

Resonant Mode Converter Topologies

by Bob Mammamo

TOPIC 1

Resonant Mode Converter Topologies

Bob Mammano

Introduction to Resonant Power Conversion

Over the years we have seen power conditioning move from simple but extravagant linear regulators, through early low frequency pulse-width modulated systems, to high frequency square wave converters which pack the same power handling capabilities of earlier designs into a fraction of their size and weight.

Today, a new approach is upon us -- the resonant mode converter -- and while offering new benefits in performance, size, and cost, this new technology brings with it an added dimension of complexity. The purpose of this paper is to offer a means of categorizing and defining the various topologies and operating modes of resonant mode converters with the hope of enhancing the capability for design, analysis, and evaluation of these new power systems.

LINEAR REGULATORS	1960's and earlier
-SIMPLE	
-POOR EFFICIENCY	
SWITCHING REGULATORS	1970's
-COMPLEX	
-HIGHER EFFICIENCY	
-DEMAND IC CONTROLS	
-HIGH NOISE	
-SLOW RESPONSE	
CURRENT MODE CONTROL	1980's
-IMPROVED REGULATION	
-BETTER PROTECTION	
-HIGHER BANDWIDTH	

Fig. 1 - Power System Development History

5 to 20 kHz	-AUDIBLE NOISE -SLOW BIPOLAR SWITCHES -LARGE L's AND C's
20 to 100 kHz	-ABOVE AUDIBLE RANGE -FAST BIPOLAR TRANSISTOR -MAGNETICS BECOME IMPORTANT -SMALL SIZES
100 to 500 kHz	-POWER MOSFET SWITCHES -LOSSES IN L's AND C's -DIODE RECOVERY TIME -RFI AND EMI -PACKAGING PROBLEMS

Fig. 2 - Power Supply Switching Frequencies

First let us define a resonant converter as a power conditioning system which utilizes a resonant L-C circuit as a part of the power conversion process. All resonant converters operate in essentially the same way: a square pulse of voltage or current is generated by the power switches and this is applied to a resonant circuit. Energy circulates in the resonant circuit and some or all of it is then tapped off to supply the output. While basically simple, this principle can be applied in a wide variety of ways, creating a bewildering array of possible circuits and operating modes.

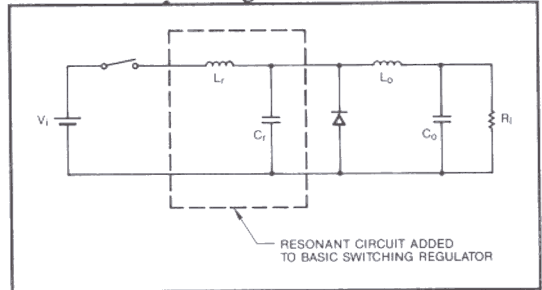


Fig. 3 - Basic Resonant Converter

Resonant Converter Advantages

Before getting into these, however, let's pause to review why we are even interested in resonant mode power conversion.

With the earliest switched-mode power converters, it became obvious that higher frequencies allow smaller L's and C's and this, in turn, should lead to smaller, lighter, and (hopefully) less costly systems. The down side to moving to higher frequencies, however, are the problems of greater susceptibility to parasitic capacitance and leakage inductance, greater stress in the switching devices, and increased EMI and RFI. A resonant mode system offers the potential of achieving the benefits while sidestepping many of the disadvantages of higher frequencies. With a resonant circuit in the power path, the switches can be configured to operate at either zero current or voltage points in the waveform, greatly reducing their stress levels; the resonant sine wave minimizes higher frequency harmon-

ADVANTAGES:

1. ZERO CURRENT SWITCHING
2. LOW COMPONENT STRESS
3. LOW EMI
4. USEFUL PARASITIC ELEMENTS
5. IMPROVED DIODE RECOVERY

DISADVANTAGES:

1. GREATER COMPLEXITY
2. HIGHER PEAK CURRENTS
3. NEW TECHNOLOGY LEARNING CURVE

Fig. 4 - Resonant Converter Advantages

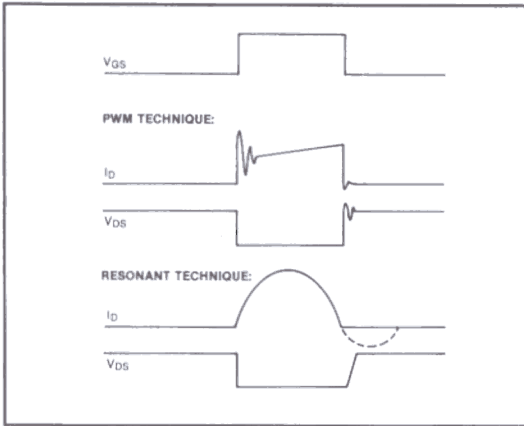


Fig. 5 - PWM vs. Resonant Switching

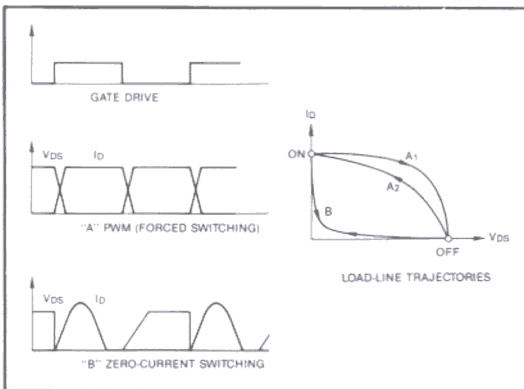


Fig. 6 - Switching Stress and Switching Loss

ics reducing noise levels; and since the circuit now requires inductance and capacitance, parasitic elements may enhance rather than detract from circuit performance. With these benefits, power systems operating in the range of 500 kHz to 2.0 MHz are now practical and - in fact - are already being produced by a few leading edge manufacturers.

