Coaxial Push Pull Transformers

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Coaxial Push Pull Transformers

Abstract:

The coaxial push pull transformer uses a magnetic structure that is similar to the flat matrix transformer technology, and it shares its characteristic low profile and excellent thermal dissipation. A single turn primary winding is used for a 1:n step-down transformer by using n modules, and the secondary current divides equally among the n modules.

The high frequency performance of the flat matrix transformer is very good, but an entirely new winding design using a coaxial arrangement between the primary winding and the secondary winding offers near ideal coupling and near zero leakage inductance in the coaxial push pull transformer. The near zero leakage inductance greatly simplifies power converter design.

The near zero leakage inductance means that the energy stored in the coaxial push pull transformer is nearly zero, reducing the turn-off inductive kick and eliminating the timing delay from primary to secondary switching so that simultaneous switching may be used.

Because there are no multiple layer windings, many of the particularly troublesome high frequency effects are absent.

A tightly integrated modular design is used so that the parasitic inductances in the external ac circuits associated with the coaxial push pull transformer are minimized.

Modifying one or more of the modules can vary the transformer's turns ratio by solid state switching, to provide a useful control scheme for some applications.

The cellular transformer is a variant used for higher step down ratios, as it is designed for multi-turn primary windings.

A module using a single coaxial secondary winding can be used for a forward converter, or in pairs for a dual forward converter.

Patents pending.

1.0. Introduction:

The coaxial push pull transformer is designed for power converters having a push pull secondary circuit, but variants can accommodate other secondary winding topologies. The primary winding may be a push pull winding, a full bridge winding, a half bridge winding or a dual forward winding.

The coaxial push pull transformer uses a magnetic structure that is similar to that of the flat matrix transformer, and an understanding of the design and application of flat matrix transformers is helpful as background information. A tutorial entitled “Design and Application of Matrix Transformers and Symmetrical Converter” can be viewed and downloaded at the FMTT, Inc. web site, http://fmtt.com.

Because there are no multiple layer windings, many of the particularly troublesome high frequency effects are absent.

The coaxial push pull winding structure is entirely new. It has many advantages, but it does require new design and application techniques, which are explained in this presentation.

1.0.1. Design Examples:

To introduce the coaxial push pull transformer technology, four design examples are presented, with their theories of operation.

1. A fixed ratio, 100% duty cycle “dc-dc transformer”.
2. A variable ratio, 100% duty cycle “dc-dc transformer” with a precise output voltage.
3. An isolated SCPC (switched-current power converter) power distribution system.
4. Bridge converter designs.

1.0.2. Low Leakage Inductance:

Each side of the push pull secondary winding is a tube through which the primary winding passes, as in a coaxial cable, yielding near perfect coupling and near zero leakage inductance within the coaxial push pull transformer modules. This offers the promise of very small inductive spikes (even with very fast turn off times) and no timing delay from the primary to secondary, if the parasitic inductances of the external connections and the associated circuitry are well controlled. To achieve this, a modular construction containing all of the switching circuits is recommended.

1.0.3 Modular Design:

The coaxial push pull transformer uses identical parallel modules, dividing the secondary current among them. The synchronous rectifiers are closely integrated with the magnetic components as modules, simplifying the circuit board layout and providing lower impedance interconnections. More importantly, a tightly integrated modular design is necessary for good control of the parasitic inductances in the circuits and associated components that are outside of the transformer itself but which carry high frequency ac currents.

Many of the most difficult circuit problems in the design and layout of power converters relate to the square of the current (I^2), so the advantages of a modular design with a lower current per module are significant.

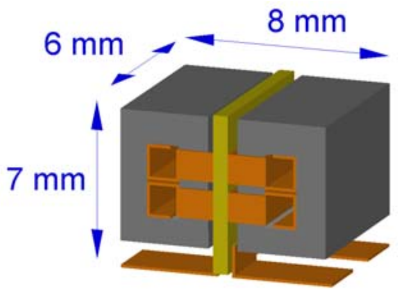

Figure 1.0.1. A small module contains two magnetic cores mounted on a daughter board. There may be a power IC with synchronous rectifiers mounted under the transformer core, for optimally low inductance connection to the transformer secondary windings.

1.0.4. Variable Turns Ratio:

A module of the coaxial push pull transform can be “removed” from the transformer using solid state switching. When a module is “removed”, the turns ratio of the transformer is changed, which is useful for voltage control. “Removing” the module also reduces the output current of the module to zero nearly instantly, allowing a very fast control of the output current, which is useful for switched current power converters. See section 4.0. Variable Turns Ratios, following.

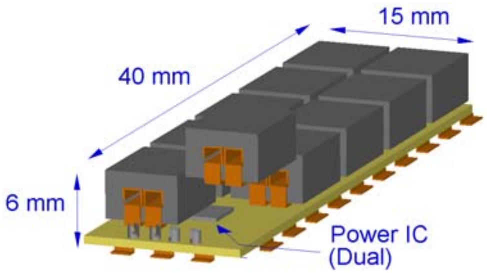

Figure 1.0.2. For low profile, the cores of a coaxial push pull transformer may be mounted flat on a small daughter board. One core is shown lifted, to show the synchronous rectifier IC on the daughter board. The dual channel IC rectifies the outputs of two transformer sections.

1.0.5. Thermal Characteristics:

As compared to a conventional transformer, the thermal paths are very short, and the surface area is comparatively very large. Heat sinking through the secondary winding terminations is excellent. The temperature rise within the transformer is very low, even with very high output currents. The losses are distributed evenly, so there are no hot spots.

1.0.6 Efficiency:

The winding resistance of the coaxial push pull transformer is very low, reducing winding losses. The very low leakage inductance of the coaxial push pull transformer results in a significant reduction in switching losses. There is no significant time delay from the primary switching to the current reversal in the secondary winding, so simultaneous switching is preferred, and the losses attributable to synchronous rectifier timing errors are eliminated

1.0.6 Cost:

The coaxial push pull transformer uses very inexpensive gap-less pressed cores with inexpensive stamped secondary windings inserted in the cores, a very economical construction.

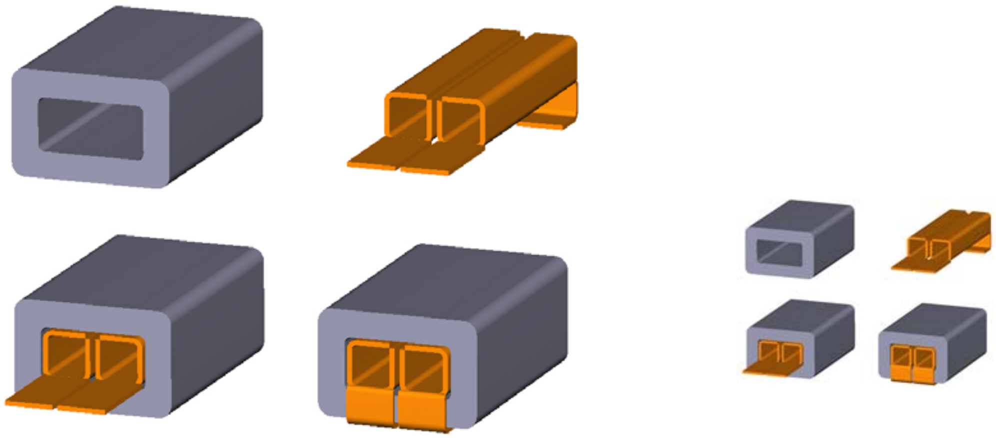

Figure 1.0.3. The core of the transformer module is a small (3 x 6 x 6 mm) gapless pressed core into which two metal windings are inserted. The leads are folded back as surface mount self leads. The core must be insulated, and there must be insulation between the windings.

