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AI SERVER POWER · TECHNICAL ARTICLE

48V AI Data Center Power:
Why Circular Wire Inductors Hit Thermal Limits

Thermal bottleneck analysis, winding geometry trade-offs, and flat wire advantages in high-density 48V AI data center power architectures

Applications: AI Data Centers · 48V Server Power Shelves · High-Density PSU · POL DC-DC

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1. Abstract

The rapid expansion of AI computing is driving a shift from conventional 12V distribution to 48V rack-level power. This increases current density at the point-of-load (POL) converter and places new thermal, electromagnetic, and manufacturing demands on the inductors at the heart of each power stage.

Traditional circular wire inductors are increasingly unable to meet these demands without penalty. This article examines why circular wire creates a thermal and EMI bottleneck in 48V AI server power systems, and how flat wire technology provides greater design margin through improved window fill, thermal path management, and production consistency.

> **Key Finding:** In 48V AI data center power shelves, flat wire inductors reduce thermal bottlenecks when current density rises and airflow is constrained. The advantage is geometric: rectangular copper fills the core window more efficiently, shortens the heat path, and enables repeatable automated winding.

2. The 48V AI Data Center Power Architecture

Modern AI training clusters require sustained power at unprecedented scale. A single GPU or NPU may draw 700 W or more; a fully loaded server rack can exceed 80 kW. Traditional 12V distribution generates excessive I^2R loss at these current levels. The 48V architecture solves this by delivering power at four times the voltage — reducing conduction loss by a factor of sixteen at the same power level — but moves the voltage conversion step directly onto the server board as POL DC-DC converters.

2.1 POL Inductor Requirements

Parameter	Typical 48V AI Server POL Requirement
Input Voltage	40–60 V DC (48V nominal ±20%)
Output Voltage	0.8–5 V (processor or memory rail)
Output Current	50–200 A per phase (multi-phase VRM)
Switching Frequency	300 kHz – 2 MHz (GaN devices)
Inductance	50 nH – 1 µH depending on frequency and ripple
DCR Target	< 0.5 mΩ at operating temperature
Temperature Rise	≤ 40°C above 40°C ambient
Package Height	< 5–8 mm in blade server designs

Each POL inductor operates in a tightly packed thermal environment with directed and constrained airflow. It must simultaneously meet strict electrical, thermal, and dimensional limits — consistently across millions of production units.

3. The Silent Limits of Circular Wire Inductors

Circular wire inductors have served power electronics well for decades. In 48V AI server applications, however, their geometric and physical properties create constraints that become binding design limitations at high current density and switching frequency.

3.1 Window Fill Factor and Wasted Core Space

When circular conductors are packed into a rectangular core window, their round cross-sections leave unavoidable air gaps. The achievable fill factor — copper cross-section divided by core window area — falls to 55–65% in practice once insulation thickness, winding tension variation, and manufacturing tolerance are accounted for. Every percentage point of unused window area is copper cross-section not carrying current.

Engineering Consequence: Unused window area forces a larger core (more height, more volume, higher cost) or fewer turns of thicker wire. In height-constrained AI server layouts, the core cannot simply be made larger.

3.2 Thermal Dead Zones and Localised Heating

Air pockets between circular conductors in the core window act as thermal insulation. Heat generated by I^2R loss at the winding centre must conduct laterally through these air pockets before reaching the core wall or outer winding surface. This creates localised hot spots that are invisible on the outer surface.

In standard testing with a thermocouple on the component surface, the measured temperature may appear acceptable while the conductor at the thermal centre is 20–30°C hotter. This discrepancy is a significant hidden reliability risk in circular wire designs operating near their thermal limit.

3.3 Skin Effect and Proximity Effect at High Frequency

At 300 kHz to 2 MHz, the AC resistance of a circular conductor is substantially higher than its DC resistance due to two effects:

- Skin Effect: current concentrates near the conductor surface. Skin depth in copper at 500 kHz is ~0.093 mm. A 1 mm-diameter conductor has a radius 5× the skin depth — most interior copper is idle at high frequency.
- Proximity Effect: alternating fields from adjacent conductors induce eddy currents that further distort current distribution. In a tightly wound multi-turn coil, proximity effect can raise AC resistance 3–10× the DC resistance at MHz frequencies.

Frequency	Skin Depth (Cu)	Ratio to 1mm-dia. Radius	Practical Impact on AC Resistance
50 kHz	0.295 mm	0.59× (moderate)	~1.3–2× DCR
300 kHz	0.120 mm	0.24× (significant)	~2–5× DCR
1 MHz	0.066 mm	0.13× (severe)	~5–15× DCR

Frequency	Skin Depth (Cu)	Ratio to 1mm-dia. Radius	Practical Impact on AC Resistance
2 MHz	0.047 mm	0.09× (most idle)	Can exceed 20× DCR

3.4 Manufacturing Variability

Circular wire winding in small-to-medium production volumes typically relies on semi-manual processes where winding tension, conductor spacing, and layer compaction depend on operator technique. This introduces batch-to-batch variation in DCR, inductance, and — critically — thermal resistance from winding to core. In AI server power applications where thousands of identical units must meet tight performance windows across temperature, production variability is a quality risk, not merely a process inconvenience.

