

[54] ZERO-CURRENT SWITCHING
QUASI-RESONANT CONVERTERS
OPERATING IN A FULL-WAVE MODE

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[51] Int. Cl.⁴ G05F 1/40

[52] U.S. Cl. 323/271; 323/235

[58] Field of Search 323/222, 235, 271, 272, 323/282-287, 319

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Assistant Examiner—Marc S. Hoff
Attorney, Agent, or Firm—Mason, Fenwick & Lawrence

[57] ABSTRACT

A family of quasi-resonant converters for providing regulated power is disclosed as comprising a voltage source, a load and a resonant switch circuit, for periodically connecting the voltage source to the load. The resonant switch circuit includes a switch, and a resonant circuit comprised of a resonant capacitor and a resonant inductor. The switch is actuated to its first state to permit a current flow in a first direction from the voltage source to the load and to block a current flow in a second, opposite direction, and deactuated to a second state to permit a current flow in the second direction from the load to the voltage source and to block the current flow in the first direction, whereby the quasi-resonant converter is operative in a full-wave mode. More specifically, the switch in its first state couples the resonant capacitor and the resonant inductor together to form a resonant switch circuit. The impedances of the resonant capacitor and the resonant inductor are selected to establish a resonating current waveform on the resonant inductor to apply zero-current conditions to the switch at turn on and turn off.

12 Claims, 82 Drawing Figures

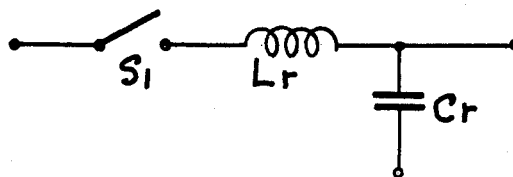


FIG-1A (PRIOR ART)

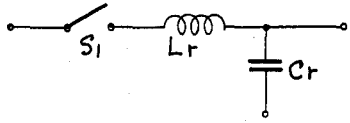


FIG-1B (PRIOR ART)

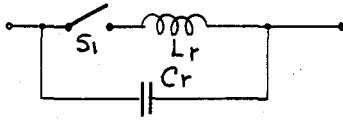


FIG-1C (PRIOR ART)

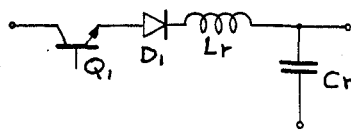


FIG-1D (PRIOR ART)

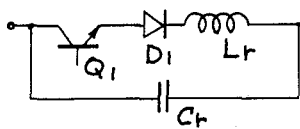


FIG-1E

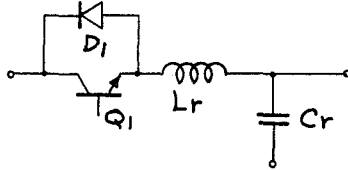


FIG-1F

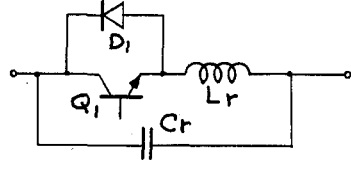


FIG-2A (PRIOR ART)

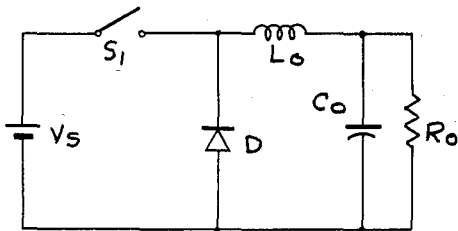


FIG-2B (PRIOR ART)

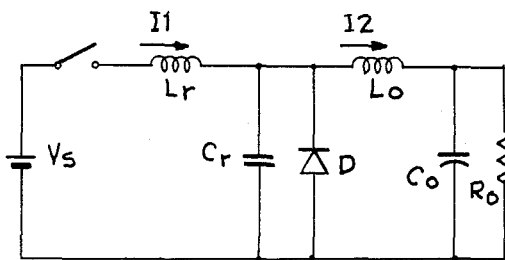


FIG-2C (PRIOR ART)

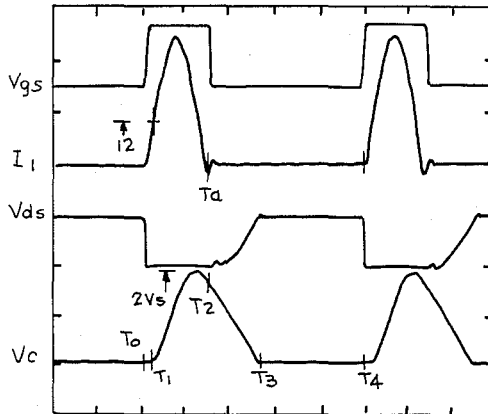
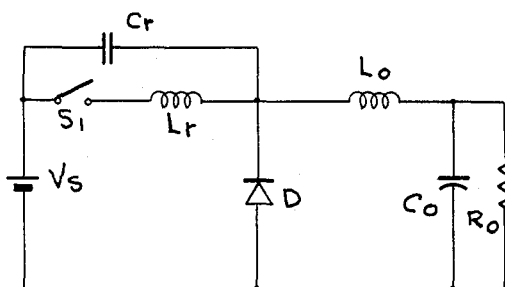


FIG-3A (PRIOR ART)

FIG-3B (PRIOR ART)

FIG-3C (PRIOR ART)

FIG-3D (PRIOR ART)

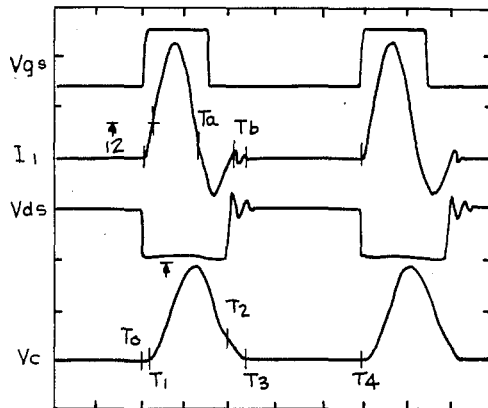


FIG-4A

FIG-4B

FIG-4C

FIG-4D

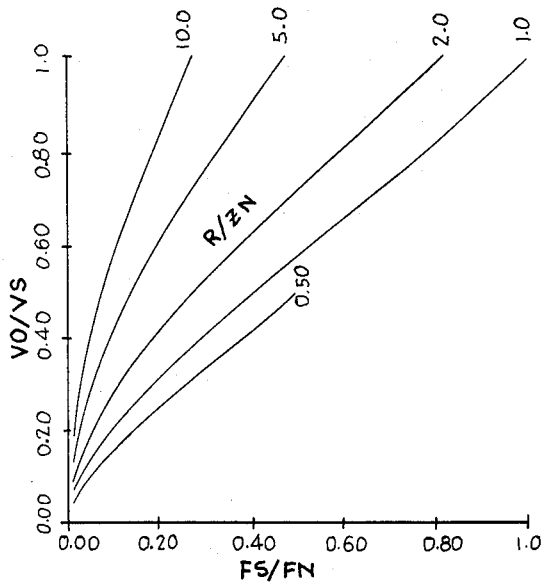


FIG-5A (PRIOR ART)