1.0.7. Patent Status.

Patents are pending on the coaxial push pull transformer and the cellular transformer. The cellular transformer patent has been allowed. Please inquire about licensing.

2.0 Coaxial Windings:

The windings of a coaxial push pull transformer are truly coaxial, primary to secondary. There have been other transformer winding designs called “coaxial”, including some designs used in flat matrix transformers, but as far as is known, this is the first to have each side of a push pull winding be a separate coaxial conductor in a modular construction.

2.1. Coaxial Push Pull Transformer Windings:

For a good high frequency transformer, it is desirable that the current flowing in the primary winding and in the secondary winding be the same at any instant, with no appreciable delay or lag. An ideal transformer has no delay or lag, because it has ideal coupling, and thus no leakage inductance. The best coupling is in coaxial conductors, and this geometry is adapted for the coaxial push pull transformer, as is seen in figure 2.1.1. Each secondary winding is tubular, and the primary winding passes through it. The magnetic core is shown in phantom.

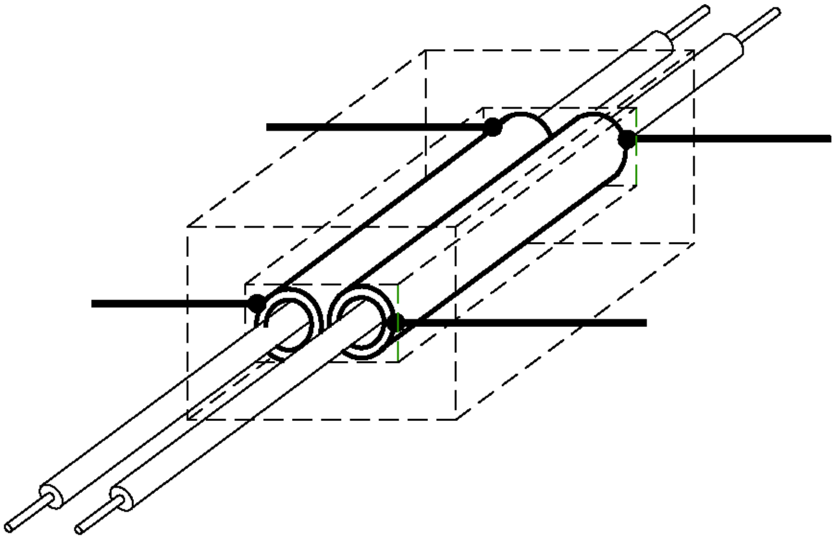

Figure 2.1.1. In the coaxial push pull transformer, the secondary winding are tubular with leads at each end of each of the tubular conductors. The primary winding passes through the secondary as a true coaxial conductor.

2.2. Secondary Rectifier Connections:

Figure 2.2.1 shows the rectifier connections for the secondary circuit as well as the current flow when one side of the push pull pair is conducting. Diode symbols are used in the drawing, but most power converter circuits would use synchronous rectifiers. Representative current flow is shown for conduction of one side of the push pull winding. This drawing is only to show the interconnections as a schematic diagram. Practical interconnections must be optimized for low parasitic inductance.

Of particular note is that the phasing of the coaxial push pull transformer now has an added factor: Not only must the primary current flow in the correct direction through the core, it must also be in the correct tubular secondary winding.

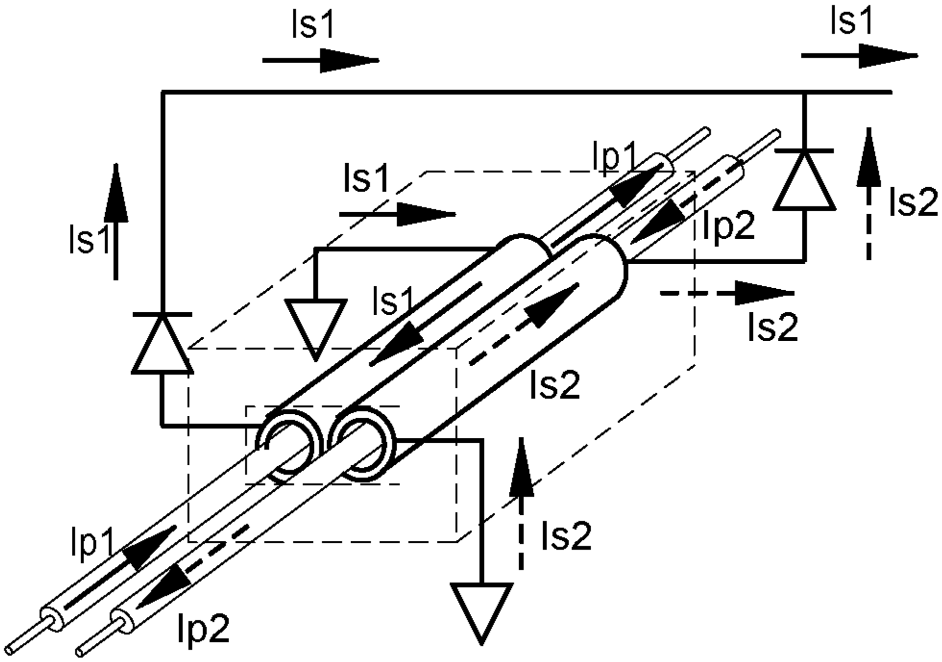

Figure 2.2.1. The secondary circuit of a coaxial push pull transformer is shown. Although most power converters would use synchronous rectifiers, diode symbols are used for simplicity. Another factor is added to the phasing of the windings: Not only must the primary current pass through the magnetic core in the correct direction, it must also be in the correct tubular secondary conductor.

2.3. MOSFET Timing in Coaxial Push Pull Transformers.

Figure 2.3.1 shows a representative coaxial push pull transformer with the primary and secondary MOSFET (metal oxide silicon field effect transistor) switches shown. The primary circuit is a fairly conventional push pull primary circuit in which MOSFETs QaP and QbP are switched alternately to provide an ac excitation for the magnetic cores of the transformer.

The secondary circuits are also fairly conventional push pull secondary circuits, each having a pair of MOSFET switches. In theory, the three secondary circuits could be paralleled, using one set of larger MOSFETs to handle the increased current, but to minimize the parasitic inductances, it is preferred that each module have its own tightly laid out switching circuit. The currents in the parallel secondary circuits will be exactly the same because they all couple the same primary current.

In conventional push pull transformers, there is a significant delay between the operation of the primary switches and the time that the current actually reverses in the secondary windings. This delay is a function of the operating point (load current), thus there is a degree of uncertainty just when the secondary MOSFETs should be turned on and off, relative to the timing of the primary switching. If the timing is not optimized, losses are increased significantly, but correctly determining the optimum timing under different circuit operating conditions is quite involved.