Classifying Resonant Converters

Before attempting to classify resonant converter topologies, it might be helpful to introduce the concept of Resonant Switches. A resonant switch consists of a switching device (a transistor with a steering diode, for example) in combination with a two-element resonant circuit. This resonant switch may be configured in several different ways, some of which are shown in Figure 7, but they always perform the same function as the conventional switch in a square wave converter. It is a useful concept as most resonant mode circuit topologies can be visualized as a conventional PWM circuit with the power switch replaced with a resonant switch. We will discuss the operation of the various switch configurations in greater detail as we get into the circuit topologies but first, let's take an overview of some of the circuit options.

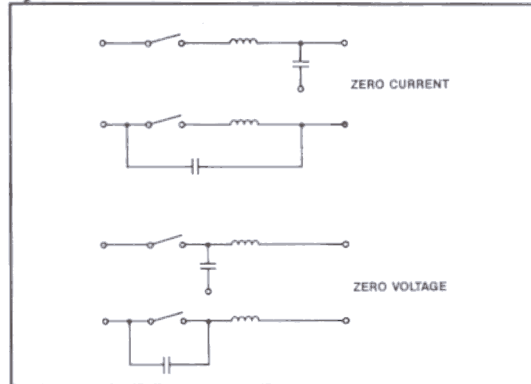


Fig. 7 - Resonant Switches

To bring some order and ease in understanding the broad range of circuit choices which are possible as we move to resonant mode operation, it helps to establish a system to classify resonant topologies by defining the following operating characteristics:

1. Is the load in series or in parallel with the resonant circuit elements?
2. Is the control system a fixed or variable frequency type?
3. Does current (or voltage) in the resonant circuit flow continuously or is it equal to zero for some portion of the switching cycle?

1. SERIES OR PARALLEL LOADED?
2. FIXED OR VARIABLE FREQUENCY?
3. CONTINUOUS / DISCONTINUOUS RESONANCE?
4. ZERO CURRENT OR VOLTAGE SWITCHING?
5. HALF OR FULL CYCLE CONDUCTION?

Fig. 8 - Classifying Resonant Converters

For discontinuous operation, it is also important to know:

4. Is the switching designed for zero current or zero voltage activation, and
5. Does the energy in the resonant circuit flow in only one direction or is there a full cycle before it returns to stop at zero?

The general properties of any resonant converter are completely dependent on these options, so they are a good basis to use as a starting point in understanding the principles involved.

Series or Parallel Loading

Since resonant converters operate by putting energy into a resonant circuit and then transferring some or all of it into the load, we need to know that there are two ways this may be accomplished as shown in Figure 9. If the load is in series with the resonant circuit elements, as in Fig. 9A, we call it a series loaded converter and the operating characteristics tend toward a current source with a high impedance output.

Parallel loading is the opposite, with a low impedance voltage source output as shown in Fig. 9B. Both modes have application to power systems with high voltage outputs usually using series loaded current source drive and low voltage supplies using parallel loading.

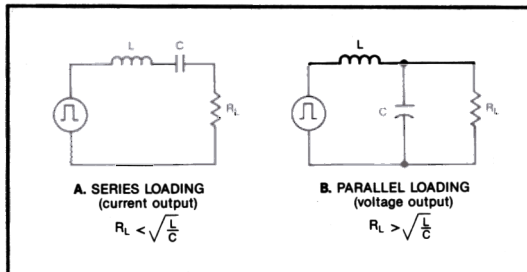


Fig. 9 - Resonant Mode Loading

Fixed or Variable Frequency

Resonant converters may be configured for either constant or variable frequency operation, but these choices infer significant differences in their operation. Fixed frequency control systems use conventional pulse width modulation to change the output in response to a control input, as shown in Figure 10. This forces a fixed-frequency system to have at least one non-zero switching transition and possibly two, thereby voiding one of the more significant reasons for choosing to use a resonant mode topology. This would usually preclude its use unless system considerations required a synchronized frequency operation.

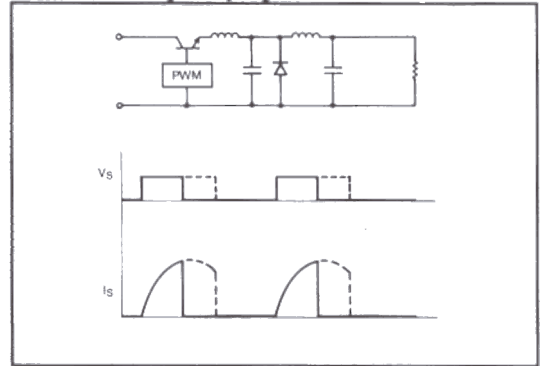


Fig. 10 - Fixed Frequency Resonance

Variable frequency operation, however, needs to be subdivided by the third classification: whether the resonant circuit current is continuous or discontinuous. A circuit operating in the continuous resonant mode uses the slope of the resonant circuit impedance curve to

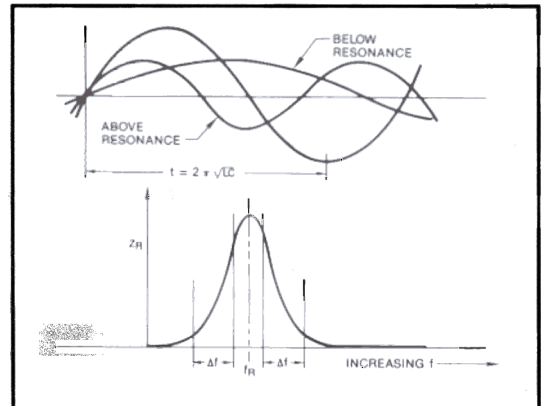


Fig. 11 - Variable Frequency Continuous Resonance

control the output. As shown in Figure 11, the circuit can operate either above or below resonance but the principle is the same: that the control circuit changes the frequency to move either toward or away from resonance, and thereby controls the amount of energy which is transferred into the resonant circuit - and therefore to the load.

