Design and Application of Matrix Transformers and Symmetrical Converters

by

Edward Herbert

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A Seminar presented at the **Fifth International High Frequency Power Conversion Conference '90**
Santa Clara, California, May 11, 1990

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PATENTS

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Preface to the First Edition

Much of the subject matter of this tutorial was first presented at the High Frequency Power Conversion Conference '89, in Naples Florida, on May 18, 1989, with the title of Design and Application of Matrix Transformers and Inductors.

K. Kit Sum was kind enough to contribute the introduction, which is reproduced here. Kit's guidance and encouragement has been invaluable to the development of matrix transformer technology. His contribution is gratefully acknowledged.

The prime purpose of this seminar is to introduce to the audience a new and exciting transformer technology, which has numerous superior performance characteristics not obtainable in conventional transformer technologies.

Many of the familiar problems in modern switch mode transformers such as: high leakage inductance, high profile, and hot spot temperature at the center of the core, are inherent in conventional designs, [1,2,3,4]. The leakage inductance of the transformer is further aggravated if fractional turns are used. Fractional turns are also uneconomical for mass production purposes. The single-turn secondary winding, e.g., for a 5-volt output, does not permit accurate turns ratio for other outputs requiring voltages other than 5 volts, but it does permit the transformer to have a minimum number of turns for a given turns ratio. The flux density is usually derated considerably to reduce core loss at high operating frequencies. For a given output current, the transformer wire window must be large enough to accommodate reasonably low loss windings to be efficient. All these limitations pose considerable difficulty in the miniaturization of the power converter.

The current popularity of resonant power conversion development can be regarded as attempts to bypass some of the problems mentioned above [8].

The matrix transformer technology [5] represents a revolutionary advancement toward improving the performance of the conventional power transformer. With this new technology, a single primary turn is possible. Since the leakage inductance of a transformer is proportional to the square of the number of turns, the single turn primary matrix transformer naturally yields a much lower leakage inductance than the conventional transformer.

The matrix transformer, formed by an array of magnetically wound cores, has a low profile, high power density, and distributed thermal properties not found in conventional transformer designs. High current density in windings without undue increase of power loss is also possible. This is due to the shorter turn length and lower turns count. Very accurate "turns ratios" are feasible.

Excellent shock an vibration characteristics are obtainable with the distributed mass, by design. The normal single hot spot of a lumped transformer does not exist here, since there are many cores to share the burden of power transfer.

In addition to the above desirable features, the matrix transformer is, by design, of very low profile and highly suited for high power density power processor synthesis.

The matrix transformer is applicable to all known power converter topologies. In the case of the flyback converter application, powder toroidal cores of controlled permeability should be used in place of the pure ferrite toroids. Design of all buck-derived topologies and some other less popular topologies can be found in [6]. A new symmetrical push-pull converter with a new concept of lossless snubbing is given in [7].

Since there are many equal secondary windings, the designer has the option to either connect all secondary windings in phase and in parallel with one set of output rectifiers; or with more even heat distribution, connect the secondary windings to separate sets of output rectifiers with the outputs of all rectifier circuits connected in parallel (the current will divide exactly and equally).

The matrix transformer can be regarded as a very significant step toward solving the problems associated with the conventional transformers. With some of the well-known problems solved, the existing pulse-width-modulated rectangular wave switch mode power converter can be drastically improved; so much so that it is now able to challenge the resonant counterpart in power density and efficiency.

K. Kit Sum

May, 1989

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Preface to the Second Edition

A look to the past, the present and the future.

The matrix transformer grew out of a wise crack. I met an inventor who needed to build a power supply into a clip board. The transformer was his biggest obstacle. I suggested that he needed a *flat transformer*.

The first sketches looked like a sandwich of corrugated roofing. A quick check of the flux capacity required "proved" that it was not practical. Later, a member of my design team had the misfortune to be assigned a power supply. I learned very quickly about the problems of conventional magnetics.

The first operating bread board matrix transformer was built into a 1.5 Mhz current mode converter design kit, substituting for the transformer which was supplied with it. Due to a math error, the very first one operated at 4000 gauss. It did work, and did not burn up, but it did get very hot. With a quick redesign, we had our first working model. We were off and running.

In due course, we learned that leakage inductance was impossible for us to measure; high dielectric isolation was practical; high frequency operation required special design; and turning FET's off and on at a Mhz was our biggest problem. We developed the symmetrical push pull configuration, and discovered the floating capacitors. The problems with the available capacitors led to the invention of the matrix capacitor.

I built our first matrix transformers with coaxial windings, and rushed to press with enthusiastic claims of its merit. My colleagues were unimpressed, and just to prove me wrong, built a model with parallel conductors that worked just as well. I remain convinced that the coaxial windings will be invaluable at high currents.

The earliest models of the matrix transformer were justly criticized for being hard to build. Our efforts turned to simplifying the assembly, which lead to the development of the picture frame matrix transformer and the modular designs. We continued to push the limits, and have achieved respectable power densities and efficiency in five volt power converters up to 2000 watts. These units are simple and basic, and use readily available components.

I am proud of what we have accomplished to date. We are a small design team, with limited facilities. In just over two years, we have brought the matrix transformer technology to where it can challenge the state of the art on two fronts, performance and economy.

Looking to the future, I can identify a number of areas where there is promise. First and foremost is the question of introducing the matrix transformer to a skeptical world. It is strange and unfamiliar. Its too complex and uses too many parts. But it works very well. As the mystery is penetrated, the apparent complexity is seen to be a simple recurring pattern. The use of a number of inexpensive and easy to install parts has a much lower installed cost than large power components. Reliability is better too, because of better energy management and distributed stress.

Pushing the limits of the matrix transformer itself has always been easy. Making the rest of the circuit work has occupied most of our efforts. Control circuits will operate at the frequencies of interest, but they will not drive large power components at that speed. By the time sufficient buffering has been added, there is so much propagation delay that the control loop is barely functional. The next generation of PWM control circuits is badly needed. A MOSFET equivalent of the Darlington circuit, with on-chip high speed gate drive circuits is probably necessary to get switching in the nanosecond range at high currents.

The compactness of our bread board layouts are limited by how close together we can mount the power components. Although packages are getting smaller and smaller, we are making our transformers unnecessarily large to accommodate the footprints of the rectifiers and FET's. Significant size reduction will be possible by using hybrid techniques, or modules with direct bonded chips.

High frequency, high power converters will also need better capacitors. The matrix capacitor should be a significant advance.

There is need for more analysis and better theoretical models to form the basis for more systematic design and better prediction of circuit performance and thermal characteristics. This will require the efforts of someone with more analytical horsepower than I possess. This work has begun at the University of Florida under the auspices of Drs. Ngo and Watson. If others are willing to help with this effort, I will be happy to add whatever support that I can.

I am intrigued about a new direction in converter technology, the variable ratio transformer operating at 100% duty cycle and fairly low frequencies. I see the promise of very high efficiency low voltage supplies. At 100% duty cycle, filtering will become much simpler, even at low frequencies. Ratio modulation can be as fast as needed for good control loop response, but the actual transistor switching speeds can be low enough in frequency to allow a return to large bipolar transistors. At 300 amperes, a large NPN can have a saturation drop of 50 millivolts. Even with a base drive, their efficiency as synchronous rectifiers should be better than anything which I am aware of. Lower frequencies will allow the high flux capacity of metal or amorphous metal cores, so the transformers should be reasonably compact.

Edward Herbert

April, 1990

I. Introduction

The Matrix Transformer represents a radical departure from the established methods of designing transformers. They are radical in arrangement and appearance only, as all of the underlying principles are unchanged and familiar.

This section highlights some of the advantages of Matrix Transformers, and shows several application examples.

The Symmetrical Converters are also introduced.

A. Unprecedented Design Flexibility

A Matrix Transformer is made of a number of smaller parts, called "elements" which are interwired in a matrix. If easy rules are followed so that the matrix transformer is "valid", the whole functions as a transformer. For good high frequency characteristics, the elements must be kept close together, but otherwise there is tremendous freedom in their physical placement.

In power supply design, the packaging is often dictated by the shape of the magnetics. The matrix transformer frees the packaging designer from this constraint.

1. Low Profile

By using elements which are of small cross section, very low profile matrix transformers can be assembled which are capable of handling substantial power. 0.25 inch high transformers have been built, and even lower ones would be feasible.

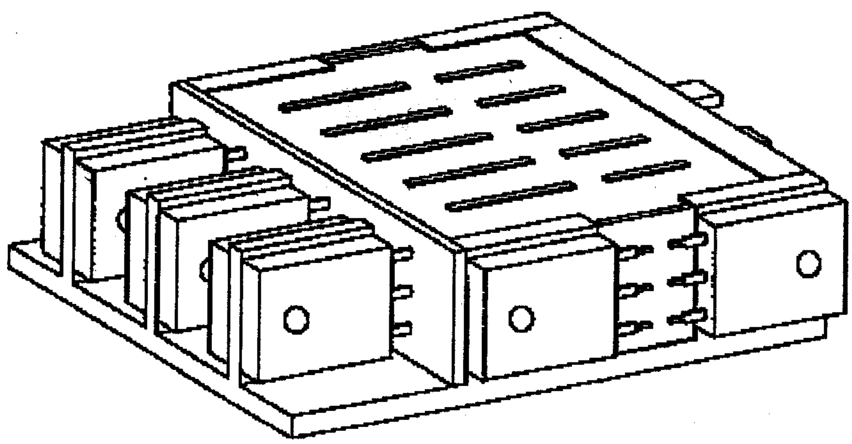


Figure 1.1. This Integrated Power Conversion Module is less than 10 cubic inches (3" x 3.25" x 0.875"), and has an output of 600 Watts at 5.0 Volts DC.

2. Thermal management

Because the matrix transformer is divided into a number of elements, each one being quite small, it is very easy to get heat out. The thermal paths are short, the surface area is very large and it is easy to heat sink. The elements can be spread out to distribute the heat, or they can be packaged very tightly, with an integrated heat sink, for high power density.

3. Shock and Vibration

Each of the elements has small mass and can be very rugged. The mass is distributed and the elements can be arranged for optimum support. The assembly as a whole is very resistant to damage due to flexing.

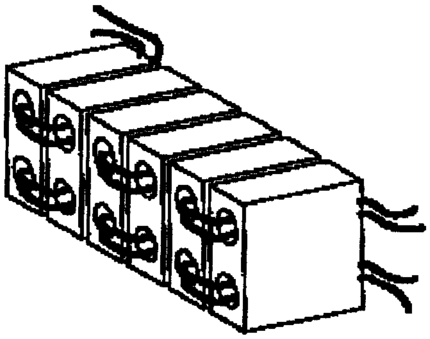


Figure 1.2. Wind the Matrix Transformer primary on six cores. Use a fixture to maintain correct spacing. Ordinary TFE hook up wire is used.

4. Superior Electrical Characteristics

Matrix transformers tend to have a single turn primary and a number of paralleled single turn secondaries. Each element has a small number of wires, and they are very tightly coupled. Proximity effects are largely eliminated, and flux and current densities can be very high without undue losses.

B. The Integrated Power Conversion Module

Figure 1.1 shows an Integrated Power Conversion Module, comprising a matrix transformer and a matrix inductor which are mounted in a common heat sink structure. The heat sink also has mounting provisions and terminals for the semiconductors which interface directly with the transformer. The best high frequency transformer would be ruined if it is interwired into the circuit incorrectly. In the Integrated Power Conversion Module, the interconnections are optimized.

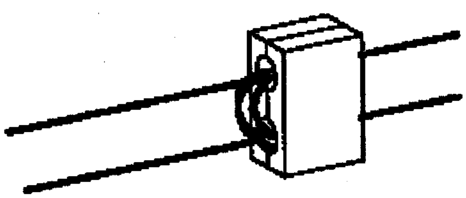


Figure 1.3. Make six small inductors. The leads will become the secondary windings of the Matrix Transformer. Use ordinary TFE hook up wire for the windings.

Figure 1.2 shows the first step, winding the primary of the transformer section. Ordinary TFE hook up wire can be used. The cores should be held in a fixture, and the wire is threaded through.

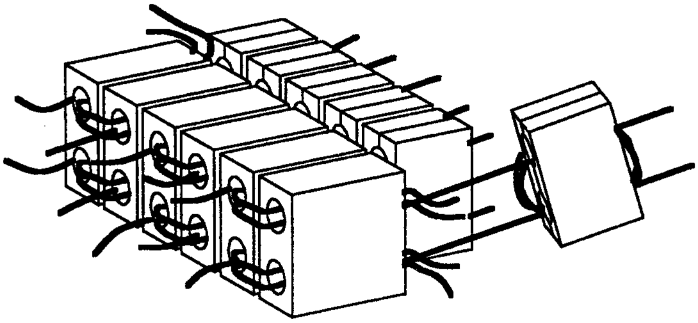


Figure 1.4. Slip the inductor leads through the Matrix Transformer cores. There are ways to make it very easy. The transformer and inductor are now completed.

Six small inductors are wound, as shown in Figure 1.3. The core halves can be cemented together, either with a spacer for the gap, or a gapped center leg. Again, TFE hook up wire can be used. The leads will become the transformer secondary windings.

Figure 1.4 shows how the inductor leads are slipped through the transformer cores. This is very easy with proper fixturing.

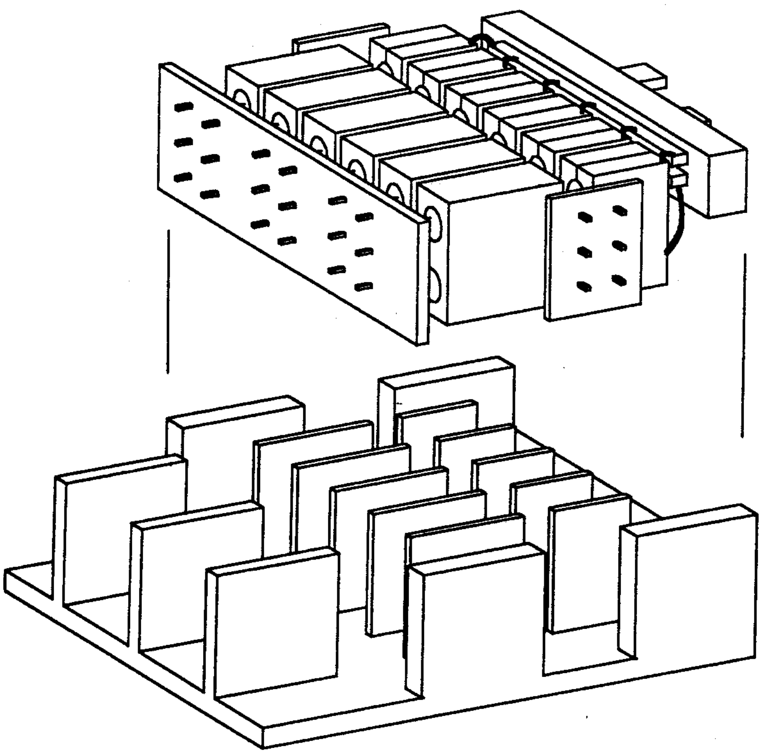


Figure 1.5. The terminal boards and output terminal block are installed using a fixture. Drop into the base casting, and fill with potting if desired.

Using a jig to hold the parts, install the terminal boards and output connector as shown in Figure 1.5. The transformer and inductor are functional now, and can be tested. The assembly is dropped into the base casting. It can be filled with potting if desired.

This might be the final step for a transformer manufacturer. The user would add the switching FET's and Schottky rectifiers, the output capacitors and a controller/driver circuit. The result is a highly optimized, very compact power converter.

This module was designed to accept semi-conductors in the TO-3P plastic package, although the concept could be adapted to other devices, including similarly shaped hermetic packages. A wide variety of devices are available in the TO-3P package, and they are good value.

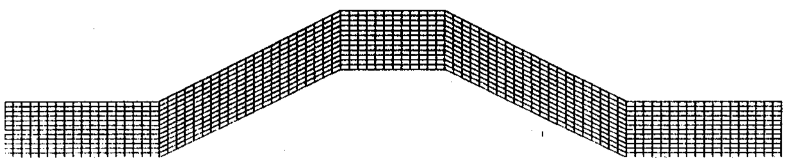


Figure 1.6. The first step in making a Matrix Transformer Module is to stamp out come copper blanks, about 0.010" thick and 0.20" wide. They should be annealed dead soft.

C. The Matrix Transformer Module

The matrix transformer module was developed to simplify assembly by eliminating hand operations in the secondary interconnections. The module comprises one or more core with the secondary conductors already installed and terminated. Through holes are provided for an undedicated primary winding to be added later.

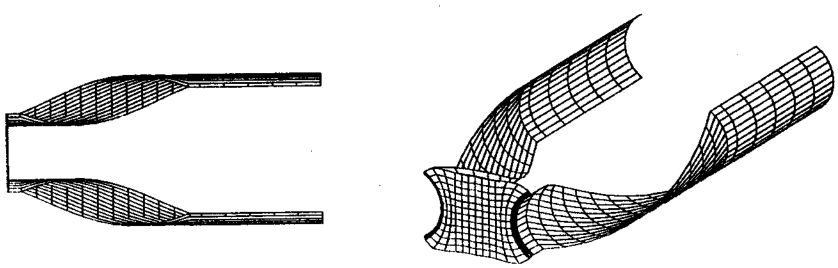


Figure 1.7. The copper pieces are formed into a "U" shaped double 180o helix which will conform to the bores of the core.

The matrix transformer module can be packaged with an inductor in one module, with through holes in the transformer section for an undedicated primary to be added later. On one end, terminals are provided which accept a rectifier package. The entire secondary circuit including the output filter inductor is pre-assembled and self contained within the module.

1. How a Matrix Transformer Module is made.

The first steps in making the matrix transformer module are to stamp out and form some copper strips. Figure 1.6 shows a flat copper stamping about 0.010" thick and about 0.20" wide. This is formed into a "U" shaped double helix which will conform to the bore of the core. Each leg twists through 180o, as shown in figure 1.7.

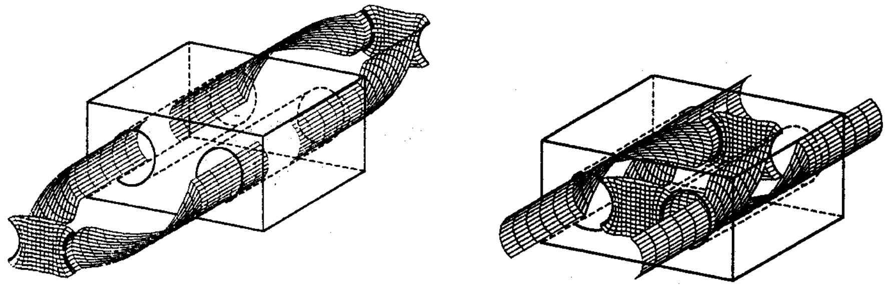


Figure 1.8. Two of the formed copper pieces are slipped into each core, one from each side. The core and/or the inserts must be insulated.

Two of the formed parts are passed through a core, one from each side, as shown in figure 1.8. The core must be insulated from the conductor. If the core material does not have a very high resistance, it, and/or the formed copper insert must be insulated. Once the formed parts are in place, they are restrained so that they cannot touch each other.

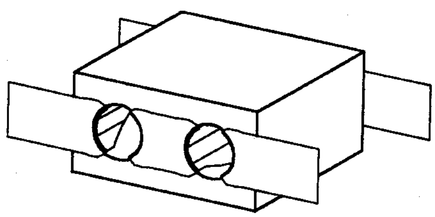


Figure 1.9. Once in place, the ends of the copper pieces are flattened against the faces of the core. Once in place, the inserts are trapped, and cannot touch each other. For some applications, they could be bonded in place, or an insulating sleeve could be cemented into the bore as additional insulation and a retainer.

Once in place, the protruding ends of the copper pieces are bent back and flattened against the faces of the core on each side, as shown in figure 1.9. At this point the metal parts are trapped in place, but for some applications it might be desirable to bond them. A plastic sleeve can be inserted to provice additional insulation and to help retain the inserts.

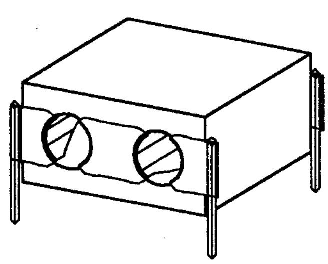


Figure 1.10. Pins can be added to the Matrix Transformer Module, for insertion into a printed wiring board.

2. Plug-in Module for Printed Circuit Board Assembly

Figure 1.10 shows a matrix transformer module with pins for mounting in a printed circuit board. The modules are mounted in a row, close together, with their through holes aligned. Once in place, tubing is slipped through the aligned holes, then the primary winding is passed through and terminated in the board, as shown in figure 1.11.

The entire transformer can be pre-assembled if care is taken to assure pin alignment, as by fixturing it or using a carrier.

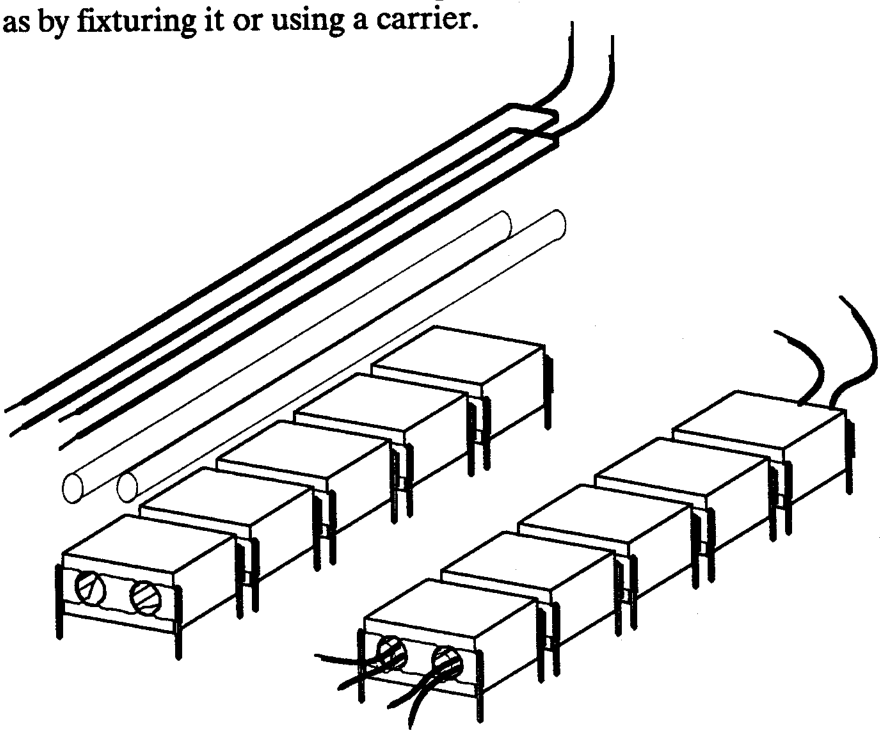


Figure 1.11. A row of Matrix Transformer Modules can be inserted in a printed circuit board, with their through holes aligned. A sleeve is slipped through the aligned holes, and the primary winding is installed. The DC input power goes on one end, the switching FET's on the other.

3. High Current Capability

The conductors formed as described above are substantial, and will carry a large current, yet take up very little space in the bore of the core. The current capability of the circuit will probably be determined by the semi-conductors. If good T0-3P dual Schottky rectifiers are used, one for each module, 100 watts per module (5.0 VDC output) is a conservative rating.

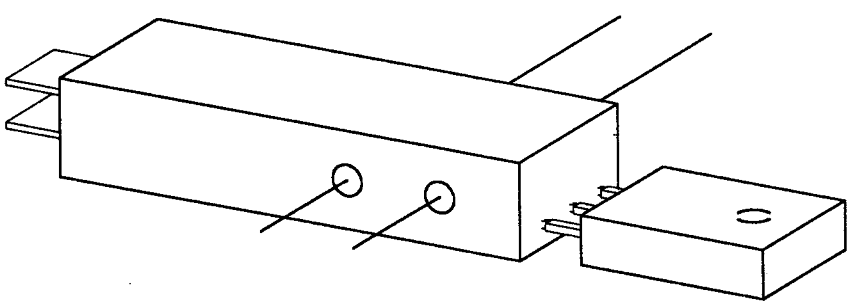


Figure 1.12. This Matrix Transformer Module contains an inductor as well as the transformer module. It is potted, with the through holes kept clear for an undedicated primary. The terminals on one end accept a T03-P dual Schottky rectifier. The output is on the other end.

4. Transformer-Inductor Module

Figure 1.12 shows a module which contains a matrix transformer module, as described above, and an inductor. Terminals on one end are designed to accept the leads of a T0-3P dual Schottky rectifier, and the 5.0 VDC output terminals are on the other end. The entire secondary circuit is contained within the module, and through holes are left for an undedicated primary winding to be added later.

As shown in figure 1.13, the transformer-inductor modules are mounted in a row, close together with their through holes aligned. The primary winding is slipped through and terminated, with the input power at one end and the switching FET's at the other. One T0-3P dual Schottky rectifier is used with each module, mounted right next to it and soldered into the terminals provided on the module.

Output filter capacitors are added to the outputs, and they are bussed together. Each module can conservatively handle 100 watts at 5.0 VDC output.

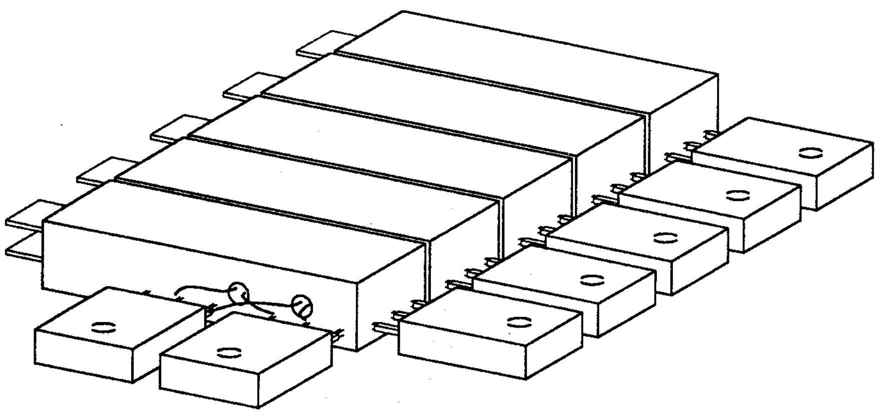


Figure 1.13. The transformer-inductor Matrix Transformer Modules are mounted in a row with their through holes aligned. The primary winding is installed. The power is applied at one end, and the switching FET's are at the other. A T0-3P dual Schottky rectifier mates with each module. Output filter capacitors are added, and the output terminals are bussed together. The power that each module can handle is limited only by the rectifier. 100 watts per module is a conservative rating.

5. Scale for Different Applications

The modules shown above were designed for optimal lead location and mounting when used with the T0-3P dual Schottky rectifier, which can mount side by side, each occupying just over 5/8". They could be scaled up or down to be compatible with other packages. For use with T0-220 rectifiers, the modules could be smaller, and conservatively deliver 50 watts each at 5.0 VDC.

D. Picture Frame Matrix Transformers

An interesting embodiment of the matrix transformer is the "picture frame" matrix transformer, in which the elements are placed end to end in a closed pattern. Figure 1.14 shows an actual size picture frame matrix transformer having a 14 to 1 step down ratio and a power output capability of 400 amperes (2000 watts) at 5.0 VDC.

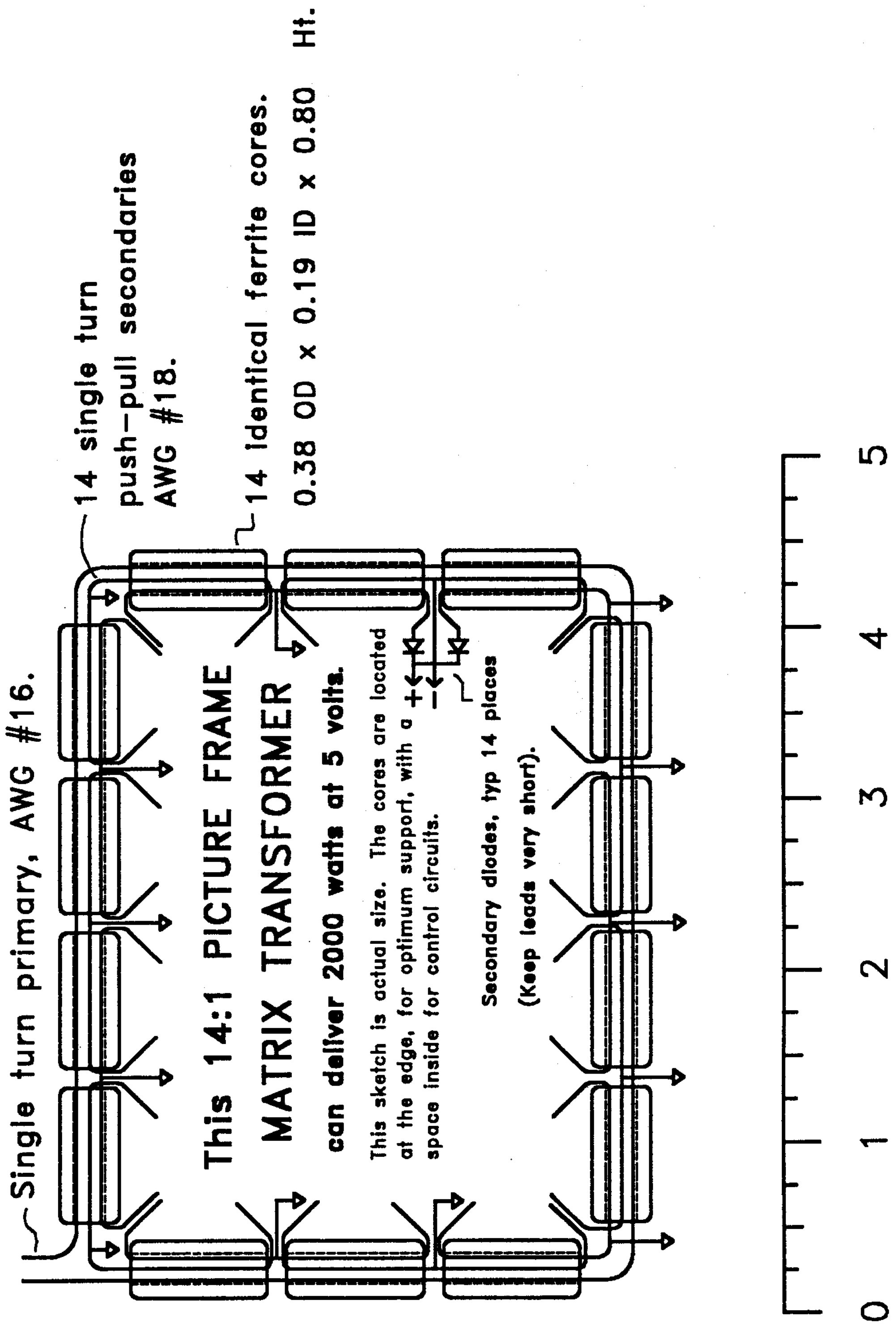


Figure 10.14. A breadboard converter was built using this arrangement of the elements and the secondary windings, but with a dual symmetrical push pull primary winding. A separate small output inductor was used with each rectifier. The rectifiers were placed around the outside edge, the inductors were on the other side of the heat sink, and the space in the center was used for the power FET's and control circuit.

1. Layout is Flexible

The rectangular layout as shown gave the picture frame matrix transformer its name, and it is ideal for many situations. The transformer can mount around the periphery of a circuit, where support and heat sinking are best, with space in the middle for the control and housekeeping circuits. The power semi-conductors can be mounted around the outside edge. With the heat sources distributed, about one third less heat sinking can be used for the same junction temperature rise.

There is no constraint on the layout of the elements of a picture frame matrix transformer as long as they are placed end for end in a closed pattern. The pattern can be circular, across the bottom an up a sidewall, in a rosette, scrunched up for high power density or spread out for better heat distribution or whatever fits in the space available.

The rectifier and FET size and placement is often the prime determining factor in sizing and locating the elements of a picture frame matrix transformer. With hybrid circuit packaging techniques, very compact power converters should be practical.

E. Symmetrical Converters with Floating Capacitors

The invention of the symmetrical push pull transformer was an evolutionary step from the high frequency matrix transformer, which in turn was a series of evolutionary steps from the matrix transformer. This process took a number of months.

1. Eureka!

The discovery of "floating capacitors" was much more exciting. We thought we were on the track of an improved snubber, but in the matter of a few short hours, we had cut the losses in a breadboard in half, and had doubled its output current capability. See figure 1.15. We knew we were on to something big.

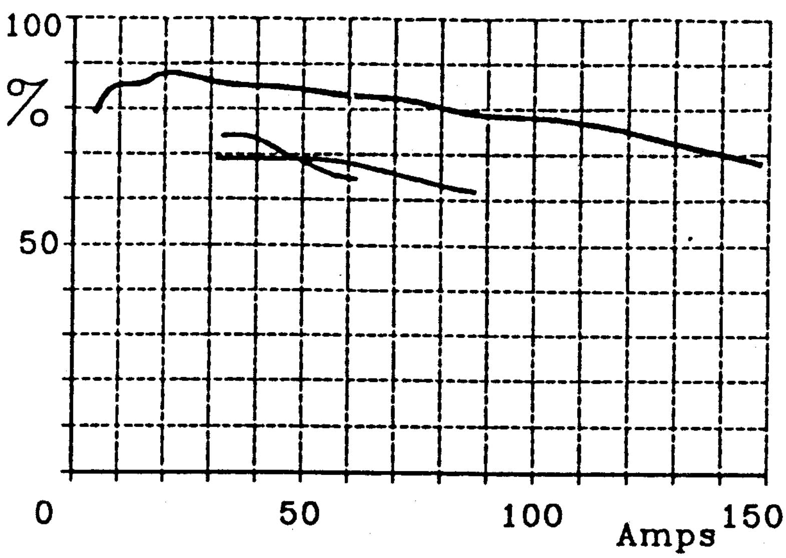


Figure 1.15. When "floating capacitors" were added to a symmetrical push pull converter breadboard, losses were cut in half, as shown by the top curve compared to the other two curves. The lower curves were the best that we could do with conventional snubbers.

We were even more surprised when we found that the breadboard had near-zero input current ripple, without any input filter, as seen in figure 1.16. It then took several months to figure out how it worked!

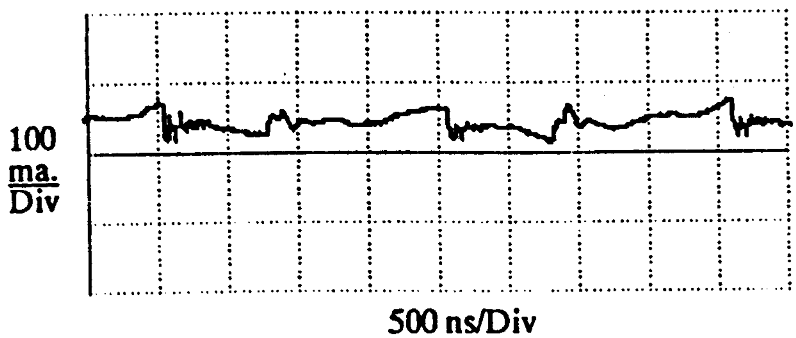


Figure 1.16. The input ripple current was nearly zero in a bread board symmetrical converter with floating capacitors. The DC average current was about nine amperes. There was no input filter on the breadboard other than the stray inductance of the power supply leads.

2. Symmetrical Winding

The "symmetrical" push pull winding is shown in figure 1.17 as it might be applied to a transformer coupled buck-derived PWM converter. Each half of the push-pull winding is divided at its midpoint for the FET switches (or rectifiers, in the secondary). The DC power and return are brought directly to the transformer windings.

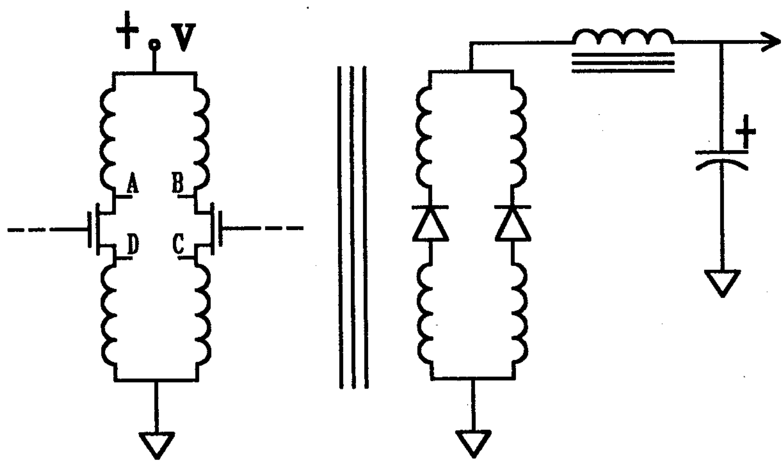
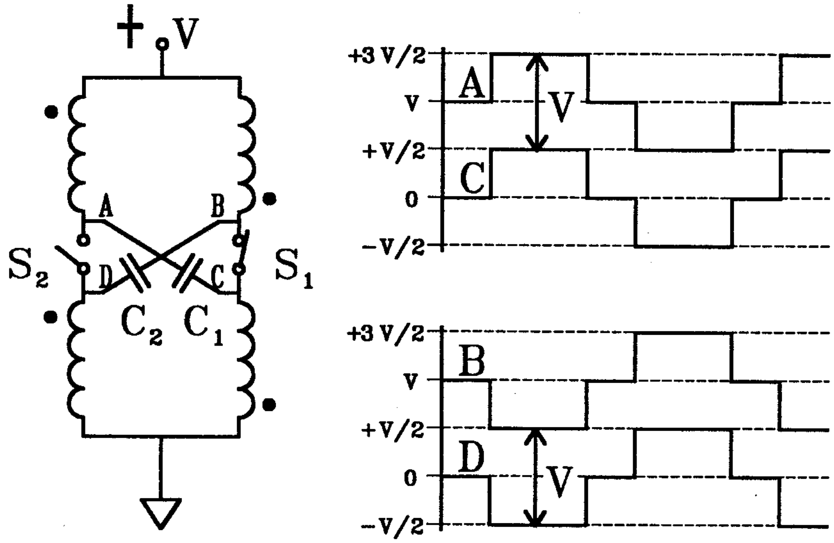


Figure 1.17. In the "symmetrical" push-pull transformer, the switches are at the mid-point of each half of the windings.

3. Floating Capacitors

Figure 1.18 shows the voltage wave forms that are present in the primary of a transformer having symmetrical windings when used as a PWM converter. The voltage on nodes A and B vary plus and minus one half the input voltage with respect to V, the input voltage. The voltage on nodes C and D also vary plus and minus one half the input voltage, but with respect to the return.



"**Figure 1.18.** "Floating capacitors" can be added as shown, because the voltage is constant from node A to C, and from node B to D.

The voltages on nodes A and C can be seen to be of similar wave shape, offset by V. The voltage difference between nodes A and C is constant, and equal to the input voltage V. The voltages on nodes B and D have the same relationship, 180° out of phase. Because there is no voltage component at the switching frequency present across these nodes, we thought that they would be ideal points for placing snubbers. The rationale was that there would be no losses at the switching frequency.

Snubbers did work well at these points, but as we optimized the snubbers with an eye on the input current, we soon discovered that the circuit efficiency was improved substantially if the capacitors were quite large, and the resistors were zero! With no resistors, they obviously were not acting as snubbers in the usual sense.

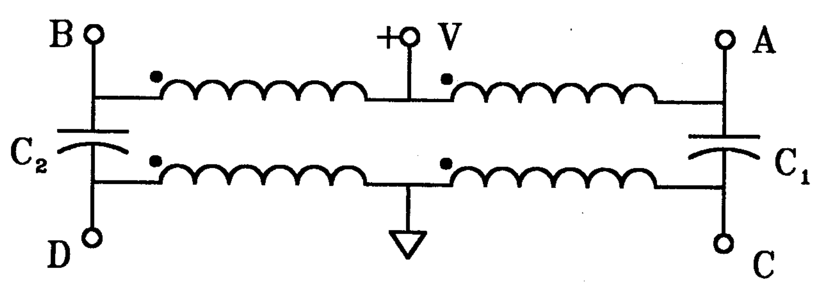


Figure 1.19. A symmetrical push-pull winding with floating capacitors as it would be implemented in a conventional transformer. The winding should be bifilar.

4. Conventional Transformer

Figure 1.19 shows how a symmetrical push pull winding with floating capacitors would be implemented in a conventional transformer. The winding would start as two bifilar windings with terminals B and D. They would be center tapped to provide terminals for the power and ground, and continue bifilar to terminals A and C. The floating capacitors would be installed between terminals A and C, and between terminals B and D, as shown. The push-pull switches would connect terminals A to D and B to C, respectively. All of the leads should be as short as possible. It would be preferred to install the capacitors on the switch terminals.

5. Matrix Transformer

The matrix transformer configuration of the symmetrical converter is shown in figure 1.20. In this case, the matrix transformer consists of five elements, with two cores in each, shown as tall, slender toroids. The matrix transformer has five parallel secondary sections, one of which is shown. Each secondary can have its own filter inductor and capacitor, with the outputs being paralleled.

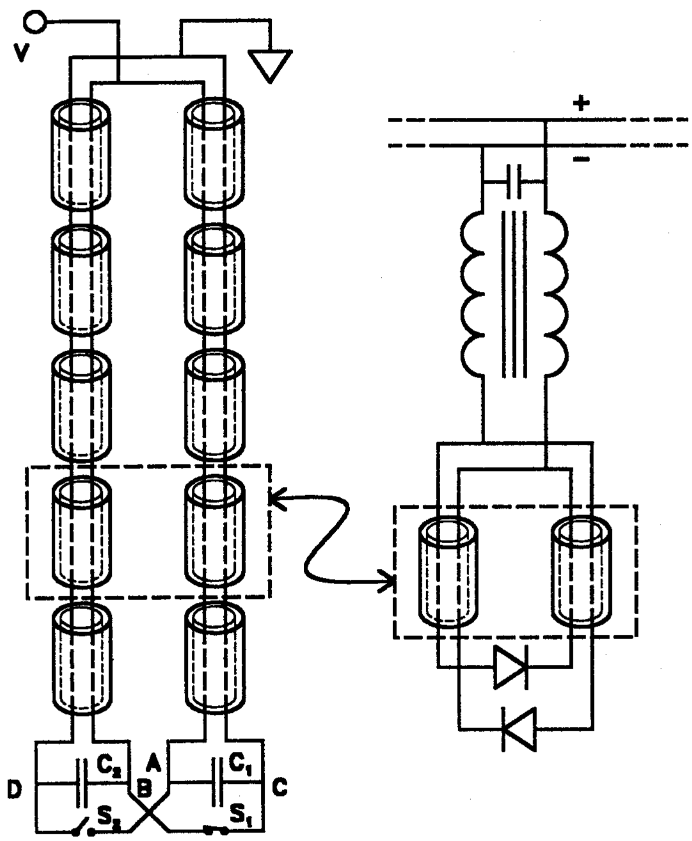


Figure 1.20. A symmetrical push-pull primary with floating capacitors in a matrix transformer is shown with one possible secondary configuration. The power and ground can be at the opposite end of the transformer from the switching FET's.

Note that in both the primary and the secondary the semiconductors are at the opposite end of the transformer from the power terminals, and that the windings are very simple. The primary is just two "U" shaped wires, center tapped for the power and ground. The floating capacitors are across each pair at the end of the core string through which they pass.

5. Through the Bore Gate Drive

The voltage wave forms of Figure 1.18 would suggest that isolated gate drive circuits would be necessary to accommodate the large changes in source voltage. Isolated gate drives are effective, and have been used in a number of breadboards, but there is another method which works very well, as shown in Figure 1.21. If another wire is installed through the matrix transformer parallel to the wire which connects to the

 Revision: 13 April, 1990

source, the FET's can be driven from the input terminal end of the transformer. All of the voltages induced in the two wires are common mode, so the gate drive signal is preserved. There is a significant impedance in the wire, and it is a good idea to add some noise immunity, so the preferred arrangement has a buffer driver at the gate. If necessary, Vcc for the buffer can be taken through the bore too.

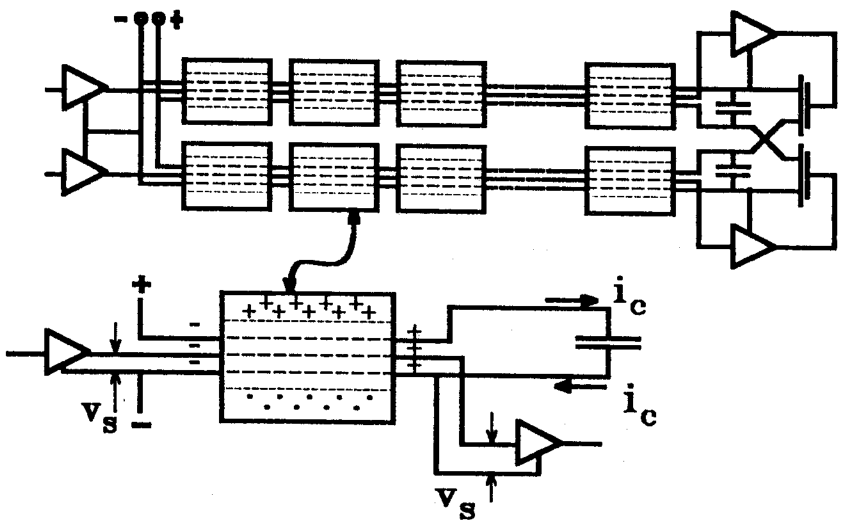


Figure 1.21. The gates of the switching FET's can be driven "through the bore". All of the induced voltages are common mode, so the drive signal is preserved.

7. The Switching FET's are Decoupled from the Trnasformer Leakage Inductance

The dramatic improvement in efficiency seen in the symmetrical converter with floating capacitors is attributed to the leakage inductance of the transformer windings being decoupled from the transistors by the floating capacitors. The consequence of this is that the FET's can be switched off just as fast as the charge can be removed from their gates, without significant Ldi/dt voltage spikes. Once the switch opens (FET turns off), the voltage in the transformer reverses, but is clamped at two times the input voltage. Current continues to flow in the winding, returning energy to the capacitors.

Since the transistors can be turned off very fast, in the order of ten nanoseconds or less, cross over power losses are just about eliminated.

The very low input current ripple, in the absence of an input filter, suggests that the floating capacitors behave as input filter capacitors even thought they are at the opposite end of the transformer. The charging path from the input terminals has a low DC impedance, and enough inductance to function as an equivalent LC input filter.

Another interesting characteristic of the symmetrical converter with floating capacitors is that during the on time current flow occurs in both halves of the push-pull winding during both halves of the push-pull cycle. This provides better utilization of the winding.

An analysis of current flow and leakage inductance is beyond the scope of this introduction, but will be found in the later chapters.

F. Versatility: the Promise of Things to Come

One of the most difficult questions to answer about the matrix transformer is "What's it good for?" A question like that is often asked by someone who has already decided that it isn't good for anything. It's too strange.

As you begin describing the versatility of the matrix transformer, and relate how well it has worked in various bread boards, you suddenly become aware that you sound like a snake oil salesman. It can't possibly do all those things and do them so well. Yet it does. Development is in its infancy. There is so much left to discover.

1. Building Blocks

Designing with a matrix transformer can be likened to building a structure with bricks, instead of carving it out of one big block. Lots of bricks that are all the same can be arranged in a variety of ways to make a variety of structures. Different kinds of bricks can be used for special problems, to meet special requirements. Many problems can be solved by attention to the small parts, the bricks, and the benefit will carry to the whole.

2. Inexpensive

It would be hard to imagine a less expensive transformer, both in material and in labor than the matrix transformer made by plugging in modules and adding a primary. Yet its performance is very good.

3. Exotic

Solving the thermal problems and leakage inductance problems has already allowed some very compact bread boards to be built that have very good performance. There is every reason to believe that the technology can be extended up and down, to very high power transformers and miniature ones, even in hybrid circuits.

a) High Power.

We have not had the facilities to build and test large transformers, but as we have built larger units, to 2000 watts, the performance of the transformer has never been a problem. The problems have been in mounting enough silicon closely enough, and switching it fast enough to take advantage of what the transformer can do.

b) High Frequency

With a monolithic transformer, as frequency is increased, a point is reached where flux derating becomes so dominate that it is impossible to achieve any more size reduction. The core geometries used in the matrix transformer have lower losses, and it is possible to get the heat out. With use of miniature, slender, high quality cores and hybrid circuit techniques, very high powers should be achievable at very high frequencies in very small packages.

II. General Theory of Matrix Transformers ‡

Matrix Transformer: a transformer comprising an array, or matrix of transformer elements, interwired so that the whole functions as a transformer.

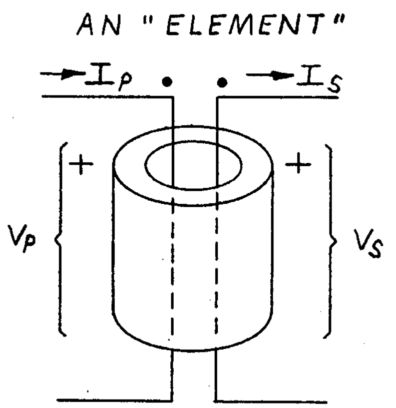
This section defines the element, and builds upon the element to develop fundamental concepts, using several examples of matrix transformers, including binary matrix transformers.

Generalized transformers of indefinite dimensions are introduced. The generalized form provides the basis for expansion or specialization of the transformer for various applications, and for a better understanding of the basic design parameters.

A. "Elements"

The basic building block of the matrix transformer is the "element". An element is defined as *the smallest elemental part of a matrix transformer which has the characteristics of a transformer, for analytical purposes.*

In a matrix transformer, a number of "elements" are interwired, according to simple rules, in such a way that the whole network of elements behaves as a transformer.



$V_P = V_S$
$I_P = I_S$
RATIO 1:1

Figure 2.1. An element consisting of one core, a single turn primary and a single turn secondary.

The "element" truly is a small transformer, and all of the principles of transformer design are applicable. In matrix transformers for high frequency power conversion, the elements tend to be simple, with a small core or two, and a small number of windings. However, in the general theory of matrix transformers, there is no such limitation. The element itself could be quite large and complex, and could even be a matrix transformer.

An element may have more than one core, for instance, a stack of small toroids. Usually an element can be recognized as an element by its function in the matrix transformer. If wires pass through a series of cores, all in

‡ U.S. Patent 4,665,357; other patents pending. FMTT, Inc.

parallel, they are probably in the same element. If wires leave the transformer, or branch in different directions, that point is probably the boundary of an element.