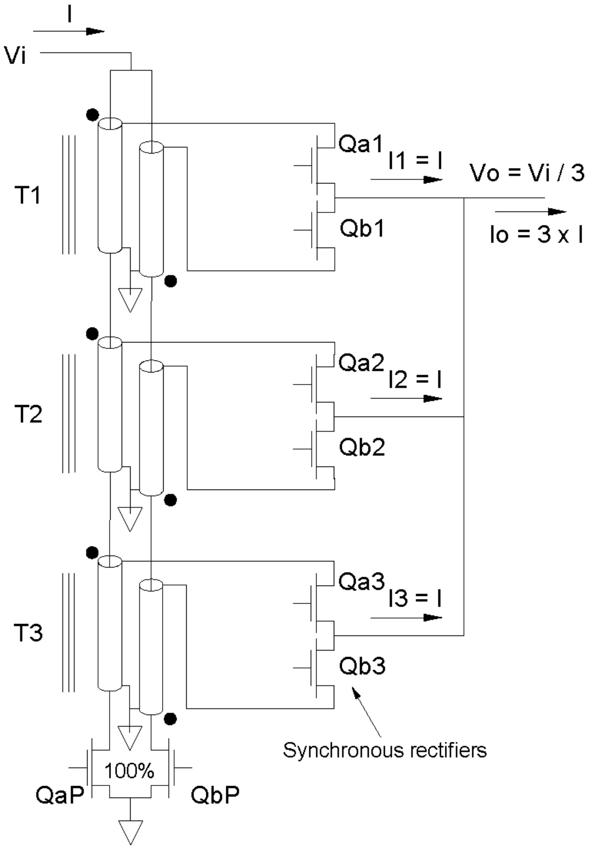

Figure 2.3.1. A coaxial push pull transformer having a 3 to 1 turns ratio is shown. The phase dots show that the windings enter the core from opposite ends. Note that the primary winding connected to the MOSFET QaP passes through the secondary windings which are connected to the secondary synchronous rectifier MOSFETs designated Qa1, Qa2 and Qa3, for correct phasing.

By contrast, in the coaxial push pull transformer, there is no appreciable delay in the secondary current, and simultaneous switching of the primary and secondary switches is preferred. Thus the optimum rectifier timing is very straightforward, independent of the load current, and requires no special logic or algorithms.

Transformers are reciprocal devices, so they can be used with current flow in either direction. In a conventional transformer isolated power converter, the required delay from primary switch operation to the secondary switch operation has to reverse with current reversal, which is very difficult to implement in logic. With the simultaneous switching used in the coaxial push pull transformer, current reversal or reciprocal operation can be accommodated with no special timing provisions.

2.4. Cellular Transformers:

As with the matrix transformer, the turns ratio can be increased by using more primary turns. By making the tubes of the secondary winding larger, two or more wires could be threaded through, but it is preferred to use a cellular transformer, one module of which is shown in figure 2.4.1.

Because there are no multiple layer windings, many of the particularly troublesome high frequency effects are absent.

Two metal inserts are used, each with several parallel through holes for receiving the primary windings, preferably one hole for each turn. Each wire is surrounded coaxially by the metal, so the bandwidth is similar to the coaxial push pull transformer. Heat sinking is excellent, and each wire is precisely located, making it easy to automate the winding.

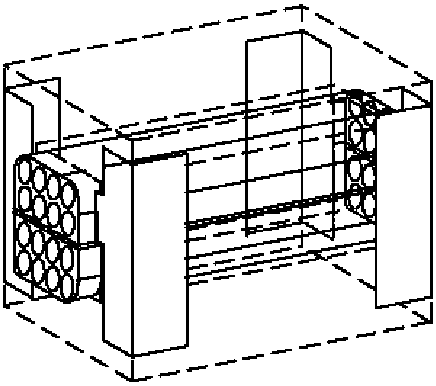

Figure 2.4.1. The cellular transformer is used to increase the effective turns ratio by using more than one primary turn. The module shown is designed for an eight turn push pull primary winding, and a transformer using these modules has a turns ratio of 8 n to 1, where n is the number of modules.

In use, the modules are placed in a row with their through holes aligned, and the primary winding is installed. Usually, two parallel rows would be used, perhaps one on each side of a printed wiring board, so that the primary turns pass through one row and return in the other.

The secondary connections are just as in the coaxial push pull winding, see figure 2.2.1. The secondary terminations may be surface mount tabs as shown in the various examples of the coaxial push pull transformer. The module shown in figure 2.4.1 has side terminations, for a high current application.

2.5. Module with a Single Coaxial Winding.

Figure 2.5.1 shows that the coaxial winding may be used in a smaller core as a single winding transformer, that is, with a single primary (added later) and a single tubular secondary winding.

Coaxial Push Pull Transformers

This module could be used for a forward converter, or it could be used in pairs as a dual forward converter. If the core is used as a dual forward converter, and the modules are mounted in pairs with similar terminations as the coaxial push pull modules, the same advantages of parasitic inductance reduction can be realized.

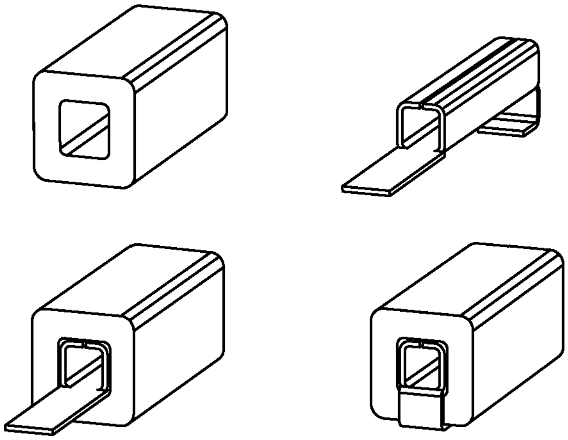

Figure 2.5.1. A coaxial winding module may also be made with a single secondary winding. This module is useful for a forward converter, or it may be used in pairs as a dual forward converter.

3.0 Modular Construction:

The coaxial push pull secondary module is a very simple, inexpensive part. The modular construction provides a flexible and easy way to assemble transformers, but a more important reason for the modular construction is to minimize parasitic inductances in the associated ac circuits. Because there are no multiple layer windings, many of the particularly troublesome high frequency effects are absent.

3.1. Coaxial Push Pull Transformer Module Construction:

The magnetic cores used in the coaxial push pull transformer are very simple, low cost pressed parts with no gap or machined surfaces. The secondary windings are simple, low cost stamped and formed sheet metal parts with the ends formed to be surface mount self-leads. The two halves of the push pull secondary windings must be insulated from each other and the core, which can be done by coating the core and using a separator between the windings.

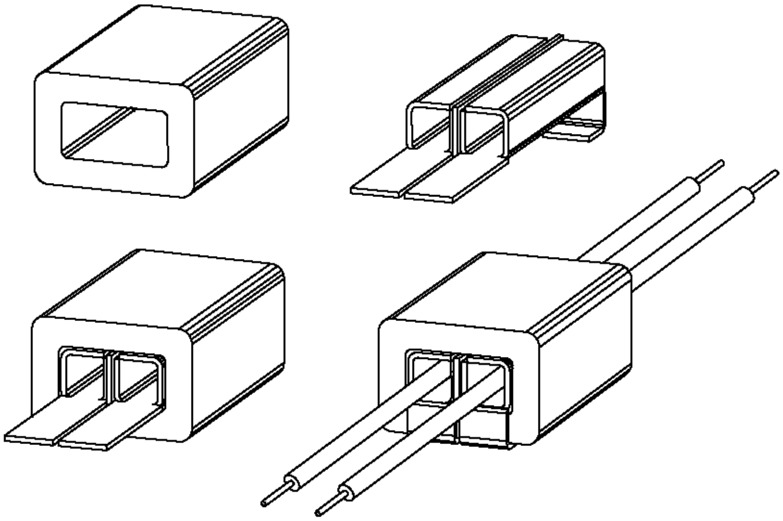

Figure 3.1.1. The magnetic core of a coaxial push pull transformer is rectangular with a rectangular through-hole, a simple pressed shape with no gap. A pair of secondary windings is formed sheet metal with their ends bent down as self leads. The secondary windings must be insulated from each other and the core. The primary winding is added later.

The magnetic area of the core is calculated as in any transformer knowing the output voltage, the frequency and the desired flux density. However, unlike conventional transformers, *the flux density does not have to be de-rated for thermal considerations*. A long, slender core will have lower losses for a particular flux density, because the total volume of the core is less, but the winding resistance will increase. This is one of the trade-offs of design.

The modules of the coaxial push pull transformer are placed in a row with their through holes aligned, and the primary winding is installed, as in figure 3.1.2.

