TECHNICAL WHITE PAPER · MAGNETIC COMPONENTS

High Power Density Magnetic Components:

From Round Wire to Flat Wire Technology

A comprehensive engineering comparison of round-wire and flat-wire magnetic components for AI, EV, PV, and energy storage power systems

Applications: AI Data Centers · EV Charging · Solar Inverters · Energy Storage · Industrial Power

PUBLISHER	Shenzhen PROMAGTECH Co., Ltd.
DOCUMENT	Technical White Paper — Magnetic Component Technology Series
AUDIENCE	Power Engineers · Hardware R&D · Procurement Engineers
WEBSITE	www.promagtech.com
EMAIL	zyong@promagtech.cn

1. Executive Summary

As AI computing platforms, 800V EV systems, photovoltaic inverters, and energy storage converters demand ever-higher power density, traditional round-wire magnetic components are increasingly becoming a limiting factor for thermal management, window utilization, and repeatable production quality.

This white paper provides a structured engineering comparison between round-wire and flat-wire magnetic component technology across five dimensions: window fill factor, AC loss characteristics, thermal path management, production consistency, and mechanical stability. The objective is not to assert that flat wire is universally superior — it is to provide engineers with the framework to determine when flat wire technology changes the design margin in their specific application.

> **Key Finding:** Flat wire magnetics improve power density by increasing copper fill factor and shortening the thermal path, but the benefit must be weighed against winding cost and tooling investment. The correct choice depends on operating current, switching frequency, package constraints, and production volume.

2. The Power Density Challenge in Modern Power Electronics

Power density — watts of output power per unit volume — has become a primary design target across virtually every segment of power electronics. The drivers are economic and physical: data centre space costs money, EV battery management systems have strict volume envelopes, solar inverter enclosures must withstand outdoor conditions in minimal footprint, and industrial motor drives compete on form factor as well as efficiency.

Magnetic components — inductors and transformers — are frequently the largest and heaviest passive elements in a power converter. They are also among the most thermally stressed, because every watt of loss in winding resistance or core material must be conducted or convected away from a component that may be densely surrounded by other heat-generating parts.

2.1 Why Magnetics Set the Power Density Ceiling

In a well-designed power converter, the power density is often limited not by the semiconductor switching devices — which continue to shrink through wide-bandgap technology — but by the volumetric efficiency of the magnetic components. Three physical constraints create this ceiling:

- Thermal constraint: winding I^2R loss and core loss must be removed; both increase with power density if the magnetic structure is not redesigned
- Saturation constraint: core volume must be sufficient to support the required flux at peak current without saturating; a smaller core means a harder saturation limit
- Window constraint: the winding window must accommodate enough copper turns to achieve the required inductance at acceptable DCR; geometric inefficiency wastes window area

Round-wire technology addresses each of these constraints adequately at moderate current densities and frequencies. As current density rises above approximately 5–8 A/mm² of conductor cross-section, or as switching frequency rises above 100–200 kHz, the geometric inefficiency of round wire begins to create compounding problems.

3. Round Wire vs. Flat Wire: Five Engineering Dimensions

3.1 Window Fill Factor

The window fill factor is the ratio of the total copper conductor cross-section area to the available winding window area of the magnetic core. It determines how efficiently the core window is converted into useful current-carrying copper.

Winding Type	Typical Fill Factor	Achievable with Good Process	Notes
Round wire (single layer)	60–70%	72%	Limited by circular cross-section geometry
Round wire (multi-layer)	50–65%	70%	Inter-layer gaps and insulation reduce factor
Flat wire (single layer)	75–85%	88%	Rectangular packing, near-zero inter-turn gap
Flat wire (multi-layer)	70–82%	85%	Film insulation between layers, very tight packing
Foil / strip winding	80–90%	92%	Maximum packing, limited to low-voltage designs

The practical consequence of a 15–20 percentage point improvement in fill factor is significant. For the same core window area and the same number of turns, flat wire achieves approximately 20–40% lower DCR than round wire — because a larger copper cross-section is carrying the same current. Alternatively, the same DCR can be achieved in a smaller core window, directly reducing magnetic volume and component height.