It may not always be immediately obvious what the elements of a matrix transformer are. Often all of the elements in a matrix transformer will be identical discrete cores, or, if not identical, the variation between them will be systematic and easy to see. Keep in mind, however, that the use of "elements" is an analytical tool, not an end in itself. If, as an analysis proceeds, the originally defined elements do not make sense, they can be redefined.

B. Two Element Matrix Transformers

Figure 2.2 shows two "elements" forming a matrix transformer having a ratio of 2:1. The primary is a single wire passing through both elements in series. The secondary has two wires, each passing through one of the elements. The wires are taken in parallel, being careful to observe polarity (phasing).

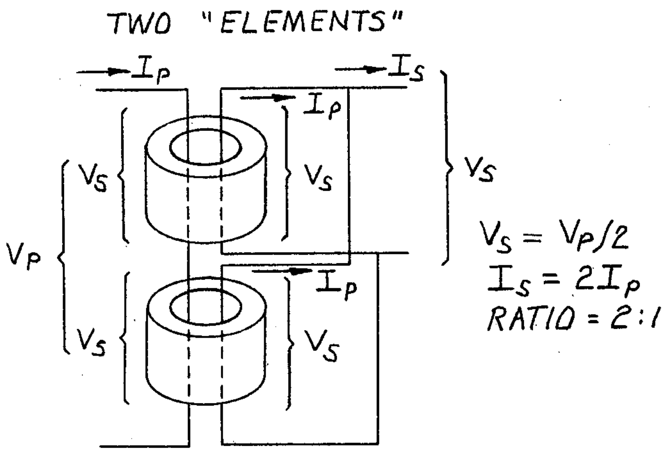


Figure 2.2. A two element matrix transformer.

C. Two Laws and Two Rules

Referring to figure 2.2, we will make some rather obvious observations. The primary wire passes through the two elements in series. Therefore the primary current is the same in the two elements. The secondary has two wires which are in parallel. Therefore the secondary voltage is the same in both elements.

Faraday's law tells us that the voltage per turn is the same for all windings coupled by the core flux. Therefor the voltage drop in the primary of each element is the same as the secondary voltage (neglecting voltage drops in the winding impedances). There being two elements, the primary voltage is twice the secondary voltage.

$$V_p = 2\,V_s$$

$$V_s = V_p/2$$

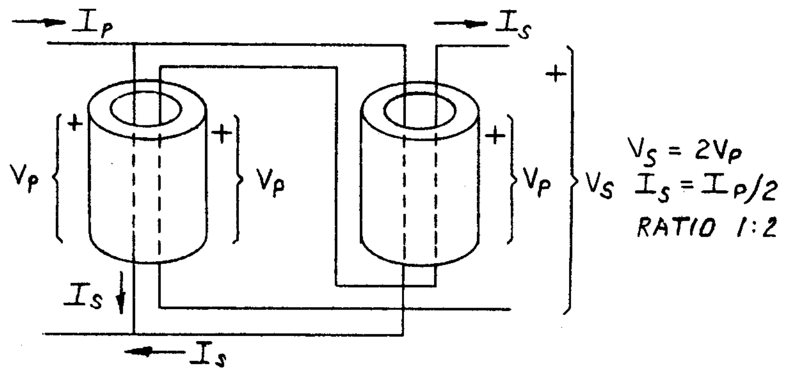


Figure 2.3. Another two element matrix transformer.

Lenz's law tells us that the net ampere turns in any transformer is zero (neglecting magnetization current). Therefore the secondary current in each secondary is equal to the primary current. There being two secondary windings in parallel, each coupling with the primary current, the secondary output current is twice the primary current.

$$I_s = 2\,I_p$$

Either relationship determines that the transformer shown in figure 2.2 has a ratio of 2:1.

Figure 2.3 shows a matrix transformer, also having two elements, and having a ratio of 1:2.

There are a number of things to consider in designing matrix transformers. First of all, it must be determined whether a proposed arrangement of the elements is a *valid* matrix transformer. The tests for validity are as follows:

Law 1: *(Paraphrasing Lenz's law).* In each element, the sum of the ampere-turns is zero.

Law 2: *(Paraphrasing Faraday's law).* In each element, the volts per turn is the same in every winding.

Rule 1: The current is equal in all parts of each series circuit.

Rule 2: The voltage is equal across all circuits which are in parallel.

D. Matrix Transformers Developed

The two dimensional matrix transformer is derived by placing elements in an array having dimensions M and N. The primary will have N columns in parallel with M elements in series. The secondary will have M rows in parallel with N elements in series.

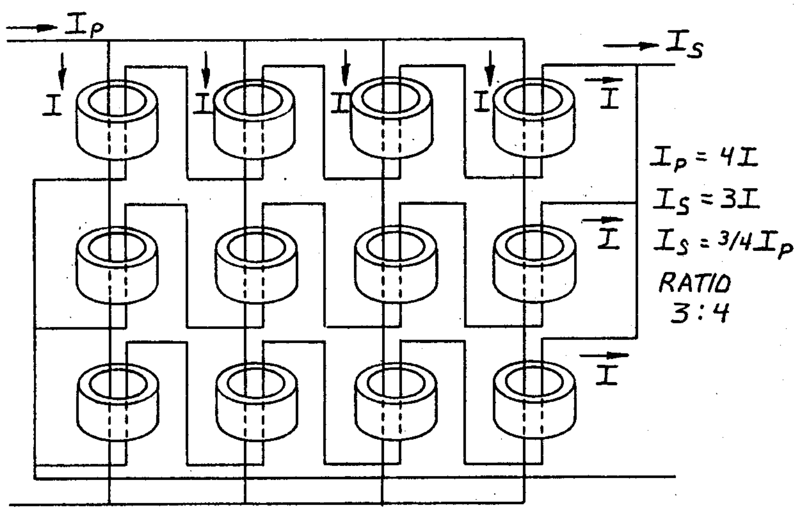


Figure 2.4. The current relationships in a 3 x 4 matrix transformer.

1. The 3 x 4 Matrix Transformer

Figures 2.4 and 2.5 both show the same 3 x 4 matrix transformer in pictorial representation, the first showing the currents , and the other showing the voltages. The primary has four parallel paths (columns) each passing through three elements. The secondary has three parallel paths (rows), each passing through four elements. In this matrix transformer, all of the elements are the same.

Figure 2.4 shows the current relationships between the windings in the 3 x 4 matrix transformer. In the first column, current I_{p1} passes through the elements of the first column, and couples with the secondary currents I_{s1}, I_{s2} and I_{s3} in the respective elements. By Lenz's law the currents in each of the elements must be equal, so:

$$I_{p1} = I_{s1} = I_{s2} = I_{s3}$$

In the first row, current I_{s1} passes through the elements of the first row, and couples with the primary currents I_{p1}, I_{p2}, I_{p3} and I_{p4}. By Lenz's law the currents in each of the elements must be equal, so:

$$I_{s1} = I_{p1} = I_{p2} = I_{p3} = I_{p4}$$

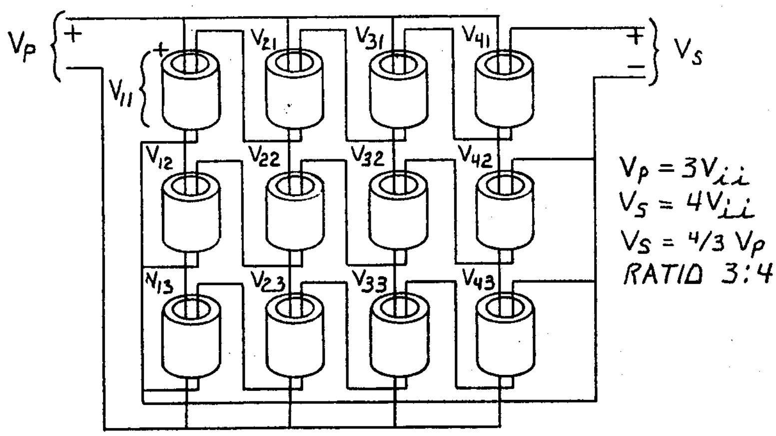


Figure 2.5. The voltage relationships in a 3 x 4 matrix transformer.

It is thus seen that all of the currents I_{pm}, I_{sn} are equal. The primary is sourced through four identical currents, and the secondary sources three identical currents. Thus the secondary current is 3/4 of the primary current:

$$I_s = (3/4)I_p$$

Figure 2.5 shows the voltage relationships in the windings of the 3 x 4 matrix transformer. The four windings of the primary pass through three elements and the three windings of the secondary pass through four elements. Each element "sees" one third of the primary potential, and one fourth of the secondary potential. According to Faraday's law, the potential in each winding of each element is equal (they are all one turn each), so the secondary voltage is four thirds the primary voltage:

$$V_s = (4/3)V_p$$

Either the voltage or the current relationship establishes that the ratio of the 3 x 4 matrix transformer is 3:4.

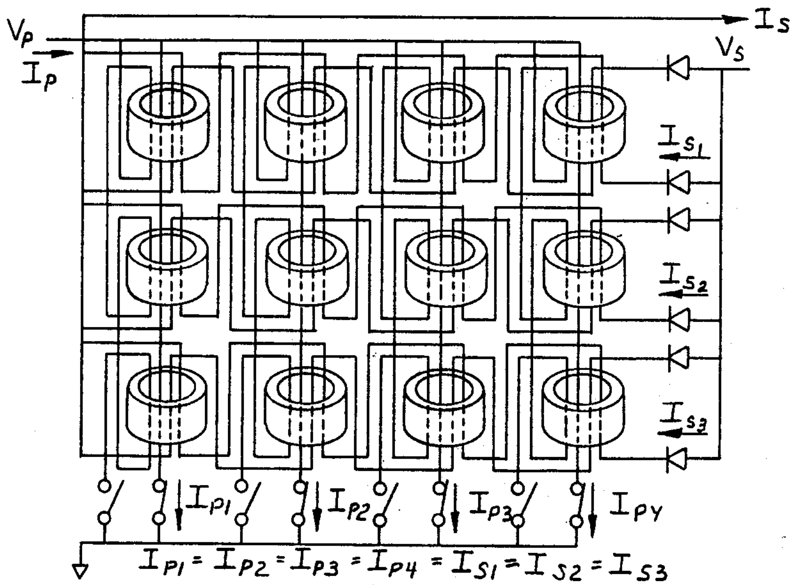


Figure 2.6. An orthogonal matrix transformer with push pull windings.

<u>2. *Orthogonal Matrix Transformer*</u>

In the above example, all of the currents I_{pm}, I_{sn} are equal. This is true of matrix transformers whose windings cross at right angles, such that every path in the primary crosses every path of the secondary at least once. Such a matrix transformer is called an *orthogonal matrix transformer.*

Because all of the currents are equal, there are some advantages which can be exploited by the circuit designer. One is that all of the windings can use the same size wire. Another is that the individual outputs can be rectified, then paralleled at the rectifiers' outputs. Since all of the currents are equal, the rectifiers will share the current equally, with no additional ballasting circuits.

It is also easy to parallel transistor switches in the primary. Since all of the currents are equal, the primary switches will share current equally, with no gimmickry required.

Figure 2.6 shows a 3 x 4 matrix transformer having push pull windings on both the primary and the secondary. The windings cross at right angles, so the matrix transformer is orthogonal. The currents in the secondary rectifiers will balance, as will the currents in the primary switches.

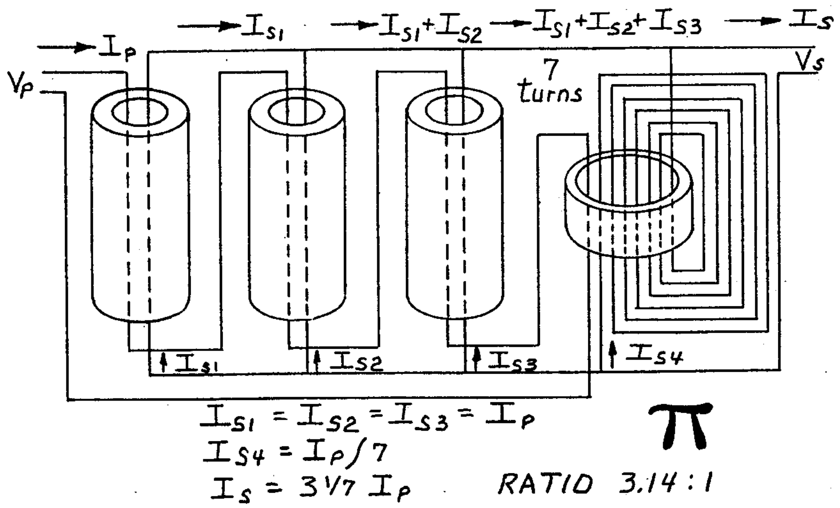


Figure 2.7. A matrix transformer having a ratio 3.14:1.

3. Non-integer Ratio Matrix Transformer ‡

Figure 2.7 shows a matrix transformer having a ratio of π (3.14:1). A primary winding makes a single series pass through four elements. The secondary has four parallel paths, three of which also make a single pass through one element. By Lenz's law, the secondary current of these three elements equals the primary current.

In the fourth element, the secondary has seven turns. Again, by Lenz's law, the net ampere-turns must be zero, so the secondary having seven turns, it must have one seventh of the primary current. Adding the contributions of the four parallel secondary windings gives a total of three and one seventh times the primary current, or:

$$I_s = 3.14 I_p$$

Note that the fourth core will have one seventh the voltage per turn of the others, so its cross sectional area can be smaller (one seventh).

This is a rather far fetched example, but it does meet all of the validity criteria. If the secondary of the fourth element had two windings, a 3.5:1 transformer would result. This might be a more practical application, and would, for instance, be a way of not having to the use a 7 x 2 matrix transformer or a monolithic transformer with a seven turn primary and a two turn secondary.

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‡ U.S. Patent pending. FMTT, Inc.

4. Binary Matrix Transformers

In a matrix transformer, the windings of the elements can have a binary progression in one or both of the dimensions. That is, for example, the primary of the elements of rows 1, 2, 3, 4, ··· can have 1, 2, 4, 8, ··· turns, respectively, on each element in the row.

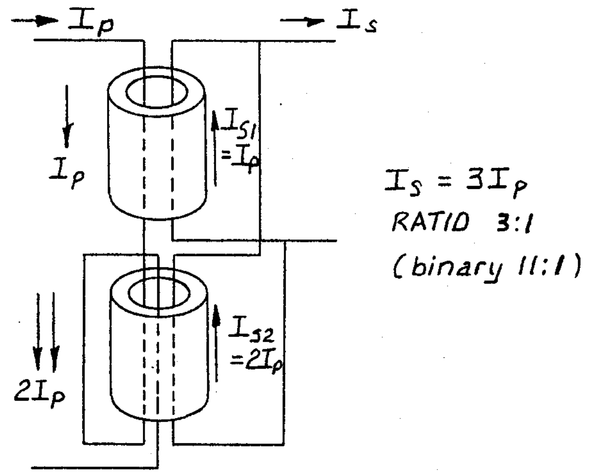


Figure 2.8. The current relationships in a simple binary matrix transformer.

The binary matrix transformer can be used for ratios that can be expressed more simply as the ratio of binary numbers. They are also particularly useful for variable ratio matrix transformers.

Figure 2.8 shows a simple two element binary matrix transformer. The primary winding makes a binary progression from row 1 to row 2 (2^0, 2^1). The secondary has a single turn in each row. Since the primary current passes through the first element once, the secondary current in the first element equals the primary current. However, the primary current passes through the second element twice, so the secondary current in the second element is two times the primary current. Therefor $I_s = 3I_p$, and the ratio is 3:1, or expressed in binary, 11:1. Figure 2.9 shows the voltage relationships in the same transformer.

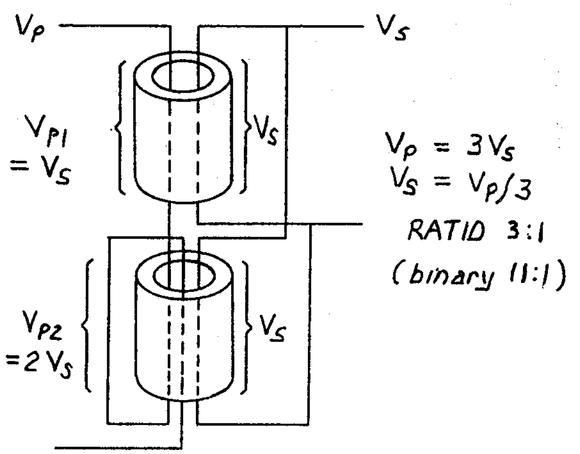


Figure 2.9. The voltage relationships in a simple binary matrix transformer.

a) The 2 x 3 Binary Matrix Transformer

Extending the binary matrix transformer to larger dimensions is straight forward.

Figure 2.10 shows the current relationships in a 2 x 3 binary matrix transformer. In the first column it can be seen that I_{s1} equals I_{p1} and I_{s2} equals two times I_{p1}. In every column the primary of row 2 has twice the turns of the primary of row 1, so the two to one relationship of I_{s2} to I_{s1} holds throughout. (This is one of the tests of matrix transformer validity).

Comparing the elements of row 1 in columns 1, 2 and 3 show that the primary currents I_{p1}, I_{p2}, and I_{p3} are 1, 2 and 4 times the secondary current I_{s1}, respectively. In the second row, the primary of each element has two turns, but I_{s2} is known to be twice I_{s1}, so again the primary currents I_{p1}, I_{p2} and I_{p3} are 1, 2, and 4 times the secondary current I_{s1}.

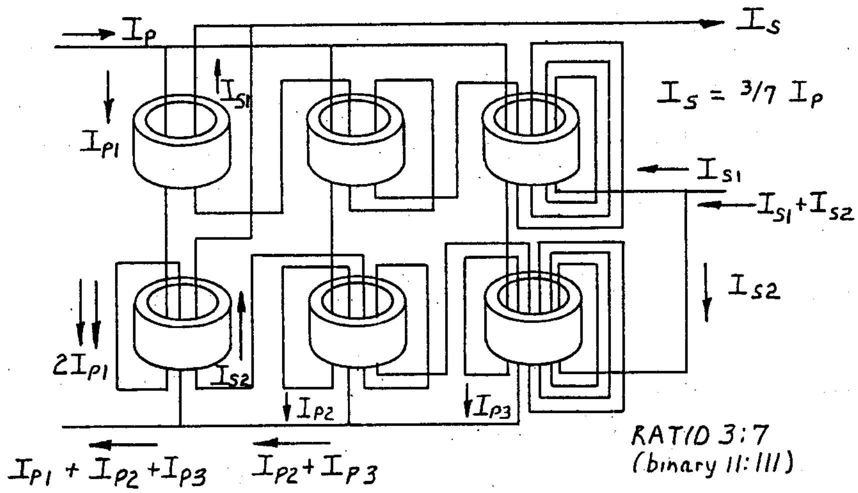


Figure 2.10. The current relationships in the windings of a binary matrix transformer.

Using $I_{s1} = I_{p1}$ in element 1,1 as the common denominator, it can be seen that the primary current is 7 times I_{s1}, and the secondary current is 3 times I_{p1}, so the ratio is 3:7. Expressed as a binary, this is 11:111.

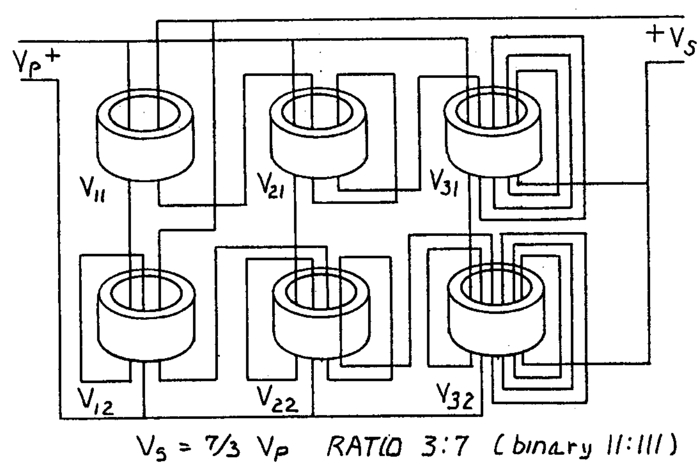


Figure 2.11. The voltage relationships in the windings of a binary matrix transformer.

Figure 2.11 shows the voltage relationships in the same binary matrix transformer. The voltage V_{mn} for the elements is the voltage per turn in that element. Thus $V_{11} + 2V_{21} = V_p$. This relationship holds in each column, so we can say $V_{m1} + 2V_{m2} = V_p$. In the secondary, $V_{1n} + 2V_{2n} + 4V_{3n} = V_s$. The voltage per turn is seen to be equal in each element, and $V_s = (7/3)V_p$. The ratio is 3:7, or binary 11:111.

5. Schematic Introduced

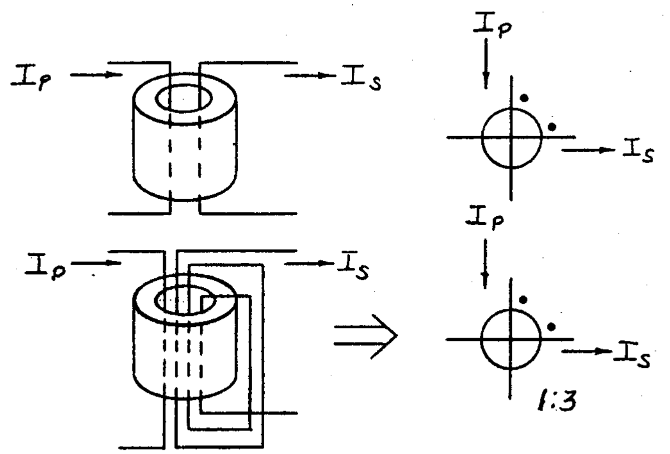


Figure 2.12. On the left are pictorial representations of some matrix transformer elements. On the right are schematic representation of the same elements.

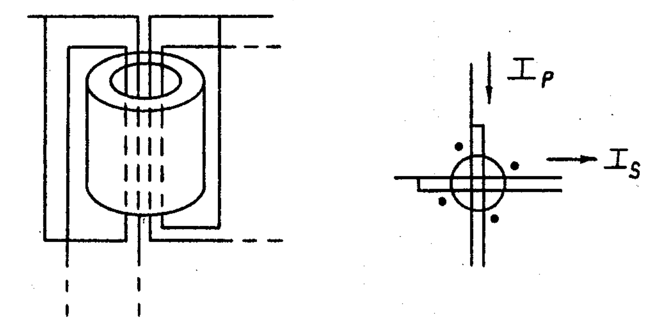


Figure 2.13. A pictorial representation of push pull windings on a matrix transformer element is shown, with the schematic representation of the same element.

So far, the matrix transformers examples have been fairly simple, but the diagrams are hard to follow. This indicates the need for a schematic notation, which is introduced in figures 2.12 and 2.13. The pictorial toroidal core is replaced with a circle, and dots are used to indicate polarity. If the number of wires in each winding is other than 1, then the ratio is indicated. It is best not to reduce the ratio, but to leave the exact number of wires, as often the exact number of wires is important to the transformer design. For instance, if an element had a 12 turn primary and a 3 turn secondary, the ratio should be expressed as 12:3, not reduced to 4:1.

6. M x N Generalized Matrix Transformer

The generalized M x N matrix transformer is shown in figure 2.14. If every element has a 1 to 1 ratio, the ratio of the matrix transformer is the matrix dimensions, M:N.

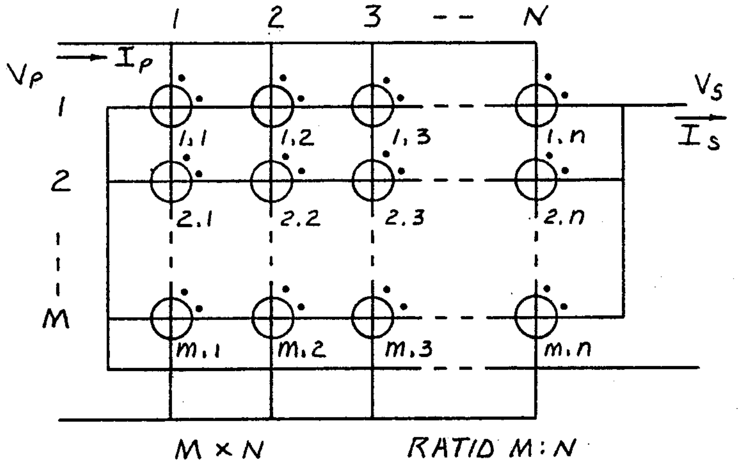


Figure 2.14. The generalized matrix transformer with 1:1 elements.

a) Matrix Transformer with Multiplier P

If every element in a matrix transformer has the same non-unity ratio P:1 (step up or step down), the ratio is the matrix dimensions times P. In a general case, the ratio would be PM:N. This is shown in figure 2.15. (Any entire row or column can be ratioed, but that is beyond the scope of this presentation).

In practice, the elements do not have to be wound individually with P turns. It is equivalent for the matrix transformer winding to make P passes, end to end in all of the columns of the primary or rows of the secondary. This could be easier to fabricate, particularly if the windings were heavy and stiff, or if there were severe dielectric isolation requirements. (When the cores of the elements are lined up, it is easier to pass several wires straight through than to make wraps around them. If dielectric sleeving is needed, it is better for it to pass straight through, end to end, than to try to wrap it around the cores).

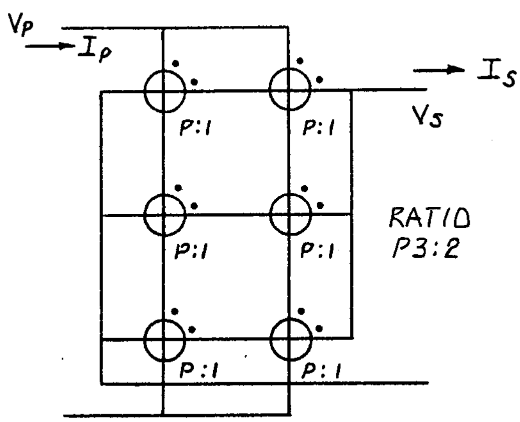


Figure 2.15. The generalized matrix transformer with elements all having the non-unity ratio P:1.

b) Generalized Binary Matrix Transformer

The generalized binary matrix transformer is shown in figure 2.16. For a binary matrix transformer having dimensions M x N, the ratio is $(2^M-1):(2^N-1)$. In binary, this is a binary number with M binary factors (1's) to a binary number with N binary factors. A 4 x 5 binary transformer, for instance, would have a ratio of 15 to 31, or binary 1111:11111.

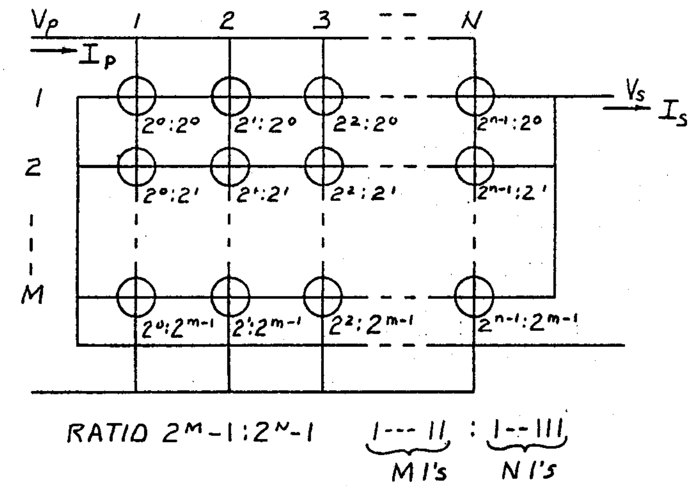


Figure 2.16. The generalized binary matrix transformer.

To make matrix transformers having binary ratios which are not all ones, leave out the rows or the columns corresponding to the binary factors where zeros appear in the binary number. See figure 2.17 for an example.

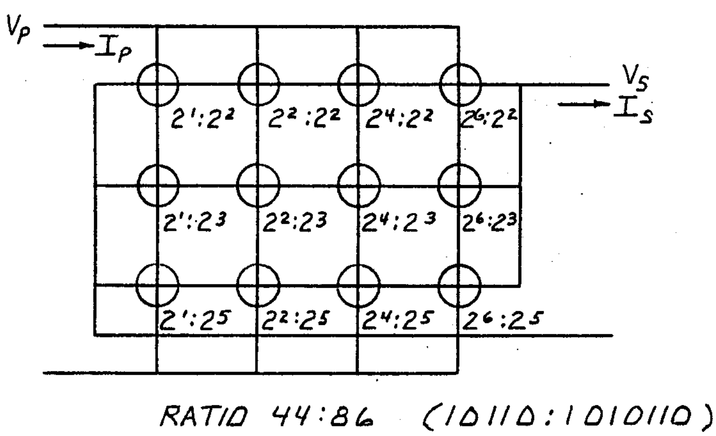


Figure 2.17. A binary matrix transformer where rows and columns corresponding to "0" factors are left out.

c) M x 1 and 1 x N Matrix Transformers

The M x 1 and 1 x N matrix transformers are degenerate cases of the matrix transformer which are very useful for transformers having high ratios. These transformers are othogonal, so the currents are equal in the parallel paths. See figures 2.18 and 2.19.

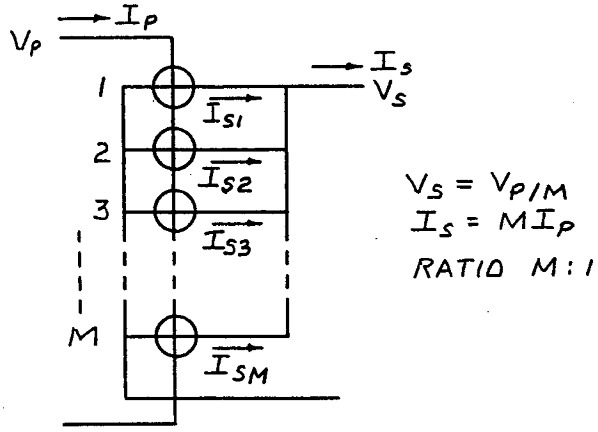


Figure 2.18. The generalized M x 1 matrix transformer.

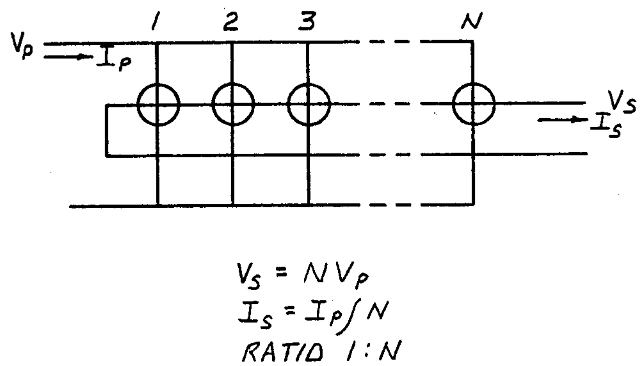


Figure 2.19. The generalized 1 x N matrix transformer.

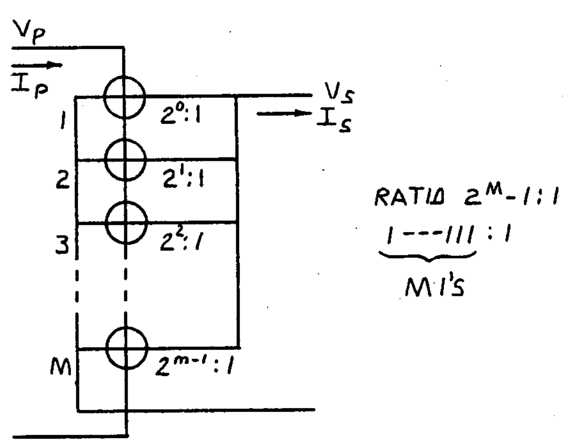


Figure 2.20. The generalized binary M x 1 matrix transformer.

d) M x 1 and 1 x N Binary Transformer

The degenerate cases of the binary matrix transformer, the M x 1 and the 1 x N transformers are particularly useful in variable ratio matrix transformers. As with other binary matrix transformers, if the binary number contains 0's, leave out the element corresponding to that factor.

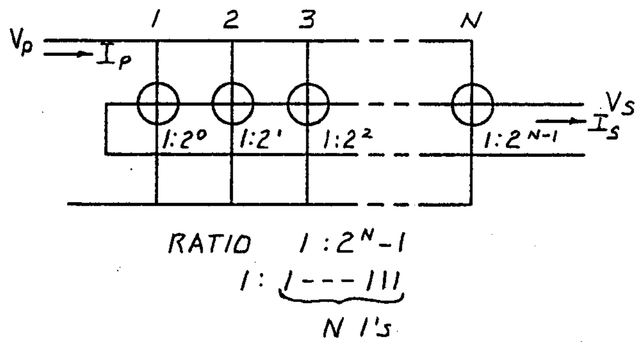


Figure 2.21. The generalized binary 1 x N matrix transformer.

7. Series Primary

Although illustrated as a primary circuit, this technique could apply to secondaries as well. Figure 2.22 shows a matrix transformer of dimensions 5 x 3. However the three parallel primaries are replaced by one series primary to give a higher ratio. Polarity (phasing) must be carefully observed.

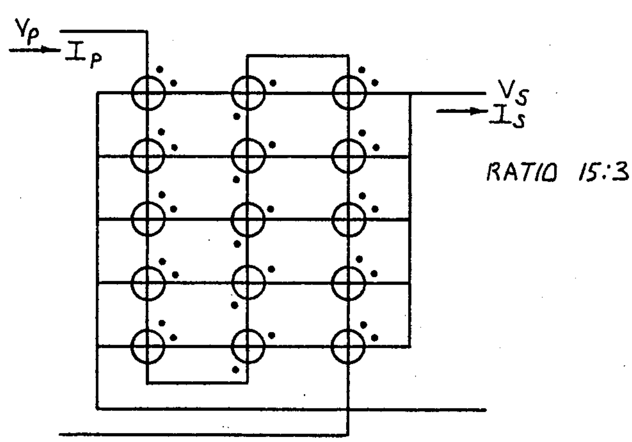


Figure 2.22. A matrix transformer having a series primary.

III. Variable Ratio Matrix Transformers ‡ [10]

The ratio of the matrix transformer can be varied with transistor switching, by effectively altering the matrix dimensions.

This provides a method of voltage control while maintaining 100% duty cycle in the transformer.

When this technique is used with a binary matrix transformer, the output voltage can be proportional to a binary number, the inverse of a binary number, or the ratio of two binary numbers.

A. Changing the Dimensions of a Matrix Transformer.

As discussed in section II, the ratio of a matrix transformer is a function of its dimensions, M and N. If either, or both of the dimensions are changed, the result will be a different ratio.

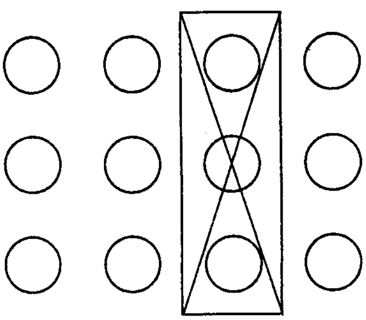


Figure 3.1. "Removing" a column from a 3 x 4 matrix transformer changes it to a 3 x 3 matrix transformer. The ratio changes from 3:4 to 3:3.

1. Removing a Column

Figure 3.1 shows an example of "removing" a column from a 3 x 4 matrix transformer, changing it to a 3 x 3 matrix, and thereby changing the ratio from 3:4 to 3:3

2. Removing a Row

Figure 3.2 shows an example of "removing" a row from a 3 x 4 matrix transformer, changing it to a 4 x 2 matrix, and thereby changing the ratio from 3:4 to 2:4.

3. Removing Columns and Rows in a Binary Matrix Transformer

Figure 3.3 shows an example of removing a column and a row from a matrix transformer. Removing a column or a row has the result of changing the

‡ U.S. Patent 4,665,357; other patents pending. FMTT, Inc.

corresponding binary factor to a zero. The ratio has been changed from 7:15 to 5:11, or, expressed as binary numbers, the ratio has changed from 111:1111 to 101:1011.

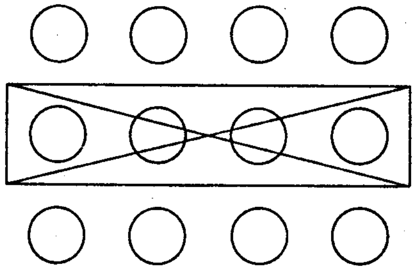


Figure 3.2. "Removing" a row from a 3 x 4 matrix transformer changes it to a 2 x 4 matrix transformer. The ratio changes from 3:4 to 2:4.

a) M x 1 and 1 x N variable ratio matrix transformers

Because of their simplicity and ease of control, the degenerate binary matrix transformers are particularly good for digital controlled applications. Figure 3.4 shows a M x 1 binary transformer with two factors (degenerate rows) removed. The ratio is changed from 15:1 to 5:1 (binary 1111:1 to 0101:1).

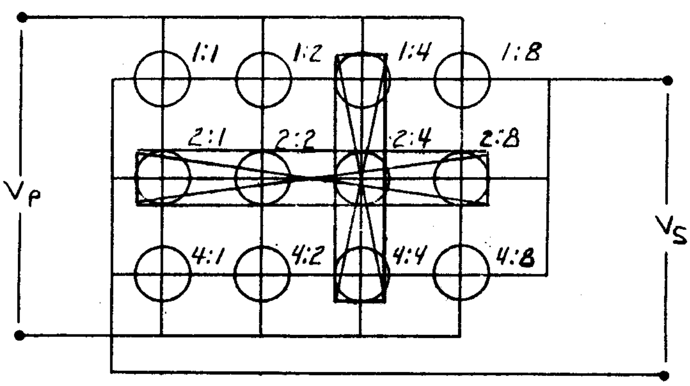


Figure 3.3. "Removing" a column and a row from a binary matrix transformer changes the ratio from 7:15 to 5:ll (from binary 111:1111 to binary 101:1011).

Figure 3.5 shows a 1 x N binary transformer, also with two factors (degenerate columns) removed. The ratio is changed from 1:15 to 1:5 (binary 1:1111 to 1:0101).

B. Techniques for Removing Elements

The matrix transformer consists of an array of elements, interwired to be a transformer. When surgery is preformed, what remains must be a valid matrix transformer, with no improper shorts and opens. To maintain validity, when a row or column is removed, a short circuit must be provided for circuit paths passing through it, and an open circuit must be provided to disconnect it from other circuit paths which are in parallel with it.

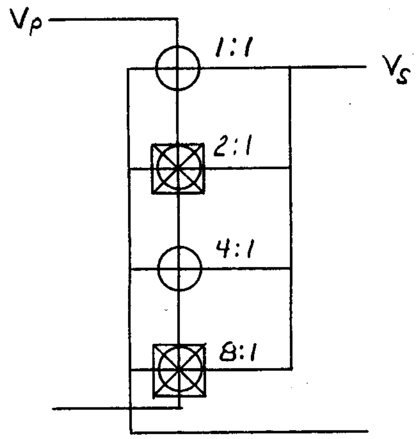


Figure 3.4. Removing two elements from a M x 1 binary matrix transformer changes the ratio from 15:1 to 5:1 (from binary 1111:1 to binary 0101:1).

Figure 3.6 shows removing the third column from a 3 x 4 matrix. The removed column must be disconnected from the other columns, and circuit paths must be maintained for the rows.

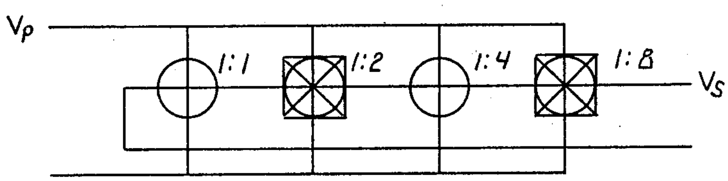


Figure 3.5. "Removing" two elements from 1 x N binary matrix transformer changes the ratio from 1:15 to 1:5 (from binary 1:1111 to binary 1:0101).

1. Using Switches

Figure 3.7 shows a very simple variable turns ratio matrix transformer. With the switch S_1 in position A, the transformer has a ratio of 2:1. Putting the switch in position B removes the second element from the transformer, resulting in a 1:1 ratio. Opening the A contact removed the row (a degenerate row having just one element) from the other row with which it was in parallel, and closing the B contact short circuited the core, which in turn reflects a short circuit to the primary, thus providing the short circuit for the series path passing through the primary.

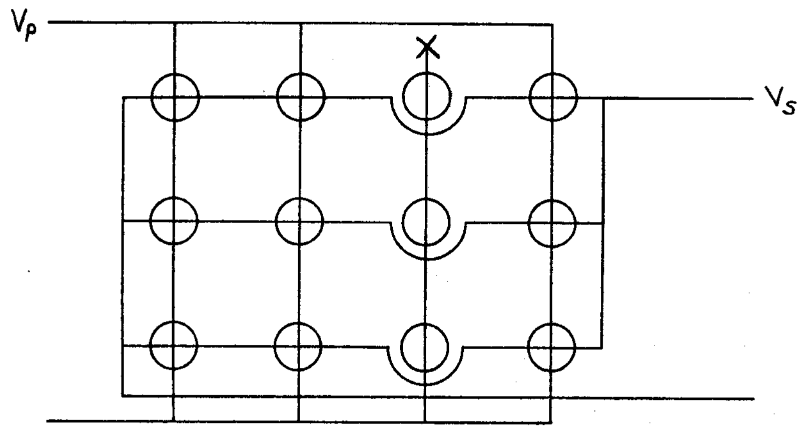


Figure 3.6. To remove a column from a matrix transformer, it must be disconnected from the other columns, and shorted across the rows.

Figure 3.8 shows an alternative method which is functionally equivalent. The ratio is changed by opening switch S_1 and closing S_2. Again, the second element is short circuited, but this figure shows that the short circuit can be applied with an isolated secondary.

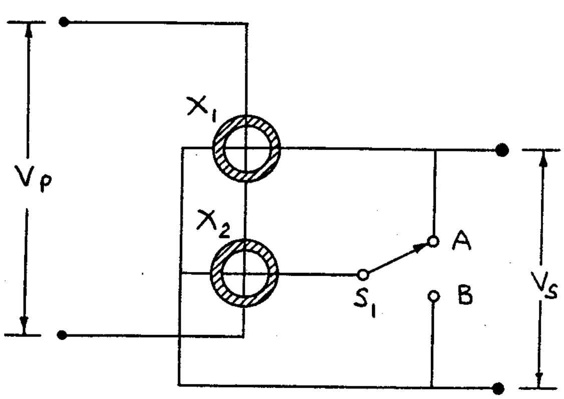


Figure 3.7. A very simple variable turns ratio matrix transformer.

2. *Using Transistors*

Figure 3.9 shows a matrix transformer in which one element can be "removed" by turning on the FET Q_1. With the transistor off, the secondary of the element is connected to the circuit through the rectifiers Cr_1 and Cr_2., and the element is "in" the circuit. With the transistor on, a short is applied to the secondary through Cr_3 and Cr_4. This short reflects to the primary. The short also reverse biases Cr_1 and Cr_2, which removes the secondary from the others which are in parallel with it.

Figure 3.10 shows the isolated version of the same circuit.

Because the rectifiers are easily back biased, removing elements in the secondary is relatively easy. To remove columns in a primary circuit a series switch in some form must be used. In a push pull circuit, the column is opened if both drive transistors are turned off. Then a short for the through circuits can be provided in the manner of figure 3.10. Alternatively, if FET's are used, the short can be provided by turning on both drive transistors. The open must then be provided by another switch.

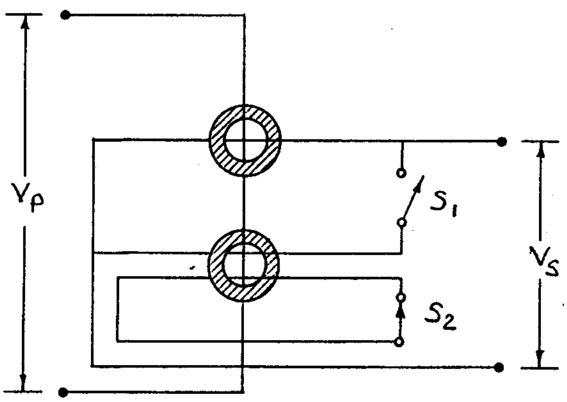


Figure 3.8. A simple variable turns ratio matrix transformer having isolated control by using a shorting winding.

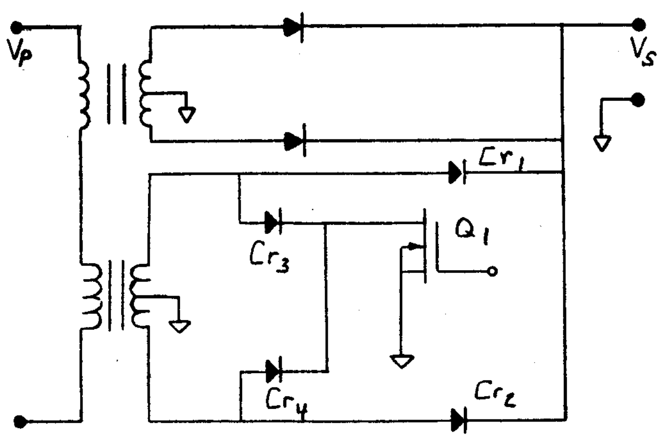


Figure 3.9. A method of "removing" an element with a transistor switch.

C. Finer Resolution

In theory, resolution as fine as required could be obtained by adding more and more stages. In a practical power converter circuit, the parasitic losses would make it very difficult to maintain monoticity.

1. Modulation between Ratios

Figure 3.11 shows a method of modulating the ratio between two values to provide a time averaged ratio of any value in between. In a practical circuit, coarse adjustment might be made with three or four binary factors, with a fine adjustment. The fine adjustment should have a range of several bits, so that hysteresis can be provided in the binary switching logic.

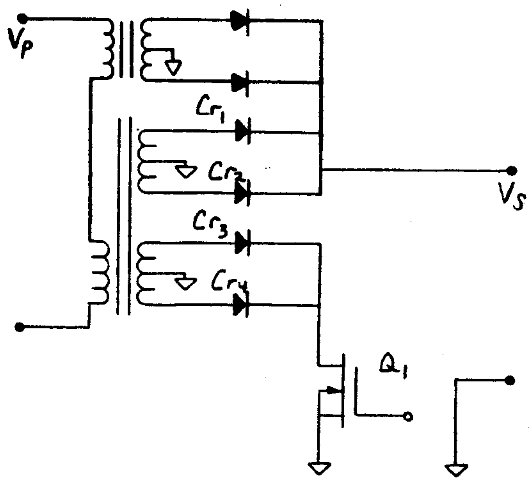


Figure 3.10. **A method of "removing" an element with a transistor which can be isolated from the input and/or output, and can be ground referred.**

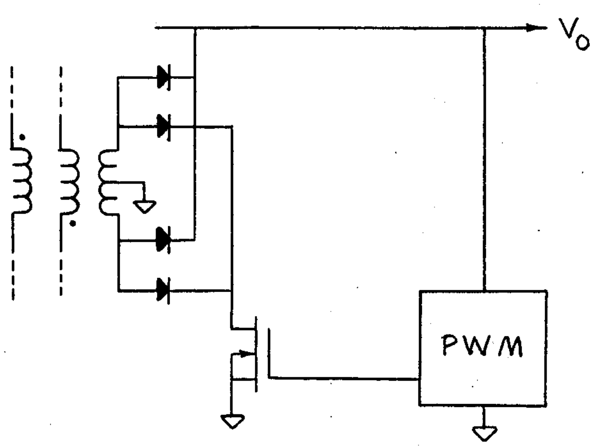


Figure 3.11. **An element of a variable ratio matrix transformer in which the ratio is modulated.**

<u>2. Linear Adjustment</u>

Figure 3.12 shows that a linear control can also be used to provide fine tuning between binary steps. The linear stage behaves differently than an element which is switched in and out. The linear stage current would never flow to the output, unless the optional clamp diode became forward biased, but a current equal to the primary current (factored by the turns ratio) always flows in the linear transistor, and effectively provides a voltage drop which reflects to the primary.

D. Filtering Considerations

A transformer that has step changes in ratio cannot have a capacitor on both its input and output, nor can it have an inductor on both. See figure 3.13. In the former case, a change in ratio requires an instantaneous change in the input/output voltage ratio, but capacitors cannot change voltage instantaneously. In the latter case, a change in ratios requires an instantaneous change in the input/output current ratio, but the inductors cannot change current instantaneously.

An exception to this would be a design in which the incremental steps were constrained to be very small.

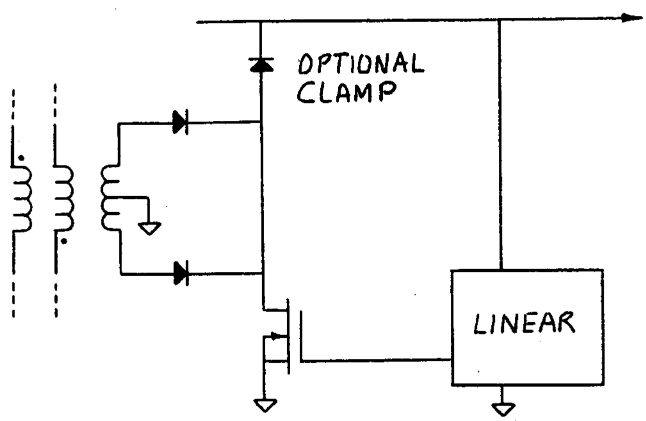


Figure 3.12. An element of a matrix transformer incorporating linear voltage regulation.

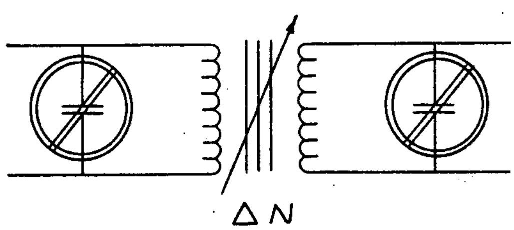


Figure 3.13. A transformer that has step changes in its ratio cannot have a capacitor on both its input and its output.

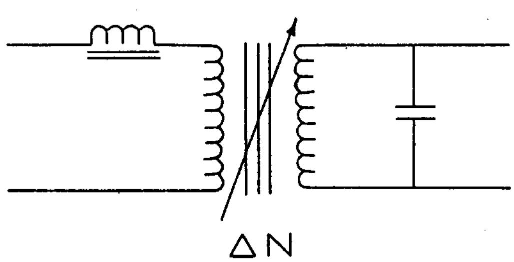


Figure 3.14. A variable ratio matrix transformer can have an inductor on its input and a capacitor on its output.