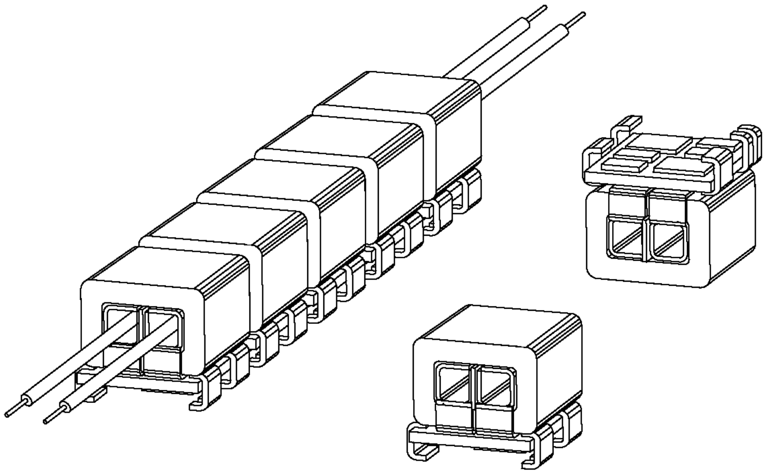

Figure 3.1.2: The surface mount modules of a coaxial push pull transformer are placed in a row with their through-holes aligned, and then the primary winding is installed as shown. In the module shown, a small circuit board containing the synchronous rectifiers and their drivers is mounted on the magnetic core with direct connections to the secondary windings, for optimally low parasitic inductance.

In figure 3.1.2, there is a small circuit board attached to the leads of the coaxial push pull transformer modules. The circuit board contains the synchronous rectifier MOSFETs and their drivers. This is a convenient and flexible method of assembling coaxial push pull transformers, but a more important consideration is that the layout is optimized for low parasitic inductances.

3.2. Reduced Costs:

There may be an assumption that more parts means more cost, but often the opposite is true. This is especially true with large currents.

The cost of silicon is largely a factor of its area, and switching a certain current requires a certain number of square millimeters. This suggests an equivalence between one large die and several smaller ones, on a dollars per square millimeter basis. However, several smaller dice require more packages, more handling, more connections and so forth, which might appear to tip the balance in favor of using one large device. This overlooks the fact that many of the problems in handling current relate to the square of the current. It is common to use several devices in parallel to distribute the load and spread the losses, even given the problem of ensuring reasonable balance among the devices. As an example, ten 20 ampere devices is a row of simple, inexpensive surface mount components with no particular problems with placement, heat sinking, or current rating in the printed wiring board. A single 200 ampere device must be mounted on a heat sink, by hand, with thermal grease, and with large conductors. The gate drive is very challenging, and it would almost certainly have to operate at a much lower frequency due to the switching time and the parasitic inductances, requiring a larger transformer and more filtering.

Many of these considerations are even more important when the magnetic components are included. The coaxial push pull transformer can operate at a much higher frequency, so the total core volume is much less. The simple pressed cores are very inexpensive, with no need for machined and polished mating surfaces that result in an inconsistent air gap no matter how skilled the assembler. The modules are well adapted for high speed, high volume automated assembly and test, and they are placed on the printed wiring board as any other surface mounted part is. There are no loose core halves to place and bond. The only special operation is installing the primary winding, and that is a pair of simple “U” shaped wires inserted from one end, an operation that is easy to automate.

Therefore, not only is the coaxial push pull transformer a superior transformer, it also results in significant savings in cost, size and weight.

3.3. Reducing Parasitic Inductance with Counter-flowing Currents:

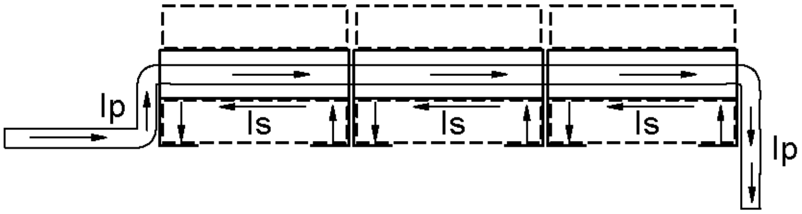

Figure 3.3.1: This sectional side view shows that parasitic inductances are reduced in the leads of the coaxial push pull transformer modules because the conductors are paired with ones in which an equal current is flowing in the opposite direction, to cancel the far field. Note that this condition exists in the adjacent leads at the ends of each module, and between the end leads and the primary winding at the ends of the transformer.

Then coaxial windings of the coaxial push pull transformer have nearly perfect coupling and extremely low leakage inductance within the transformer cores. However, the parasitic inductances of the external circuits can dominate if the layout is not carefully done. This can largely negate one of the most important advantages of the coaxial push pull windings, its very low leakage inductance.

One way to reduce the inductance of a circuit is to arrange the conductors so that each conductor is paired with another carrying an equal current in the opposite direction, so that the far field is cancelled. Of course, this exists within the coaxial portion of the windings, within the magnetic core.

Figure 3.3.1 shows a side section view of one side of a push pull pair in a coaxial push pull transformer, with the cores shown in phantom. Counter flowing currents are present in the leads of adjacent modules, as can be seen by the arrows indicating current flow. When a current Ip flows in the primary winding, and equal and opposite current Is flows in each secondary winding and its leads. At the ends of the transformer, counter flowing currents are present in the end lead and the primary winding.

The secondary rectifiers usually will be MOSFET synchronous rectifiers. One side of a push pull pair is shown connected to one half of the push pull secondary winding of a module in figure 3.3.2. It is contemplated that the MOSFET die is centrally located under the transformer core, and the return and the output are ground and power planes, respectively. The secondary currents flow to the center, as shown.

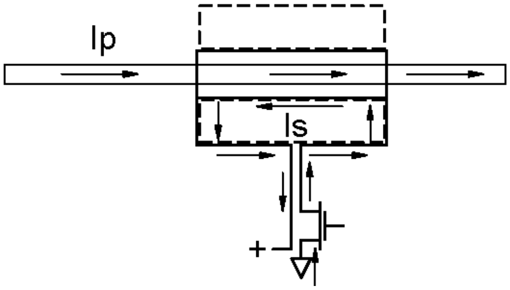

Figure 3.3.2. For a current flowing in the primary as shown, the corresponding secondary side synchronous rectifier will be turned on, and secondary currents will flow as shown by arrows.

In figure 3.3.3, more transformer modules are added, three on each side of a printed wiring board, to make a complete coaxial push pull transformer having a 6 to 1 turns ratio. One side of the push pull pair is shown in cross section, to show the current flow when that side is on and current is flowing.

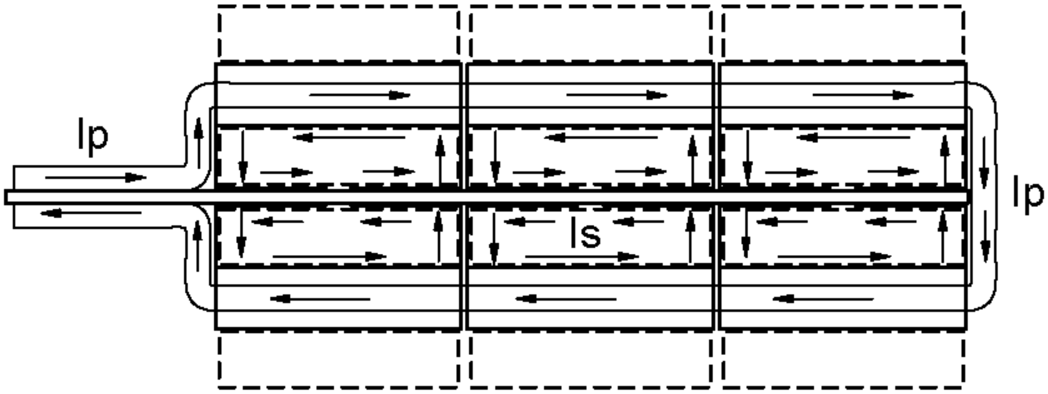

Figure 3.3.3. A section through a representative coaxial push pull transformer is shown, with six modules surface mounted on a printed wiring board (three on each side). Note that in *every part of the circuit* each conductor is paired with another conductor carrying an equal current flowing in the opposite direction, to minimize the parasitic inductances throughout the coaxial push pull transformer.