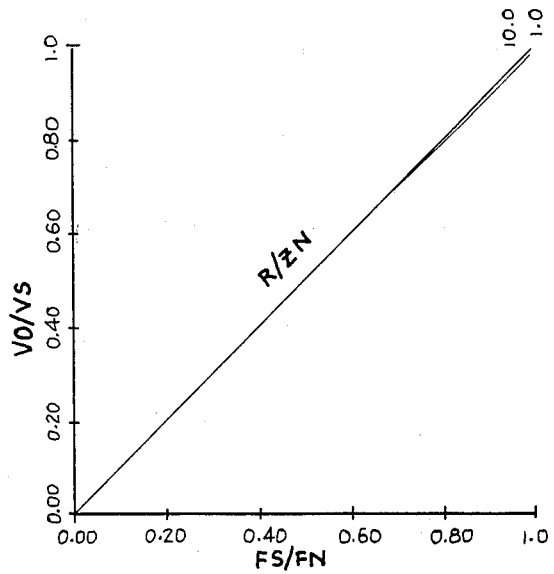


FIG-5B

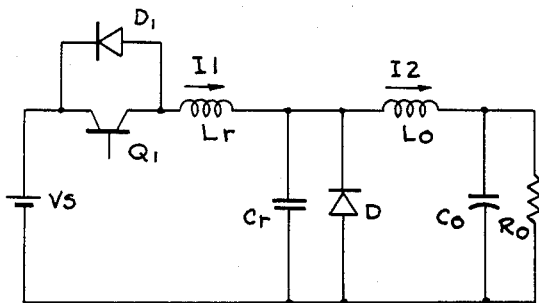


FIG-6A

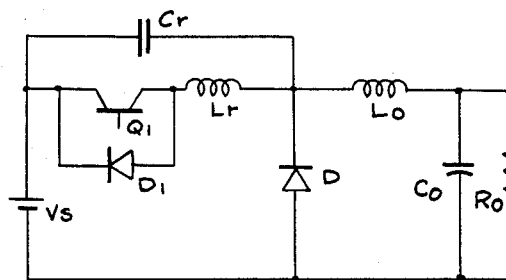


FIG-6B

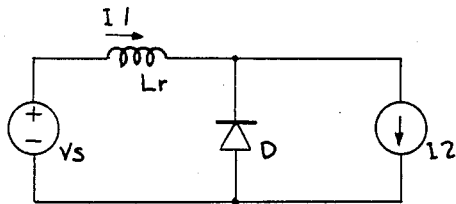


FIG-7A

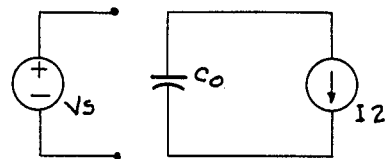


FIG-7C

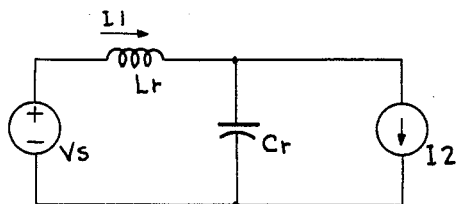


FIG-7B

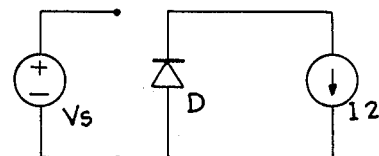


FIG-7D

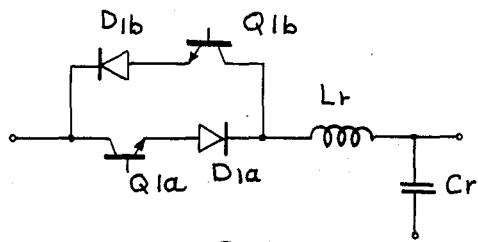


FIG-8A

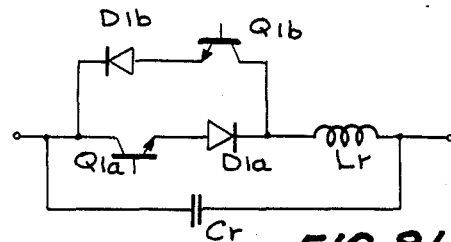


FIG-8b

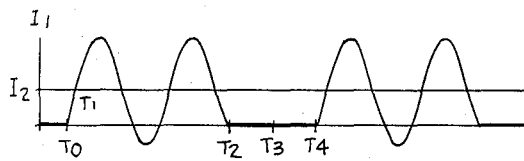


FIG-9A

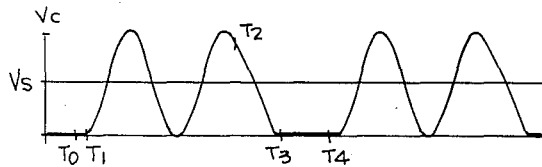


FIG-9B

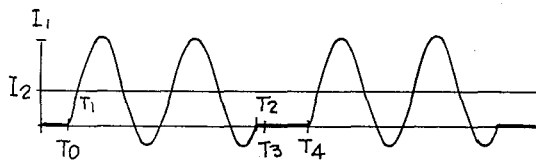


FIG-9C

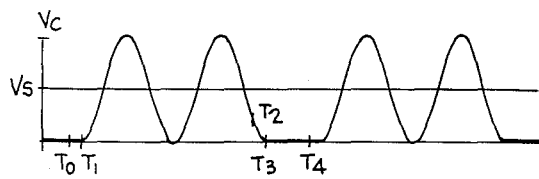


FIG-9D

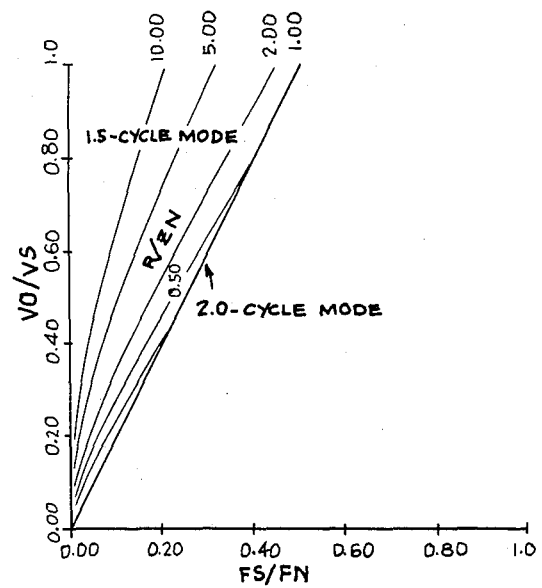


FIG-9E

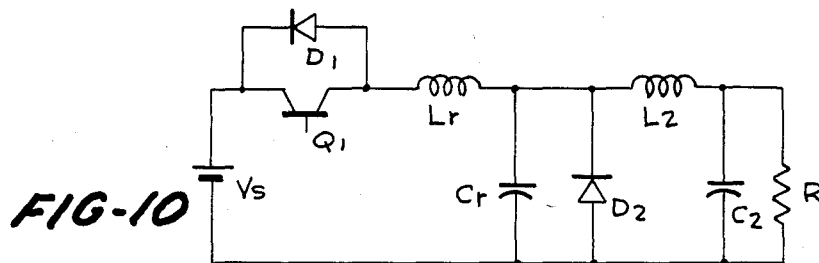


FIG-10

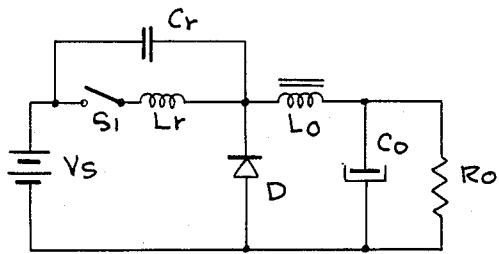


FIG-11A

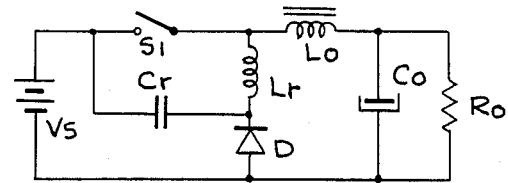


FIG-11D

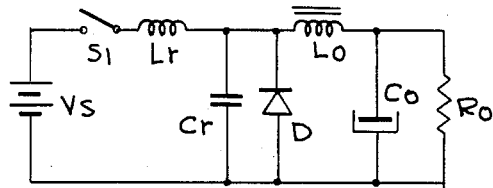


FIG-11B

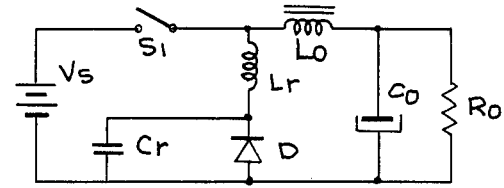


FIG-11E

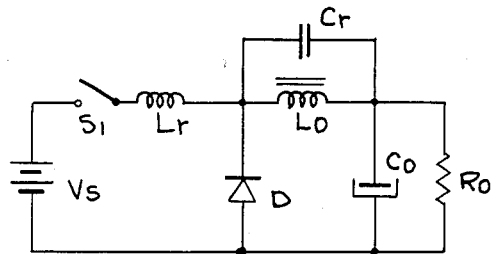


FIG-11C

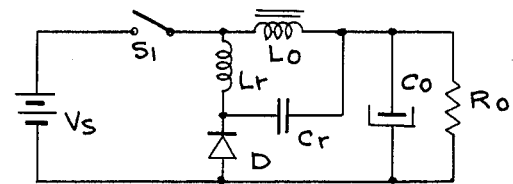


FIG-11F

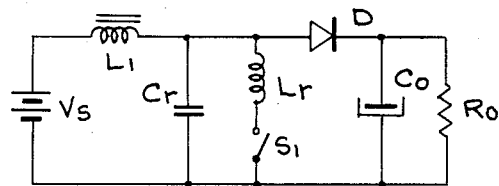


FIG-12A

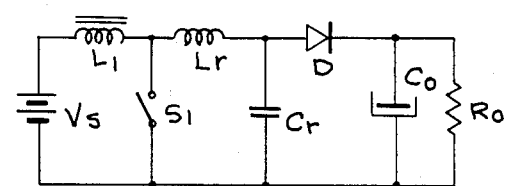


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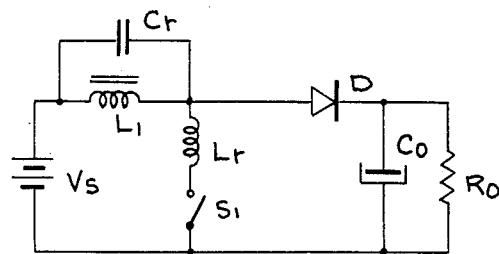