While many practical systems have used continuous conduction, variable frequency operation, there are several disadvantages:

1. The non-zero switching adds stress to the transistors.
2. As the frequency approaches resonance, peak currents or voltages can get very high, adding stress to the resonant components.
3. The control transfer function is very non-linear following the resonant impedance curve.

The major advantage of the continuous mode of operation is that the frequency varies over a much smaller range than with the discontinuous mode.

Discontinuous Resonance

The discontinuous operating mode works by supplying constant packets of energy to the load with the rate, i.e. frequency, determined by load power demand.

Perhaps the most popular and important class of resonant converters with variable frequency and discontinuous current is often called *Quasi-Resonance*. Most of the remaining portion of this discussion will be oriented toward this Quasi-Resonant converter category

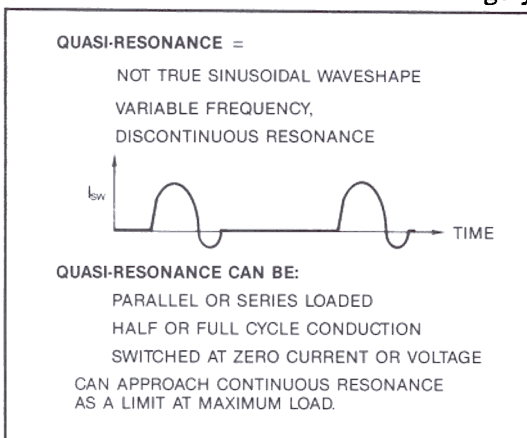


Fig. 12 - Quasi-Resonance Definition

but even within this class there are still many variations in circuit operation.

As indicated in Figure 12, quasi-resonant circuit waveforms are not sinusoidal, but have two essentially linear portions interspersed with two sinusoidal portions.

A quasi-resonant converter control loop is usually configured as shown in Figure 13 with a pulse generator driving the resonant circuit at a repetition rate defined by the control circuit. The pulse generator may be set for constant pulse width - defined by the resonant circuit - or set to sense zero crossing of either current or voltage. With maximum loading and low line voltage, a quasi-resonant converter can approach continuous resonance as a limit when the individual pulses run together.

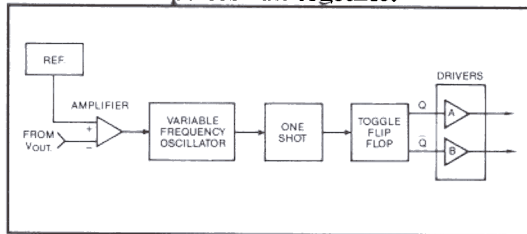


Fig. 13 - Quasi-Resonant Control

Within the variable frequency, discontinuous mode of operation there are two remaining decisions a designer must make which will have significant effect on the characteristics of his power supply:

Zero-Current or Zero-Voltage Switching

Since reducing the stress on the switching components is a major incentive for resonant operation, we need to understand ways in which that might be accomplished. The most common approach, and the one to which most of this paper will address, is to switch at zero current so that the dynamic load line stays very close to the V-I axes. With a sine wave current shape, it should be clear that the peak current will be close to twice the value of an equivalent square wave system, and although this adds to the I^2R losses, most semiconductor devices are much more comfortable with this than the high peak power levels reached with square wave switching.

Of course, low switching stress may also be achieved by switching at zero voltage and one

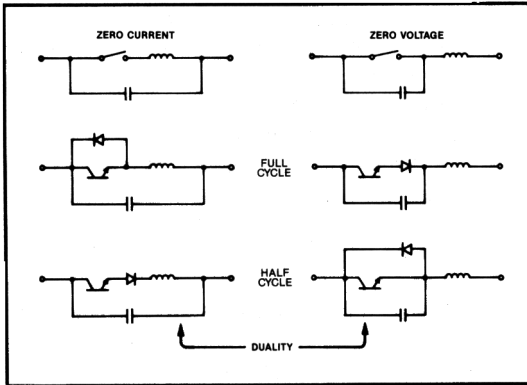


Fig. 14 - Switch Activation

should realize that this approach is merely a dual of zero current as shown in Figure 14. The choice of which approach is best is usually determined by whether the parasitic inductance of the load or the capacitance of the switch is the bigger problem. Zero voltage switching is primarily appropriate with very high frequency operation where rapid charging and discharging of the semiconductor switch capacitance could represent substantial power loss. Note from the duality of characteristics shown in Figure 15

CHARACTERISTIC	ZERO-CURRENT SWITCH	ZERO-VOLTAGE SWITCH
CONTROL	CONSTANT ON-TIME	CONSTANT OFF-TIME
SWITCH VOLTAGE WAVEFORM	≈ SQUARE	≈ SINUSOIDAL
SWITCH CURRENT WAVEFORM	≈ SINUSOIDAL	≈ SQUARE
LOAD RANGE	$R_{min} \rightarrow \infty$	$0 \rightarrow R_{max}$
SWITCH LIMITATIONS	PEAK ON CURRENT	PEAK OFF VOLTAGE

ZERO-VOLTAGE USAGE:

1. VERY HIGH FREQUENCIES WHERE SWITCH PARASITIC CAPACITANCE WOULD CAUSE EXCESSIVE POWER LOSS AT SWITCHING

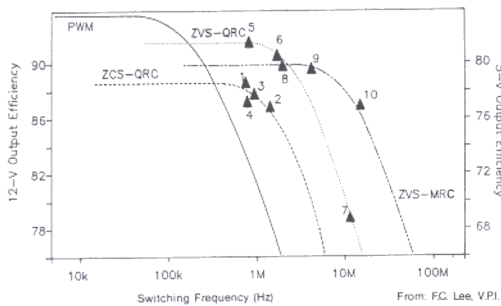


Fig. 15 - Switching Techniques Compared

that zero voltage switching, with its sine voltage waveform, would force high peak voltages on the switch and, although it loses control at light loads, is unaffected by a short circuit.