The MOSFET dice for the synchronous rectifiers are centrally located under each module, so the currents in the primary winding and the six secondary windings are as shown by arrows in figure 3.3.3. All of the currents are equal, and the six secondary currents are paralleled in the output. Note that everywhere in the transformer the current flows in counter flowing pairs of conductors, affording an opportunity to significantly reduce the parasitic inductances in the leads and components that are external to the transformer cores.

4.0 Variable Turns Ratios

4.1. Removing a Module:

In the coaxial push pull transformer, the turns ratio is determined by the number of modules. If a coaxial push pull transformer were taken apart and reassembled with more or fewer modules, the turns ratio is changed. It is possible to achieve the same result electronically.

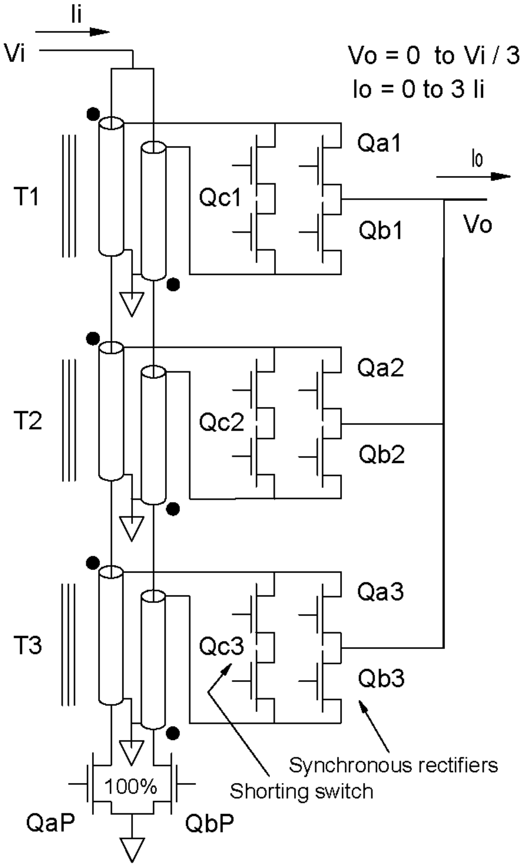

Figure 4.1.1. In normal operation, the synchronous rectifiers Qa# and Qb# switch alternately. A module is “removed” by turning off both synchronous rectifiers and turning on the shorting switch Qc#.

First, consider the coaxial push pull transformer of figure 4.1.1 operating normally, with the primary MOSFET switches QaP and QbP switching at 100 % duty cycle, and the synchronous rectifiers Qa# and Qb# operating normally as well. The turns ratio is 3 to 1, and the output voltage Vo is Vi / 3.

Consider next that in the first module the synchronous rectifiers Qa1 and Qb1 are both turned off and the shorting switch Qc1 is turned on. This places a short circuit on the secondary of the module that will be reflected to the primary, so there is no primary voltage drop across the module. With the synchronous rectifiers Qa1 and Qb1 turned off, there is no contribution to the output current from this module. It is as if the module were not there, and the transformer ratio will be 2 to 1. Because it is the ends of the push pull secondary winding that are shorted, the secondary winding is two turns with respect to the shorting switch, and the current that will circulate in the secondary winding and the shorting MOSFET switch Qc1 is equal to one half of the primary current.

More than one module can be removed electronically, so the transformer of figure 4.1.1 can have turns ratios of 3 to 1, 2 to 1, 1 to 1, or the output voltage can be turned off entirely.

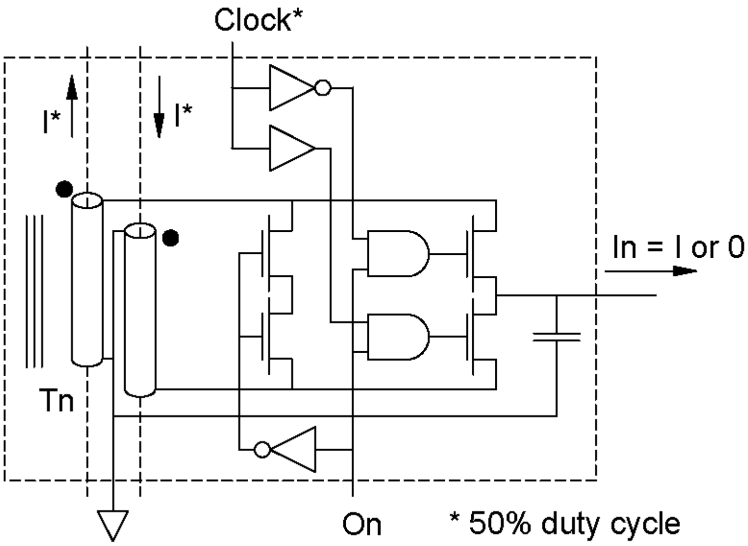

Figure 4.1.2. The logic for driving the secondary MOSFETs is shown. Normally, the "On" input is high, and the synchronous rectifiers switch alternately in response to the 50% duty cycle "Clock" input. If the "On" input is low, the synchronous rectifiers are both turned off, and the shorting switch is turned on, effectively short-circuiting the module.

Figure 4.1.2 shows representative logic to implement module electronic removal. The clock is synchronized to the primary MOSFET switches and is a 50 percent duty cycle square wave. When buffered and inverted, this drives the two sides of the synchronous rectifier to produce a 100 percent duty cycle output when the On input is high. If the On input goes low, both of the synchronous rectifiers turn off, and the shorting MOSFET switch turns on. A module's removal can be pulse width modulated with a duty cycle D. For example, in the coaxial push pull transformer of figure 4.11, if the first module is removed electronically 50 percent of the time, the equivalent turns ratio is, on average, 2.5 to 1.

When a module is removed electronically, there is no voltage in the windings, so the flux change in the magnetic core is zero and the core losses are zero. There is, however, a circulating current, which has some losses. Because the current flows through both halves of the push pull pair, the circulating current is one half of the primary current. The resistance of the secondary winding is very low, and MOSFET are now commercially available with very low on resistance, so the associated I^2R losses are minimized.

5.0 Design Examples

5.1. “DC-DC Transformer”:

A dc-dc transformer does not exist except as an idealized SPICE element. Still, it would be a very useful circuit element, and it is closely approximated by a good transformer excited with a “100%” duty cycle square wave.

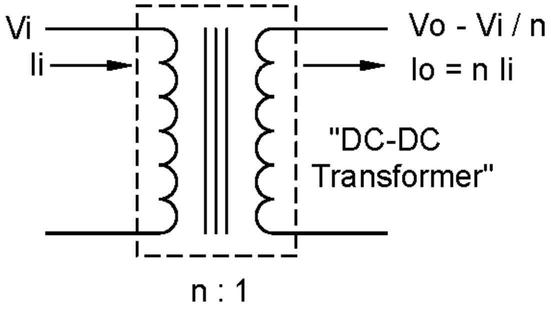

Figure 5.1.1. An ideal dc-dc transformer would be a very useful component, providing isolation and voltage level shifting with no loss of energy.

