“Matrix Transformer Building Blocks for High Frequency Applications”

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The Multinational Power Electronics Association

Outline of the presentation

1. Matrix transformers, brief history
2. “String-of-beads” Inductors.
3. Matrix transformers and symmetrical excitation.
4. Symmetrical inductor
5. Packaging
6. Gate drive
7. Multi-cell transformers
8. Proposed 2 MHz “Solid-State” medium voltage transformer

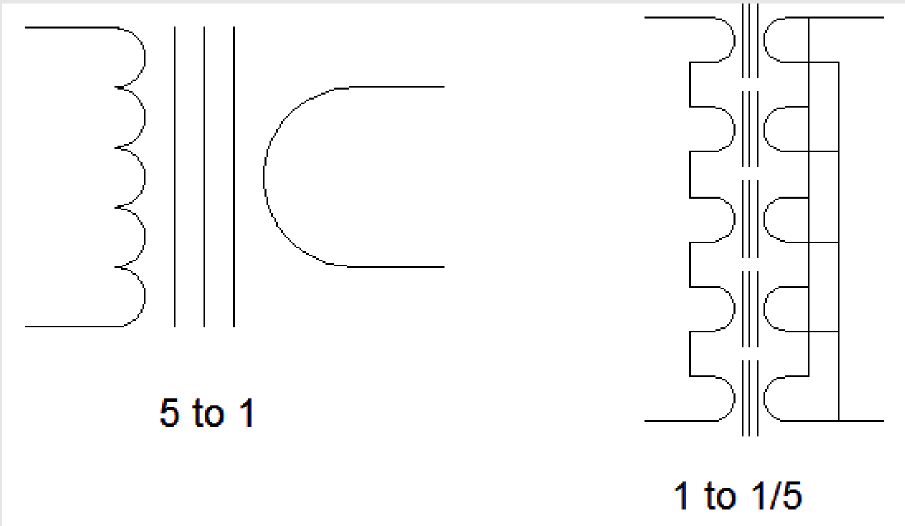
Brief history of the matrix transformer

- The first Matrix Transformer patent issued in 1985.
- The tutorial “Matrix Transformers and Symmetrical Converters” was published in 1990. It is on line at http://fmtt.com/pdffiles/Tut2.pdf
- Now, all of the original patents have expired and that IP is in the public domain.

Conventional transformer *vs.* matrix transformer

Comparison:

5:1 wound transformer   5:1 matrix transformer.



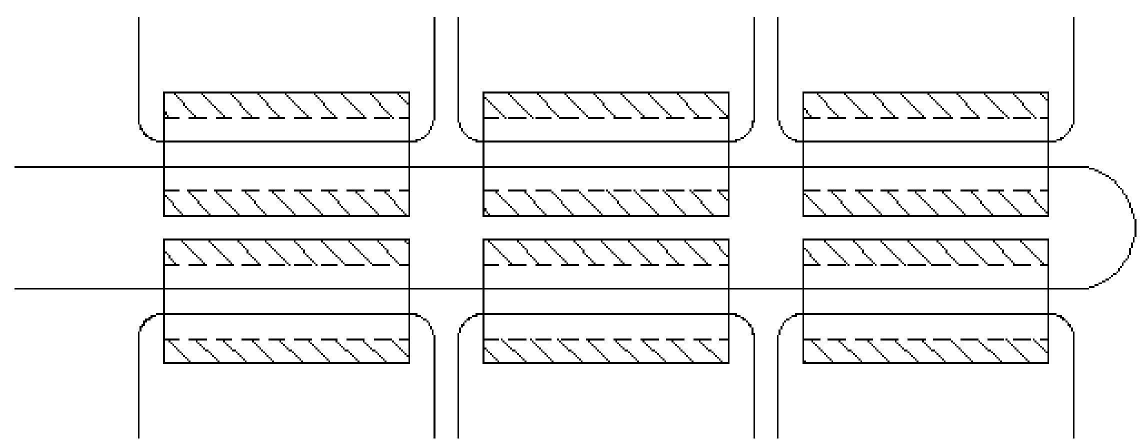
Matrix Transformers

While the 5 core transformer looks more complex, it isn't.

The cores usually are simple gap-less toroids or "squareoids", and most windings are simple "U" turns.

No gap.

No "fringing" losses.



6 to 1 matrix transformer

Math principle, converting one core to many

Example: Convert a 5 turn inductor to a 1 turn inductor:

$\hat{H} = \frac{N*I}{l_e} * \sqrt{2}$; To have the same $\hat{H}$ with one turn, l_e must be 1/5th.

$L = N^2 * \mu_0 * \mu_e * \frac{A_e}{l_e}$; To have the same L with N^2 = 1 and l_e = 1/5th,

A_e must be 5 times.

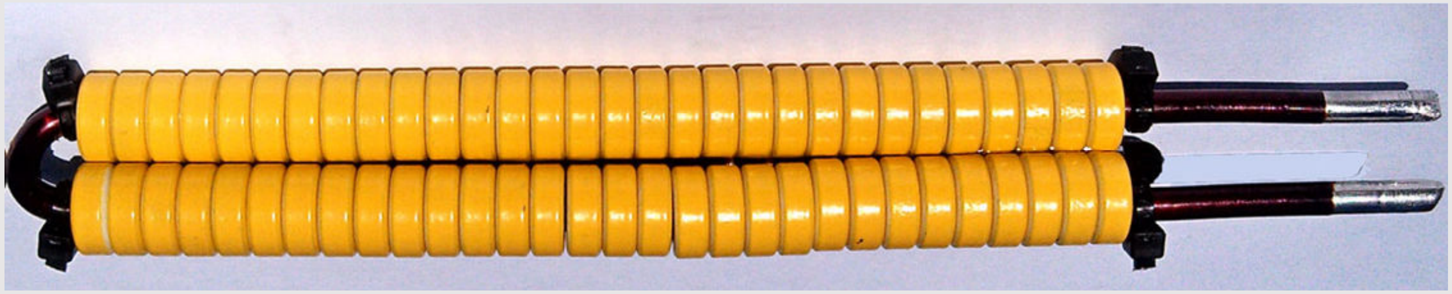
If the $\frac{ID}{OD}$ ratio is kept the same, with l_e = 1/5th and A_e = 5 times,

the core height ht must be 25 times.

The core volume V_e is unchanged.

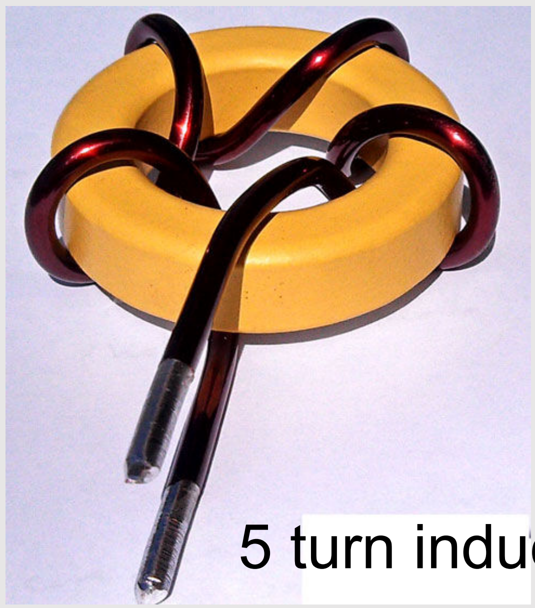
Matrix Transformer Building Blocks for High Frequency Applications

Examples:



U-turn equivalent inductor

Spiral equivalent inductor

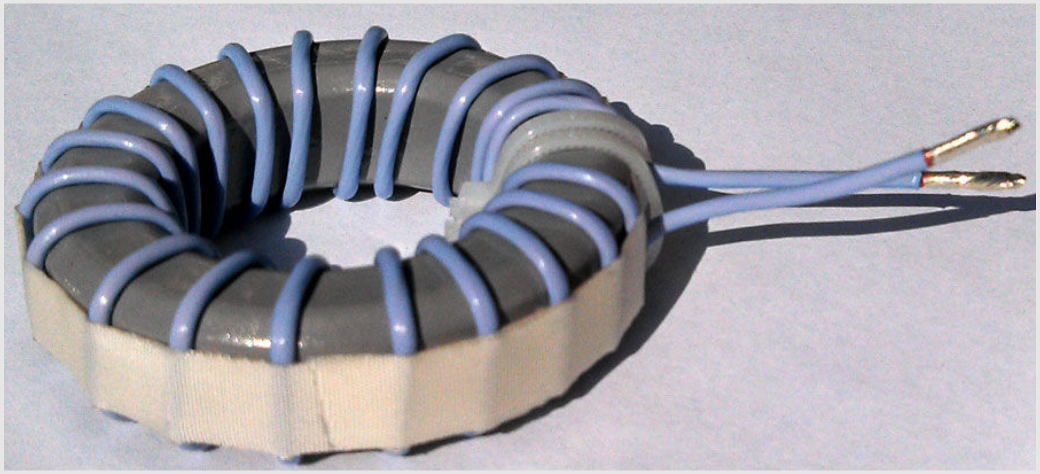


5 turn inductor

	L μH	*Q*	*Wt g*
5-turn	1.81	3.29	196
U-turn	1.82	3.27	156
Spiral	1.79	3.54	156

Example with multiple turns

A 20-turn inductor can convert to a 4-turn inductor exactly the same way.



	L, µH	Q	Wt, G
20 turn	59.2	7.83	185
4 turn Spiral	63.3	7.29	196

Advantages of “string of beads” inductors

1. It is much easier to wind, particularly if the wire is heavy.
2. The inductance L is adjustable by adding more or fewer cores. In the example, L can be adjusted in 2% increments. Special smaller cores with the same $\frac{ID}{OD}$ ratio could be made for smaller adjustments.
3. The stray field is largely contained within the cores, as they surround the winding.
4. Heat dissipation, especially for core losses, is much better. It is easy to heatsink the cores.

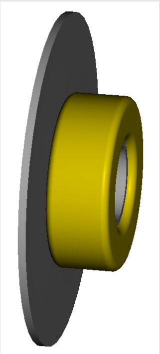
Most conversions to matrix style will be to go to higher frequency at the same current and voltage.

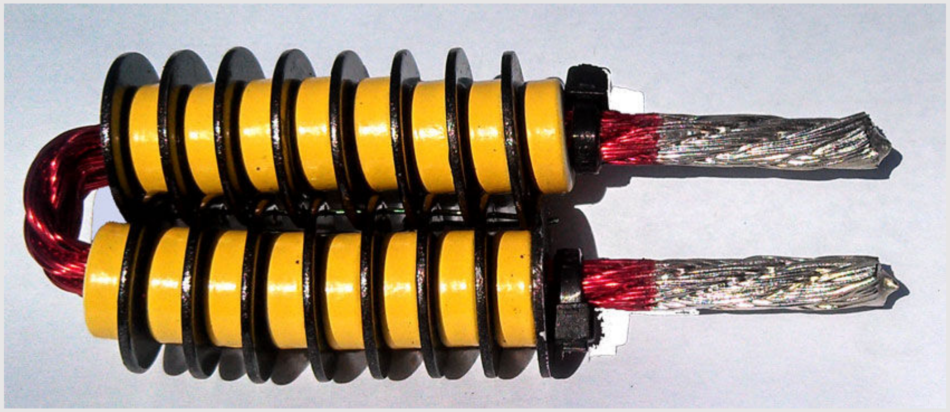
NI will be the same, but L can decrease, so fewer cores are needed.

