COMPLEMENTARY-RESONANT DC TRANSFORMERS ACHIEVE LOW-RIPPLE INPUT AND OUTPUT CURRENTS WITH MINIMAL ENERGY STORAGE

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ABSTRACT

Complementary-resonant converters are current-fed parallel-resonant converters in which the input and output inductors are placed on a common core so that the flux produced by the input windings is essentially canceled by the flux produced by the output windings. The structure of these new converters allows the parallel-resonant tank to oscillate freely, independent of the level of load current. Complementary resonance is shown to be a special case of a broader phenomenon called complementary conversion. Several related topologies employing complementary-resonance are described, and the performance of a prototype converter is reported. (Patent pending)

1. Introduction

There are many situations where fixed-ratio converters are adequate. Typical fixed-ratio square-wave DC-DC converters are compact because, unlike variable-ratio converters, they do not require much energy storage in their capacitive and magnetic components. These simple converters, however, have all of the disadvantages of square-wave switching.

Resonant zero-voltage switching eliminates the problems associated with square-wave switching at the price of increased energy storage. Conventional resonant circuits store energy during some parts of the resonant cycle and release energy during other parts. Enough energy must be stored to maintain oscillation for the greatest anticipated load. In the case of a parallel-resonant tank, this means that the current which circulates between the resonant elements is typically greater than the current which flows through the load.

The initial idea for complementary resonant converters came from examining a novel base-drive scheme for a current-fed, parallel-resonant inverter [1]. As a matter of economy, an inductor used to provide a constant base current was placed on a common core with the main input inductor. The constant base current was actually achieved by developing a constant voltage across a resistor. After some analysis, the author deduced that a topologically similar scheme could transform a current-fed, parallel-resonant converter into a low-ripple, fixed ratio DC-DC converter.

Current-fed, parallel-resonant converters [2,3] require an input inductor to allow the parallel-resonant tank to oscillate. They also require an output inductor for each rectifying circuit. Placing the input and output inductors on a single magnetic core restricts the converter to fixed-ratio conversion, but it also produces two advantageous results. First, the flux produced by the current in the output windings essentially cancels the DC flux produced by the input current. This greatly reduces the need for energy storage in this component, which reduces its required size.

When used in the topologies described in this paper, these coupled inductors form a structure which the author calls a "complement transformer" because, as will be explained later, the voltage across it is the complement of the voltage across the main transformer. Complement transformers, like ordinary transformers, operate with AC voltages, and need to store little energy. Unlike ordinary transformers, complement transformers operate with DC instead of AC currents, and are intended for ripple cancellation instead of being used for transferring power.

The second beneficial result of using a common core is that the symmetry of the resulting DC-DC converter produces a condition in which the tank can freely oscillate with a small resonant current, independent of whatever load currents are applied. The magnetizing inductance of the main transformer can therefore be made relatively large, and the parallel capacitance can be made relatively small, both resulting in minimal energy storage. The author has termed this unique condition "complementary resonance."

Analysis of complementary resonance led to the discovery of a more general condition, called "complementary conversion". Complementary conversion topologies are structured so that the input current flows through a series connection of windings of the complement and main transformers, and that the output current also flows through a similar set of series-connected windings. These series connections allow an AC voltage waveform of any desired shape to be impressed upon the main transformer without dissipating much power. This property allows the tank to oscillate freely in complementary-resonant converters.

The voltage waveform of the main transformer in complementary-resonant converters is determined by a parallel-resonant tank. Because of their simplicity, complementary-resonant converters have been chosen to illustrate the principles of complementary conversion. This paper describes several related complementary-resonant converter topologies which achieve the low ripple of integrated-magnetics converters and the efficient switching characteristics of zero-voltage-switching resonant converters, while requiring only the modest energy storage of square-wave converters.

The basic complementary topologies include center-tapped, half-bridge, and full-bridge configurations. In addition, polyphase topologies are possible. The following description of the center-tapped configuration shown in Figure 1 illustrates operating principles common to all complementary converters.

2. Center-tapped Configuration

The input current flows from the positive input terminal to the negative input terminal through the following elements connected in series: the primary winding of the complement transformer, T1, at least one of the primary windings of the main transformer, T2 and at least one of switches S1 and S2.

Capacitor C1 is connected in parallel with the primary of T2 to form a resonant tank. The switches create sinusoidal oscillations by steering the input current through the tank in alternating directions whenever the tank voltage passes through zero. Both switches are briefly on at the same time during the transition. The inductance of the primary winding of T1 prevents the switching overlap from causing spikes in the input current.

In general, each switch in a complementary converter is turned on when the voltage across it drops to essentially zero volts. The switch is turned off when the voltage across another switch reaches zero volts and is turned on. This switching sequence is illustrated by waveforms in Figure 2. V2 represents the tank voltage, while V3 and V4 represent the voltages across switches S1 and S2, respectively. Synchronizing the switches to the tank voltage ensures that the flux in the core of the main transformer has an essentially zero average value even when the turn-off times of the switches are unequal.