The coaxial push pull transformer of figure 2.3.1, switching with 100 % duty cycle, is an example of a circuit that can function as a “dc-dc transformer”. The very low leakage inductance of the coaxial push pull transformer allows the designer to use lower voltage rated devices, which saves cost and allows for lower Rds(on) devices.

5.1.1. Leakage Inductance Effects in Conventional Transformers:

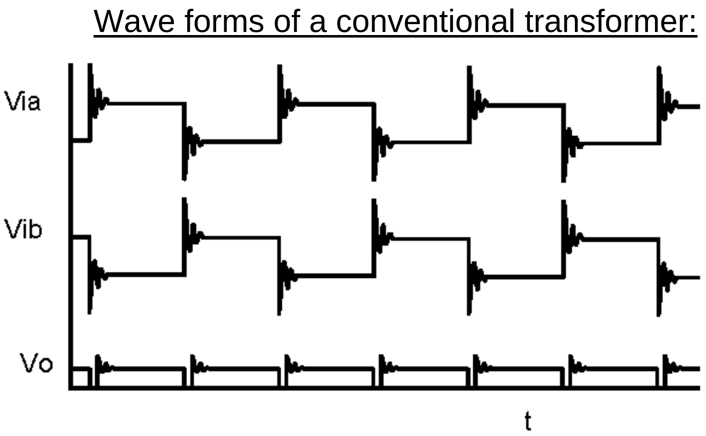

Figure 5.1.2. In a conventional transformer, the leakage inductance causes spikes and gaps in the rectified output voltage. Via and Vib are the voltage on push pull MOSFETS, while Vo is the rectified secondary voltage with no filtering.

In conventional transformers, the leakage inductance causes spiking and a notch in the rectified secondary voltage as the current decays in one side of the push pull secondary winding and builds up in the other. During the time that current is flowing in both secondary windings, the secondary is short-circuited and the output voltage is zero.

The leakage inductance is a series inductance reflecting to both the primary and secondary that will limit the bandwidth of the transformer and cause large spiking on the output if the load is removed quickly. A fairly large capacitor is needed to smooth out the notches, further reducing the frequency response.

5.1.2: Frequency Response of Coaxial Push Pull Transformers:

Unlike a transformer coupled buck converter, which is pulse width modulated, in a “dc-dc transformer” the switching frequency and the frequency response are not related. The switching frequency can be kept low, for good efficiency, and the frequency response can be orders of magnitude higher.

Within the coaxial push pull transformer, the bandwidth is that of a coaxial conductor, virtually unlimited, much higher than is needed for power converter applications. The parasitic inductances of the external conductors and components are the limiting factor, and care should be taken to minimize them.

When either side of the push pull winding is on, a voltage on one side of the transformer will be reflected faithfully to the other, with very high bandwidth. This is both an advantage and a disadvantage. It is an advantage, because the transformer’s bandwidth will be high enough not to affect the loop gain if it is closed around the transformer. It is a disadvantage because noise will be passed through without attenuation.

Obviously, during the switching time there will be a transient condition during which the dynamics of the switching will dominate, but very fast switching minimizes this effect. Very fast switching is also beneficial in that it minimizes the consequences of the Miller effect, significantly reducing crossover power and reducing switching losses.

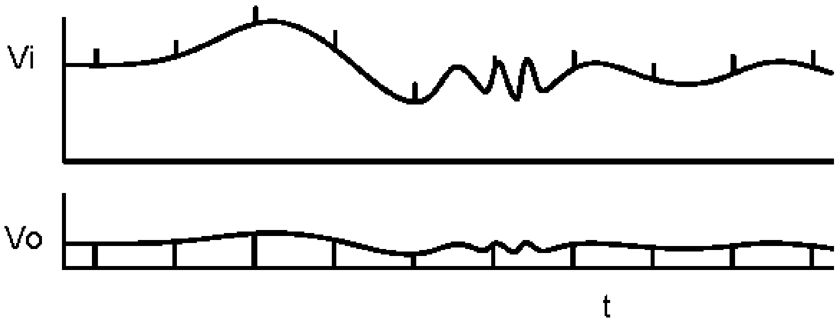

Figure 5.1.3: In a 100% duty cycle transformer, the bandwidth is not limited by the switching frequency. It is limited only by the leakage and parasitic inductances. However, an excessive notch due to slow switching speed will introduce distortion.

The exact sequencing and dynamics of switching will affect the waveforms. In figure 5.1.3 the primary and secondary MOSFETs switch simultaneous and very fast, in the order of nanoseconds or fractions of a nanosecond. A slightly faster turn off than turn on may be used in the primary switches so that the switch turning on can have zero voltage switching. The inductance driving the voltage reversal is very low, however, so a very high di/dt is necessary in the switch being turned off, and the drain-source capacitance will tend to attenuate the voltage rise time.

For good efficiency, a larger transformer operating at a low frequency may be beneficial. Just what constitutes a “low frequency” will depend on the application and v-a that the transformer handles, but for a moderate power electronic power supply 100 to 250 kilohertz is representative. The switching times should be a few nanoseconds.

5.1.3. Output Voltage Regulation:

Whether or not a ‘dc-dc transformer’ can provide a sufficiently accurate output voltage will depend upon the application. Fundamentally, the output regulation is no better than the regulation of the input voltage, but many power converters either are, or could be, operated from a tightly regulated supply. The current reflected to the input will be increased by the magnetizing current of the cores, and the voltage reflected to the output will be reduced by the conduction losses in the windings and the MOSFETs.

The winding resistance in the coaxial push pull transformer is very low. The secondary windings are very short and are quite heavy, so each winding has a low resistance and they are all in parallel. Recently, MOSFETs have become better and package impedances are reduced. Therefore, it realistic to have an output impedance in fractions of a milliohm, making this technology very viable commercially.

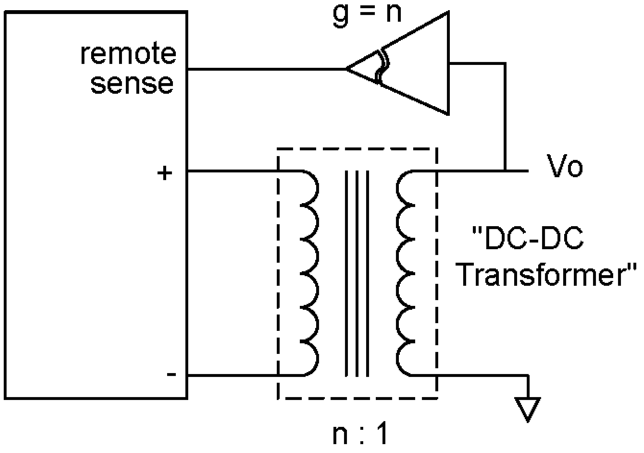

Figure 5.1.4. The output voltage of a dc-dc transformer is regulated precisely if the output voltage is taken to the remote sense of the power supply that powers the dc-dc transformer through an amplifier with a gain equal to the step down ratio.

As an example, consider a coaxial push pull transformer with ten modules, for a 10 to 1 ratio. The on resistance of the MOSFET synchronous rectifiers is the dominant resistance, so the output impedance will be well under a milliohm because the on resistance will be divided by ten in the paralleled output. The IR drop in the transformer may be sufficiently low so that its load regulation is acceptable for many applications.

If more accuracy is needed, the voltage loop may be closed around the transformer. If the power supply that is powering the dc-dc transformer has a remote sense output, the remote sense may be used to adjust the primary voltage to regulate the secondary voltage, as shown in figure 5.1.4. An amplifier having a voltage gain equal to the step-down ratio is used between the output voltage and the remote sense of the input power supply. Adjustments to the compensation may be necessary, particularly if isolation is required.