If losses are held constant, power density increases.

The matrix style inductor is much better than a wound toroid for heat dissipation, but heat removal is important.

Heat Sinks may be beneficial.



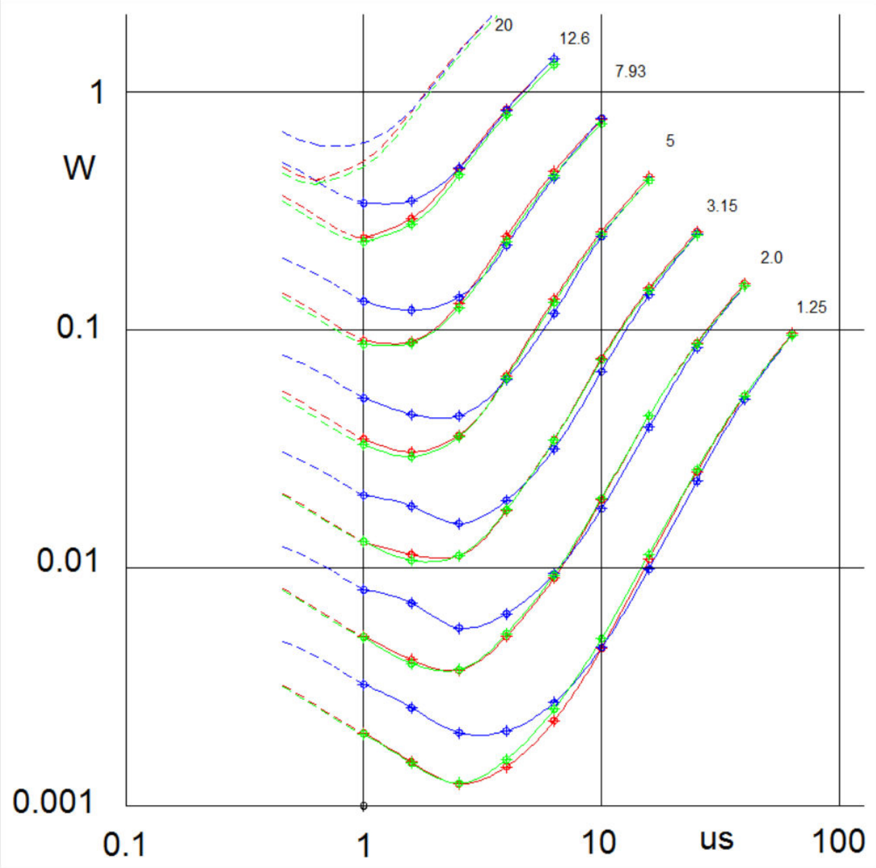


Matrix style inductors may have lower core loss

Data taken during the Phase III Core Loss Studies at Dartmouth suggest that the core loss for a string of ferrite beads may be 1/2 that of a solid toroid equivalent core at high frequency.

<u>Caveat:</u> Too few tests were done to be conclusive.

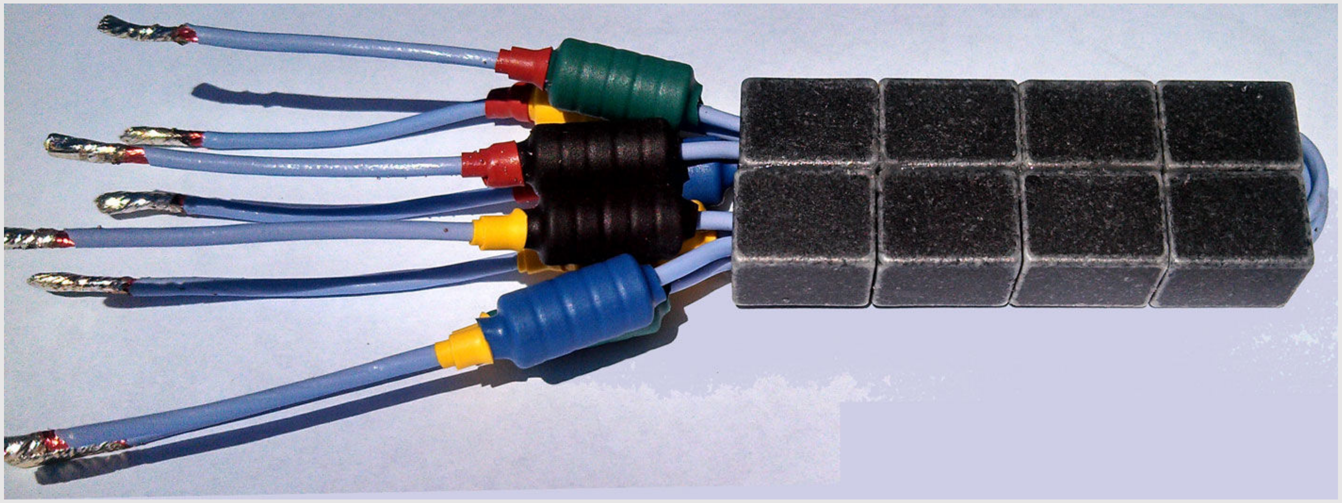
We need to test more examples.



The matrix conversion also applies to transformers

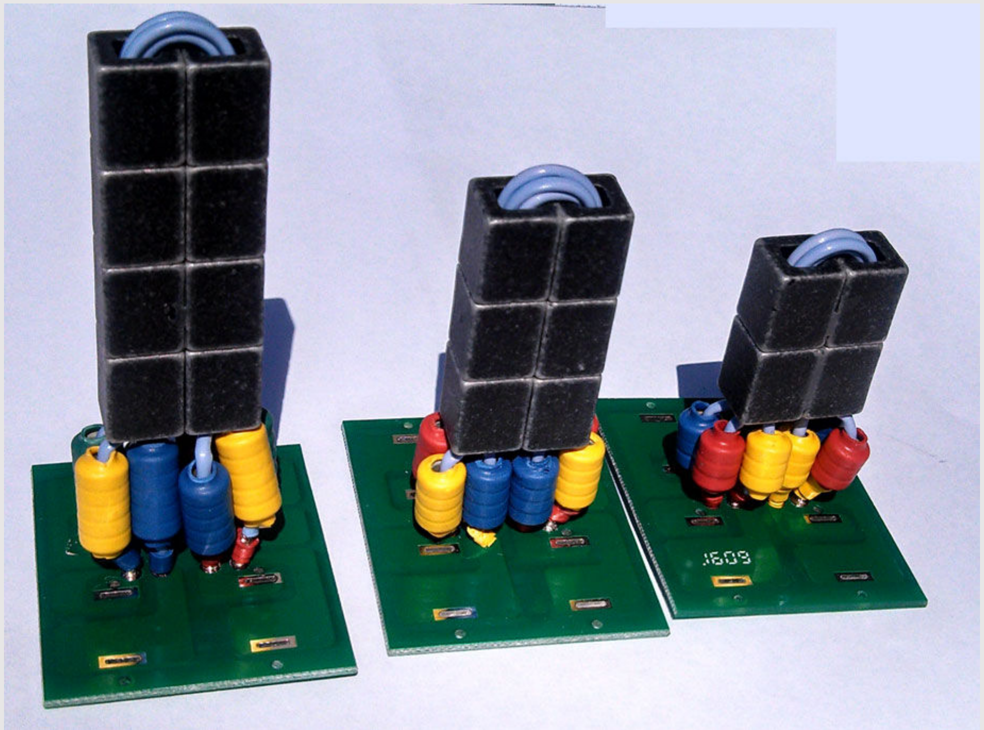
.8 core 1:1:1:1 transformer

Single turn windings greatly reduce proximity effects.

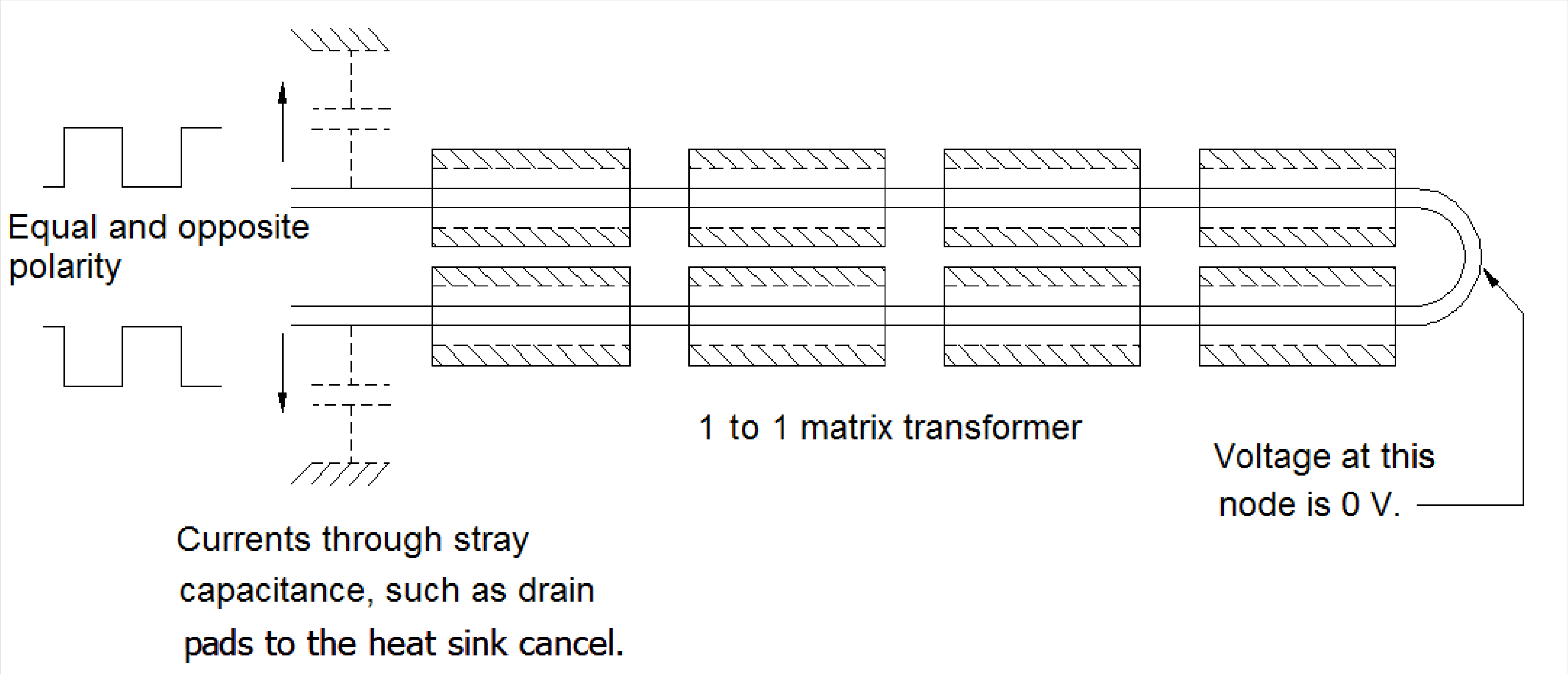


Adjusting A_e for different voltage and frequency

It is easy to adjust A_e to adjust for different voltages and/or frequencies without affecting other parameters by using more or fewer cores.

