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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G05F 1/10, 1/652, 1/656

A2

(11) International Publication Number: WO 98/28672

(43) International Publication Date: 2 July 1998 (02.07.98)

(21) International Application Number: PCT/US97/22825

(22) International Filing Date: 12 December 1997 (12.12.97)

(30) Priority Data:
08/764,167 13 December 1996 (13.12.96) US

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(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, GW, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
Without international search report and to be republished upon receipt of that report.

(54) Title: APPARATUS AND METHOD FOR IMPROVING THE EFFICIENT UTILIZATION OF A POWER SOURCE

(57) Abstract

A circuit for extending the operating time of a battery is provided. A power source, typically a battery or other portable voltage source, is cyclically connected into a tuned circuit that includes a load. The circuit includes a means for switching the voltage source into and out of the circuit. The switching means also provides an alternate conduction path during the time the voltage source is not connected to the circuit so that current, and hence energy, can flow through the load. In this manner, the battery is actually in use for brief intervals of time while the load receives a constant energy supply from the circuit.

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APPARATUS AND METHOD FOR IMPROVING THE EFFICIENT UTILIZATION OF A POWER SOURCE

BACKGROUND OF THE INVENTION

1. The Field of the Invention

The field of this invention relates to circuits for extending the operating time of batteries. Also, switching circuits for switched power supplies is another related area to the present invention. More particularly, the present invention relates to battery life extension circuits involving selectively switching the battery to a load through specialized circuitry.

2. Present State of the Art

Battery powered portable power supplies are prevalent and used in many different applications and in connection with a myriad of devices. Typically, such power supplies have a finite amount of power associated therewith due to their portable nature. A common example would be the types and varieties of batteries found in all sorts of consumer electronics, notebook computers, and even automobiles to name just a few applications.

A number of trade offs are associated with battery power and other forms of portable power supplies. An important trade off to balance is the energy capacity of a power supply versus its size and weight. Usually, a higher capacity power supply will be larger and heavier than a lower capacity power supply. The added bulk and weight can be a significant disadvantage for the portable applications that such power supplies find their most beneficial use.

A prime example is the area of notebook computers, which commonly derive their power from a rechargeable battery, such as a nickel-cadmium, nickel-hydride or similar battery, when a source of line power is not available. Such notebook computers are carried by businessmen between office and home or office and client site and can be used during travel on a commercial aircraft. With a portable computer, as is generally true with all portable, battery operated electronic devices, the consumer desires the longest possible battery life (sometimes referred to herein as the "operating time" of a battery) in order to maximize the length of time the computer or other device can be used. In other applications, wherein nonrechargeable batteries are used to provide power, the longest possible battery life is a similarly important, so as to obtain the longest service from a battery before it has to be replaced.

Consequently, much research and effort has been expended to maximize the effective service life or operating time of batteries. Heretofore, such efforts have been directed generally in a three principle areas. First, major advances have been achieved by attempting to optimize the chemical compositions of the batteries themselves so as to develop batteries with a greater energy density or storage capacity and, thus, a longer effective battery life. The resulting developments and technology have continually increased the energy storage capacity of batteries so that more energy can be stored within a particular size and weight battery. However, all of these efforts are directed at developing a better battery design and do not provide a circuit that utilizes more efficiently energy derived from a battery source thereby increasing the operating time of a given battery.

Another approach to increasing battery life has been to reduce the overall power consumption of a particular device so as to minimize the power demands placed on the battery and thereby improve and extend the period of time that the device is able to operate on battery power. For example, notebook computers commonly include power management circuitry that turns off computer display, hard drive motors, etc., when the computer has been inactive for a pre-determined period of time, circuitry to reduce power to the microprocessor and other circuitry when inactive for a certain amount of time, display blanking circuitry for computer inactivity, development of semiconductor devices that require very little power to operate effectively, etc. However, this type of approach also introduces significant inconveniences to the user. Furthermore, many of the solutions in this area are specific to the particular battery operated device and are not readily transferred from one device to the next.