> **Design Impact:** In a high-current design where DCR is the binding constraint (e.g., a 200A energy storage inductor with ≤0.5 mΩ DCR limit), the fill factor improvement from round wire to flat wire can be the difference between fitting the required inductance in the available core and having to use a larger, heavier component.

3.2 AC Loss Characteristics

At DC or low frequency, winding loss is simply $I^2 \times R_{DC}$. At high switching frequencies, two additional electromagnetic phenomena increase the effective resistance of the winding beyond its DC value.

Skin Effect

Current in a conductor at frequency f concentrates in a surface layer of depth δ (the skin depth):

$$\delta\ (\text{mm}) = 66.1 / \sqrt{f(\text{Hz})} \quad \rightarrow \quad \delta \approx 0.209\ \text{mm @100 kHz}, \quad \delta \approx 0.066\ \text{mm @1 MHz}$$

For a round conductor with diameter d >> 2δ, most of the conductor cross-section is not used for current conduction at high frequency. A flat conductor with thickness t ≈ 2δ uses essentially all of its copper area, giving lower AC resistance for the same cross-section area.

Proximity Effect

Alternating magnetic fields produced by adjacent turns induce eddy currents in neighbouring conductors, further increasing AC resistance. Proximity effect can raise AC resistance by a factor of 3–20× the DC value in tightly wound multi-layer coils at MHz-range frequencies. Flat wire windings can be designed with fewer layers to control proximity effect, particularly in LLC resonant and high-frequency DC-DC applications.

Frequency	Skin Depth (Cu)	Round Wire AC/DC Ratio (1mm dia.)	Flat Wire AC/DC Ratio (t=2δ, matched)
10 kHz	0.66 mm	~1.0–1.1×	~1.0× (t=1.3 mm)
100 kHz	0.21 mm	~1.5–2.5×	~1.0–1.1× (t=0.42 mm)
500 kHz	0.093 mm	~3–8×	~1.0–1.2× (t=0.19 mm)
1 MHz	0.066 mm	~6–15×	~1.0–1.3× (t=0.13 mm)
2 MHz	0.047 mm	>15×	~1.1–1.5× (t=0.09 mm, multi-layer foil)

Note: These ratios are indicative and depend on the number of winding layers, conductor geometry, and core geometry. Actual values should be determined by FEM simulation or impedance measurement for the specific winding design.

3.3 Thermal Path Management

The thermal path from winding to ambient is arguably more important than the electrical resistance at the design point. A component that dissipates 5 W total but cannot conduct that heat to the ambient efficiently will overheat, regardless of how low the electrical loss appears in simulation.

Round Wire Thermal Limitations

In a round-wire winding, the spaces between conductors and between conductors and the core wall are filled with air or potting compound. Air has a thermal conductivity of approximately 0.026 W/m·K; standard potting compound is 0.5–2.0 W/m·K; copper is 400 W/m·K. The thermal bottleneck is often not the copper conductor but the inter-conductor medium that connects the copper to the core or outer surface.

This creates localised hot spots at the thermal centre of the winding bundle. In a thermocouple measurement on the component surface, the peak temperature inside the winding can be 15–40°C higher than the measured outer surface temperature, depending on winding configuration, potting material, and power dissipation level.

Flat Wire Thermal Advantages

Flat wire conductors share large flat surfaces with adjacent turns, with only a thin insulation film (typically 25–100 µm of polyimide or polyester film) between them. This creates a much shorter and lower-resistance thermal path from the conductor interior to the conductor edge, and from there to the core wall or baseplate.

Thermal Parameter	Round Wire Winding	Flat Wire Winding
Inter-conductor medium	Air gaps + potting compound	Thin insulation film (25–100 μm)
Thermal conductivity (gap)	0.026–2.0 W/m·K (air/potting)	1–5 W/m·K (film, depends on type)
Peak-to-surface ΔT	15–40°C typical at rated load	5–15°C typical at rated load
Thermal path length	Longer (through inter-wire gaps)	Shorter (direct conductor-to-core path)
Cooling method compatibility	Natural/forced air; limited baseplate	Excellent baseplate coupling; forced air

Thermal Caution: The thermal advantage of flat wire is geometry-dependent. It requires correct insulation film selection, controlled winding tension, appropriate potting or thermal interface material, and a mounting design that utilises the improved thermal path. Flat wire does not automatically mean lower temperature — it means better geometry for achieving lower temperature when the rest of the thermal design is appropriate.