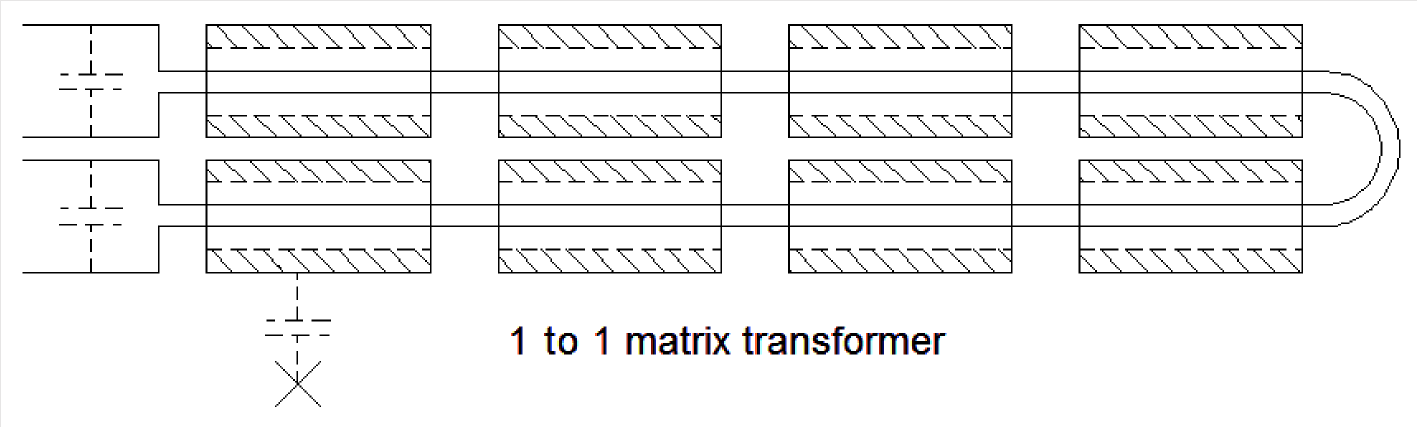


Symmetrical excitation cancels noise



Matrix style transformers and stray capacitance:

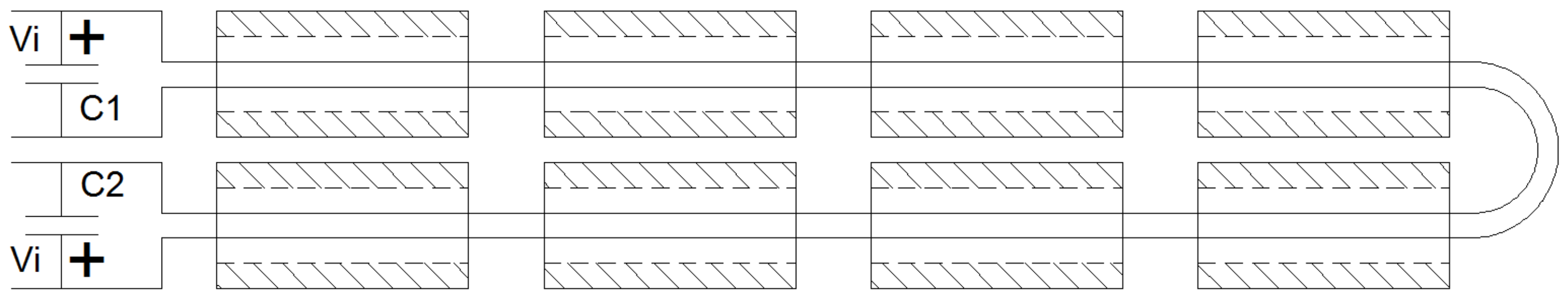
In a 1 to 1 matrix transformer, the inter-winding capacitance actually helps, marginally, making the transformer like an RF transformer during transitions.



Stray capacitance to the cores leads nowhere, if they are isolated.

Matrix transformers with common-mode capacitors:

A matrix transformer with a symmetrical push-pull primary has common-mode capacitors on its input. The voltage is equal to the input voltage Vi.

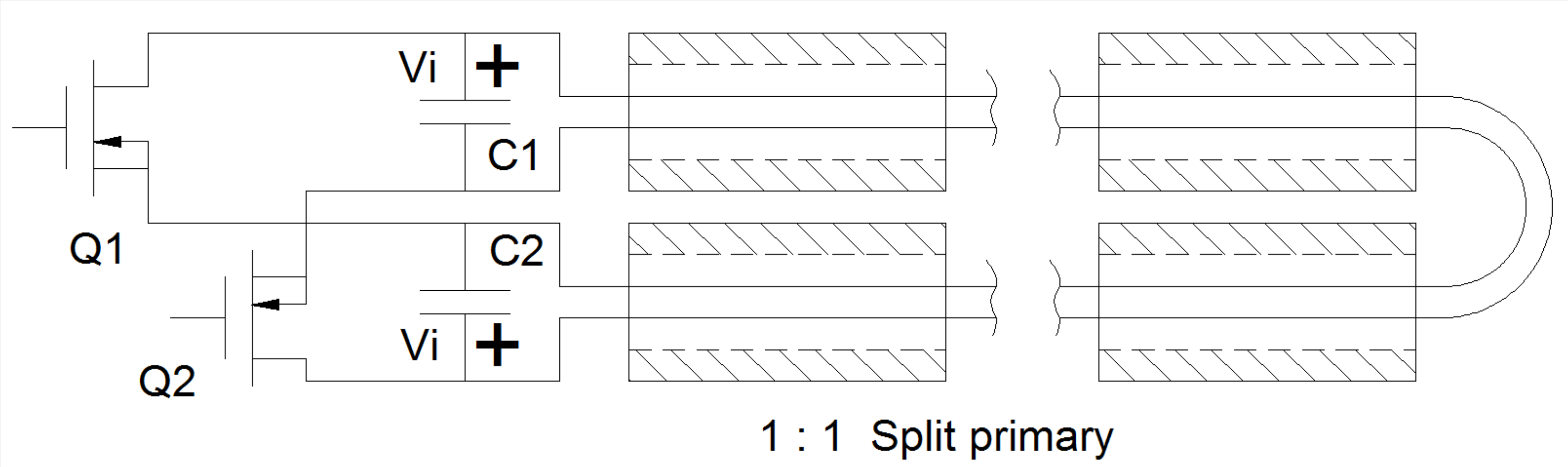


Symmetrical push-pull (split) primary

How the voltage on C1 and C2 is maintained at Vi will be shown shortly.

Switched-capacitor symmetrical excitation:

MOSFETs cross-couple the common-mode capacitors, and "see" only the capacitors, effectively de-coupling the MOSFETs from the transformer.



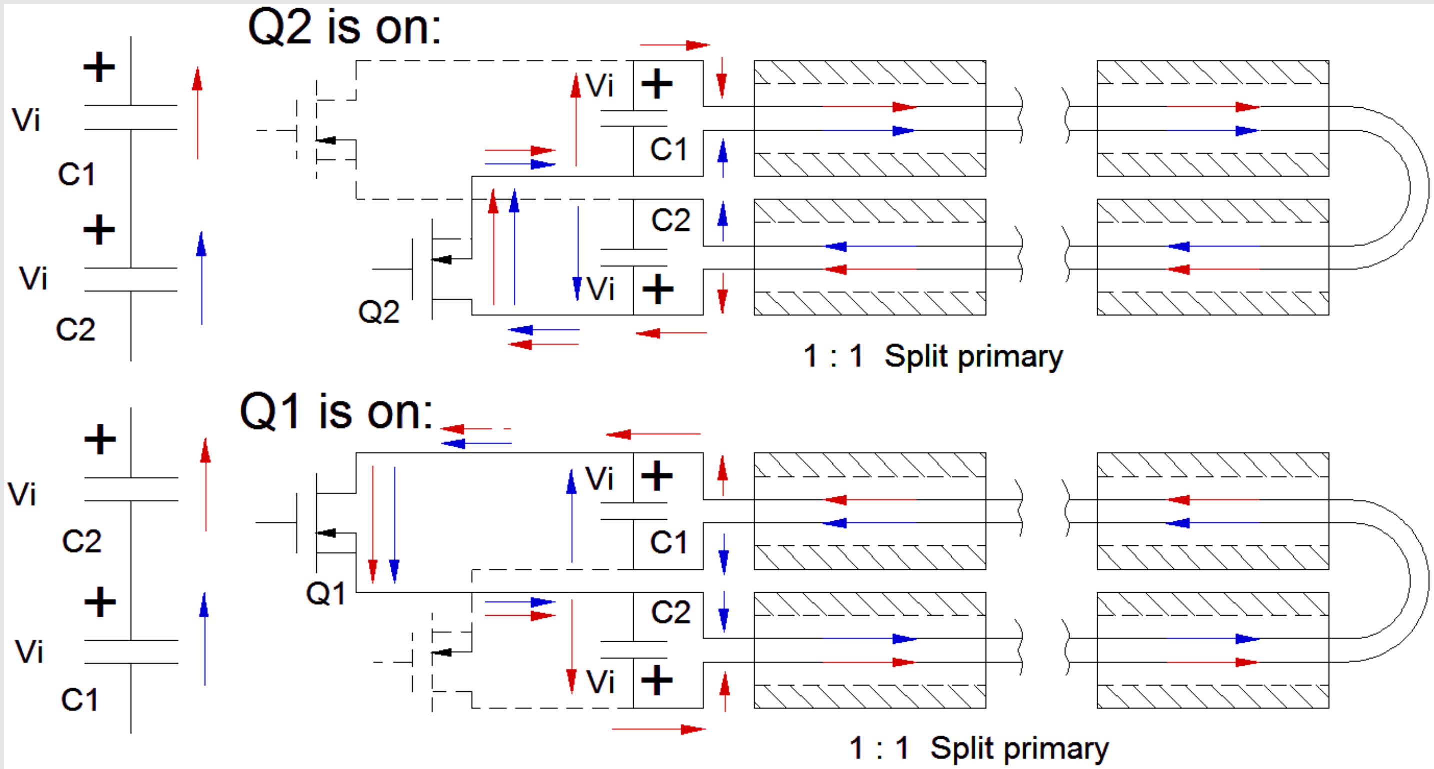
In the secondary, the same circuit a synchronous rectifier.

Switched-capacitor symmetrical excitation:

Symmetrical push-pull (split) windings:

Unlike conventional push-pull windings, both halves conduct $I_{in}/2$ for both half-cycles.

The MOSFETs alternately carry the input current I_{in}.

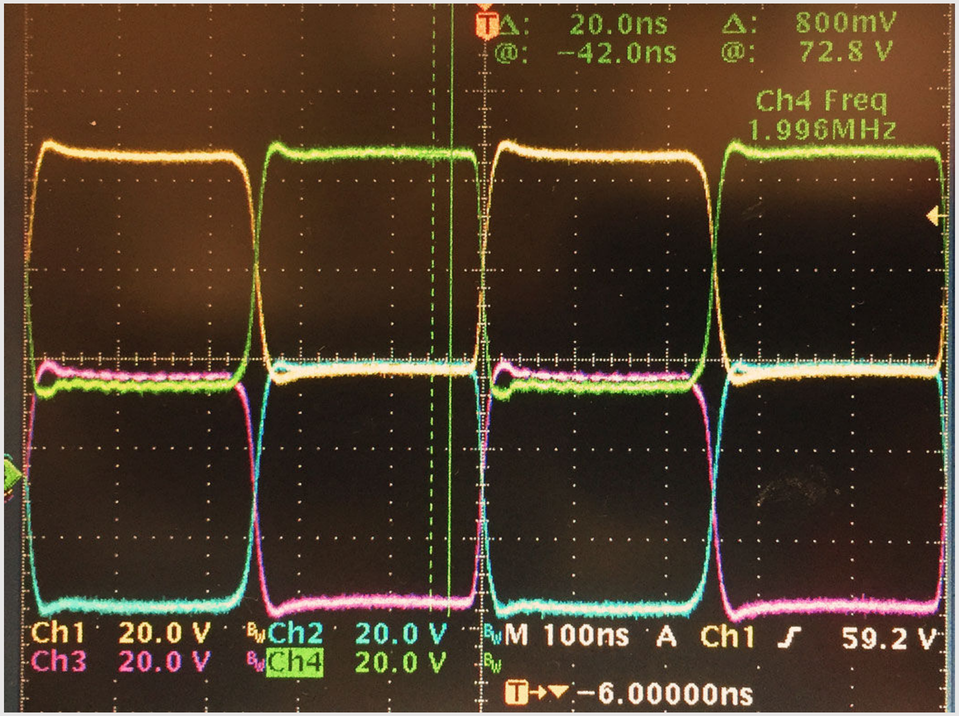


Symmetrical push-pull wave-forms

The oscillograph shows the symmetrical excitation.