An inductor on the input and a capacitor on the output would work well as in figure 3.14, and is probably preferred for most applications, but the opposite combination is permissible too. The L-C product will be ratio dependant. See also "Cascaded Matrix Transformers", section XVIII.

IV. Design Considerations for High Frequency

The high frequency matrix transformer ‡ is a flat matrix transformer that has been optimized for high frequency.

The matrix transformer has characteristics which offer improved performance over the monolithic transformer. These are freedom from the single turn limitation, good coupling, minimal proximity effects, reduced currents in the windings and good thermal properties.

When optimized for high frequency by using closed circuit windings and minimal external wiring, leakage inductance is very low.

A. No Single Turn Limitation

In designing transformers for high frequency power conversion, there is often a need to have large step down ratios. In a monolithic transformer (a conventional transformer, having one core) the minimum number of turns for practical design is one, so the primary has to have a number of turns equal to the step down ratio, or some integer multiple of it.

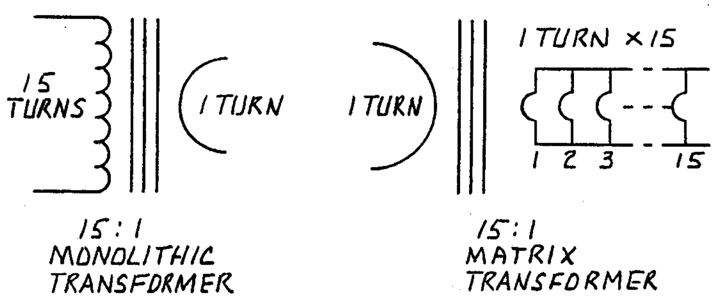


Figure 4.1. In a hypothetical 15:1 step down transformer, the monolithic transformer must have a fifteen turn primary. The matrix transformer can have a single turn primary, with 15 paralleled single turn secondaries.

Because the leakage inductance associated with a transformer is proportional to the square of the number of turns, it is desirable to have a single turn primary winding. Proximity effects are the result of a number of windings being located where they are coupled by the leakage flux of other windings, and result in excessive losses. This is another consideration favoring a small number of windings.

The matrix transformer for high frequency usually has a single turn primary, or may have a small number of turns, two or three perhaps. The secondary has a large number of parallel paths. See figure 4.1.

‡ U.S. Patent pending. FMTT, Inc.

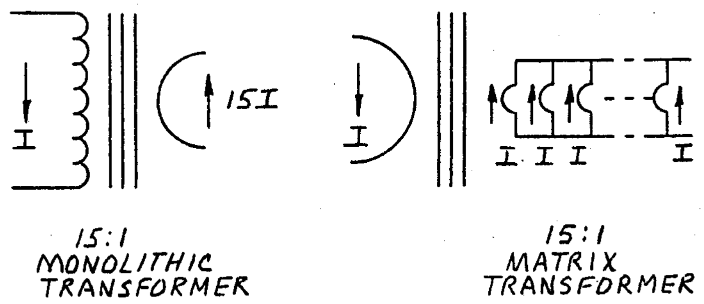


Figure 4.2. In the hypothetical 15:1 monolithic transformer, the secondary current is fifteen times the primary current. In the matrix transformer, the secondary has 15 parallel windings in which the current equals the primary current.

Problems at high frequency are much more severe if the currents are large. In the matrix transformer, the currents are much smaller in any given winding. This makes it easier to keep the parasitics under control. See figure 4.2

B. Leakage Inductance in External Leads

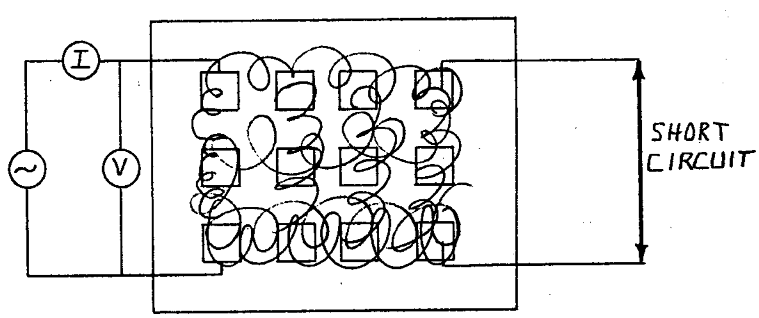


Figure 4.3. An early attempt at measuring the leakage inductance in a matrix transformer by shorting the secondary and measuring the primary impedance.

The usual way to measure leakage inductance in a transformer is to short one of the windings, and measure the impedance of the other. An early attempt at applying this technique to the matrix transformer is shown in figure 4.3. It was just about impossible to get consistent results, and the leakage inductance was much higher than expected.

As lead dress was improved, the leakage inductance went down, as expected. The improvement was in fairly direct relationship to the shortening of the wires. For a matrix transformer having single turn elements, the leakage inductance can be closely approximated by measuring the total length of the *external* wires, and multiplying by the *inductance per unit length* of the wire. This is about 15 to 20 nanohenries per inch. This is illustrated in figure 4.4.

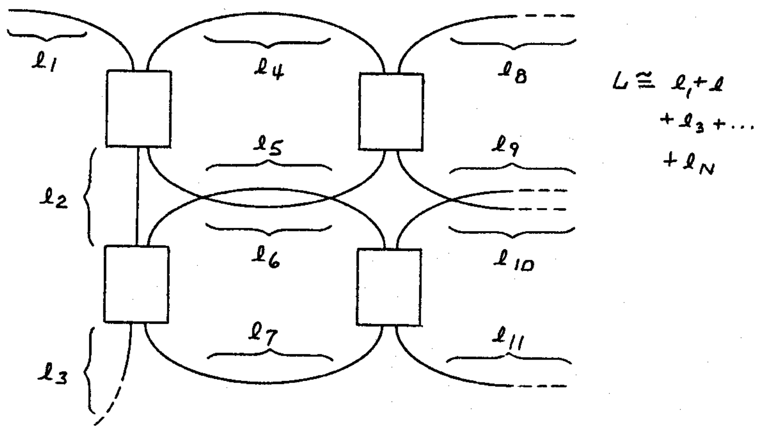


Figure 4.4. In a matrix transformer, the leakage inductance was found to be closely approximated by the inductance of the external wires, figured at 15 to 20 nanohenries per inch.

We eventually stopped trying to measure leakage inductance, because we were unsure of the applicability of our small signal test results to full-power, in-circuit conditions. We felt that efficiency in a real converter circuit was more relevant, and it is easier to measure.

The subject of impedances is discussed in more detail in section XVI.G. The effects of leakage inductance on circuit performance is the subject of section XII.

C. Coupling and Proximity Effect

The elements in a matrix transformer tend to be small diameter cores, or something equivalent. The flux paths are very short, the number of wires enclosed is small, and they are close together. See figure 4.5. There is very little leakage flux, and coupling is excellent.

With very small leakage fluxes and the low number of wires, the proximity effect is greatly reduced.

D. Closed Paths

The leakage inductance in a matrix transformer is largely attributable to external lead length. This is obviously minimized if the transformer can be arranged in a pattern such that a winding starts and ends at the same place, and all of the elements which the winding goes through are put end to end in a closed pattern. This is usually possible. Figure 4.6 shows an example of a secondary winding segment passing through four elements.

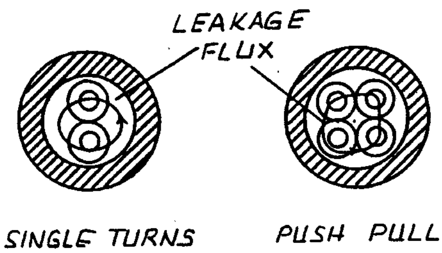


Figure 4.5. Cross sections of typical matrix transformer elements, showing single turn windings and push pull windings. The flux paths are very short and close to the windings. The leakage fluxes that would reduce coupling or cause problems with proximity are virtually non-existent.

E. Identify High di/dt Circuits

To optimize a matrix transformer layout for high frequency operation, the first step is to identify the parts of the circuit that have high rates of change in current. Figure 4.7 shows an example of a secondary of a transformer coupled buck converter with a push pull full wave rectified secondary.

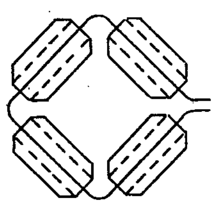


Figure 4.6. As a generality, it is preferred to design the layout of the elements of a matrix transformer so that the windings have a closed path. A possible secondary circuit is shown, and would be one of several.

From the perspective of optimizing transformer layout, the circuits of interest are those which have large di/dt's. In figure 4.7, these are from the centertap of the transformer, through the windings, through the rectifiers and to the common cathode connection. During the "on" time, one side of the transformer and its rectifier carry all of the current. During the "off" time, the current divides equally between the two sides of the circuit. The inductance of this closed circuit determines how fast this transition can occur, and is a large source of the turn off transient voltage seen by the primary circuits.

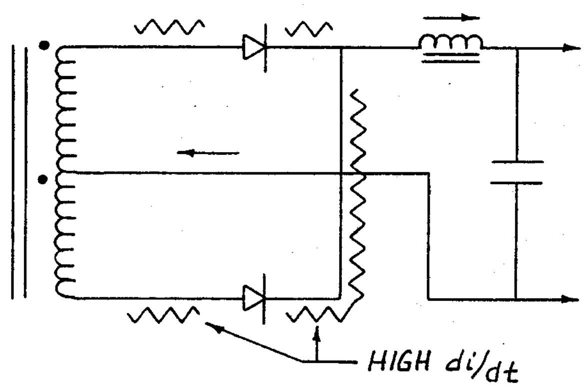


Figure 4.7. A typical secondary for a transformer coupled buck converter is shown. The portions of the circuit having high di/dt's are identified.

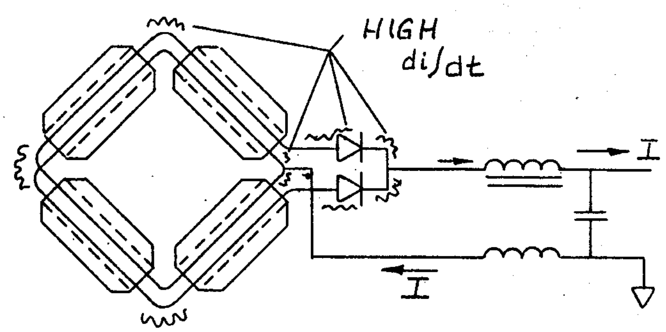


Figure 4.8. Placing the rectifiers as close to the transformer as possible minimizes the external circuitry which have high di/dt's.

Other parts of the circuit may have an alternating current component, and especially an alternating voltage. These circuits are from the center tap of the transformer to the capacitor and from the common cathode connection to the inductor. These circuits are of concern from an EMI point of view, but do not contribute to the problem of leakage inductance. In fact, leakage inductance in these wires would simple add to the filter inductance.

1. Keep Circuit Runs Short

Once the circuits which have high di/dt's are identified, component placement should be chosen to minimize lead length as much as possible. Figure 4.8 shows a secondary segment of a matrix transformer coupling four elements. The rectifiers have been place right at the transformer output. In this way the leakage inductance of the secondary is kept very low.

Looking at the secondary circuit in the matrix transformer, it is a series path, from the center tap, through the four elements, through the rectifier and to the common cathode connection. Being a series circuit, there is no restriction on the order of the components, and the rectifiers could be put anywhere along its length. Figure 4.9 shows a possible arrangement with the rectifiers inside the transformer ‡. Thus there

‡ U.S. Patent pending. FMTT, Inc.

would be no external leads with high di/dt's. If load currents were appreciable, heat sinking would be needed. Small snubber components could also be located with the rectifiers if required.

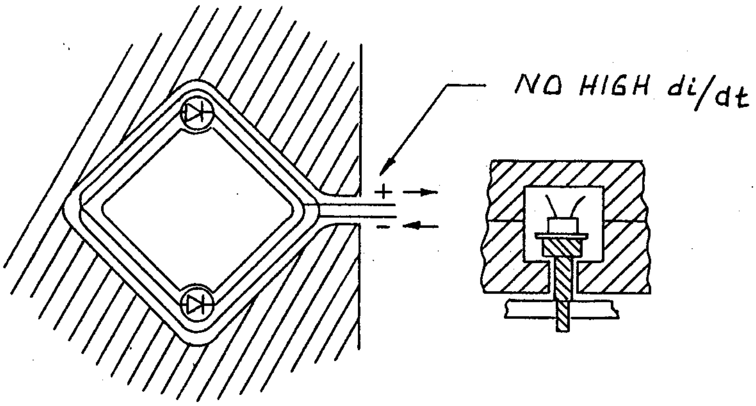


Figure 4.9. It is proposed that the optimum location for the rectifiers is *inside* the transformer. Because the secondary is a series circuit, the location of the rectifiers is arbitrary. Heat sinking and snubbing may be necessary.

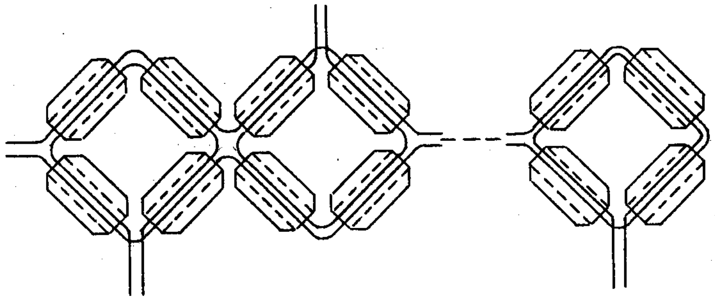


Figure 4.10. If the secondary circuits are placed corner to corner, it is possible to define a closed loop primary through them.

F. Primary Circuit

Just as in the secondaries, it is important that the primary circuit be a closed path and be kept tight. If the elements making up the secondaries are place corner to corner, the primary can be interwired through it, as in figure 4.10. The primary is a series path in this example, and the placement of any one element along it is arbitrary as long as each element is coupled to the primary with the correct phasing.

The "diamond" pattern of figure 4.10 is close to optimum, but is not easy to make using cores. A reasonable compromise is a double row of long toroids as shown in figure 4.11.

G. A Design Example.

Figure 4.12 shows a practical secondary layout for a transformer coupled buck converter. The primary is shown as a single wire, as might be used with a full bridge or half bridge drive. A push pull winding could be substituted.

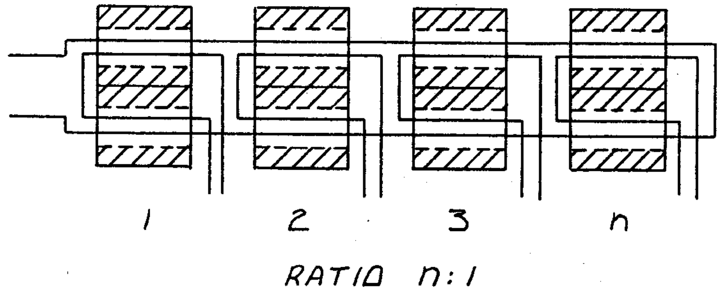


Figure 4.11. A double row of long, slender toroids is a good compromise matrix transformer layout, for ease of assembly.

The secondary layout does not conform exactly to the guidelines formulated above, but the differences are instructive. The secondary windings start with a ground plane identified as the row of ground symbols. In each secondary segment the winding passes in opposite directions through the lower core, then again in opposite directions through the top core. If the primary is traced, it can be seen that the phasing is correct.

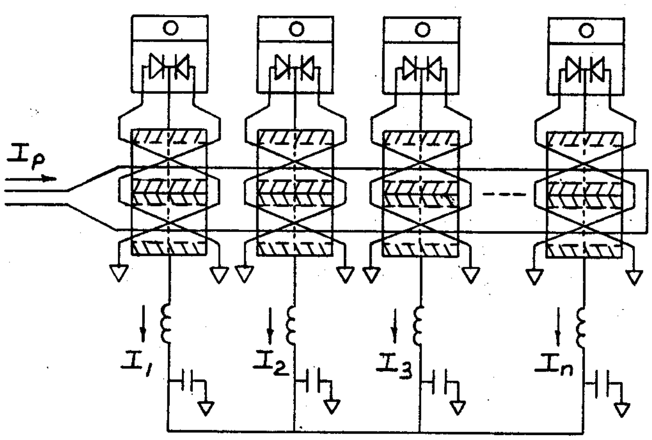


Figure 4.12. If the pitch of the transformer is about 5/8", the secondaries match well to TO-3P dual rectifiers. $I_1 = I_2 = I_3 = \cdots = I_n$.

The windings then exit the matrix transformer and go to the terminals of a row of TO-3P dual Schottky rectifiers. *These windings do not start and end at the same place.* However, the ground connections are to a ground plane, which has very low inductance. The outputs to the anodes of the rectifiers are made as short as possible, given the location and lead spacing of the rectifier packs.

As with any design task, it is important to understand the underlying principles behind design "rules", so that exceptions can be identified. A rule to end a winding where it starts is fine if it can be hooked up there. In this case, the wire length to return to the most remote rectifier anode terminal from a common starting point would be longer.

V. "Picture Frame" Matrix Transformers ‡

The Picture Frame layout of the matrix transformer is particularly well adapted for high frequency converters of moderate to high power for mounting on a circuit board or a plate. The semiconductors can be mounted on the periphery for optimum cooling, and there is room in the center for control and housekeeping circuits.

The picture frame winding arrangement can also be used in a pot core like structure.

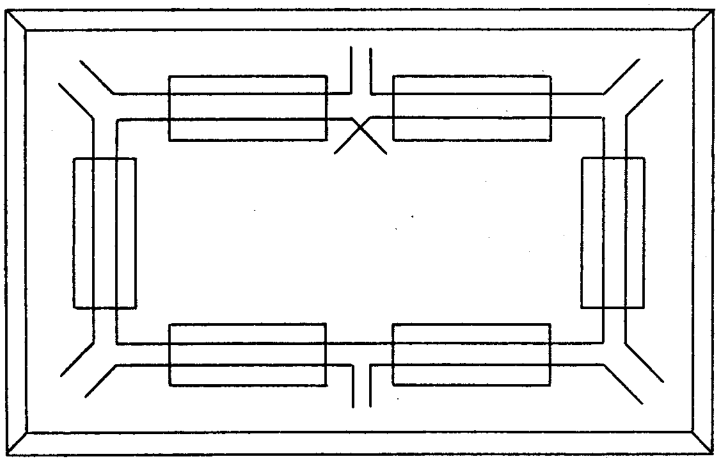


Figure 5.1. The "Picture Frame" matrix transformer.

A. The "Picture Frame" Layout

In section IV, some general criteria for high frequency matrix transformers were introduced, and matrix transformers of the general form of 4N x 4 or 2N x 2 were used as examples, with series primaries. Theses transformers tend to layout in a straight line, though of course they can be looped or snaked around if desired.

Another family of matrix transformers has been dubbed the "picture frame" matrix transformer, though it too can be arranged in different shapes. It is characterized by having all of the elements placed end to end in a closed pattern, starting where it ends, with an open center.

The main advantage of the picture frame matrix transformer is that the power components are spread out around the periphery, which is optimum for heat sinking. The space in the middle can be used for control and housekeeping circuits.

B. Picture Frame Primary Winding

Figure 5.2 shows the generalized form of the primary winding for the picture frame matrix transformer. The winding shown would be suitable for a converter using full or half bridge drivers. A push pull winding could be used as well, and other possibilities will be introduced later.

‡ U.S. Patent pending. FMTT, Inc.

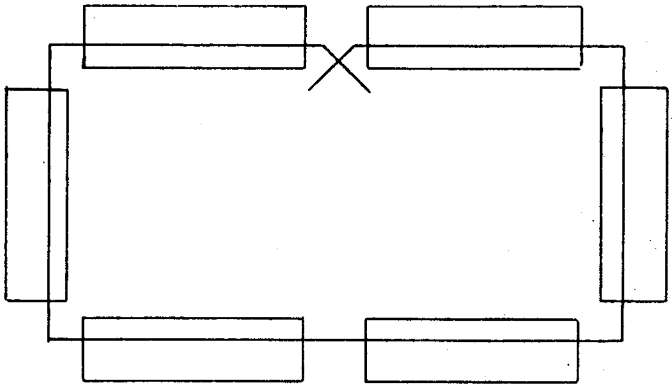


Figure 5.2. The primary of the picture frame transformer makes a closed loop, and so meets the criteria for high frequency.

C. Picture Frame Secondary Windings

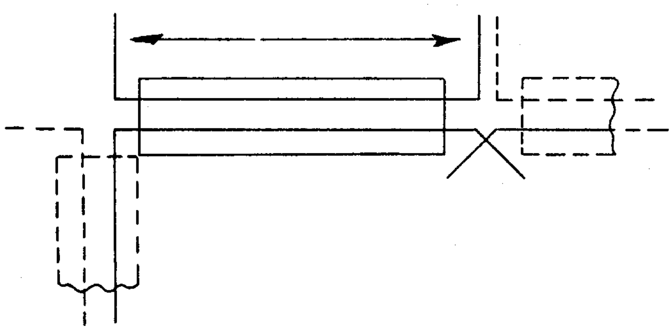


Figure 5.3. The picture frame matrix transformer secondary violates the criterion of starting and ending at the same place.

The secondary winding segments in the picture frame matrix transformer go through the elements from one end to the other. This puts the start of the winding quite far from the end, and would seem to violate the criterion for high frequency operation of making a closed loop, starting and ending at the same place. However, the criterion is satisfied if *a* start and *an* end, having currents of the same magnitude and opposite phase are located together. See figure 5.4.

By Lenz's law, the secondary current in each element must equal the primary current, so the secondary currents must equal each other.

1. Full Wave (Bridge) Rectifiers

Figure 5.5 shows a picture frame matrix transformer secondary with full wave bridge rectifiers. As can be seen, the two wires coming out between the elements are taken to the rectifier, just as if they came from the same winding. As long as the pattern is unbroken around the whole transformer, it is equivalent.

Tracing the circuitry carefully, it can be seen that the positive output current from one rectifier will be sourced from the negative of the *next* rectifier, clockwise or counter clockwise around the transformer, depending upon the phase. As is the nature of matrix transformers, the current will balance evenly between the rectifiers, without any ballasting. The rectifiers can be very closely coupled to the transformer, yet spread out around the periphery of the circuit for best heat sinking.

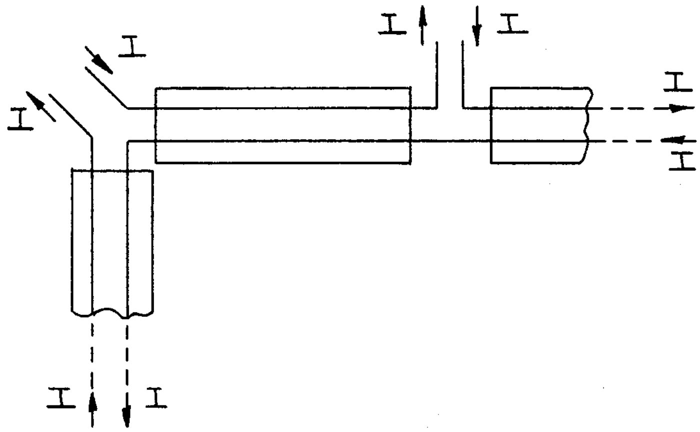


Figure 5.4. In the picture frame matrix transformer, the start of one secondary is located with the end of another. This satisfies the high frequency criterion.

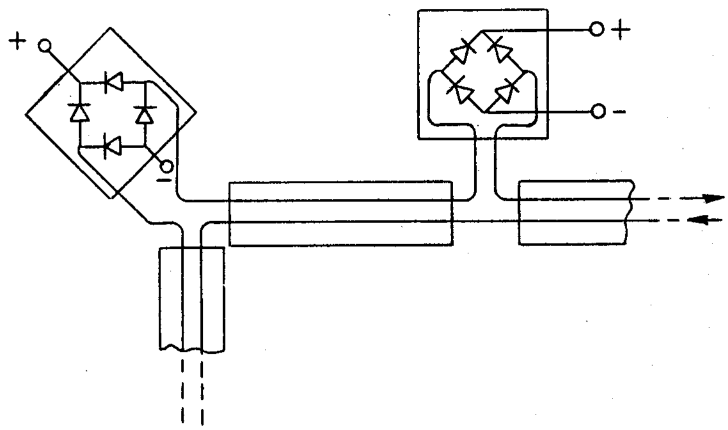


Figure 5.5. A partial drawing of a picture frame matrix transformer showing full wave bridge rectifiers on the outputs of the secondary windings. The + and - terminals would be paralleled, either before or after filtering.

2. Full Wave (Push Pull) Rectifiers

Figure 5.6 shows a picture frame transformer secondary with push pull windings and full wave rectifiers.

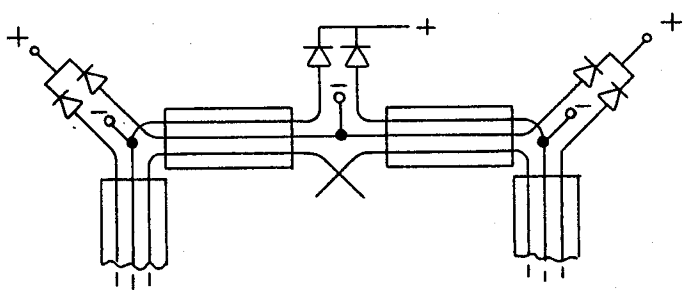


Figure 5.6. Push pull secondary windings in a picture frame matrix transformer, with rectifiers. The + and - terminals would be paralleled, either before or after filtering.

VI. Matrix Inductors

Matrix Inductor: an inductor comprising an array, or matrix of inductor elements, interwired so that the whole functions as an inductor.

Using a plurality of elements to make an inductor is a logical extension of the matrix transformer concept. Some transformers, such as flyback transformers, are really more like inductors, and coupled inductors overlap transformers in their behavior. The conversion of a transformer like device to an inductor like device by adding an air gap is fairly obvious.

This section introduces some less obvious applications of the matrix inductor. In one, windings are paralleled but offset physically, as part of a picture frame matrix inductor. A variation of this has dual windings, to filter both the power and return in the same core structure.

A. Matrix Inductor Elements

As with a matrix transformer, and particularly when used *with* a matrix transformer, the matrix inductor has the advantage of using a number of smaller matrix inductor elements, each carrying a smaller current, rather than one large inductor carrying the entire current. Many of the advantages of the matrix transformer will also be realized in the matrix inductor: low profile, distributed layout, excellent thermal characteristics, and good resistance to shock and vibration.

1. Individual Matrix Inductor Elements

The step down matrix transformer usually has a large number of parallel outputs. To eliminate external wiring having large di/dt's, the rectifiers are preferably located immediately next to the transformer terminals. Because of the current sharing characteristics of the matrix transformer, the current is a known fraction of the total output current.

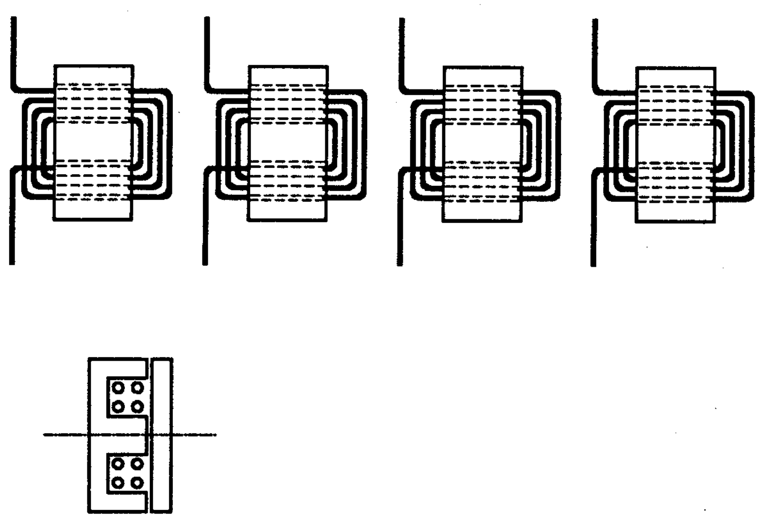


Figure 6.1. The rectified outputs from a matrix transformer can be taken to a number of matrix inductor elements, each located close to the matrix transformer output.

While the outputs could be paralleled and brought to one inductor, there are advantages of filtering the outputs before they are paralleled. Each rectified output of the matrix transformer can have its own matrix inductor element located optimally. The outputs of the matrix inductor are paralleled and output capacitors are added as required.

A typical matrix inductor is shown in figure 6.1. It is wound on "E" cores with air gaps under their covers. Each one has an input and an output, and four turns. It would be no trouble at all calculating its inductance if the physical parameters were know. Obviously, any of a variety of core types can be used for the matrix inductor elements, such as pot cores, E-E cores, toroids, etc., and the gap can be as shown or entirely in the center leg, or it can be distributed.

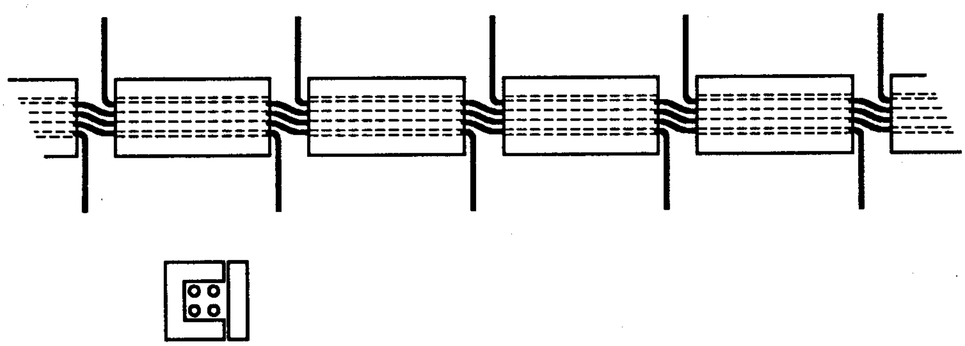


Figure 6.2. A "picture frame" inductor can be designed to align with the outputs of a picture frame transformer. The cores used in this inductor have the same area as the cores used in the inductor in figure 6.1. The inductance seen by each wire is equal to the inductance of the individual inductor elements.

a) Picture Frame Matrix Inductor ‡

Figure 6.2 shows a portion of a picture frame matrix inductor, using cores having the same area as is used in the matrix inductor of figure 6.1. Just as with the picture frame matrix transformer, the entire picture frame matrix inductor is in a closed pattern, with its cores placed together end to end. There are a number of inputs and an equal number of outputs evenly spaced around the picture frame matrix inductor. They may align with the outputs of a picture frame matrix transformer.

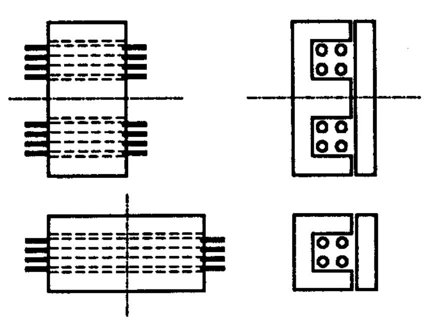


Figure 6.3. A comparison of the cores used in the matrix inductors of figures 6.1 and 6.2 shows that each has the same area and gap. If the conductors carry the same current (as they must due to current sharing), the inductance seen by any wire is equal in either configuration.

‡ U.S. Patent pending. FMTT, Inc.

It can be seen in figure 6.2 that any one input enters the picture frame matrix inductor at the top, passes through four cores clockwise, and exits. At each point, it is paralleled by three other wires, each carrying an equal current due to the inherent current sharing of the matrix transformer to which it is mated.

Comparing the picture frame matrix inductor to the matrix inductor of figure 6.1, the wires there also enter at the top, each passes through the core four times, and exits. At any point it is paralleled by three other wires, each carrying an equal current. As shown in figure 6.3, the area and gaps of the cores are the same, so the current in each sees an equivalent magnetic circuit environment at any point along its length. It is therefore evident that the inductance seen by each conductor is equivalent in either configuration.

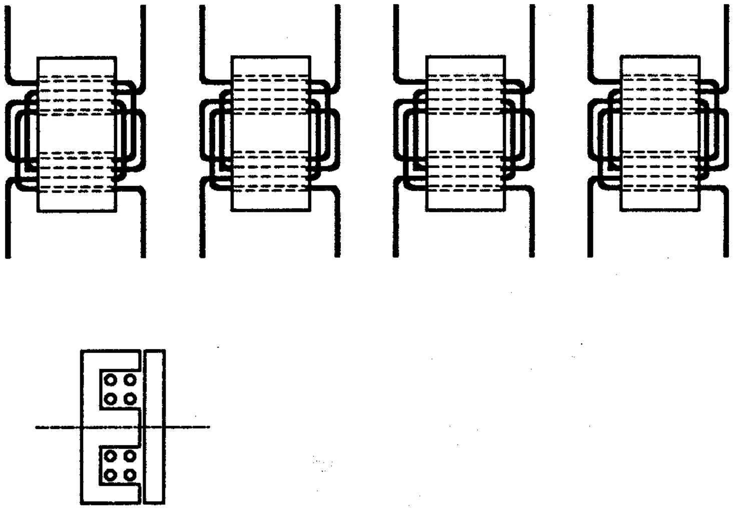


Figure 6.4. A matrix inductor in which the output power and the output return are both taken through the inductor, in opposite direction.

2. Matrix Inductor for Power and Return

In some circuits, it is desirable to have both the output power and the output return pass through the inductor, in opposite directions to accommodate the opposite direction of current flow. Figure 6.4 shows a matrix inductor configured this way using individual matrix inductor elements. The net inductance seen by the circuit is the same as in the matrix inductor of figure 6.1.

a) Picture Frame Matrix Inductor for Power and Return

The picture frame matrix inductor can also be configured for the output power and the output return as shown in figure 6.5. In this example, the conductors for the output power enter the top of the schematic, and pass through two cores, clockwise, and exit at the bottom. The conductors for the output return enter at the bottom, and pass through two cores, anticlockwise, and exit at the top.

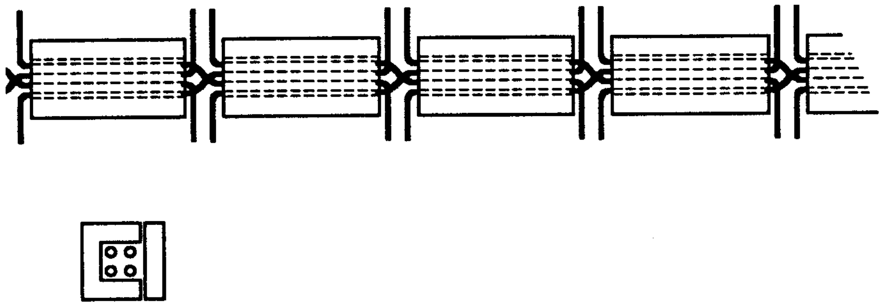


Figure 6.5. This "picture frame" matrix inductor has conductors for both the output power and output return. It is electrically equivalent to the matrix inductor of figure 6.4.

3. Pot Core Like Structure ‡

There is no reason that individual cores must be used for the matrix inductor. Figure 6.5 shows a pot core like structure. The wires of the matrix inductor enter, make a pass through two sections, the positive wires one direction, and the negative wires in the other, and exit.

The inductor could be wired directly from an integrated matrix transformer section, as shown in the cross section in figure 6.5, with no exposed noisy wires. (This configuration assumes a symmetrical push pull secondary, which has the rectifiers at different nodes of the secondary than at the outputs).

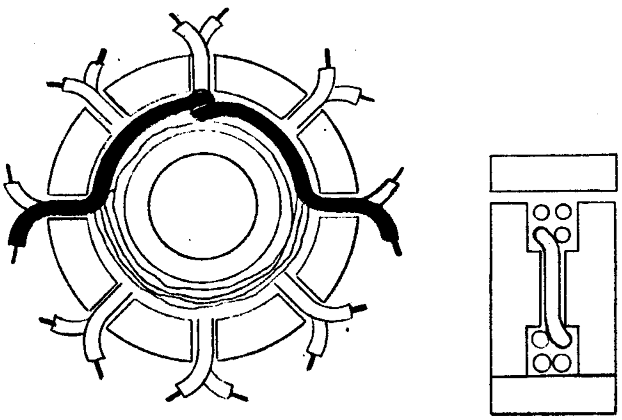


Figure 6.6. A picture frame matrix inductor can be wound in a pot core like structure. The section shows that it can be in the same core structure as the matrix transformer.

‡ U.S. Patent pending. FMTT, Inc.

VII. Using Matrix Transformers and Inductors on Printed Circuit Boards

Using printed circuit board construction solves many problems by reducing the number of loose parts and eliminating wiring errors. The matrix transformer technology allows these advantages in much higher power circuits.

The matrix transformer is well adapted to printed circuit layout, particularly the picture frame matrix transformer. The magnetic components, and those dissipating the most heat can be located at the edges.

Matrix transformers can be built using printed circuit windings. In any part of the transformer, there are only a few conductors, typically two to four, even if it has a high ratio. This makes printed wiring layout practical even for high power transformers.

A proposed Power Plane matrix transformer-inductor module is described.

A. Plug in Elements

There are a number of ways in which matrix transformers and matrix inductors can be constructed on a printed circuit board. One is with the use of plug in elements.

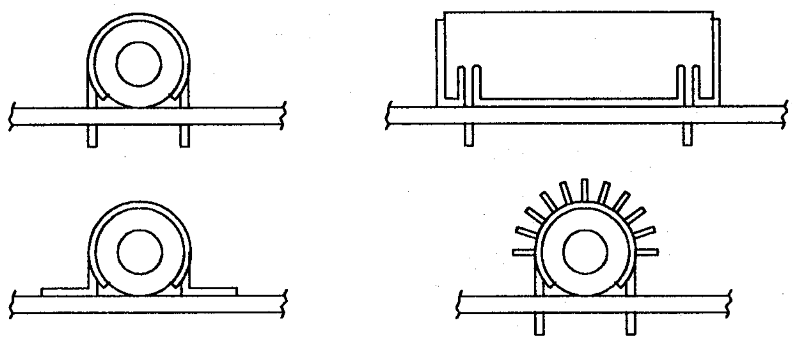


Figure 7.1. Several cores adapted for printed circuit board use. One has mounting feet instead of pins; another has cooling fins.

1. Plug in Elements for a Picture Frame Matrix Transformer

Figure 7.1 shows several cores which are adapted for mounting on a printed circuit board and which are suitable for making a picture frame matrix transformer, or, with a gapped core (cut or distributed), a picture frame matrix inductor. The first core, shown with an end and a side view, is jacketed with a metal wrap nearly enclosing it. Pins extend downward into the board.

A second core is similar, but has mounting feet, or tabs, instead of pins. Another has cooling fins. Other variations are possible. The windings are threaded through the cores as they are assembled to the printed circuit board, or afterward.

The core can be made with one ferrite toroid, as shown, or it can be a stack of smaller cores, a stack of washers or a tape wound coil. A square cross section can be used.

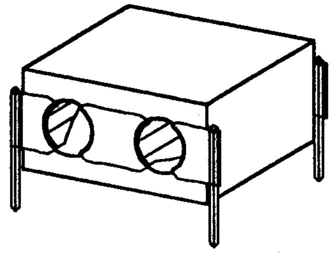


Figure 7.2. A matrix transformer module for printed circuit board use includes the secondary winding conductors inserted into a balun like core.

2. *The Matrix Transformer Module.*

Figure 7.2 shows a matrix transformer module having a balun like ferrite core, and having the secondary windings formed into the module. (The manufacturing steps in making this module are shown in Chapter I). The secondary windings are formed so through holes remain for the primary.

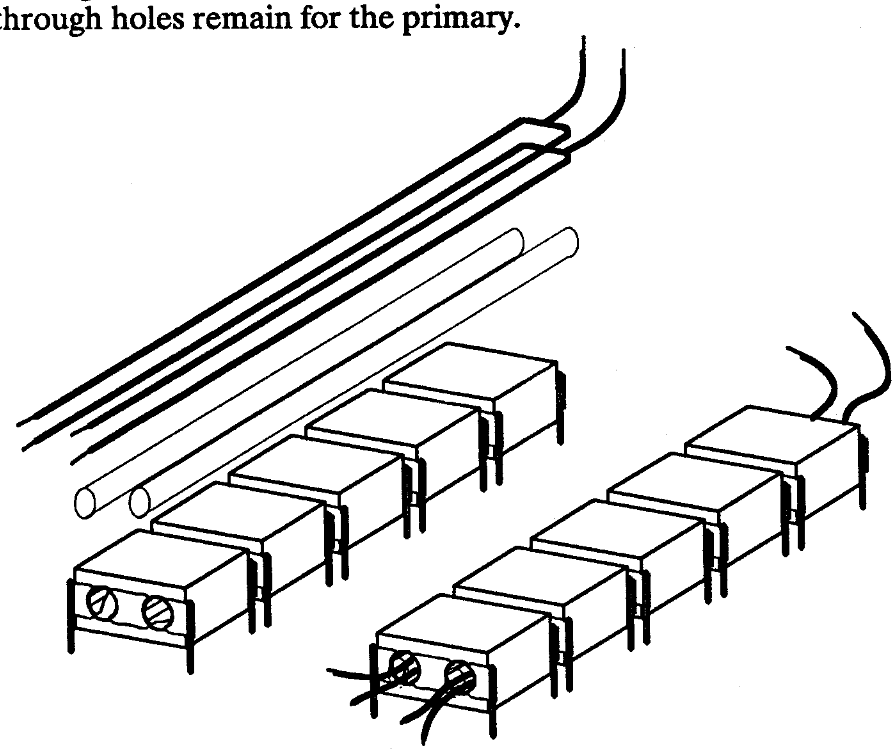


Figure 7.3. Matrix transformer modules are installed on a printed circuit board with their through holes aligned. An insulating sleeving is slipped through the aligned holes, then the primary winding is installed and terminated in the board.

Figure 7.3 shows five matrix transformer modules assembled into a printed circuit board. The modules are installed with their through holes aligned. Sleeving is passed through the holes, and the primary winding is installed. The design of the module is based upon a certain output voltage and frequency range. The number of modules, the number of primary turns and the duty cycle are determined by the primary voltage.

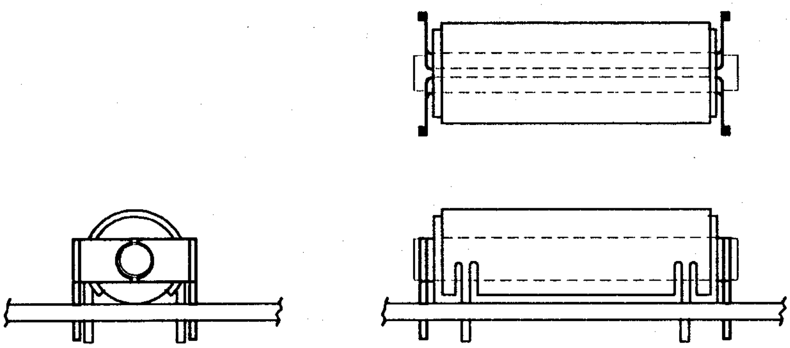


Figure 7.4. A matrix transformer module adapted for printed circuit board use in a picture frame transformer includes the secondary winding conductors.

a) Matrix Transformer Modules for Picture Frame Transformers

The matrix transformer modules shown in figure 7.4 are based upon the cores shown in figure 7.1. Secondary conductors conform to the sides of the bore, as shown in phantom, and pins are provided to plug into the circuit board. The two conductor, four pin module shown is the most versatile. Variations include a six pin module with two cores for a symmetrical push pull secondary, or with coaxial windings, both of which are discussed in later chapters. The equivalent inductor structure is made by incorporating an air gap or by using a low permeability cores.

The primary winding can be installed as the transformer is assembled to the printed circuit board.

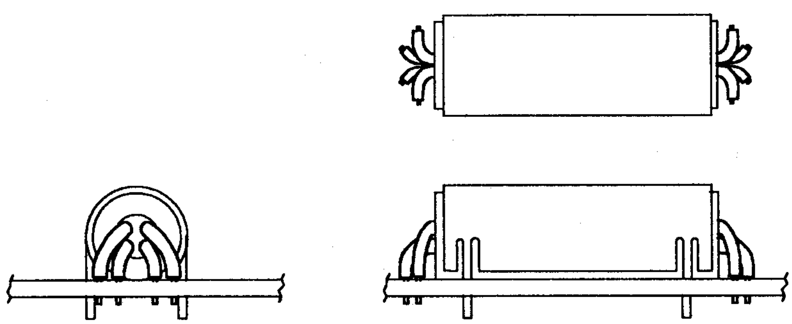


Figure 7.5. These picture frame matrix transformer modules have both the primary and secondary windings.

Figure 7.5 shows a picture frame matrix transformer module with four conductors. It is envisioned that two of the wires would be brought out as the secondary circuit, and the other two would be connected in series, module to module, as the primary winding. Figure 7.6 shows that the primary windings are installed immediately adjacent to the next modules, for minimum spacing and direct current flow.

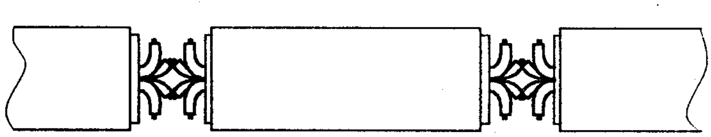


Figure 7.6. The modules are installed end to end in the printed circuit board.

B. Matrix Transformers with Printed Circuit Windings

There have been many transformers built using printed circuit windings, with special cores sandwiching the printed circuit board. Since they become single blocks when assembled, they share many of the problems of conventional transformers, particularly the thermal problems.

The matrix transformer uses a number of elements, each having only a few conductors. This means that the winding can be laid out with short, wide conductors, and without having to use multiple turn coils and crossovers or feed throughs. The magnetic return path is much shorter.

1. Picture Frame Matrix Transformers with Printed Circuit Windings

Figure 7.7 shows a hypothetical layout of a picture frame matrix transformer on a printed circuit board. The transformer is located around the edge of the printed circuit board, but set in enough so that the higher powered components can be optimally located for heat sinking around the edge. The center space is available for control and housekeeping circuits. Four layers, or perhaps six, are enough to interconnect the circuitry with good, heavy land lines.

A picture frame inductor can be located with the transformer.

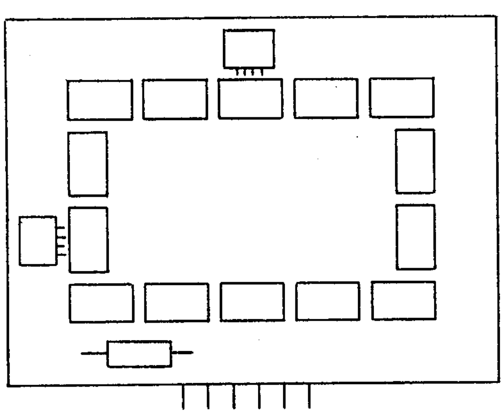


Figure 7.7. A printed circuit board matrix transformer has the power components around the edge, for best heat sinking. The control and housekeeping circuits could be in the middle. With fourteen elements as shown, the ratio is 14:1. With two primary turns, the ratio would be 28:1.

2. Cores for Printed Circuit Boards ‡

Cores for a printed circuit board matrix transformer can resemble dominos, with flux return paths which passed through the board. A flat plate cover would be cemented or clamped in place. Figure 7.8 shows a portion of a printed circuit picture frame matrix transformer, with a plain view and two sections. The cover of one of the cores is off, to show the flux paths in the corner posts.

The land lines preferably leave and enter the transformer at the sides of the cores, or at the corners. Spacing the cores apart sufficiently to provide conductors between them would waste space and degrade the high frequency performance.

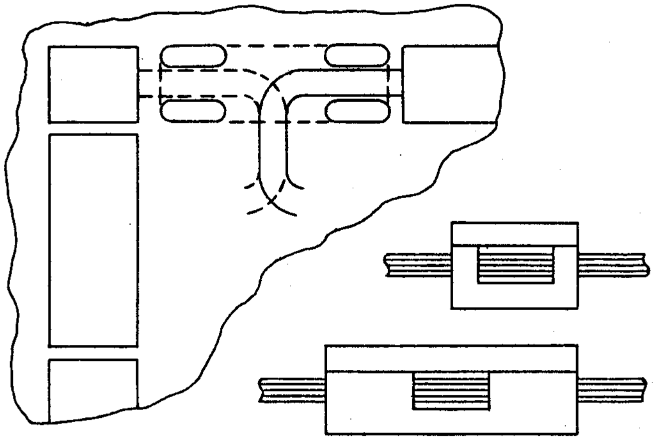


Figure 7.8. The cores for printed circuit board mounting can be domino like blocks, with the magnetic return paths passing through the board.

a) Closed Flux Paths

With the land lines leaving the sides of the cores, there is a closed flux path around the land lines as they leave. Any currents must be balanced, but that is the nature of the windings in a matrix transformer. The closed flux path helps to suppress common mode currents, such as might be coupled through by inter-layer capacitance.

C. Current and Heat Conduction

Designing power converters on a printed circuit board, whether using plug in magnetic cores or printed circuit windings with applied cores, requires careful attention to current and heat conduction.

These are related considerations, because ultimately the limitation to the amount of current that can be conducted is a thermal problem of managing I^2R losses and temperature rise.

1. Good Conductors Carry Heat and Current

Copper is an excellent conductor of both heat and current. Optimum designs require making the copper do double duty, carrying both current and heat. For both, the conductors should be short, wide and uninterrupted.

a) Distributed Sources

To maintain a low voltage drop (IR), the current density must be low. To maintain a low temperature rise, the heat flux density must be low. Both objectives are helped if the sources are distributed, the conductors are wide, and there is a large contact area at conducting interfaces.

The matrix transformer is ideal in many respects. The number of paralleled secondaries means that he current is sourced from a number of places. The output rectifiers are distributed, and they are a principle source of heat.

2. Planes, Thermal and Electrical

The best way to collect distributed heat or current is with planes. Ground plane, power plane, thermal plane, shield plane or whatever. For every plane, a substantial copper layer extending to the board edge provides optimum conduction.

a) Electrical separation

For good heat sinking, there must be an uninterrupted conduction path to the chassis and out. The electrical circuits, however, must be isolated. In a circuit board, that usually means that the conductor is interrupted by etching. Even a gap of a few mils, particularly in a buried layer, presents a very large thermal impedance. Glass epoxy is a very poor conductor of heat. None the less, a fairly thin layer of glass epoxy is adequate for electrical insulation. If there is substantial area, heat transfer between layers will be fairly good.

The implication of this is that a buried power or ground plane can still be an effective heat conduit if the dielectric insulation is thin and has large area contact with other planes which have a good thermal pathway off the board. Once the electrical plane has been interrupted for electrical isolation, it can and should continue on to the board edge to help with the thermal conduction. As long as breaks do not align, layer to layer, heat conduction will flow to adjacent planes and back, as shown in figure 7.9.