Half or Full Cycle Conduction

In a quasi-resonant circuit, energy transmission begins and ends at zero followed by a wait defined by the needs of the load. Full or half cycle conduction relates to whether each pulse will allow current to flow only from source to load, or ring in the resonant circuit allowing surplus energy to return to the source. The waveforms shown in Figure 16 describe the operation which is controlled by the placement of diodes either in series or antiparallel with the switch. Effective power supplies can be implemented with either approach but, as one would expect, there are significant differences in their characteristics.

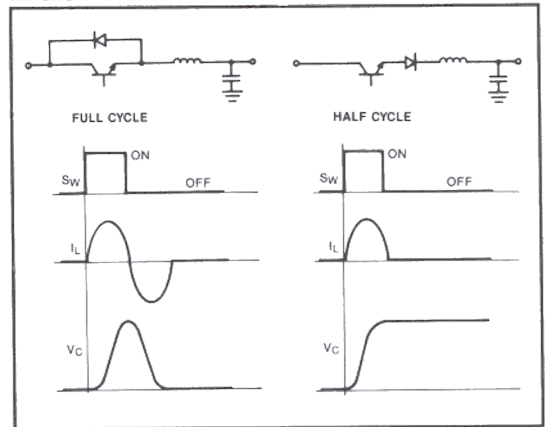


Fig. 16 - Half and Full Cycle Waveforms with Unloaded Resonant Switch

While half cycle operation may be easier to implement, the pulse repetition rate is a direct function of the loading and, when coupled with input voltage variations, can result in huge swings in switching frequency. A full cycle configuration usually requires a diode in series with the switch as well as the antiparallel diode in order to prevent any reverse conduction through the slow switch body diode. Additionally, with current flowing in both directions, conduction losses tend to be greater. The advantage is that by returning surplus energy to the source, switching frequency is independent of load.

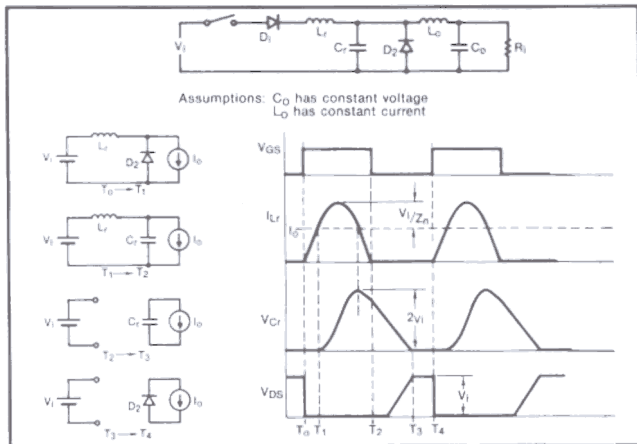


Fig. 17 - Quasi-Resonant Switching Operation

Resonant Converter Basic Operation

After having defined the various classifications of resonant mode topologies, we will now describe the detailed operation of one such circuit. This material, derived from work done by Dr. Fred Lee and the Power Electronics Group at V.P.I. is illustrated here in Figure 17. The circuit is a single-ended, buck-derived, parallel-loaded, half-cycle, zero-current switching, quasi-resonant converter. We will later extrapolate this operation to other circuit topologies.

A resonant converter, like all switching regulators, requires an output filter to smooth the power delivered to the load. This output filter must have a break frequency less than one fifth the lowest switching frequency. Therefore we assume the current through L_o and the voltage across C_o are both essentially constant at the switching frequency. The waveforms on the right of Figure 17 define the current and

voltages during the four time increments, T_0 to T_4 , which make up the total switching period. The portions of the circuit which are active during each time increment are shown on the left.

At time T_0 , the output current is all flowing through D_2 and with the activation of the switch, inductor current, I_{Lr} , starts to ramp up linearly with constant V_i across L_r .

At time T_1 , the output current transfers to L_r and the inductor current continues to rise in a sine wave to a peak defined by V_i and the resonant tank impedance. At the same time, C_r starts to charge with a cosine function to a value of $2V_i$. When the inductor current falls below I_o , C_r

begins to contribute to I_o and its voltage starts to fall.

At time T_2 , the current through L_r reaches zero and I_o can come only from C_r . With a constant I_o , the voltage on C_r falls linearly and when it reaches V_i , diode D_1 lets the voltage transfer to the open switch. Note that the switch can open at any time between this point and T_2 .

At time T_3 , the resonant tank is dry and I_o flows completely from D_2 until the next switch activation.

The same process can be used to analyze other circuit topologies remembering that a square wave circuit can be converted to a resonant circuit by merely adding a resonant switch. Figure 18 shows four such configurations.