5.2. "DC-DC Transformer" with Voltage Control by Varying the Effective Turns Ratio:

The variable ratio coaxial push pull transformer provides a method of voltage control over a moderate range. A representative application is a "dc-dc transformer' operating from a power bus with loose regulation, for example, 48 plus or minus 10 percent (± 4.8 volts). By controlling the ratio by pulse width modulation, the dc output is precisely controlled.

Consider the variable ratio coaxial push pull transformer of figure 5.2.1. As a 3 to 1 transformer with a 48 ± 4.8 volt input, the output voltage is 16 ± 1.6 volts, and as a 2 to 1 transformer; the output voltage is 24 ± 2.4 volts. With a transformer that modulates between a 3 to 1 and a 2 to 1 turns ratio, the output voltage is controlled to a precise voltage, for example, 18 plus or minus 0.1 percent volts (± 0.018 volts). A feedback amplifier controlling the pulse width modulation of the transformer ratio is all that is needed, by using the logic of figure 4.1.2 and pulsing the On input with a PWM controller.

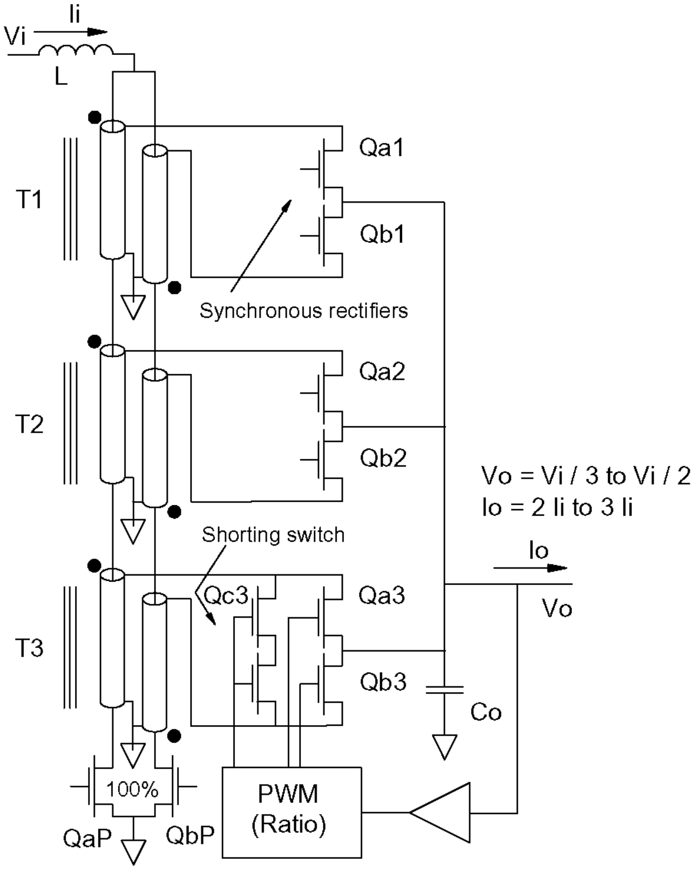

Figure 5.2.1. By pulse width modulating the transformer turns ratio, a precise output voltage Vo is derived from a loosely regulated input voltage Vi.

5.3. Isolated SCPC Power Distribution:

5.3.1. Switched Current Power Converter

If the variable turns ration coaxial push pull transformer of figure 4.1.1 is powered from a constant current source (rather than a voltage source), the output current maybe be varied from zero to n times the input current (where n is the number of modules) by controlling whether the various modules are conducting to the output or short circuited. Because the state of the modules can change as fast as the MOSFETs can switch, the control of the output current is extremely fast. This design is one variant of the switched current power converter.

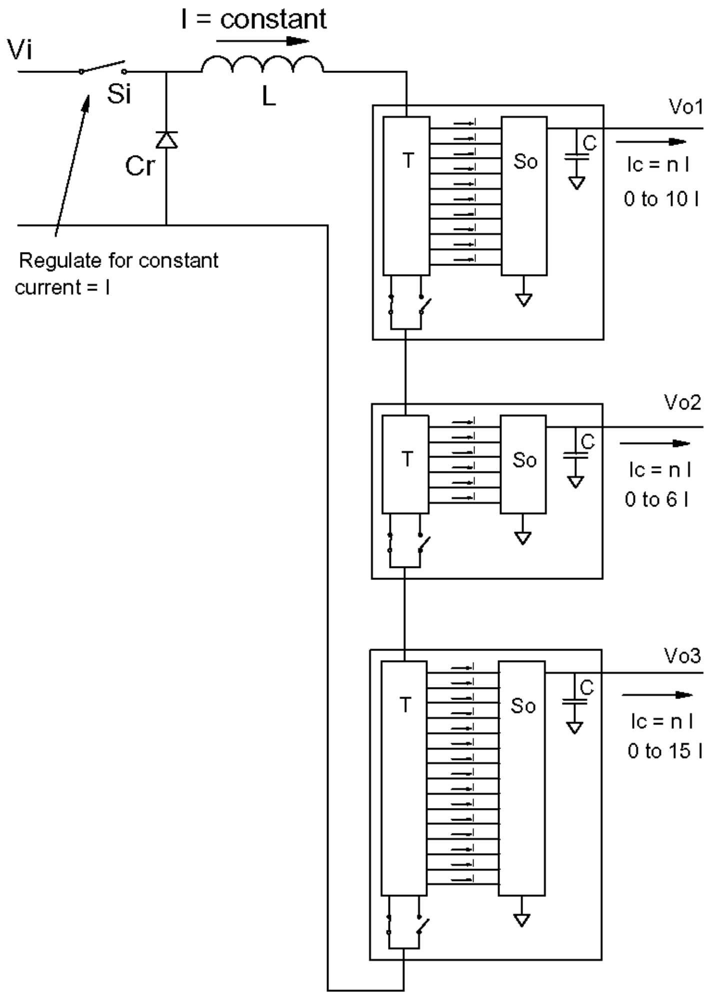

Figure 5.2.1. Several switched current power converters can be powered in series from a single constant current source. Because the coaxial push pull transformer provides isolation, upstream isolation is not necessary.

The constant current source may be a buck converter without an output capacitor, as shown in figure 5.2.1. The buck converter is inherently a current device, and it is easily controlled for constant current with a simple control that senses the output current. A hysteretic control works well, and is preferred for its simplicity.

Figure 5.2.1 also shows that several switched current power converters can be powered from a single constant current source as long as the input voltage is sufficiently high. The input voltage must be higher than the sum of the primary voltages of the transformers that are in series. The analysis of the switched current power converter is beyond the scope of this presentation. More information about switched current power converters can be found at the web site: http://eherbert.com.

Because the coaxial push pull transformer provides isolation, the constant current source may be an unisolated source. Having the isolation at the switched current power converters increases efficiency, as the transformers are operating at 100 percent duty cycle and the modules that are switched out during light load operation have no core losses.

5.4. Bridge Converters:

The coaxial push pull transformer is well suited for operation in a bridge converter, either a full bridge or a half bridge. Bridge converter transformers usually have a single primary winding, but the preferred winding arrangement for coaxial push pull bridge transformers uses two windings in parallel, one through each side of the push pull secondary winding, as shown in the figures following.