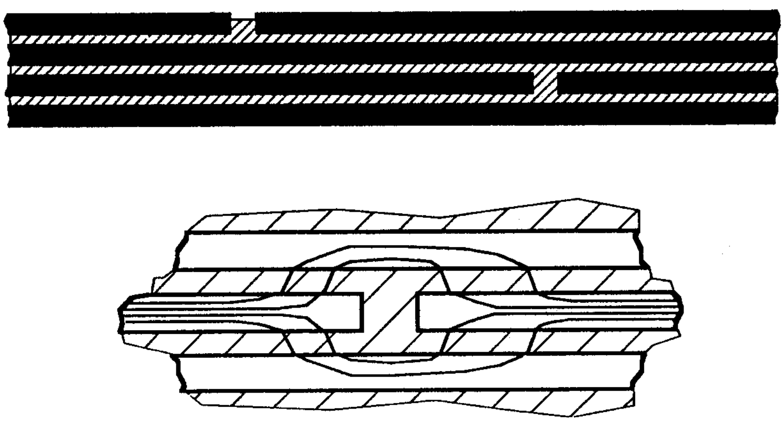


Figure 7.9. If copper planes separated by a thin insulating layer overlap with a sufficient area, heat will flow into the adjacent planes and back, around an electrically insulating gap.

b) Capacitive conduction

The same criteria that allow good heat transfer from layer to layer also allows capacitive coupling of high frequency signals. This can be beneficial or harmful, depending on where it occurs and what is conducted. An AC short between power and ground is beneficial, as is the shorting of noise into a shield. Conduction of noise into the chassis could be unfortunate for EMI control.

c) Wide Area Electrical Connections

To maintain low current density, the output current should not be collected, concentrated in one large cable or bus bar. It is far better to use a wide area connection, as distributed as possible. If connector pins must be used, a large number should be paralleled, along the long dimension of the board. A preferred method would be to make contact all around the board, or at least on two opposite edges.

3. Card Frames and Stiffeners

Pushing the limits of a printed circuit power converter to hundreds amperes is possible and practical, but problems of heat and current conduction are challenging, and require ingenuity to squeeze the last bit of performance from every part. A high power circuit board might benefit from the addition a card frame or stiffeners for mechanical integrity. These should be integrated into the design and used to help the heat and current flow.

Card frames and stiffeners are good places to mount small power components if they have a good thermal path to ambient. With forced air cooling, they can be especially effective as heat sinks. They also can be used as power and/or ground buses.

A card frame, consisting of two separate parts, one mounted to each side of a circuit board, would make an ideal power and ground bus for a high current supply.

D. Power Plane Matrix Transformer Module

A very high density matrix transformer and inductor power converter module has been propose which would be assembled and integrated onto a pair of very heavy copper sheets separated by a dielectric layer. A mechanical mock up was built, but it was not finished nor tested. Extrapolating from other breadboards which have been built and tested with similar circuitry, the power plane module should be able to handle about 1500 watts (300 amperes) at 5.0 VDC, with an input of 200 VDC.

1. Planes as Secondary Output and Heat Sink

The power plane module was built on two sheets of copper, about six inches square and 0.06 inches thick. The matrix transformer and matrix inductor cores were wound and mounted on the module, half on each side, complete with the primary and secondary windings. Provisions were made to mount the power semiconductors to the planes at the edges, again half on each side, with consideration given to balancing the voltage transients for noise cancellation on each side of the power plane.

All wires were kept as short as possible, and the five volt output was connected directly to the power plane. It was envisioned that the power plane converter would be built up including the transformer and inductor, with mounting provisions for the power semiconductors and output filter capacitors. The user would then add these parts and a piggy back control board of his own design to complete the power converter.

Power output and heat sinking would be from the card edges using specially designed card guides. See Chapter XXVII.

VIII. High Dielectric Isolation ‡

The matrix transformer is easy to insulate for very high dielectric isolation, without degrading its good high frequency characteristics.

If required, safety shields can be used. For critical applications a bonded intermediate winding can be used.

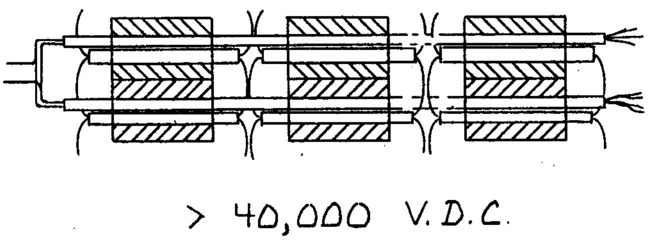


Figure 8.1. The limit of the test equipment was *40,000 VDC!* The insulation did not break down.

A. 40,000 VDC Dielectric

A sample of a matrix transformer was built using high dielectric insulation, as shown in figure 8.1. We tested it to the limits of the available test equipment, which was 40,000 volts DC, with no break down between the windings. There was some intermittent flash over, across the whole transformer, but when the holding fixture was rearranged, the insulation system was found to be intact. Our intention was to test the unit to destruction, but we were unable reach that level.

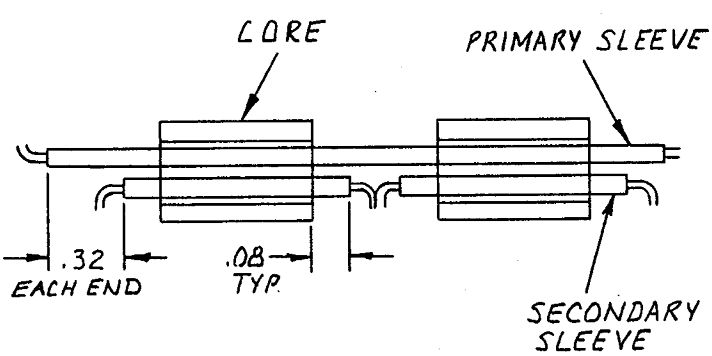


Figure 8.2. Sleeving extends beyond the cores to meet the creepage specified.

‡ U.S. Patent pending. FMTT, Inc.

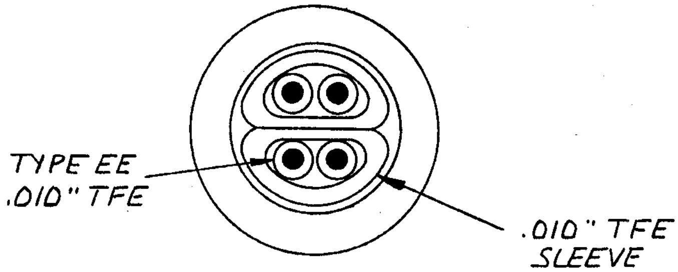


Figure 8.3. The wire insulation and the sleeving add to provide the required insulation thickness and number of layers.

B. Creepage and Insulation

The physical design parameters which were used to design the high dielectric matrix transformer test specimen are as follows:

Creepage:

Primary to core	0.32 in
Secondary to core	0.08 in
Primary to secondary	0.32 in

Insulation:

Primary to core	0.02 in, two layers
Secondary to core	0.02 in, two layers
Primary to secondary	0.04 in, four layers

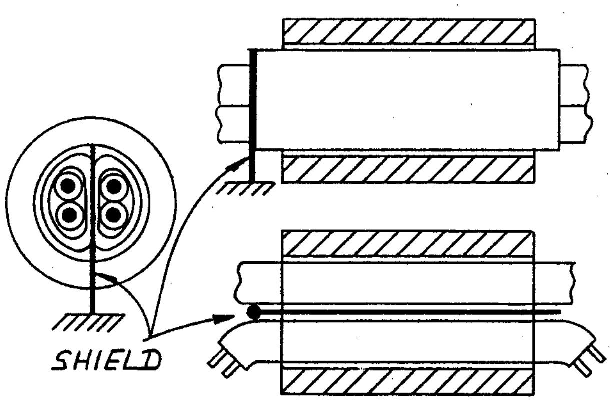


Figure 8.4. A shield can be added between the primary and secondary windings. The shield is bonded on one end only. It can completely inclose either or both windings.

Regular type EE hook up wire was used for both the primary and the secondary windings. This wire has a 0.010 nominal insulation thickness. 0.010 TFE sleeving was used to complete the insulation build up. The construction details are shown in figures 8.2 and 8.3.

1. Shielding

Shielding can be provided using a copper "flag" in each core, as shown in figure 8.4. The bond connection is made on one end only. None the less, the conduction path is very short, and it can easily be made to handle more current than the windings can provide with negligible drop.

The shield can be extended to wrap around either or both of the windings. Because there is a potential voltage induced in the shield, insulation must be provided where necessary so that there are no short circuit return paths. If all of the shields are grounded on one end, the other ends could provide convenient terminals for snubbing networks. Out of phase voltages could be coupled with appropriate RC networks. Since the shields will have very low inductance, attenuation of high frequency noise and ringing should be very good, and it should be particularly effective for snubbing ringing due to secondary parasitics interacting with primary parasitics.

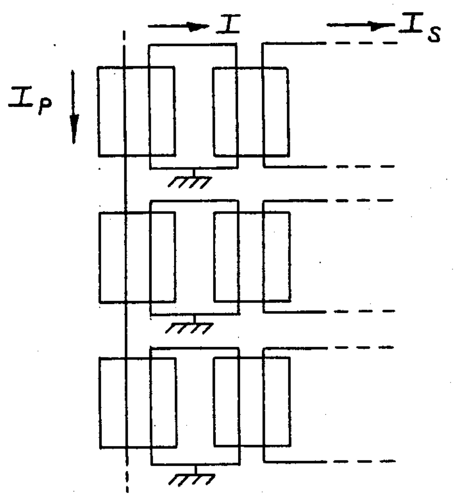


Figure 8.5. For maximum isolation, the primary and secondary are in separate cores, coupled by a bonded safety ground intermediate winding.

2. Safety Ground Intermediate Winding

Figure 8.5 shows that the primary winding can be put in one set of elements, with as much insulation as necessary, and the secondary can be put in an entirely separate set of elements. A short loop of wire can be used to link the elements, and that loop of wire can be bonded to the ground plane at any one point. The bond can easily handle any possible fault current.

If desired, the primary elements and the secondary elements can be on opposite sides of the ground plane. It is preferred to pair equal and opposite currents in the wires passing through the holes. (This occurs naturally if the transformer is a picture frame transformer.)

IX. Symmetrical Push Pull Matrix Transformer ‡ [7]

The symmetrical push pull matrix transformer with floating capacitors ‡ promises to be a significant advance in power converter design.

The input ripple current is nearly zero, and the transformer leakage inductance is decoupled from the switching FET's.

This section provides the background of the symmetrical transformer winding and the floating capacitors.

A technique for driving the FET's without isolation transformers is developed.

A. Symmetrical Push Pull Windings

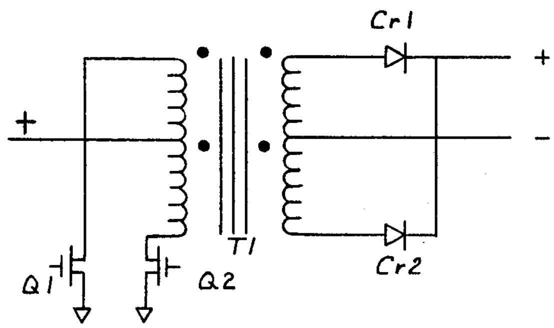


Figure 9.1. The familiar push pull windings.

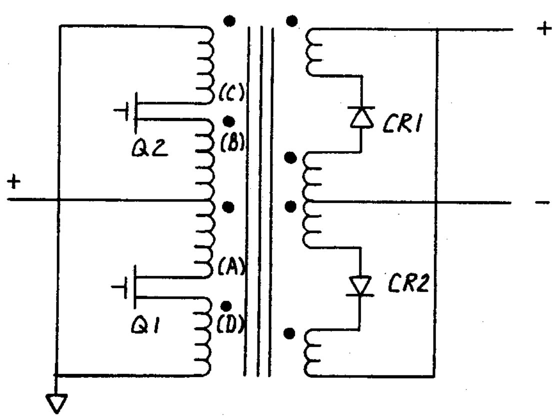


Figure 9.2. The symmetrically divided push pull winding.

There is a certain symmetry in any push-pull winding. The familiar push pull primary and secondary in a monolithic transformer is reviewed in figure 9.1. Since the push

‡ U.S. Patent pending. FMTT, Inc.

pull winding and its switches (FET's or rectifiers) are series circuits, the location of the components is arbitrary. However, the connection shown is used invariably, because it minimizes the transformer connections.

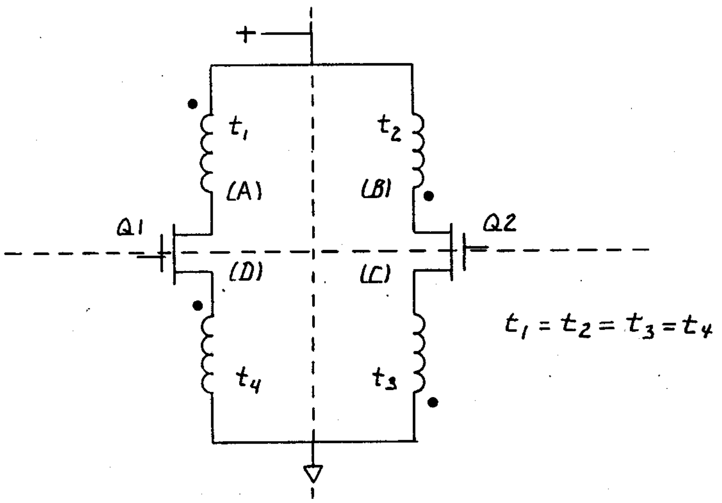


Figure 9.3. The symmetrically divided push pull primary circuit redrawn. There are equal turns in the four sections t_1-t_4.

1. Each Side is Divided Again

The "symmetrically divided push pull winding" further divides each half of the push pull windings in half again, as shown in figure 9.2. The name "symmetrical push-pull winding", or "symmetrical winding", has been adopted for this arrangement.

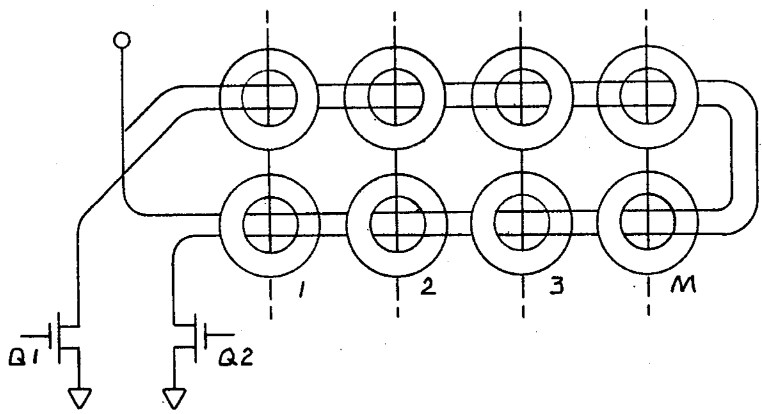


Figure 9.4. A push pull primary winding in a matrix transformer.

If the primary is redrawn as in figure 9.3, the symmetry becomes more apparent. The four sections t_1 through t_4 have equal turns, and the positive and negative inputs are center taps of t_1-t_2 and t_3-t_4 respectively.

We have not done any work with the symmetrical push pull winding in a monolithic transformer, but some of the attributes of the configurations discussed below might be advantageously applied. The recommended winding would be to take the start (dot end) of t_2 bifilar with the start of t_4, both center tapped to the respective supply voltage terminals, and continued bifilar through t_1 and t_3.

B. Symmetrical Push Pull Primary in a Matrix Transformer

Figure 9.4 shows a push pull primary in a matrix transformer of general dimension 2M x 2. Figure 9.5 shows the symmetrical push pull winding in the same elements. Note that the switching transistors (FET's) are on the *opposite end* of the transformer from the supply leads.

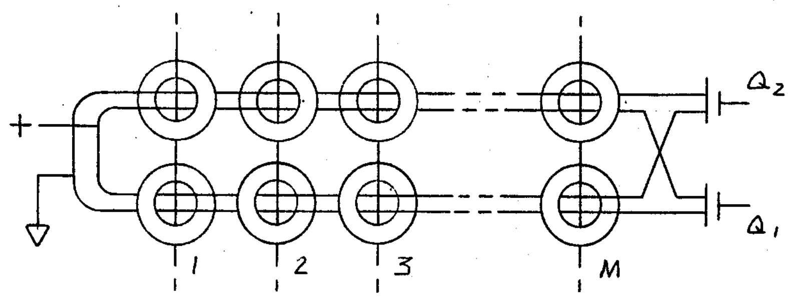


Figure 9.5. A symmetrical push pull primary winding in a matrix transformer. Note that the switching FET's and the supply voltage terminals are on *opposite ends*.

C. Voltage Waveforms

With reference to figure 9.6, it can be seen that the voltages appearing on the switches vary as half the supply voltage, but out of phase. Thus the switches still see two times line voltage, as with the conventional push pull primaries. Since the switch voltages both have large voltage swings, it would seem that transistor switches would have to have floating drives (transformer or opto-isolated base or gate drives). However a solution for this problem will be presented later in this section.

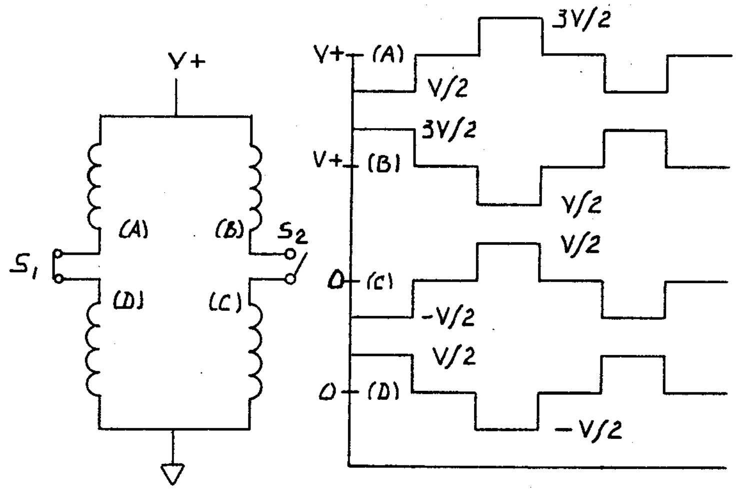


Figure 9.6. Ideal wave forms in a symmetrical push pull primary, as might be seen in a switch mode power converter.

D. Matching Voltage Wave Forms.

A comparison of the voltage on node A with the voltage on node C in figure 9.6 shows that they have the same wave form. This is also true of voltages at nodes B and D. Figure 9.7 emphasizes this relationship, and shows the idealized differential voltage between node A and node C. It is a DC voltage, equal to the input voltage.

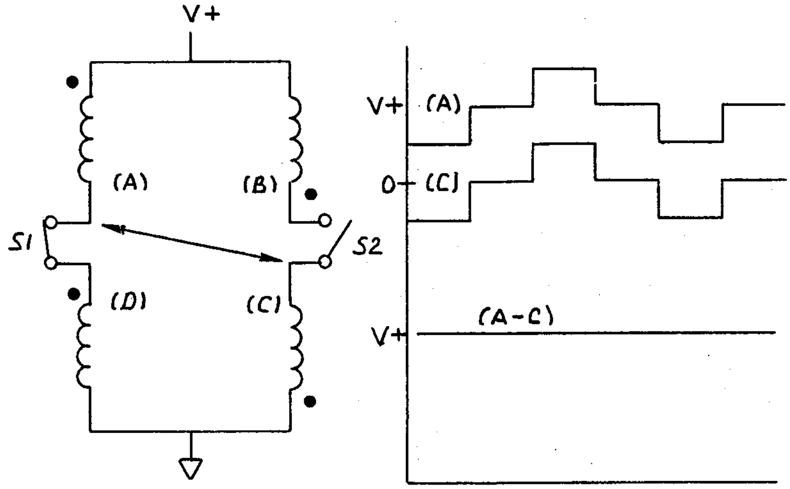


Figure 9.7. There is a constant potential between A and C.

1. Floating Snubbers

It was realized that these nodes should be ideal locations for snubbing networks as shown in figure 9.8. Because the voltage present is nominally a DC voltage equal to the input voltage, the only AC voltage would be due to noise and transients. Thus snubbers located here would not have losses due to the switching frequency.

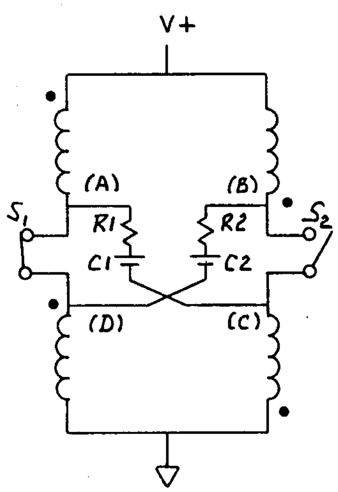


Figure 9.8. With no AC voltage except for noise and transients, snubbers should have low losses.

a) Floating Capacitors

However as we were optimizing the snubber component values, we noticed that the efficiency of the test bed converter got better and better as the capacitance value increased and the resistance value decreased. The best performance circuit is represented by the schematic of figure 9.9. In some circuits, it is desirable to use an R-C snubber to reduce ringing. This can be placed from "D" to "C", (source to source) where it provides effective damping, and does not discharge into the FET's when they are turned on.

b) Floating Capacitors in a Matrix Transformer

When the floating capacitors are installed in a matrix transformer, the schematic of figure 9.10 results.

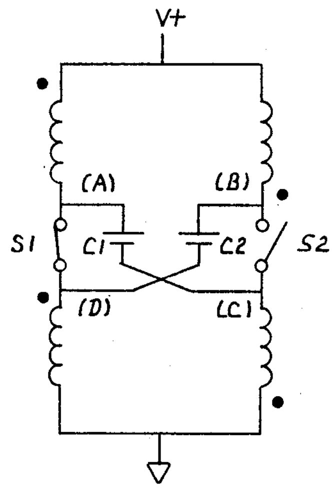


Figure 9.9. Tests showed that capacitors alone worked better.

c) Primary Circuit, (Quiescent)

The primary circuit with floating capacitors is redrawn in figure 9.11 without the switches, to represent the circuit during the "off" time, when both switches are open. An enlarged section of one of the elements shows the relationship of the flux in the core of the element to the symmetrical push pull windings.

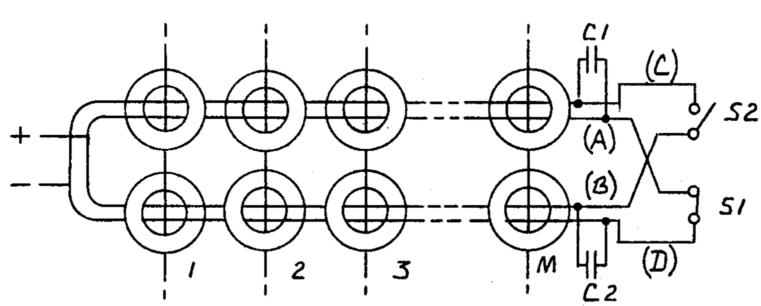


Figure 9.10. Floating ca pacitors in a matrix transformer with a symmetrical push pull primary.

d) Capacitor Charging Currents do not Couple Flux

Tracing the windings from the input terminals to the floating capacitor terminals shows that both go through the cores of the elements. As the result of the changing flux in the core, there are induced voltages as indicated in figure 9.11.

(1) The Voltage is Common Mode

Because the changing flux induces equal voltages in both windings in the element, the voltage is common mode to the capacitor. The changing flux cannot charge or discharge the capacitor.

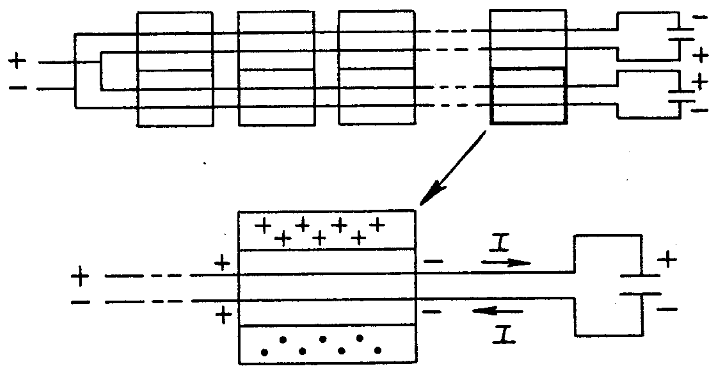


Figure 9.11. The symmetrical push pull primary during the "off" time. The floating capacitors connect to the input through the elements. Voltage induced from the core is common mode, and the net ampere turns when charging the capacitors is zero.

(2) The Net Ampere-Turns is Zero

The equal and opposite capacitor charging current from the input terminal is also seen to pass through the core of the element, so the net ampere-turns is zero. Without any net ampere-turns, there can be no magnetizing force (H), so the core cannot load the circuit.

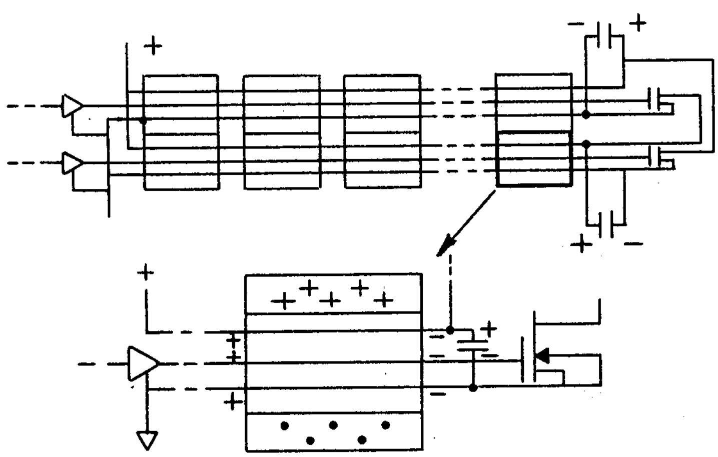


Figure 9.12. The gates of the FET's can be driven "through the bore". Any voltage from the cores in the gate wire and the source wire is common mode.

E. "Through the Bore" Gate Drive

Figure 9.12 shows that the gates of the FET's can be driven "through the bore". Voltages in the gate lead and the source lead are common mode. The base of a bipolar transistor can be driven similarly.

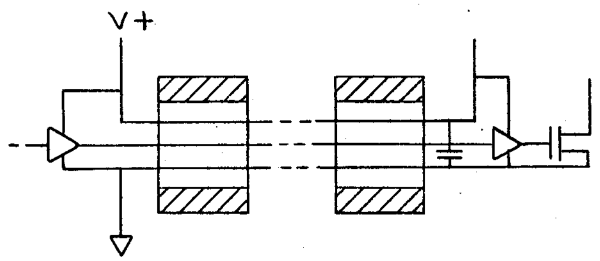


Figure 9.13. A partial schematic shows a "through the bore" logic drive. In this example, the input and the floating capacitors provide the Vcc for the logic.

1. With Floating Logic at the Gate

Figure 9.13 is a partial schematic showing that a buffer-driver circuit can be located next to each FET. By using a buffer at the FET, the drive through the bore of the transformer does not have to provide the power to drive the gate. Because the drive wires are in the same cores as the power windings, and the source lead is the circuit return, there is significant noise present, so the input to the buffer-driver should have a high threshold. Notice that the buffer-driver gets its power from the floating capacitor. The floating capacitor is a reasonably steady source of DC power, and is ideally located to provide the gate drive power.

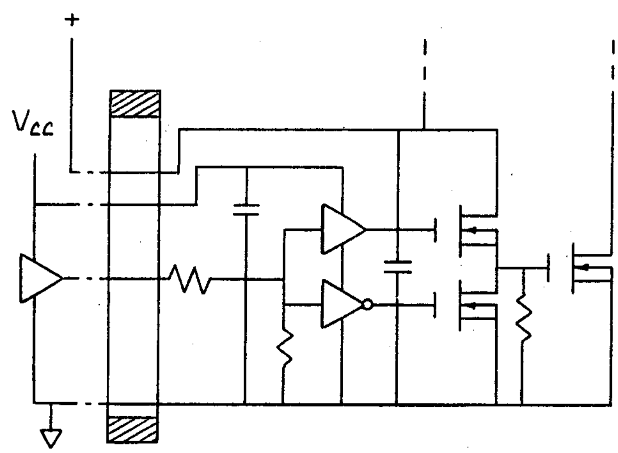


Figure 9.14. Vcc can go through the bore too, if the input voltage is too high.

a) Vcc Through the Bore

Often the voltage on the floating capacitor is too high to be suitable for logic power. It is equal to the input voltage. In this case the Vcc can also go through the bore, as shown in figure 9.14. In this circuit Vcc supplies the gate drive for a pair of totem pole FET drivers which in turn drive the main power FET. If Vcc is the source voltage for the gate drive of the upper totem pole driver FET, its output will be a source follower at a somewhat lower voltage. Thus the upper totem pole driver can derive its power from the floating capacitor, but still does not risk over driving the power FET's gate.

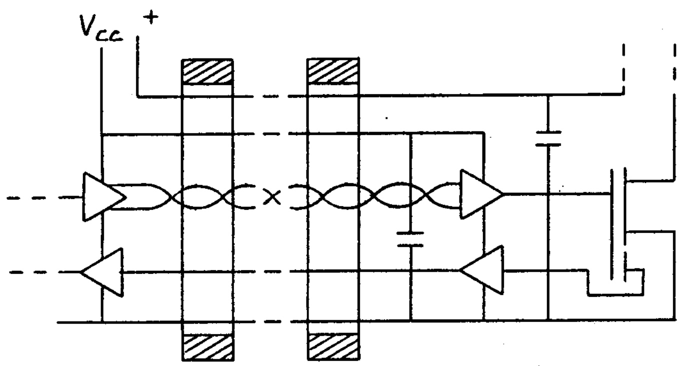


Figure 9.15. There really is no limit to what can be taken through the bore if care is taken to insure good noise immunity.

b) Everything Through the Bore!

Figure 9.15 shows a differential driver going through the bore, and a monitoring signal returning. In this example, an amplifier might monitor current in a current sensing FET.

X. Linear Symmetrical Push Pull Circuits ‡

The switching transistors in a symmetrical push pull primary can be used in the linear mode to limit or regulate the transformer voltage.

A. Source or Emitter Follower Circuit

With the switching transistors (FET's or bipolar NPN transistors) located at the mid point of the transformer winding, it can be seen that the circuit from the source or emitter to the ground terminal has the configuration of a source or emitter follower.

Usually the transistor will be driven as a saturated switch, either by a drive that is isolated and referenced to the source or emitter lead, or by a drive in which the gate or base drive has the same common mode voltage as the source or emitter. In either case, the source-ground or emitter-ground voltage does not affect the switch.

1. Voltage Limiting Circuit ‡

Figure 10.1 shows that if the gate leads of the switching FET's are clamped to a voltage which is referred to ground, such as a zener diode drop, the source voltage cannot exceed the voltage determined by the source follower circuit.

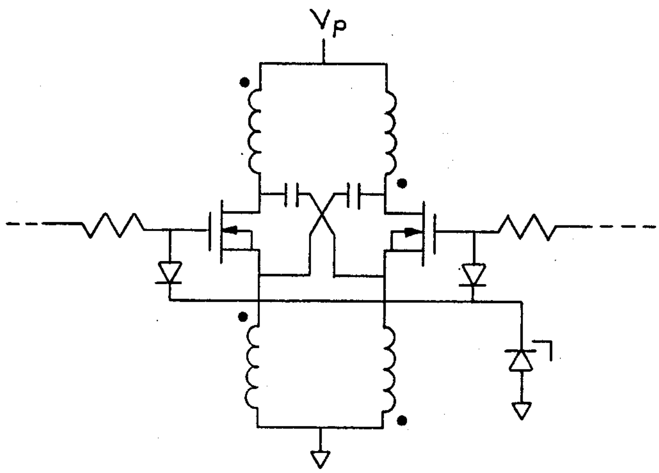


Figure 10.1. **If the gates of the FET's are clamped relative to the negative terminal of the symmetrical push pull transformer, the resulting source-follower circuit limits the maximum voltage seen by the transformer windings.**

If the voltage on any winding of the transformer is limited, the voltage on the whole transformer is also limited, and the drain to source voltage will rise to absorb the difference. It would be equivalent if the voltage source for the gate drive had a fixed limit with respect to ground.

The circuit of figure 10.1 can be used to limit the peak output voltage of the transformer during transient conditions, as long as the FET has sufficient power handling capacity. If only short duration voltage spikes are of concern, the average

‡ U.S. Patent pending. FMTT, Inc.

power would be low. The gate drive must have a high enough impedance, (or low enough stored charge) not to damage the zener diode.

Matching of the gate-source characteristics might be necessary.

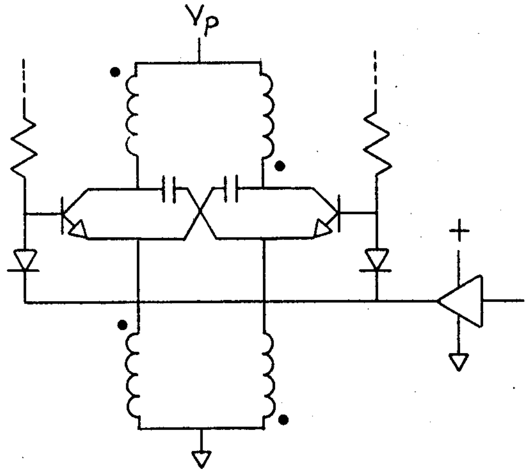


Figure 10.2. If the base voltage of the transistors is regulated, the resulting emitter follower circuit effectively regulates the transformer voltage.

2. Voltage Regulating Circuit ‡

Figure 10.2 shows an emitter follower voltage regulator in a symmetrical push pull transformer drive circuit. During the turn-on time, and rise-time, the base drive is unaffected by the regulator circuit, but once the diodes are forward biased, the transformer coil voltage would be limited by the emitter follower circuit.

This circuit might be useful to implement a current limit in a variable ratio transformer circuit.

‡ U.S. Patent pending. FMTT, Inc.

XI. Currents in Symmetrical Windings [11]

This section describes the current flow in the symmetrical push pull transformer.

When used with floating capacitors in the primary, the input ripple current is very low, and the switching FET's are decoupled from the primary leakage inductance.

A. Push Pull Primary Current Flow

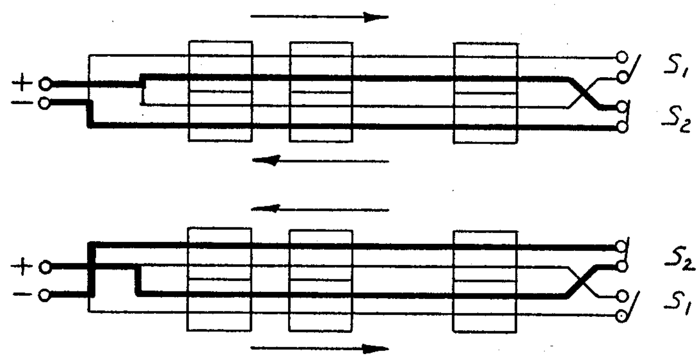


Figure 11.1. Current flow in a symmetrical push pull primary winding.

The current flow in a symmetrical push pull matrix transformer primary winding is shown in figure 11.1. With S_1 closed, there is a clockwise current flow from the positive input terminal, through the top row of cores, through the switch S_1 and to the negative terminal though the bottom row of cores. During the "off" time, with neither switch closed, there is no current path. With S2 closed, the current flow is reversed.

B. Primary Current Flow with Floating Capacitors

Once floating capacitors are added to the symmetrical push pull primary circuit, the current flow is more complicated, as shown in figure 11.2. The addition of floating capacitors can have a tremendously beneficial effect on converter efficiency. Improvements of ten to fifteen percent have been seen. The currents are conducted in both push pull windings, and the switching FET's are *completely decoupled* from the transformer leakage inductance.

If a current transformer is needed for current mode control, it can be put anywhere around the primary circuit. Figure 11.2 shows the preferred location.

1. Near Zero Input Ripple Current

Tests show that the input current at the positive and negative terminals is a DC current, with practically no AC ripple current. The AC component of the transformer current comes entirely from the floating capacitors. The floating capacitors behave like filter capacitors on the input, and at the high frequencies used, only a small inductance is required as the L part of an equivalent L-C filter. Stray inductances in the input leads and the circuit were sufficient to reduce the input ripple current to less than 1%.

2. *Floating Capacitors Provide AC Currents.*

The floating capacitors C_1 and C_2 are each nominally charged to the voltage of the input. As the switches are closed alternately, the capacitors are effectively placed in series, by the switch. With S_1 closed, the negative end of C_2 is connected to the positive end of C_1. When S_2 closes, the negative end of C_1 is connected to the positive end of C_2.

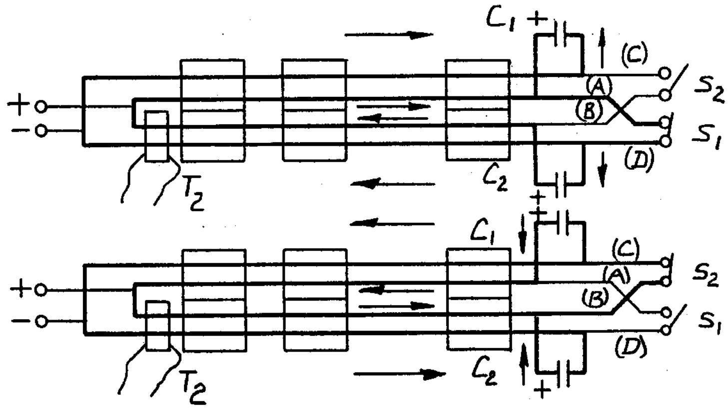


Figure 11.2. The current flow in the symmetrical push pull primary winding with floating capacitors. T_2 is an optional current transformer, if needed for current mode control.

3. *Rearrange Primary Schematic*

To better illustrate the current flow in the transformer, it is helpful to rearrange the primary schematic, as in figure 11.3.

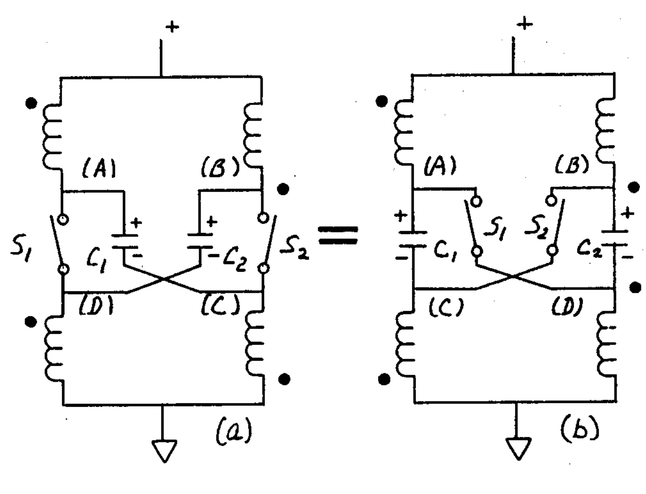


Figure 11.3. Rearranging the schematic of the push pull primary.

Figure 11.3 reviews the symmetrical push pull primary circuit (a), and also shows it redrawn (b), with the lower windings swapped, side for side, and the capacitors and switches changed accordingly. There is no difference in the schematics electrically, or in the physical model which they represent.

If the redrawn symmetrical push pull schematic is related to the pictorial diagram of the matrix transformer in figure 11.2, it can be seen that the path from the positive terminal to node A through C_1 to node C and back to the input negative terminal passes through the top row of cores. The circuit path to C_2 through the bottom row of cores is similar.

4. Rotary Switch Model

In figure 11.4, the switches, S_1 and S_2 of figure 11.3 have been replaced with a "rotary switch", and the three states of the switches have been identified.

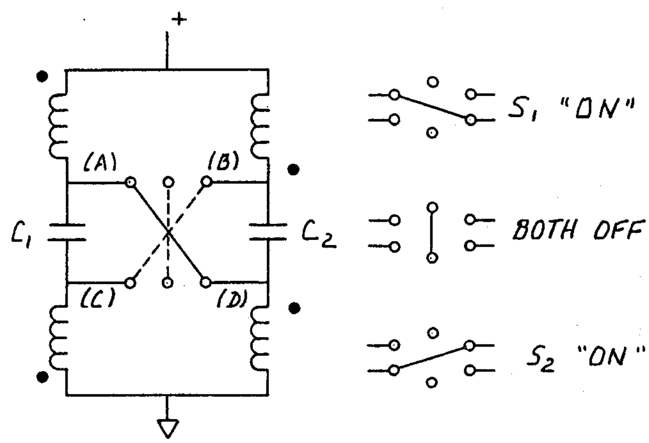


Figure 11.4. The switches are replaced by an equivalent "rotary switch". The three states, S_1 "on", both "off" and S_2 "on" are identified.

a) S_1 On

Figure 11.5 shows the current flow when S_1 is "on". The switch connects the negative end of C_2 to the positive end of C_1, effectively putting the capacitors in series. Since each capacitor is nominally charged to line voltage, this places two times line voltage between node B and node C.

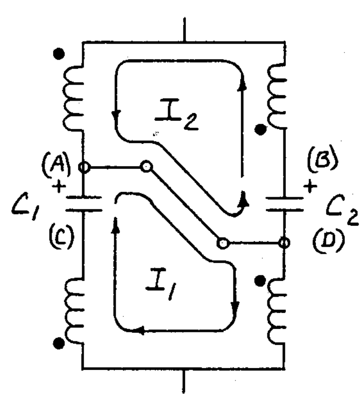


Figure 11.5. Current flow in the symmetrical push pull winding with S_1 "on". Both currents I_1 and I_2 are into the dots. $I_1 + I_2$ goes through S_1.

From another perspective, with the switch closed as shown in figure 11.5, there is a closed path from the positive terminal of C_2 into node B, through the winding to the positive terminal, through the other winding to node A, and then back to the negative end of C_2. Since C_2 is nominally charged to line voltage, the current I_2 will flow. A similar condition exists with respect to I_1. Note that both currents are out of the positive terminal of the capacitors, and into the dot ends of the windings. Note also that both currents ($I_1 + I_2$) go through the switch.

b) S_2 On

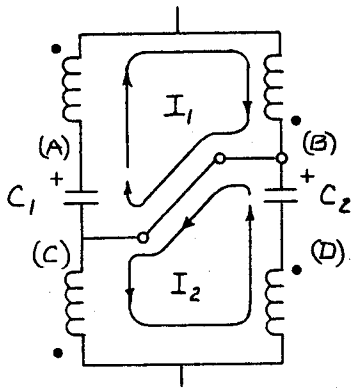


Figure 11.6. Current flow in the symmetrical push pull winding with S_2 "on". Both currents I_1 and I_2 are out of the dots. $I_1 + I_2$ goes through S2.

Figure 11.6 shows the currents in the primary winding with switch S_2 "on". I_1 and I_2 are redefined in this schematic, but they are equivalent to the I_1 and I_2 of figure 11.5, and remain associated with the capacitors C_1 and C_2 respectively having the same reference designator. The current flow is similar, but now the currents are flowing out of the dot ends of the windings. This phase reversal is necessary for push pull transformer excitation.

c) Off Time

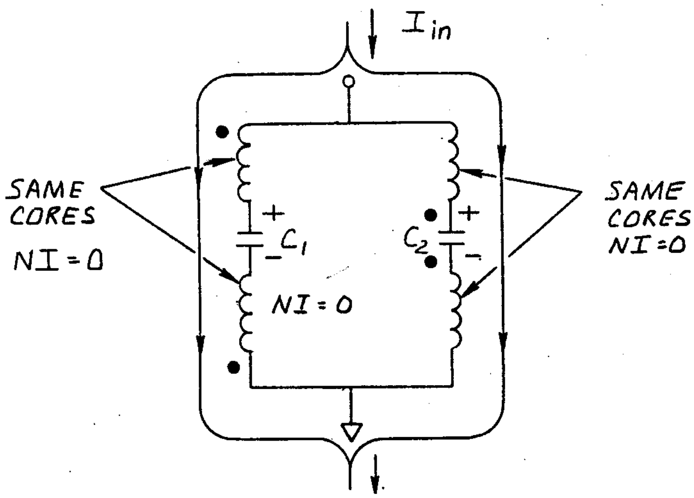


Figure 11.7. The "off" time schematic. The current I_{in} is actually present as a nearly ripple free DC current all of the time, superimposed upon I1 and I2 of figures 11.5 and 11.6.

During the "off" time, the floating capacitors are recharged, as shown in figure 11.7. Actual bench test measurements show that the input current I_{in} is a DC current with very little ripple. I_{in} is therefore always present, and is superimposed on I_1 and I_2 during the "on" times.

When used in a buck converter, the input current I_{in} is a function of the duty cycle and the load on the output of the converter. The peak primary currents, $I_1 + I_2$, equals the output current reduced by the inverse ratio of the transformer. I_{in} is $d(I_1 + I_2)$, where d is the duty cycle. This circuit behaves fundamentally as any other transformer coupled buck converter would.

C. Push Pull Secondary Current Flow

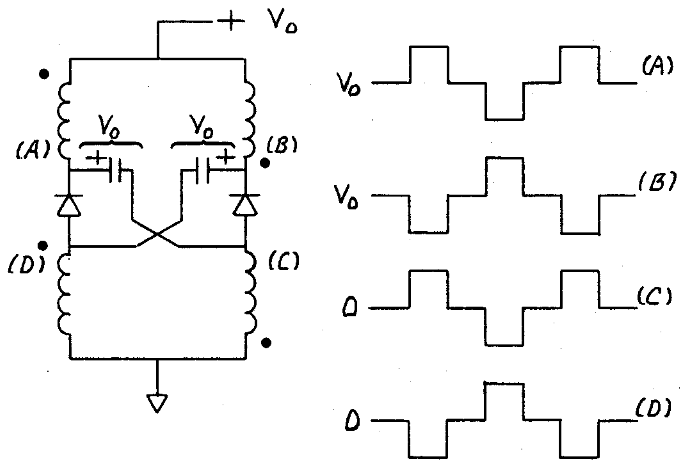


Figure 11.8. The symmetrical push pull secondary circuit with full wave rectifiers and floating capacitors.

Transformers, including matrix transformers, are completely reversible. Either winding can be the primary or the secondary, depending upon the application. The secondary can have floating capacitors too, as shown in figure 11.8.

1. Floating Capacitors Cannot be used with an Inductive Load on the Output

Floating capacitors tend to have quite high values, and they have a very low impedance paths to the transformer terminals. The capacitors cannot change voltage rapidly.

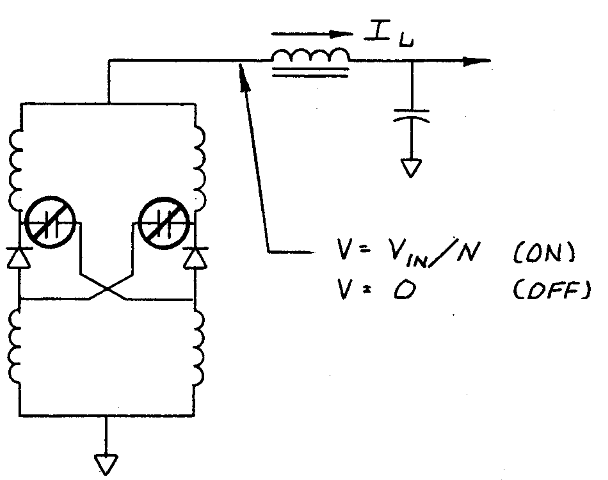


Figure 11.9. Floating capacitors *cannot* be used with an inductive load, or an L-C output filter.

With an inductive load, such as the L of the buck converter L-C output filter, the terminal voltage must change from V_{in}/N to zero and back twice in each cycle. This is obviously incompatible. See figure 11.9.

2. Secondary Current Flow with Floating Capacitors

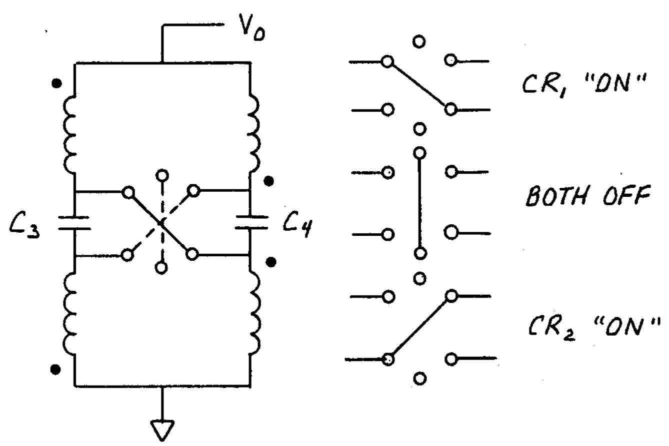


Figure 11.10. The "rotary switch" model for the secondary is very similar to the one shown in figure 11.4 for the primary.

With a compatible circuit, the current flow in symmetrical push-pull secondary circuits having floating capacitors is quite similar to the current flow observed in the primary. Because rectifiers are equivalent to a closed switch when forward biased, and an open switch when reverse biased, a rotary switch model similar to figure 11.4 can be used to model the secondary. This is shown as figure 11.10.

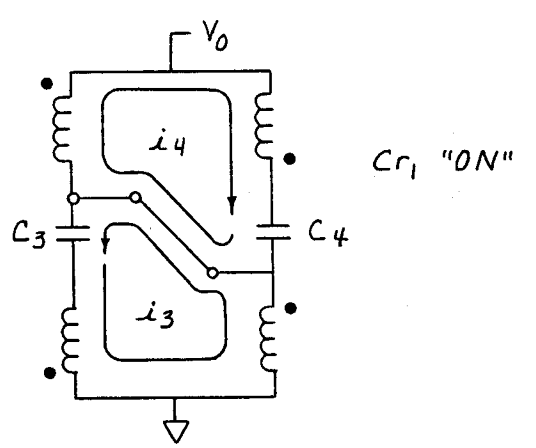


Figure 11.11. The current flow with Cr_1 conducting. Note that i_3 and i_4 are out of the dot ends of the windings. The current in Cr_1 is $i_3 + i_4$.

When S_1 is "on" (Cr_1 is forward biased), a current i_3 flows, charging C_3, and a current i_4 flows, charging C_4. C_4 and C_3 are in series. See figure 11.11.