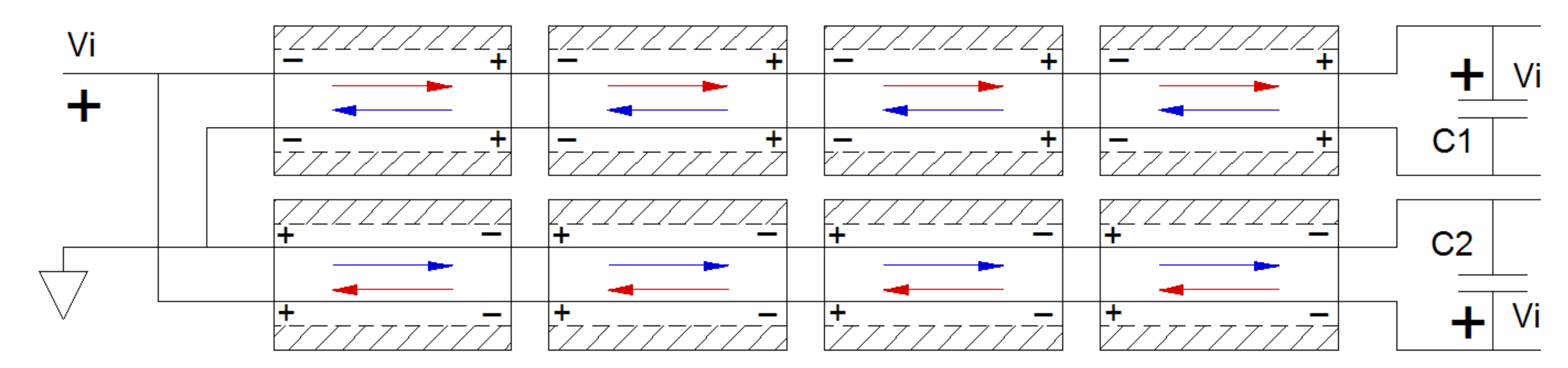
The yellow and green traces on the top are the drain voltages, alternating between 1/2 Vi and 3/2 Vi.

The pink and blue traces on the bottom are the source voltages, alternating between 1/2 Vi and –1/2 Vi.



The Symmetrical Inductor:

Voltage on the capacitors is maintained by the symmetrical inductor.



The voltages in the cores are common mode. Nothing that the flux does can affect the capacitor voltage, and *vice versa.*

The currents in the cores cancel. Nothing that the current does can affect the flux, and *vice versa.*

Dc current in the symmetrical inductor.

The currents charging the common-mode capacitors are dc, so skin effect is not an issue. The conductors can be solid and very heavy with almost no loss.

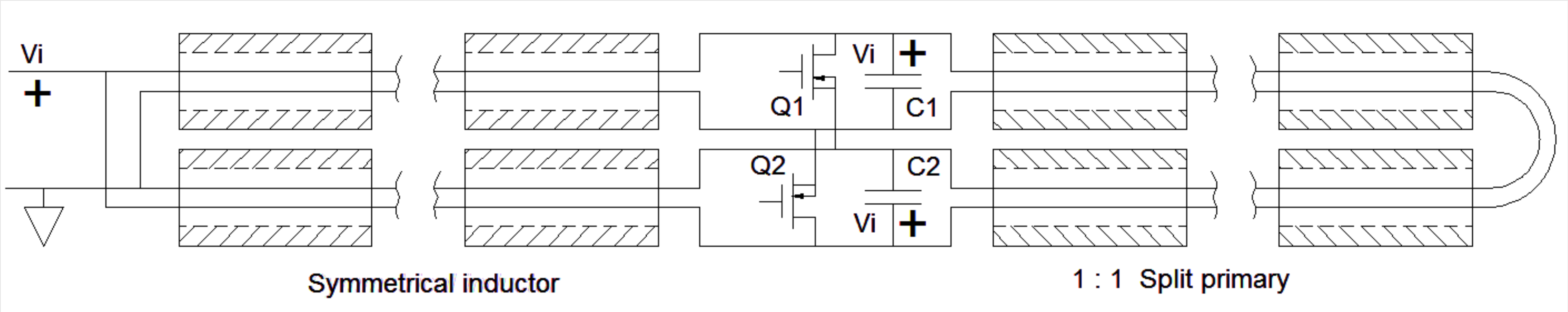
When operating, there is a small ac magnetization current.

The cores see an ac voltage equal to the input voltage Vi on both conductors. The positive side is off-set by a dc voltage equal the input voltage Vi.

Looking at the MOSFET sources, referenced to the input ground, the voltage is a square-wave equal to +/- ½ Vi, as seen in the next slide.

Looking at the MOSFET drains, referenced to the input ground, the voltage is a square-wave equal to Vi +/- ½ Vi, or from Vi/2 to 3 Vi/2.

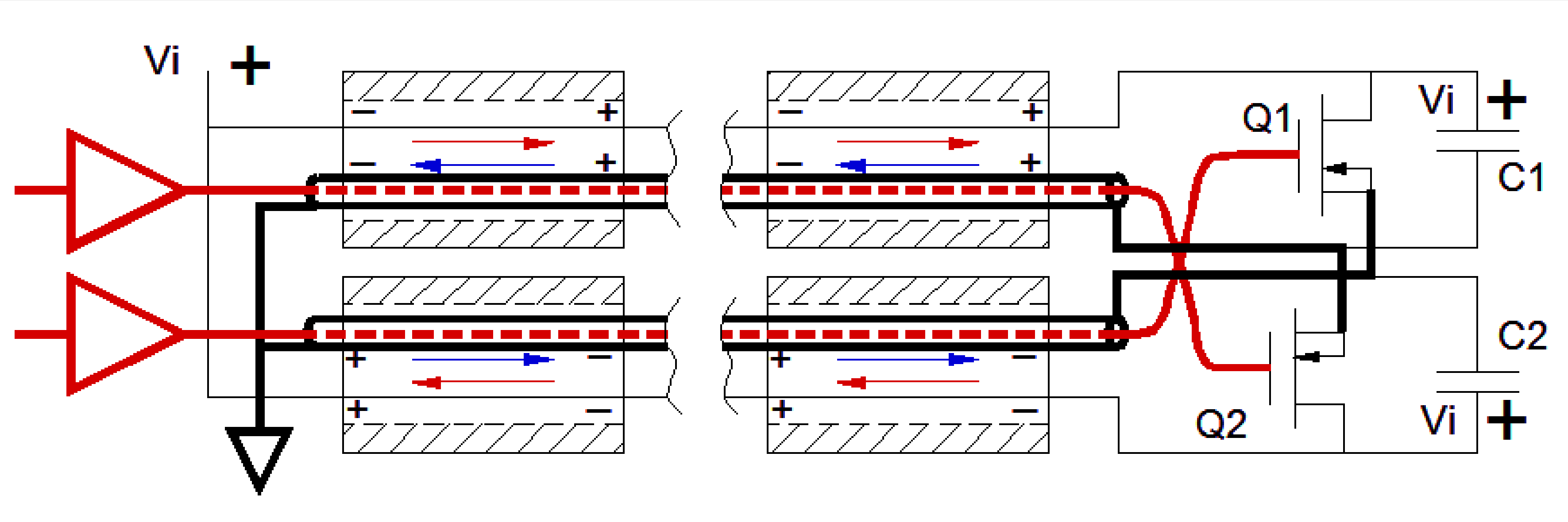
Connection to the MOSFETs and transformer:



The symmetrical inductor connects directly to the common-mode capacitors of the transformer. The voltage on the capacitors is equal to the input voltage Vi.

Symmetrical excitation at the center node cancels at the input, for very low noise.

"Through-the-bore" gate drive.



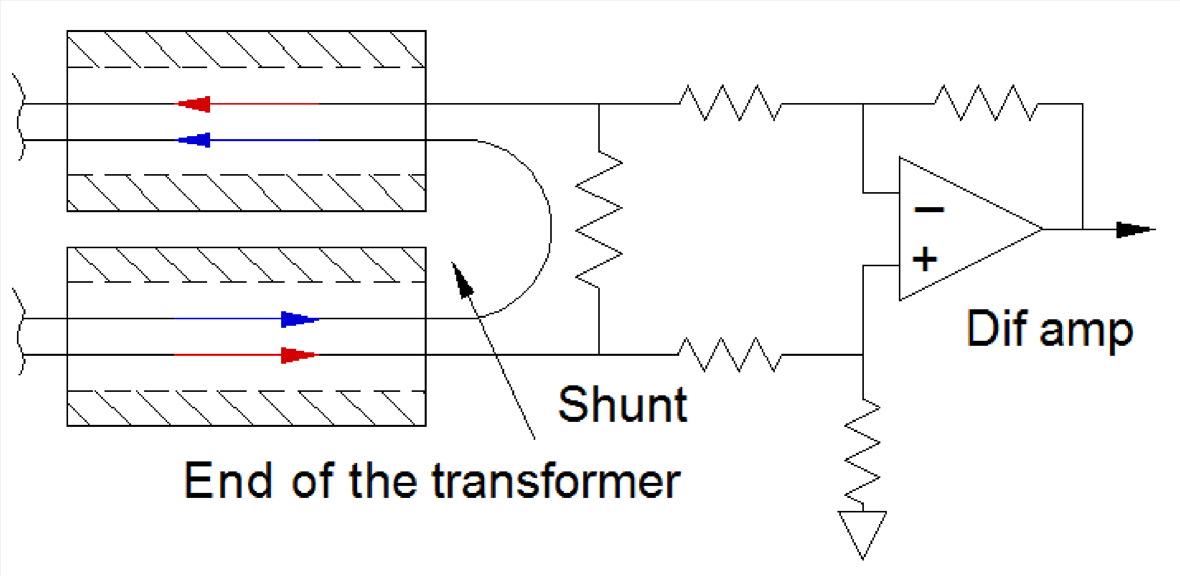
Because the voltages are common-mode through the cores, the gate drive logic can be passed through-the-bore as well, on the side that is common to the sources.

Through-the-bore on the transformer end:

Because the end of the transformer is a null point, it is an ideal place to put current sensing.

