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Matrix Transformers May Find New Life In The SiC And GaN Era

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Many said that the matrix transformer was before its time, which may be true. It is particularly well suited for high frequencies, 300 kHz and higher. In 1989, when it was introduced, few power converters operated there. Now, with switching frequencies commonly in that frequency range and higher, and with GaN and SiC devices promising higher switching frequencies yet, it may be time to take another look at the matrix transformer and its derivatives.

Previously, the matrix transformer was licensed exclusively to one company, but the now patents listed in the table have all expired, so anyone can use the technology in those patents.

Table. Matrix transformer patents.

U.S. Patent No.	Patent
4,665,357	Flat Matrix Transformer
4,845,606	High-Frequency Matrix Transformer
4,942,353	High-Frequency Matrix Transformer Power Converter Module
4,978,906	Picture-Frame Matrix Transformer
5,093,646	High-Frequency Matrix Transformer
5,999,078	Transformer and Rectifier Module with Half-Turn Secondary Windings

The matrix transformers have very low parasitic inductance, which reduces spiking and switching losses. With their short thermal paths, large surface area and distributed losses, the temperature rise is very low compared to conventional transformers of comparable rating, making them particularly good when the power density is high.

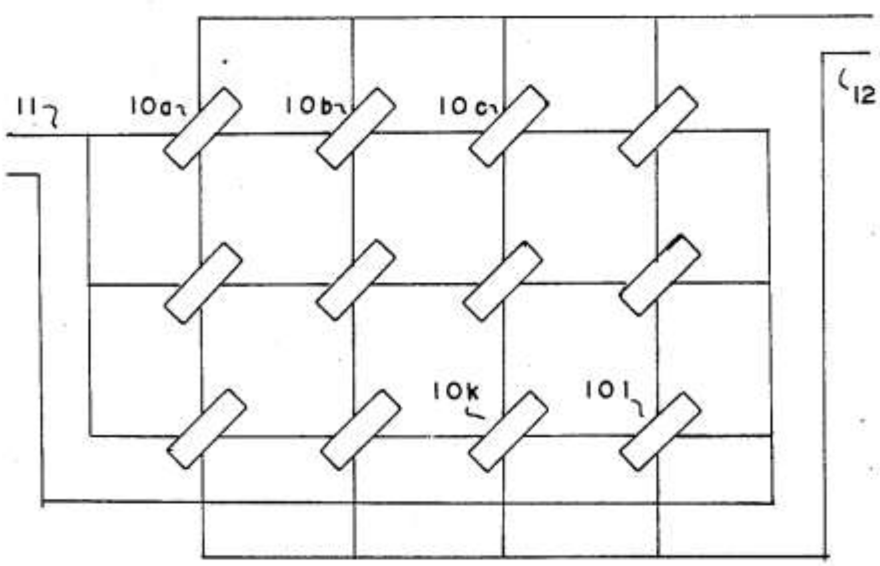

Fig. 1. The original "Matrix Transformer." With four columns and three rows, the effective turns ratio is 4:3.

The name “matrix transformer” came from its original configuration, which had rows and columns. The matrix transformer of Fig. 1 has four columns and three rows, giving it an effective turns ratio of 4:3. There are a number of ways that a matrix transformer can be wound, including serpentine windings and push-pull windings.

Early experiments showed that the coupling was extremely good, as long as a pattern was chosen that had a minimum of exposed wire. In Fig. 2, the windings all end very close to where they start. The primary winding passes through all of the modules in a closed loop, and the secondary windings pass through the individual modules. The effective turns ratio with a single-turn primary winding is m:1, where m is the number of modules.

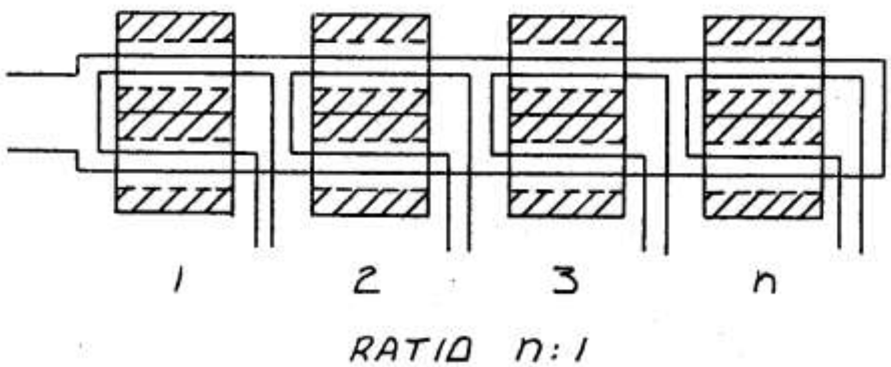

Fig. 2. Most matrix transformers were made using two-core modules. With single-turn primary and secondary windings, the effective turns-ratio is determined by the number of modules.