Similar, numerous electronic circuits have been developed to manage, conserve and prolong the energy stored in a given battery. For example, U.S. Patent No. 4,023,068 to *Harvey* discloses a battery life extending circuitry for a photo-flash wherein a monitor circuit couples the battery to a charging circuit when the charge on the firing capacitor is below a predetermined level and, conversely, decouples the battery from the charging circuit when the charge on the firing capacitor is above a predetermined level. U.S. Patent No. 5,101,335 to *Ludden et al* discloses a DC-to-DC converter which is operated using coupled inductor current sensing and a predetermined ON time so that optimum performance of a low level voltage DC power source and the converter is achieved. The circuit includes a switching means for selectively interrupting the current flow through the primary winding of the inductor. The circuit also includes means for sensing the current in the secondary winding of the inductor and reactivating the switching means whenever the current in the secondary winding falls below a predetermined level. U.S. Patent No. 4,130,780 to *Ban et al* discloses selective connection and disconnection of the battery from the load through the use of an electro-mechanical switching means which disconnects the battery from the charging circuit after a predetermined time interval. U.S. Patent No. 5,528,087 to *Sibata et al* discloses a power supply for hand-held electronic devices with volatile memory, which combines a battery, diode and charge capacitor. While the device is on, the battery charges the capacitor. When the device is turned off, the supply voltage stored in the capacitor is compared with a reference voltage and the battery is automatically coupled to the boosting circuit for a predetermined time whenever the supply voltage stored in the capacitor drops below the reference voltage. U.S. Patent No. 4,237,897 to *Beane et al* discloses a battery life extender circuit for use in an implantable tissue stimulator, which supplies a substantially constant voltage to volatile memory for a longer period of time by gradually reducing the amplitude of output pulses from the output circuit. U.S. Patent No. 5,387,820 to *Imagawa* discloses a power management circuit which compares a battery voltage with a reference voltage and automatically switches the power sources to a battery or a step up circuit output when the battery voltage is higher or lower, respectively, than the reference voltage.

What is needed is a relatively simple and inexpensive circuit that will significantly improve the utilization of any battery as it applies to a given system load, regardless of type or chemistry of the battery, and that is readily adaptable to provide the voltages and power consumption requirements of a wide variety of applications.

SUMMARY OF THE INVENTION

In accordance with the invention as embodied and broadly described herein, apparatus and methods for extending the life of a power source are provided. More specifically, the invention combines a tuned RLC circuit with multiple high side switching circuitry to selectively connect and disconnect the battery from the load at precise intervals so as to utilize the energy stored in the circuit components to sustain the current during the period when the battery is removed from the circuit. The tuned circuit has a capacitor and an inductor in series with the load to be powered by the power supply. The circuit has a resonant frequency f_0 and thus a cycle period T_0, which is determined by the particular values of the capacitor and inductor. Furthermore, a switchable isolation path is provided to complete the circuit when the power supply is switched out of the circuit to keep current flowing to the load in an uninterrupted manner. Switching of the isolation path and the power supply into the energy extension circuit is accomplished through high speed switching devices.

In accordance with the present invention, the battery is connected to the load during the first portion of each half cycle between time t_0 and time t_1 and is disconnected from the load each half cycle between time t_1 and time $T_0/2$. At time t_0, the capacitor is charged to a pre-defined reference voltage. Between time t_0 and time t_1, the capacitor voltage aids the battery voltage in the circuit. When the battery is disconnected from the circuit between time t_1 and time $T_0/2$, the charge stored on the capacitor continues to provide a voltage to the circuit and the inductor tries to sustain the current. In other words, during the time the battery is disconnected and isolated from the circuit, energy stored in the components of the tuned circuit is extracted and delivered to the load. If the relative timing is properly maintained, the energy delivered to the load between time t_1 and time $T_0/2$ is greater than the energy delivered to the load between time t_0 and time t_1. During each half cycle, the circuit receives a "boost" when the stored energy is at its maximum so that a relatively small amount of energy from the battery is required to provide the momentum necessary to maintain the current through each half cycle. At the end of each half cycle, the switching circuit then reverses the polarity of the battery, which in turn reverses the charge on the capacitor, and the process is repeated. By repeating this operation during steady state operation of the circuit, the tuned circuit produces a near sinusoidally shaped AC output current, which effectively passes an amount of energy to the load that is equal to several times the amount of energy drawn from the battery. In this manner, the present invention extends the life of a power source by connecting a battery or other power supply to the tuned circuit, and thus the load, for only a fraction of the total cycle time of the circuit that transmits the energy to the load. The battery or power supply is only depleted part of the time while the tuned circuit maintains a constant or appropriate energy transfer to the load itself.

Energy is initially placed into the circuit by pre-charging the capacitor using conventional circuitry known in the art and continues reciprocating between the capacitor and inductor while the battery or other power source is disconnected. During this time, the load constantly receives the power necessary for proper operation.

The battery adds energy to the tuned circuit in short time intervals, and that energy is dissipated through the load in a more efficient manner thereby extending battery life. In a sense, the battery aids or boosts the energy in the circuit to compensate for energy dissipated in the load and gains an efficiency of transfer through the circuit so that less energy is required from the battery itself to power the same level of load.

The present invention also effectively functions as a digital power converter, converting the supply voltage from a DC voltage input to an AC output voltage. The AC output can then be used directed to power a given load or, if DC voltage is required, can be passed through a rectifier bridge and related circuitry before being applied to the load.