3.4 Production Consistency

In high-volume power electronics manufacturing, the performance variation between the best unit and the worst unit in a production batch is a reliability and quality risk. Wide variation in DCR, inductance, or thermal resistance can push some units to the edge of their operating envelope even when the nominal design appears comfortable.

Quality Parameter	Round Wire (Manual Winding)	Flat Wire (Automated Winding)
DCR variation (batch-to-batch)	±8–15%	±3–5%
Inductance variation	±5–12%	±3–7%
Winding geometry consistency	Operator-dependent	Tooling-controlled
Thermal resistance variation	High (inter-wire gap variation)	Low (controlled film thickness)
Process capability (Cpk)	Typically 0.7–1.0	Typically 1.3–1.8 with process validation
Suitability for SPC monitoring	Difficult (manual process variables)	Straightforward (closed-loop control)

For AI server, automotive, and energy storage programs where field failure has significant downstream cost, production Cpk is a specification requirement, not merely a quality metric. PROMAGTECH targets Cpk ≥ 1.33 on DCR for flat wire inductor programs as a standard production commitment.

3.5 Mechanical Stability

In high-vibration environments — EV powertrains, industrial motor drives, rail traction — the mechanical robustness of the winding assembly can determine component lifetime more than the electrical or thermal design. Flat wire windings offer several structural advantages:

- Stacked flat conductors lock together under the natural spring tension of the winding, forming a structurally coherent assembly that resists vibration-induced conductor displacement
- Flat wire terminals (DIP pins, bus bar extensions) can be formed with precise geometry, eliminating the weak points of round-wire termination soldering
- Potted flat wire assemblies achieve better void-free fill because the flat geometry allows potting compound to flow between layers uniformly
- Assembly height is more predictable because the winding cross-section is defined by the flat conductor stack height rather than a loosely packed circular bundle

4. Strategies for Breaking Power Density Bottlenecks

Switching from round wire to flat wire is one tool for improving power density, but it is most effective when combined with complementary design strategies.

4.1 Electromagnetic Simulation (FEA/FEM)

Legacy inductor and transformer design methods based on area-product calculations and empirical fill-factor estimates are adequate for conservative designs at low frequency. At high current density and switching frequency, finite element analysis (FEA) or FEM magnetic simulation provides substantially better prediction of:

- Flux density distribution and saturation margins at peak current
- Leakage inductance and interwinding capacitance (critical in LLC and CLLC designs)
- AC copper loss distribution through the winding cross-section at the operating frequency spectrum
- Core loss distribution, including surface effects and uneven flux density

PROMAGTECH uses electromagnetic simulation as part of the custom magnetic component design process, particularly for applications where operating frequency is above 100 kHz or where the required power density pushes the design close to thermal or saturation limits.

4.2 Thermal Network Modelling

Magnetic component thermal performance is determined by the complete thermal network from winding to ambient — not by the winding loss alone. An accurate thermal model includes:

Thermal Network Elements for Accurate Magnetic Component Modelling
• Winding copper loss: I^2R_{DC} + AC copper loss at each harmonic of the switching frequency
• Core loss: $P = k \times f^{\alpha} \times B^{\beta} \times V_{core}$ (Steinmetz equation, with correction for non-sinusoidal waveforms)
• Insulation thermal resistance: film thickness / (k_{film} × contact area)
• Core material thermal conductivity: varies by material; ferrite ~3–5 W/m·K, amorphous alloy ~10–15 W/m·K
• Potting compound: critical for gap filling; thermal conductivity 0.5–3.0 W/m·K depending on filler content
• PCB copper spreading: often the dominant thermal path for surface-mount components
• Heatsink or baseplate coupling: contact pressure, TIM material, and interface area
• Ambient airflow: velocity, direction, and temperature uniformity across the component surface

4.3 Magnetic Integration

Where the converter topology permits, integrating multiple magnetic functions into a single core structure can reduce total converter volume significantly:

- Integrated transformer + inductor (e.g., CLLC with integrated resonant inductor): eliminates one discrete component and its associated mounting and interconnect
- Coupled inductors in multi-phase converters: exploits magnetic coupling between phases to reduce ripple current with smaller total core volume

- Integrated EMI choke + PFC inductor: combines differential-mode and common-mode filtering in a single core where the operating conditions permit

Integration decisions must be validated against the current waveform, mutual coupling requirements, and insulation constraints. Not all topologies benefit from integration; in some cases, the coupling between integrated functions introduces constraints that a discrete design handles more cleanly.