The primary winding may have more than one turn passing through all of the modules, in which case the effective turns ratio is (m * n):1, where n is the number of primary turns.

The earliest matrix transformers were wound using ferrite beads and hook-up wire, and that still is a good way to make quick breadboards for proof of concept and to verify the layout.

A significant improvement was the introduction of foil secondary windings bonded to the inside of the cores (Fig. 3.) Transformers wound with foil are better thermally and have improved coupling. Use of foil also provides a larger window area for the primary winding.

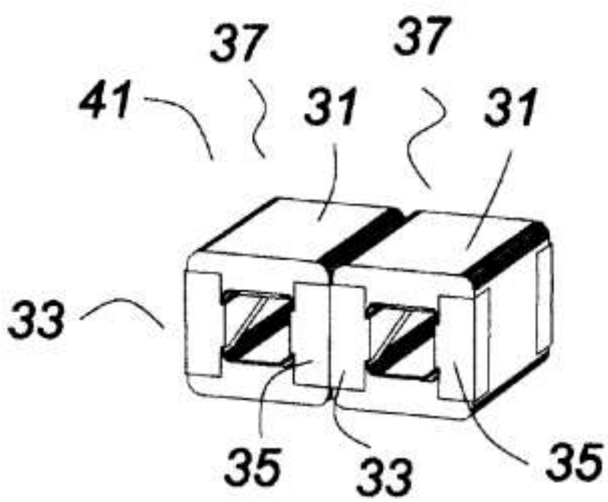

Fig. 3. Foil secondary windings are bonded to the inside of the cores, which were usually used in pairs soldered together at the corners.

For safety insulation purposes, the core is considered to be part of the secondary circuit, so only working insulation is needed between the secondary winding and the core. Double- or triple-insulated hookup wire meets the safety isolation requirements for the primary winding.

The matrix transformer module has a buck inductor in the same package (Fig. 4.) Most matrix transformers have push-pull secondary windings. To minimize stray inductance, the modules were designed so that a T03-P Schottky rectifier could be connected directly to the secondary windings. The stray inductance of the rectifier package dominated.

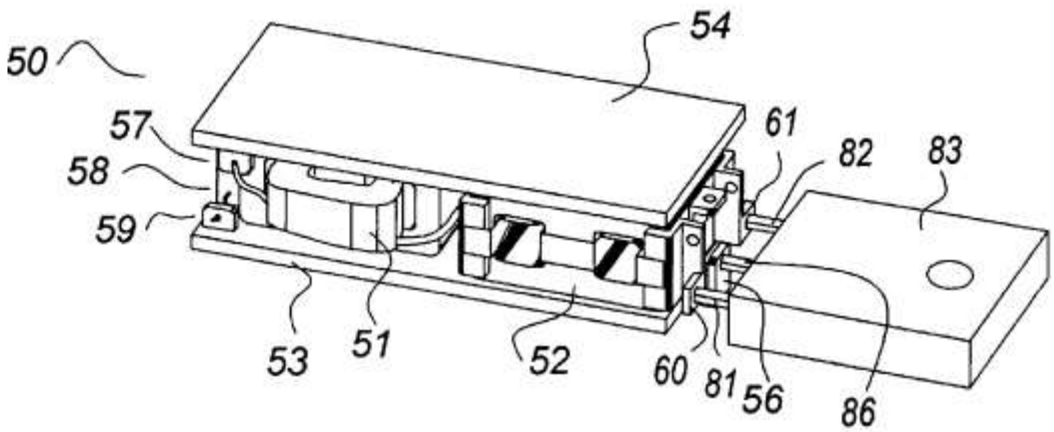

Fig. 4. The matrix transformer module often was packaged with an inductor for a buck converter output.