Transformer Coupling

The introduction of a transformer into the power path does not change anything from a topology standpoint but it adds some interesting and useful features. Figure 19 shows some possible extensions of the simple buck regulator discussed above. In Fig. 19A, the resonant circuit is in the primary and the transformer provides merely an impedance match to a parallel load. This approach has the advantage that the transformer passes only load current and therefore current sensing is easily done in the primary side. Fig. 19B moves the resonating capacitor to the secondary with two benefits: the leakage inductance of the transformer is no longer

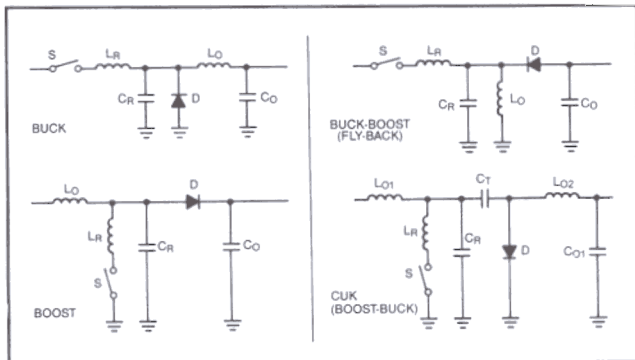


Fig. 18 - Parallel-Loaded Resonant Converter Versions of Square-Wave Power Conversion Topologies

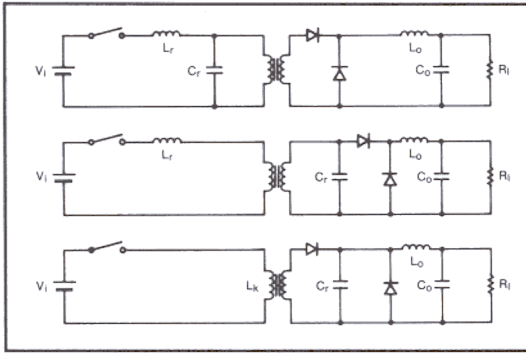


Fig. 19 - Transformer Coupling

a parasitic but adds directly to the resonating inductance, and with sine wave current flow, secondary diode switching is soft with less tendency for transient ringing.

The Vinciarelli Circuit of Fig. 19C moves the capacitor further to the other side of the rectifying diode and while transformer reset must now be accomplished by some other means, the lack of reverse current frees the primary side of the need for high-voltage, high-speed blocking diodes. In addition, the transformer now sees only the square voltage waveform from the primary switch and thus has to support less volt-seconds. The practical implementation of this circuit also builds enough leakage inductance into the transformer such that it becomes the total resonating inductance, eliminating a separate component.

Alternate Resonant Operating Modes

Without going into the same depth that was used above in the description of the single-ended, buck-derived circuit, we will now examine and compare the whole range of operating modes for both series and parallel resonant converters. For this comparison, we will use a classic half-bridge topology as shown in Figures 20 and 21. These circuits have been normalized with all waveforms drawn to the same scale and the following definitions apply:

- V_s : The switched input voltage into the resonant circuit
- I_r : The resonant current in the inductor
- V_r : The voltage on the resonating capacitor
- V_d : The voltage at the transformer secondary
- I_d : The current through each leg of the output diodes

In all cases, V_o is assumed constant and the primary diodes defining full-cycle or half-cycle operation are not shown.

The Series Resonant Converter

Figure 20A; Variable-frequency, Half-cycle, Discontinuous Mode: In this mode, current is allowed to flow in only one direction through each switch as can be seen from the I_r waveform. This power stage has a constant power output characteristic where the output power is given by $1/2 C_r V_s^2 F_s$. An increase in either the input voltage or the switching frequency will proportionately increase the power delivered to the load, irrespective of the load impedance. In the ideal case, the output voltage can rise almost infinitely and some method must be used to limit it under no load conditions. The slope of the output curve changes with the load impedance which affects the small signal gain of the power stage and makes it more difficult to include inside a feedback loop. The switching frequency is also dependent on both the input voltage and the load current and so may have a very wide switching frequency range. This circuit and its derivatives are among the most simple and least costly to produce converter circuits available but the resultant dynamic performance has been traded for this low cost.

Figure 20B; Variable-frequency, Full-cycle, Discontinuous Mode: As the I_r waveform shows, in this mode the switches carry current in both directions which gives the circuit a constant current output characteristic. The low frequency model is simply a voltage controlled current source feeding the output capacitor. The switching frequency variation in this converter mode is directly related to the output current. If a wide output current range is needed, the switching frequency range will also be wide. This will restrict the control loop bandwidth when used for a constant voltage output. This circuit is most commonly used for high voltage outputs because peak voltage on the secondary is simply equal to the output voltage. An interesting aspect of this converter is the way the resonant current waveform changes slope abruptly on each half cycle as the current crosses through zero. The output