4. How Flat Wire Inductors Change the Design Margin

Flat wire winding does not eliminate the physics of skin effect, proximity effect, or thermal resistance. What it does is give the engineer more geometric control over where those effects occur and how severe they are.

4.1 Window Fill Factor: Geometric Advantage

Rectangular copper conductors can be stacked in a core window with near-zero gap between adjacent turns on the same layer. The achievable fill factor rises to 75–88% in production, compared to 55–65% for circular wire.

Parameter	Circular Wire	Flat Wire	Engineering Benefit
Typical Fill Factor	55–65%	75–88%	More copper per unit window area
DCR (same turns, core)	Baseline	20–40% lower	Reduced copper loss, lower temp rise
Z-axis Height	Baseline	10–25% lower potential	Better fit in height-constrained designs
Window Utilization	Lower	Higher	Smaller core achievable for same spec

4.2 Thermal Path: Continuous Copper Surface

In a flat wire winding, adjacent turns share a large flat copper surface with only a thin insulation film between them. Heat generated anywhere in the winding can conduct laterally along the copper layer and down through the stacked layers to the core or baseplate — no air pockets interrupt this path.

The result is a more uniform temperature distribution throughout the winding cross-section. In a well-designed flat wire inductor, the difference between peak conductor temperature and the surface-measured temperature can be significantly smaller than in a comparable circular wire design.

> **Thermal Caution:** This advantage is geometry-dependent. Poor insulation selection, inadequate venting, or an incorrect thermal interface will prevent realising the potential improvement. Flat wire provides better thermal geometry; actual performance must still be validated against the waveform, airflow, ambient temperature, and thermal interface design.

4.3 High-Frequency Loss: Matching Conductor Thickness to Skin Depth

Flat wire can be specified with thickness matched to approximately one to two skin depths at the operating frequency. A conductor one skin depth thick uses essentially all of its copper cross-section for current conduction — there is little wasted interior copper.

Switching Frequency	Target Copper Thickness (2× skin depth)	Flat Wire Benefit
300 kHz	0.24 mm (2 × 0.120 mm)	AC resistance close to DC resistance
500 kHz	0.19 mm (2 × 0.093 mm)	Effective copper utilization
1 MHz	0.13 mm (2 × 0.066 mm)	Low AC loss with thin foil
2 MHz	0.09 mm (2 × 0.047 mm)	Multi-layer thin foil or PCB winding

4.4 Production Consistency: Automated Winding

Flat wire winding is well-suited to automated forming and winding processes. Once tooling and process parameters are validated, the geometric relationship between turns is fixed by the tooling rather than operator technique.

- DCR variation batch-to-batch: flat wire process achieves ±3–5%; manual circular wire typically ±10–15%
- Inductance variation: improved fill consistency reduces winding geometry variation
- Thermal resistance: consistent winding geometry produces consistent inter-turn contact

> **PROMAGTECH Production Standard:** Automated flat wire winding with machine vision inspection. Batch DCR Cpk ≥ 1.33 is the production target for AI server supply programs.

5. Design Considerations and Trade-offs

Flat wire inductors are not universally superior to circular wire designs. The decision should be based on the specific requirements of the converter design.

5.1 When Flat Wire Provides the Greater Advantage

Flat Wire Is Typically the Better Choice When:

- Operating current per phase exceeds 30 A and DCR is a binding constraint
- Switching frequency is above 100 kHz and AC resistance contributes meaningfully to copper loss
- Package height is constrained and window fill efficiency determines whether the design fits
- Production volume and consistency requirements call for automated winding
- Thermal environment is demanding (>70°C ambient or limited airflow)
- Saturation current must be maximised for a given core volume

5.2 When Circular Wire May Still Be Appropriate

Circular Wire May Be Sufficient When:

- Current per phase is below 15–20 A and thermal margin is comfortable
- Switching frequency is below 100 kHz where skin effect contribution is small
- Package height is not constrained and core volume can be sized generously
- Production volume is low (prototype / NPI) and flat wire tooling investment is not yet justified
- Turn count is high (many turns at low current) and flat wire per-turn cost becomes prohibitive

5.3 Key Parameters for the Design Review

Parameter	What to Specify	Impact on Selection
Inductance & Tolerance	nH or µH ±% at operating bias	Determines turns and core size
Rated Current (RMS)	A at worst-case duty and frequency	Wire cross-section, DCR, temp rise
Peak / Saturation Current	A including ripple + transient	Core saturation margin
Switching Frequency	kHz or MHz, fixed or variable	Skin effect, AC resistance

Parameter	What to Specify	Impact on Selection
DCR Limit	mΩ at operating temperature	Copper loss, thermal budget
Temperature Rise Limit	°C above ambient	Thermal path, fill factor
Package Dimensions	L × W × H mm, PCB footprint	Core geometry selection
Cooling Method	Natural / forced air / baseplate	Thermal design approach
Certification	AEC-Q200, UL, RoHS, others	Material and process constraints

6. Application Scenarios in 48V AI Data Center Infrastructure

6.1 48V-to-Output POL DC-DC Converter

The highest-stress application for inductors in the 48V AI power stack is the POL converter producing the processor or memory supply voltage. Modern AI accelerators operate at 0.7–1.1 V while drawing 200–1000 A per processor. The multi-phase VRM uses one inductor per phase — at 10–20 phases per processor, the total inductor count per server board is significant.