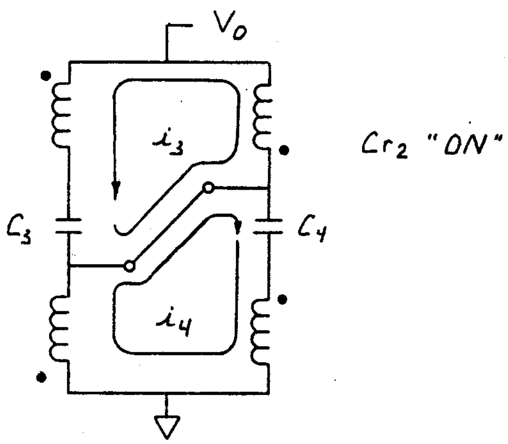


Figure 11.12. The current flow with Cr_2 conducting. Note that i_3 and i_4 are into the dot ends of the windings. The current in Cr_2 is $i_3 + i_4$.

When S_2 is "on", the currents flow in the opposite direction through the coils, but are still in the direction to charge the capacitors. See figure 11.12.

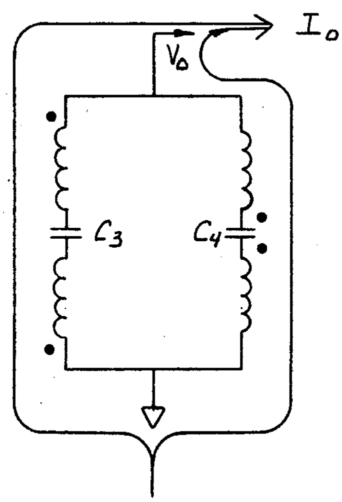


Figure 11.13. The current flow in the secondary when neither diode is conducting.

When S_1 and S_2 are both off (neither Cr_1 nor Cr_2 forward biased), current I_o can still flow to the output, as shown in 11.13. The output terminal voltage is the capacitor voltage.

XII. Leakage Inductance

In the symmetrical push pull transformer with floating capacitors, the leakage inductance of the primary is completely decoupled from the switching FET's.

To explain the mechanism of the decoupling phenomenon, first the dynamics at turn off will be reviewed as it occurs in a conventional push pull circuit. Then the distinctions between the conventional push pull transformer and the symmetrical push pull transformer having floating capacitors will be explained.

A. Dynamics at Turn off.

In the following discussion, the turn off dynamics of a push pull transformer coupled buck converter will be used, for illustration. Although a conventional (non-symmetrical) push pull winding is shown, the analysis would apply as well to a symmetrical push pull transformer which did not have floating capacitors.

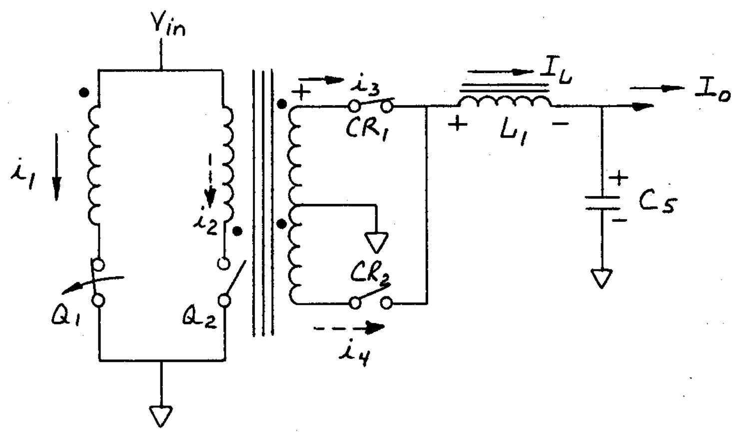


Figure 12.1. A schematic of a conventional push pull transformer in a buck converter circuit, showing the "on" time current flow. Q_1 opens at time t_o.

If a small enough time interval is defined, the currents in a buck converter will be the same just before and just after the switch, Q_1, opens. Figure 12.1 shows this condition.

After some time has passed, and all the transients are over, the primary current is zero. Because there is no current path in the primary, there can be no primary current. Lenz's law requires that there be no net current in the secondary. This is satisfied if the net ampere-turns is zero. Thus $i_3 = i_4$. This condition is shown in figure 12.2. Note that the filter inductor L is now a current source, continuing to supply current I_L. The voltage on the switch, v_{Q1}, equals the supply voltage, V_{in}.

In the following discussions, t_o is defined as the instant that Q_1 opens. With ideal components, the voltage on the switch would rise just to the input voltage, V_{in}. As anyone who has worked with switch mode power supplies knows, the voltage tends to be much higher.

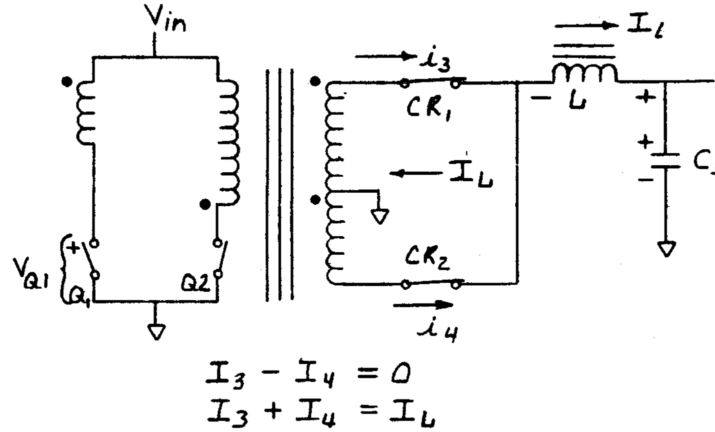


Figure 12.2. In the push pull transformer coupled buck converter at steady state during the "off" time, the voltage v_{Q1} across the switch Q_1 equals the input voltage V_{in}, and i_3 equals i_4. I_L equals i_3 plus i_4.

The primary circuit from the input terminal V_{in} through the transformer to the switch Q_1 is shown in figure 12.4. The transformer coil is shown as an ideal transformer winding T, in series with a primary leakage inductance l_1. Just after t_o, the voltage v_{Q1} on the switch has three identifiable parts, the input voltage V_{in}, a v_{lp}, the leakage inductance voltage from $l_1(di_1/dt)$ and a voltage from the ideal transformer coil, v_{t1}.

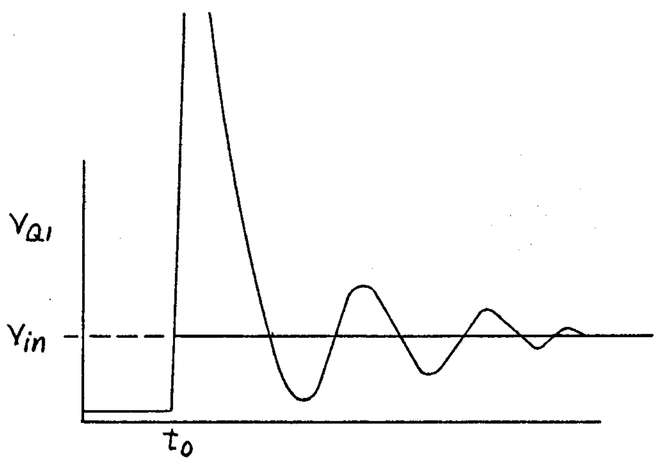


Figure 12.3. In an ideal transformer, the voltage on the switch Q_1 would rise to the input voltage V_{in}. In a real circuit, it is much higher.

1. Voltage from the Leakage Inductance

The voltage v_{l1} from leakage inductance l_1 is due to the changing current i_1 flowing in it. v_{l1} equals $l_1 di_1/dt$.

2. Voltage from the Transformer Core.

It is possible to separate the voltage due to the changing current in leakage inductance from the voltage coming from the ideal transformer coil. The leakage inductance l_1 is, by definition, uncoupled, so any voltage across v_{l1} will not induce a changing flux in the transformer core.

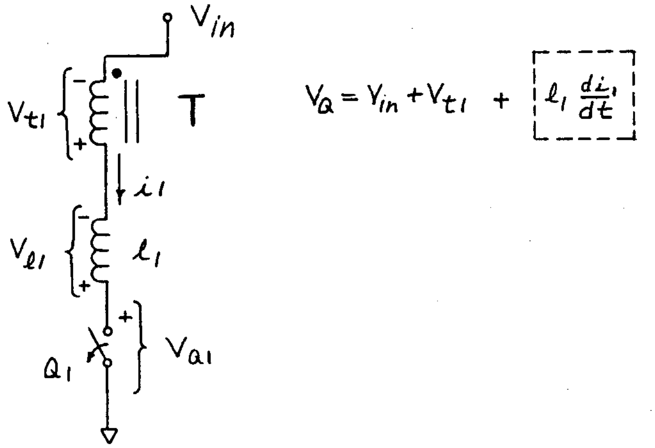


Figure 12.4. The equivalent circuit from the input Vin through the transformer winding to the switch Q1. The leakage inductance is represented by inductor l1, in series with an ideal transformer T.

The transformer voltage component v_{t1}, however, as it has been defined, does come from the changing flux. By Faraday's law, this voltage will appear on every winding on the core.

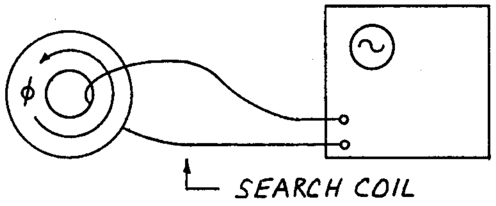


Figure 12.5. A search coil around the transformer core will reveal the actual voltage resulting from the changing flux in the core.

a) Search Coil.

Using the setup of figure 12.5, it is possible to see the voltage induced from the core on an oscilloscope. If care is taken with parasitics, any coil on the core could be used. In a transformer with a push pull winding, the other half of the transformer winding is not conducting current, and so it can be used in place of a search coil, as shown in figure 12.6.

In figure 12.6, channel 1 is the voltage v_{Q1} across the switch, including the voltage v_{l1} from the leakage inductance l_1, the supply voltage V_{in} and the induced voltage v_{t1} from the changing core flux. Channel 2 is the supply voltage, and also the induced voltage from the changing core flux, but with opposite polarity. By referencing the scope to V_{in}, the supply voltage becomes common mode, and is thus removed.

By then adding the traces, we can then display the difference, which is the leakage inductance $l_1(di_1/dt)$ voltage spike. It is probably not possible to operate a circuit without snubbers, and there are other parasitics which will modify the voltages seen, but the technique is useful for a qualitative analysis, and to get a rough idea of the sources of the transient voltage.

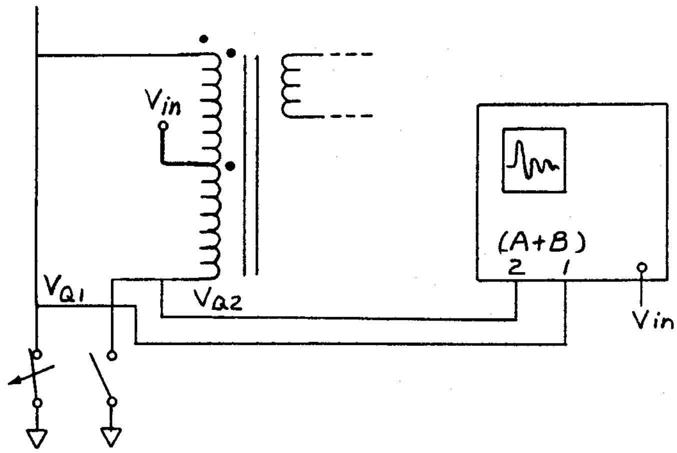


Figure 12.6. A good approximation of the leakage inductance voltage spike can be displayed on an oscilloscope by adding the voltage on the two sides of the primary. The effects of snubbers and parasitic capacitors will modify the voltage.

3. Oscillograph

An example is shown in figure 12.7. The top half shows the switch voltage and the voltage on the "other half"(inverted). The bottom trace shows the difference, which is the transient from the leakage inductance. This example is not from a conventional push pull transformer, however. It shows the leakage inductance spike in a matrix transformer with coaxial windings.

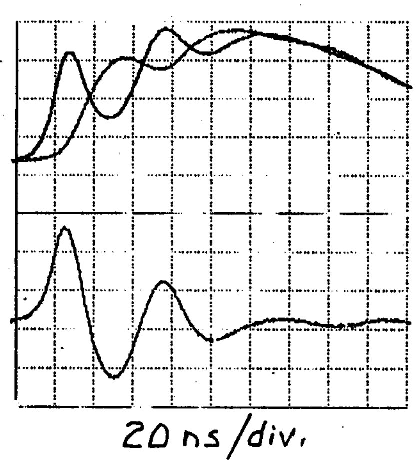


Figure 12.7. The bottom trace shows an oscillograph of the voltage transient from the leakage inductance in a matrix transformer with coaxial windings.

4. Analyzing the Transformer Coupled Portion of the Transient.

First, we will look at the secondary circuitry to identify contributions made by it to the transient, figure 12.8. The secondary leakage inductances are shown as l_3 and l_4.

a) The Output Filter Inductor becomes a Current Source.

With respect to the time interval of interest, the duration of the turn off transients, the current in the output inductor L can be regarded as constant, I_L. During the "on" time, the output inductor L was connected, through the transformer, to the input voltage, and was resisting an increase in current. Once Q_1 opens, not only is V_{in} removed, but the primary is now (theoretically) an open circuit. L therefore becomes a current source, reverses potential, and becomes a driver of the circuit.

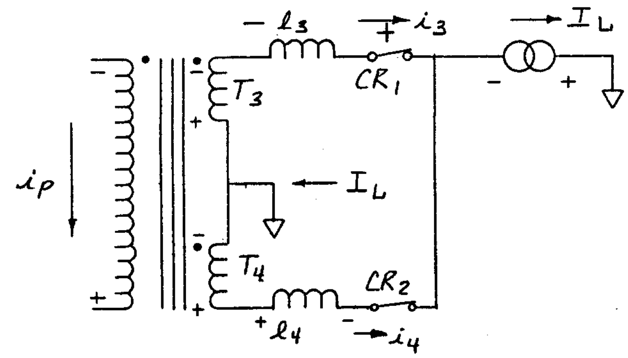


Figure 12.8. The secondary equivalent circuit in the buck converter just after turn off. The output inductor becomes a current source.

In the steady state, $i_3 = i_4$, but that cannot happen instantaneously, because both currents flow in circuits having inductance. This is shown in figure 12.8.

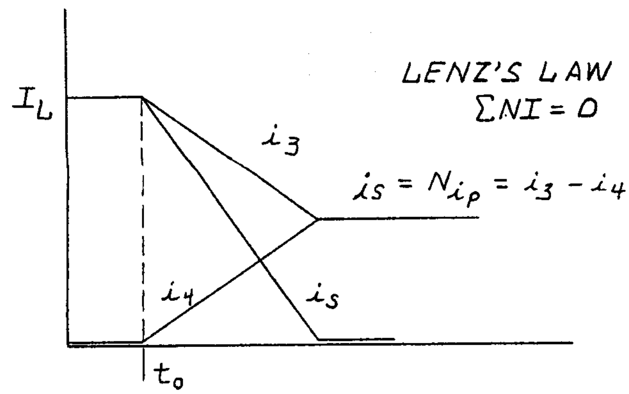


Figure 12.9. The secondary currents i_3 and i_4 cannot change instantaneously. Until they reach equilibrium, a primary current must continue to flow.

b) Difference Current Drives Primary

Because neither i_3 nor i_4 can change instantaneously, there will be a difference current $i_s = i_3 - i_4$ during the transition. Again by Lenz's law, there cannot be any net current in the transformer, so there must also be a primary current, i_p, related by the turns ratio, N. This is shown in figure 12.9.

c) Secondary Terminal Voltage is Zero.

Once current i_4 begins to flow at all, Cr_2 becomes forward biased, and both output terminals of the secondary are one diode drop above the common cathode connection, thus equal. Therefore the secondary terminal voltage V_s is zero, as shown in figure 12.10.

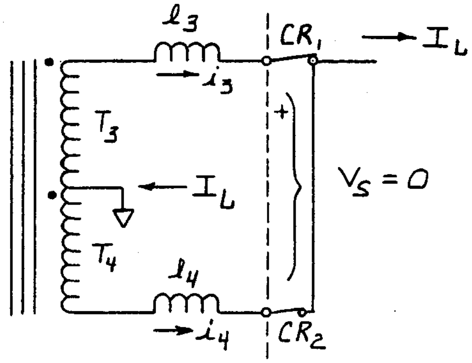
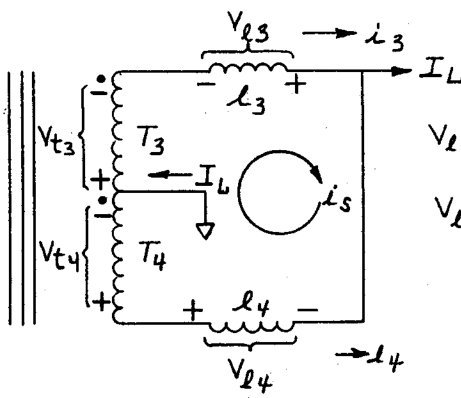


Figure 12.10. Once current i_4 begins to flow, the voltage across Cr_2 is the same as the voltage drop across Cr_1. Since the transformer secondary terminals are both one diode drop above the common cathode connection, the voltage difference is *zero*.

Because the secondary terminal voltage is zero, it is possible to sum the voltages around the secondary loop, as defined in figure 12.11. The secondary loop current i_s is the difference between i_3 and i_4. It can be see that its value will be I_L during the "on" time, and zero during steady state "off" time, so its definition is consistent with the current i_s defined in figure 12.9.



$$V_{l3} = l_3 \frac{di_3}{dt}$$

$$V_{l4} = l_4 \frac{di_4}{dt}$$

$$i_s = i_3 - i_4$$

$$V_{t_3} + V_{t_4} + V_{l_3} + V_{l_4} = 0$$

Figure 12.11. Because the terminal voltage is zero, it is possible to write the loop equation for the secondary in terms of the difference current i_s. T_3 and T_4 are ideal transformer windings, with the leakage inductance represented separately as l_3 and l_4.

d) Filter Inductor is not a Factor.

Note that the filter inductor dropped out of the analysis. It provides the driving current that forced Cr_2 to become forward biased, therefore shorting the secondary. The results would be the same with any other mechanism that short circuited the secondary.

e) Leakage Inductance Voltage Forces Voltage in the Transformer.

Because the loop voltage is zero, the voltage appearing on the transformer turns must equal the voltage on the leakage inductances due to l(di/dt). In other words, there must be an induced voltage on the transformer core which is equal and opposite the voltage due to di/dt in the secondary leakage inductances. This is the only way that the loop voltage can be zero, and still have changing currents in the secondary leakage inductances.

f) Secondary Transient Voltage in Primary.

The secondary circuit is simplified, and shown in figure 12.12 as driving a primary current i_p. It is a bit of an exercise to keep the units straight when consolidating the split windings into a single winding model, but it is qualitatively correct.

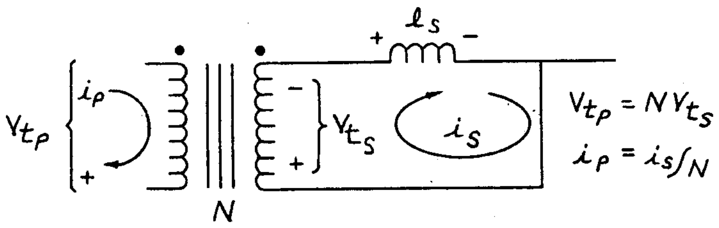


Figure 12.12. The secondary is lumped into an inductor l_s in series with the transformer secondary winding. Lenz's law requires that there be a primary current equal to the secondary current divided by the turns ratio N.

The transient voltage resulting from the secondary $l_s(di_s/dt)$ depends upon the primary impedance seen by the primary current i_p. The schematic of the secondary driving the primary is shown in figure 12.13. There being two open switches, the voltage should go to infinity. Do not loose track though, that at the first instant, when the switch opened, i_p is the primary current i_1 that was flowing during the "on" time, and the secondary current i_s is the output current, I_L.

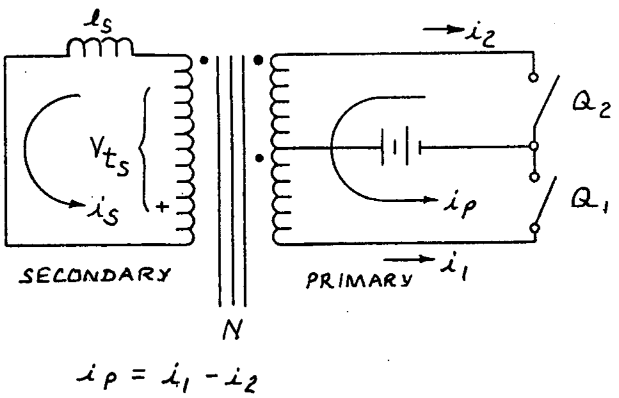
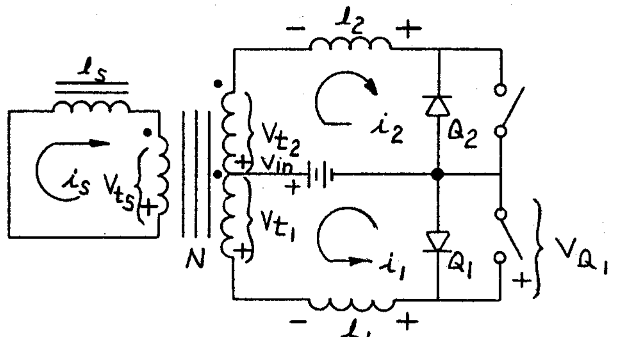


Figure 12.13. There being two paths in the primary, we can define two currents i_1 and i_2. The difference is defined as i_p.

g) Same Current, Different Winding

This qualitative analysis might seem to have come a complete circle, but not quite. After all, it was switch Q_1 opening that started the whole sequence, and i_p cannot flow there. Figure 12.14 expands the primary circuit, and shows the body diodes of the switches Q_1 and Q_2 (assumed to be MOSFET's). Being driven by the secondary, the transformer voltage has reversed, and if the voltage exceeds the supply voltage V_{in}, the body diode of Q_2 becomes forward biased, and i_2 can flow.



$$V_{Q_1} = V_{in} + V_{t_1} + l_1 \frac{di_1}{dt}$$

$$V_{t_1} = V_{t_2} = V_{in} + l_2 \frac{di_2}{dt}$$

Figure 12.14. The primary circuit model is expanded to show the body diodes of the switching FET's Q_1 and Q_2, and the leakage inductances l_1 and l_2.

Assuming Q_1 opens at time t_o, and current flow stops, and further assuming that $i_s/N = i_p$ must persist, a current transition must occur in the primary as shown in figure 12.15. (The non-zero rise and fall times presume some cross over current, or flow into a snubber).

Taking the voltages around the loop defined by i_2 in figure 12.14, we see that the ideal transformer voltage v_{t2} equals the input voltage V_{in} plus the voltage across the leakage inductance, $l_2(di_2/dt)$.

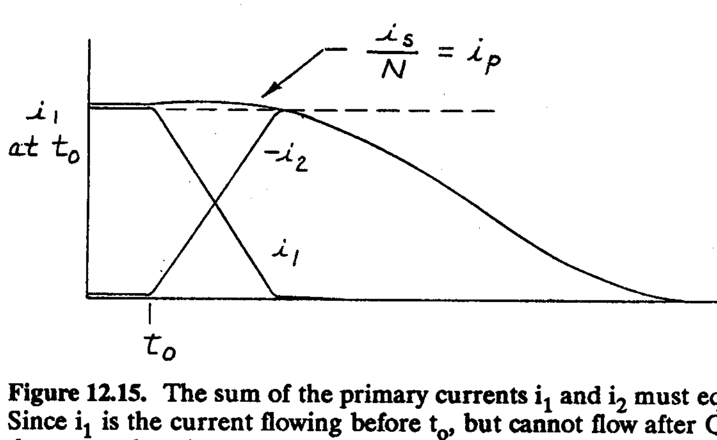


Figure 12.15. The sum of the primary currents i_1 and i_2 must equal i_s/N. Since i_1 is the current flowing before t_o, but cannot flow after Q_1 opens, there must be a fast transition.

By Faraday's law, v_{t1} equals v_{t2}. Thus the turn off transient voltage is dissected.

B. With Floating Capacitors, there is No Spike!

When turn off of Q_1 occurs in a buck converter using a symmetrical push pull transformer with floating capacitors, much of the same dynamics results. However, its effect is minimized by the current flow patterns in the primary winding.

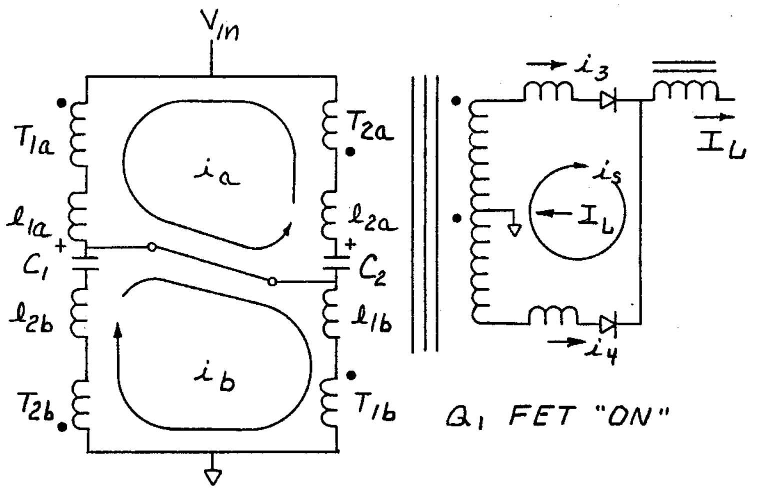


Figure 12.16. The current flow in a model of the symmetrical push pull primary winding and a buck converter secondary during the time that Q_1 is conducting. Note that i_a and i_b are both into the dot ends of the windings, and tend to discharge the capacitors C_1 and C_2.

1. Secondary Turn Off Dynamics

All of the discussion above as it relates to the secondary turn off dynamics remains the same. As soon as the drive from the primary is removed, the output inductor becomes a current source, and forward biases the second rectifier, thus short circuiting the transformer secondary. Until such time as i_3 equals i_4, the difference current i_s persists. The secondary difference current i_s also requires a primary current i_p to satisfy Lenz's law until the difference current has decayed to zero.

2. Before and After Primary Currents

Before turn off at t_o, the primary currents are as shown in figure 11.5. This diagram is expanded upon to become figure 12.16, which also shows the leakage inductances, and the secondary circuit in its "on" time state. Note in particular the primary currents i_a and i_b.

Just after turn off at t_o, the leakage inductances in the secondary have become the drivers, and the primary has become a symmetrical push pull secondary with floating capacitors, with current flow as shown in figure 11.11. This diagram is expanded upon to become figure 12.17, which also shows the leakage inductances, and the secondary, in its state as a driver, just after t_o. Note in particular the primary currents i_a and i_b.

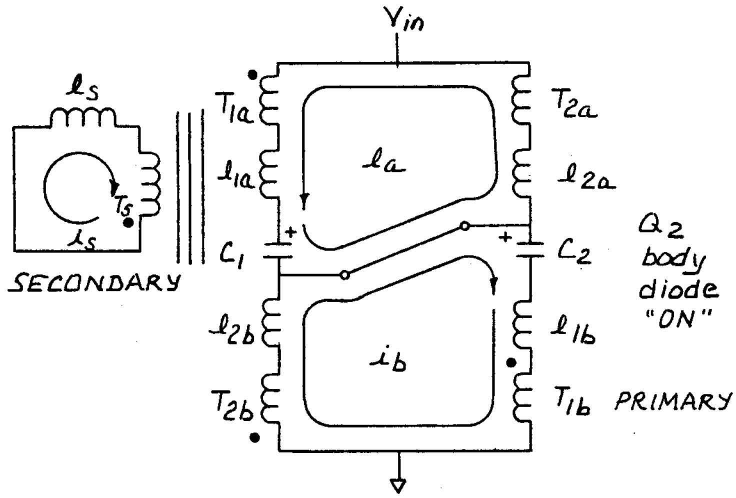


Figure 12.17. The current flow in a model of the symmetrical push pull primary winding and a buck converter secondary after Q_1 has turned off. The body diode of Q_2 is conducting, driven by the leakage inductance l_s of the secondary. Note that i_a and i_b are still both into the dot ends of the windings, but now tend to charge the capacitors C_1 and C_2.

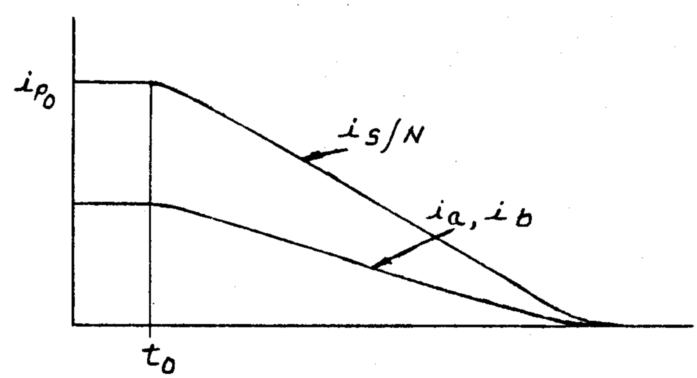


Figure 12.18. The primary currents i_a and i_b in the symmetrical push pull transformer with floating capacitors does not change instantaneously at t_o. The currents ramp to zero at a rate determined by the input voltage.

3. i_a and i_b do not change at t_o!

Note that in figure 12.16 and 12.17, i_a and i_b are the same, before and after t_o. This is shown graphically in figure 12.18. Once turn off has occurred, the secondary leakage inductance sees only the capacitance voltage (equal to V_{in}) reflected by the turns ratio N. This voltage divided by the net inductance l_t determines di/dt, (di/dt = V_{in}/l_t), which ramps linear to zero (ideally--actually it tends to overshoot, and ring).

Although the current in the transformer windings did not change, the currents have reversed in the capacitors C_1 and C_2, and whereas Q_1 was conducting during the on time, it is the body diode in Q_2 that conducts initially during the off time, once the transformer voltage has reversed. Thus there is no "instantaneous" di/dt in the primary leakage inductances. The only inductance in which current changes "instantaneously" at t_o is the lead inductance of the FET's Q_1 and Q_2 and of the capacitors C_1 and C_2, and their interconnections. This inductance can be kept small.

4. Reversing Current Flow Limits Duty Cycle.

Although the mechanism described above allows the turn off voltage spike to be clamped, and the turn off transient to be well behaved, it still puts a limit on high frequency operation. During the time when the current is flowing "backward", turning on Q_2 will not terminate the off time. The current will continue to flow. Until it reverses, and has built up to equal the reflected current in the output inductor L (with due account of the turns ratio), both rectifiers in the secondary will be conducting, the secondary terminal voltage will be zero, and no voltage appears on the output inductor.

Thus the time that the current takes reversing in the transformer windings limits the realizable duty cycle, even if the control circuit were to try to go to 100%. This emphasizes the importance of minimizing the transformer inductance even if the transients can be made to be well behaved.

C. Zero Volt Switching is Possible

Just after t_o, there is an opportunity for zero voltage switching. When the current is flowing through the body diode of the "other" FET, Q_2, there is "zero" voltage across the switch. If Q2 is turned on during this time, zero volt switching is achieved. This can substantially improve the efficiency of the circuit. Unfortunately, voltage control is lost because it precludes using pulse width modulation.

If voltage control is not needed, or is implemented in another way, such as with a variable turns ratio or a preregulator, switching turn on losses can be essentially eliminated.

XIII. Matrix Capacitor ‡

The matrix capacitor has a plurality of leads like a bed of nails across its surface, interconnecting the plates in a matrix, or grid pattern, for very low inductance, high current capability, and heat sinking.

A. Minimizing the Turn Off Voltage Spike.

In the symmetrical push pull transformer with floating capacitors, the turn off transient seen by the switching FET's is determined largely by the inductance of the partial circuit shown in figure 13.1 consisting of the two FET's, the floating capacitors, and their interconnections. Very high turn off di/dt's are possible if this inductance can be kept low.

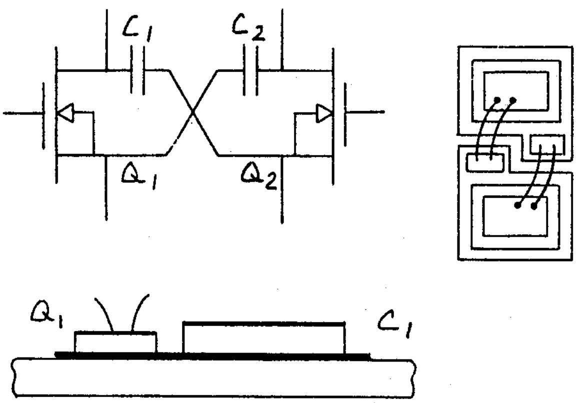


Figure 13.1. In a matrix transformer with symmetrical push pull windings and floating capacitors, the transformer leakage inductance is decoupled by the floating capacitance. Very large di/dt's are possible if the inductance of the FET's, the floating capacitors and their interconnections can be kept small.

To meet this objective, it is proposed that a *matrix capacitor* be used, mounted on a pad that is the extension of the drain metalization, and connected with very short leads to the source of the other FET. A proposed layout is shown in figure 13.1.

1. Minimizing the capacitor parasitic inductance

To substantially reduce the parasitic inductance in the capacitor, the matrix capacitor has a large number of leads, arranged in a grid across its surface, alternate pins contacting one or the other of the two capacitor plate stacks via through holes. For each pin, there is dielectric clearance to one set of plates and contact with each layer of the other set.

Although other terminations are possible, the alternating pins could terminate in top and bottom metal plates as shown in 13.2. The bottom plate with its pins would be a good heat sink as well as a high current termination.

‡ U.S. Patent 4,916,576, FMTT, Inc.

In manufacturing the matrix capacitor, techniques can be borrowed from the filter pin connector capacitors and the discoidal feed through capacitor. The metalization of the plate layers would have to clear alternate holes and come to the edges of the others.

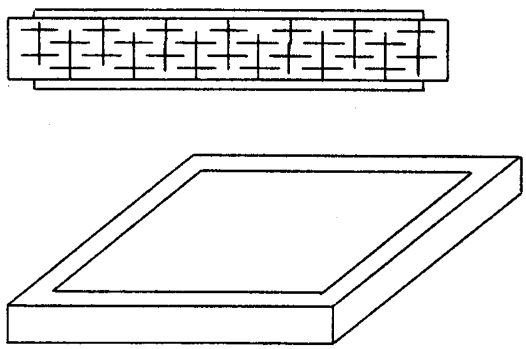


Figure 13.2. A proposed matrix capacitor. The two sets of capacitor electrodes are connected using a "bed of nails" interconnection to surface plates.

2. Large, Heavily Metalized Holes

The capacitor element could be a multi-layer ceramic capacitor, or a film capacitor. As shown in figure 13.3, the holes are preferably large enough that heavy metalization can be used, and large enough to keep the current density around the holes low. In the symmetrical push pull transformer with floating capacitors, the capacitor provides all of the AC current.

A variety of methods are available to make contact with the dielectric plates in the holes in the matrix capacitor. For small geometries, a bus wire soldered in would do, just as in some discoidal feed through capacitors. In larger geometries, differences in thermal expansion must be considered. The contact should either be compliant, or have a slip-friction contact, or have a matched temperature coefficient.

If a short length of oversized tubular tinned copper braid is inserted into a solder metalized hole, the solder could be reflowed to bond the braid to the bore. If a soft solder is used, a very sound, very compliant connection should result.

3. Stress Relieve the Terminal Plates

For many applications, terminating the internal leads of the matrix capacitor to two flat plates, one on each side, would provide the lowest inductance, highest current connection. As with the leads, mismatch of the thermal coefficients of expansion must be prevented, and would be particularly critical on larger geometry devices. Again the choices are a compliant connection, a slip-friction or compression connection or matching the temperature coefficients of the materials.

Flat braid or screening could make a compliant connection. Higher precision could be achieved with a pierced and folded copper foil. A series of holes could be pierced or etched into a sheet of copper. It could then be folded through the holes in two directions to make a series of standing ridges for stress relief.

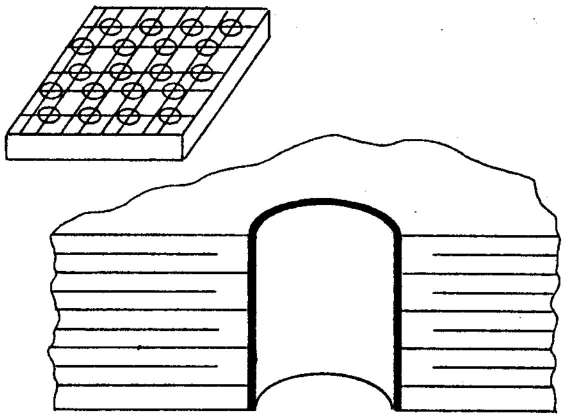


Figure 13.3. The holes in the capacitor should be large, to allow good metalization, and to keep the current density low around the terminals.

B. Three and Four Lead Matrix Capacitors

Given a capacitor that has a large number of parallel, low inductance leads, the possible connections are limited only by the imagination of the design engineer. For many applications, the capacitor would be mounted to a printed circuit board, and the application specific connection would be implemented by the etch pattern. Other applications would benefit from a discrete package, terminated as required. The discrete package could be heat sinked, and could include film resistors or ferrite materials to make snubbers or filters.

In some circuits, such as in input line filters, the matrix capacitor can be configured as a three or four terminal capacitor. DC current could pass through the capacitor foils, in one group of the leads, through the foil and out though other leads. Control of the current density would be particularly important. Alternatively, it could be used as a superior feedthrough, with many parallel paths and many ground returns.

XIV. Coaxially Wound Matrix Transformers ‡

Coaxial windings, particularly coaxial push pull secondary windings, offer advantages in matrix transformer design.

The side to side coupling can be improved, which reduces the secondary leakage inductance. The coaxial winding can be designed to provide superior heat sinking to the transformer core, it can provide a convenient modular secondary construction, and it leaves a through-hole which is optimum for installing the primary windings.

A. Reduced Secondary Leakage Inductance

In section XII, Leakage Inductance, the difference current i_s in the leakage inductance l_s in the secondary was identified as the principle source of the energy returned to the primary during the turn off transient. The energy is 1/2 $(l_s I^2)$, and at the turn off time t_0, the current is always equal to the output current. Therefore, the only opportunity to reduce the stored energy is to reduce the leakage inductance l_s.

Leakage inductance is, by definition, uncoupled. If the coupling between the windings is improved, the leakage inductance should be reduced. It would also stand to reason that if the winding inductance is reduced, the leakage inductance should be reduced as well. The coaxial secondary winding accomplishes both.

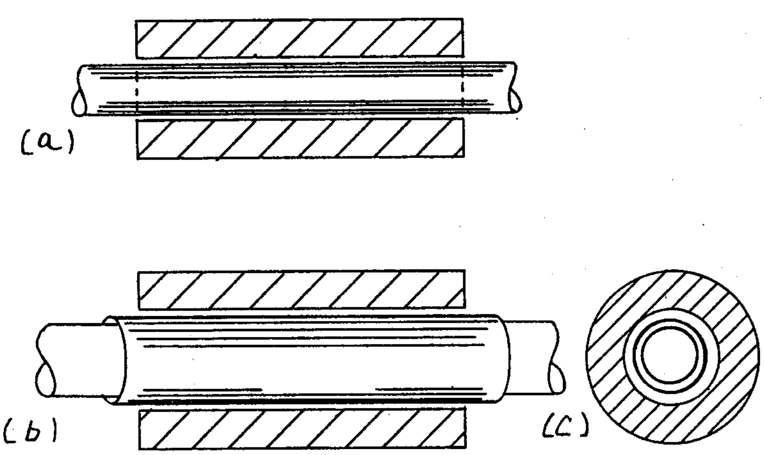


Figure 14.1. The top drawing shows the minimum inductance wire in a core. The lower drawing shows a push pull secondary winding, consisting of two concentric tubes, in a matrix transformer element.

1. Reduce inductance

In comparing the inductance of different windings that could be put through a core of a matrix transformer, the lowest is probably a tube of the largest possible outside diameter. The L of a wire goes down as its diameter increases. Since a push pull winding requires two conductors, the next best winding would be another tube of the largest possible diameter inside the first. If there is suitable insulation for the tubes,

‡ U.S. Patent pending. FMTT, Inc.

and terminations, the result is the coaxial secondary winding. See figure 14.1. This configuration should also have the best possible coupling.

Notice that the inside is entirely open, available for the primary windings.

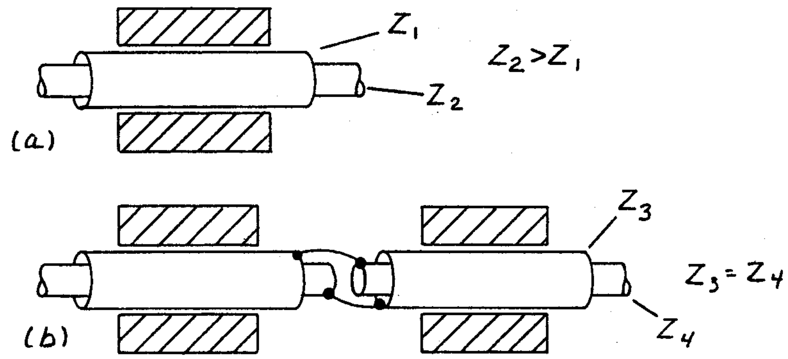


Figure 14.2. The inside tube has a higher impedance than the outside tube. If a winding couples two elements, and has a crossover, the impedances will be equal.

a) Unequal impedance

As can be seen in figure 14.2, the two sides of a push pull secondary winding will have different impedance if one side is an inside tube and the other is an outside tube. The secondary becomes balanced if there is a crossover so that there is an equal length of inside tube and outside tube in each circuit. The figure should be understood as being a schematic. The physical realization should be tight, without unnecessary spaces, and should use low inductance conductors.

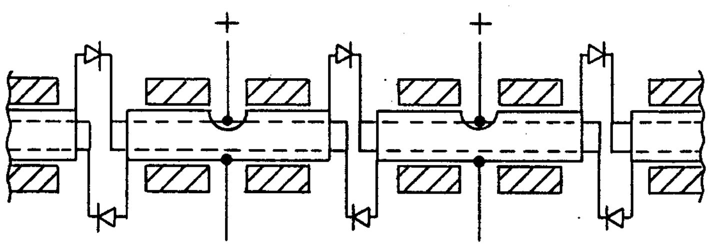


Figure 14.3. In a picture frame matrix transformer with symmetrical push pull windings, the inside tube can be the positive output, the outside tube can be the negative output. The crossover for equal impedance is at the diode connections, which should be wide and flat for low inductance.

2. Coaxial Secondary in a Picture Frame Transformer

Figure 14.3 shows a segment of a picture frame matrix transformer having a symmetrical coaxial secondary winding. Note that the secondary could be assembled as pairs of elements, and that there is a pattern to the diode connections. In all cases, the outer tube connects to the anode, and the inner tube connects to the cathode . This provides the crossover to balance the impedance, and has a recurring pattern that should be useful in the manufacturing of the transformers.

The positive and negative outputs are the center of the inner and outer tubes, respectively. If floating capacitors are used, they connect inner tube to outer tube at both ends of each assembly.

a) Keep Tight

The drawings in this chapter are quite open, with lots of space around the cores and leads to more clearly the interconnections. In practice, very careful attention to leakage inductance is necessary. When leads enter and leave the matrix transformer, they should be strip lines or coaxial, with equalized current flow (which is inherent in the matrix transformer unless it is compromises somehow).

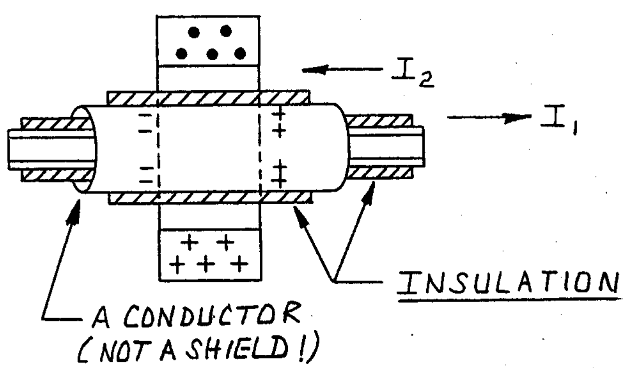


Figure 14.4. The coaxial winding is not a shield. It must be insulated just as any other winding would be.

3. Coaxial Winding is Not a Shield!

The coaxial winding looks like a shield, but it is *not.* It is a current carrying winding, just as any other winding, and has an induced potential along its length. It must be insulated, just as any other winding would be, and will not act as a shield for EMI. See figure 14.4.

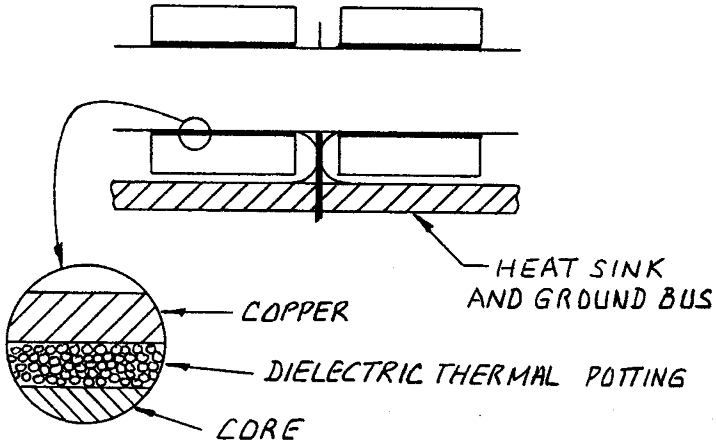


Figure 14.5. The coaxial secondary outer conductor can be a heat sink too, particularly if the heat sink is the negative ground plane.

4. Good Heat Sink for Cores

Unless the core is made of material which is a good insulator, the coaxial conductor must be electrically insulated from the ID of the core. This insulation can be a good quality thermal potting, however, so that there is good heat transfer from the core to the tube. Thus the coaxial winding can also provide a good thermal path out of the transformer. See figure 14.5. If differing temperature coefficients are a problem, several smaller toroids can be used.

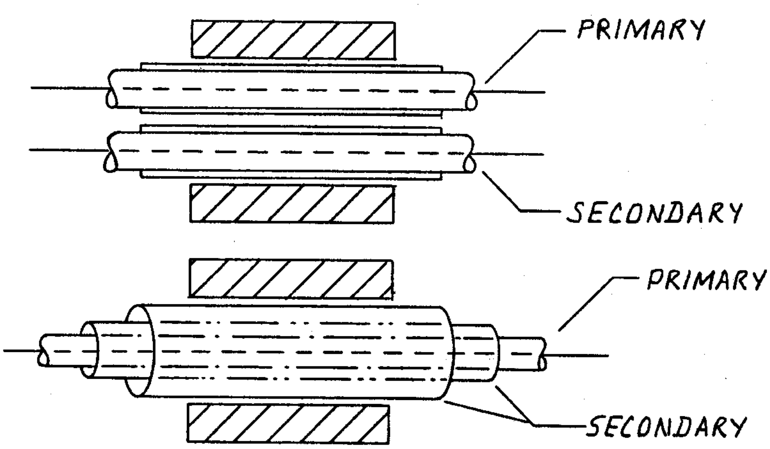


Figure 14.6. The primary winding can be coaxial too, either in parallel or concentric. The floating capacitors are connected from the inside conductor to the outside conductor at each end.

B. Coaxial Primary Windings

A coaxial primary winding can be used in parallel with a coaxial secondary, or within the coaxial secondary, as shown in figure 14.6. It is also possible to use a coax within a coax to provide a conduit for "through the bore" signals such as FET gate drives, as shown in figure 14.7.

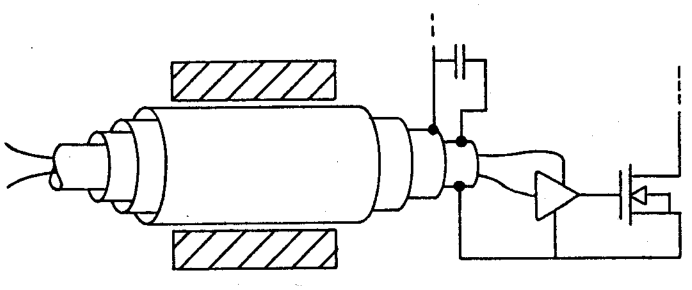


Figure 14.7. The inner conductor of the primary can also be tubular, for "through the bore" signals.

C. Coaxial Shield or Safety Ground

An additional coaxial layer can be used as a shield or safety ground, and would be placed between the primary and the secondary. Each shield can be grounded or bonded at one point only, preferrable in its center, but any number of segments could be used, each grounded once.

Where the physical layout permits the ends of the shields to be close together, a very good snubber termination is available. It should be particularly good for suppressing ringing resulting from the interaction of secondary parasitics with primary parasitics.

XV. Multi-turn Primaries and Paralleled Secondaries

High ratio step down matrix transformers have a large number of parallel outputs. While it is desirable to rectify and filter each one of them before paralleling them, the quantity of them may make it impractical.

Using multi-turn primaries and paralleled groups of secondaries can solve the problem of too many outputs.

A. Too Many Rectifiers!

A number of paralleled outputs, with individual rectifiers is very useful if the design is of the size and configuration where paralleled rectifiers makes sense. The matrix transformer solves the current sharing problems, and the thermal distribution is good.

On the other hand, too many parts can be a problem itself, and in small power supplies, where one or a few parallel rectifiers is sufficient, techniques are needed to consolidate the matrix transformer outputs without loosing its high frequency advantages.

1. Multiple turns in the primary

In a large step down ratio monolithic transformer, N:1, the problems of the N turns and N^2 leakage inductance is a real problem. The single turn matrix transformer is attractive, but N outputs may not be. As a compromise, the primary can have multiple turns, P, and the number of outputs drops in proportion.

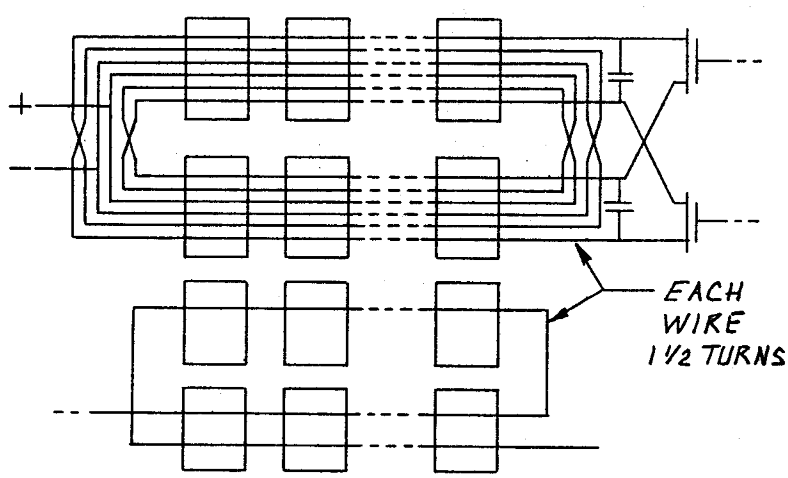


Figure 15.1. The matrix transformer can have multiple turn primaries. The primary winding shown above is a symmetrical push pull primary winding having three turns.