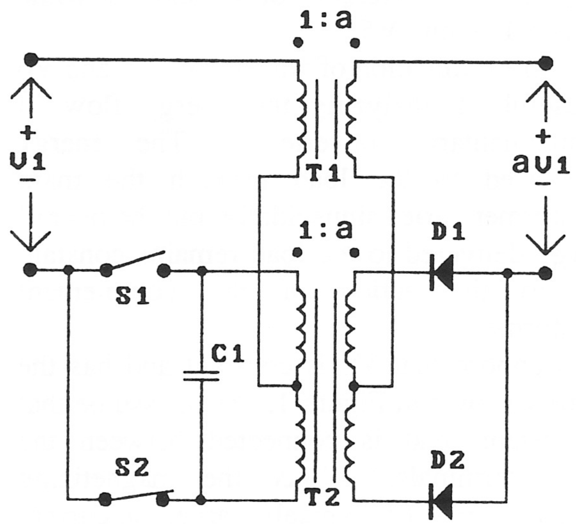


Figure 1. Center-tapped Complementary-resonant Converter.

In the complementary-resonant converters of Figures 1, 3, 4, and 5, the zero crossings of the switch voltage waveforms coincide with zero crossings of the tank voltages. In contrast, Figure 7 illustrates that in polyphase configurations, such as the wye converter of Figure 6, the switch voltages drop to zero when the difference between two tank voltages is zero.

Waveform V6 in Figure 2 represents the voltage across the primary winding of T1, measured from the positive input terminal to the primary center-tap of T2. V5 represents the voltage from the primary center-tap of T2 to the negative input terminal. Therefore, the sum of V5 and V6 is always equal to V1. Because of this, V5 and V6 are called complementary voltages, and T1 is called the complement transformer.

The turns ratios of the transformers are adjusted so that, like the inverting section, the voltages of the series-connected windings of the rectifying section add to an essentially constant value. In Figure 1, both of the transformers have a turns ratio of 1:a. Thus the full-wave rectified voltage measured from center-tap of the T2 secondary winding to the negative output terminal is 'a' times V5, and

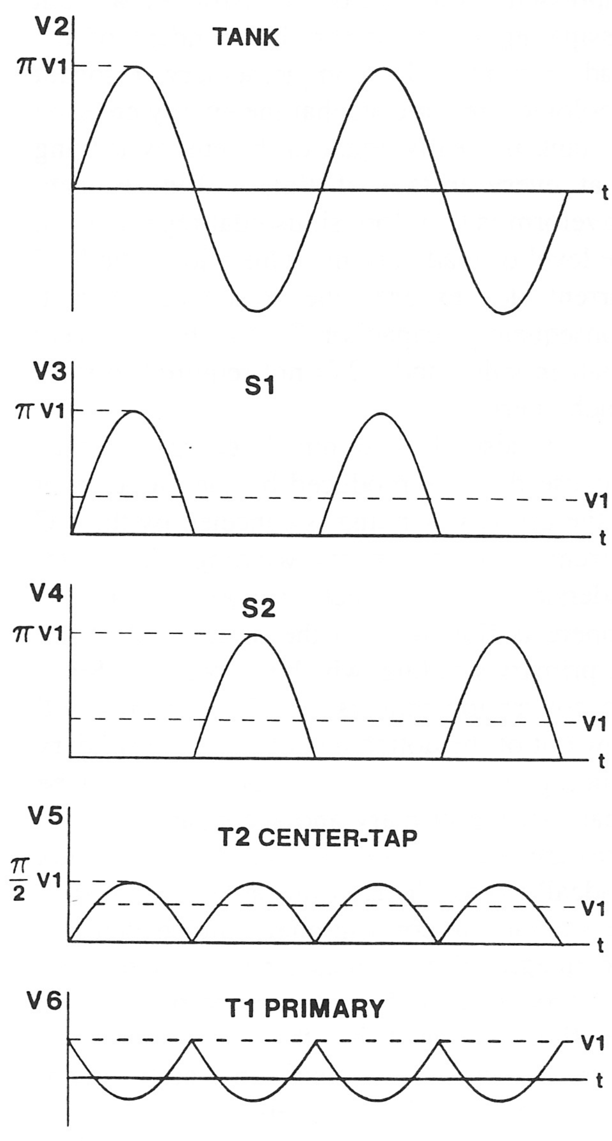


Figure 2. Ideal Waveforms For a Center-tapped Complementary-resonant Converter.

the voltage across the secondary winding of T2 is 'a' times V6. Consequently, the output voltage is 'a' times V1. Since the output voltage is ideally a constant times the input voltage, little filtering is required. In essence, the AC voltage across the secondary winding of the complement transformer cancels the ripple, or AC component, of the rectified output of the main transformer.

A unique property of complementary topologies is that, due to the series connections of the complement and main transformer windings, an AC voltage waveform can be impressed upon the main transformer without dissipating much power, independent of the load current. In complementary resonant topologies, this means that the energy entering the tank is ideally equal to the energy leaving it at every instant of time. The resonant waveform is therefore sinusoidal regardless of the level of load current. This allows the load current to exceed the resonant current. Consequently, capacitor C1 can be relatively small in value and T2 is not required to store much energy.

T1 also has minimal energy storage because the flux produced by the DC current in the primary winding is canceled by the DC current in the secondary winding. To better understand this effect, suppose that one ampere is flowing into the dotted end of the T1 primary winding, which has N turns. Since the conversion ratio is 1:a, 1/a amperes will flow out of the dotted end of the T1 secondary winding, which has aN turns. It should be clear that the primary and secondary ampere-turns are both equal to N, and that the net flux is ideally zero. This is in marked contrast to the situation in conventional coupled-inductor and integrated-magnetics circuits wherein the flux produced by the output windings adds to the flux produced by the input windings. Because the net flux in complement transformers is ideally zero, the core can realize a large magnetizing inductance while having a small physical size. Having a large magnetizing inductance greatly reduces the input ripple current.