At GaN-enabled switching frequencies of 500 kHz to 2 MHz, flat wire inductors with thickness matched to the skin depth at operating frequency sustain AC resistance close to their DC resistance, keeping copper loss predictable and consistent across the multi-phase array.

6.2 48V Bus PFC and Rectification Stage

The AC-DC conversion stage feeding the 48V bus typically uses a PFC front-end at 65–250 kHz. At these frequencies, circular wire PFC inductors operating at high current (20–100 A) can face significant skin and proximity effect. A flat copper winding optimised for the PFC frequency reduces AC loss and supports higher efficiency at the supply input, directly reducing data centre cooling load.

6.3 LLC and CLLC Resonant Converters

Some 48V power shelf designs use an LLC or CLLC stage for 48V-to-intermediate-voltage conversion with high efficiency and natural ZVS operation. The resonant inductor carries a near-sinusoidal current and is sensitive to AC resistance at the resonant frequency. Flat wire winding with thickness selected for the resonant frequency minimises this loss contribution.

7. Requesting a Design Review from PROMAGTECH

To evaluate whether a flat wire inductor is the right solution for a specific 48V AI data center application, provide the following information. Incomplete specifications result in generic responses that may not reflect the true engineering optimum.

Information to Provide	Detail Level Required
Converter topology	Buck, Boost, PFC, LLC, CLLC, multi-phase VRM, etc.
Input and output voltage	Min / nominal / max, including transient range
Phase current (RMS and peak)	Per phase, at rated load and worst-case transient
Switching frequency	Fixed or variable; min and max if variable
Target inductance	Nominal value and acceptable tolerance (±%)
DCR limit	Maximum DCR in mΩ at operating temperature
Temperature rise limit	Maximum ΔT above ambient; state ambient temperature
Package envelope	Maximum L × W × H in mm; PCB land pattern if known
Cooling method	Natural convection / forced air (CFM) / baseplate
Quantity and schedule	Prototype (pcs) / NPI / mass production (pcs/month)
Certification requirements	AEC-Q200, UL, TUV, IEC, RoHS, REACH

PROMAGTECH Response Commitment: Upon receiving a complete specification, PROMAGTECH engineering will provide a preliminary design assessment within 24 hours and a formal design proposal or quotation within 3 business days.

8. Frequently Asked Questions

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

No. All figures are engineering references and illustrative ranges. 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, electrical measurement at operating bias, thermal validation at rated current, and hi-pot testing before production release.

Q2: Is flat wire always better than circular wire for 48V AI server inductors?

Not always. The advantage of flat wire is strongest at high current density, high switching frequency, and constrained package height. At lower current (below ~15 A per phase) and lower frequency (below ~100 kHz), the geometric advantage may not justify the higher component cost or tooling investment for low-volume programs.

Q3: How does flat wire affect saturation current (Isat)?

Isat is primarily determined by the core material, core geometry, number of turns, and any deliberate air gap — not directly by the winding conductor geometry. However, because flat wire achieves a higher fill factor, it can allow more copper cross-section per turn, potentially enabling more turns in the same core window: higher inductance at the same Isat, or the same inductance at a smaller core.

Q4: What is the typical lead time for a custom flat wire inductor from PROMAGTECH?

Standard production items from inventory: 1–2 weeks. Custom prototypes (new winding specification on existing core tooling): 3–4 weeks from order confirmation. Custom prototypes requiring new core tooling: 5–8 weeks. Mass production first batch after sample approval: 4–6 weeks.

Q5: Can PROMAGTECH provide side-by-side comparative data for circular vs. flat wire?

Yes. For programs where the design team is evaluating both approaches for a specific application, PROMAGTECH can provide comparative data for inductance, DCR at 25°C and 85°C, temperature rise at rated current, and dimensional comparison. Provide converter topology, current, frequency, inductance target, DCR limit, and package envelope.

9. Related Resources

Resource	Description	URL
SMD Flat Wire Inductor	Low-profile surface-mount flat wire inductors for compact power modules	promagtech.com/products/smd-flat-wire-inductor.html
High Power Density Flat Wire White Paper	Round-wire vs. flat-wire trade-offs for window fill, AC loss, thermal path	promagtech.com/technical-resources/high-power-density-flat-wire-magnetics-white-paper.html
Flat Wire Inductor Selection Guide	Compare flat vs. round wire for DCR, thermal path, saturation, and power density	promagtech.com/technical-resources/flat-wire-vs-round-wire-inductors.html
AIDC & ESS Inductor Design Guide V4	12-chapter guide: 800V ESS, AI Server, PFC, core materials, DCR, temperature rise	promagtech.com/tech/aidc-ess-inductor-design-guide

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