As an example, a 15:1 monolithic transformer has the problems of the 15 turn primary, and the whole secondary current is in one winding. The 15:1 matrix transformer has 15 outputs. As seen in figure 15.1, a matrix transformer can have a three turn primary. The 15:1 transformer would use a matrix transformer having dimensions of 5:1 with a ratio factor P of 3. This transformer has 5 outputs, each with

20 % of the output current. A 3:1 with five turns has 3 outputs with one third the output current on each.

2. Parallel the Outputs

The main reason for rectifying the outputs of a matrix transformer right at the output is to reduce the external wiring which has high di/dt's. Collecting all of the outputs of a large ratio matrix transformer to use with one or two rectifiers could add so much lead length as to negate much of the advantages of the matrix transformer.

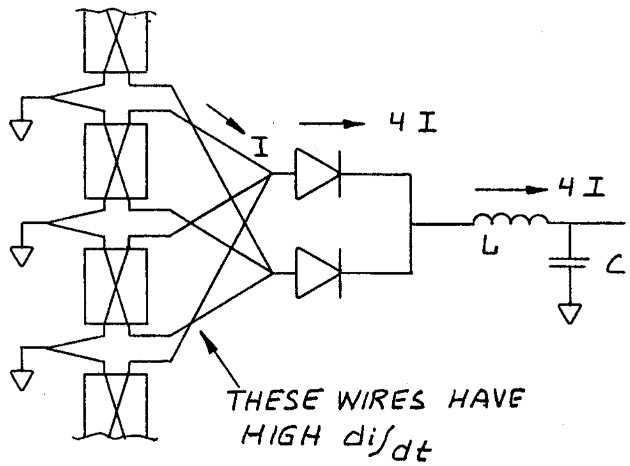


Figure 15.2. Be careful paralleling secondaries. The lead inductance could be excessive.

The elements of the matrix transformer are individual entities, however, and their physical location is arbitrary, as long as they are close together where wires pass between them. In the case of the picture frame matrix transformer, this just means that they must be laid out end to end, but they can loop, twist, double back or whatever works best.

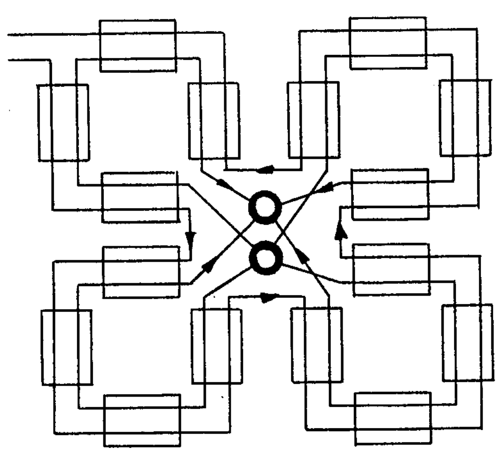


Figure 15.3. If a "picture frame" transformer is "pinched in", the outputs of the secondary can be brought together. Observe polarity.

This means that with some imagination, it is possible to bring the outputs together with minimum space between them, either all of them, or in groups. There are no restrictions on which of the outputs are brought together. If they have the same terminal voltage, they can be paralleled. Also each one has an equal current, so groups of outputs also have equal current, just proportionately larger.

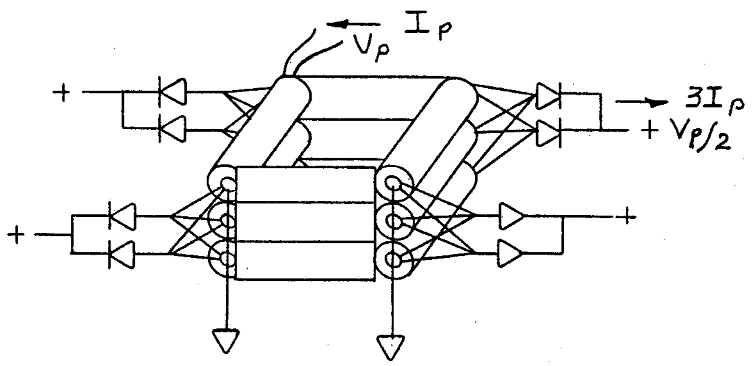


Figure 15.4. A 12:1 "picture frame" matrix transformer has been looped over itself three times. There are three paralleled outputs in each corner, reducing the rectifiers from 12 sets to 4 sets.

3. Low Inductance Interconnections

Even if the outputs cannot be brought right together, and with a large number they cannot be, it may be sufficient just to get them fairly close, then parallel them with good low inductance interconnections. Examples would be printed circuit board planes, coaxial or twisted pair cables with balanced currents (the currents tend to be balanced).

Within a close magnetic structure, balanced currents can be carried in closed channels or tubes, and will have the further advantage that common mode currents will tend to be rejected.

XVI. Transformer Ratios and Validity Criteria

This section reviews validity criteria and develops the their foundation in more detail.

The ratio of a matrix transformer is determined by its interconnections, not the core geometry. The basics of the flux and voltage relationships within elements will be developed, and techniques for applying them to design multiple output transformers will be shown.

Flux and current density are thermal problems. This is the topic of section XX.

A. Validity Criteria

A matrix transformer is "valid" if a proposed arrangement and interconnection satisfies the laws and rules introduced in section II.C., and developed below. While these rules seem simple, they can be tricky to apply, particularly in the more complex matrix transformers. The more complex situations would include transformers having non-integer ratios, transformers having different isolated outputs, variable ratio transformers or transformers having side loops for current balance, pre- or-post regulation or auxiliary outputs.

The usual consequences of trying to make a transformer which is invalid would be large circulating currents, or perhaps some elements that had a disproportionately high voltage drop. This would usually create enough smoke to make the problem obvious.

If a transformer operates in several modes of operation, the validity criteria must be met for every condition. This would apply to transformers which have varying turns ratios, or which can be hooked up is several ways, as for different input voltages.

As designers get more familiar with matrix transformers, and discover the tricks that can be done with them, validity may be conditional, based, for instance, upon the relationship of the output loads, or some such factor.

1. Review of Validity Criteria

a) Lenz's law (paraphrased): *In each element, the sum of the ampere turns is zero.*

The application of Lenz's law to non-ideal transformers is an approximation, because the excitation current is subtracted from the current in whichever winding is driving the flux. In some circuits, the element may behave more as an inductor.

In the case of a power matrix transformer not having characteristics of an inductor, examples of the problems which might occur would be having an element with one winding in which the current is driven by the circuitry, and having another winding where the circuit impedance would not allow the current to flow, or having the current in the element as dictated by the turns ratio, and having the external circuitry require a different current.

a) Faraday's law (paraphrased): In each element, the volts per turn is the same in every winding.

The application of Faraday's law is an approximation when applied to non-ideal transformers, because, with respect to the changing flux in the core of the element, voltage drops due to the currents in the winding impedances are subtracted from the input voltage in primary winding and added to the output voltage in the secondary windings.

In a power matrix transformer, examples of the problems that might occur would be having a voltage source on one winding which is reflected to a winding with too low an impedance to support the voltage, or having the external circuitry require a different voltage relationship than the turns ratio would allow.

b) Equal Current in Series Circuits.

As a winding makes its way through a number of elements, it is easy to forget that the current must be the same everywhere along its length. In a high ratio step down transformer, the primary winding typically will go through all of the elements. The output of every element must be compatible with that current *for all possible load conditions, for all possible switch positions, and any other combination or state under which the transformer may be expected to operate.*

c) Equal Voltage across Parallel Circuits

With a large number of parallel outputs, such as in the secondary of a high ratio step down transformer, the voltage will be equal, and that voltage will be reflected into all of the other windings, which may in turn reflect to other likewise constrained circuits or the input. If the voltages do not match due to incompatible ratios, *they will match by causing sufficient circulating currents so that the voltage drops in the circuit impedances make up the difference* (or something breaks).

d) An Example Failing the Criteria for Current

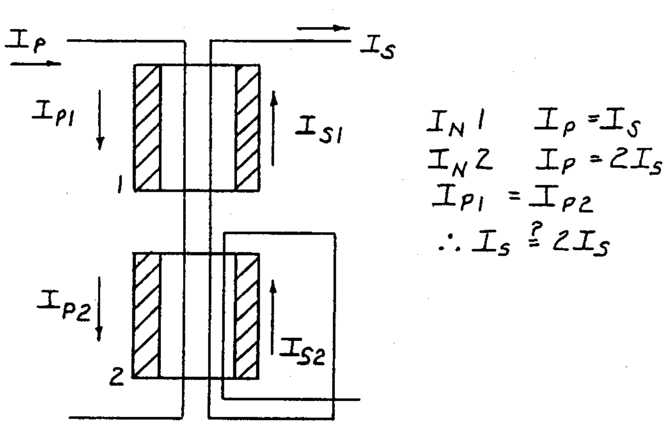


Figure 16.1. This matrix transformer fails the validity test for currents.

An example of a matrix transformer which fails the criteria for currents is shown in figure 16.1. In the first element, the secondary current must equal the primary current. In the second element, the secondary current must equal one half of the primary current. These are mutually exclusive.

e) An Example Failing the Criteria for Voltage

An example of a matrix transformer which fails the validity criteria for voltages is shown in figure 16.2. In the first element, the secondary voltage must equal the primary voltage. In the second element, the secondary voltage must equal two times the primary voltage. These requirements are mutually exclusive.

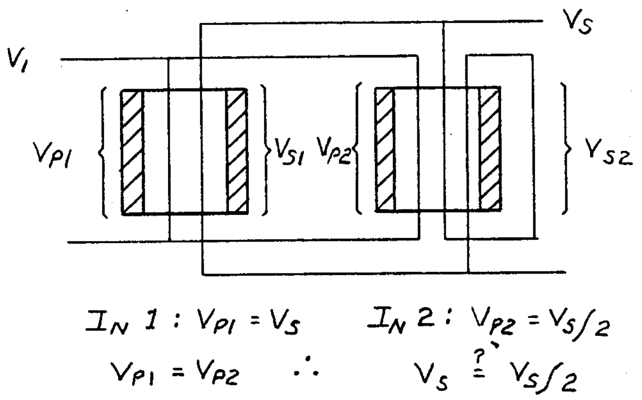


Figure 16.2. This matrix transformer fails the validity test for voltages.

B. Dimension Ratio Is Determined by Interconnections

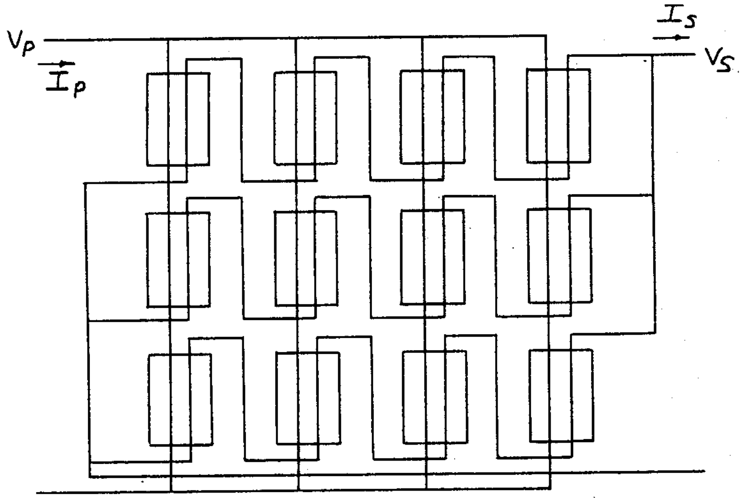


Figure 16.3. Reviewing figure 2.14, this 3 x 4 matrix transformer has a ratio of 3:4.

The elements in most matrix transformers used for high frequency power conversion will have single turn primaries and secondaries. For these matrix transformers, the ratio is the same as the matrix dimensions, M:N, where M and N are the dimensions of the matrix (see section II.D.7). If the ratio in the elements is not 1:1, the ratio is probably of the form PM:N, where P:1 is the non-unity ratio of the elements (see section II.D.7.1). The "picture frame" matrix will probably have dimensions M x 1, and ratio M:1, (or PM:1).

Sorting out all the M's & N's reveals that in all cases the ratio is the number of paralleled secondaries M to the number of paralleled primaries N (factored by P, if necessary).

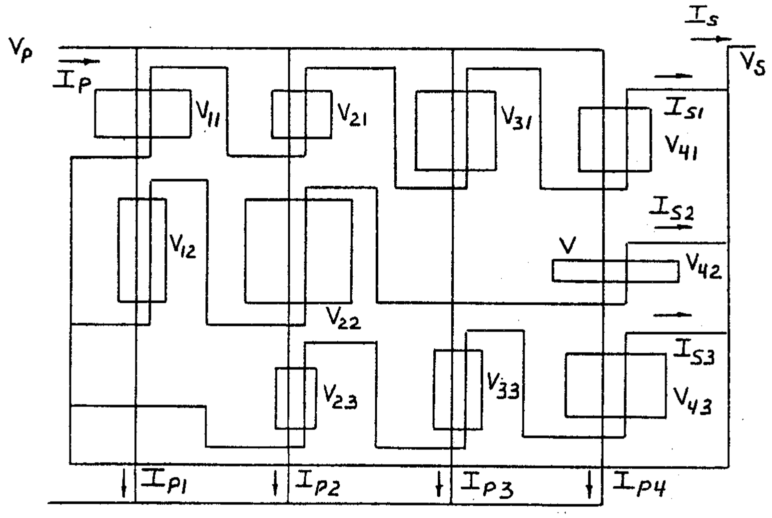


Figure 16.4. This matrix transformer also has a ratio of 3:4.

Figure 16.3 reviews the generalized matrix transformer from section II.D, and shows a 3:4 matrix transformer. Figure 16.4 shows another matrix transformer, also having a ratio of 3:4. Sorting out the voltage relationship would be a matter of solving some messy simultaneous equations, but the current relationship is easy to see by inspection. Picking column 2 (because it is complete), Lenz's law requires that $Ip_2 = Is_1 = Is_2 = Is_3$. In row 1, $Is_1 = Ip_1 = Ip_2 = Ip_3 = Ip_4$. Therefore all of the currents are equal. The secondary current is 3/4th of the primary current.

1. Flux must be Sufficient

The matrix transformer of figure 16.4 shows that the cores do not have to be equal, but the cores together in each series circuit must have sufficient flux capacity to support the voltage waveform appearing across the series circuit. In general, the matrix transformer is optimized when the flux density is equal in all elements, but there are exceptions and special circumstances.

The matrix transformer of figure 16.4 is exaggerated to make a point. Assuming core area and geometry is approximately to scale, the flux capacity of the elements is hardly equal. Some are even missing, but that has not affected the ratio of the whole transformer at all.

It is a recurring misunderstanding that core area and flux density will determine voltage. In a matrix transformer, the flux density is almost always a *dependant* variable.

C. Element Voltage, and Total Transformer Voltage

Two convenient definitions for the discussion which follows are the "element voltage" and the "total transformer voltage". The element voltage is defined as the voltage induced in one turn by the changing flux in the core(s) of the element. The total transformer voltage is defined as the sum of the element voltages. This parameter can be related to the total flux capacity of the matrix transformer, if the voltage waveform (but not necessarily the amplitude) is the same throughout the matrix transformer. See figure 16.5.

1. Core Area as a Function of Element Voltage

Usually the matrix transformer will be designed with one size of core, and equal flux density throughout. If every core is not the same size, they will probably at least have the same ID and OD. If the ID and OD are constant, then the core area is a function of height. Since the flux capacity is a function of core area, the flux capacity is also a function of height. Taking this one step further, and assuming equal flux density, the core voltage (element voltage) can also be said to be a function of height. See figure 16.6.

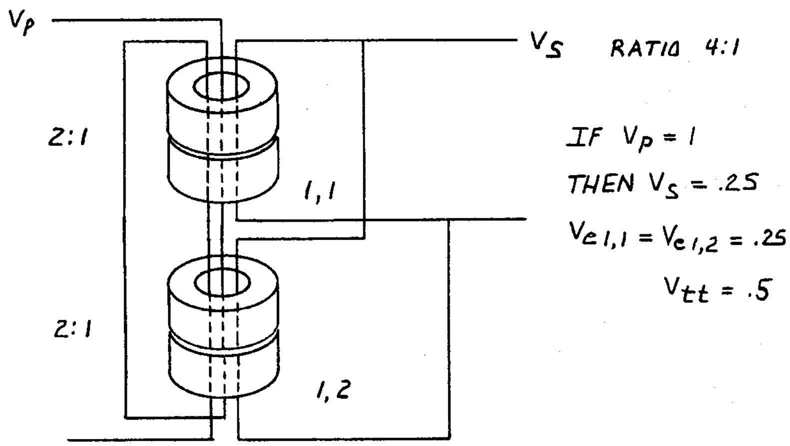


Figure 16.5. **A 2 x 1 matrix with P = 2. With V_p = 1, the "element voltage" is 0.25, and the "total transformer voltage" is 0.5. If each toroid is considered to be a separate core, the "core voltage" is 0.125.**

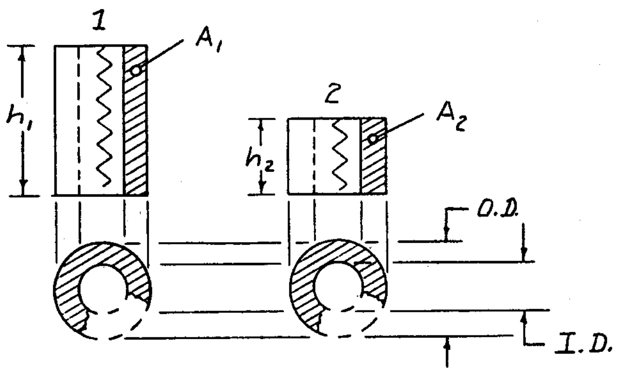


Figure 16.6. **Given certain assumptions, the core area will relate linearly to the "core voltage". Core 1 has twice the area, so it has twice the flux capacity. It will support twice the voltage, (given the same wave shape and flux density).**

As is true with many design aids, the relationship of core area to voltage must be linked to its underlying assumptions and conditions. It assumes a waveform and a flux density, a constant ID and OD and the same material magnetic characteristics. These are reasonable assumptions, but there will be exceptions.

It must also be kept in mind that core voltage so defined is actually the capacity to support the voltage under the assumed conditions. The core could obviously support any lesser voltage, and may be able to support a higher voltage. In any case, the voltage must relate to a voltage source, the voltage due to the currents in the load, and the whole circuit.

a) Flux ***is not*** *Related to Current or to Power.*

Nowhere in the equations defining flux, changing flux, flux density or any other flux related factor is there any mention of current or power, provided only that there is sufficient current to magnetize the core (magnetization current). In a good transformer design, impedances will be sufficiently low so that voltage drops in impedances are not a significant factor, either.

In the design of *monolithic* transformers, and *if* the design is not based upon the minimum number of turns possible, then voltage per turn and ampere-turns are traded off against turns, window area and core area, often based upon VA (volt-amperes). There are lots of neat nomographs and equations to do this. Unfortunately, the trade offs and assumptions, especially the thermal assumptions, are usually pretty well hidden, and therefore beyond the designers grasp and control.

D. Elementary Design

The concepts introduced above can now be applied to the general relationship of the elements in a matrix transformer.

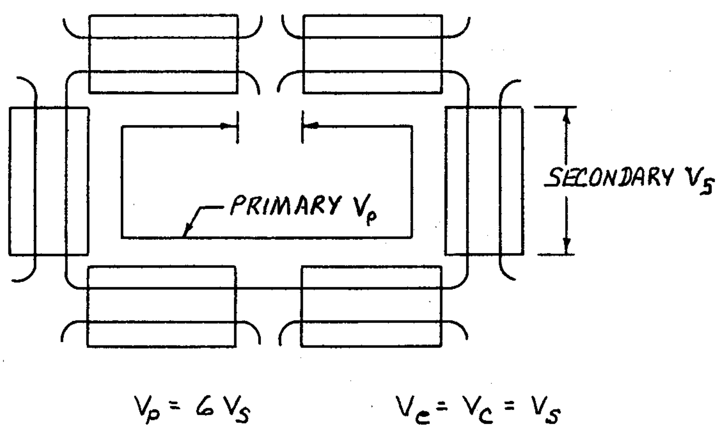


Figure 16.7. In a simple 6:1 picture frame matrix transformer, the "primary core area" A_p is six times the "secondary core area A_s.

1. Picture Frame Matrix Transformer ‡

An M x 1 picture frame matrix transformer is shown in figure 16.7. The example is a 6:1 transformer, and the area of each core can be related to the secondary voltage. There is one turn in each element, and there is one core in each element, so the secondary voltage, the element voltage and the core voltage are all equal. The primary voltage is six times the secondary voltage.

‡ U.S. Patent pending. FMTT, Inc.

2. Core Cutting ‡

The example above provides a good introduction to a design aid, core "cutting". A single "total transformer core" is envisioned, having a core area sufficient to support the total transformer voltage. This will have the area of all of the cores in the transformer taken together.

To make a picture frame matrix transformer of ratio M:1, the total transformer core is simply "cut" into M equal pieces. The secondary voltage is $(1/M)V_p$, so an area of 1/M is just right.

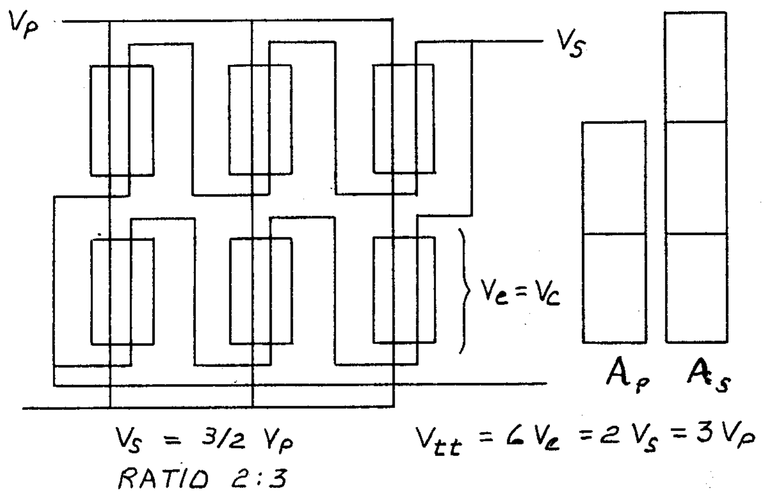


Figure 16.8. A 2 x 3 matrix transformer. The element voltage is one half the primary voltage, and one third the secondary voltage. The total transformer voltage is six times the element voltage.

3. M x N Matrix Transformer

An example with a matrix transformer having the general form M xN is shown in figure 16.8. The element voltage is $(1/M)V_p$ and $(1/N)V_s$. The total transformer voltage is $MNV_e = NV_p = MV_s$. The "primary core area" A_p and "secondary core area" A_s are shown.

The total transformer core area would be determined from the total transformer voltage. The element cores can be derived by cutting the total core into M times N pieces.

It can be seen that as the N dimension of an M x N matrix transformer increase, the total size of the cores increases. After all, each of the N parallel primaries has to support the primary voltage. It is only because the matrix transformer will operate at much higher frequencies, with much higher flux and current densities, and has current sharing, that the trade off is favorable in those applications which can take advantage of it.

E. Picture Frame Transformer with Two Ratios ‡

It is frequently a requirement for a transformer to supply more than one output voltage. There are several ways to do this, but one of the best is the multiple output picture frame matrix transformer.

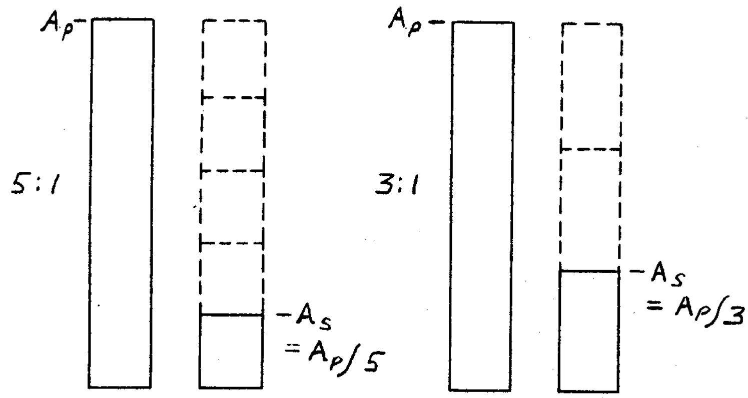


Figure 16.9 A total transformer core as it would be cut for a 5:1 matrix transformer, and also as it would be cut for a 3:1 matrix transformer.

In high frequency power conversion, often the primary voltage will be the highest voltage, and the secondary voltages will be integral fractions of the primary voltage. In this case, the primary voltage is the common denominator upon which the design is based.

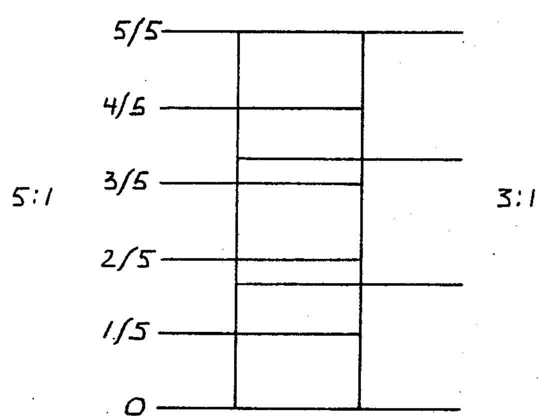


Figure 16.10. The total transformer core cut to provide for both a 5:1 and a 3:1 output ratios.

1. Define Secondaries Independently

First, use the primary voltage V_p as the total transformer voltage to define a total transformer core. Then "cut" the core equally to define the first ratio. Using the same total core, "cut" it again to define the second ratio. Figure 16.9 shows a total core having A_p cut into five for a 5:1 winding. The same core is also cut into three for a 3:1 winding. Figure 16.10 shows the same core cut to accommodate both windings in one transformer.

‡ U.S. Patent pending. FMTT, Inc.

2. 15:5:3 Example

To express the ratio of a transformer having both a 5:1 output and a 3:1 output in one ratio suggests using 15:5:3. It could also be 5:(5/3):1. Figure 16.11 shows a picture frame transformer in which the total transformer core has been cut as required, and the primary winding and the 3:1 secondary winding have been installed. In this partial stage of completion, there is a single turn primary passing through all of the elements. The secondary winding has three segments, which are used in parallel, and each couples the primary in 1 2/3 cores, which is one third of the total core area. The relative placement of the primary and the secondary (clockwise or counterclockwise) is arbitrary as long as they are isolated.

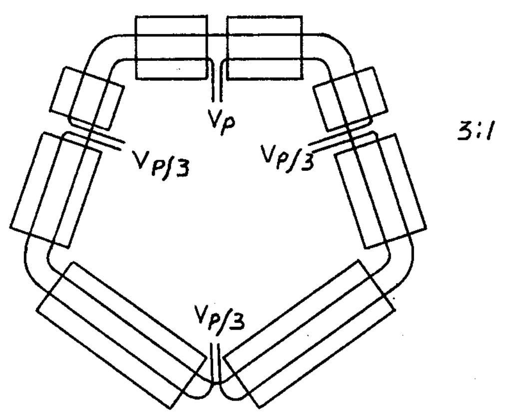


Figure 16.11. A partially wound picture frame matrix transformer is shown. The total transformer core has been cut to allow a 5:1 winding and a 3:1 winding. The primary and the 3:1 winding are installed.

Figure 16.12 shows the same cores as used in figure 16.11, but with the primary winding and the 5:1 secondary winding installed.

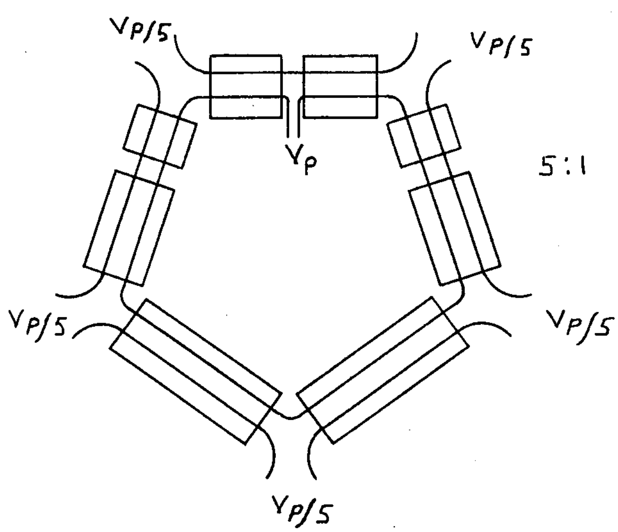


Figure 16.12. A partially wound picture frame matrix transformer is shown. The total transformer core has been cut to allow a 5:1 winding and a 3:1 winding. The primary and the 5:1 winding are installed.

Figure 16.13 shows the completed 15:5:3 picture frame matrix transformer. Note that a 5:3 transformer results if the primary winding is left out!

Figure 16.14 shows a transformer which is equivalent to the transformer of figure 16.13, except fifteen equal sized cores have been used.

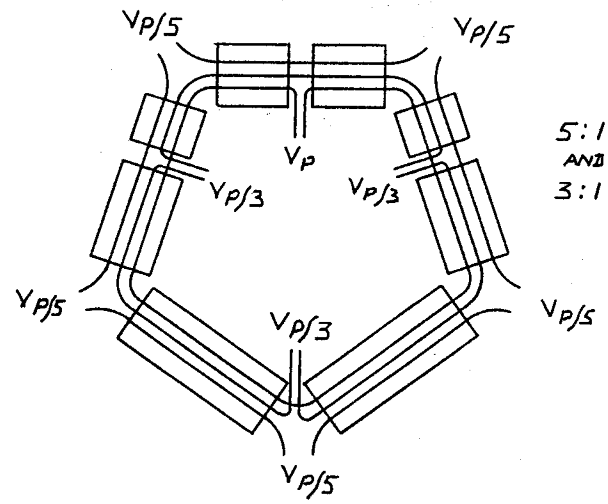


Figure 16.13. A picture frame matrix transformer having both a 3:1 secondary winding and a 5:1 secondary winding.

3. Converting to a Picture Frame Layout

Converting an M x N matrix transformer to a picture frame layout is straightforward. First define the total transformer core. "Cut" the total transformer core to define M:1 windings, and again to define N:1 windings. Then install the N and the M windings.

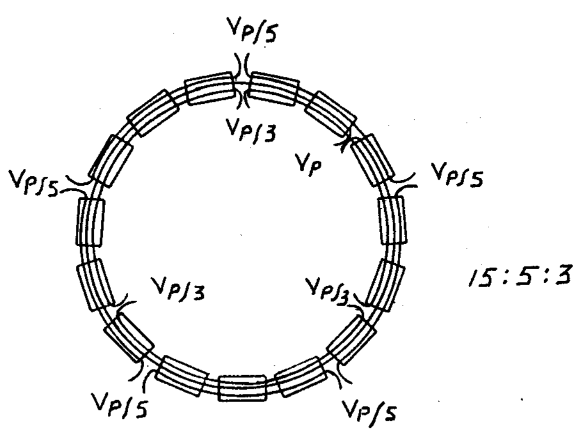


Figure 16.14. A 15:5:3 picture frame matrix transformer.

F. Unequal Flux Density ‡

There are several good reasons why a transformer might be designed with unequal flux density, such as using a longer than necessary core for standardization, or stretching the transformer physically to solve a mechanical problem, or allowing some

‡ U.S. Patent pending. FMTT, Inc.

part of the matrix transformer to operate with a lower flux density so that it will be cooler, to solve a thermal problem.

It is probable best to design the transformer with equal flux density first to provide a base line. Afterwards, any of the cores can be made longer. Since the ratio is not determined by the core size, the only effect is that the longer core will have a lower flux density, and will probably run cooler.

This might be done if the total core is double-cut to make a two output picture frame transformer, which may result in a number of odd areas. The shorter ones could be replaced with a standard core, and the longer ones could be replaced with a stack of the same core.

DO NOT "round off" the design by discarding the smallest cores and bringing terminations from different windings out at the same place without thoroughly analyzing the result. You could be making an *INVALID* matrix transformer.

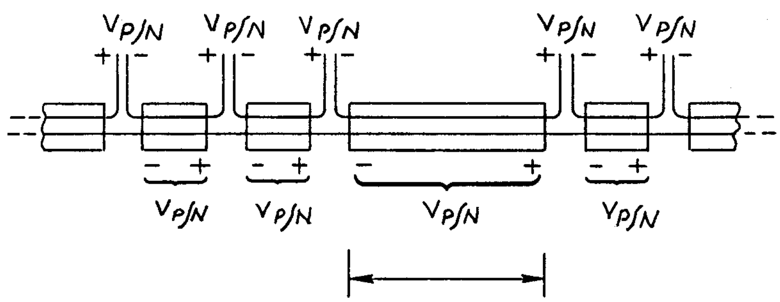


Figure 16.15. A portion of an M:1 picture frame matrix transformer showing a long core installed for more space.

1. Bridging ‡

An extra long core can be inserted anywhere in a picture frame transformer without affecting the ratio, and the long core will probably run much cooler because of the lower flux density. (A note of caution is that the *wire* length is also increased. If I^2R losses dominate, or if winding impedance is critical, it may not work as well.)

Bridging might be used to avoid having transformer terminations in a busy area, such as around the connector, or to provide more space between the terminations for secondary rectifiers and the terminations for primary switching FET's. It might be used so as to have lower losses (heat generation) in parts of the circuit that has less heat sinking. It might be used to allow optimum placement of components.

Figure 16.15 illustrates the concept of bridging. It shows that a longer core can be substituted for a smaller one to allow more space between terminations.

a) Example with Card Rail Heat sinking

On printed circuit cards, often the only available heat sinking is at the sides of the card, as shown in figure 16.16. By bridging from side to side, all of the secondary rectifiers can be located along the heat sink rail. There is less heat dissipation in the

‡ U.S. Patent pending. FMTT, Inc.

center of the card, and the top and the bottom of the card are kept relatively free of terminations.

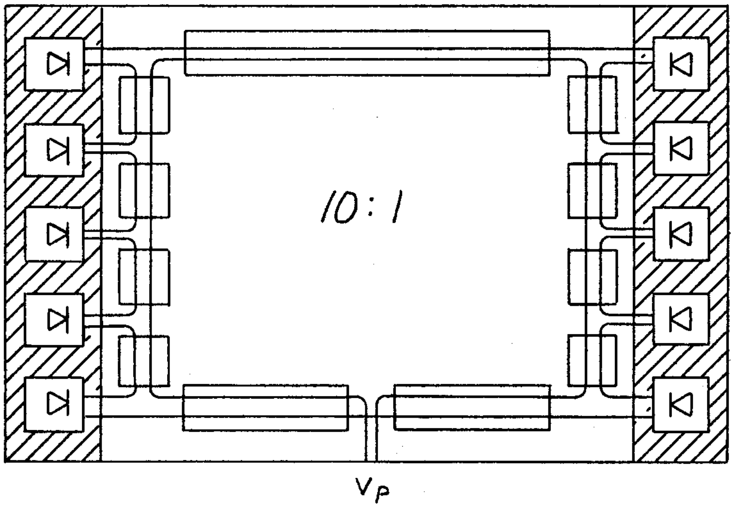


Figure 16.16. A picture frame matrix transformer on a printed circuit card. The transformer is bridged from one side of the card to the other so that the rectifiers are all near the card rail. It also frees up the center of the card for more circuitry and the connector.

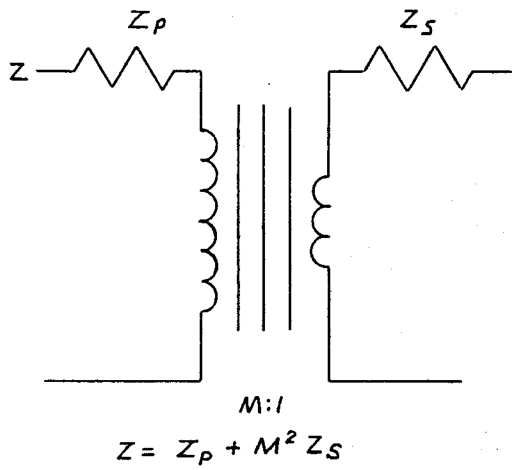


Figure 16.17. In a monolithic transformer, the secondary parasitic impedances reflect to the primary as the square of the turns ratio M.

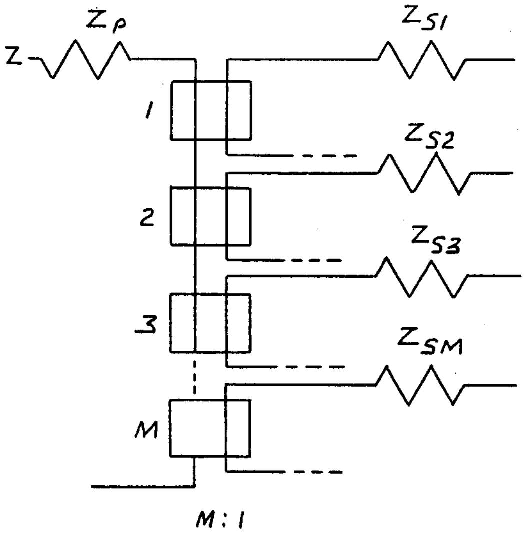
G. Reflected Impedances

It is well known that the secondary impedance of a transformer is reflected to the primary as the square of the turns ratio. This relationship is reviewed in figure 16.17.

This is true in the matrix transformer as well. After all, the laws of physics have not been rewritten, just rearranged a little. When calculating the effect of an output load on the primary of a matrix transformer, the "old fashioned" way is still the best.

1. Parasitic Impedances are Summed in the Primary

For the general case of matrix transformers having single turn windings in their elements, there is an easier way to reflect the parasitic impedances, and any other impedances which are more easily measured on a per winding basis. Figure 16.18 shows a M:1 matrix transformer having M parallel secondaries, each having a secondary parasitic impedance Z_{sm}. Each one can be seen to reflect one to one to the primary, where they are all in series. Thus you can just add them up.



$$Z = Z_p + Z_{s1} + Z_{s2} + Z_{s3} + \dots + Z_{sM}$$

Figure 16.18. **In the matrix transformer, the parasitic impedances in the secondary windings are reflected to the primary as their sum.**

To reconcile this with the square of the turns ratio, consider that the M impedances Z_{sm} are in parallel. Thus $Z_s = Z_{sm}/M$. When this is multiplied by M^2, the result is MZ_{sm}.

It is thus apparent that the impedance of every little snippet of extra wire anywhere reflects to the primary equally.

In the case of a transformer having a single turn primary, and two secondaries of different ratios, separately sum the impedances of the secondaries. This reflects each one to the primary. Then calculate the parallel impedance of the reflected secondary impedances.

This relationship holds even with different windings having different ratios to the primary. If the primary happens to make multiple turns, P, with all single turn secondaries, then the same relationship holds, modified by P^2.

XVII. Conditionally Valid Matrix Transformers ‡

This sections teaches the designer how to cheat. If enough is known about the loads on a transformer, and some restraints are acceptable, very significant simplifications can be realized.

A. Very Low Current Outputs.

Much of the importance of the concept of validity in a matrix transformer has to do with Lenz's law, and the need to keep the ampere-turns at zero in each element. However, if the current is very low, a small portion of the other currents, its effects may be able to be ignored. Also, much of the concern with currents has to do with stray inductances and lead lengths. Again, if the current is small, impedances may be unimportant.

As an example, consider a 100 watt, 5 volt converter. The output current will be 20 amperes. If some operational amplifiers needed plus and minus 15 volts at 10 ma, there would be no reason to worry about validity. Just loop a wire through any three elements, and rectify and filter it. Add a post regulator if necessary.

B. Moderate Current Outputs.

Even with currents that are not negligible, it may be possible to cheat, and sneak off an auxiliary output winding from a small number of elements. More care is needed, and the transformer may be conditionally valid.

As an example, consider a 15:1 matrix transformer used in a 5 volt power supply having a 150 watt output. The output current is 30 amperes, and each of the 15 parallel elements supplies 2 amperes. A 500 ma minus 5 volt output is needed.

It is possible to put a second winding on one element to derive the minus voltage. The consequence is that the current balance in the secondary is upset, the difference being the current drawn from the auxiliary minus 5 volt secondary. In order to maintain zero net ampere turns, the current in the main secondary winding of the element will be reduced by the amount drawn by the auxiliary winding.

That is not too bad. Its rectifiers will run a little cooler, and the other 14 will pick up the extra load.

This transformer is conditionally valid, and the condition is that the auxiliary winding current must always be less than the primary current. This means that if the main output has a light load, the output capability of the auxiliary winding is reduced.

Figure 17.1 shows two ways of sneaking a minus 5 volt winding in a picture frame transformer. In one, separate windings have been used. The other takes some minus 5 from "behind" two of the plus 5 rectifiers. Note that in this latter case, those particular wires carry *extra* current. It is the *other* wires in the elements that have a lower current.

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‡ U.S. Patent pending. FMTT, Inc.

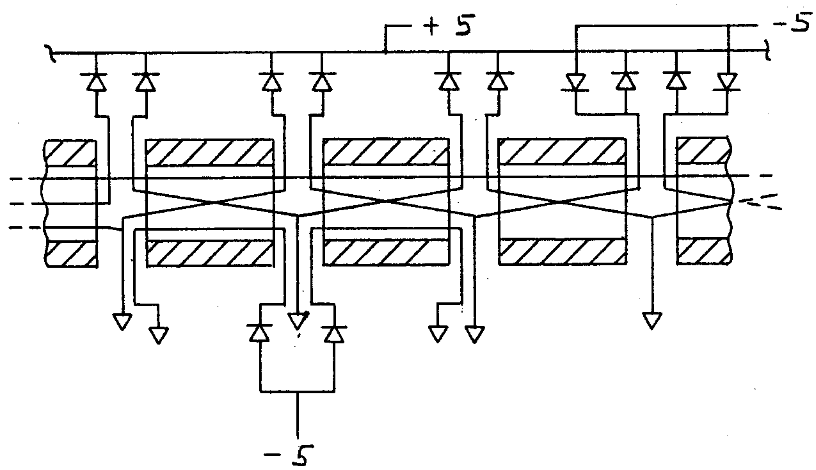

Figure 17.1. On the left, an extra winding passes through two elements to sneak off a little minus 5. On the upper right, a second method is shown.

a) Automatic Current Limit ‡

The conditional validity can be used to advantage, as a current limit in the auxiliary winding. Consider the case of an overload on the auxiliary output. As the current increases, more and more current will be "stolen" from the main output, until there is no more. This is the limit at which the auxiliary current equals the primary current. If the auxiliary load impedance is reduced further, the current cannot increase, and the current will limit at a constant value determined by the primary current.

The primary current is probably determined by the main load, as it is divided between the remaining elements. A short circuit on the auxiliary winding will effectively alter the transformer ratio, reducing M by one.

b) Multi-element Auxiliary Windings.

With care, the above technique can be extended. Considering the same example, a 500 ma 15 volt winding could "steal" from three elements, a 50 ma 24 volt winding could "steal" from five others, and so forth. This works very well if the main output *element current* is always larger than the auxiliary winding *element current.*

If an auxiliary winding involves more than a small portion of the elements, be particularly careful to consider the consequences of a short circuit. The short circuit will tend to reduce the voltage to zero on the affected elements. The rest of the elements in the primary will then have to support the whole primary voltage. The short circuited elements are effectively "removed" from the transformer, just as if it were a variable ratio transformer, and the secondary diodes of the "removed" elements will be reverse biased. The transformer ratio will be altered, the output voltage may be too high, and the remaining elements may be over stressed or saturated.

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‡ U.S. Patent pending. FMTT, Inc.

XVIII. Cascaded Matrix Transformers ‡

Matrix transformers can be cascaded, the secondary of one driving the primary of one or more others.

Cascading the matrix transformers multiplies the ratios, and has fewer parallel windings with higher currents in the output secondaries. One transformer can drive several others, for multiple outputs. The interstage windings are isolated, and can be used for power conditioning.

Cascaded transformers can be closely integrated, and the interstage winding can be a number of low current parallel paths.

A. Ratio Multiplication

If a first transformer has a ratio of M_1:1, and a second transformer has a ratio of M_2:1, the two cascaded will have a ratio of M_1M_2:1. Figure 18.1 shows a cascaded matrix transformer in which a 4:1 matrix transformer drives a 5:1 matrix transformer. The input:output ratio is 20:1, and there are five paralleled secondary output windings.

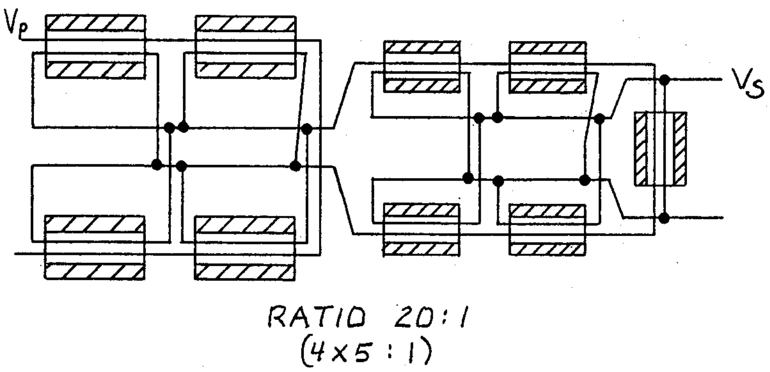

Figure 18.1. Cascaded matrix transformers have ratio multiplication. The second stage elements have lower voltage and higher current.

B. Multiple Outputs

One matrix transformer can provide a secondary that drives several other matrix transformers, each of which can have a different ratio, for multiple outputs.

This feature could allow a product line in which a variety of different output matrix transformers could be added at will for different applications. If the first transformer had a voltage regulating feature, such as pulse width modulated drive, then all cascaded stages will also be regulated, (or at least pre-regulated).

Figure 18.2 shows a converter with a matrix transformer (A) with a 5 volt output. An interstage secondary is also wound on the same elements, and drives two other matrix transformer modules (B and C). The regulator for the main secondary serves as a pre-regulator for the cascaded transformers.

‡ U.S. Patent pending. FMTT, Inc.

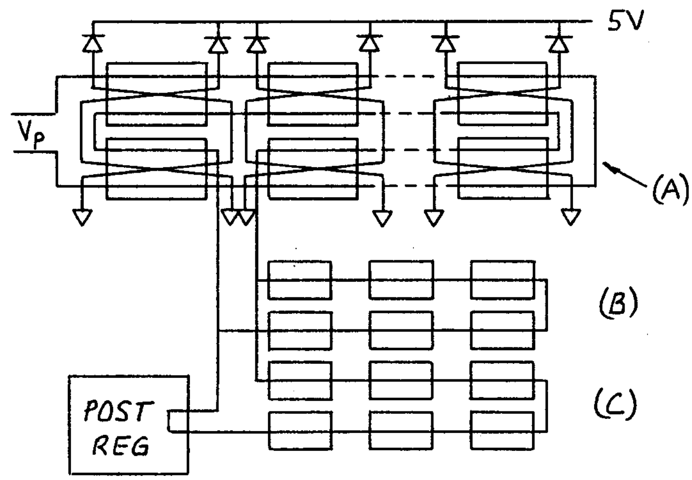

Figure 18.2. A matrix transformer with a five volt output also has an interstage winding added, to power cascaded matrix transformers.

The secondaries of modules B and C have been left off to leave the drawing less cluttered, but they could be any matrix transformer secondary. Note that the post regulator is on a branch of the interstage winding. The interstage winding is a good place install a regulator, as it is isolated, and probably is a single wire.

C. Interstage Power Conditioning.

The interstage winding can be used to condition power as it is transferred between the first transformer and the cascaded one(s). The interstage winding is usually carrying power at an intermediate level of voltage and current, and it is isolated from both the input and the output. The interstage conditioning may be some means of regulation, or it might be a filter.

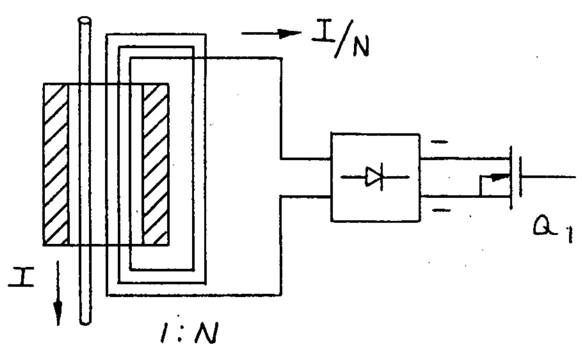

Figure 18.3. An interstage winding has a regulator element installed. The interstage current I is reflected to the secondary of the regulator element as I/N, rectified, and loaded by a linear regulator, Q_1. The voltage drop on Q_1 is reflected back to the interstage winding.

1. Interstage voltage regulation ‡

If an interstage winding is passed through an extra element or two, and the output of a secondary on the element is full wave rectified, as shown in figure 18.3, any voltage

‡ U.S. Patent pending. FMTT, Inc.

drop appearing on the output will be reflected as a voltage drop in the interstage winding.

The voltage drop might be provided by a linear device, as shown in figure 18.3. The regulation will be linear and lossy. This could be used to fine tune the output in a converter where a pre-regulator was used in the first stage.

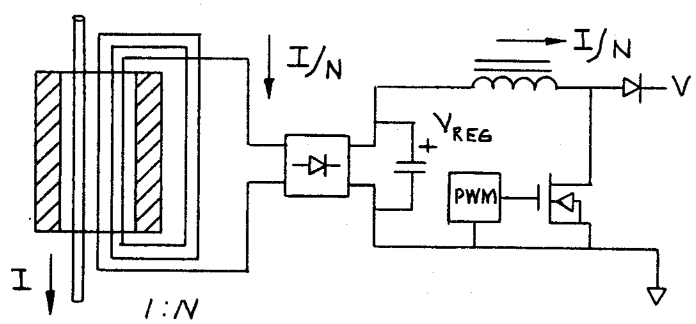

Figure 18.4. The switch mode interstage regulator is a voltage sink.