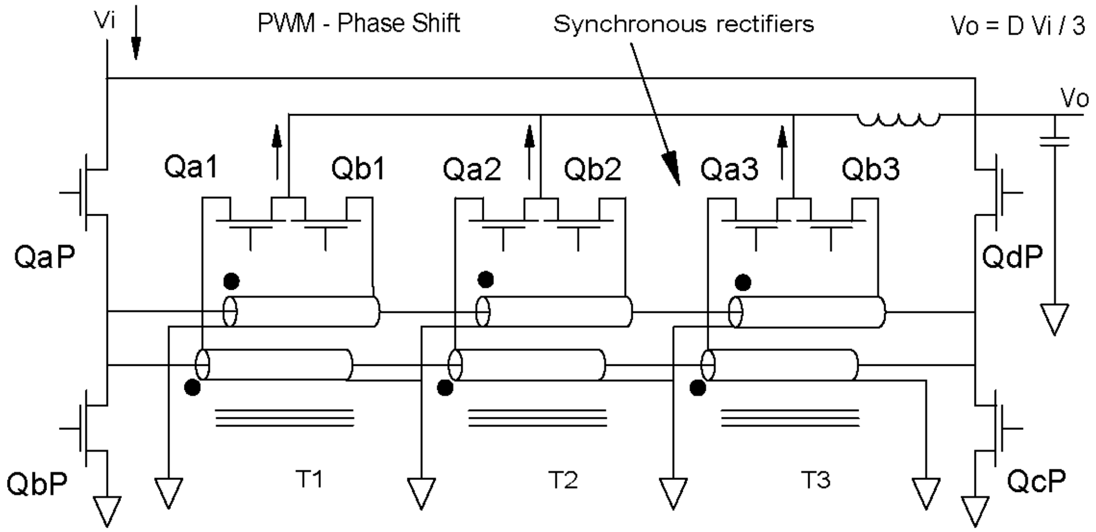

Figure 5.5.1. The full bridge transformer circuit is usually considered to have a single primary winding, but with a coaxial push pull transformer it is preferred to use two parallel primary wires, one through each side, to retain the frequency response of the coaxial coupling. For a phase shifted full wave bridge, the wires must be connected in parallel at the ends so that the off time circulating current can flow.

Unlike a conventional full bridge, the preferred winding arrangement will be different depending upon the mode of operation contemplated. For a phase shifted full bridge, the current must be able to circulate in the primary winding during the off time, through either the two top MOSFETs or the two bottom MOSFETs. This requires that the two primary winding actually be connected in parallel, as shown in figure 5.5.1.

For one hundred percent duty cycle operation (no significant off time at all), or for pulse width modulation where the off time is really off (no circulating currents), then he winding arrangement of figure 5.5.2 is preferred. The phasing is very important. Not only must each wire go through the transformer in the correct direction, it must also go through the correct half of the tubular push pull secondary winding. When two MOSFETs are on, for example, QaP and QcP, the winding connected between them must pass through the side of the push pull winding which will be conducting, that is, the one connected to the secondary synchronous rectifiers Qa1, Qa2 and Qa3, as shown. While the windings may be paralleled as in figure 5.5.1, the arrangement of figure 5.5.2 has the advantage that the sources of the top MOSFETs do not connect directly to the drains of the bottom MOSFETs, so there can never be direct shoot through current. (This does not mean that the designer can be sloppy about overlapped conduction, however, as very large currents will still flow through transformer coupling, if all four of the primary switching MOSFETs are on at the same time).

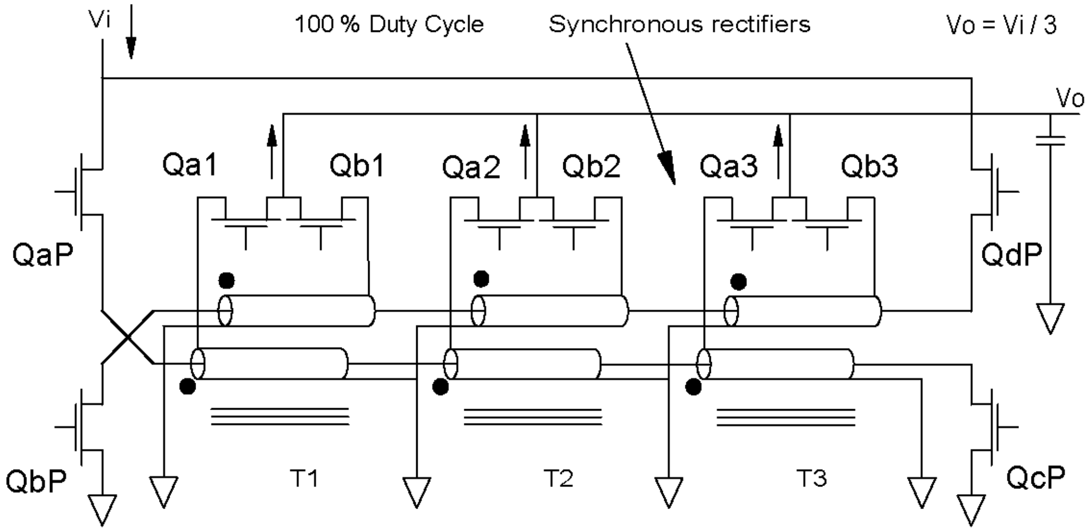

Figure 5.5.2. In a full bridge transformer operated at 100 percent duty cycle (or in a pulse width modulated circuit in which the MOSFETs are all turned off during the off time), the primary winding may be connected separately, to avoid any direct connections between the top and bottom MOSFETs. The primary windings must be correctly phased, not only the direction through the transformer but also through the correct side.

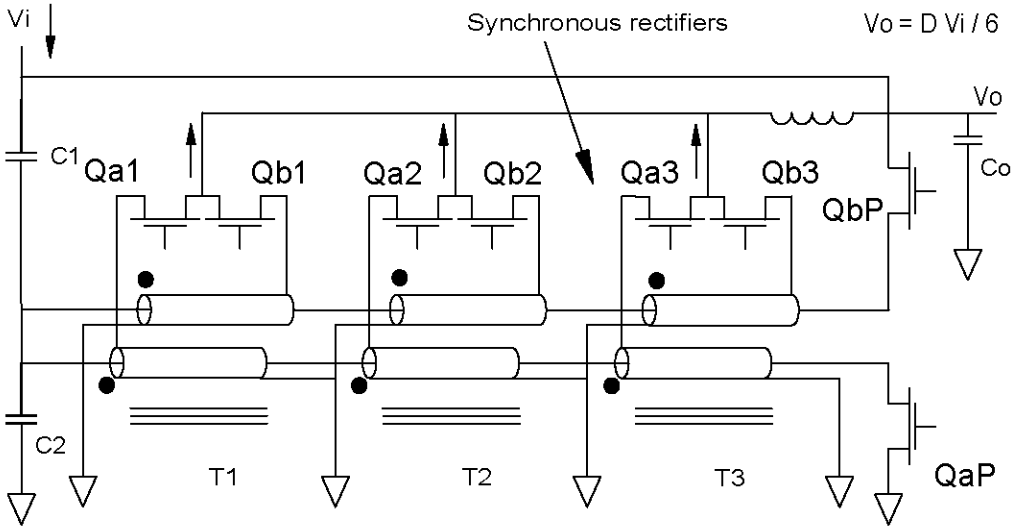

Figure 5.5.3. In a half-bridge coaxial push pull transformer, it is preferred to connect the primary windings separately, to avoid any direct connection between the top and bottom MOSFETs. The primary windings must be correctly phased, not only the direction through the transformer but also through the correct side.

The transformer would operate with the correct turns ratio if a single wire looped through both sides of the secondary push pull winding, and the turns ratio would be 2 n to 1, where n is the number of modules. However, there would be true coaxial coupling in only one half of the secondary, and the current there would be one half. The leakage inductance, while still very good, would be higher, with all of its associated problems.

Figure 5.5.3 shows the corresponding connections for a half bridge converter. Again the phasing is critical for optimum frequency response and low leakage inductance.

The bridge converters can be used with the variable turns ratio configurations as shown in section 4.0.