Toward the end of production, the Schottky rectifiers were replaced with synchronous rectifiers, improving efficiency a lot.

An interesting variant of the matrix transformer is shown in Fig. 5. A string of cores is arranged in a closed pattern. The primary winding ends where it starts, but the secondary windings do not. However, at each secondary connection point there is a start and an end that carry the same current in opposite directions. This minimizes stray inductance.

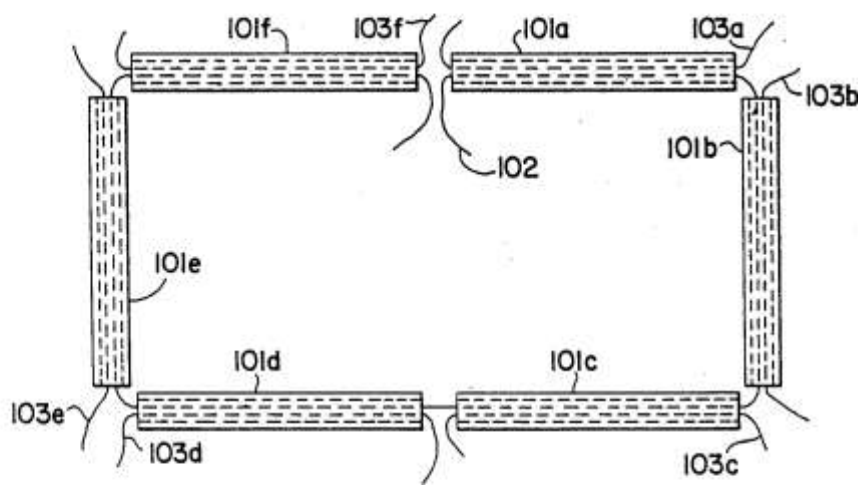

Fig. 5. The "picture frame" matrix transformer has a single string of cores arranged in a closed pattern.

The matrix transformer was introduced in 1989. A 162-page tutorial was written in 1990 for a seminar for the High Frequency Power Conversion Conference in Santa Clara, Calif. This tutorial is available online (see the reference.)

Much has been learned since the tutorial was written, but it has a good explanation of the fundamental considerations. The laws of physics were not rewritten—the matrix transformer follows all the same rules as a conventional transformer—but the details are not familiar.

An example of a picture-frame matrix transformer is shown actual size on page 8 of the tutorial. It is rated at 400 A at 5 V dc (2000 W), and is made with 3/8-inch cores, so that is its height.

The tutorial also explains the "symmetrical push-pull" winding. An explanation of the symmetrical push-pull winding is beyond the scope of this column, but the reader is encouraged to see the tutorial for more information.

The symmetrical push-pull winding could, in theory, be used with any transformer, but it was particularly easy to use with the matrix transformer. Using a symmetrical push-pull winding with "floating capacitors," the circuit was self-snubbing and the switching MOSFETs were effectively decoupled from the parasitic inductance, which significantly reduced the switching losses. Almost all production matrix-transformer power converters were wound that way.

The matrix transformer proved to be very easy to design, once we learned its characteristics. In making breadboards, we spent about 5% of the time making the transformer and 95% making the gate drives for the MOSFETs. MOSFETs were relatively new devices in 1990, and there were few gate drivers available.

Power converters made using the matrix transformers were very efficient for their time, with the losses in the Schottky rectifiers dominating. The very low parasitic inductance allowed hard switching with reasonable losses.

In production matrix transformers, magnetic core losses seemed to be much lower than expected, even though we were using a material that was not particularly good. Recent work sponsored by the PSMA at Dartmouth may suggest why.

In Fig. 6, the blue lines are the core losses versus pulse width for a toroid core with five turns. The red and green lines are the same excitation on a string of beads with one turn. The losses are similar at lower frequencies (higher pulse widths), but the string of beads has significantly lower losses at higher frequency. (The pulse width is half of the period, so 1-µs pulse width is a frequency of 500 kHz.)