The magnitudes of the ideal waveforms can be calculated by recalling that the average voltage across any transformer winding is zero, and that the peak of a full-wave rectified sinusoid is $\pi/2$ times its average value, while the peak of a half-wave-rectified sinusoid is π times its average value. Thus the peak values of waveforms V3, V4 and V5 can be determined by recognizing that the average value of each of these waveforms is equal to V1. V2 is the difference of V3 and V4, while V6 is V1 minus V5.

An examination of waveforms V5 and V6 is useful in analyzing the energy flow in complementary converters. The energy transferred to the load through the main transformer varies sinusoidally, but the overall energy delivered to the load remains constant due to the action of the complement transformer.

Suppose that V1 is constant and has the polarity shown in Figure 1. Also, assume that a constant load is connected between the output terminals. Since the magnetizing inductance of T1 is typically large, the current through its primary winding is nearly constant. When V6 is positive, energy flows through T1 to the load. This compensates for the fact that, at the same time, the energy delivered to the load by T2 is less than its average value. When the energy transferred by T2 is greater than its average value, the excess energy flows back to the inverting section through T1, because voltage V6 is negative at that time. Since the average value of V6 is zero, the net energy transfer of T1 is also zero.

3. Single-tank, Half-bridge Configuration

Figure 3 shows a complementary-resonant DC transformer having single-tank, half-bridge inverter and rectifier sections. This circuit uses a tapped complement transformer to produce alternating currents in a single tank winding.

Half-bridge configurations are useful because the peak voltages across the switches and diodes are only one half of the peak voltages found in center-tapped configurations. The cost of obtaining lower voltages is that the current passing through the switches is double that of center-tapped configurations.

Assuming that one ampere of current is flowing into the positive input terminal in Figure 3, and that the switches are in the states shown, two amperes would then flow through S1, the upper primary winding of T1, and the primary winding of T2. If capacitors C1 and C2 are equal, then the current flowing from T2 will split equally, with one ampere flowing out of the negative input terminal, and one ampere adding to the one ampere of input current already passing through S1.

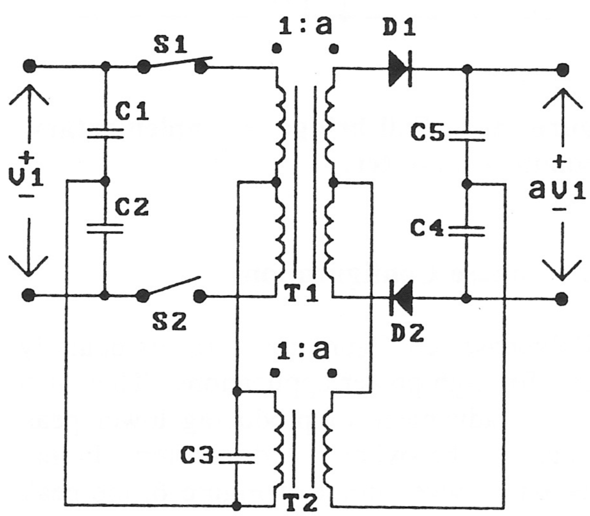


Figure 3. Single-tank Half-bridge Complementary-resonant Converter.

Capacitors C1 and C2 should be large enough so that the voltage change across them during one half cycle is small compared to the input voltage. The input ripple current is minimized when these capacitors are equal.

Capacitor C3 forms a parallel-resonant tank in combination with the primary magnetizing inductance of T2. The interwinding capacitance between the primary windings of T1 adds to the effective tank capacitance. If these windings are bifilar wound, the capacitance may be great enough to eliminate the need for C3.

When the sinusoidal voltage across the primary winding of T2 passes through zero, the switches are changed to the opposite states. S2 will then reverse the direction of current passing through the tank. The current in the secondary windings of T1 essentially cancels the DC flux in the core produced by the current in the primary windings.

The waveforms of the circuit in Figure 3 have the same shapes as the waveforms shown in Figure 2, but the amplitudes are different. The peak switch voltages are $\pi/2$ times V1, and the peak voltage across the primary winding of T2 is $\pi/4$ times V1. The peak-to-peak voltage across each of the primary windings of T1 is also $\pi/4$ times V1.

The rectifying section operates similarly to the inverting section, with currents flowing alternately through D1 and D2. Because T1 and T2 each have a primary-to-secondary turns ratio of 1:a, the output voltage is 'a' times V1.

4. Split-tank Half-bridge Configuration

Figure 4 shows a complementary-resonant DC transformer having split-tank, half-bridge inverter and rectifier sections. C3 and C4 are connected in parallel with the two primary windings of T2 to form a tank.

The properties of this circuit are very similar to those of the circuit in Figure 3. Suppose one ampere of current is flowing into the positive input terminal, and that the switches are in the states shown in Figure 4. Two amperes would then flow through the upper primary winding of T1, and through the upper tank section. Assuming that C1 and C2 are equal, the current flowing through the upper tank section will split equally, with one ampere flowing out of the negative input terminal and one ampere adding to the one ampere of input current passing through S1.

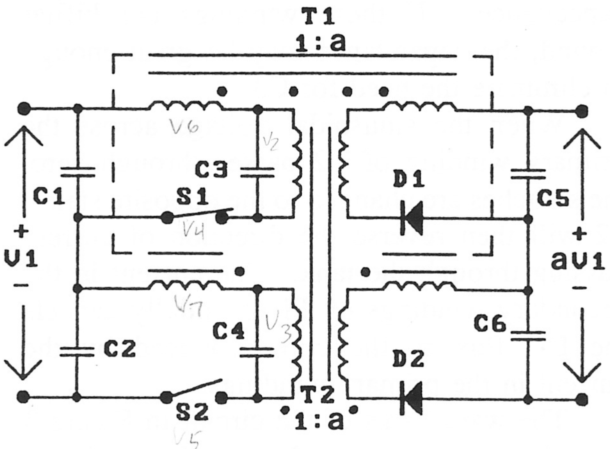


Figure 4. Split-tank Half-bridge Complementary-resonant Converter.

