperature Rise and Thermal Validation

Request a temperature rise test result at rated current, not merely a thermal simulation. The test should be conducted at the rated ambient temperature with the component mounted in a representative thermal environment (free air, forced air, or heatsink contact as applicable). The test should run until thermal equilibrium is reached, typically 30 to 60 minutes for a component of this type.

4.4 Insulation and Hi-Pot Testing

Common mode chokes in high-voltage systems must withstand the electrical stress between windings and between windings and core. The required hi-pot test voltage depends on the system working voltage:

Working Voltage (DC or Peak AC)	Typical Hi-Pot Test Voltage	Duration
Up to 300 V	AC 1500 V	1 minute, no breakdown or flashover
300 V – 600 V	AC 2000–2500 V	1 minute, no breakdown or flashover
600 V – 1000 V	AC 3000 V	1 minute, no breakdown or flashover
Above 1000 V	AC 4000 V+	Per application standard

Partial discharge testing should be added for designs where the working voltage is above approximately 300 V peak and where long service life is required. Partial discharge onset voltage (PDIV) should exceed the maximum system working voltage with appropriate margin.

4.5 Differential Mode Inductance and Leakage

Measure DM inductance to confirm that the winding symmetry is acceptable. DM inductance that is too high can add unwanted filtering on the DM path, distort the converter current waveform, and interfere with DM filter components that are designed for a specific DM impedance environment.

4.6 Reliability and Environmental Tests

For automotive applications, request compliance with AEC-Q200. For industrial applications, relevant standards include IEC 60068 environmental tests (temperature cycling, damp heat, vibration) and IEC 60950 or IEC 62368 for safety. For products entering the EU market, RoHS compliance documentation should be provided with material declarations.

5. Manufacturing Considerations

The two-stage integrated common mode choke is more difficult to manufacture consistently than a single-stage design. The engineering team at PROMAGTECH has identified the following process disciplines as critical to achieving specified performance across production lots:

Critical Manufacturing Process Controls

- Winding tension and pitch control: flat copper wire must be wound with controlled tension to prevent insulation cracking and to keep inter-turn spacing consistent across all units
- Insulation system selection: the insulation between stages must be rated for the full working voltage plus hi-pot test voltage; film type, thickness, and dielectric strength must be documented in the process specification
- Magnetic coupling control: the spatial relationship between the two winding stages determines the coupling coefficient; fixture-controlled winding ensures that this relationship is repeatable
- Soldering process control: flat wire terminations require controlled soldering temperature and contact time to avoid damaging the insulation or creating cold joints
- Core handling: amorphous and nanocrystalline cores are brittle; handling, fixturing, and encapsulation processes must not introduce mechanical stress that cracks the core or degrades permeability
- Final impedance verification: 100% CM impedance measurement at one or more spot frequencies confirms that the winding configuration is correct before shipment

Engineering Discipline: Performance claims such as high current capability, automotive reliability, or RoHS compliance must be supported by project-specific drawings, material specifications, qualification test records, and traceability documentation. PROMAGTECH prepares component reviews around the customer application, not around a catalogue photograph.

6. How to Specify a Two-Stage Integrated Common Mode Choke

The following parameters should be defined before requesting a design review or quotation. Vague requests such as "common mode choke for EV charger" cannot be evaluated without this information.

Parameter	What to Provide	Why It Matters
Converter Topology	PFC + DC-DC, CLLC, DAB, H-bridge, etc.	Determines switching waveform and noise character

Parameter	What to Provide	Why It Matters
Rated Voltage	AC input or DC bus voltage, including range	Sets insulation class and hi-pot requirement
Rated Current	RMS and peak, with duty cycle if pulsed	Determines wire gauge, DCR, temperature rise
Switching Frequency	Fundamental and harmonics if relevant	Determines which frequency range must be filtered
Target EMI Standard	CISPR 25 Class 5, CISPR 32 Class B, etc.	Sets attenuation target at each frequency
CM Impedance Requirement	Impedance target at key frequencies (Ω)	Allows selection of core and turns
DCR Limit	Max DCR in mΩ, at operating temperature	Controls copper loss and thermal budget
Insulation Requirement	Working voltage + hi-pot level + standard	Determines insulation film type and thickness
Package Envelope	L × W × H in mm, PCB footprint, pin pitch	Constrains core size and winding window
Cooling Condition	Free air, forced air, heatsink, immersion	Determines thermal design basis
Certification	AEC-Q200, UL, TUV, IEC, RoHS	Affects material selection and test scope
Annual Volume	Prototype / NPI / mass production quantity	Determines manufacturing process selection