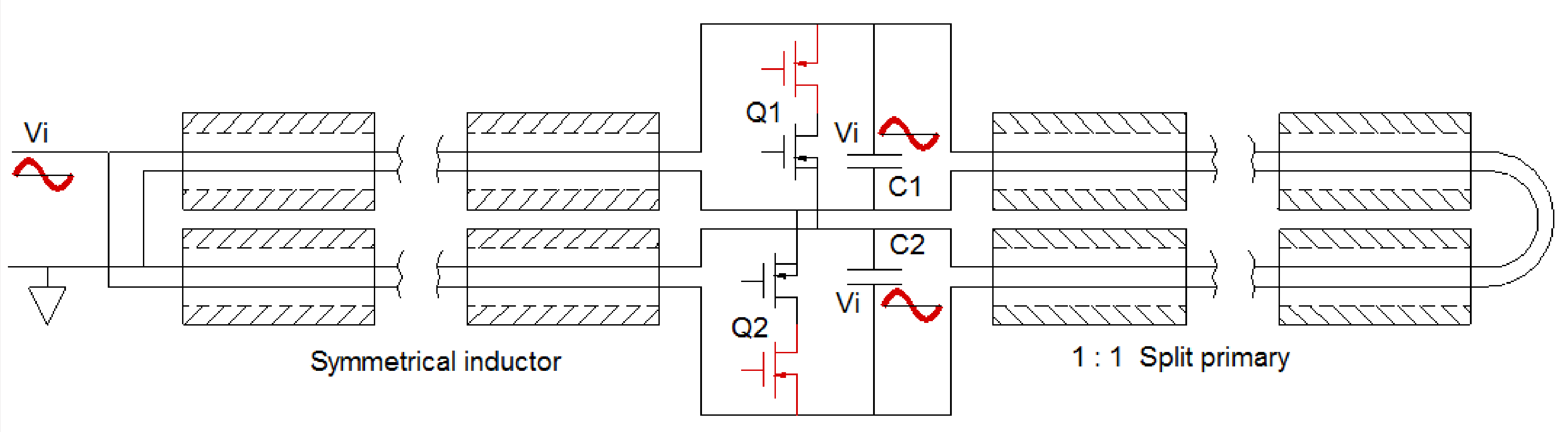
A shunt is shown with a dif amp, because there is some voltage offset.

A current transformer is an option.



Symmetrical converter for ac-ac conversion:

To use a symmetrical converter for ac-ac conversion, replace the MOSFETs with ac switches. Back-to-back MOSFETs are shown.



The secondary circuit is the same, as a synchronous rectifier.

Switching losses

Zero-Volt-Switching (ZVS).

There should be sufficient stored energy to fully charge C_{DS} when the MOSFET is turned off. Usually, the magnetization current is sufficient.

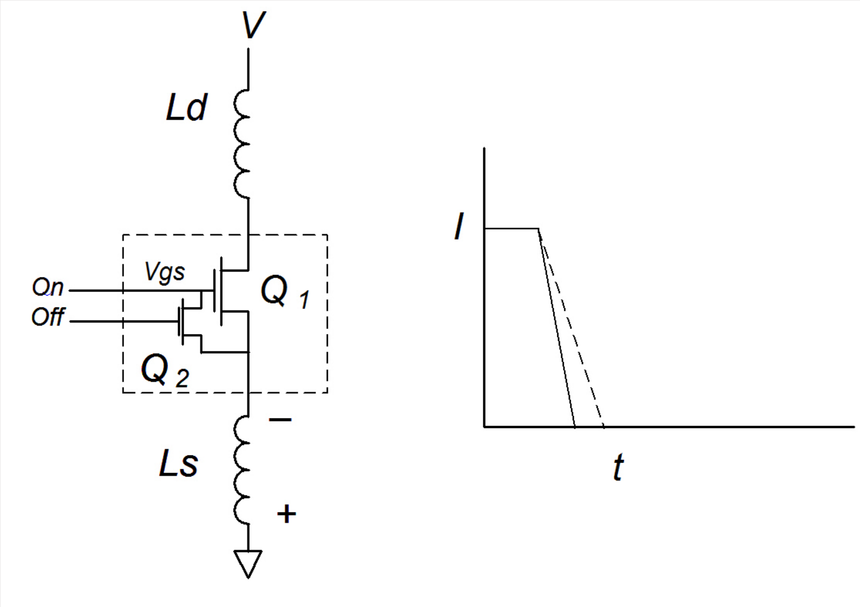
When the voltage on C_{DS} reaches 2 times the input V_i the other MOSFET will have zero V_{DS} and can be turned on with ZVS.

There is nearly ideal snubbing with complete energy recovery through the common-mode capacitors and the body diode of the other MOSFET.

"No-loss" non-zero-current turn-off

There are no inherent losses in turning off a MOSFET with non-zero current.

Losses are attributable to leaving the MOSFET in its active region for too long (cross-over power), and to poor control of the stray inductance.

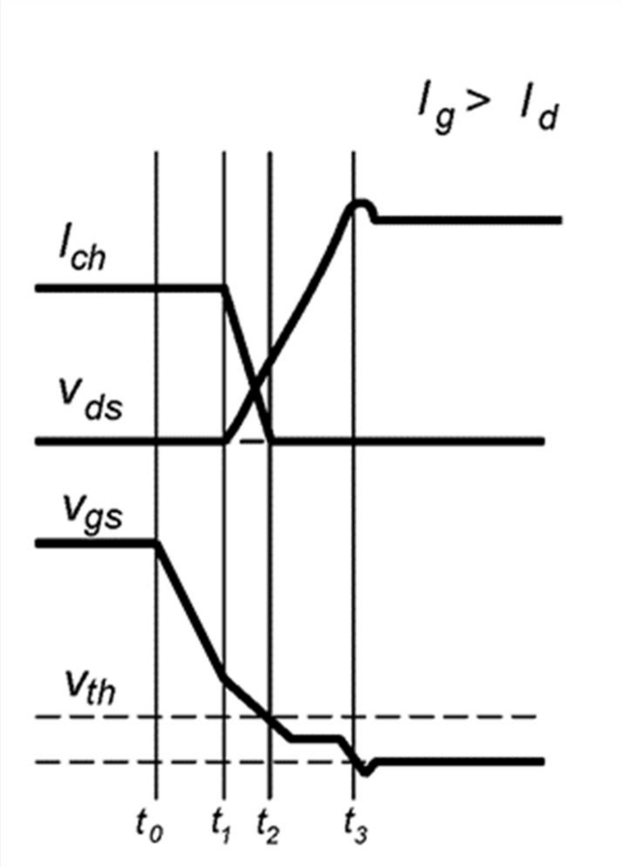


"Anti-Miller" circuit

If I_g >> I_D, then there is no "Miller shelf," that is, there is no flat region on the V_{gs} curve.

Ideally, the gate-source capacitor C_{cs} is discharged below the gate threshold voltage V_{th} before the drain-source voltage V_{ds} rises appreciably.

Unfortunately, the gate mesh resistance R_g is much too high on commercial MOSFETs. The low-side driver really should be integrated into the MOSFETs.



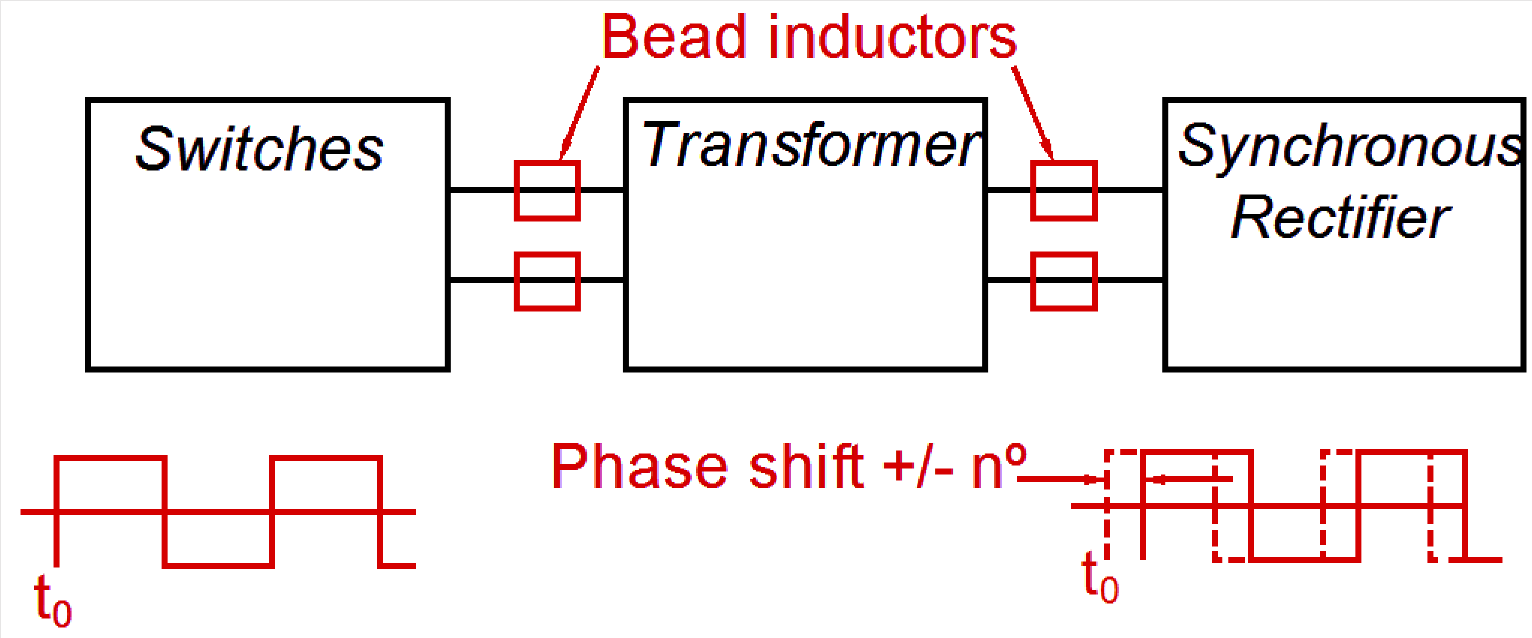
DAB (Dual Active Bridge) circuit

2 x input voltage across inductance during phase shift forces very fast *di/dt*.

Best for circuits where Vi ≈ Vo.

Ideal for removing load regulation.

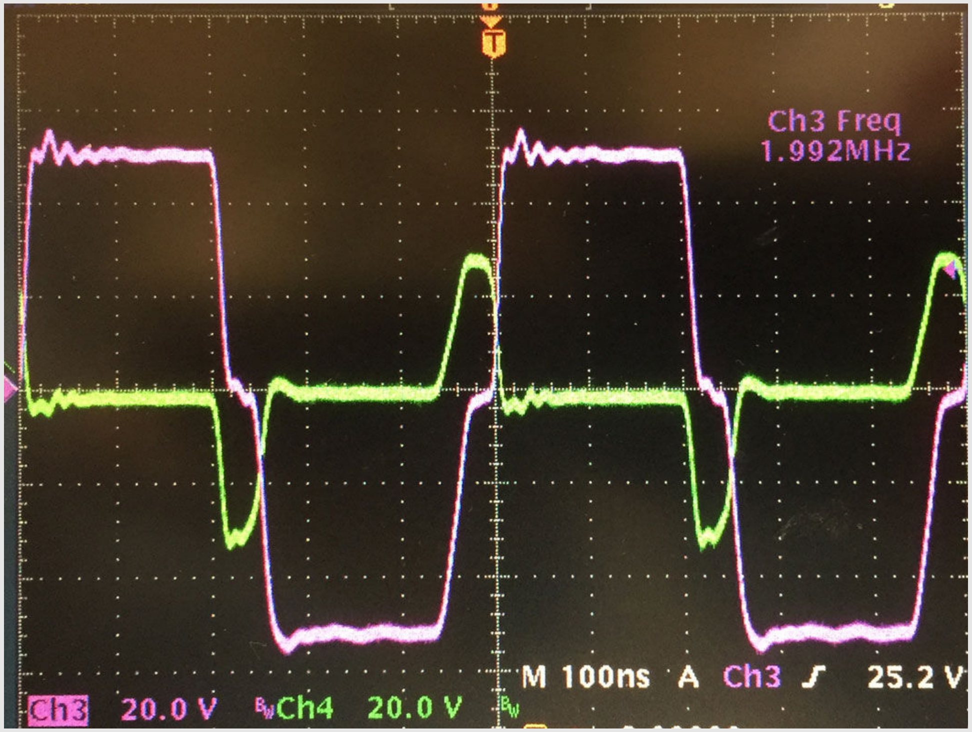
The fact that DAB can compensate for small input voltage variations is a bonus.