FIG-12B

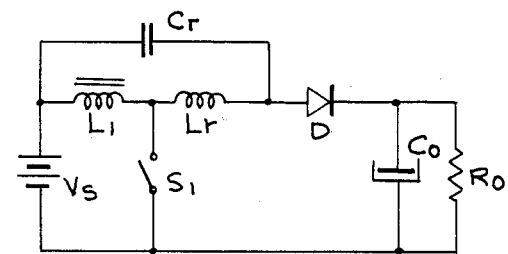


FIG-12E

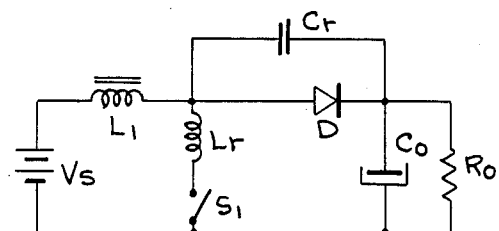


FIG-12C

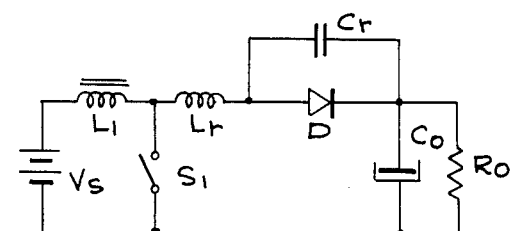


FIG-12F

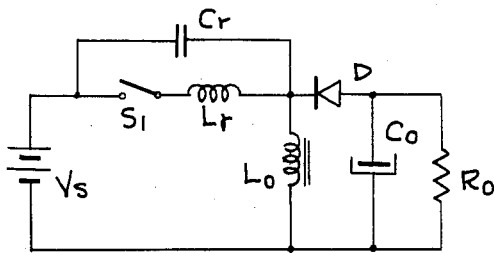


FIG-13A

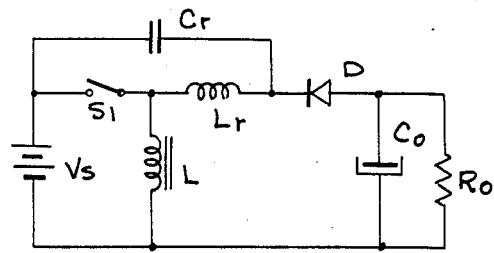


FIG-13D

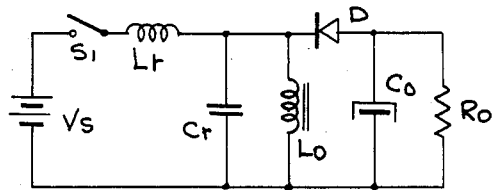


FIG-13B

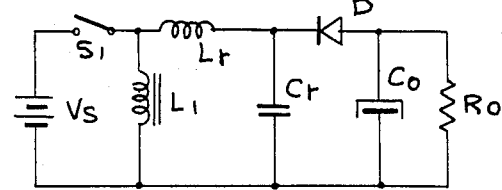


FIG-13E

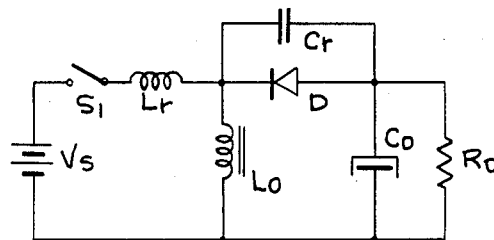


FIG-13C

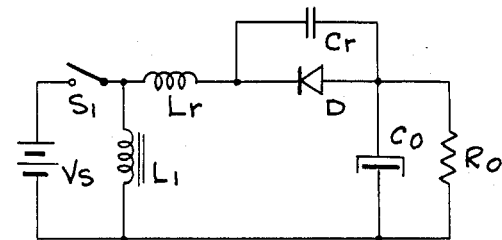


FIG-13F

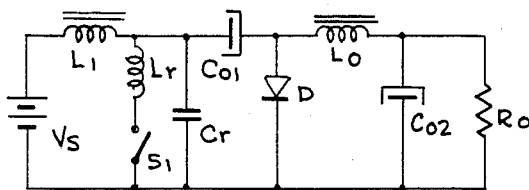


FIG-14A

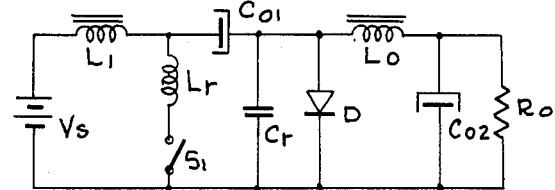


FIG-14D

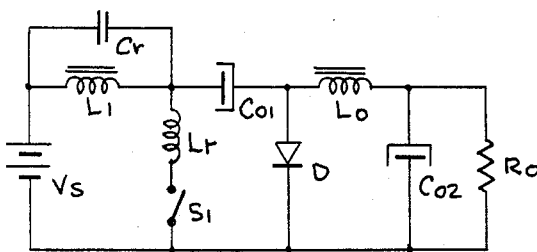


FIG-14B

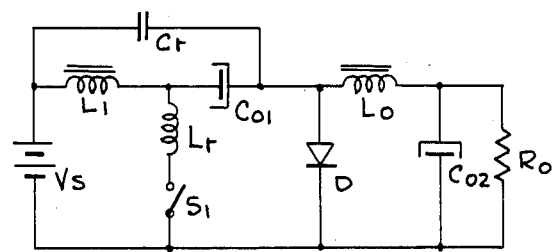


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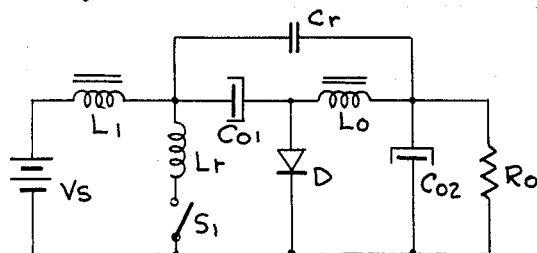


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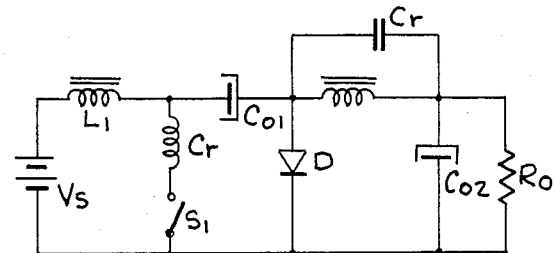


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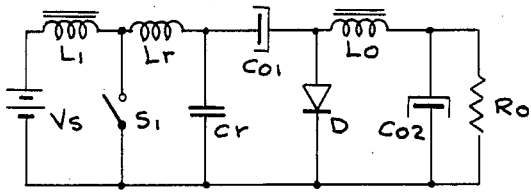


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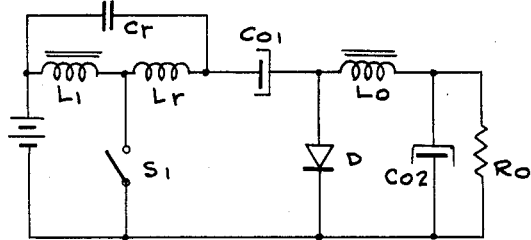