When the tank voltage passes through zero, the switches are made to assume the opposite states. S2 will then direct current through the lower tank section.

The waveforms of the circuit of Figure 4 have the same shapes and amplitudes as the waveforms generated by the circuit of Figure 3. Each tank section in Figure 4 has the same voltage as the single tank in Figure 3, but the transformer utilization is not as good since the load current only flows half the time in each winding.

5. Full-bridge Configuration

Figure 5 shows a complementary-resonant DC transformer having full-bridge inverting and rectifying sections. As in the previous two circuits, the peak voltages across the switches and diodes in full-bridge configurations are only half of that seen by their counterparts in center-tapped versions. Unlike half-bridge configurations, the current flowing through the switches is the same as the input current. Switches S2 and S3 alternate with S1 and S4 at the zero crossings of the tank voltage.

The waveforms generated by the circuit in Figure 5 have the shapes shown in Figure 2, but the amplitudes are different. The peak switch voltages and the peak voltage across the primary winding of T2 are each $\pi/2$ times V1. The peak-to-peak voltage across the primary winding of T1 is also $\pi/2$ times V1.

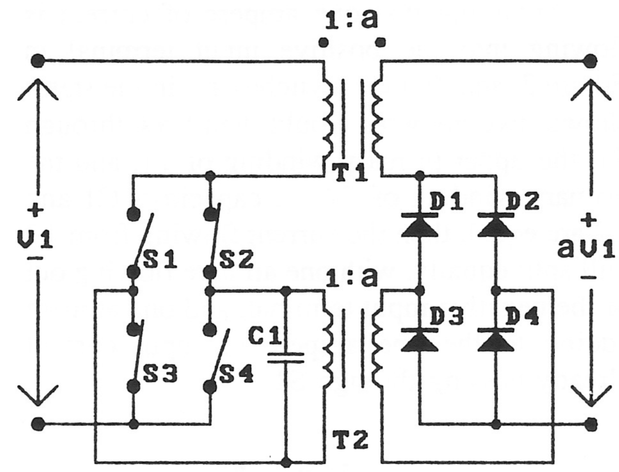


Figure 5. Full-bridge Complementary-resonant Converter.

6. Polyphase Configurations

Polyphase configurations are particularly useful for high-power applications. They also have the advantage of producing lower peak voltages on the switches and rectifiers. In the three-phase wye circuit of Figure 6, the peak switch voltages are only $\pi/3$ times the DC input voltage.

Any polyphase rectifier circuit can serve as the basis for a complementary converter. The complementary transformer fills the position normally occupied by a filter choke. The inverting and rectifying sections can be based on different topologies so long as the waveforms on the primary and secondary of the complement transformer do not conflict. A main transformer with a wye-connected primary, for example, is compatible with a star-connected secondary winding but not a delta-connected secondary winding.

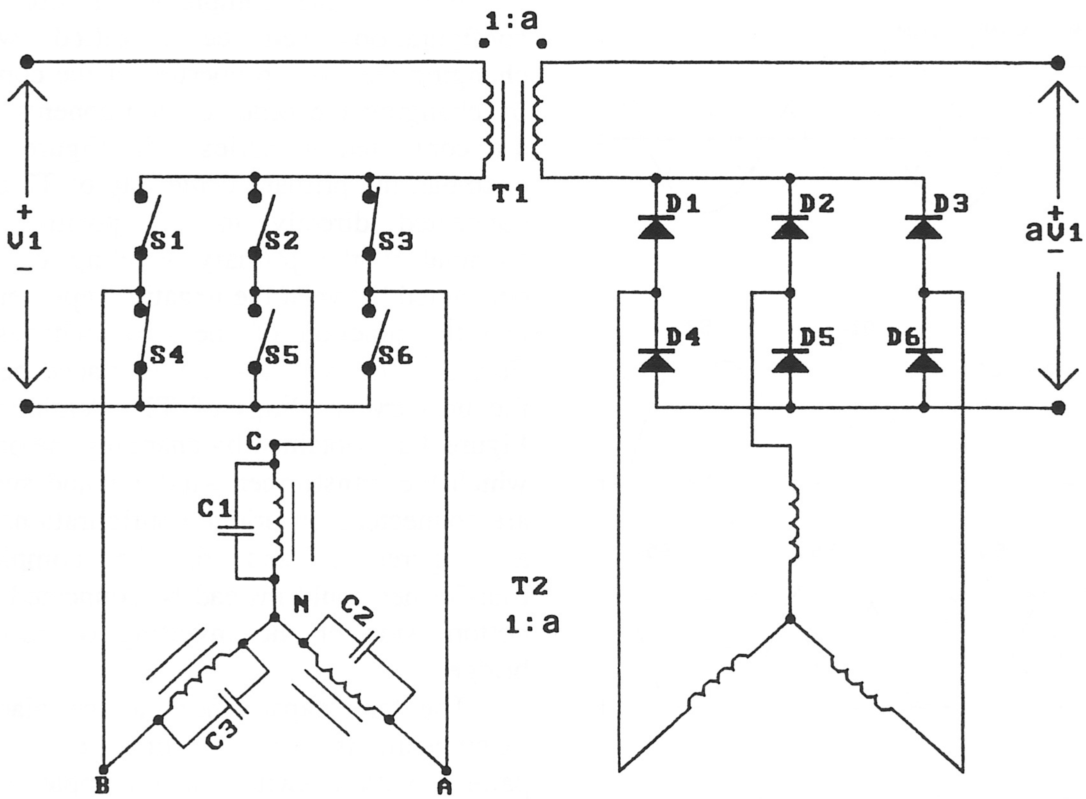


Figure 6. Three-phase Wye Complementary-resonant Converter.