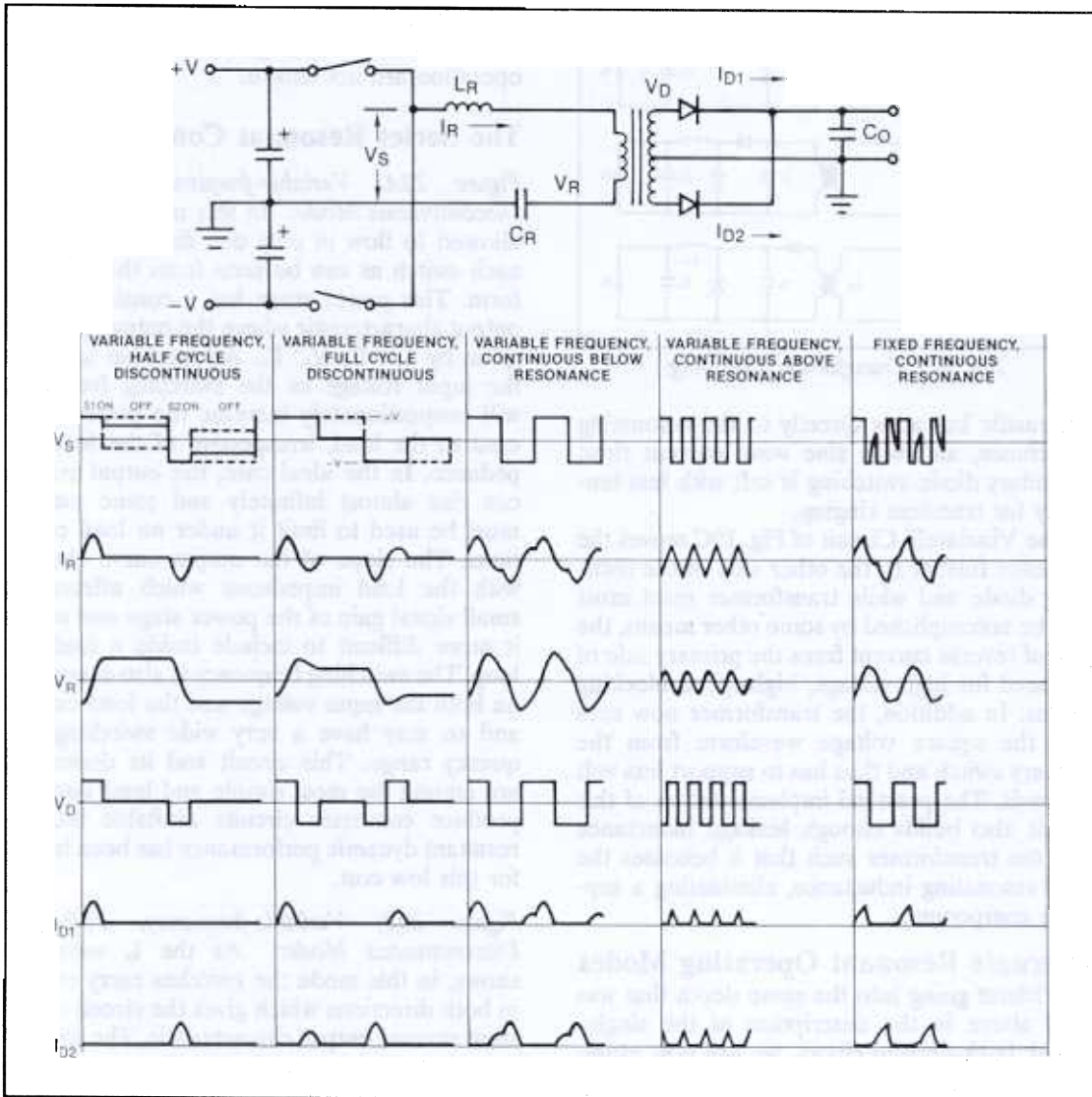


Fig. 20 - Series-Loaded, Half-Bridge Converter

voltage is reflected into the resonant circuit through the diode bridge and when the current reverses, the reflected output voltage changes sign. This lowers the effective voltage across the resonant circuit and hence the resonant current is lower. Note that although the current through the switches and diodes is sinusoidal, the voltage waveforms are square. This behavior is characteristic of all series resonant converters.

Figure 20C; Variable-frequency, Continuous, Below Resonance: Notice that in this mode the resonant voltage and current are both partial sine waves. Because the current in the inductor is continuous, each switch transition must force commutate the antiparallel diode of the opposite switch. Also, as noted before, the diode voltage is still square although the current is sinusoidal. Phase shift is occurring between the switch voltage and the resonant current. The transfer function of the power stage is nonlin-

ear since its gain is dependent on the impedance slope of the resonant circuit. This makes this circuit somewhat difficult to stabilize but reasonably wide control bandwidths can be maintained as long as the output load is able to keep the circuit in continuous resonance. If the load goes open the switching frequency will go to zero. The small signal analysis of this mode is given in Ref. [3] for both above and below resonance.

Figure 20D; Variable-frequency, Continuous, Above Resonance: As was noted in the preceding paragraph, below resonance each switch must force the opposite antiparallel diode off and carry the current which was flowing through it. Above resonance the switch turns on naturally at zero current because its antiparallel diode conducts first, but the switch must turn off with current through it. The antiparallel diode of the opposite switch will conduct immediately and is then naturally commutated by the resonant circuit in its turn. Above resonance, the resonant current resembles a sawtooth wave more than a sinusoid even though it is made up of sinusoidal sections. The capacitor voltage is the integral of the current and it more closely resembles a sine wave. The frequency range of this mode of operation is generally low and it operates on the slope of the resonant circuit impedance curve the same way it does below resonance. A required limit on minimum switching frequency allows the control loop bandwidth to be wide although the transfer function of the circuit in this mode is still very nonlinear. Also note that with a large load current variation, the switching frequency range will be wide and if the load goes to an open circuit the switching frequency will go to infinity.

Figure 20E; Fixed-frequency, Continuous, At Resonance: The waveforms in this mode are similar to the ones of variable frequency continuous resonance mode above resonance. The switch voltage is different because the resonant circuit begins to ring after the current goes to zero. This shows up as the funny looking blip in V_s which is the start of ringing. Obviously, the switching frequency does not vary with load or input voltage but the pulse width may vary over the whole range. The operation of the

circuit is similar to an amplitude modulation system. The square wave coming from the switches has a fundamental frequency and many harmonics. A change to the pulse width produces a similar change in the amplitude of the fundamental frequency component. The action of the resonant circuit eliminates the harmonics and passes a sinusoidal current at the fundamental frequency to the output where it is rectified and filtered.