4.4 Insulation and Cooling Synergy

The insulation system in a flat wire magnetic component determines three things simultaneously: electrical clearance, thermal resistance, and mechanical integrity. Selecting the insulation material and thickness solely for electrical rating leaves thermal and mechanical performance as unoptimised secondary outcomes.

Insulation Material	Dielectric Strength	Thermal Conductivity	Typical Thickness	Best Application
Polyester (PET) film	150–250 V/µm	0.14–0.22 W/m·K	12–50 µm	General purpose, <200V working
Polyimide (PI) film	200–300 V/µm	0.12–0.16 W/m·K	12–75 µm	High temp (up to 220°C), <600V
Polyphenylene Sulfide	150–200 V/µm	0.29 W/m·K	25–100 µm	800V systems, good dimensional stability
Nomex (aramid paper)	20–30 V/µm	0.13 W/m·K	75–250 µm	Slot liner, mechanical protection
Thermally conductive film	100–200 V/µm	1.0–5.0 W/m·K	50–200 µm	Premium thermal path in high-loss designs

5. Application Areas and Specific Requirements

5.1 AI Data Centres — 48V Power Architecture

AI training and inference clusters have fundamentally changed the scale of power delivery required at the server board level. The move from 12V to 48V distribution reduces bus current and conduction loss, but moves the voltage conversion burden onto the board as point-of-load (POL) multi-phase DC-DC converters switching at 300 kHz to 2 MHz.

Design Requirement	Round Wire Limitation	Flat Wire Response
DCR ≤ 0.5 mΩ at 200A+	Window fill limits achievable DCR	Higher fill factor achieves same DCR in smaller core
Package height ≤ 5–8 mm	Circular bundle adds height unpredictably	Defined flat stack height fits envelope reliably
Freq 300 kHz – 2 MHz	AC resistance rises 5–20× vs DC	Thickness matched to skin depth controls AC loss
EMI-sensitive PCB layout	Leakage field from round bundle harder to control	Flat conductor layer reduces leakage inductance
Cpk ≥ 1.33 per program spec	Manual winding Cpk typically 0.7–1.0	Automated flat wire winding achieves 1.3–1.8

5.2 EV Charging and 800V Platforms

800V EV charging systems — both on-board chargers (OBC) and DC fast chargers — place magnetic components under simultaneous stress from high current, high voltage isolation requirements, automotive temperature cycling, and mechanical vibration.

Key Magnetic Component Requirements for 800V EV Systems

- PFC boost inductor: rated current 15–60 A, switching frequency 65–200 kHz, DCR ≤ 5 mΩ, ΔT ≤ 45°C at rated load
- Insulation: hi-pot AC 3000 V / 1 min minimum between winding and core for 800V systems; partial discharge (PDIV) testing required
- Temperature cycling: -40°C to +105°C per AEC-Q200 for under-hood mounting; -40°C to +85°C for trunk-mounted applications
- Vibration: IEC 60068-2-6 or USCAR-1 vibration profile; flat wire winding provides structurally superior resistance to conductor displacement
- Saturation current margin: Isat ≥ 1.3–1.5× rated current (L -20% definition); verify at 105°C since Isat decreases with temperature

5.3 Photovoltaic and Energy Storage Inverters

Grid-connected solar and battery storage systems operate under variable irradiance and load conditions, with long service lives measured in years of continuous operation. Magnetic components must maintain thermal stability under sustained partial load as well as peak rated conditions.

MPPT boost inductors in string inverters typically operate at 20–60 kHz with current ripple ratios of 15–30%. At these frequencies, the additional AC resistance of round wire is modest, and flat wire provides its primary benefit through improved DCR and higher saturation current margin in a given core volume. For three-phase storage inverters operating at 50–100 kHz per phase, the AC loss benefit of flat wire becomes more significant.