Oscillograph of the DAB voltages

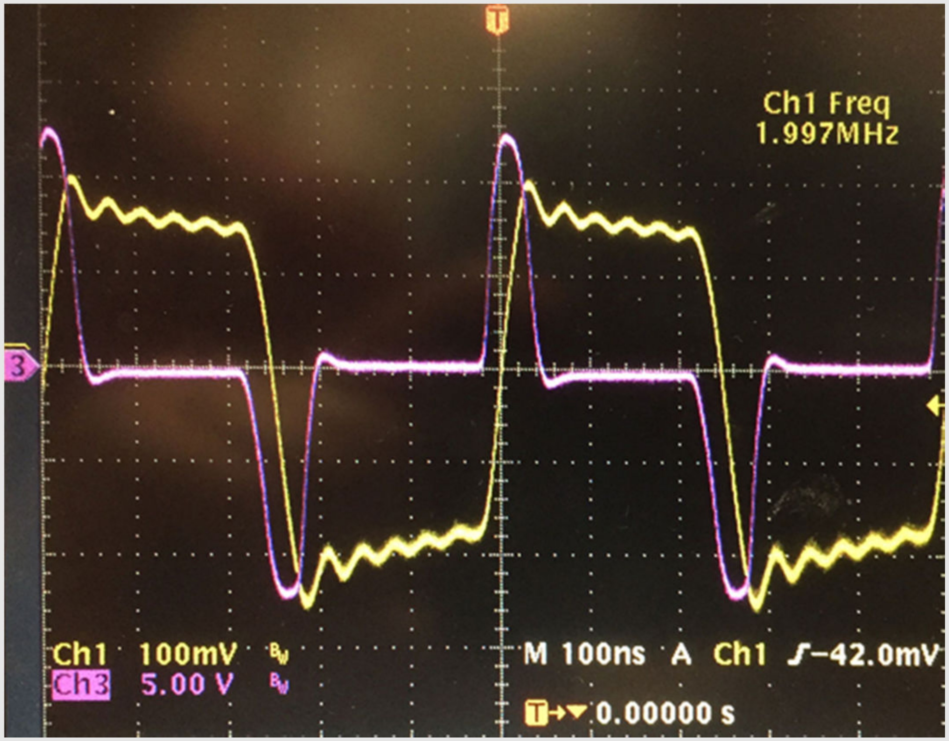
The oscillograph shows the transformer winding voltage (pink) with a sense winding and the DAB inductor voltage (green) with a sense winding.

In theory, the voltages should be the same peak voltage, but the difference may be the voltage on the transformer's stray and leakage inductances.



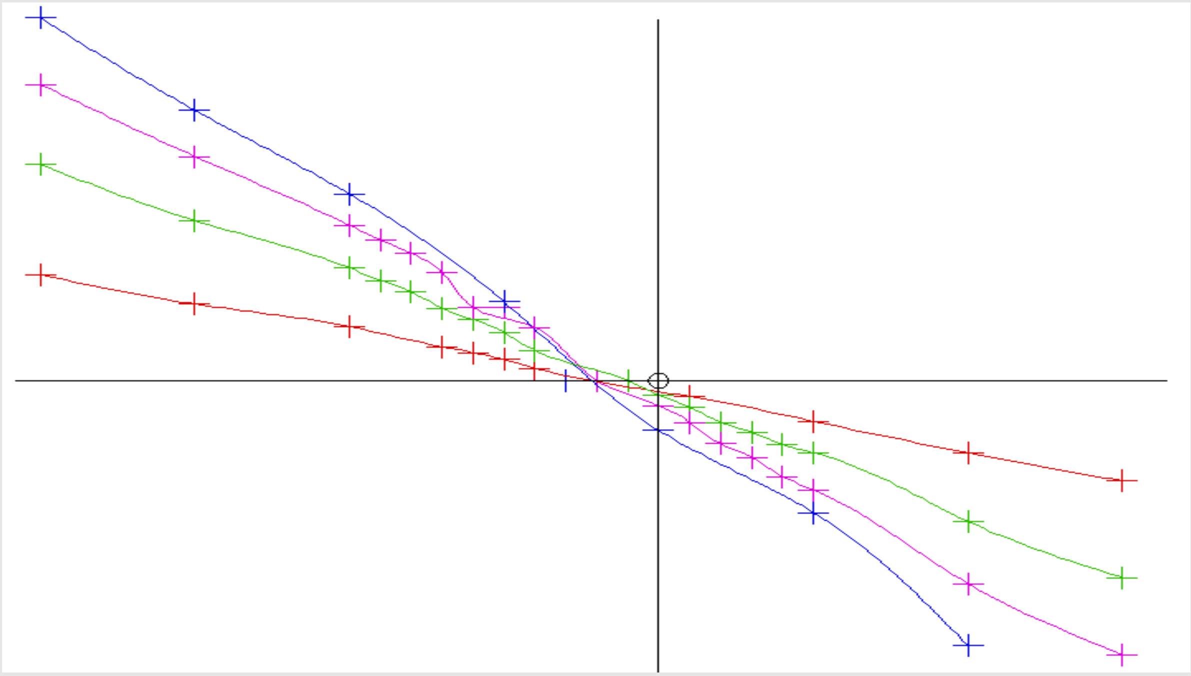
Oscillograph of DAB current

The oscillograph shows the transformer current (yellow) and the voltage on the DAB inductor (pink) using a sense winding.



DAB controls the current

The current is roughly determined by the phase angle and the voltage.

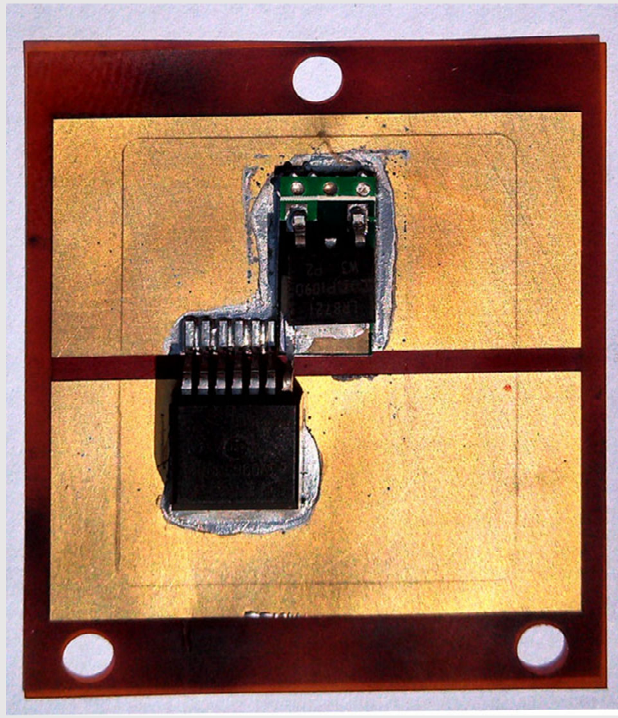


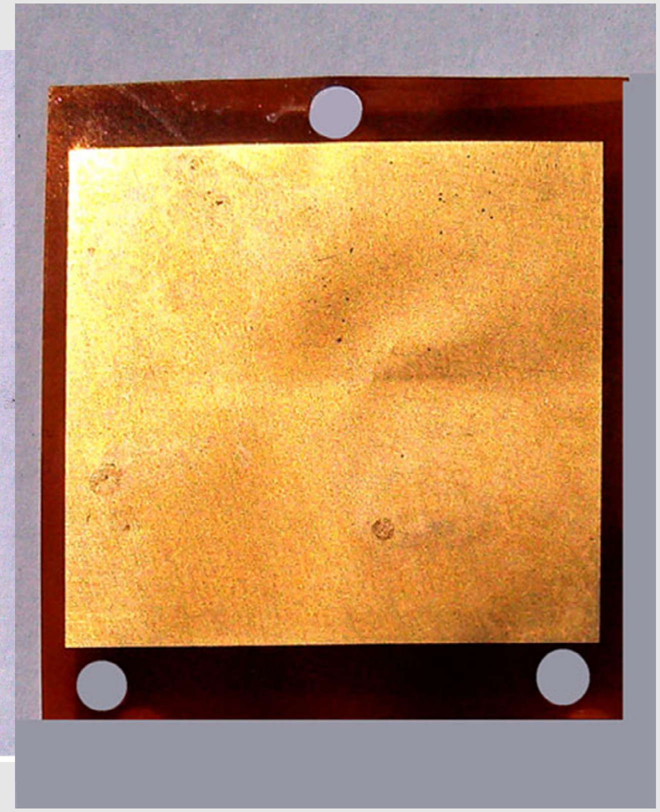
The MOSFET boards:

The MOSFET boards are blank slates that can be customized for various MOSFETs and driver circuits.

The front is shown with a SiC MOSFET.

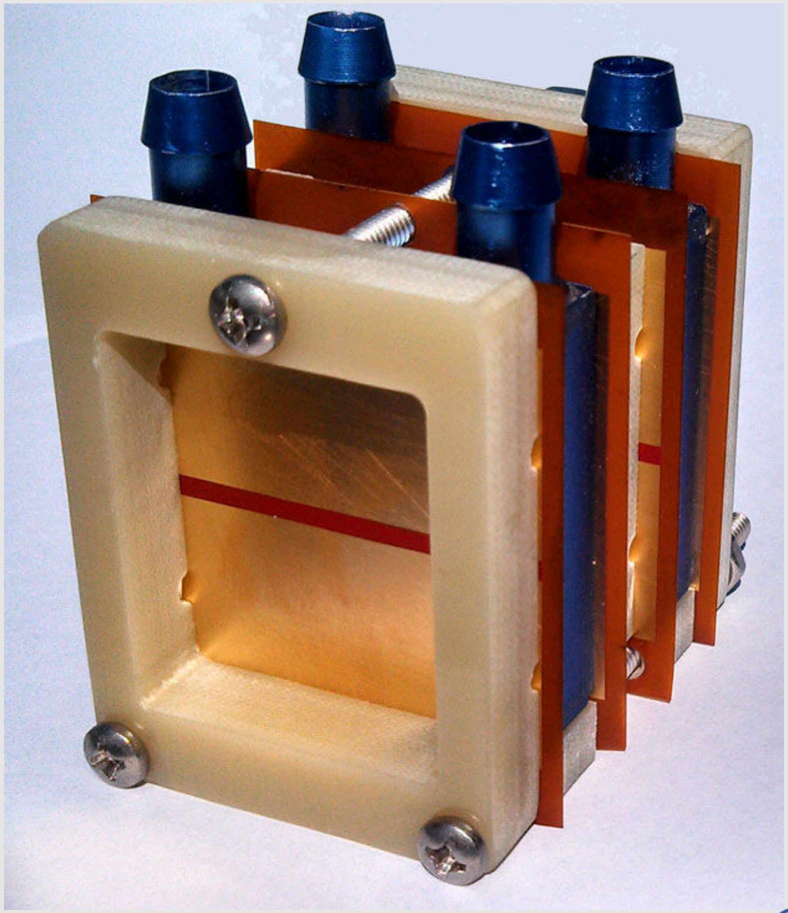
The back is a heat spreader.