In the circuit of Figure 6, V1 is divided between the primary winding of complement transformer T1 and two of the primary windings of T2, the main transformer assembly. T2 can be constructed with separate transformers or as a single structure. Capacitors C1-C3 are connected in parallel with the primary windings of T2 to form a three-phase resonant tank. Switches S1-S6 are arranged to form a three-phase bridge.

Figure 7 illustrates the switching sequence of switches S1-S6 for an ABC phase sequence. Waveforms VAN, VBN, and VCN are the voltages between points A, B, and C and point N. Each switch is turned on when the voltage across it drops to zero. This occurs when the voltages across two of the primary windings of T2 have equal values. Each switch is turned off later in the resonant cycle when another switch is turned on. For example, S3 is turned on when VAN equals VCN. It is turned off when VAN equals VBN, and S1 is turned on. S4 is on at the start of the waveforms, and S3 has just closed. V7 is the voltage across the inverter bridge, measured from the upper to the lower side. V8 is the voltage across the primary winding of T1, measured from the positive input terminal to the junction with the inverter bridge. Assuming ideal switches, the sum of V7 and V8 is equal to the input voltage, V1. The voltage across the secondary winding of T2 cancels the ripple in the voltage rectified by diodes D1-D6. Thus the output voltage is 'a' times V1. T2 can be quite small since the RMS ripple of a six-pulse rectifier is about five percent of the rectified voltage.

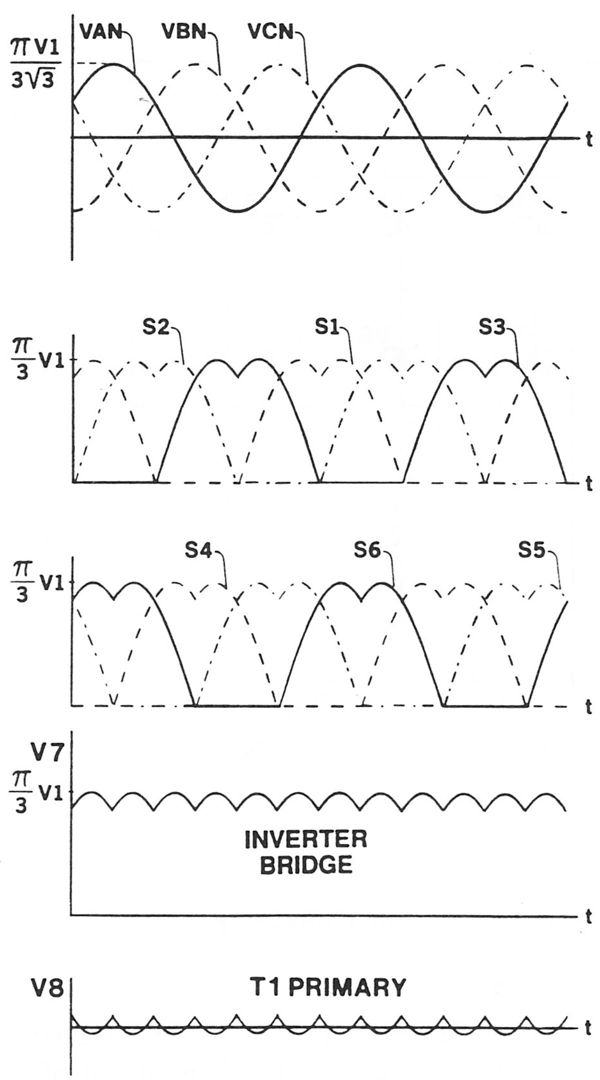


Figure 7. Ideal Waveforms For a Three-phase Complementary-resonant Converter.

7. Modifications.

A complementary converter has at least one inverting section and one rectifying section. Any combination of the basic topologies of inverting and rectifying sections may be connected to form a complementary converter. For example, a converter with a half-bridge inverting section could have one rectifying section with a center-tapped configuration, and another rectifying section configured as a full bridge.

Each of the complementary-conversion configurations can be modified without changing the basic properties of the converter by changing the order of components which are connected in series. In Figure 1, for example, the primary center-tap of T2 can be connected directly to the positive input terminal if the primary winding of T1 is connected between the negative input terminal and the junction of the two switches. In Figure 3, the switches can be placed between the primary windings of T1. Variations of Figure 4 are obtained by changing the order in which the transformer windings and switches are connected. In bridge configurations, such as Figures 5 and 6, the complement transformer could instead be connected to the bottom side of the inverting or rectifying bridges.

The tank capacitance can be placed in many positions. Any capacitance connected in parallel with a switch in a complementary-resonant converter is effectively in parallel with the tank. The capacitance connected directly across winding of the main transformer could therefore be augmented or even replaced by capacitors placed in parallel with the switches. Although not as obvious, any capacitance from the center-tap of the main transformer primary winding to either of the input terminals also adds to the effective tank capacitance. It is generally preferable to have most of the tank capacitance connected directly across the main transformer since the resonant current which flows through capacitors placed in other positions must also flow through one of the switches. Placing part of the tank capacitance on the secondary side of the main transformer can damp ringing caused by leakage inductance.