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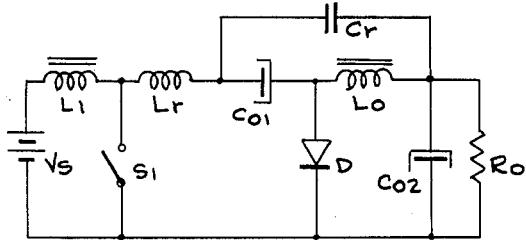


FIG-14I

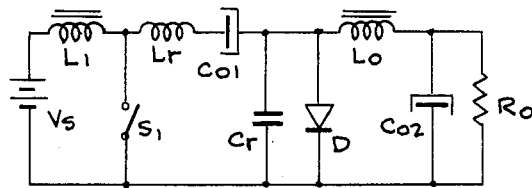


FIG-14J

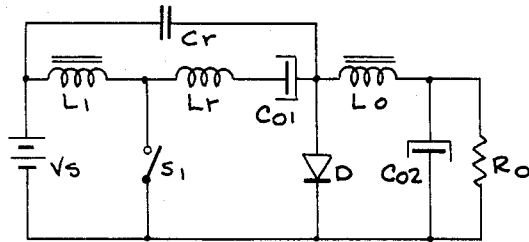


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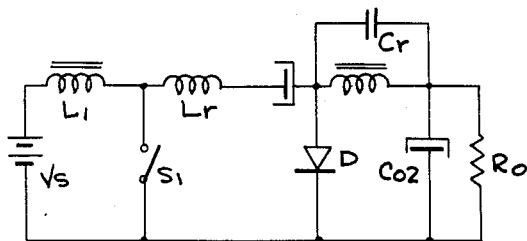


FIG-14L

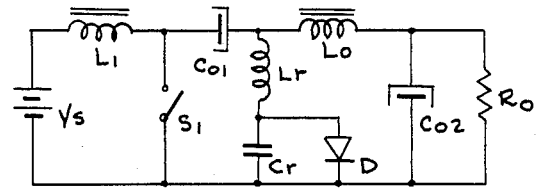


FIG-14M

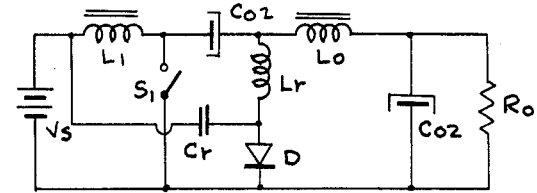


FIG-14N

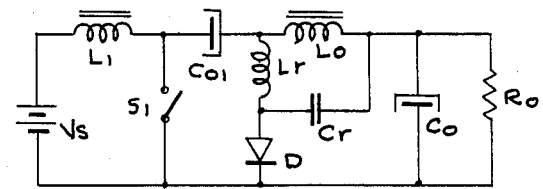


FIG-14O

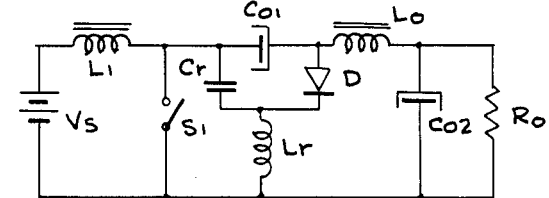


FIG-14P

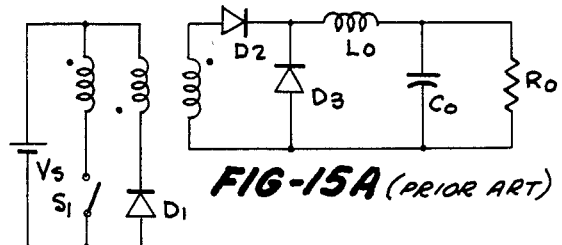


FIG-15A (PRIOR ART)

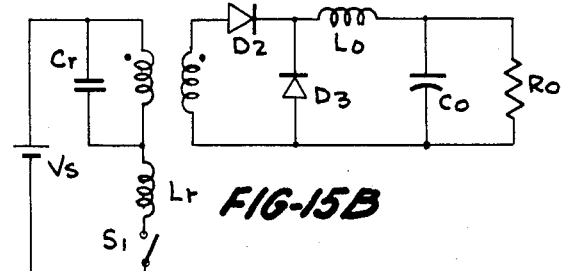


FIG-15B

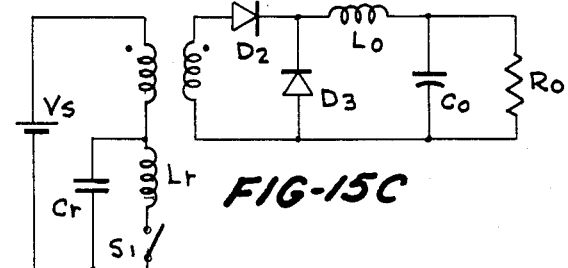
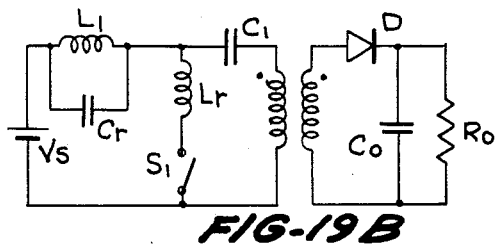
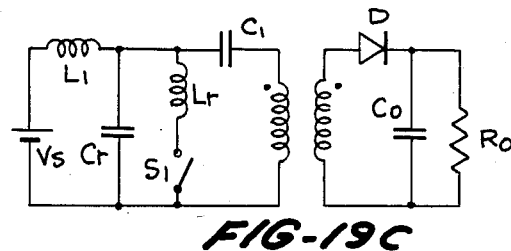
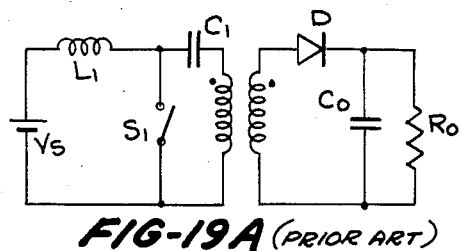
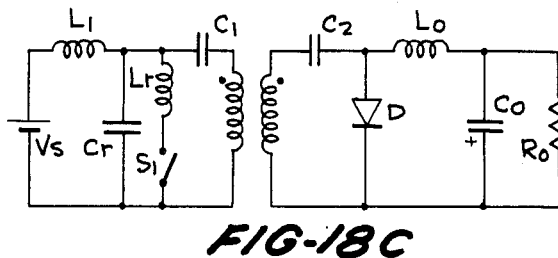
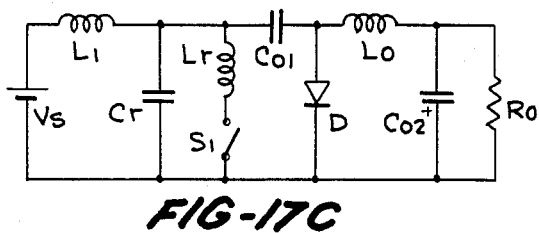
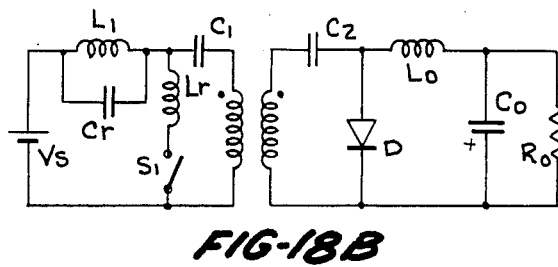
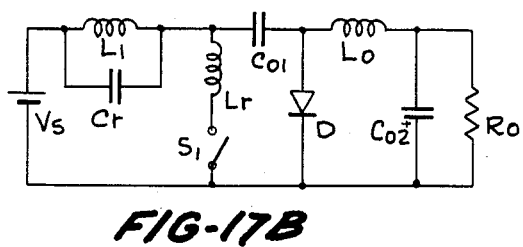
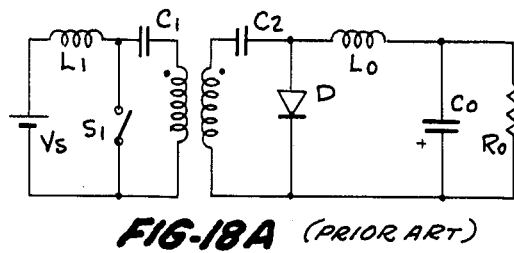
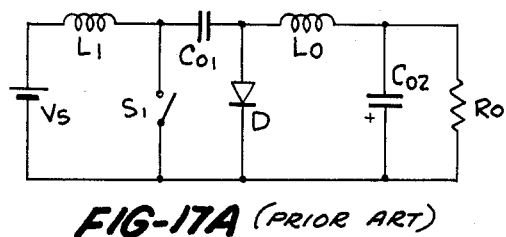
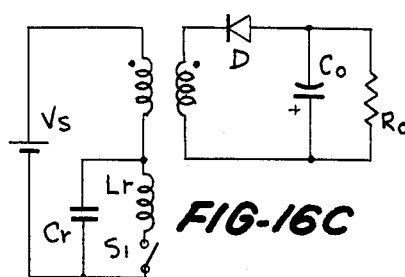
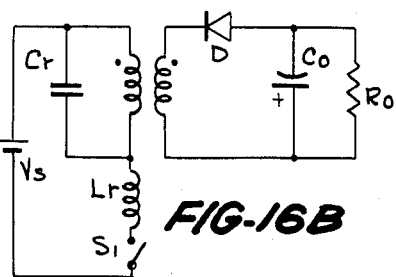
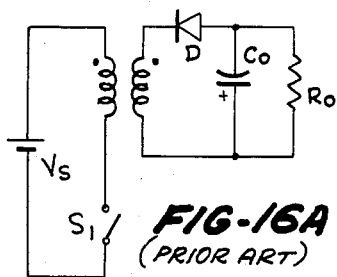


