A Miniaturized Data Center Power Supply Using a Split-Phase, Fractional Turn Transformer

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CICS Review
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Data Centers Are An Important and Growing Load

- Much of our virtual world “lives” in data centers
- Represent ~2% of total US electrical energy consumption
  - ~ Total solar PV energy produced in 2019

L. Barroso, J. Clidaras, U. Holzle, The Datacenter as a Computer. 2nd ed. Morgan & Claypool, 2013. p. 49, Fig. 4.1
Data Centers Rely on Many Power Electronic Converters

- 75% eff. typical (converters only)
- Much lower if cooling power included

On server level, power supply miniaturization especially important

L. Barroso, J. Clidaras, U. Holzle, *The Datacenter as a Computer*. 2nd ed. Morgan & Claypool, 2013. p. 52, Fig. 4.2
R. Miller, “Facebook Opens its Server, Data Center Designs.”
What Does This Supply Look Like Schematically?
Three Conversion Steps, but the Transformer Does the Most

Convert to ac

384V

Step down

16:1

192V

12V

Convert to dc

12V

1kW, 83A

https://www.ti.com/tool/PMP20289
High Step-Down, High Current Transformer is a Critical Bottleneck

Convert to ac

Step down

Convert to dc

12V/500W

12V/1kW

12V/3kW

1kW, 83A

384V → 192V

16:1

12V

12V

12V

48V/3kW

12V/500W

12V/1kW

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[A] https://www.ti.com/tool/PMP20289

[B] https://benchmarking.ihsmarkit.com/550162/teardown-delta-dps-1600ab-4-a-psu


Review: Transformer Operating Principle

\[ \frac{d\Phi}{dt} = \frac{v}{N} \] (sign by Lenz’s Law)
Review: Transformer Operating Principle

\[ \frac{d\Phi}{dt} = \frac{v}{N} \text{ (sign by Lenz’s Law)} \]

\[ \frac{v_p}{N_p} = \frac{v_s}{N_s} \Rightarrow v_p : v_s = N_p : N_s \]

e.g. \( N_p : N_s = 4 : 1 \)
Planar Transformers Use PCB Windings

- Windings of inductors/transformers implemented as copper traces on printed circuit boards (PCBs)

Fig. 1. Planar transformer.

Planar Magnetics are Cheap, Easy to Build, with Great Thermals

- Low profile (minimize box volume)
- Good thermal characteristics (high surface area to volume)
- Ease of manufacturability
- Highly repeatable
- Lower cost than wire-wound alternatives

Fig. 1. Comparison of thermal behavior between conventional core and planar core.

Many Turns and High Currents are Difficult in Planar Transformers

- Twice the number of turns
- >2x reduction in trace width
- >4x the dc resistance
- Poor “fill factor”
- Little area for copper

- Large penalty for many turns on a layer
It Can Also Be Difficult to Use Additional Layers

Non-interleaved

-paralleled sec. turns
- series primary turns

Most current flows on first two layers
High magnetic field

Interleaved

Current more evenly distributed between layers
Resistance vs. Capacitance Trade-off of Interleaving

Not interleaved

Interleaved

Ideally interleaved

ac resistance

lower

capacitance

higher
Resistance vs. Capacitance Trade-off of Interleaving

- Not interleaved
- Interleaved
- Ideally interleaved

**ac resistance**
- Not interleaved: higher
- Interleaved: lower
- Ideally interleaved: lower

**capacitance**
- Not interleaved: lower
- Interleaved: higher
- Ideally interleaved: lower

**termination loss**
- Not interleaved: lower
- Interleaved: lower
- Ideally interleaved: Much higher
With Realistic Terminations, Loss Can Be Much Higher Than Expected

Ideal, perfectly terminated

Practically terminated

0.29Ω  

0.73Ω

Key: Avoid complex vertical stack-ups in this application space
With Realistic Terminations, Loss Can Be Much Higher Than Expected

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\[ 0.29\Omega \quad \rightarrow \quad 0.73\Omega \]

Key: Avoid complex vertical stack-ups in this application space
Minimizing Turns Count is Greatly Advantageous

16:1

Copper Loss
Core Loss
Minimizing Turns Count is Greatly Advantageous

32:2

16:1

66W

28W

Copper Loss
Core Loss
A Fractional Turn is What We Want...