Another modification which retains the condition of complementary conversion is to replace the rectifiers with switches which are operated in synchronism with the input switches. This technique can be used to achieve a smaller voltage drop than is possible with diodes. Synchronous rectification can also be used to obtain bidirectional power flow between two converter sections by allowing the inverting section to function also as a rectifying section, and by allowing a rectification section to act as an inverting section.

If switches and driver circuits adapted to operate with any direction of voltage and current are employed, then changing the polarity of the input voltage would change the polarity of the output voltage. Complementary converters can thus be made to emulate an ideal transformer, passing both AC and DC voltages, so long as the frequency of the AC input voltage is small compared to the switching frequency of the converter.

The peak voltages of the sinusoidal waveforms across the switches and diodes in complementary-resonant converters are higher than they would be if the main transformer waveform were more square. The peak voltages can be reduced by operating the main transformer core near saturation, which causes the peaks to become more flattened.

The waveform of the main transformer can be determined without using a resonant tank by allowing the core to saturate as is done in Royer converters. This type of complementary converter was independently discovered by Labelle [4]. These converters are only practical at low power levels because the core losses become excessive in larger transformers. One possible way around this problem is to use a small saturating inductor in parallel with a large transformer operated in its linear range.

The main transformer voltage of complementary converters can be made to assume a specific waveform by connecting at least one winding of the main transformer to an oscillator which produces the desired waveform. The waveform must have an essentially zero average value, and must have an amplitude which also allows the voltage across the complement transformer windings to have an essentially zero average value. This scheme would be most useful in high power converters.

It is often helpful to have some leakage inductance in the complement transformers to smooth out switching transients. This is done at the expense of increased energy storage because the flux cancellation is proportional to the coupling between the primary and secondary windings.

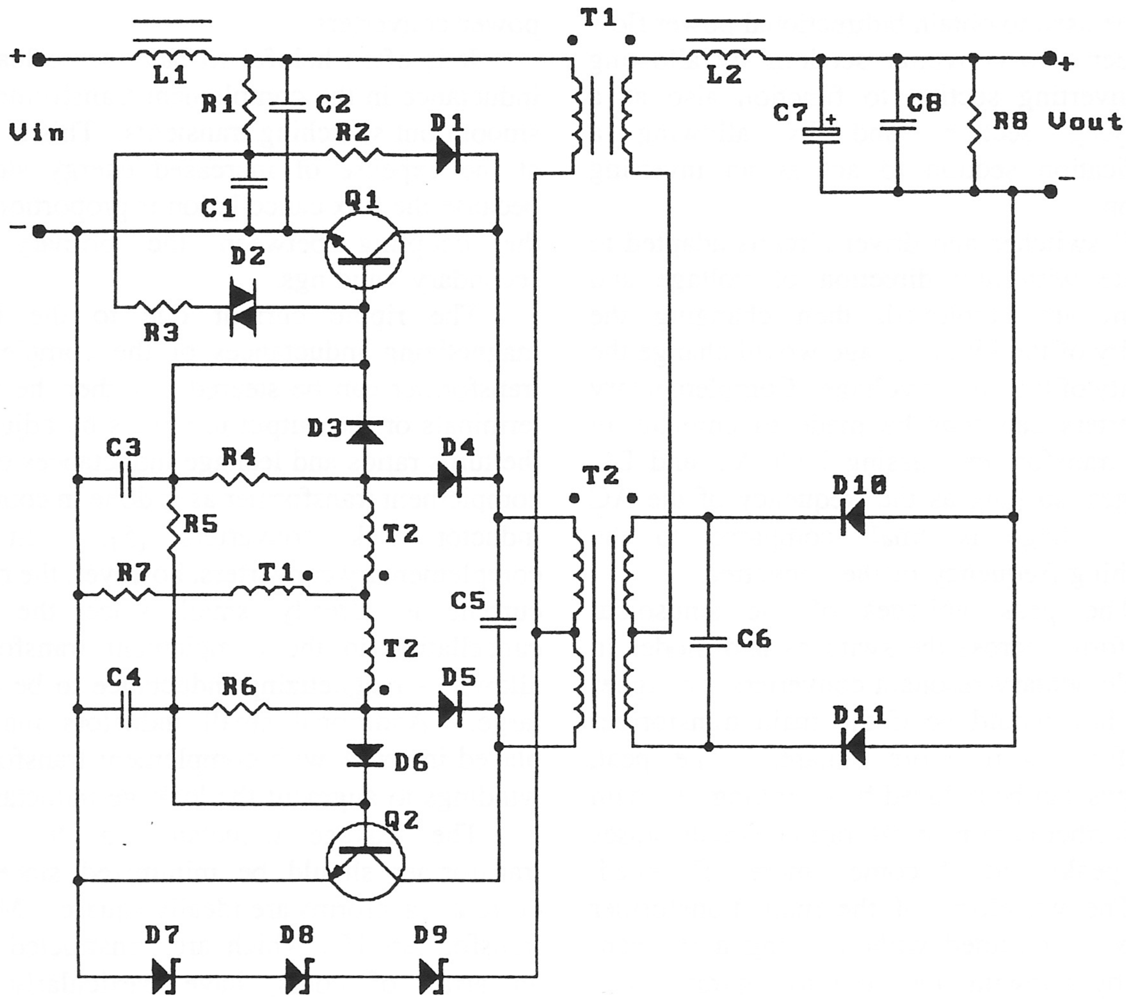
The ripple current due to the finite magnetizing inductances of the complement transformer can be steered to either the input terminals or the output terminals by adjusting the turns ratios and leakage inductances of the complement transformer as is done in coupled-inductor Cuk converters [5]. In the complementary converters, however, the ripple current is already small since the flux cancellation in the complement transformer allows its magnetizing inductance to be quite large. Additional small inductors may be placed in series with complement transformer windings to augment the leakage inductances.