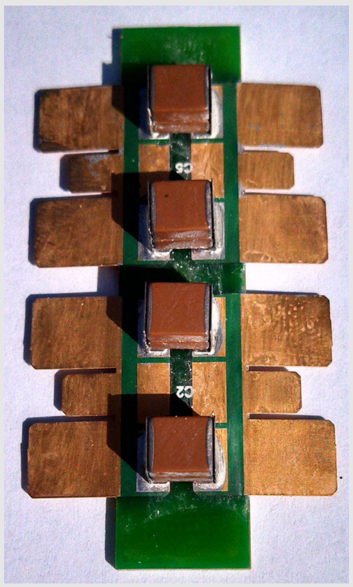
Heat sink assembly

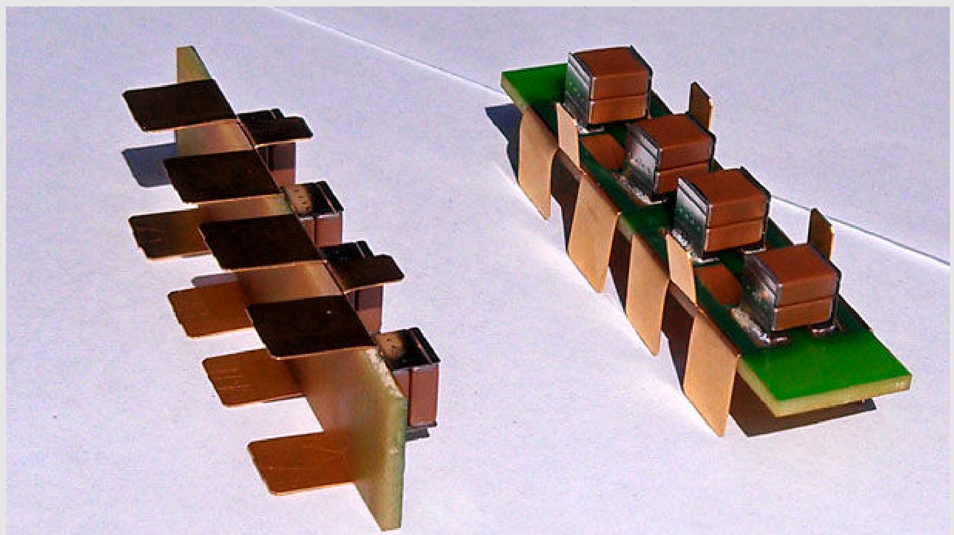
Once the MOSFET boards are populated, they are put on the heat sink blocks and clamped tightly (with their mating components, shown later).



Capacitor boards

The capacitor boards contain the common mode capacitors. The fingers are bent up and down to make connection to the MOSFET boards.

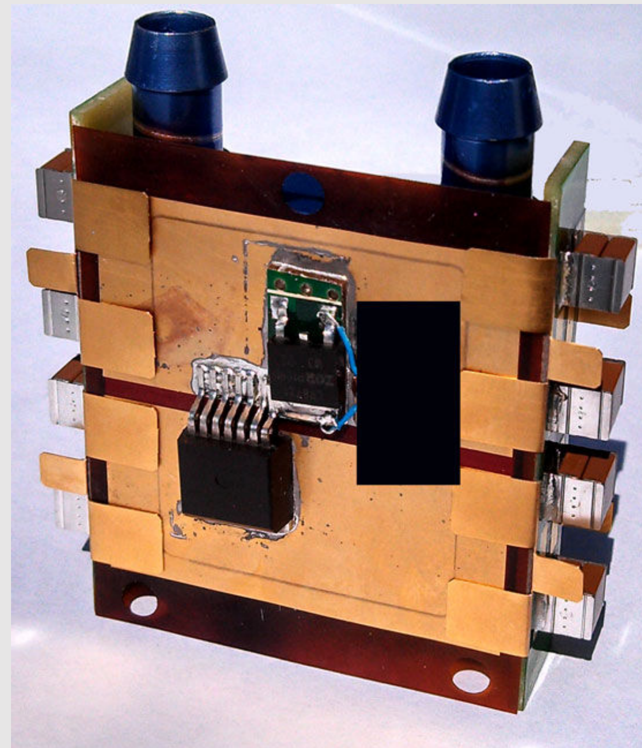




The common-mode capacitors are added.

The common-mode capacitors on the capacitor boards clamp tightly to the MOSFET boards.

Having very low ESL and ESR usually is more important than the capacitor value.

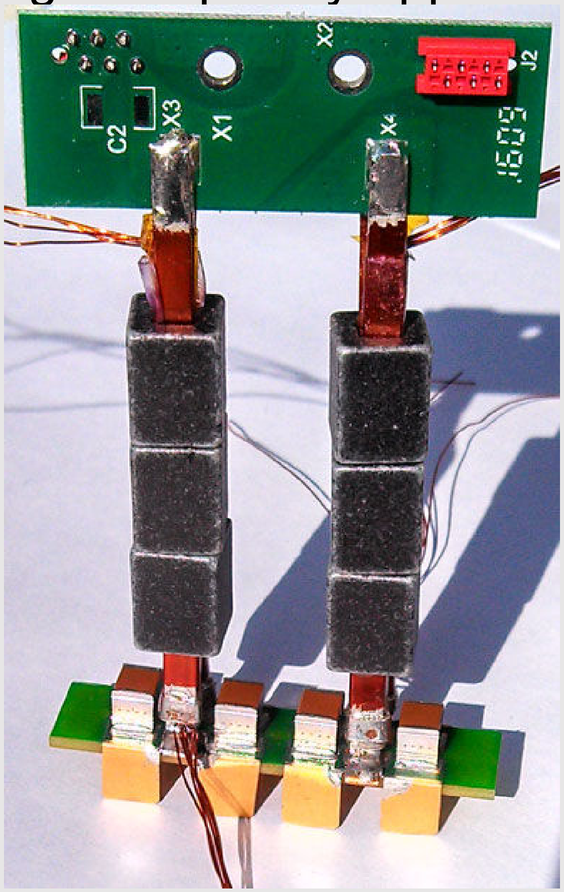


The symmetrical inductor

This is a partly assembled symmetrical inductor. It is not as photogenic as a finished assembly, but it is more interesting.

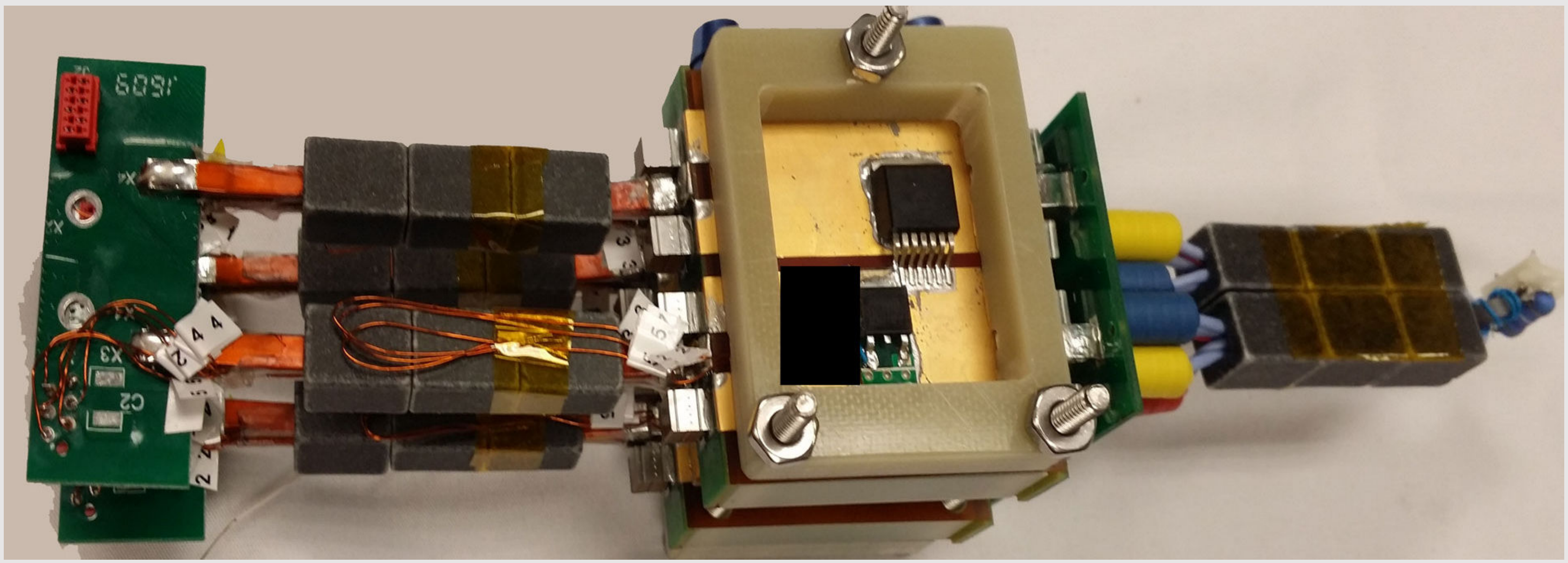
The wires through the bore show more prominently.

The symmetrical inductor mounts on a capacitor board, and they are installed on the heat sink blocks as an assembly.



The whole converter

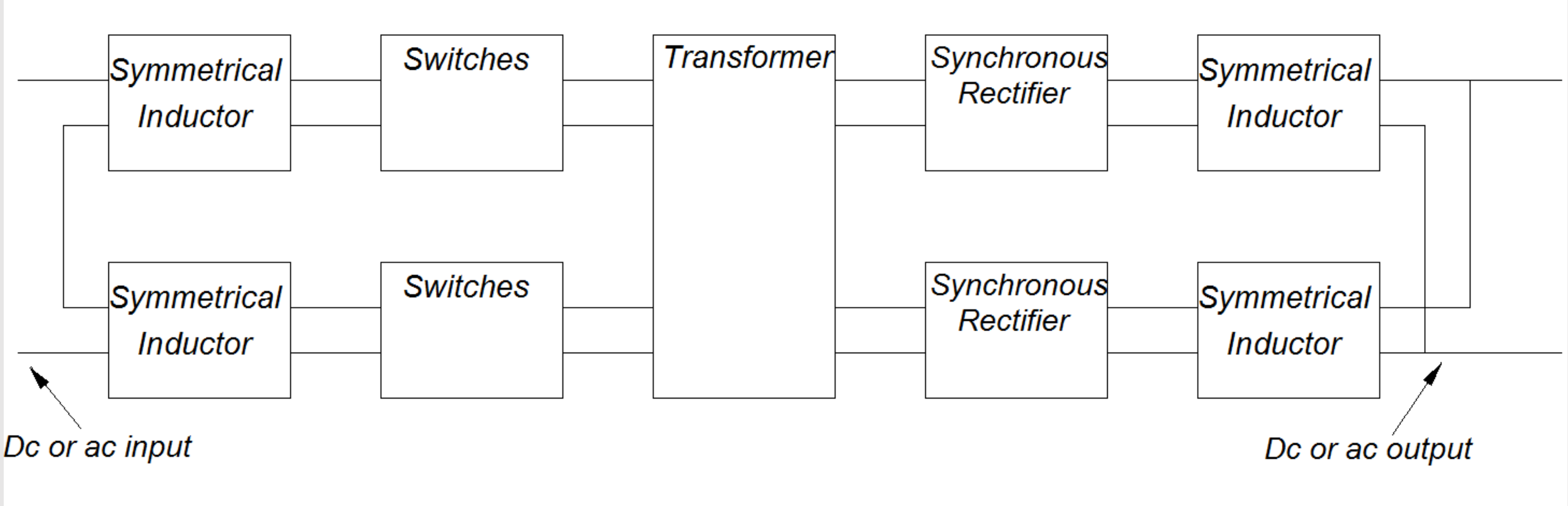
This converter was built as a prototype, and has current sense and extra test points.