7. Frequently Asked Questions

Q1: Can the values in this article be used directly in production?

No. All values presented in this article are design references and illustrative examples. Production values must be confirmed through application-specific design review, approved samples, DC bias measurement, DCR measurement at operating temperature, hi-pot testing, and thermal validation at rated current.

Q2: What is the main difference between a two-stage integrated choke and two separate chokes in series?

Electrically, both approaches can achieve similar attenuation if designed to equivalent specifications. The practical differences are PCB space, component count, and inter-stage parasitic inductance. The integrated design saves PCB area and reduces the parasitic inductance introduced by PCB traces between two separate components. The trade-off is higher component design complexity and typically longer lead time for custom parts.

Q3: Is nanocrystalline core always better than amorphous core for this application?

Not always. Nanocrystalline core offers higher permeability and lower core loss at frequencies above 100 kHz, making it well-suited for designs that need strong CM attenuation above 1 MHz. However, nanocrystalline cores are more costly and the material is more brittle, requiring more careful handling and fixturing. For designs where the dominant EMI problem is below 500 kHz and cost is important, amorphous core can be the better choice. The correct selection depends on the specific impedance requirement and frequency range of the application.

Q4: Why is the component height important in EV OBC designs?

EV on-board chargers are often mounted in thermally constrained housings where vertical clearance is limited. The common mode choke on the AC input side is frequently in the tallest component in the EMI filter section. If the choke exceeds the available height envelope, it cannot be used regardless of electrical performance. The use of flat copper wire and a closed rectangular core helps PROMAGTECH keep the component height within the envelope while meeting the electrical specification.

Q5: Which EMI standards apply to EV OBC designs?

The most common standards for automotive applications include CISPR 25 (for radiated and conducted emissions in vehicles, typically Class 5 for high-performance OEM designs), CISPR 12 (for external radiated emissions from complete vehicles), and CISPR 36 (for electric and hybrid vehicle low-frequency emissions). In China, GB/T 18655 mirrors CISPR 25. Industrial chargers may additionally need to meet CISPR 11 and IEC 61000-6-4. The design team should confirm which standards and class levels apply to their specific product and market before setting attenuation targets.

8. Request a Design Review

PROMAGTECH engineering is available to review two-stage integrated common mode choke requirements for specific applications. To initiate a review, provide the parameters listed in Section 6 above. A preliminary technical response is typically provided within 24 hours of receiving a complete specification.

Contact PROMAGTECH Engineering: Email: zyong@promagtech.cn | Website: www.promagtech.com/contact.html

9. Related Technical Resources

Resource	Description	URL
High-Frequency Amorphous CM Inductor	Amorphous-core EMI filter magnetics for SiC/GaN and compact power modules	promagtech.com/products/high-freq-amorphous.html
Three-Phase Common Mode Inductor	Three-phase CM chokes for inverter and storage converter EMI filtering	promagtech.com/products/three-phase-common-mode.html
Common Mode Inductor EMI Design Guide	Core material, winding and impedance review points for conducted EMI	promagtech.com/technical-resources/common-mode-inductor-emi-design-guide.html

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www.promagtech.com

zyong@promagtech.cn

Flat Wire Power Inductors · Transformers · Custom Magnetics

Product Capabilities

- Two-stage and single-stage common mode chokes
- Amorphous and nanocrystalline closed-core EMI filter magnetics
- Three-phase common mode inductors for inverters and converters
- Flat wire PFC and DC-DC inductors for EV, solar, and storage
- Custom design review available for application-specific requirements