The leakage inductance of the main transformer should be minimized since the current waveforms are ideally square. Matrix transformers [6], which are constructed with an array of cores, have particularly low leakage inductances and thus make excellent main transformers in complementary converters.

8. Experimental Results

Figure 8 shows the circuit diagram for an experimental 75 watt, 155 to 28 volt complementary-resonant DC-DC converter. A center-tapped topology is used for both the inverting and rectifying sections.

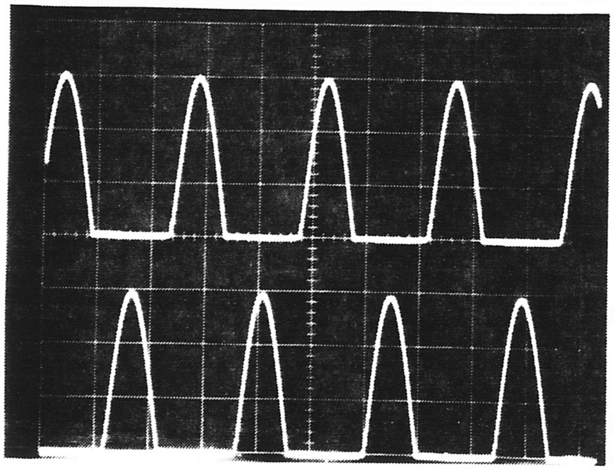
The base-drive circuit is very similar to the rectifying part of the circuit. Consequently, it develops a relatively constant voltage across R7, which determines the average base current. C3-4 and R4-6 increase the base current just after the transistors turn on, and decrease the base current before they



C1	0.1 uF polyester	D1	1N4007	L1	330uH
C2	O.22 uF polyester	D2	HT-32	L2	13 uH
C3-4	0.01 uF polyester	D3,6	1N5408	Q1,2	BUT11A
C5	470 pF mica	D4,5	FR107	R1	1 M
C6	0.0033 uF polypropylene	D7,8	P6KE150A	R2,8	10k
C7	10 uF tantalum	D9	P6KE110A	R3	100 ohm
C8	3.3 uF monolythic	D10,11	FR303	R4-6	220 ohm
				R7	75 ohm

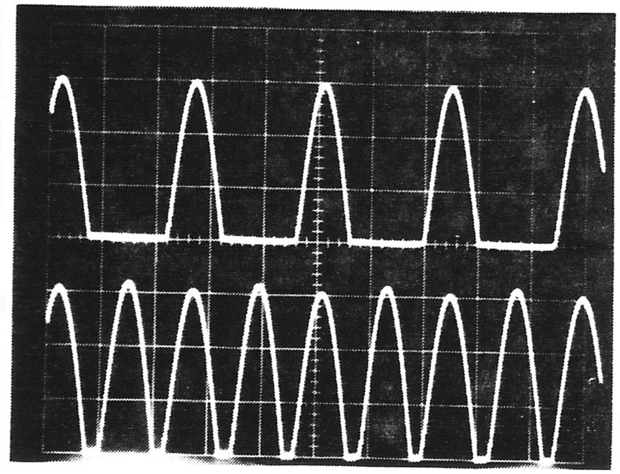
T1	Core: EE187 SB7C	T2	Core: EE375 B52
	Gap: none		Gap: 1.5 mil spacers
	Primary: 95 T #28		Primary: 63 T #28x2 each half
	Primary inductance: 8.2 mH		Primary inductance: 14.6 mH
	Secondary: 18 T #28x5		Secondary: 12 T #28x6 each half
	Feedback: 3T #33		Feedback: 2 T #28 each winding

Figure 8. 75 W Experimental Complementary-resonant Converter.



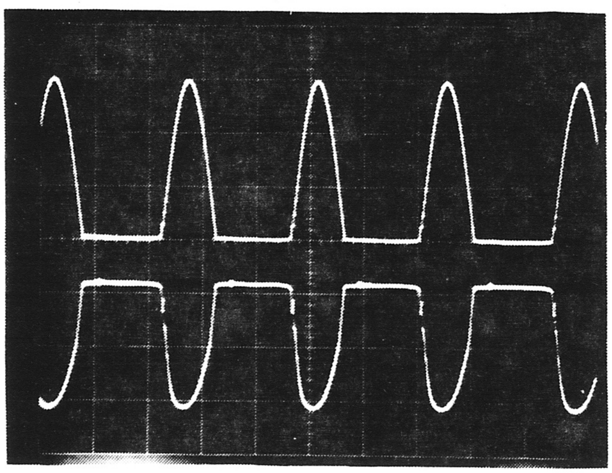
(a)