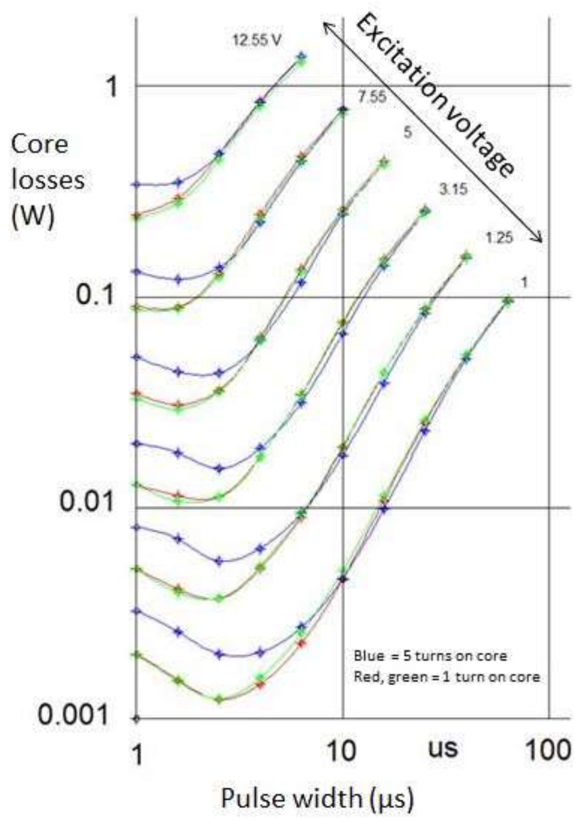

Fig. 6. Comparison of core losses for a string of beads versus a toroid core at various excitation voltages and pulse widths.

The tests were interrupted before much data could be taken, so the data is suggestive, not conclusive. The curves in Fig. 6 must be considered hypothetical, as they were manipulated somewhat for presentation, but they are based upon real data. The result is consistent with our experience with production matrix transformers, and more testing is indicated.

The results of the studies at Dartmouth sponsored by PSMA are summarized on the PSMA website and there are links to the full reports.

The matrix transformer patents were licensed exclusively to one company, though it went through several reorganizations with several names. Although the company was not successful, a number of their power converters using the matrix transformer were very successful.

The first product line was a number of higher-power (3000 W) "shoe box" power converters. They showed great promise. When the company was refinanced, the new investors urged a shift to modular power supplies, and quarter-brick sized converters using the matrix transformer lead the field for several years. However, when bricks became a commodity, the company had not scaled up production and could not compete, so production ended.

The matrix transformer and its derivatives are particularly well suited for high-current applications, where the very low parasitic inductance is an advantage. There are multiple secondary windings, all very short and effectively in parallel, so the secondary winding resistance is very low. Usually, each secondary has its own rectifiers, and the current divides exactly, as every module couples to the same primary current.

Once properly tooled and down the learning curve, the matrix transformer is very economical. A significant factor in the cost is that the matrix transformer can operate at a much-higher frequency, so its volume is significantly smaller. Even buying premium high-frequency ferrite, the material cost is much lower. They wind induction motors automatically, so tooling up to wind matrix transformers should be comparatively very easy.

In theory, any conventional transformer could be made with a smaller core and operate at a higher frequency. In practice, the losses tend to increase at higher frequency. With a smaller volume, the power density is higher, and with a smaller surface area, the ability to remove heat becomes a real challenge.

The matrix transformer solves these problems. With its lower parasitic inductance and secondary resistance, it can operate at higher frequency while decreasing the losses. It has a smaller size, consistent with the higher frequency, but its thermal paths are short and its surface area is large. In a well-made matrix transformer module, the temperature rise at full load tended to be about 10ºC. In general, the rated current was dictated by the semiconductors, not the transformer, suggesting that it could be pushed much harder with newer devices, particularly with GaN and SiC power switches.

Reference

"Design and Application of Matrix Transformers and Symmetrical Converters," seminar by Edward Herbert, presented at the Fifth International High Frequency Power Conversion Conference, Santa Clara, Calif., May 11, 1990, available online at http://fmtt.com/pdffiles/Tut2.pdf.

About The Author

Edward Herbert is a member of the PSMA's Board of Directors, co-chairman of the PSMA's Magnetics Committee and co-chairman of the PSMA's Energy Efficiency Committee. Over the years, Ed has held a variety of positions in industry, working as a design engineer, a project engineer, an engineering supervisor, and as an engineering manager. Since 1985, he has been independent, promoting patented technology for license.

Ed has been issued 54 patents with several more pending. Of interest to this forum, Ed is the inventor of the matrix transformer. Ed holds a Bachelor of Engineering degree in electrical engineering from Yale University.

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