FIG-15C



ZERO-CURRENT SWITCHING QUASI-RESONANT CONVERTERS OPERATING IN A FULL-WAVE MODE

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to switching converters particularly adapted to switch at relatively high frequencies and, in particular, to such converters that achieve switching on and off at zero current level, whereby high efficiency at such high frequencies is achieved.

2. Description of the Prior Art

In conventional pulse width modulation (PWM) switching DC-to-DC converters, a switching device typically in the form of a semiconductor switch turns on and off repetitively at high current levels to achieve output voltage conversion and regulation. Such converters employ magnetic components and capacitors for energy storage/transfer and ripple/filtering. Operating such magnetic components and capacitors at high frequencies reduces their size and cost. In typical PWM converters, the inductive impedance of such magnetic components is coupled in circuit with the semiconductor switches. High frequency switching of such inductive impedances, adversely affects these switches. As the switch is turned on and off rapidly, switching transients involving high levels of current and voltage occur, whereby high switching stresses and losses are imposed upon the semiconductor switch. When such a switch is switched or "forced off", the energy still present in the coupled inductive element imposes high current and high voltage and thus high switching stress and loss on the switch. Furthermore, the pulsating current waveforms resulting from rapid switching, cause severe electromagnetic interaction (EMI) problems as the switching frequency is increased. It is desired to switch such semiconductor switches at relatively high switching frequencies to increase the effectiveness of the voltage control and regulation and, at the same time, minimize the size and cost of the inductive and capacitive elements employed in such converters. However, as the switching frequency increases, the above-noted switching stresses and losses increase and the converter's overall efficiency and reliability decrease.

Snubber circuits are commonly used to alleviate the switching stresses mentioned above. Simple RC or RDC snubber circuits suffer from high power loss at high frequencies. Lossless snubber circuits, on the other hand, increase circuit complexity considerably.

To overcome these problems of switching stress and loss, the technique of "zero current switching" has been described in "Resonant Switching Power Conversion Technique," by E. E. Buchanan and E. J. Miller, IEEE Power Electronics Specialists Conference, 1975 Record, pp. 188-193 and in "Resonant Switching Power Conversions," by E. J. Miller, IEEE Power Electronics Specialists Conferences, 1976 Record, pp. 206-211. Such "zero current switching" technique utilizes an LC resonant tank circuit to force the current through the semiconductor switch to oscillate, whereby the semiconductor switch turns off at zero current level, thereby drastically reducing switching stresses and losses.

To generalize the zero-current switching technique, the concept of resonant switch was described in "Resonant Switches—A Unified Approach to Improve Performance of Switching Converters," by the inventors of

this invention, IEEE International Telecommunications Energy Conference, 1984 Proceedings, pp. 344-351. This paper shows the use of "resonant switches" in various conventional pulse-width modulated switching converters to achieve "zero-current-switching". Generally, such resonant switches are a subcircuit consisting of a semiconductor switch S_1 , a resonance inductor L_r , and a resonance capacitor C_r . There are two types of resonant switch configurations as shown respectively in FIGS. 1A and B, an L-type and an M-type resonant switch. In both cases, the inductor L_r is connected in series with the switch S_1 to slow down the current change rate, and the capacitor C_r is added as an auxiliary energy storage/transfer element. If switch S_1 is a device without reverse voltage blocking capability or contains an internal anti-parallel diode, an additional diode D_1 is needed and should be connected in series with the switch S_1 and the inductor L_r , as shown in FIGS. 1C and 1D. The inductor L_r and the capacitor C_r together constitute a series resonant circuit with respect to the switch S_1 . When the switch S_1 conducts, current flows through switch S_1 and inductor L_r into the capacitor C_r with a quasi-sinusoidal waveform. As the inductor current drops to zero, the capacitor voltage is charged up with a polarity that reverse biases the switch S_1 , thus commutating off the switch S_1 . The resonant switch therefore, provides zero-current-switching properties during both turn on and turn off.

A conventional buck converter is illustrated in FIG. 2A, as comprising a switch S_1 for applying upon being rendered conductive a voltage source V_s across a commutation diode D . The commutation diode D is coupled to an output circuit comprised of an output inductor L_o disposed in circuit with an output capacitor C_o connected in parallel with an output resistor R_o . This conventional buck converter is modified as shown in FIG. 2B by the addition of the L-type resonant switch, as first shown in FIG. 1A, between voltage source V_s and the commutation diode D . The output inductance L_o is selected to be much larger than inductance L_r , thus making the resonant frequency of the resonant circuit comprised of capacitor C_o and the inductor L_o much smaller than that of the resonant circuit comprised of the capacitor C_r and the resonant inductor L_r . It is also assumed that inductor L_o is sufficiently large so that the current I_2 through the inductor L_o , remains relatively constant throughout a switching cycle.

The operation of the buck resonant converter employing the L-type resonance switch as shown in FIG. 2B, will now be explained with reference to the waveforms as shown in FIGS. 3A to 3D. Before time T_0 , the semiconductor switch S_1 is turned off, whereby the commutation diode D carries the output current I_o with the capacitor voltage V_c clamped at zero. In the first of four distinct switching stages, the semiconductor switch S_1 is turned on at time T_0 , whereby current I_1 flowing through the semiconductor switch S_1 and the resonant inductor L_r rises linearly as shown in the waveform of FIG. 3B. Between times T_0 and T_1 , the output current I_2 shifts gradually from the path through the commutation diode D to the path through the semiconductor switch S_1 and the resonant inductor L_r .

At time T_1 , the current I_1 becomes equal to current I_2 , whereby the commutation diode D is turned off and, as seen in FIG. 3B, the current I_1 begins to charge capacitor C_r . As seen in FIG. 3B, the flow of the current of I_1 through the resonant inductance L_r and the voltage V_c

appearing on resonant capacitor C_r is substantially sinusoidal rising to a peak and falling back to zero at time T_2 . As shown in FIG. 3D, the voltage V_C across the resonant capacitor rises to a peak of approximately $2V_s$ shortly before time T_2 , whereby a reverse voltage of $V_C - V_s$ is applied to the semiconductor switch S_1 commutating it off naturally at time T_2 . As shown in FIG. 3B, zero current is flowing in the semiconductor switch S_1 at time T_2 , when it is commutated off. As shown in FIG. 3D, the capacitor C_r discharges in the time interval from time T_2 to time T_3 . The capacitor voltage V_C drops linearly to zero at time T_3 . In the fourth stage from time T_3 to time T_4 , the output current I_2 flows through the commutation diode D and, with the switch S_1 open, the resonant capacitor C_r is clamped to zero voltage. At time T_4 , the switch S_1 turns on again, starting the next switching cycle.