Multi-cell circuits:

There are two types of multi-cell circuits.

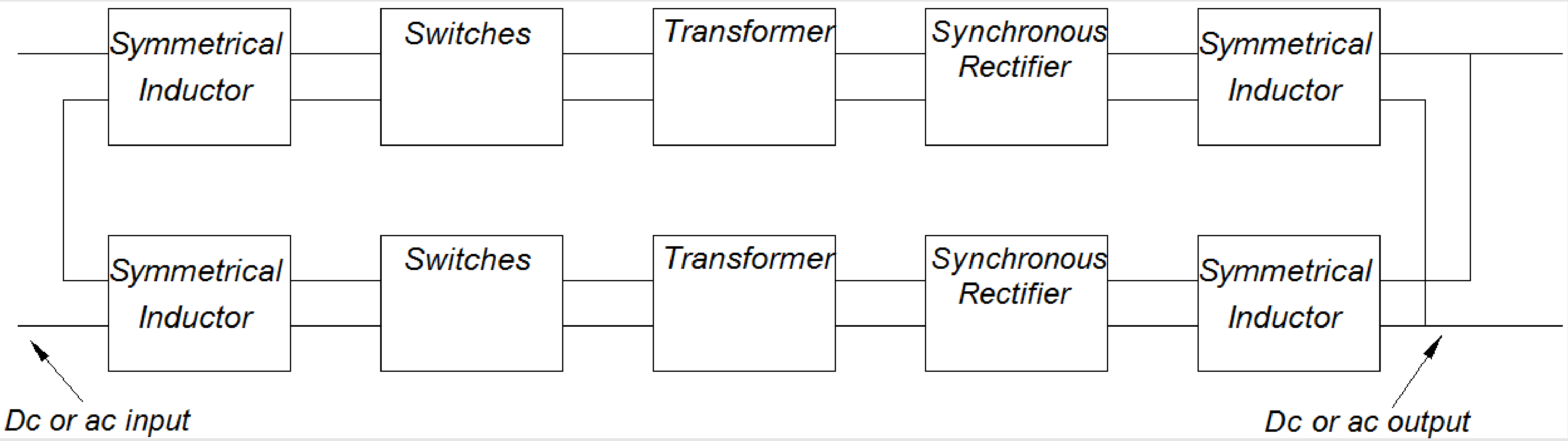
1. Two or more cells on one transformer.



Switching must be synchronous.

Multi-cell circuits:

2. Two or more cells on different transformers.



Switching can be asynchronous, interleaved or intermittent.

Multi-cell circuits:

A large modular system may have many modules that are multi-cell circuits with one transformer per module.

The system may have a number of these modules each with its own transformer.

Within a one-transformer module, switching must be synchronous, but between modules, switching can be asynchronous, interleaved or intermittent.

For example, a 13,800 kV to 240 V ac might have 16 modules, each module having 4 cells on its own transformer. 16 x 4 = 64 to 1.

That is an excess of total cells needed, but some can be switched "off" to adjust the ratio. Failed cells also can be switched out until they can be replaced.

Medium voltage transformers (13.8 kV to 480 Vac)

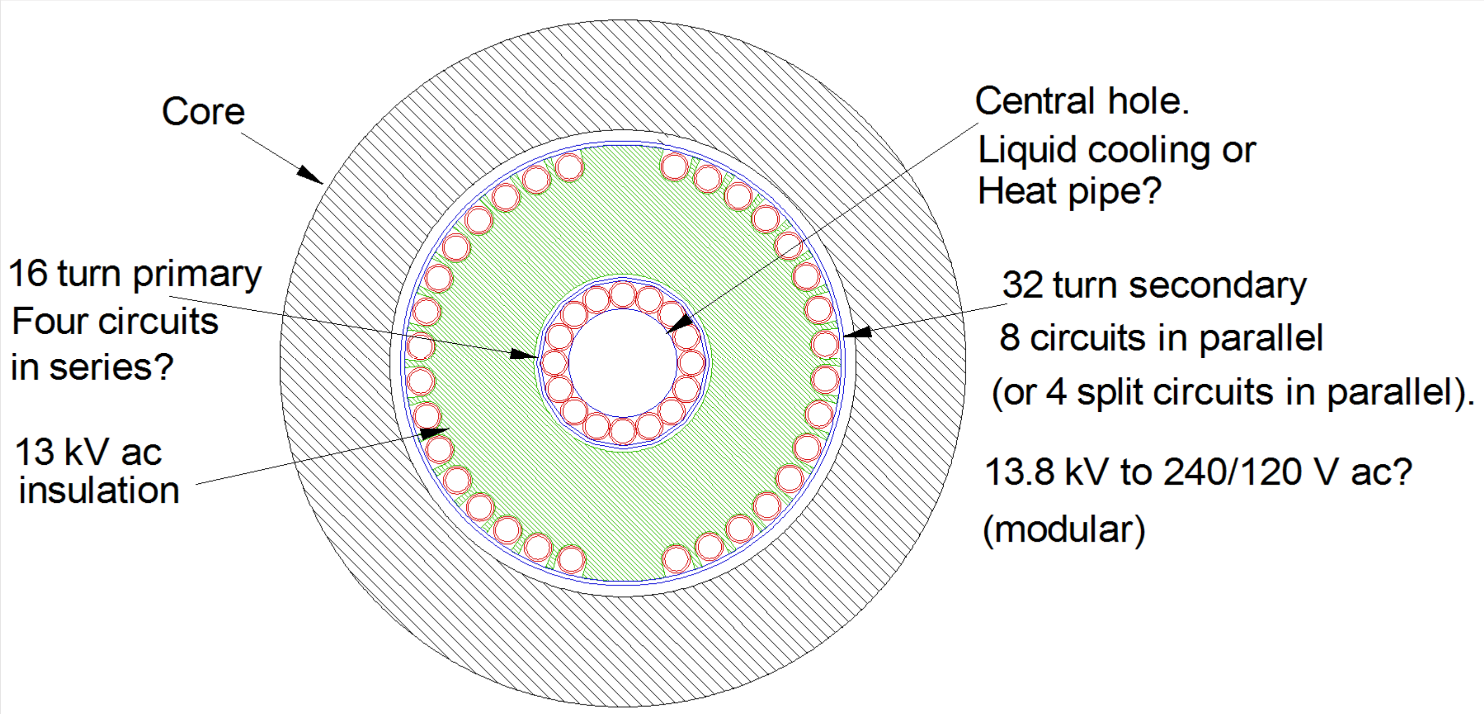
If a low frequency transformer is converted converted to a single turn transformer with many small cores using the matrix conversion of slide 6, the total core height is very large. Unreasonably large.

If the purpose is to go to a higher frequency, *much higher*, then A_e can be much smaller, and the core height (the number of small cores) becomes reasonable.

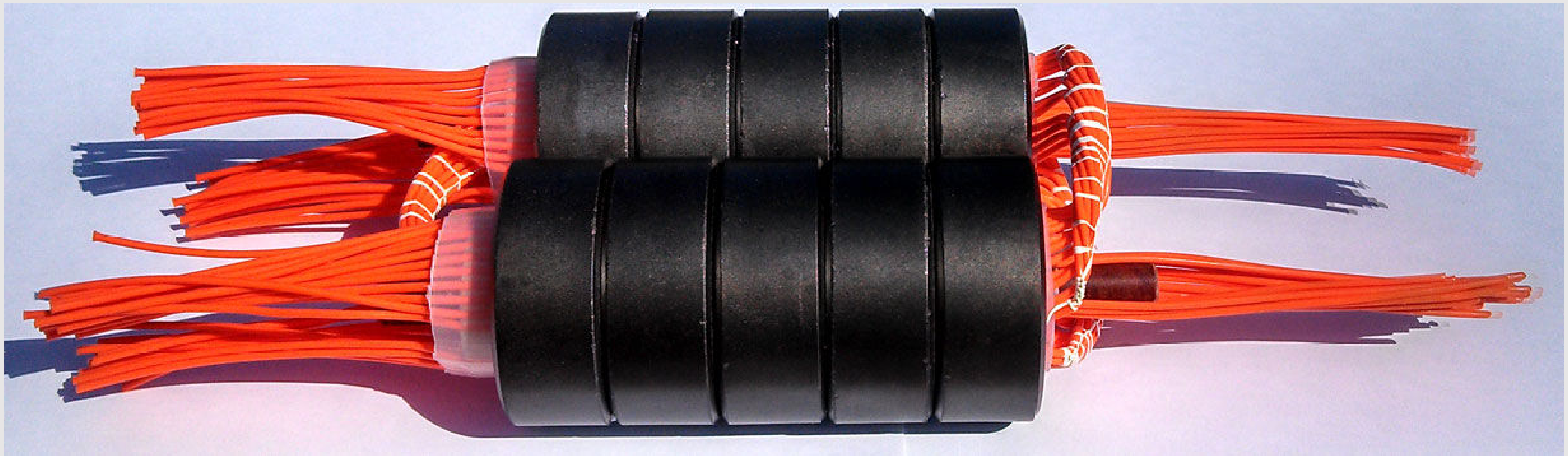
Further, the core height can be divided into a number of sections without affecting the total volume V_e.

Each section supports a lower voltage, but the primary circuits can be placed in series with parallel secondary circuits to make a step down transformer.

Medium voltage matrix transformer (Cross section):



Medium voltage matrix transformer mock-up.



The windings should be Litz wire, but the mock-up uses Teflon hook-up wire. The module will have four cells, and the "solid state" transformer would have 16 primary and 32 secondary modules per phase. Estimated rating is 1 MVA per phase.

Modular transformers (multi-cell)

With n cells in series, each circuit sees 1/n of the input voltage. Low voltage (900 V) parts can be used, and they can operate at very high frequency (2 MHz?).

With n modules in parallel, the secondary output current can be very large.

- Logistically, the modules of a very large transformer can be delivered by FedEx.
- Instead of many months, the parts can be delivered and assembled in days.
- Failed or damaged modules can be switch out while the rest remain operative.
- Failed or damaged modules can be replaced in a few days.
- At low loads, individual modules can be turned off to save energy.
- A high frequency modular transformer is very much smaller.

"Solid-state" transformer variant using ac modules:

There is no DC link, so it is not suitable for changing frequency or phase..

However, there are fewer conversion stages, so it smaller, lighter, less expensive and more efficient.

At light loads, individual modules can be shut down or run intermittently in burst mode, so no-load or low-load "magnetizing" current is very low.

DAB can remove load regulation, so Z=0 is possible.

There is very little stored energy, so it cannot sustain arc-flash no matter how large the transformer.

Questions?

Thank you!

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