5.4 Industrial Motor Drives and UPS

Industrial power conversion systems demand reliability measured in tens of thousands of hours of continuous operation under varying load, vibration, and temperature. Magnetic components in these applications benefit from flat wire's combination of lower DCR (reducing thermal stress at rated load), improved mechanical stability (resisting vibration-induced wire movement), and better production consistency (reducing in-field variation within a large installed fleet).

6. Selection Framework: When to Specify Flat Wire

The following framework guides the decision between round-wire and flat-wire magnetic components based on the key operating parameters.

Specify Flat Wire When Two or More of These Conditions Apply:

- Rated current per phase or per winding exceeds 20–30 A continuously
- Switching frequency is above 100 kHz and AC resistance contributes meaningfully to copper loss (estimate AC/DC resistance ratio > 1.5)
- DCR target is below 2 mΩ and the core window area cannot be increased (height or footprint constrained)
- Package height is a binding constraint and round-wire fill factor inefficiency is preventing the design from meeting the envelope
- Temperature rise target is below 40°C above ambient and the thermal path from winding to ambient is critical
- Production volume exceeds 10,000 units per year and DCR Cpk ≥ 1.33 is a quality commitment
- Application is automotive (AEC-Q200) or energy storage (AEC-Q200 class) where process traceability and consistency are contractual

Round Wire May Be the Better Choice When:

- Current per winding is below 10–15 A and thermal margin is comfortable at rated load
- Switching frequency is below 50 kHz and AC resistance contribution to total copper loss is below 20%
- Turn count is high (> 20 turns per winding) and the flat-wire per-turn cost at small wire cross-section becomes prohibitive
- Production volume is low (< 1,000 units) and flat wire tooling investment cannot be amortised over the program
- The converter topology requires a complex multi-layer winding structure (e.g., interleaved transformer) where flat wire layer management adds more complexity than it removes

7. Buyer Evaluation Checklist

When evaluating magnetic component suppliers or preparing a request for custom design, the following parameter list ensures a complete specification. Incomplete specifications result in conservative designs that may not represent the engineering optimum for the application.

7.1 Electrical Parameters

Parameter	Detail to Specify	Why It Matters
Inductance & Tolerance	nH or μH, ±% at operating bias current	Determines core size and turns; bias characteristic must be specified
Rated Current	RMS A per winding, at rated load and temperature	Sets copper cross-section and DCR requirement
Saturation Current	Peak A at L -20% (or L -10% for strict designs)	Sets core size and DC bias margin; verify at operating temperature
Ripple / AC Current	Peak-to-peak A and frequency	Determines AC loss and core loss contribution
DCR Limit	mΩ at 25°C and at max operating temperature	Copper loss and thermal budget; high-temp value often overlooked
Operating Voltage	DC and peak AC across winding and to core	Insulation class and hi-pot requirement
Switching Frequency	Fundamental and significant harmonics	AC loss calculation and core material selection

7.2 Thermal and Mechanical Parameters

Parameter	Detail to Specify	Why It Matters
Temperature Rise Limit	ΔT °C above ambient; state ambient temperature	Thermal design basis; must state ambient
Cooling Method	Natural convection / forced air CFM / baseplate	Determines achievable thermal resistance
Potting	Potted / unpotted; potting material type	Affects thermal path and insulation class
Package Dimensions	Max L × W × H mm; PCB footprint; pin pitch	Constrains core selection and winding window
Mounting	Through-hole DIP / SMD / bus bar / chassis mount	Affects mechanical stability and thermal contact
Vibration Environment	G-level, frequency spectrum, duration	Determines winding fixity requirements
Operating Temp. Range	Min and max; storage temperature	Materials and process qualification class

7.3 Insulation and Certification

Parameter	Detail to Specify
Insulation Voltage	Working voltage + hi-pot test voltage + standard (e.g., AC 3000V/1min)
Partial Discharge	PDIV requirement if working voltage > 300V peak; test standard reference
Safety Certification	UL, TUV, CE, CQC, AEC-Q200, IEC 62368, or specific standard
RoHS / REACH	Material compliance documentation requirements
Country of Origin	Required for customs and procurement traceability

7.4 Production and Qualification

Parameter	Detail to Specify
Annual Quantity	Prototype (pcs) / NPI run / production rate (pcs/month or year)
DCR Cpk Target	Minimum Cpk value; 1.33 is standard; 1.67 for safety-critical programs
Qualification Tests	Hi-pot, DCR, inductance at bias, temperature rise, vibration, thermal cycling
Approved Suppliers	Any restrictions on core or conductor material sourcing
Traceability	Lot traceability, date code, material certificates

8. Frequently Asked Questions

Q1: Can the performance numbers in this white paper be used directly in production?