FIG. 2C shows a buck resonant converter circuit in which the resonant capacitor C_r is coupled in parallel between the voltage source V_s and the resonant inductor L_r instead of in parallel with the commutation diode, whereby an M-type resonant switch, as shown first in FIG. 1B, is formed. The modified buck resonant converter of FIG. 2C operates in four stages in a manner similar to the operation of the buck resonant converter as described above with respect to FIG. 2B.

The operation of the converter circuits with the L-type and M-type resonant switches as shown in FIGS. 2B and 2C, is in the half-wave mode as shown in FIG. 3B. In other words, the current I_1 is permitted to flow through the switch S_1 in but a single direction. As will be explained below, these resonant converters as operated in the half-wave mode suffer from a draw back, namely, the DC voltage conversion ratio is sensitive to load variations.

SUMMARY OF THE INVENTION

It is an object of this invention to provide a family of new and improved resonant converters, named quasi-resonant converters, which eliminate switching stresses and losses.

It is a more particular object of this invention to provide a family of new and improved quasi-resonant converters, employing switches that turn on and off at zero current conditions.

It is a still further object of this invention to provide a family of new and improved quasi-resonant converters operating in a full-wave mode, whereby the converter's voltage conversion ratio is made substantially independent of the variations in the load imposed upon the converter.

In accordance with these and other objects of the invention, there is provided a quasi-resonant converter comprising a voltage source, a load and a resonant switch circuit, for periodically connecting the voltage source to the load. The resonant switch circuit includes a switch, and a resonant circuit comprised of a resonant capacitor and a resonant inductor. The switch is actuated to its first state to permit a current flow in a first direction from the voltage source to the load and to block a current flow in a second, opposite direction, and deactuated to a second state to permit a current flow in the second direction from the load to the voltage source and to block the current flow in the first direction, whereby the quasi-resonant converter is operative in a full-wave mode. More specifically, the switch in its first state couples the resonant capacitor and the resonant inductor together to form a resonant circuit. The im-

pedances of the resonant capacitor and the resonant inductor are selected to establish a resonating current waveform on the resonant inductor to apply zero-current conditions to the switch at turn on.

In a further aspect of this invention, the switch is periodically actuated and deactuated at a selected switching frequency F_s , and the impedances of the resonant capacitor and the resonant inductor are selected such that the resonant frequency F_n of this resonant circuit is greater than the switching frequency F_s to ensure that the current waveform imposed on the switch by the resonant inductor is at substantially zero current, when the switch is next disposed to its second or off state.

In a still further aspect of this invention, a switch or switch subcircuit as comprised of a transistor and diode coupled with each other, is incorporated within a quasi-resonant converter, to effect converter operation in a full-wave mode. In particular, the transistor and diode are coupled in anti-parallel with each other to form a parallel circuit, which is in turn connected to the resonant inductor and the resonant capacitor. Alternatively, the parallel circuit is coupled in series with the resonant inductor to form a series circuit, which is coupled in parallel with the resonant capacitor.

BRIEF DESCRIPTION OF THE DRAWINGS

A detailed description of a preferred embodiment of this invention is hereafter made with specific reference being made to the drawings in which:

FIGS. 1A-1F show respectively an L-type and an M-type resonant switch subcircuit, and an L-type and an M-type resonant switch subcircuit of half-wave configuration employing a unidirectional switch, both sets of resonant switch subcircuits being known in the prior art, and an L-type and an M-type resonant switch subcircuit of a full-wave configuration employing a composite, bidirectional switch in accordance with the teachings of this invention;

FIGS. 2A, 2B, and 2C are respectively a conventional buck converter, a buck quasi-resonant converter incorporating the L-type resonant subcircuit as shown in FIG. 1A, and a buck quasi-resonant converter incorporating the M-type resonant switch as shown in FIG. 1B, all known in the prior art;

FIGS. 3A, 3B, 3C and 3D are respectively current and voltage waveforms occurring in the course of the operation of the buck quasi-resonant converter as shown in FIG. 2B;

FIGS. 4A, 4B, 4C and 4D are respectively voltage and current waveforms occurring in the course of the operation of the buck quasi-resonant converter in the full-wave mode in accordance with this invention as shown in FIG. 6A;

FIGS. 5A and 5B show plots of the voltage conversion ratio, i.e. the ratio of the output voltage V_o to the supply voltage V_s as a function of the ratio of the switching frequency F_s to the resonant frequency F_n of the resonant subcircuit incorporated within a quasi-resonant converter, as operated in a half-wave mode and a full-wave mode, respectively;

FIGS. 6A and 6B are respectively a buck quasi-resonant converter incorporating the L-type resonant subcircuit as shown in FIG. 1E and operating in a full-wave mode, and a buck quasi-resonant converter incorporating the M-type resonant switch as shown in FIG. 1F and operating in a full-wave mode, both in accordance with the teachings of this invention;

FIGS. 7A, 7B, 7C and 7D show respectively the various switching stages of the buck quasi-resonant converter as shown in FIG. 6A;

FIGS. 8A and 8B show respectively an L-type and an M-type resonant switch employing plural unidirectional switches and capable of conducting a selected number of half-cycles during their on time;

FIGS. 9A, 9B, 9C, 9D and 9E show respectively the current and voltage waveforms of, as well as the DC voltage conversion ratio for, a buck quasi-resonant converter employing respectively the L-type and the M-type switches as shown in FIGS. 8A and 8B;

FIG. 10 is a detailed circuit diagram of a buck quasi-resonant converter as operative in the full-wave mode of operation in accordance with the teachings of this invention;

FIGS. 11A to 11F show a family of buck quasi-resonant converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect full-wave operation in accordance with the teachings of this invention;

FIGS. 12A to 12F show a family of boost quasi-resonant converters incorporating one of the resonant switch subcircuits as shown in FIGS. 1B and 1F to effect a full-wave mode of operation in accordance with the teachings of this invention;

FIGS. 13A to 13F show a family of buck-boost quasi-resonant converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect a full-wave mode of operation in accordance with the teachings of this invention;

FIGS. 14A to 14P show a family of boost-buck quasi-resonant converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect a full-wave mode of operation in accordance with the teachings of this invention;

FIG. 15A shows a forward converter in accordance with the prior art, and FIGS. 15B and 15C show a family of forward quasi-resonant converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect a full-wave mode of operation in accordance with the teachings of this invention;

FIG. 16A shows a flyback converter in accordance with the prior art, and FIGS. 16B and 16C show a family of flyback quasi-converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect a full-wave mode of operation in accordance with the teachings of this invention;

FIG. 17A shows a CUK converter in accordance with the prior art, and FIGS. 17B and 17C show a family of CUK quasi-resonant converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect a full-wave mode of operation in accordance with the teachings of invention;

FIG. 18A shows a CUK converter including a transformer in accordance with the prior art, and FIGS. 18B and 18C show a family of CUK quasi-resonant converters including a transformer and one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect a full-wave mode of operation in accordance with the teachings of this invention; and

FIG. 19A shows a SEPIC converter in accordance with the prior art, and FIGS. 19B and 19C show a family of SEPIC quasi-resonant converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F to effect a fullwave mode of operation in accordance with the teachings of this invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Referring now to the drawings and in particular to FIGS. 1E and 1F, there is shown an L-type and an M-type resonant switch subcircuit adapted, as will be explained later, to be incorporated into a family of quasi-resonant converters, whereby such converters operate in a full-wave mode. By way of comparison to the L-type and M-type resonant subcircuits of the prior art as shown respectively in FIGS. 1A and 1B, the generalized switch S_1 is replaced by a bidirectional composite switch comprised of a transistor Q_1 and a diode D_1 connected in anti-parallel relation with the transistor Q_1 , as shown in both of FIGS. 1E and 1F. In both of these subcircuits, a resonant conductor L_r is connected in series with the bidirectional composite switch to limit di/dt of the composite switch, and a resonant capacitor C_r is connected as an auxiliary energy storage/transfer element. The resonant inductor L_r and the resonant capacitor C_r constitute a resonant LC circuit whose oscillation is initiated by the turn on of the composite switch. In essence, the resonant LC circuit is used to shape the current waveform through the composite switch. The transistor Q_1 may illustratively take the form of a well known bipolar transistor or MOSFET. At the instant of turn on, the voltage V_{ce} or V_{ds} across the output of the transistor can be driven into saturation state before the current slowly rises in a quasi-sinusoidal waveform. Because of the resonance between the inductor L_r and the capacitor C_r , the current through the composite switch will oscillate, thus, allowing the composite switch to be naturally commutated.