Upper: Q1 Vce 200V/div
Lower: Q2 Vce 200V/div
10μS/div



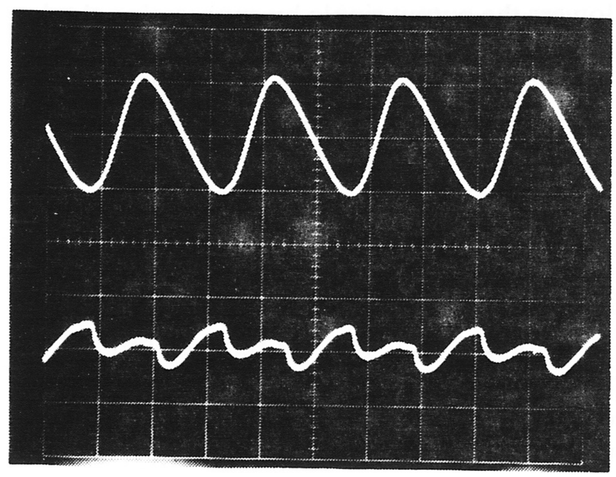
(b)

Upper: Q1 Vce 200V/div
Lower: T2 primary center-tap 100V/div
10μS/div



(c)

Upper: Q1 Vce 200V/div
Lower: Q1 Vbe 5V/div
10μS/div



(d)

Upper: Input ripple current 5mA/div
Lower: Output ripple voltage 100mV/div
10μS/div

Figure 9. Experimental Waveforms.

INPUT VOLTS	INPUT CURRENT	INPUT WATTS	OUTPUT VOLTS	OUTPUT CURRENT	OUTPUT WATTS
155	11.7 mA	1.81	29.15	0	0
155	548 mA	89.94	27.95	2.788 A	77.92

Table 1. Experimental Converter Performance.

are about to turn off, so as to increase the switching speed. 1N5408 diodes were selected for D3 and D6 because they store enough charge to help turn off the transistors. Zener diodes D7-9 protect the transistors from line transients, and from internally generated transients that can occur when a heavy load is suddenly removed.

The tank circuit is split between the primary and secondary windings of T2. C6 lowers the output ripple by suppressing ringing in the secondary windings of T2.

Table 1 shows performance data for the converter. The full-load efficiency is 91.7 percent, and the no-load to full-load regulation is 4.1 percent.

Figure 9 shows waveforms of the experimental converter obtained when the circuit was fully loaded. As seen in the lower waveform of part (b), the turn-off time of the switching devices may be a significant fraction of the period of the resonant cycle. If To is the period of tank resonant frequency, and T is the actual period, then the actual peak voltages are the ideal peak values multiplied by T/To.

In this experimental circuit, the resonant frequency is about 50 kHz but the circuit operates at about 40 kHz due to the turn-off time of the transistors. The increase in the peak voltages is, therefore, about 25 percent. Although the internal voltages of the converter are affected by the turn-off times of the transistors, the conversion ratio of the converter remains fixed.

T1 does not perfectly cancel the input ripple current, and so a small external inductor, L1 is used. Similarly, the output ripple voltage is not entirely canceled by the secondary of T1, so another small inductor L2 is used. These inductors typically have 3 to 5 percent of the inductance of their associated windings on T1. In many cases, the leakage inductance of the complement transformer makes external inductors unnecessary.

Figure 9d shows that the input ripple current is about 12 mA pp out of 548 mA, and that the output ripple voltage is less than 100 mV pp out of 28 V. If separate inductors were used in place of T1, which uses an EE187 core, they would each need to be about the size of T2, which uses a much larger EE375 core, in order to achieve the same ripple characteristics. Notice that the input capacitor is only 0.22 uF, and that the total output capacitance is only 13.3 uF.

The size of the experimental converter is not as small as it could be due to the low operating frequency dictated by the transistors. Bipolar transistors were used in this simple, self-oscillating circuit because using MOSFETs would require more complicated drive circuitry, including a high-speed voltage comparator and gate-drivers.

This converter is best suited for operation with a resistive load such as an incandescent lamp. The diac starting circuit will not start the circuit if the output is shorted or has a highly capacitive load. Current feedback in the base drive circuitry has been successfully used in another experimental converter designed to operate with capacitive loads.

9. Applications

There are several areas where complementary converters could be useful. One of the most promising areas is in conjunction with linear regulators in applications where noise is a concern. Linear regulators have limited ripple rejection characteristics at high frequencies, so it is important to begin with a converter with minimal high-frequency ripple.

Another area complementary converters could be used is for converting a high-voltage bus to a low-voltage bus in distributed power systems. For example, the 300 V output of a power factor correction circuit could be lowered to 24 V and distributed to on-card regulators. Aircraft and naval power systems are moving toward high-voltage DC power distribution, and complementary converters could be used to provide power for equipment designed to operate at lower voltages. Using a more complicated converter in these applications seems unwarranted if the low-voltage equipment does not need a tightly regulated input voltage.

Another situation where complementary converters could replace more complicated equipment is in uninterruptible power supplies. Computer power supplies could be easily adapted to operate from a high-voltage DC input connected across the output of the existing rectifier or power factor correction circuits. A fixed-ratio converter would be used to convert the battery voltage to the required level. This would be far more reliable than more complicated conventional systems which provide a clean sine wave, only to have it rectified.

Since complementary converters can be made to provide bidirectional power flow with any polarity of input voltage, these converters could be used to create a light-weight 220 to 120 V power converter for travelers. The low-ripple characteristics of complementary converters allow the input and output sections to operate with very little capacitance, which is an essential condition for a practical AC-AC converter.

10. Conclusions

Complementary converters provide a compact and efficient way to achieve low-ripple fixed-ratio voltage conversion. The advantages of these converters suggest that they be considered for applications which have previously required more complicated circuits.

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