16:1

28W

8:0.5

Copper Loss
Core Loss
A Fractional Turn is What We Want... But Not Practical

16:1

28W

8:0.5

Copper Loss
Core Loss
A Fractional-Turn Transformer Using a New Kind of Structure

Orthographic View

Side View

Top View
Assume Physical Symmetry About Center of the Core

Orthographic View

Side View

Top View
Excite the Primary Winding, Flux Flows Symmetrically

Orthographic View

Side View

Top View

Assume symmetry
Symmetry and Magnetic Core Enforce Equal Currents

Assume symmetry

\[ \oint H \cdot dl = 8i_p - i_1 = 8i_p - i_2 \Rightarrow i_1 = i_2 \text{ by symmetry} \]
Symmetrically Distribute Two Full Bridge Rectifiers Around the Core

Top View

Step down

16:1

12V

Convert to dc

12V

1kW, 83A
The Structure Behaves Like a Fractional Turn Transformer

- Free to treat conductors as independent elements
- Connections yield:

\[
2V_o = \frac{V_p}{N_p}
\]

\[
\frac{V_o}{V_p} = \frac{1}{2}
\]

A fractional turn transformer

\[\begin{align*}
\text{Step down} & : 16:1 \\
\text{Convert to dc} & : 12V, 1kW, 83A
\end{align*}\]
Equivalence of induced currents is ensured by symmetry.
VIRT: An Example of a Coupled Electronic and Magnetic System

Equivalence of induced currents is ensured by symmetry

Connecting electronics are physically distributed around the core

Electronics can be controlled to modify magnetic properties

- FB/FB: $N_p : \frac{1}{2}$
- FB/HB: $N_p : \frac{2}{3}$
- HB/HB: $N_p : 1$
- HB/0: $N_p : 2$

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Higher switch count, but each carries less current (effectively paralleled).

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Higher switch count, but each carries less current (effectively paralleled)

Requires a different modeling framework

VIRT Exponentially Reduces Copper Loss

\[ P_{cu} \propto i^2 R \]

\[ \frac{P_{cu}}{4} \]

Increase Degree of Fractional Turn
Exponential Rebalancing

16:1

Single-phase

Single-phase Half-turn

\[ \sim \frac{P_{cu}}{4}, \sim 2^R P_{core} \]

Copper Loss
Core Loss
VIRT Exponentially Reduces Copper Loss and Increases Core Loss

\[ P_{cu} \propto i^2 R \]

\[ P_{core} \propto \left( \frac{V}{N} \right)^\beta \]

\[ P_{core} \times 2^\beta \]

Increase Degree of Fractional Turn

Exponential Rebalancing

Single-phase Fractional Turn

16:1

\[ \sim \frac{P_{cu}}{4} \]

\[ \sim P_{cu}/4, \sim 2^\beta P_{core} \]
The Conventional Approach: Increasing Phase Count

Wound such that equal and opposite flux flows on outer legs

Combine cores for volume reduction
Increasing Phase Count Yields Linear Rebalancing

Increase Phase Count \[\rightarrow\] Linear Rebalancing

Single-phase
\[P_{cu}, P_{core}\]

Split-phase
\[\sim P_{cu}/2, \sim 2P_{core}\]
These Techniques Offer Distinct Loss Trade-offs

What we’ve been doing

Increase Phase Count → Linear Rebalancing

Increase Degree of Fractional Turn

Exponential Rebalancing

Single-phase $P_{cu}$, $P_{core}$

Split-phase $\sim P_{cu}/2$, $\sim 2P_{core}$

Single-phase Half-turn $\sim P_{cu}/4$, $\sim 2^5 P_{core}$

What we can do now
SPHTV Prototype

- 4 layer, non-interleaved SPP, 3/2/3oz
Prototype is Extremely Efficient

High efficiency

97.7% @ 500W

97.1% @ 1kW

Efficiency (%) vs. Output Power (W)
Losses and Thermal Performance Well Predicted

**Losses fit expectation**

![Losses graph]

Fig. 12: Estimated loss breakdown at full load, not including hotel power (2.7W) and fan power (1.44W).

**Thermal performance**

![Thermal performance diagram]

Fig. 7: ANSYS Icepak thermal simulation of the transformer.

Fig. 11: Thermal image of secondary-side under full-load (obtained after 15 minutes of continuous operation, 22°C room temperature). The fan is located to the right of the PCB.
SPHTV: Much Lower Loss and Much Smaller than Best Alternatives

380-12V, 1kW

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a ‘G’ is a secondary layer tied directly to secondary ground


SPHTV: Much Lower Loss and Much Smaller than Best Alternatives

![Diagram of SPHTV](image)

**380-12V, 1kW**

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SPHTV: Much Lower Loss and Much Smaller than Best Alternatives

- **20-33% less loss**
- **15-33% smaller**

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Much More Efficient, Capable, Smaller than Industry Reference Design

Top
Front
Orthographic

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<th>Volume</th>
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<th>Efficiency</th>
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<td>33cm³</td>
<td>500W</td>
<td>96.8% @500W</td>
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<td>14.5cm³</td>
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- 2.3x smaller
- 2x more capable
- 25% less loss

https://www.ti.com/tool/PMP20289
Conclusion

- Coupled Electronic and Magnetic System (CEMS) paradigm enables the VIRT concept
- Fractional and variable turns ratios unachievable in conventional design
- Used to build much smaller and much more efficient datacenter supply