In FIGS. 6A and 6B, there is shown a converter similar to that shown in FIGS. 2A, 2B and 2C, but modified in accordance with the teachings of this invention to include one of the bidirectional resonant switch subcircuits of FIGS. 1E and 1F to provide a buck quasi-resonant converter operative in a full-wave mode. In the case of a buck quasi-resonant converter, a voltage source V_s is selectively coupled by the bidirectional resonant switch subcircuit of either FIG. 1E or 1F across a commutation diode D. In turn, the commutation diode D is coupled to an output circuit comprised of an output inductor L_o connected in series with an output capacitor C_o , which is in turn connected in parallel with an output resistor R_o . As understood in the prior art, the output inductor L_o and the output capacitor C_o function as a filter circuit. If the impedance of the output inductor L_o is made much greater than that of the resonant inductor L_r , the output inductor L_o , the output capacitor C_o and the load resistor R_o are treated as a constant current sink to produce a current I_2 , as indicated in the equivalent circuits of FIGS. 7A, 7B, 7C and 7D. The buck quasi-resonant converter as shown in each of FIGS. 6A and 6B have the following characteristics:

$$\text{Characteristic impedance } Z_n = \sqrt{L_r/C_r}$$

$$\text{Resonant angular frequency } \omega = 1/\sqrt{L_r/C_r}$$

$$\text{Resonant frequency } F_n = \omega/2\pi$$

The buck quasi-resonant converter of FIG. 6A operates in a full-wave mode, exhibiting the voltage and current waveforms as shown in FIGS. 4A, 4B, 4C and 4D. As shown in FIGS. 4, the voltage and current waveforms occur in time such that the buck quasi-resonant converter of FIG. 6A is considered to operate in the four following switching stages: (1) a first, linear stage from times T_0 to T_1 ; (2) a second, resonant stage from times T_1 to T_2 ; (3) a third, recovering stage from times T_2 to T_3 ; and (4) a fourth, free-wheeling stage from times T_3 to T_4 . The equivalent circuit of each of these four stages is respectively shown in FIGS. 7A, 7B, 7C and 7D.

Before time T_0 , the output current I_2 is kept constant by the relatively large value of the output-filter inductor L_o , the transistor Q_1 is off, capacitor voltage V_c on the resonant capacitor C_r is zero, and the output current I_2 is free-wheeling through diode D. At time T_0 of the first or linear stage, the transistor Q_1 turns on, whereby the input current I_1 flows into the resonant inductor L_r and rises linearly between times T_0 and T_1 , as shown in FIG. 4B as reflected in the equivalent circuit of FIG. 7A, the current I_1 flows in a completed circuit through the resonant inductor L_r and the commutation diode D.

In the second or resonant stage, the diode D stops conducting at time T_1 when the input current I_1 reaches the level of the output current I_2 . The input current I_1 then starts to charge up the resonant capacitor C_r . Due to the resonant circuit formed by the resonant inductor L_r and the resonant capacitor C_r , as shown in its equivalent circuit of FIG. 7B, the input current I_1 oscillates in a quasi-sinusoidal fashion and reverses its direction after a certain time interval, as shown in FIG. 4B. The negative current flows back to the capacitor C_r through the anti-parallel diode D_1 . The transistor Q_1 remains conductive as long as the input current I_1 is positive. When the input current I_1 goes negative, the transistor Q_1 turns off at zero current, and the anti-parallel diode D_1 is rendered forward biased to conduct the negative going input current I_1 . As the transistor Q_1 is completing a resonant cycle, a packet of input energy is transferred to and stored in the resonant capacitor C_r .

After the transistor Q_1 is off at time T_2 , the third or recovering stage starts, in which capacitor C_r keeps discharging its energy into the current load until time T_3 , when its charge is depleted, as shown in FIG. 4D.

At time T_3 , the fourth or free-wheeling stage begins, wherein the commutating diode D conducts and carries the free-wheeling output current I_2 through the output-filter inductance L_o . At time T_4 , the transistor Q_1 turns on again and starts the next cycle.

Typical waveforms of the forward buck quasi-resonant converter circuit are illustrated in FIGS. 4A, 4B and 4C. The zero current switching property is evidenced by examining the current and voltage waveforms, i.e. the input current I_1 is zero when either the transistor Q_1 or the anti-parallel diode D_1 turns off and on. Also, energy is transferred to the output in a packet, whereby voltage regulation can be achieved by varying the turn-on repetition rate, i.e. the switching frequency F_s of the transistor Q_1 .

Considering now in detail full-wave mode as illustrated in FIG. 4B, the input current I_1 goes in both a negative and a positive direction, whereby it is said that the buck quasi-resonant converter, as shown in FIG. 6A, operates in a full-wave mode. By contrast, a buck converter with a resonant switch of either FIG. 1C or 1B, is said to operate in a half-wave mode. As shown in

FIG. 3B, the input current I_1 of this prior art buck converter does not go negative and there is no corresponding transfer of energy to the voltage source V_s . More specifically, if a half-wave resonant switch subcircuit as shown in FIGS. 1C or 1D is used, its switch will be naturally commutated at time T_a , when the resonating input current I_1 returns to zero, as shown in FIG. 3B. On the other hand, if a full-wave switch resonant subcircuit as shown in either of FIGS. 1E or 1F is used, the input current I_1 will continue to oscillate going through zero at time T_a into a negative voltage region as shown in FIG. 4B, and feed energy back to the voltage source V_s through the anti-parallel diode D_1 , as shown in FIG. 6A. The current through the anti-parallel diode D_1 returns to zero at time T_b as shown in FIG. 4B.

Voltage conversion ratios for the buck quasi-resonance converter are plotted in FIGS. 5A and 5B for that converter as shown in either of FIGS. 2B or 2C as operated in the half-wave mode and for that converter as shown in either of FIGS. 6A or 6B as operated in its full-wave mode, respectively.

FIG. 5A shows the output-to-input voltage conversion ratio V_o/V_s as a function of the normalized frequency, i.e. the ratio of the switching frequency F_s to the resonant frequency F_n as defined above. As R_o/Z_n , i.e. the ratio of the output resistance to the characteristic impedance, decreases from 10 to 0.5 corresponding to an increase of load, a distinct graph for each of such loads is shown as a function of the normalized frequency. Thus, the buck resonant converter of FIGS. 2B or 2C exhibits significantly different voltage conversion ratios as its load changes. By contrast, the buck quasi-resonant converter of FIGS. 6A or 6B as operating in a full-wave mode, exhibits a set of voltage conversion ratios as seen in 5B. As shown, the load on the full-wave mode, quasi-resonant converter may vary significantly, i.e. the ratio R_o/Z_n may vary from 10 to 1, without significantly changing the voltage conversion ratio. FIG. 5B suggests that the voltage regulation of the full-wave mode quasi-resonant converter of FIG. 6A or 6B, may be made dependent only upon the normalized switching frequency F_s/F_n . Noting that the resonant frequency F_n remains substantially constant once the elements of the circuit are set, the desired conversion ratio may be controlled in this embodiment by determining the switching frequency F_s .

The resonant frequency F_n is dependent as defined above upon the values of the leakage inductance L_r and the resonance capacitor C_r . The resonance frequency F_n determines the period and frequency of the oscillations of the input current I_1 , as shown in FIG. 4B. As shown in FIG. 4D, the period and frequency of the oscillation of the resonant capacitor voltage V_c is dependent upon the values of the resonant capacitor C_r and the resonant inductor L_r . When the current flows from the resonant inductor L_r to the resonant capacitor C_r , the resonant capacitor C_r is charged with an oscillating voltage as shown in FIG. 4D. As may be observed in FIGS. 4, the switching frequency F_s of the transistor Q_1 must be set lower than the frequencies of the waveforms of FIGS. 4B and 4D, to permit the input current I_1 to return to zero so that the transistor turns on and off under zero-current conditions. A further embodiment of an M-type and an L-type full-wave resonant switch is shown in FIGS. 8A and 8B, respectively. These switch subcircuits are capable of conducting multiple cycles of the input current I_1 during its on time. As seen in FIGS. 8A and 8B, the subcircuits comprise first and second

transistors Q_{1a} and Q_{1b} , each coupled respectively in series with its anti-parallel diode D_{1a} and D_{1b} . FIGS. 9A and 9B show current and voltage waveforms of a buck quasi-resonant converter similar to that shown in FIGS. 6A or 6B incorporating one of the subcircuits as shown in FIGS. 8A or 8B, as operating in a 1.5-cycle mode. Similarly, FIGS. 9C and 9D show the waveforms of a similarly modified buck quasi-resonant converter operating in a 2.0-cycle mode. Gating signals are applied to the bases of the transistors Q_{1a} and Q_{1b} so that the transistor Q_{1a} is rendered conductive when the input current I_1 is positive and to the transistor Q_{1b} when the input current I_1 is negative, as seen in FIGS. 9A and 9B. The voltage conversion ratio modes have been plotted for the multicycle operation as described above and as shown in FIG. 9E, indicating that the voltage conversion ratio of a 2.0-cycle mode are twice that of the single cycle full-wave mode.