These and other objects and features of the present invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the manner in which the above-recited and other advantages and objects of the invention are obtained, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments thereof which are illustrated in the appended drawings. Understanding that these drawing depict only typical embodiments of the invention and are not therefore to be considered to be limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

Figure 1 is a functional block diagram, graphically illustrating the present invention and showing a battery, a tuned circuit, a circuit for pre-charging the capacitor in the tuned circuit, logic circuitry for operating the switches of the tuned circuit, and the load that will draw or dissipate energy from the battery through the tuned circuit;

Figure 2 is circuit diagram, modeling the tuned circuit, the battery, and the load in more detail;

Figures 3A to 3D are circuit diagrams of the circuit illustrated in Figure 2, showing the operation of the tuned circuit with the various conductive paths, which are shown in bold, that are presented during operation of the present invention;

Figures 4A-4D are circuit diagrams that model the equivalent circuits corresponding to Figures 3A-3D, respectively, and which show the direction of current flow and the polarity of the capacitor voltage across the capacitor;

Figure 5 is a set of graphs illustrating the voltage across the capacitor, the current through the load, the battery voltage as contributed to the tuned circuit, and the switch statuses for each of the six switches (all of the foregoing relationships being expressed in terms of the period of the resonant frequency of the tuned circuit);

Figure 6 is a circuit diagram of a simplified model of the tuned circuit;

Figure 7 provides graphs of the current through the load and voltage across the capacitor during one-half cycle of operation of the present invention;

Figure 8 is a graph showing the current through the load during one complete cycle of operation of the present invention; and

Figure 9 is a detailed circuit diagram of one presently preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Figure 1, the circuit of the present invention 10 consists generally of a tuned circuit 12, a battery 14, a load 16, a logic circuit 18, and a pre-charging circuit 20. As graphically depicted in Figure 1, battery 14 provides power to all of the other modules of the present invention. The present invention is readily adaptable to be used with any type of conventional battery or voltage source currently available and, as discussed in more detail below, will significantly extend the effective life or operating time of the battery 14. As used herein, the term "operating time" as it relates to a battery shall mean the amount of time that a given battery provides power to a given load between the time the battery is in a fully charged condition and the time the battery is fully discharged. The tuned circuit has a capacitor and an inductor in series with the load to be powered by the voltage source. Furthermore, a switchable isolation path is provided to complete the circuit when the voltage source is switched out of the circuit to keep current flowing to the load in an uninterrupted manner. Switching of the isolation path and the voltage source into the tuned circuit is accomplished through high speed switching devices.

As will be discussed in more detail below the tuned circuit 12 consists of a capacitor C_1, an inductor L_1 and a resistor R_1 (which may comprise or include load 16). The tuned circuit also includes six switches S1-S6 interposed between the various circuit elements, which operate under the control of logic circuit 18, to reconfigure the conduction path of the circuit at predetermined time intervals during operation of the circuit and to selectively connect and disconnect battery 14 from the load 16 at precise intervals so as to utilize the energy stored in the circuit components to sustain the current during the period when battery 14 is removed from the circuit.

In accordance with the present invention, battery 14 is connected to the load 16 during the first portion of each half cycle between time t_0 and t_1 and is disconnected from the load 16 each half cycle between time t_1 and $T_0/2$. Prior to initial operation, pre-charging circuit 20 is used to charge capacitor C_1 to a pre-defined initial voltage. Between time t_0 and t_1, the voltage across capacitor C_1 aids the voltage V_B of battery 14 in the circuit. At that point, the tuned circuit will have energy stored therein in capacitor C_1 and inductor L_1 as represented by the standard energy equations:

$$E_{L1} = \tfrac{1}{2}L_1 i^2$$

and

$$E_{C1} = \tfrac{1}{2}C_1 V^2$$

When battery 14 is disconnected from the circuit between time t_1 and $T_0/2$, the charge stored on capacitor C_1 continues to provide a voltage to the circuit and inductor L_1 tries to sustain the current. If the relative timing is properly maintained, the energy delivered to the load 16 between time t_1 and $T_0/2$ is actually greater than the energy delivered to the load between time t_0 and t_1. During each half cycle, the circuit receives a "boost" when the stored energy is at its maximum so that a relatively small amount of energy from battery 14 is required to provide the momentum necessary to maintain the current through each half cycle.