The Parallel Resonant Converter

Figure 21A; Variable-frequency, Half-cycle, Discontinuous: This mode again blocks reverse current flow through the switches which is readily seen in the I_r waveform. Like the series resonant converter in this mode, the parallel resonant converter also has a constant power output characteristic which is given by the same equation: $P_o = 1/2 C_r V_s^2 F_s$. An increase in the switching frequency will produce a similar change in the power delivered to the load irrespective of the load impedance. In the ideal case the output current can become quite high under a short circuit and some means must be used to provide a maximum current limit. The constant power output characteristic makes the small signal gain of the stage dependent on both the output load and the input voltage, so it is more difficult to stabilize a feedback loop around a converter operating in this mode. The switching frequency dependency on both the input voltage and the load current results in a very wide switching frequency range if there is a large variation in the load current. A circuit with a 1 MHz resonant tank might be operating near 50 kHz at high line and light load. As was the case with series resonance, this circuit and its derivatives trade performance for simplicity and low cost.

Figure 21B; Variable-frequency, Full-cycle, Discontinuous: Full-cycle conduction provides for current flow in both directions through the switches. The resonant current in the inductor has a DC component on each half of the switching cycle which is equal to the output inductor current. This is also responsible for the small time delay on the leading edge of the resonant voltage waveform, V_r . This voltage is clamped at zero as long as the output diodes

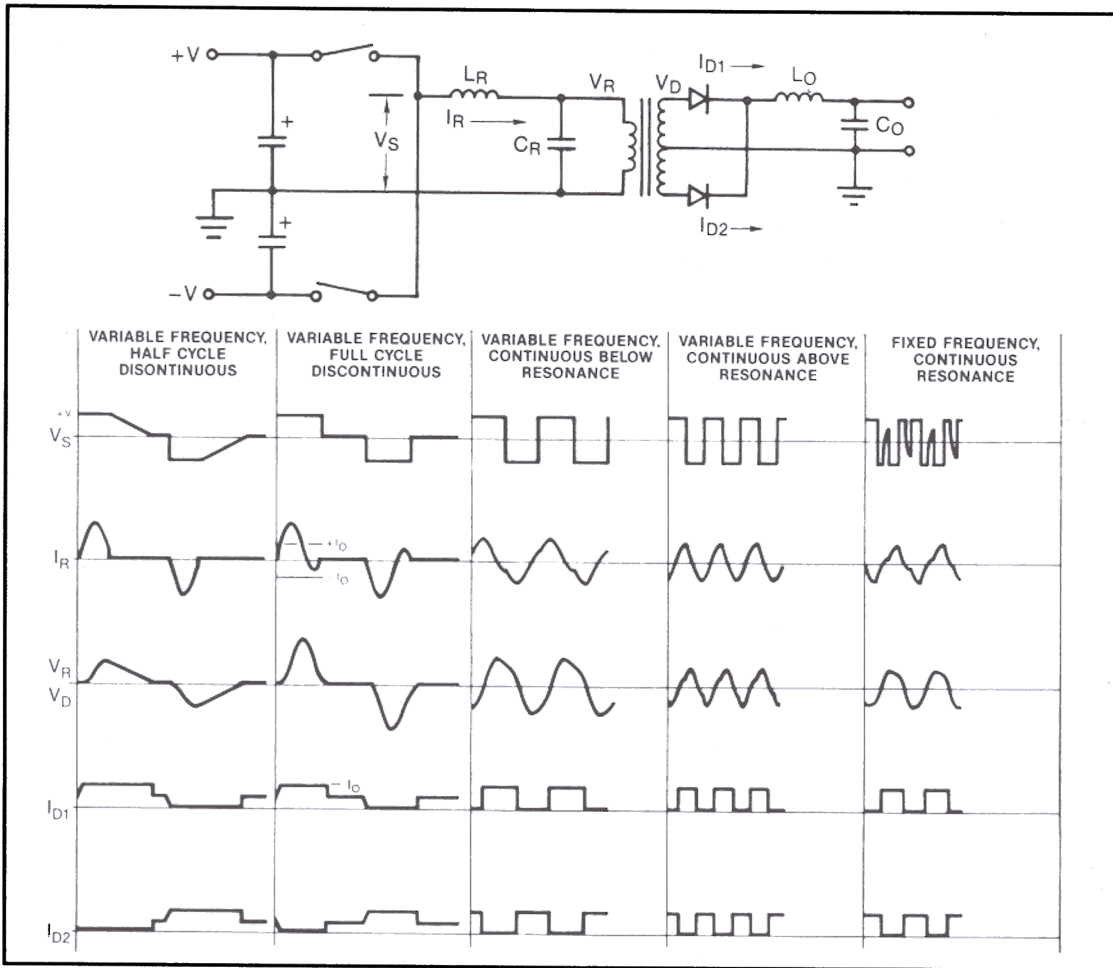


Fig. 21 - Parallel-Loaded Half-Bridge Converter

are all conducting. This is the case at the beginning of a cycle and it continues until the resonant inductor current, I_r , is equal to the output inductor current. The resonating inductor current does not have to reverse as shown here but if not, the switches must be force commutated off and the switch dissipation and EMI output go up considerably. If I_r is as shown in the figure, the switches will commutate naturally. Both switch transitions occur at zero current and it is thus true zero current switching. This mode of operation has an extremely linear transfer function and a low output impedance which makes it an excellent voltage source. Its dynamic characteristics are very similar to those of a standard PWM buck

converter. It is easy to close a voltage loop around this circuit and achieve excellent dynamic performance and wide loop bandwidth. The switching frequency is not dependent on the load current so the switching frequency range is reasonably small. This circuit is well suited to a wide variety of applications.