A detailed embodiment of a buck quasi-resonant converter is shown in FIG. 10, wherein the impedances of the circuit elements and the circuit elements are selected as follows:

$L_r = 6.4 \mu\text{H}$
 $C_1 = 0.016 \mu\text{F}$
 $L_2 = 50 \mu\text{H}$
 $F_n = 500 \text{ kHz}$
 $Z_n = 2 \text{ ohm}$
 $Q_1 = \text{IRF531}$
 $D_1 = \text{IR 31DQ6}$
 $D_2 = \text{IR 31DQ6}$
 $V_s = 20 \text{ V}$

The circuit of FIG. 10 is capable of operating at 500 kHz to deliver 30 watts in its full-wave mode of operation. If the resonant inductor L_r is replaced by a short circuit, the lead inductance and the resonant capacitor C_r will form a resonant tank circuit such that the resultant buck quasi-resonant converter can operate at 5.2 MHz.

A limited number of embodiments of a zero-current quasi-resonant converter are described in detail above. However, it is understood that the principals of this invention may be applied to a large number of different types of converters, as will now be illustrated. In FIGS. 11, there is shown a family of buck quasi-resonant converters modified by including one of the subcircuits as shown in FIGS. 1E or 1F, wherein similar elements are similarly designated. FIG. 12 similarly show a family of boost quasi-resonant converters similar to prior art boost converters, but modified to include one of the resonant subcircuits as shown in FIGS. 1E or 1F, with similar elements bearing notations similar to that previously used. FIG. 13 illustrates a further family of buck-boost quasi-resonant converters, similar to the buck-boost converters of the prior art, but modified to include one of the resonant subcircuits as shown in FIGS. 1E or 1F, with similar elements bearing notations similar to that previously used. FIG. 14 show a still further family of boost-buck quasi-resonant converters resembling boost-buck converters of the prior art, yet modified to include a resonant subcircuit as shown in FIGS. 1E or 1F, with similar elements bearing notations similar to that previously used.

In FIG. 15A, there is shown a conventional forward converter, whereas FIGS. 15B and 15C show a family of forward quasi-resonant converters similar to the prior art converter as shown in FIG. 15A, but modified to include a resonant switch subcircuit as shown in FIG. 1E or 1F with similar elements bearing notations similar

to that previously used. FIG. 16A shows a conventional flyback converter in accordance with the prior art. FIGS. 16B and 16C show a family of flyback quasi-resonant converters similar to that shown in FIG. 16A, but modified to include a resonant switch subcircuit as shown in FIG. 1E or 1F with similar elements bearing notation similar to that previously used. In FIG. 17A, there is shown a conventional CUK converter as known in the prior art. FIGS. 17B and 17C show a family of CUK quasi-resonant converters including one of the resonant switch subcircuits as shown in FIGS. 1E and 1F with similar elements bearing notations similar to that previously used. FIG. 18A shows a CUK converter including a transformer as known in the prior art. FIGS. 18B and 18C show a family of CUK quasi-resonant converters as including a transformer and one of the resonant switch subcircuits as shown in FIGS. 1E and 1F, with similar elements bearing notations similar to that previously used. FIG. 19A shows a SEPIC converter as known in the prior art. FIGS. 19B and 19C show a family of SEPIC quasi-resonant converters similar to that shown in FIG. 19A, but modified to include one of the resonant switch subcircuits as shown in FIGS. 1E or 1F with similar elements bearing the notations similar to that previously used.

Thus, there has been described above a family of quasi-resonant converters using a bidirectional resonant switch subcircuit, which switches on and off under zero current conditions. The resonant switch subcircuit is used to replace a conventional semiconductor switch in a wide variety of prior art PWM converters, thus forming the quasi-resonant converter of this invention. Such a converter offers many distinct advantages including: zero switching stresses, low switching losses, self commutation, quasi-sinusoidal current waveforms, and reduced EMI levels. The quasi-resonant converter of this invention operates at high efficiency and at high switching frequencies in excess of 1 MHz, whereby the size, weight and cost of its circuit elements can be reduced, and the dynamic performance and transit response improved. The bidirectional resonant switch of this invention can be applied to a large number of conventional converters, as only partially demonstrated above, whereby these converters are capable of operating at very high frequencies. The operation of such quasi-resonant converters in their full-wave mode renders them relatively insensitive to variations of loads.

In considering this invention, it should be remembered that the present disclosure is illustrative only, and the scope of the invention and should be determined by the appended claims.

We claim:

1. A quasi-resonant converter for providing regulated power comprising:

- (a) a voltage source;
- (b) a load;
- (c) a low pass filter formed from at least an inductor and a capacitor for filtering signal applied to said load;
- (d) bidirectional resonant switch means to be periodically actuated and deactuated, said switch means including a switch, a resonant capacitor, and a resonant inductor, said switch being actuated to a first state to permit a current flow in a first direction from said voltage source to said load and to block a current flow in a second, opposite direction, and being actuated to a second state to permit

a current flow in said second direction from said load to said voltage source and to block the current flow in said first direction, for operating said quasi-resonant converter in a full-wave mode; and

(e) said switch means being actuated to its first state to couple said resonant capacitor and said resonant inductor to form a resonant circuit, and to apply a charging current from said voltage source to said resonant capacitor, said resonant capacitor and said resonant inductor having respective selected impedances to establish a resonating current waveform on said resonant inductor, said resonating current waveform being applied to actuate and deactuate said switch means under zero current conditions.

2. The quasi-resonant converter as claimed in claim 1, wherein said charging current develops a resonating voltage waveform on said resonant capacitor, and there is included means coupled to said resonant capacitor and said load for rectifying and applying said resonating voltage waveform to said load.

3. The quasi-resonant converter as claimed in claim 1, wherein said switch means comprises a semiconductor switching device actuated to its first state to permit the current flow in said first direction, and a diode coupled in parallel with said semiconductor switching device to apply the current flow in said second direction.

4. The quasi-resonant converter as claimed in claim 3, wherein said semiconductor switching device comprises a bipolar transistor.

5. The quasi-resonant converter as claimed in claim 3, wherein said semiconductor switching device comprises a FET.

6. The quasi-resonant converter as claimed in claim 5, wherein said FET comprises a parasitic body diode, said diode comprising said parasitic body diode.

7. The quasi-resonant converter as claimed in claim 1, wherein said switch means operates periodically at a switching frequency F_s , said resonant capacitor and said resonant inductor having impedance values such that the resonant frequency of such resonant circuit is greater than F_s .

8. The quasi-resonant converter as claimed in claim 1, wherein said switch comprises a first semiconductor switching device coupled in series with a first diode for conducting in said first direction to form a first series circuit, and a second semiconductor switching device connected in series with a second diode disposed to conduct current in said second direction to form a second series circuit, said second series circuit being coupled in parallel with said first series circuit.

9. The quasi-resonant converter as claimed in claim 8, wherein said resonant inductor is coupled in series with each of said first and second series circuits and is connected to said resonant capacitor.

10. The quasi-resonant converter as claimed in claim 8, wherein said resonant capacitor is coupled in parallel across said resonant inductor and said first series circuit.

11. The quasi-resonant converter as claimed in claim 9, wherein there is included means for actuating said first semiconductor switch to its first state and said second semiconductor switch to its second state, and then said first semiconductor switch to its second state and second semiconductor switch to its first state whereby said charging current is permitted to establish multiple cycles of said resonating voltages on said capacitor.

12. The quasi-resonant converter as claimed in claim 1, wherein there is included means for actuating said switch to its first state and then to its second state at a switching frequency in excess of 1 MHz.

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