No. All figures in this document are engineering references and illustrative ranges based on typical designs. Actual production values depend on the specific core geometry, winding configuration, conductor dimensions, insulation system, operating waveform, cooling design, and thermal environment. Production values must be confirmed through approved samples, DC bias measurement, DCR measurement at operating temperature, thermal validation at rated current, and hi-pot testing before production release.

Q2: What is the economic justification for flat wire versus round wire in a moderate-volume program?

The economic break-even depends on the current level, frequency, and production volume. At high current (> 30 A) and moderate-to-high frequency (> 100 kHz), the reduction in core size enabled by flat wire's higher fill factor can reduce magnetic material cost by 15–30%, potentially offsetting the higher winding cost. At low volume (< 5,000 units), the tooling amortisation typically makes flat wire more expensive per unit unless the design cannot be achieved at all with round wire. At volumes above 20,000 units per year, the process quality benefits (Cpk, in-field consistency) often justify the technology choice independently of unit cost.

Q3: Can flat wire be used in high-turn-count transformer windings?

Flat wire is most cost-effective in low-to-moderate turn count windings where the conductor cross-section per turn is relatively large. In transformer windings with more than 20–30 turns per layer, the conductor cross-section at each turn is typically small enough that the circular wire AC loss penalty is less severe, and the per-turn cost of flat wire starts to dominate. For high-turn-count transformer windings at high frequency, Litz wire or PCB winding may be a better technology choice than flat wire.

Q4: How does flat wire affect the saturation current (Isat) of an inductor?

Isat is determined by the core material, core geometry, number of turns, and any deliberate air gap — not directly by the conductor geometry. Flat wire improves fill factor, which means that for the same core window, a larger copper cross-section is available. This can support more turns in the same window (higher inductance at the same Isat), or the same turns at lower DCR. The Isat itself is not changed by the winding conductor shape, but the ability to achieve the required Isat within a constrained package volume may be improved.

Q5: Is flat wire available for transformer applications, not just inductors?

Yes. Flat wire winding is used in transformers for PFC stages, LLC and CLLC resonant converters, isolated DC-DC stages, and bidirectional converter designs. In transformer applications, flat wire is particularly valuable in the primary or secondary winding where high current and low DCR are the primary targets. The inter-winding insulation system must be designed to meet the required creepage and clearance between primary and secondary, which may require additional insulation between the flat wire layers.

9. Related Resources and Contact

Resource	Description	URL
High Current Flat Wire Inductor	Custom high-current flat wire inductors for EV, storage and industrial converters	promagtech.com/products/flat-wire-inductor.html
Planar Flat Wire Transformer	Planar and flat-wire transformer assemblies for high-frequency resonant converters	promagtech.com/products/planar-transformer.html
48V AI Data Center Article	Thermal and winding-limit analysis for high-density 48V AI server power architectures	promagtech.com/technical-resources/48v-ai-data-center-flat-wire-inductors.html
Flat Wire vs Round Wire Guide	Compare flat wire and round wire for DCR, thermal path, saturation, and power density	promagtech.com/technical-resources/flat-wire-vs-round-wire-inductors.html
Two-Stage Integrated CMC	Two-stage integrated common mode choke for EV OBC, AI server, and inverter EMI suppression	promagtech.com/technical-resources/two-stage-integrated-common-mode-choke.html

Shenzhen PROMAGTECH Co., Ltd.

深圳市谱磁科技有限公司

www.promagtech.com

zyong@promagtech.cn

Flat Wire Inductors · Transformers · Custom Magnetics

Request a Custom Design Review

- Send converter topology, current, frequency, DCR target, and package envelope
- 24-hour preliminary response to complete specifications
- Sample lead time: standard 2 weeks / custom 3–4 weeks
- Application areas: AIDC · EV · Solar · Storage · Industrial