The voltage drop could also be provided by a switch mode circuit, as shown in figure 18.4. The regulator must be a regulated voltage sink (not source). The interstage current I, modified by the element turns ratio 1:N, must flow in the regulator secondary, and will keep on flowing out of the regulator as (1-d)I/N, where d is the regulator duty cycle. The V on the right must be able to sink the pulsing current.

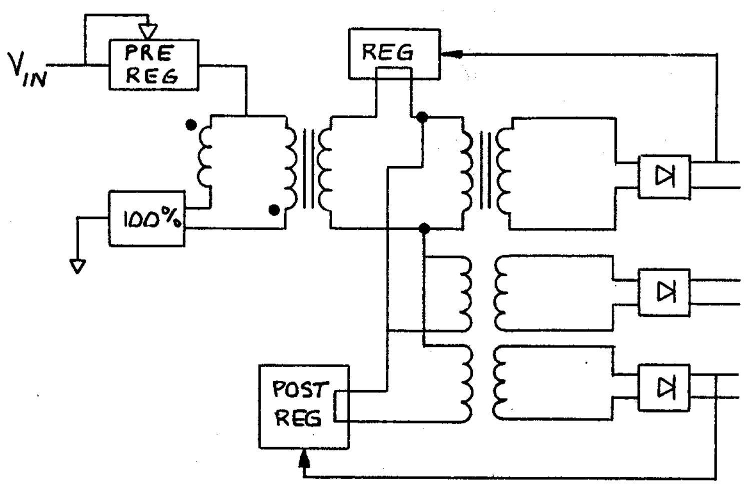

Figure 18.5. This block diagram shows a three output converter, operating at 100% duty cycle. Minimal output filtering would be needed.

Several elements could be placed on the interstage winding, and they could be configured like a variable ratio matrix transformer. If they were binary stages, digital feed back could be used, perhaps with a linear fine regulator.

Figure 18.5 shows a block diagram of a power converter having multiple outputs. The input voltage is pre-regulated, then switched as a 100% duty cycle square wave. An interstage winding is further regulated with feed back from the main output. The interstage winding then drives several other cascaded matrix transformers, one of which has an interstage regulator as a post regulator. Because the entire transformer is switching at 100% duty cycle, very minimal output filtering is needed, just to clean up the rectifier noise.

a) Interstage Voltage Regulation Techniques Applied to Other Windings

The interstage voltage regulation techniques can be used in other windings of matrix transformer, as well. Although illustrated above in an interstage winding, the technique is broadly applicable to introduce a controlled voltage drop into any winding, by passing it through some extra elements having the appropriate circuitry. Applied to a primary winding, it becomes a regulator for the entire transformer. Applied to a secondary, it becomes a post regulator for that output only.

If used with a picture frame matrix transformer, it is prefered to make a side loop for the regulator circut, so that the pattern of the picture frame is not interrupted.

2. *Interstage Filtering* ‡

The variable ratio matrix transformer, having step changes in its ratio, cannot have a capacitor on both its input and its output. This is particularly true if the ratio steps are relatively large, and modulation between the closest two ratio steps is used to provide infinite resolution.

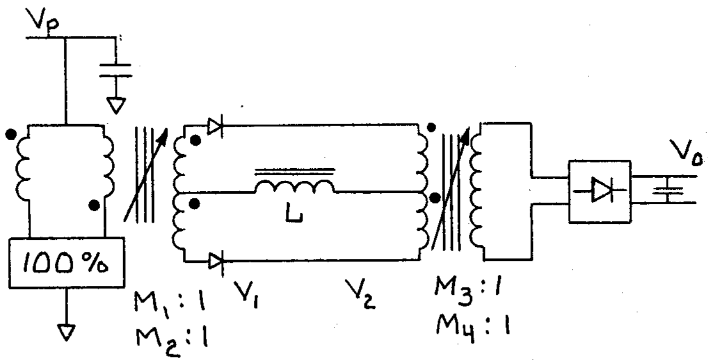

Figure 18.6. An interstage filter inductor can be used between variable ratio matrix transformers, so that a capacitor can be used on both the input and the output.

An interstage filter inductor, as shown in figure 18.6, can be used to provide a suitable impedance, and both transformers can have a variable ratio. In figure 18.6, the first transformer is a pre-regulator, responding with feed-forward from the input. It is ratio modulated for infinite resolution. The second transformer is also a variable ratio transformer, responding to feed-back from the output.

The first transformer has a capacitor on its input, so its input voltage cannot change quickly. As its ratio is modulated between the closest steps, its output voltage V_1 will be V_p/M_1 when the ratio is M_1:1, and V_p/M_2 when the voltage is M_2:1. If the duty cycle d is defined as the time when the ratio is M_1:1 divided by the period, then the average first stage output voltage V_1 will be given by:

$$V_1 = V_p/\{dM_1 + (1 - d)M_2\}.$$

‡ U.S. Patent pending. FMTT, Inc.

A similar expression relates the second stage input voltage V_2 to the output voltage V_o:

$$V_2 = \{d'M_3 + (1-d')M_4\}V_o$$

The quantity d′ is the second stage duty cycle, and M_3:1 and M_4:1 are the ratios between which the second stage transformer is being modulated. On average, V_1 must equal V_2, and the inductor provides the impedance to allow the instantaneous voltage differences.

The voltage across the inductor, on average, must be zero. The AC voltage will be small if both the first and second stage transformers have a sufficiently large number of steps so that the incremental steps between which modulation occurs are small. The variable ratio transformer would usually have 100% duty cycle switching.

D. Currents in the Interstage Winding

The interstage winding carries a high frequency AC current, with high di/dt's. Routing it around indiscriminately would cause severe problems, both due to the leakage inductance in the wire, and due to EMI.

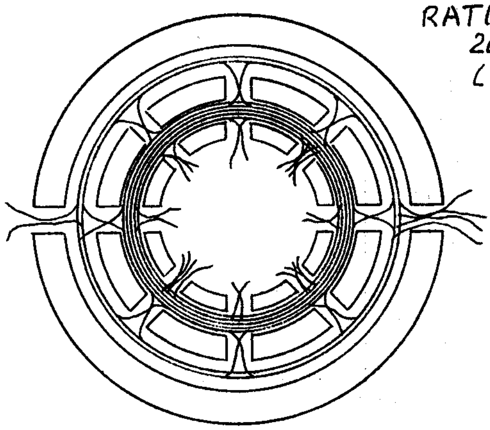

Figure 18.7. A cascaded matrix transformer in one pot core like magnetic structure. The interstage windings are not paralleled, but rather are kept as eight separate windings, to minimize leakage inductance.

If the cascaded stages are only for small, auxiliary outputs, with low currents, then the problem is more manageable. The inductance of the interstage winding in that case is a parallel impedance to the main secondary, and would not degrade the operation of the primary switching.

Where all of the power is going through the interstage winding, it is important to keep the runs as short as possible, and as low inductance as possible. This is difficult to do if the outputs of the first transformer are brought together, paralleled, and then distributed as one winding. One approach would be to use power planes in a printed circuit board, with short wide runs.

1. Use Parallel Interconnections ‡

A better approach is to not collect the currents, but keep them as individual wires, as is the philosophy in much of the matrix transformer concept. It is best to align them immediately with their destination. In other words, as the parallel wires exit the secondary windings of the first transformer, they should enter an immediately adjacent second transformer. An example of this is shown in figure 18.7.

The windings in the transformer figure 18.7 are a little difficult to follow. Figure 18.8 shows one of the eight interstage windings, and one of the output windings, in more detail. The primary winding detail is not shown, but it could be any primary suitable for a matrix transformer, such as a symmetrical push pull winding with floating capacitors.

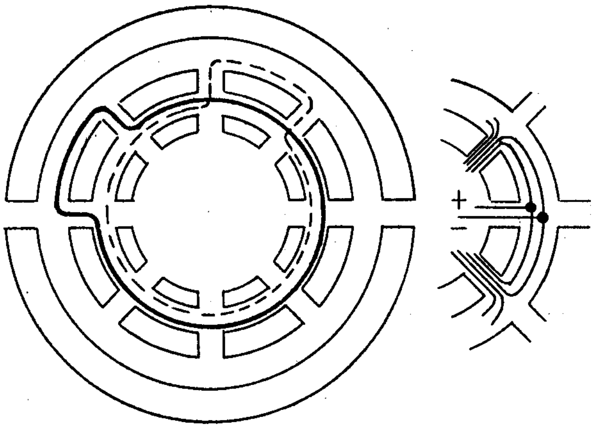

Figure 18.8. One of the interstage windings, and one of the output windings are shown in detail. The primary could be a symmetrical push pull winding, and could have several turns, for an even greater ratio.

In figure 18.7, the primary winding of the first stage matrix transformer makes a single turn around through the outer eight elements. Eight parallel secondaries exit the first stage transformer, just as in a picture frame matrix transformer. Each one is taken to the second stage, passing into it immediately, and making a single turn through *seven* of the eight elements. This provides the optimum alignment, so that each winding passes immediately from the first transformer to second and back.

This provides eight overlapping primary windings for the second stage, each of the eight windings coupling *seven* elements. Each has coupled the first primary in the first stage transformer, so each of the eight carries a current equal to the primary winding.

In any one core of the second stage transformer, there are seven wires, each carrying a current equal to the primary winding. Therefor, the first stage ratio is 7:1 to the primary of the second stage transformer. As shown in figure 18.7, the second stage secondary has a 4:1 ratio from the secondary stage primary. The total ratio of the two stage cascaded transformer is thus 28:1.

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‡ U.S. Patent pending. FMTT, Inc.

Note that the first stage cores must have seven times the flux capacity of the second stage cores. The current in the second stage is seven times the primary current. In the second stage primary, it is carried in eight isolated wires. There is no reason to parallel them.

The outputs windings of the second stage transformer also each carry seven times the primary current. The currents will be balanced. The primary could have two or more turns, for even greater ratios.

XIX. Voltage and Current Balancing

"Balancing", as used with matrix transformers, means the precise division of voltage or current, usually equally. In many configurations of the matrix transformer, voltage and/or current balancing are inherent.

This section looks at some exceptions, and some circumstances under which balance can be lost, with techniques for maintaining it, and some situations where balance is not obvious.

A. Voltage Balancing

Because of Faraday's law, voltage balancing is inherent and taken for granted when windings are coupled by a common flux. Differences will usually be attributable to impedances and the load currents.

It is not so obvious that there can be voltage balance between sections of a primary which are in series, or between isolated outputs on different elements (cores).

1. Series Primaries

Series primaries can be used to reduce the required voltage ratings of component parts, or to make a dual input voltage circuit.

a) Voltage squared!

If a transformer is being designed to work with a high input voltage, consideration should be given to designing it with several series primary sections, with voltage balancing to maintain equal voltage division. There are some losses which get worse as the voltage squared. By halving the voltage, these losses can be reduced to one fourth. The series circuit therefore has half the net loss attributable to these factors.

This is particularly advantageous if the circuit is large enough that extra devices are needed anyway, to handle the power. It can be much better to use series devices than parallel devices.

Factors which get worse as the voltage squared include:

> The R_{DS} of FET's tends to be higher as the square of the voltage rating.
>
> The part of the turn on switching losses due to discharge of parasitic capacitors into the device has losses proportional to $CV^2/2$.

Another, less obvious factor is the Miller charge on the gate (or base), which is a function of the voltage, and which limits the speed of turn on and turn off. With higher voltages, turn on and turn off is slower, which increases crossover losses.

With bipolar transistors, the effects of dynamic saturation are much worse in transistors having a high voltage rating.

b) Symmetrical Push-Pull Topology

A number of symmetrical push-pull matrix transformer primary circuits can be put in series, and the voltage across each of them will be balanced under most circumstances as long as their secondaries are paralleled. As an example, for a four hundred volt input, and a 5 volt output, a turns ratio of forty to one would be about right, assuming a nominal 50% duty cycle. With a single primary section, 1000 volt devices would be required.

With two series sections, 500 volt devices could be used. With four sections, 250 volt devices are feasible. The secondary circuits are virtually identical.

During the "on" time, the primary circuits all drive the same paralleled output, so the voltage has to be the same. The "floating capacitors" are large enough to maintain voltage balance during the "off" time.

To assure voltage balance at the instant of turn on, the floating capacitors should all have the same value. If there is an operating mode where voltage could be applied with an extended quiescent "off" time, a resistor divider might be needed, so that leakage currents do not cause the voltages to drift.

If the secondaries of the transformer elements each has its own rectifiers and inductor element, then the timing of the primary switching can be offset in time to smooth the wave form.

c) Dual Voltage

Symmetrical push-pull primaries can be used to make a dual voltage supply, for instance 150/300. For the lower voltage, they are paralleled, for the higher voltage, they are used in series. Switching can be automatic.

B. Voltage Balance in Isolated Outputs.

Usually all of the sections of a secondary winding are taken in parallel. There are circuits where it might be useful to have them mutually isolated. An example might be isolated gate or base drives for transistors. Each should have the same drive, but they cannot be paralleled.

1. Outputs are current sources

Isolated outputs, all having the same series primary, will have the same output current, to satisfy Lenz's law. Thus each behaves as a current source. This is ideal for transistor base drives, but can be a problem if the load impedances are not suitable. See figure 19.1.

a) Voltage Balancing Winding ‡

To "convert" the isolated outputs to voltage sources, a voltage balancing winding can be added. This is essentially an extra winding, with a secondary for each element, taken in parallel, observing polarity. It is left open circuited (but it does not need to

‡ U.S. Patent pending. FMTT, Inc.

be), and it will constrain the voltage in every other winding on the elements to have the same voltage (per turn). The winding will carry current only sufficient to satisfy Lenz's law. See figure 19.2.

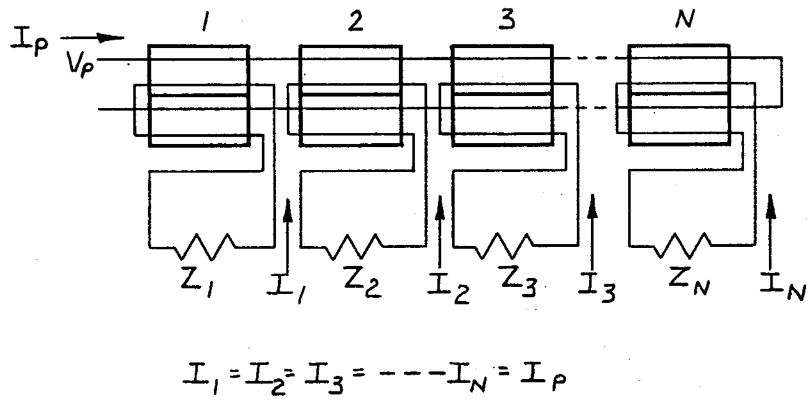

Figure 19.1. Normally the outputs of a matrix transformer are taken in parallel. If they are kept isolated, each behaves as a current source, and equal voltage would depend upon equal impedances.

If the winding is used to compensate for small variations in nominally equal loads, a very small wire will suffice, and impedances will be of minor concern. If, however, some of the secondaries could be an open circuit, the winding must be designed to handle full current, and leakage inductance should be minimized.

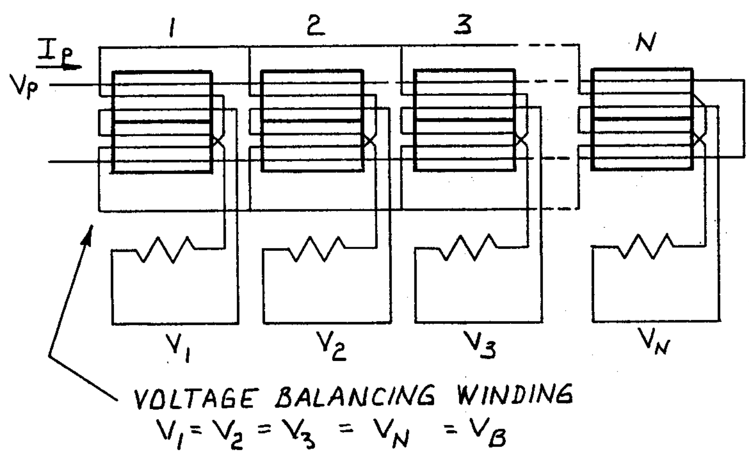

Figure 19.2. A voltage balancing winding can be used to keep isolated windings at the same potential regardless of impedance.

C. Current Balance in Primary Circuits

A review of the orthogonal matrix transformer in section II, and many of the figures, such as figure 2.4, shows that current balance in the primary is inherent in these layouts. Current balance is inherent in these circuits, and needs no further discussion.

1. Current Balance among Windings in One Set of Elements

In some designs, it is advantageous to put two primary windings in the matrix transformer, on the same elements in parallel. If isolated, they could be used in as series or parallel arrangement for two voltage operation. In series, the current must balance, as the one flows into the other. This is not guaranteed when the circuits operate in parallel unless provisions are made to ensure it.

If two or more windings are in parallel in the same elements, Lenz's law will be satisfied regardless of how the current divides among them. Only the FET's on-resistance and the winding impedance itself would serve to ballast the circuits. The current balancing inherent in matrix transformers has been lost.

a) Current Balancing Element ‡

Current balance can be restored if two primaries are taken from the transformer, as loops, and put in opposition in a current balancing element. This can be anywhere along the length of the circuit, as shown in figure 19.3. The current balancing element nominally would have no voltage drop, but would develop a potential sufficient to restore the balance if the currents were unequal.

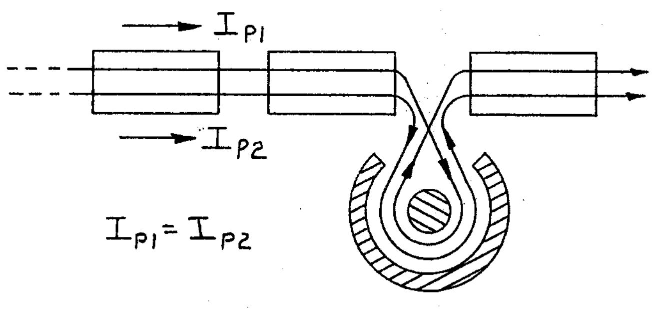

Figure 19.3. A portion of the primary (only) of a picture frame matrix transformer is shown. Paralleled primary currents can be balanced if they are passed in opposition through a current balancing element.

D. Current Balance with Multiple Outputs

When a matrix transformer is designed with more than one output, and current balancing is desired, care must be taken that one winding cannot "steal" ampere-turns from another. After all, it is satisfying Lenz's law that forced the current balance. But Lenz does not care in which winding the current flows. If one can increase at the expense of another, he will be happy. This is a risk particularly if one winding is a factor of the other (as a 5 volt and a 15 volt winding), or if there is a large ratio between them (as a 25 volt winding and a 3 volt winding).

The M x N matrix transformer is less prone to this problem, because each winding crosses all of the others. In a picture frame transformer, the balance is improved by

‡ U.S. Patent pending. FMTT, Inc.

providing as much overlap as possible. The most positive solution is either to use separate transformers (they can share the primary switches), or to use cascaded transformers.

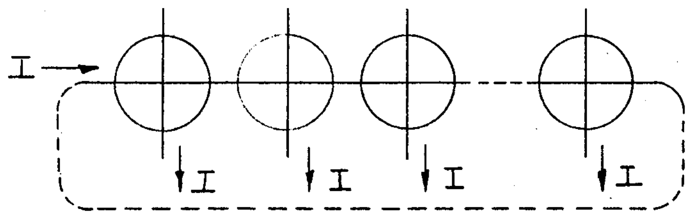

Figure 19.4. Currents can be balanced in as many parallel paths as required by passing each through a current balancing element. A single shorted turn is then taken through all of them, with care to minimize leakage inductance.

a) Current Balancing Elements ‡

Current balance can also be assured if the parallel secondaries of one of the outputs are each taken through an extra small element. A single wire then is passed through all of these elements and shorted on itself. This will cause a circulating current in the extra winding, but there will be no net voltage drop, so the current balancing elements do not need much flux capacity. Lenz's law will require that the current be equal in each secondary so coupled. See figure 19.2. Care must be taken to minimize leakage inductance.

‡ U.S. Patent 4,665,357; other patents pending. FMTT, Inc.

XX. Winding and Core Design

This section considers the sizing of the transformer windings and cores, which is mainly a thermal problem.

Determining conductor size is a trade off of acceptable temperature rise against other constraints such as the available heat sinking, required current capacity, element length, required efficiency, and so forth. At high frequencies, penetration depth is a factor.

The core size and geometry are a trade off of acceptable temperature rise against other constraints such as the available heat sinking, required flux capacity, conductor and insulation size, required efficiency, and so forth.

A. Design Method

The art of designing monolithic transformers is fairly mature, and lots of tables, nomographs and short-cut equations are available. These do not exist yet for the matrix transformer. Matrix transformer design at this time is largely empirical. We can provide some guidelines, some considerations and a few examples. Once something works, it becomes the starting point for the next experiment.

One of the advantages of the matrix transformer is that the possible layouts and arrangements are infinitely varied. The monolithic transformer is basically a block. Perhaps it can be flattened some, but there is not much else that can be done to it. The matrix transformer can be stretched out or scrunched up, looped around, overlapped, folded, or wrapped around a cylinder. This great freedom of choices, as well as the sparseness of the experience base, makes it difficult to do an A, B, C · · · set of cook book instructions.

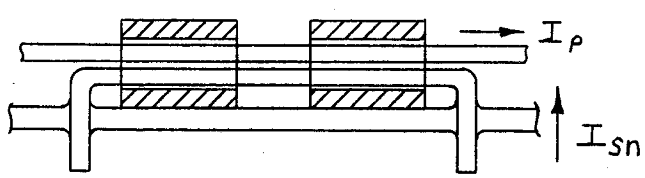

Figure 20.1. This element, with two cores and four wires has a power budget of 0.5 watt, or about 0.06 watts per wire. For 8.5 amps RMS, use No. 18 wire.

Even in monolithic transformers, over reliance on tables, nomographs and short cut equations rarely provides an optimum design. It gives pat answers, though, and usually they are conservative enough to work OK at line and audio frequencies. For high frequency transformer design, every factor must be considered, as everything is interrelated. In matrix transformer design, the same considerations apply. The laws of physics were not amended with its discovery. Although unfamiliar, nothing should be mysterious. We expect that matrix transformer design will actually be much easier, once the mystery is penetrated.

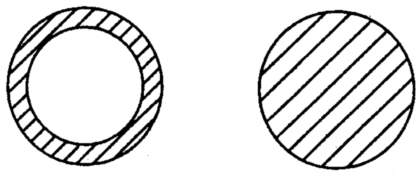

Figure 20.2. At high frequencies, the penetration depth may limit the conductor area available for current conduction. It does not reduce the area for thermal conduction. Litz wire is not recommended.

1. Principle Parameters, Form and General Layout

For a successful high frequency converter design, the transformer is not designed separately. Before starting, as much as possible should be known about the environment that the transformer will work in: converter topology, input and output voltages, currents, frequency, duty cycle, whether paralleled drive FET's and rectifiers are needed or desired. Constraints on physical space, preferred geometry and available heat sinking must be known.

At this point, make a first cut at a layout and arrangement of the cores, considering the ratio, the number of parallel outputs, rectifier location and so forth. It may be that the core and wire size will be most constrained by the distances between the semiconductors on their heat sinks, or the geometry of the available space.

2. Power Budget

Make a power budget. For some systems, the power budget will be driven by efficiency considerations, but usually it is a factor of the available heat sinking and acceptable temperature rise. Of course, it is always best to keep power dissipation as low as practical.

Knowing the number of elements, determine the budgeted power per element.

B. Conductor Design

Knowing the number of elements, and the maximum output current rating, the maximum current output per element can be determined by dividing the output current by the number of elements. With consideration to the converter switching wave forms, estimate the RMS current in the windings.

Once the current is known, and the power per element has been budgeted, if half of the power is allocated to the windings, the power budget per wire is known. A typical design will have 1:1 push pull windings in the elements, so the current is approximately the same in each of four wires.

Knowing the RMS current, calculate the acceptable resistance, using $R = P/I^2$. Knowing the element length, find the ohms per thousand feet, and look it up in a wire table. See figure 20.1. We have found that a wire size of about 50 to 60 circular mils per ampere is about right for the bread boards that we have built. This is about an order of magnitude smaller that can be used in the bulk wire build up of a conventional transformer. It will vary depending on allowed temperature rise and the heat sinking.

Check the wire radius against the penetration depth for the frequency. See figure 20.2. It may be necessary to use a larger wire to get the required conduction area.

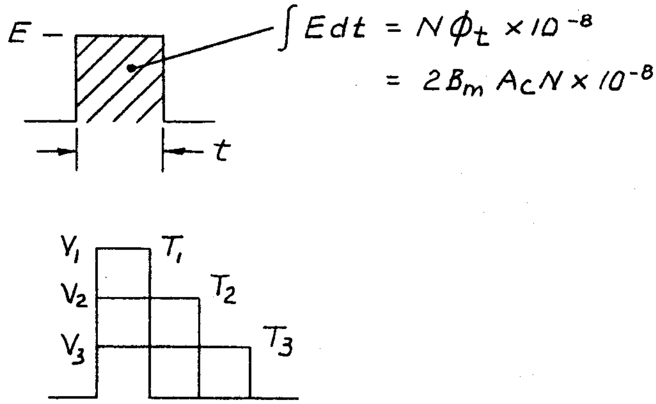

Figure 20.3. The flux capacity required in a buck converter tends to be independent of input voltage.

1. Don't Use Litz Wire.

As shown in figure 20.2, some of the conduction area may be lost due to the penetration depth. But none of the area is lost from the thermal conduction, and that is important too.

Litz wire is awful to work with, and has no potential benefit unless proximity effects are important. They do not seem to be a factor with the small number of wires and the good coupling of the matrix transformer elements. The winding factor with Litz wire is very low, 20% or so, because it is mostly insulation and air.

We usually use ordinary type E or EE hook up wire for the matrix transformer windings. Solid wire is somewhat smaller, and stays in place fairly well.

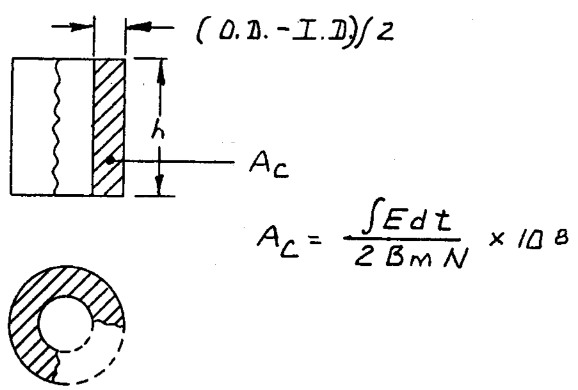

Figure 20.4. The core cross sectional area is a function of the integral of the voltage wave form with respect to time, and the flux density.

2. Insulation Thickness

The insulation required can be determined from the design specification. Type E or type EE hook up wire should be suitable form most applications. A sleeve can be added for higher isolation.

C. Core Size

Knowing the wire size and the insulation, the core ID can be determined. You should always mock up some cores, and make sure the wires and the insulation fit.

1. Flux Capacity

The flux capacity required is determined from the volts-seconds (V t) of element voltage wave form and Faraday's law. See figure 20.3. For single turn elements, required flux capacity ϕ_t is:

$$\phi_t = V\,t \times 10^8$$

In a buck converter, the volts-seconds tends to be constant. See figure 20.3.

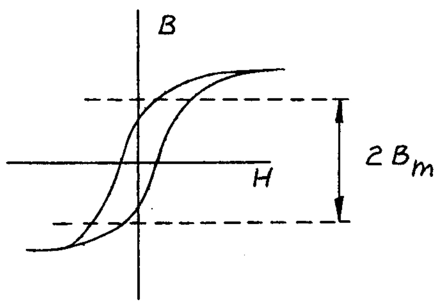

Figure 20.5. In lower frequency transformers cores, the flux density is limited by core saturation.

2. Core Area

The cross sectional area A_c of the core is determined from the required flux capacity ϕ_t and the flux density B_m:

$$A_c = \phi_t/2B_m$$

Given that there is already an ID and core height (from the first cut layout and element length), the A_c provides the last information needed to size the core. Calculate the OD to give the required A_c. See figure 20.4.

Unfortunately, it is very difficult to predict what flux density should be used.

D. Flux Density

For low frequency, determining flux density is easy. It will depend upon the saturation of the core, derated somewhat. See figure 20.5.

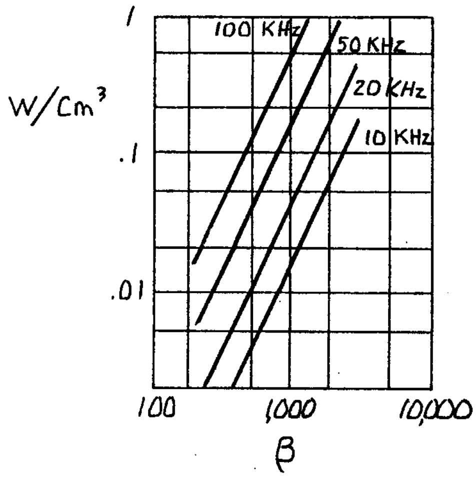

Figure 20.6. At higher frequencies, the flux density is limited by dissipation and heat sinking.

1. Flux Density is Thermally Limited

At high frequencies, the flux density will be thermally limited, by dissipation and the heat sinking available. Manufacturers of ferrites usually include a graph like the one in figure 20.6, relating the frequency, the flux density and the power dissipation per unit volume of material.

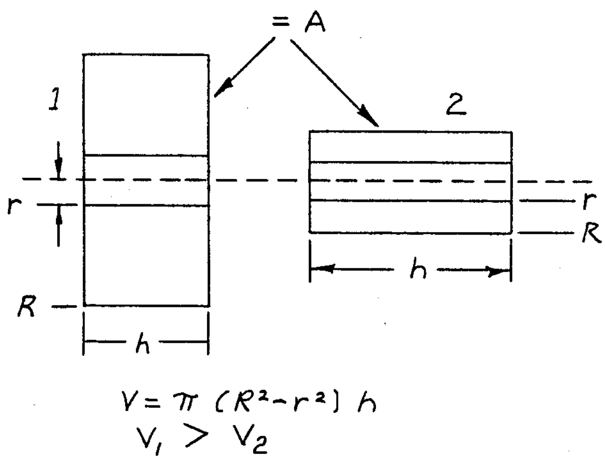

Figure 20.7. Given an inside diameter and an area A_c, a longer core will have a smaller volume.

There may or may not be a note somewhere stating the conditions under which the data was taken. A one inch OD toroid is typical. Whatever the reason, the data does not seem to apply to the geometries of the cores used in matrix transformers. We have found that the losses seem to be about 25% to 40% as high as predicted.

2. Minimize Volume

Regardless of whether the data curves give the correct answer or not, losses in a ferrite are a function of volume, all else being equal.

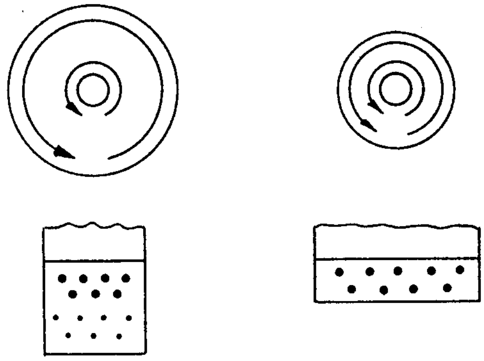

Figure 20.8. The outer flux paths have a higher reluctance, so the flux density will be lower at larger radii. Despite equal area, the fat core will have a higher flux density (more losses) at its ID, just where it is not wanted.

a) Long, Skinny Cores

There are a number of factors favoring long, skinny cores. Figure 20.7 shows that, for a given ID and area A_c, the longer core will have a smaller volume. Since losses at a given flux density and frequency are a function of volume (W/cm^3), a smaller volume core will have a smaller core loss, in direct proportion.

The long, skinny core also has better heat dissipation. The thermal path through a skinny core from the ID to the OD is shorter, and the surface area to volume ratio is higher. One trade off is that the winding losses go up as the length increases, and the thermal path through the length of the wire is longer.

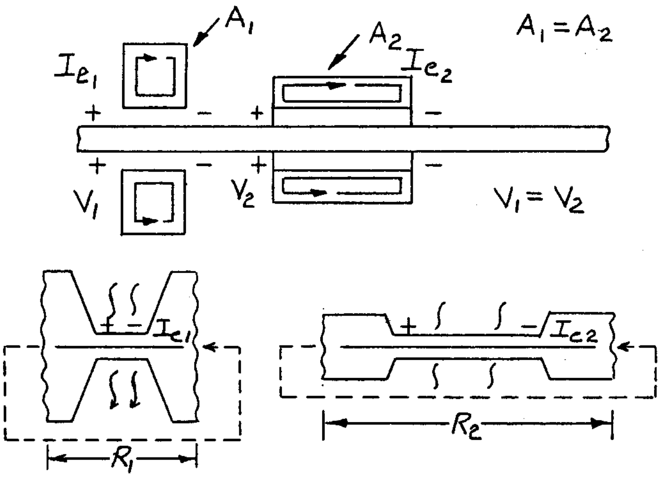

Figure 20.9. If the core material has significant conductivity, eddy currents will flow. In a longer core, the voltage gradient is lower, and the surface conduction path is longer and higher resistance.

The flux distribution in a skinny core is better. Figure 20.8 shows that the difference between the longest and the shortest flux path is much greater in a fat core. If μ is homogeneous and linear, the flux density at any radius will vary as the path length, which is proportional to the radius. If the flux density is much higher near the ID, a disproportionate amount of the heat will be generated there, just where it isn't wanted.

b) Eddy Currents

If the core material has a significant conductivity, the eddy current conduction losses should be less in a long skinny core. Figure 20.9 shows current flow through the wire, and the resulting eddy currents induced in the core for a fat core and a skinny one. The driving voltage will be the same, but the ϵ field is much lower in the longer core, and the resistance of the current path is much higher.

At higher frequencies, losses are reduced in ferrites by laminating them. That is, the cores can be sliced, and reassembled with an insulating film between the parts to break the conduction path. The cuts should be parallel to the flux path, which suggest doughnut like slices. In metal cores, tape wound construction is used. There might be an advantage to using a stack of thin washers instead.

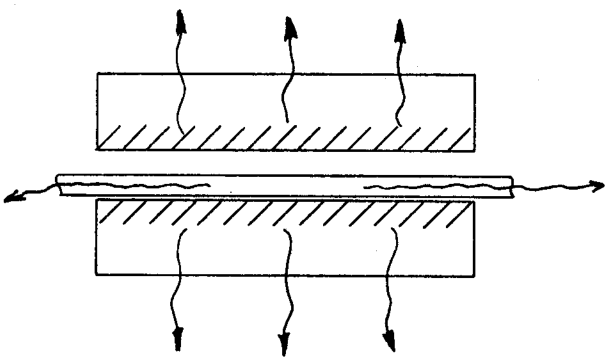

Figure 20.10. The heat *per unit length* is much lower in a longer, skinnier core, the thermal conduction path through the core is shorter, and the surface area to volume is higher.

E. Thermal Considerations

Figure 20.10 shows the heat paths from the core of a matrix transformer. The heat production is higher in the area around the bore, where the flux density is higher and the conduction losses occur. A longer, skinnier core would have less heat generated, in absolute quantity for a given element voltage, but of particular significance, its heat per unit length is much lower. The thermal path length through the core is shorter, and the surface area to volume is higher. Heat sink contact area, if one is used, would be higher. The offsetting negative factor is the increased I^2R losses in the conductor, and the longer thermal path along the conductor.

1. Thermal Model

Figure 20.11 shows a thermal model that has been developed for toroidal matrix transformer cores to allow approximate calculation of the heat flow and temperature rise. The windings are approximated by a copper cylinder having a circumference equal to the total *exposed* area of the wires, that is, the area that is on the outside of the bundle. This is covered by an insulation equalling the wire insulation in thickness and material, including any build up of sleeving. All of the wire losses are lumped into this cylinder. The area of the cylinder is made equal to the area of the copper in the wires. Hollow out the center if necessary. Heat flux in or out through the insulation or along the length should be modeled fairly accurately by this model.

Since copper is a very good conductor, there model will have no gradient radially, but may have a significant gradient lengthwise. The length of the model wire will have to be extended to any identifiable heat sinks, and may have to have branches.

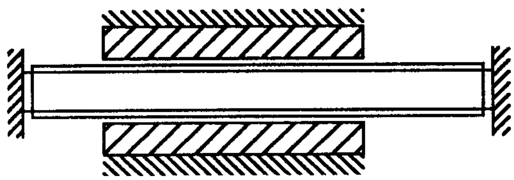

Figure 20.11. Thermal model of a matrix transformer core.

Losses in the core are assumed to generated on the ID surface, and are conducted radially outward. This model is conservative, because some of the losses are actually generated in the bulk of the core and have a shorter thermal path to the OD.

The outside of the core is either ambient air or a heat sink, as appropriate.

2. Heat Sinking

Heat dissipation from the elements of the matrix transformer can be improved considerably if the core is surrounded by a metal heat sink, or if the core is bonded to a heat sink. In the latter case, a flat sided core is preferred, or a conforming groove can be milled in the heat sink. A conforming metal clamp provides an additional improvement.

F. Flux Density Used in Breadboards

We have used flux densities ranging from 800 to 1650 gauss at 250 Khz to 400 to 800 gauss at 1 Mhz. No particular effort was made to heat sink the cores in most units, and the materials which we used are not considered to be particularly good at high frequency.

1. Core Selection became Trivialized

Our first cores were selected just because they were readily available, inexpensive, and of a size that was easy to handle. They worked well enough that flux losses were never a serious factor, and our attention was diverted to more immediate problems. In general, core length ("height" of toroids) was determined mainly by how closely we could mount the semiconductors.

This suggests that much smaller cores could be used with improved material, heat sinking and smaller semi-conductor packaging, such as dice, mounted as in hybrids.

XXI. Solid Core Structures

The matrix transformer windings can be in a solid structure rather than individual cores.

The matrix transformer can be integrated with other transformers and inductors, in one structure. Provisions can also be made for incorporating rectifiers, FET's, capacitors, or even entire circuits with a closed ferrite enclosure.

A. Block Core Structures ‡

Although the matrix transformer is made up of a matrix or array of elements, there is no reason that the various elements have to have individual cores. The elements can all be in one larger core structure, designed so that the various elements have definable windings and flux paths.

1. Plate with Holes ‡

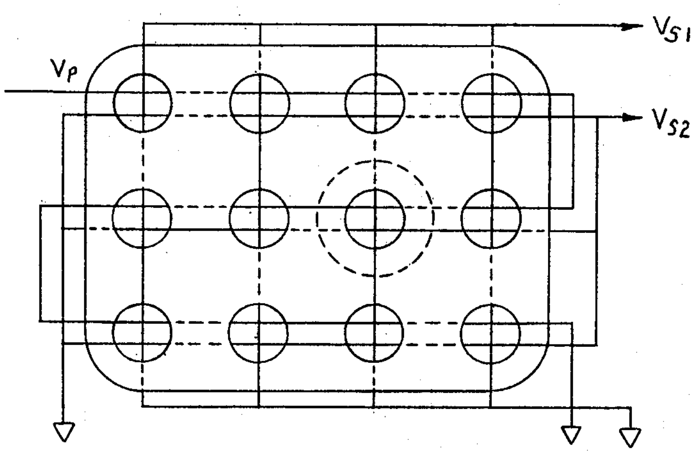

Figure 21.1. A matrix transformer can be wound through holes in a plate of ferrite or a stack of perforated laminations. The material surrounding the hole is equivalent to a toroid.

A simple unified core structure for matrix transformers is a plate of ferrite with holes through it, or a stack of perforated laminations. See figure 21.1. The material around each hole is equivalent to a toroid. This form has the advantage of having no air gap, yet it doesn't have loose parts.

The matrix transformer shown in figure 21.1 has a series primary through all of the holes, and two secondaries, one having a 4:1 ratio and the other having a 3:1 ratio with respect to the primary. Note the stitchwise threading of the winding, so that adjacent "cores" have opposite flux direction.

2. Grooves in Blocks ‡

A transformer core structure can have provisions for laying the windings in open grooves. The windings could be pre-assembled, like a wiring harness, or could be laid in as part of the assembly process. See figure 21.2.

‡ U.S. Patent 4,665,357; other patents pending. FMTT, Inc.

Two halves of an assembly could be pre-wired with a choice of primaries, and a choice of secondaries, which would then get mated as required. Alternatively, all of the windings could go into one grooved structure, which could the be closed with a flat plate. Yet another alternative would be to have the tops of the grooves slightly tapered, and close them with wedges having the same taper. This latter arrangement has the advantage that some of the elements could be shimmed with non magnetic material to make a gap, for use as inductor elements.

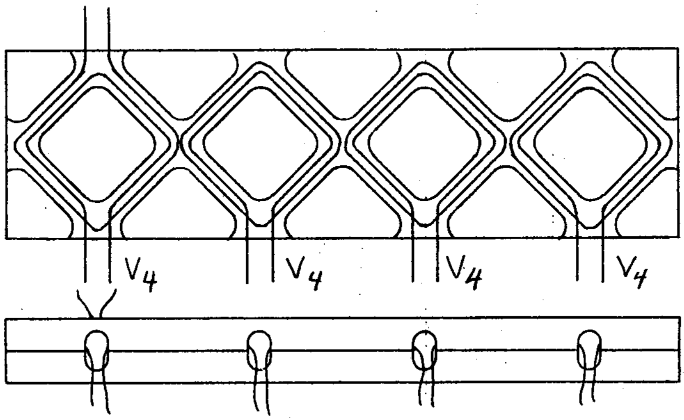

Figure 21.2. A core structure for a matrix transformer having two blocks with matching grooves. The primary winding could be potted in one half, with the secondary in the other half. Different parts could then be mated as required for different applications.

a) Current Balancing may be Compromised

Current balancing in the elements of a matrix transformer is based upon Lenz's law, which requires that the net ampere turns coupled by the flux must be zero (neglecting magnetization). That is still true, but the flux path is no longer so constrained in a block structure. Some of it may extend out and couple other conductors.

This influence could be reduced, while retaining the handling characteristics of the block if it were fabricated of separate pieces, and assembled with non magnetic separators to divide the elements.

B. Cores Resembling Pot Cores ‡

Picture frame matrix transformers can be in a pot core like structure with a channel for the windings and a cover or matching part to close the flux path. See figure 21.3.

Using a step down transformer as an example, the primary can make one or more turns around the whole channel. In the bottom of the channel (or any where else that is convenient) there are a number of holes, spaced more or less evenly depending on the ratio wanted. Picture frame type windings are wired from hole to hole, and the spaces between the holes defines the elements.

‡ U.S. Patent pending. FMTT, Inc.

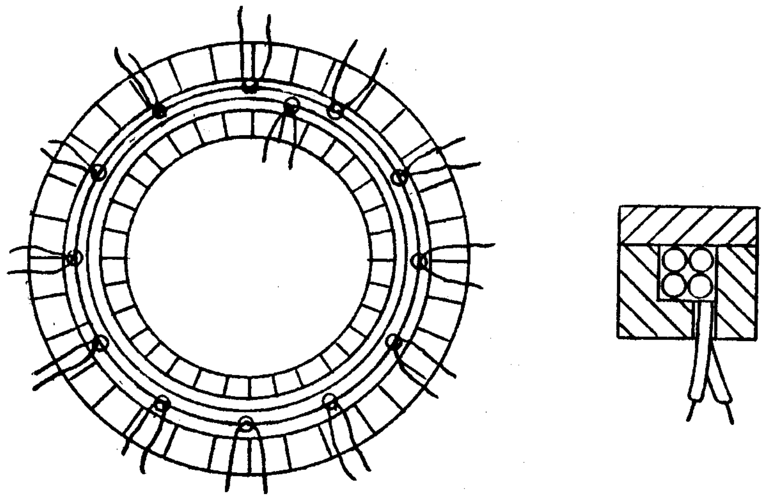

Figure 21.3. A "picture frame" matrix transformer can be made in a pot core like structure. As shown, the transformer has a 12:1 ratio, with a single turn primary and 12 parallel secondaries. Other secondaries with other ratios could be added, just by using other sets of holes.

Another set of holes could be used for another output having a different output voltage.

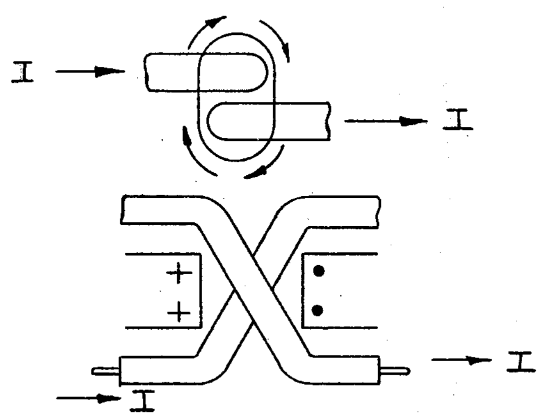

Figure 21.4. There is a closed flux path around the holes through which the windings enter and leave. The currents must be balanced, but that is the nature of matrix transformer windings.

1. Closed Flux Path Around Holes

As shown in figure 21.4, there is a closed flux path around each hole in the pot core. This is true even if grooves in the side wall are used, once the cover is in place. The wires going through the holes must be paired so that the currents are equal and opposite, so that the net ampere-turns is zero. This happens naturally in the matrix transformer.

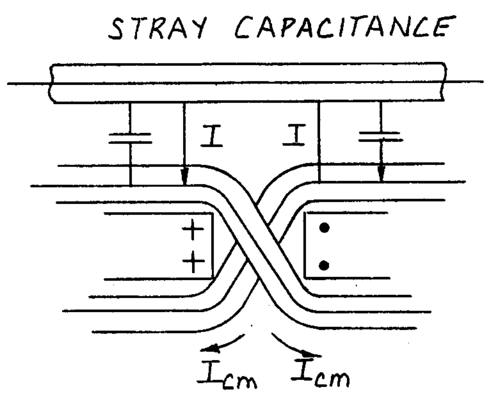

Figure 21.5. The closed flux path around the holes will tend to reject common mode currents.

a) Common Mode Noise Rejection

Figure 21.5 shows the current path for common mode noise currents, such as might result from capacitive coupling between windings. The closed flux path around the opening would tend to reject this noise. The hole length could be made greater, or the wires could be laid together in a channel to increase this effect.

C. Integrated Structures ‡

With a modicum of care, core structures can have integrated functions, such as a transformer integrated with its filter inductor or a cascaded transformer. Often the transformer layout can be arranged so that its terminals align naturally with the integrated structure. An example would be a pot core like picture frame transformer with a pot core like picture frame matrix inductor on its opposite side.

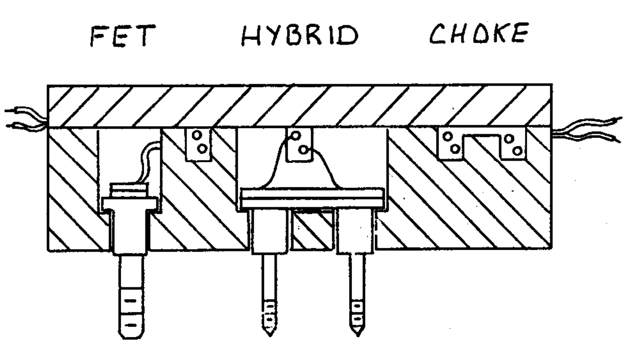

Figure 21.6. Components can be mounted on heat sinks within a matrix transformer. The heat sink stud can double as a mounting stud for the transformer.

‡ U.S. Patent pending. FMTT, Inc.

D. Core Structures Containing Components ‡

Much of the leakage inductance associated with matrix transformers is in the external leads. This can be reduced by incorporating the rectifiers and switching FET's within the integrated magnetic structure, as shown in figure 21.6. If symmetrical push pull windings are used with floating capacitors, the terminations are DC. Drive circuits coming into the transformer for the FET's would have to be balanced signals.

An integrated core structure containing rectifiers and an integrated inductor could provide the transformer, the secondaries and the L for a transformer buck converter. The outputs could go to immediately adjacent filter capacitors.

1. Heat Sinking

If the internal components have any significant power dissipation, heat sinking would be required. Figure 21.6 shows an example. Note that the heat sink can double as a mounting provision for the integrated transformer structure. Because there is a closed flux path around the heat sink stud, capacitively coupled currents would tend to be rejected.

2. Entire Circuits ‡

Entire converter circuits could be contained within an integrated core structure, with only heat sink studs and DC terminations coming out. The outside could be sealed, and metal clad if desired.

‡ U.S. Patent pending. FMTT, Inc.

XXII. Bridge Circuits

The half bridge and bridge circuits work well with the matrix transformers.

A symmetrical push pull full bridge arrangement has the sources of the power FET's at ground potential.

A. Half Bridge and Bridge Windings

The familiar half bridge and bridge circuits are ideal for single or multiple turn flat matrix transformer primaries. Figure 22.1 shows a half bridge circuit. Figure 22.2 shows a full bridge circuit with a picture frame matrix transformer.

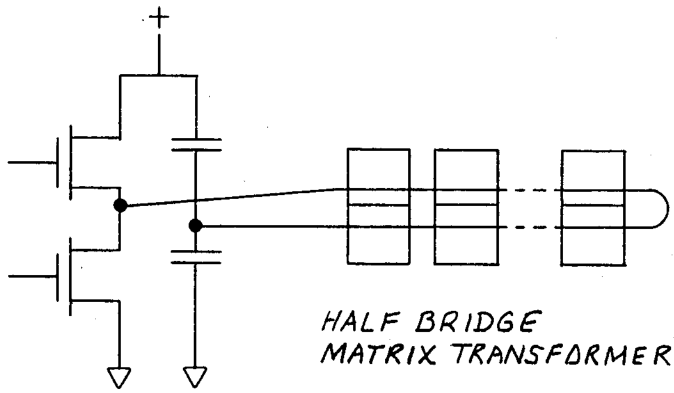

Figure 22.1. A matrix transformer primary driven with a half bridge circuit.

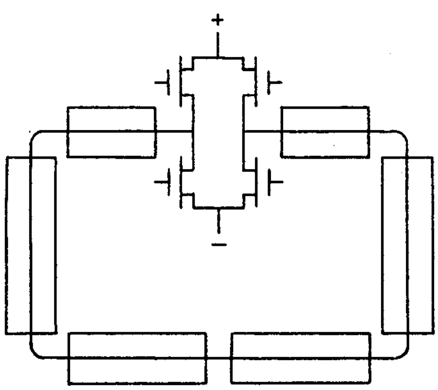

Figure 22.2. A picture frame transformer is driven with a bridge circuit. One turn is shown, but multiple turns could be used as well.

B. Symmetrical Push Pull Full Bridge ‡

An interesting circuit results if each transistor in a symmetrical push pull primary is replaced with a series pair, and a plus and minus power supply is used. See figure 22.3.