Figure 21C; Variable-frequency, Continuous, Below Resonance: In this mode, when each switch turns on it must force commutate the current flowing in the opposite antiparallel diode and thus has some switching loss although the switches are commutated off naturally. The output diodes see a square wave of current but a sinusoidal voltage, as expected from a single tuned converter. The transfer

function for this mode of operation is nonlinear because it is operating on the slope of the resonant circuit impedance curve and its small signal properties are similar to those of the series resonant converter. The overall switching frequency change is reasonably small as long as the circuit is operating in continuous resonance so the bandwidths may be reasonable and the circuit will have good dynamic performance. If the load current goes to zero, the current in the output inductor will become discontinuous and this will force the switching frequency toward zero.

Figure 21D; Variable-frequency, Continuous, Above Resonance: Above resonance the switches are force commutated off but turn on naturally at zero current because their anti-parallel diodes conduct first. Note that this circuit has a phase change from that observed when operating below resonance. In this mode also, the switching frequency variation will be small unless the load becomes an open circuit,

in which case the switching frequency will go to infinity. The known minimum switching frequency allows a wide control loop bandwidth to be achieved, however, the nonlinear transfer function makes it more difficult to stabilize a feedback loop.

Figure 21E; Fixed-frequency, Continuous, At Resonance: These waveforms are very similar to the continuous resonance mode above resonance. One of the switch transitions again requires that the switch be force commutated. The sawtooth section in V_s is caused by the start of ringing when the switch current goes to zero. The switching frequency of the circuit is obviously fixed but the pulse width may cover the entire range. The operating principle of this circuit is similar to amplitude modulation. The resonant circuit eliminates the harmonics and allows only the fundamental to reach the output circuit. As the pulse width of the switches

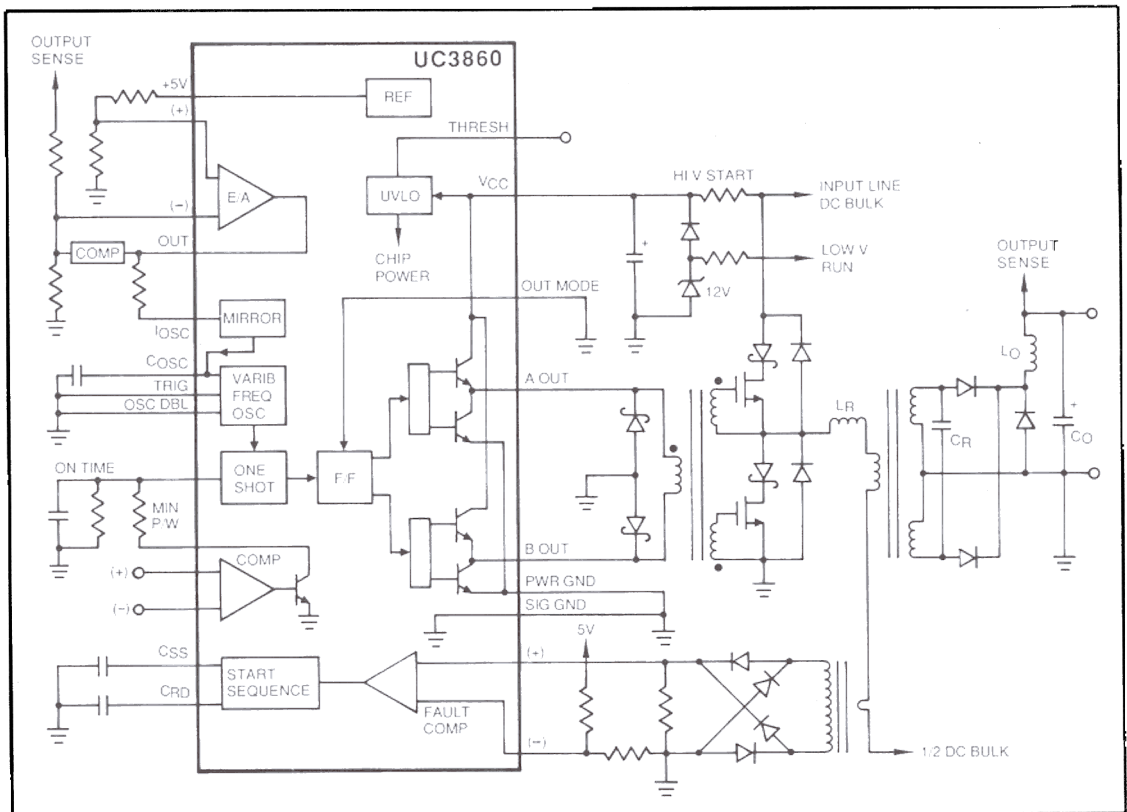


Fig. 22 - Half-Bridge Off-Line Quasi-Resonant Converter

changes, the amplitude of the fundamental component of the voltage will change correspondingly. This varies the amplitude of the fundamental voltage across the resonating capacitor and thus the output. The rectified sine waves are then averaged by the output filter.

A Practical Resonant Converter Example

To show a more complete power supply architecture, the schematic of Figure 22 combines a half-bridge resonant power stage with a new IC control chip designed by Unitrode for use in resonant mode power converters of many different topologies. This application features the parallel-loaded, half-bridge topology in a variable frequency mode. It includes full current limiting, minimum frequency limiting, and over voltage control for zero loaded conditions, as well as many other protection and programming functions needed for practical power supply operation. With the introduction of control circuits like the UC3860, the use of resonant mode power conversion techniques can be expected to rapidly advance and become the technique of choice in the next few years.

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