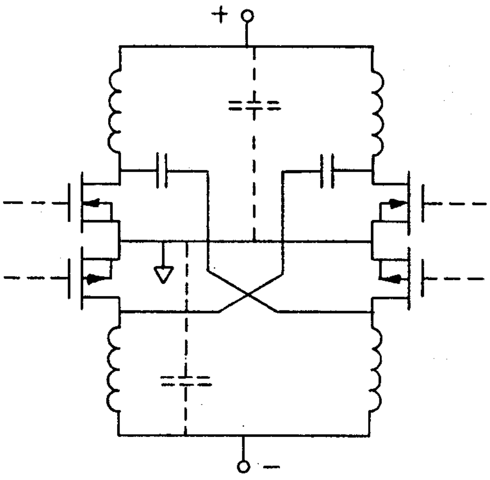

Figure 22.3. A symmetrical push pull bridge circuit. If N-channel and P-channel FET's are used, all four FET's can be *ground referred.*

The drains of the N-channel FET's (the upper pair) have voltages of plus V, plus or minus V, or ground to 2V. The drains of the P-channel FET's are ground to -2V. With both FET's one side turned on, the sources will be at ground potential, fixed by the symmetry of the transformer. When both are off, the source voltage is indeterminate, but it can be fixed to ground without affecting performance.

It is therefor possible to tie all four sources together, and tie them to ground. The floating capacitors are connected around the whole set. The circuit function is not dependant upon the nature of the switches.

An optional capacitor divider could stabilize the ground with respect to the plus and minus input, or could create a "ground" for the FET drives if none existed.

1. Symmetrical FET's can be Located with the Input Power.

Throughout this presentation, the symmetrical switching FET's have been shown on the opposite side of the transformer from the input power. This is often desirable, to isolate the switching noise from the line. This happens only if the primary has an odd number of turns (1, 3, 5 etc.). With an even number of turns, the switches will be located at the power source. In the circuit of figure 22.3, that might be preferred.

‡ U.S. Patent pending. FMTT, Inc.

XXIII. Floating Capacitors and Inductors

Floating Capacitors cannot be used in symmetrical push pull transformer secondaries which drive inductive loads, or the filter inductor of a buck converter.

The inductor can be brought into the symmetrical push pull circuit, however, inside the floating capacitor terminals.

This works particularly well with a full wave forward converter secondary. ‡

A. L-C Filters with Floating Capacitors

The reason that floating capacitors cannot be used with inductive loads is that the floating capacitors "float" with the output terminal voltage. During the off time, the inductor voltage changes from V_p/M to ground, and back again at the next on time. Thus the output terminal voltage sees very large and fast voltage swings.

Figure 23.1 shows that the filter inductor can be brought into the transformer circuit, as split coupled inductors, one side in series with each of the rectifiers. This would require very good coupling in the inductors. A coaxial picture frame inductor might be well enough coupled.

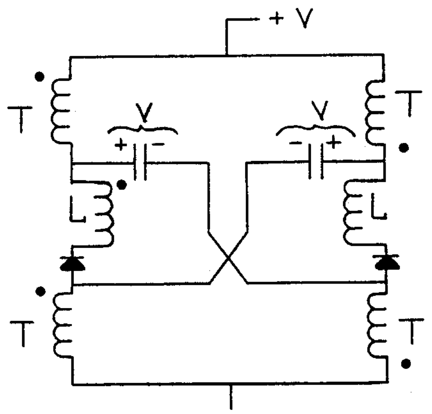

Figure 23.1. The symmetrical push pull winding with floating capacitors can be used with an inductor, if the inductor is split into two coupled inductors, and brought inside the floating capacitor terminals.

B. Forward Converter

A very common topology for power conversion is the forward converter. It is often chosen for its simplicity, but it has good operating characteristics as well.

The primary circuit can be similar to a symmetrical push pull circuit, with one of the FET's replaced with a catch diode. More positive reset is accomplished using both FET's, but one can be a low power FET.

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‡ U.S. Patent pending. FMTT, Inc.

Either of these primary circuits could drive the half-wave forward converter primary, reviewed in figure 23.2.

Figure 23.2 also shows that the forward converter secondary can be arranged for full wave operation. This would require that both FET's in the primary be power FET's.

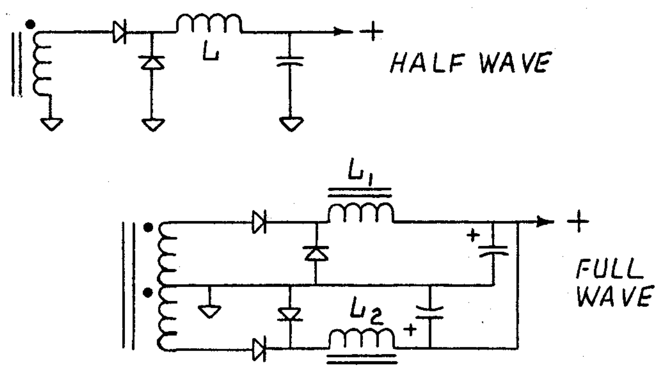

Figure 23.2. A half wave forward converter secondary is shown, with the full wave forward converter. Either circuit can be used with a matrix transformer.

1. Forward Converter Secondaries with Floating Capacitors.

Either the half wave or the full wave forward converter can be used with a symmetrical secondary with floating capacitors if the inductor is brought inside the floating capacitor terminals, as shown in figure 23.3. Note particularly in the full wave forward converter, the L's are not coupled.

If full wave rectifiers are used around the inductor, a single inductor can be used with full wave operation.

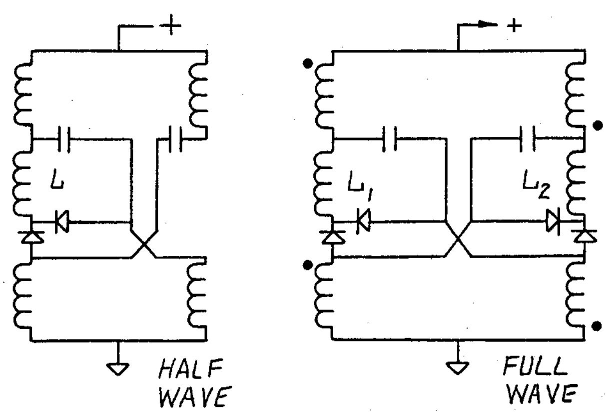

Figure 23.3. Symmetrical secondaries can be used with floating capacitors and inductor filtering, if the inductor is brought inside the floating capacitor terminals as shown.

Similar considerations would allow adapting of the symmetrical primary circuit for use with a boost converter, with floating capacitors.

XXIV. Offset Symmetrical Windings ‡

The symmetrical push pull winding with floating capacitors has a constant DC potential between the windings at any point in the transformer.

In a completely isolated winding, the choice of reference can be anywhere.

A. Through the Bore Revisited

Referring to sections IX.D and IX.E., the input voltage V_{in} appears throughout the symmetrical push pull transformer as a DC potential, with any differences from core to core being common mode voltages in both windings. This allowed the "through the bore" gate drive technique.

1. Shifting Reference

In an isolated circuit, the choice of a reference is arbitrary. Figure 24.1 shows the symmetrical push pull primary with the input voltage applied to points A and B. If an isolated DC voltmeter were applied to points C and D, the same potential would be found as is applied to A and B. This is true anywhere in the transformer circuit, right up to, and including, the floating capacitors.

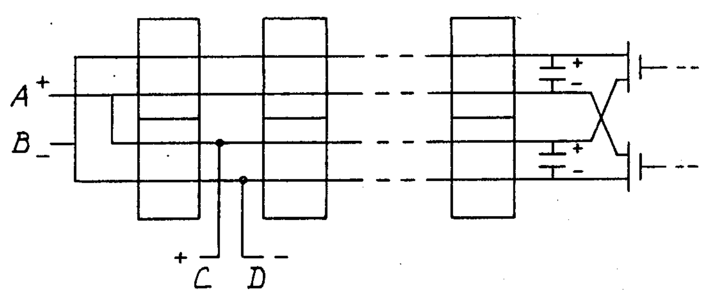

Figure 24.1. There is a fixed DC voltage between the windings in a symmetrical push pull winding with floating capacitor. If the circuit is otherwise completely isolated, the input power could be applied at any point.

If point D were arbitrarily called the reference, the relative voltages within the circuit are unaffected, though with respect to the new reference, they are somewhat harder analyze and draw. Taken one step further, the voltage can be applied to points C and D, or, in fact any corresponding points in the circuit, including the terminals of either of the floating capacitors. This will be transparent to the operation of the circuit.

2. Offset the Drive, Too!

The through the bore gate drive was able to interject the gate drive with reference to the negative terminal because there was a common mode voltage everywhere to the gate and the source. This remains true if the voltage source is offset, as shown in figure 24.2. A little more care is required, however, as the impedance of the two paths is now somewhat different.

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‡ U.S. Patent pending. FMTT, Inc.

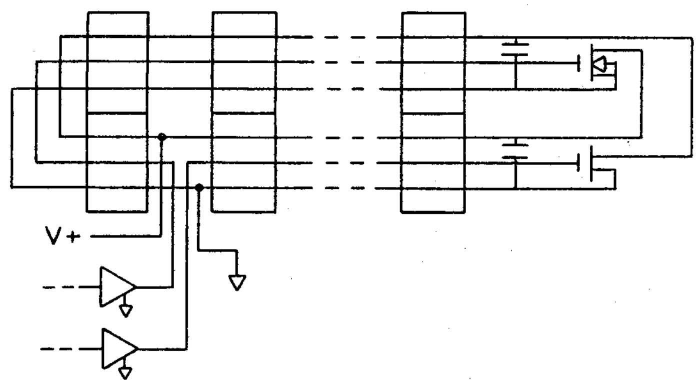

Figure 24.2. "Through the bore" gate drives, referred to the ground can be applied wherever the ground is.

3. Double Offset

In as much as there are common mode voltages throughout, it becomes apparent that the source to source winding is a common reference throughout the transformer, just having common mode voltage differences from point to point. As in Figure 24.1, this lead could be used anywhere as an isolated reference to monitor the state of the other windings.

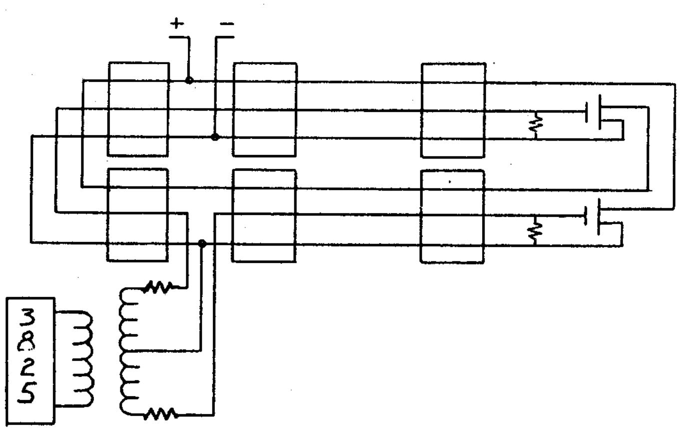

Figure 24.3. An isolated gate drive can be referred to the "ground" lead at any point. Although shown offset for emphasis, the isolated "through the bore" gate drive is preferably applied at the conductor mid-point to equalize impedances.

Therefor any point on this winding can be used as an injection point for the gate drive, as long as it is referred to the source to source winding. Figure 24.3 shows an isolated gate drive injecting a through the bore gate drive at a point offset both from the winding mid point, and from the supply voltage.

The utility of this is that it is very important to keep the circuitry tight, and the leads short. This is easier to do if every thing does not pile up in the same physical location.

B. Offset Forward Converters

The matrix transformer primary circuit can be configured as a forward converter by replacing one of the FET's with a diode. The floating capacitors are used exactly as before, and they function to decouple the leakage inductance of the transformer from the FET, just as described in section 12, though the details vary a little.

Because the input voltage can be applied offset to any point in the primary windings (up to and including at either of the floating capacitors), with only one FET, it makes sense to reference the input voltage and the control circuit to its source, as shown in figure 24.4.

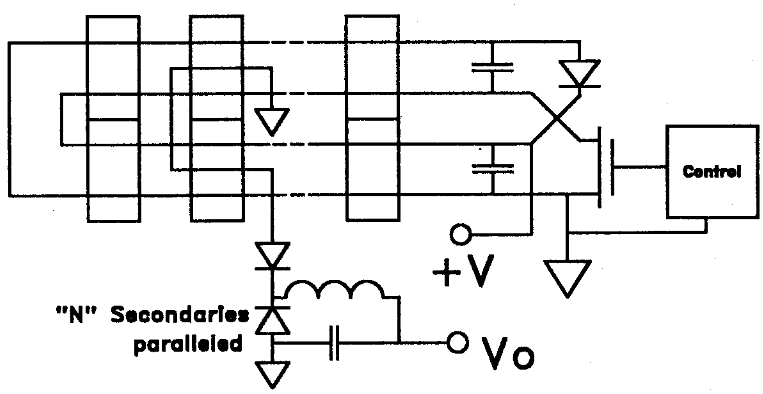

Figure 24.4. A matrix transformer symmetrical forward converter. The input voltage has been "offset" so that the control circuit can be referenced to the source of the FET.

1. Forward Converter with Active Reset

A forward converter which is reset with a diode, as above, uses only the flux capacity above remnance. With an active reset, more of the flux capacity of the cores can be used. With equal on time and reset duty cycle, the cores are actually slightly over reset, because the reset current has less IR drop, and thus a slightly higher voltage.

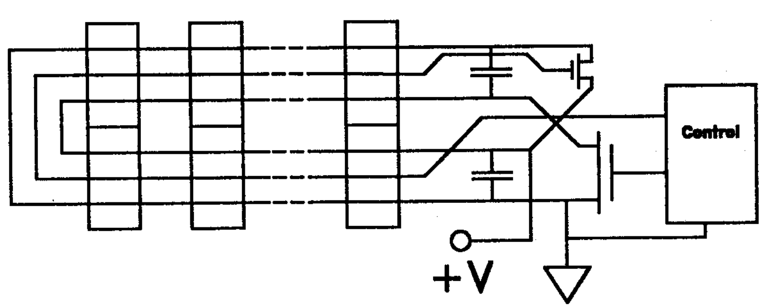

Figure 24.5. A matrix transformer forward converter having an active reset. The input voltage is "offset" so that the control circuit can be referenced to the source of the power FET. The smaller reset FET is driven "through the bore".

XXV. Superimposed Offset Symmetrical Windings ‡

There have been many examples in this discussion where the rectifiers, and their losses, have been distributed for better heat spreading.

The power in the primary switches can be similarly distributed, yet still maintain a single power connection point.

Provisions can be made to put windings in series or in parallel, to accommodate different input voltages.

A. Offset Picture Frame Winding

With reference to section XXIII, figure 25.1 shows an offset symmetrical push pull winding in a picture frame transformer.

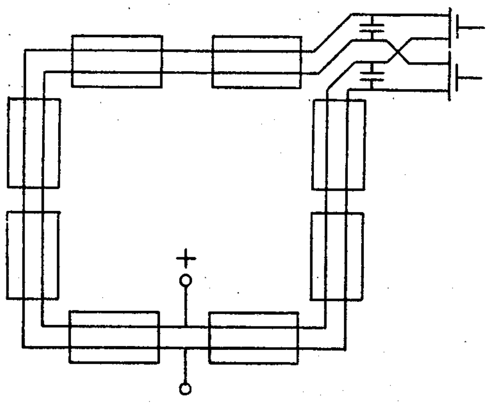

Figure 25.1. The power and ground terminals of a symmetrical push pull picture frame transformer primary can be offset.

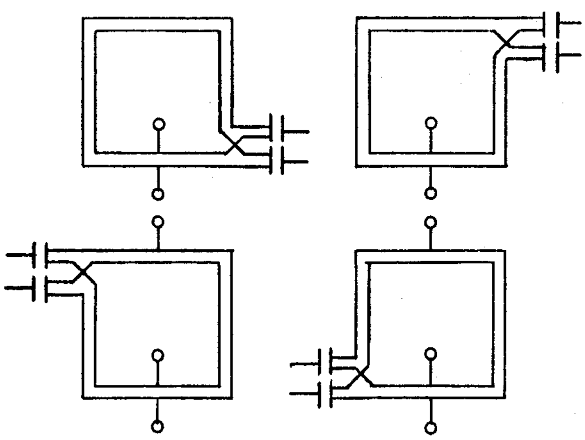

Figure 25.2. Four of the possible offsets for the picture frame transformer.

‡ U.S. Patent pending. FMTT, Inc.

With respect to the transformer in figure 25.1, the off set could have the four orientations shown in figure 25.2. Of course others are possible as well.

It is obvious that the four windings of figure 25.2 could also be installed in a single set of picture frame elements, just as in figure 25.3, and the input terminations would be at the same place.

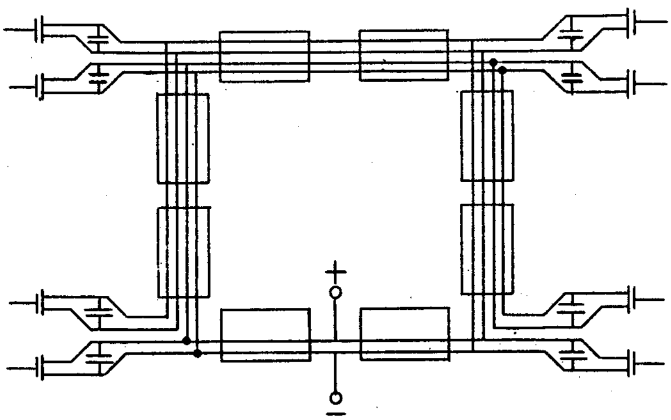

Figure 25.3. The offset picture frame windings can be superimposed, and wires having a common potential can be replaced with one wire (larger).

1. Parallel Wires having the Same Voltage.

Once the four windings of figure 25.2 are put in the same transformer and connected to the same voltage source, it is apparent that some of the windings will have the same potential. If these are identified and replaced with a common wire (larger), the transformer of figure 25.3 results.

While somewhat complex, this transformer allows paralleled FET's to drive the transformer, with good, low inductance short connections, yet to be spaced far apart for optimum heat distribution. Thus the heat spreading characteristics of the paralleled secondaries can be extended to the primary.

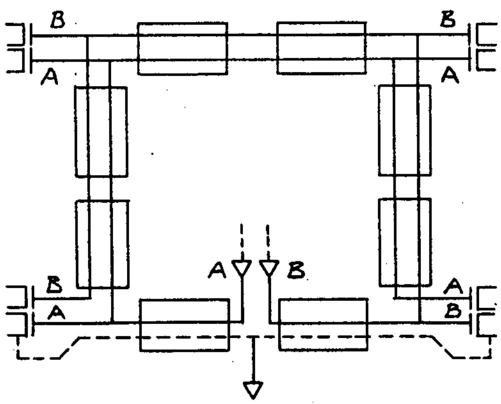

Figure 25.4. A single set of drivers can drive all of the FET's "through the bore". Only the gate leads are shown. The source leads must parallel them so that the voltages are common mode.

2. Through the Bore Drive:

Through the bore gate drive can be used in this arrangement, as shown in figure 25.4. On pair of drivers can drive all four sets of FET's, because the common mode voltages cancel in the source leads and the gate drive leads. Obviously some attention has to be paid to drive impedances. It would be preferred to use a buffer at each gate. Figure 25.5 shows that a common Vcc can be taken through the bore too, to power the buffer drivers.

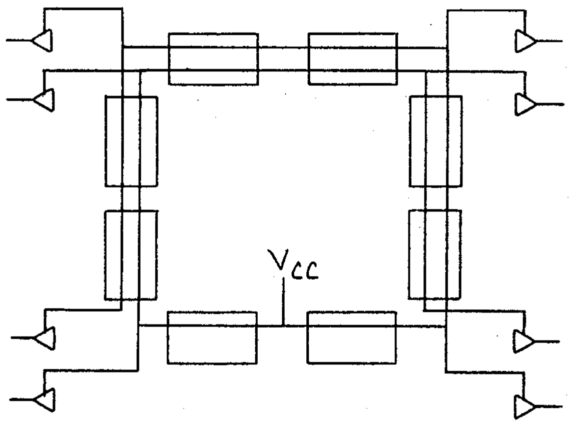

Figure 25.5. A common Vcc can be taken through the bore too, to drive buffers at each gate.

B. Series and Series-Parallel Primaries.

With reference again to figure 25.2, when the windings are installed in the picture frame elements, they are in theory undedicated, and could be wired in parallel, as discussed, or in series, or two pairs in parallel, the pairs being in series.

Again, once the windings are drawn out completely, it can be determined which windings have the exact same voltage, and they can be replaced with one winding.

1. Offset the Drives

Series windings will usually require isolated gate drives. These can be offset, in the manner of Figure 24.3, so that no one point on the transformer gets to busy.

XXVI. Mechanical and Fabrication Ideas

Most of the work done to date with matrix transformers has been bread board work, to prove principles of operation. Stringing beads makes it very easy to try out different ideas with no special fabrication or tooling involved. Labor is high.

Transformers having large step-down ratios for power converters will likely be the first commercial application for this new technology.

This section summarizes some ideas for simplifying the manufacturing process, and suggests some packaging and layout techniques for reducing EMI and improving power and heat conduction

A. Secondary Modules

Matrix transformers with large step down ratios have a number of parallel secondaries, with several wires for each. Constructing the secondaries as modules which can be plugged in or assembled without terminating lots of wires is essential for economical assembly. Two examples were discussed, in sections I and VII.

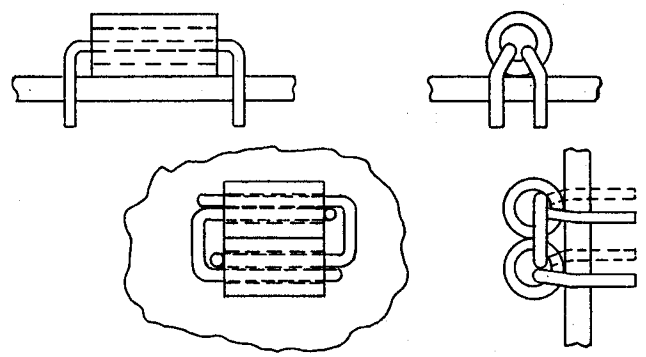

Figure 26.1. "Staples" or preformed wires cemented in place can make a plug in module of the secondary windings. Note the open area remaining for the primary winding.

1. Bread Board Modules

Until there are more tooled modules available for bread board work, it is easy to simulate modular construction with toroids and solid insulated wire. Figure 26.1 shows how to mock up picture frame and dual plug in modules. As long as the core cross section is comparable to the contemplated module, performance will be similar.

a) Staples

Secondary windings can be as simple as a U shaped piece of wire passing through a core, and terminated in a board at each end. Even if the shape is more complex, formed wires can be pre-installed in cores, and perhaps cemented in place or held by a carrier. The wire ends would serve as pins for printed board installation.

2. Surface Mount

No surface mount modules have been illustrated, but it is easy to envision modules being made with leads that folded underneath, for reflow soldering to a circuit board. Surface mount modules could leave a through hole for an undedicated primary to be added later, or they could include the primary winding arranged so that it would be interconnected, module to module, by pads on the circuit board. For higher separation and space saving, the leads for the primary could bend upward, away from the circuit board. If they were aligned so that each touched the next, the primary conductors could be reflow soldered together, module to module above the board, perhaps with an interlocking feature or clip to ensure positive contact.

3. Upright Modules.

Upright modules are designed to minimize the printed circuit board area when that is a more important criteria than having a low profile. They also have more separation between the primary and secondary terminations. Figure 26.3 shows an example of an upright module, with a sketch of how they are assembled.

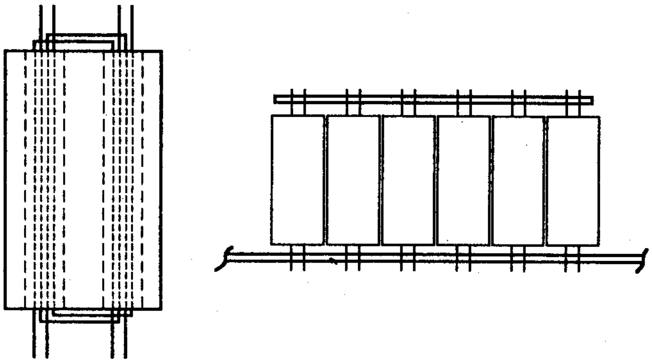

Figure 26.2. The upright matrix transformer module has printed circuit pins on each end. One end mounts in a circuit board. The other may be interconnected with a small daughter board, which can be installed ahead of time.

The upright module works particularly well if the secondary outputs are to be paralleled first, before rectification, as the pins are closely spaced and can connect to low inductance busses in the circuit board.

Having the primary circuit in a daughter board also allows additional floating capacitors to be installed between elements in a symmetrical converter. Having a number of capacitors distributed between the common mode conductors will provide better filtering. With all of the terminations open and available, some imaginative snubbing schemes could be tried, on an element by element basis.

B. Heat Sinking

As power densities increase, heat sinking becomes more important. Although there are some other advantages to a more compact circuit, the prime reason for miniaturization is to save space. If all of the saving is used up with large heat sinks, much of the benefit is lost. It is also important to find ways to make assembly easier.

1. Distributed Power

Heat sink efficiency is greatly improved if the heat sources are distributed. As compared to the same heat being generated at one point, evenly distributed heat sources will require one third less heat sink for the same temperature rise.

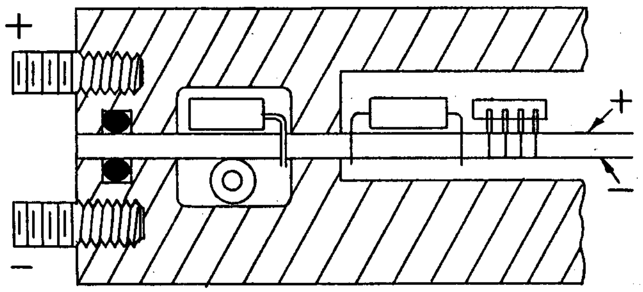

Figure 26.3. A converter is assembled and tested at low power on a heavily clad printed circuit board. A pair of castings then clamps the board, making thermal and power contact, and becomes combined power bus and heat sinking.

2. Combined Heat Sink and Power Bus

Power buses and heat sinks are both fairly large structures in high power converters. In as much as the same materials are suitable for both, maximum utilization of material results if current and heat can be conducted by the same structure.

a) Power and Ground Planes

On printed circuit assembly, it is fairly common practice to use power and ground planes. With high currents, these planes have to be thick, and well laid out so that currents do not crowd in narrow lands. The same factors which make good power and ground planes also makes good thermal planes. Heat sink half of the power components to each side.

b) Chassis

Because the matrix transformer are often flat, but spread out, a flat plate for a heat sink can be used. Using two plates, as a sandwich, would be even better, and would enclose the circuitry. With a picture frame layout, the low power control and housekeeping supplies could be on a printed circuit board in the middle. One of the plates could be the positive power bus and the other could be the ground bus.

c) Circuit Board with Castings ‡

A very effective use of a heat sink as a power bus can be realized by making the circuit board converter as described above, with some clear space around the edge, and around each component which needs heat sinking. Castings could then clamp on the board, top an bottom, making broad contact across the two surfaces. See figure 26.3. Large studs into the castings could provide terminations for power cables.

A low impedance contact from the chassis halves to the board planes would be necessary, both thermally and electrically. The chassis parts could be tinned with very low temperature solder, and reflowed in place. Thin metal gaskets could be used. An "O" ring around the edge could provide a seal.

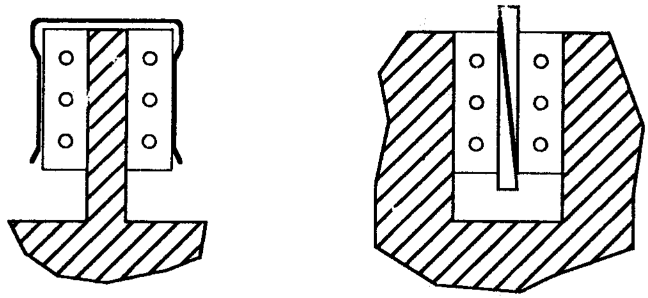

Figure 26.4. With T03-P parts mounted on edge, they can be much closer together. The left hand examples has the parts mounted on a heat sink fin with a strong clamp. In the other example, the wedge presses the parts against the side of the channel.

3. Component Mounting

We have found that screwing transistors down to a flat heat sink is an unsatisfactory method of assembly, for several reasons. One is the hardware involved--loose screws, threaded holes or nuts, washers, insulators, etc. Quality control is difficult. If it is too tight, the case can crack or the part can be warped, and have less contact. If it is too loose, heat sinking will be poor, and the parts could move or loosen further. Even when installed correctly, the screw mount does not apply pressure where it is most effective.

Another problem is that flat mounted parts take up too much space. In several of our designs, the transformers are much larger than necessary just because of the limit of how closely parts could be mounted on a flat heat sink. It is very important that the terminals of the components be very close to the transformer.

a) T03-P Transistors and Rectifiers

Figure 26.4 shows several variations of mounting T03-P parts on edge. The first sketch shows a pair of parts on either side of a fin. A strong spring clip retains them, and applies pressure against the fin. The second sketch shows two parts in a channel.

‡ U.S. Patent pending. FMTT, Inc.

A wedge between them exerts pressure outward to clamp the parts against the side. In both cases, the parts can be assembled and tested before they are installed.

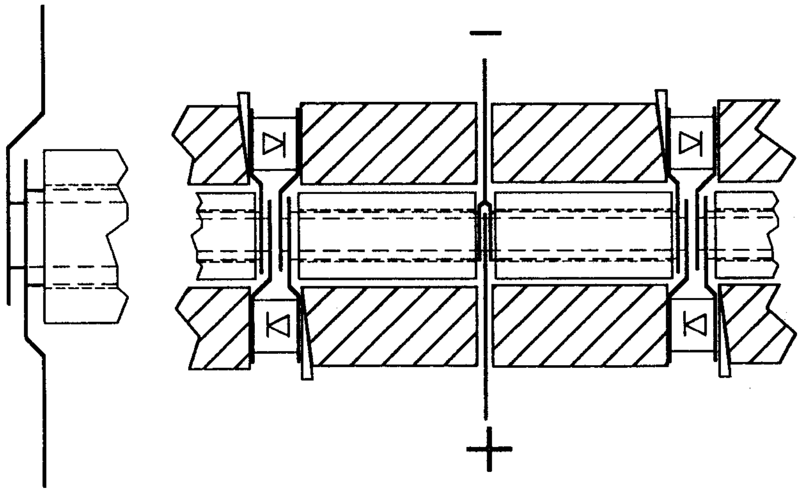

Figure 26.5. Secondary modules for a picture frame matrix transformer have a coaxial secondary. The tubes are terminated with wide flat conductors (for low inductance), and are connected directly to rectifiers in flat packs.

b) Very Low Inductance Mounting

Figure 14.3 showed a picture frame matrix transformer using coaxial secondary windings which promises to have exceptionally low leakage inductance. The advantages could easily be lost by careless wiring to the rectifiers. Figure 26.5 shows a method of mounting rectifiers in a heat sink with very low inductance.

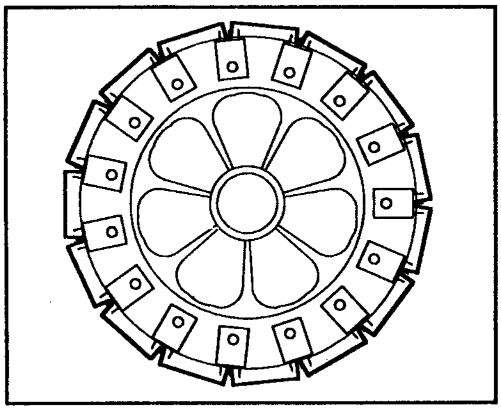

Figure 26.6. A picture frame matrix transformer is build around a fan, for optimum cooling of the rectifiers.

At each end of the coaxial modules, the inner and outer tubes are terminated in a wide, flat strips which contact the entire periphery of each tube and leave the assembly at right angles. Insulation is not shown, but the need for it is obvious. The flat strips are formed to fit into heat sink slots, and to make the contact with one side of flat pack rectifiers. The opposite polarity flat strip from the next module makes contact with the other side of the rectifier, and a wedge holds the whole stack up in compression against the heat sink..

4. Fan Incorporated into Picture Frame Matrix Transformer Heat Sink

Figure 26.6 shows a sketch of a picture frame matrix transformer which is assembled on a circular heat sink. The rectifiers are mounted on one surface, and are optimally place for low inductance termination to the transformer. A fan mounts in the center, and exhausts radially to provide cooling.

C. Jacketed Cores

Most of the bread board matrix transformers have been built with long toroids. Mounting them is a challenge, and usually they have just been left supported by their windings. In one model, the cores were epoxied into milled slots of the correct radius.

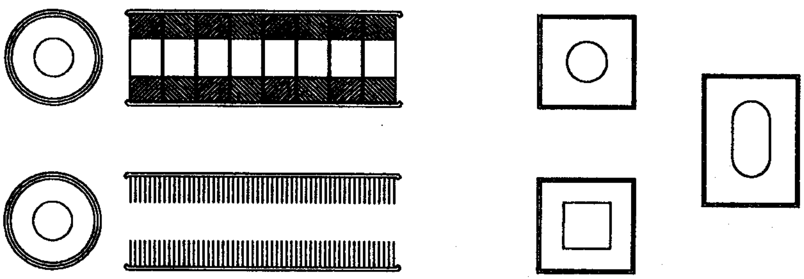

Figure 26.7. Matrix transformer cores can be assembled in a metal tube or jacket. The upper assembly is a stack of small ferrite toroids. The lower one is a stack of metal or amorphous metal washers.

1. Core Assemblies

In some instances, the core is a slug of ferrite. In other cases the core is an assembly. There is an advantage to enclosing the core or the core assembly in a metal jacked. The jacket could be aluminum, which can be hard anodized to insulate it, or it could be steel or copper, which are solderable. Plastic or heat shrink tubing would provide more insulation at the expense of heat sinking.

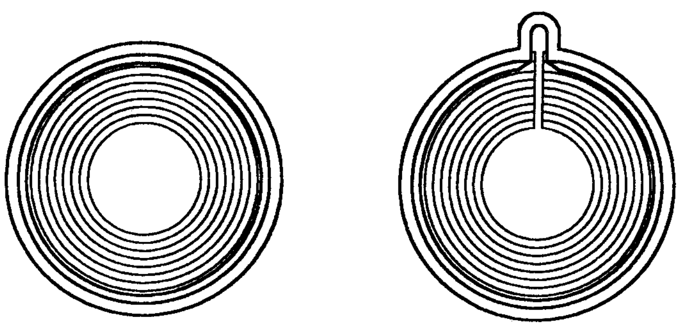

Figure 26.8. These jacket cores are tape wound, from metal foil or amorphous metal. The second one has a cut core, for use as an inductor. The bump provides clearance to the metal for the fringing flux, and also can be pinched or flattened to close or open the gap.

Figure 26.7 shows several core assemblies in metal jackets. In the first sketch, a number of short toroids are enclosed in a tube. This will have lower losses than one solid core, and is stronger. A crack in one core would not propagate to the rest. Unless they are ground, ferrite cores have poor mechanical tolerances. The OD of the tube will be much better.

The second sketch shows a stack of washers. Cores made of metallic foil or amorphous metal are usually tape wound, but washers would have better heat flow radially. Other variations shown have different cross sections.

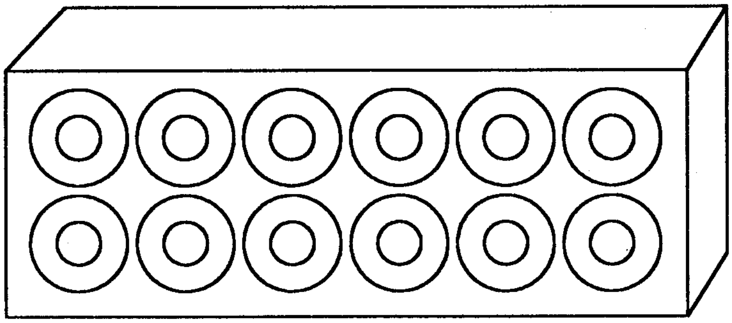

Figure 26.9. A matrix transformer module in which a number of cores have been assembled into an aluminum block.

Figure 26.8 shows a core assembly in which a tape would core has been wound to a somewhat tighter radius, then allowed to expand into a tube. The second cross section shows an inductor made with a cut tape wound core. The jacket is bumped around the gap for two reasons. First, the fringing flux is kept away from the metal jacket. Second, it provides for adjusting the air gap. The bump can be pinched to close the gap or expanded to increase it.

D. Multi-Core Modules

The integrated power conversion module described in section one was assembled with loose cores on a fixture, then installed into a base plate heat sink. An alternative approach is described below.

1. Matrix Transformer Multi-Core Module

Figure 26.9 shows a module in which a number of cores have been installed in a block. Aluminum would be a good choice, and it could be hard anodized to insulate it. Other applications might be served better with other materials. The cores could be solid ferrite, or any of the variations shown above. They could be jacketed first, or assembled directly in the block.

a) A Hint for Winding Blocks.

In assembling a matrix transformer in a module such as the one in figure 26.9, the primary winding is usually installed first, and it threads stitch wise through the cores. One problem is that the wires tend to find the center of the core and cross it side to side, effectively blocking the bore and making it very difficult to get the rest of the wires in even though there is plenty of room.

To prevent this, make the wires go through the bore in a 180° helix, hugging the side. To do this, cut some metal strips which are just the diameter of the bore in width. Put them in a vice, and twist them 180°. Put these in the bore before threading the wires through. When the winding is complete, they can be slipped out.

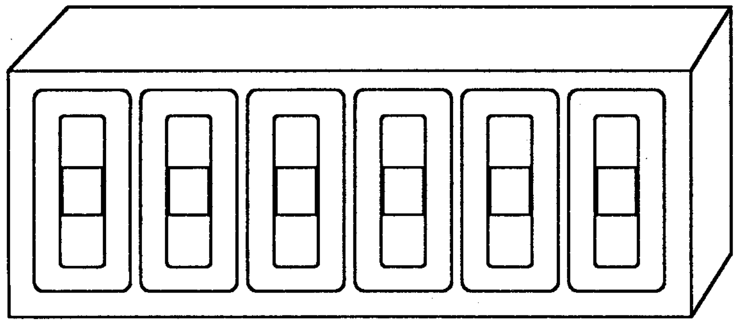

Figure 26.10. This module contains cores for a matrix inductor. The center legs are removable, to facilitate winding.

If a shield is being used, it can have the correct twist, and stay in place. It would also be possible to fabricate some plastic parts with the right helix, perhaps cross shaped to better guide four wires or a double "D" with flanges for extra insulation.

2. Matrix Inductor Multi-Core Module

Figure 26.10 shows another module in which a number of cores have been bonded, but in this case the cores are rectangular, and have a removable center leg. The inductor windings are wound on the removable center legs, then they are inserted into the module at assembly. Figure 26.11 shows two variations of the inductor core.

To prevent the center leg from cocking when it was installed, it could be shimmed or wedged. That could be difficult though, as the gaps would be very small. If the center leg were bonded in, as with epoxy, the viscosity of the liquid and the surface tension might center it adequately. Otherwise filler screened to the right size could be used. A slight lengthwise taper would help.

This core should not be used for half turns. The DC current will saturate the outside of the core. It is ideal for balanced inductors, as the high permeability of the outside of the core will block common mode currents.

E. EMI

EMI is always a concern for power converter designers. The flat matrix transformer should be a help in reducing emissions, particularly if some care is taken.

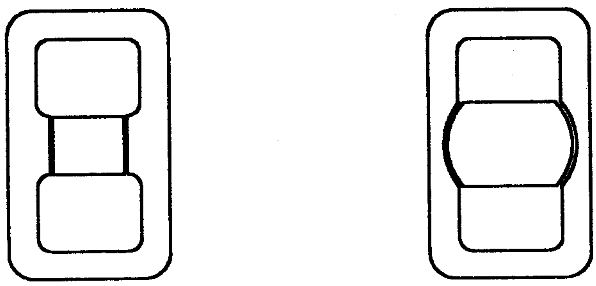

Figure 26.11. The inductor cores have removable center legs. One is ground flat, the other is ground with a radius.

1. Balance the Noise Sources.

The symmetrical winding topology has the advantage that most currents and voltages are balanced with an equal and opposite counterpart. This symmetry can be used to cancel many of the noise sources.

a) Capacitive Coupled Noise in Heat Sinks

Insulating hardware under power components is a parasitic dielectric conductor to the heat sink. If one component has a dv/dt of one polarity, try to find a complement to put next to it. The drains of the symmetrical push pull FET's have such a relationship, and the voltage amplitude is half that of a conventional push pull.

There is some incentive to put half of the power components on each side of a circuit card for thermal balance. Make sure EMI is balanced too.

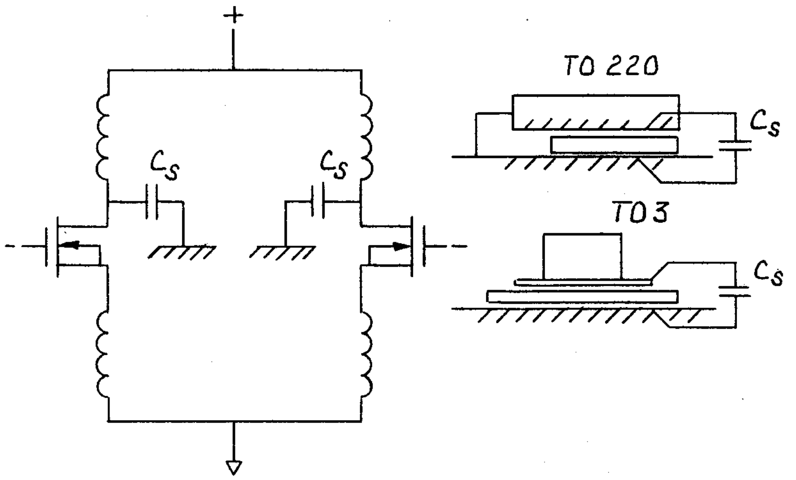

Figure 26.12. The heat sink mounting of power FET's has parasitic capacitive coupling to the drains. In the symmetrical push pull transformer, the voltages at these points are complementary, and noise should largely cancel in the heat sink.

b) Currents

Large currents are prime sources of noise. In flat matrix transformer circuits, the currents are usually balanced. Keep them balanced as they are routed around. It reduces leakage inductance and noise. When making runs, lower current runs of opposite polarity in parallel, alternating, would have much less noise than larger parallel conductors.

c) Decoupling

If power planes or chassis parts are used as power buses, a good number of decoupling capacitors spread around will help significantly, to short circuit high frequency noise.

2. *Inductors*

The design and location of the inductors in the secondary output filters is important. If the secondary is a conventional push-pull circuit with dual common cathode rectifiers, then the inductor should be single, and in the negative side, in series with the center tap of the secondary winding. This allows the cathodes of the rectifiers to be at the positive voltage, steady state. The cathode is mounted on the heat sink, and will couple into it if there are voltage transients present.

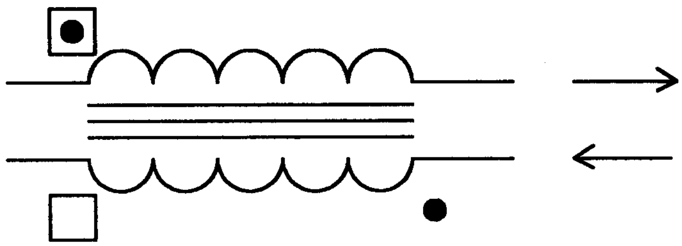

Figure 26.13. A schematic of the dual balanced inductor shows the dots, indicating the inductance to the DC current path. The squares indicate the inductance seen by common mode currents.

With a symmetrical push pull secondary, dual balanced inductors are preferred. Both sides of the bus are filtered, and the dual filter can be designed to reject common mode currents. See the schematic in figure 26.13. The dot shows the inductance presented to the DC power. The square represents the inductance of the high permeability outer core as seen by the common mode current.

XXVII. Power Distribution and Heat sinking

High current power supplies have two problems: getting the heat out and getting the current out.

Good electrical conductors are also good heat conductors.

A. Power Distribution

Power distribution within an electronic system is a serious problem, particularly as voltages become lower and currents go up. The connector of a power supply is particularly troublesome with plug in assemblies. It is hard to design large bus bars or power and ground planes with sufficiently low impedance to carry power any significant distance.

1. Distributed Systems

A usual proposal for solving the power distribution problem is the use of distributed systems. This has much appeal, and matrix transformer power supplies will have an important contribution due to their high efficiency, high power density and low profile.

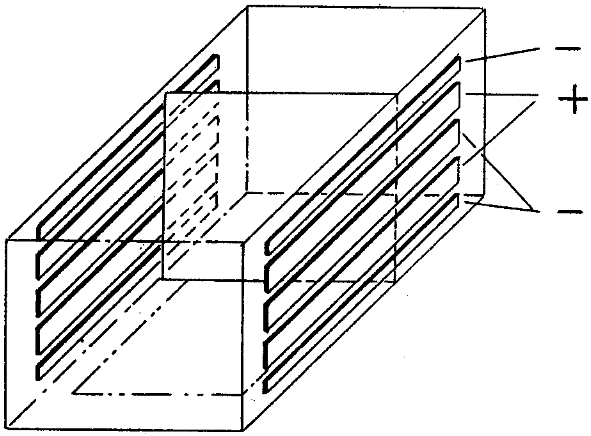

Figure 27.1. It is proposed to use power busses down each side of the chassis to distribute high current, low voltage power. It will provide heat sinking as well.

B. Heat Sinking

As power densities increase, heat sinking becomes more an more important. There may be a point of diminishing returns in miniaturization as the thermal structure for heat sinking becomes dominant.

1. Card Edge Heat Sinking

A very usual method of heat sinking printed circuit modules is to use specialized card guides which have been optimized for heat conduction.

C. Heat Sink and Carry Current

In as much as good conductors of electricity are good heat sinks as well, it is proposed to integrate the heat sink and power distribution ‡. This would allow the very large area available at the card edge to provide a very low impedance connection, and the side walls of the chassis can be used as a power bus. See figure 27.1. From there, low impedance connections can be made to ground and power planes on the circuit cards. See figure 27.2.

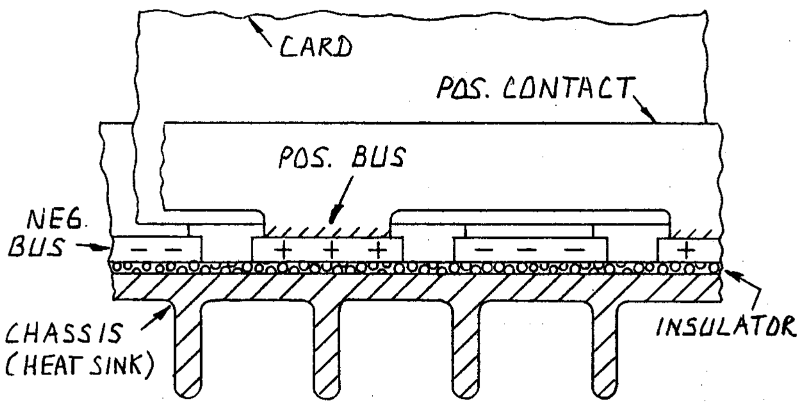

Figure 27.2. The power busses on the side of the chassis are wide, and have a low thermal impedance path to the chassis through a thin dielectric layer. They also have a low impedance path, thermally and electrically to heavy card guides.

1. Power Supply Module

When a matrix transformer is used for a power supply, there tends to be a number of parallel outputs, distributed around, and they are probably at the periphery of the circuit card for good heat sinking. Rather than keep the heat sink isolated, and collect the output current to the output connector, the card can have the plus and minus of the highest current output be a power and ground plane of the assemble. These can extend to the card edge on all sides.

a) Card Guide Connector

If the two sides of each card guide are configured as the positive and negative terminal, then power flow from the power supply can be from the entire card edge on both sides. The contact area should be substantially solid, and firmly clamped, for good heat and power conduction. See figure 27.3.

Similar card guide connectors could be used on logic cards, though perhaps they could be less heavy duty.

Input power should still come through a conventional connector, so that power is disconnected when the card is removed. House keeping signals and lower power auxiliary outputs should go through the connector as well, but a card guide connector could be divided to provide for multiple high current outputs.

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‡ U.S. Patent pending. FMTT, Inc.

The power bus/heat sink structure would have to be isolated from the chassis with electrically insulating material. Preferable the contact area is wide and thin for good heat conduction. Wide flat conductors bonded with a good filled epoxy should do well. A film dielectric layer or two could be included, as well as some insulated mechanical fasteners.

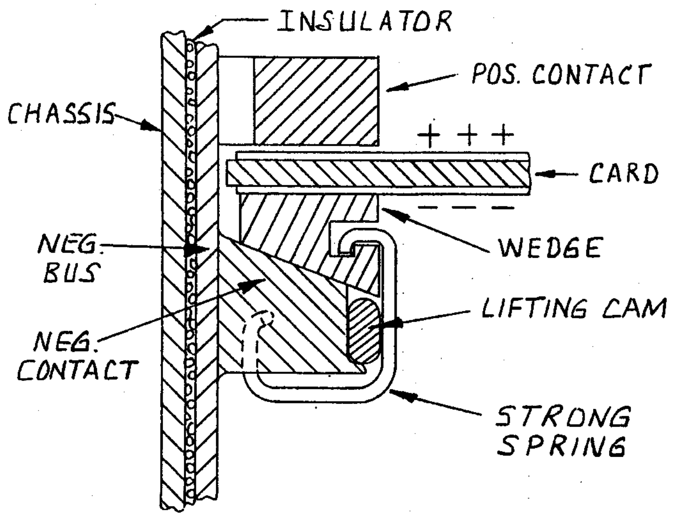

Figure 27.3. The circuit cards, including the power supply, would have a power plane on one side, and a ground plane on the other side. Both are brought to the card edge, to make broad, low impedance electrical and thermal contact. For plug in assemblies, a wedging card guide would provide solid contact. A cam lifts the wedge for easy removal. ‡

A number of parallel conductors, alternated plus and minus would ensure that the conduction paths from the card guide was short. Each guide would have to bridge over the bus of the other polarity, or at lease be electrically insulated from it. The area of the positive and negative busses should be equal, so that the capacitive coupling is equal. This would keep capacitively coupled noise as common mode.

‡ U.S. Patent pending. FMTT, Inc.

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