At the end of each half cycle, switching circuit 18 then reverses the polarity of battery 14, which in turn reverses the charge on capacitor C_1, and the process is repeated. In this manner, the present invention extends the life of a power source by connecting a battery 14 or other voltage source to the circuit for only a fraction of the total cycle time of the circuit that transmits the energy to the load 16. Thus, battery 16 or other voltage source is only depleted part of the time while the tuned circuit maintains a constant or appropriate energy transfer to the load itself. In this manner, the battery adds energy to the circuit 12 in short time intervals that is dissipated through the load in a more efficient manner, thereby extending battery life. In a sense, the battery aids or boosts the energy in the circuit to compensate for energy dissipated in the load and gains an efficiency of transfer through the circuit so that less energy is required from the battery itself to power the same level of load. In another sense, the present invention functions as a digital power converter, converting the DC voltage supplied by battery 14 to an AC output. The AC output can then be used to power a given load 16 or, if DC voltage is required, can be passed through a rectifier circuit and related circuitry before being applied to the load 16.

The operational components of the circuit 10 will now be described in general terms with reference to Figure 2, which illustrates a simplified circuit model consisting of the tuned circuit 12, the battery 14 and the load 16. Although load 16 is represented by a resistor R_1, depicting a fully resistive load, the load 16 may be of any type and may have other components rather than being purely resistive. A resistive load is shown for simplicity in explaining the operation of the circuit and for being representative of a common load element. Electrically coupled in series with resistor R_1 are capacitor C_1 and inductor L_1. A pair of diodes D_1 and D_2 are connected in parallel with the series connection of resistor R_1, capacitor C_1, and inductor L_1. A first pair of switches S1 and S2 are coupled in parallel between the positive terminal of battery 14 and the passive components of the circuit as illustrated in Figure 2. Similarly, a second pair of switches are coupled in parallel between the negative terminal of battery 14 and the passive components of the circuit. Finally, a third pair of switches S5 and S6 are provided, with switch S5 being coupled in series with diode D_1, and switch S6 being coupled in series with diode D_2. As will be discussed in more detail below, switches S1-S6 and diodes D_1 and D_2 operate in conjunction to provide alternate conduction paths to complete the circuit to allow current to flow through the circuit, and hence through the load 16, at all times during the operation of the circuit. The timing at which switches S1-S6 open and close during operation of the circuit is controlled by logic circuit 18.

Switches S1-S6 can be constructed using standard semiconductors, such as IGFETs or MOSFETs, as well as more rugged componentry, such as SCRs, depending on the requirements and characteristics of the particular implementation. Inherent in all switching are switching times, including rise time, fall time, and delay time. The faster such switching times can be made, the more efficient the operation of the present invention. Switches S1-S6 are represented more conveniently in the form shown in Figure 2 rather than as discreet electronic components and it will be understood by those skilled in the art that the particular construction of the switches is not particularly significant as long as they operate and function as described herein. In effect, switches S1-S4 form a switching matrix situated in series between tuned circuit 12 and battery 14. As will be discussed in more detail below, the switching matrix formed by switches S1-S4 alternately connects battery 14 in series with tuned circuit 12 for a predetermined portion of each half-cycle and disconnects and isolates battery 14 from tuned circuit 12 during the remainder of each half-cycle. In addition, the switching matrix formed by switches S1-S4 reverse the polarity of battery 14 relative to tuned circuit 12 during each successive half-cycle. In addition, switch S5 and diode D1, and switch S6 and diode D2, form a pair of switched shunts that are connected in parallel with tuned circuit 12. As will be discussed in more detail below, these shunts are used to provide alternate conduction paths for the tuned circuit for those portions of each half cycle during which battery 14 is disconnected and isolated from tuned circuit 12.

The general operation of the present invention will now be described with reference to Figures 3-5. However, before the circuit can be placed in steady state operation, it is necessary to charge capacitor C_1 to an initial pre-determined voltage V_{C0}. This is accomplished by connecting leads O and O' to the output of pre-charging circuit 20 (the details of which will be disclosed in detail below) until the voltage across capacitor C_1 reaches V_{C0}. This pre-charging of capacitor C_1, which occurs while the circuit is disconnected from battery 14 and before placing the circuit into operation, primes the circuit with a certain amount of energy that will be maintained through conservation of momentum by selectively coupling battery 14 to the circuit at discreet time intervals throughout steady state operation of the circuit. Battery 14 provides energy to the circuit as energy is dissipated through the load. Once pre-charging of capacitor C_1 is complete, the circuit is ready to be placed in operation.

Reference is now made to Figures 3-5. Figures 3A-3D illustrate and highlight the circuit appearance and associated conduction paths as switches S1-S6 are opened and closed at various times under the direction of logic circuit 18. Figures 4A-4D illustrate the equivalent circuits corresponding to Figures 3A-3D, respectively. Figure 5 provides a timing diagram, graphically illustrating (beginning from the top to the bottom of Figure 5) the relationship between: the voltage across capacitor C_1 (Figure 5A); the current through the load 16 (Figure 5B); the voltage contributed to the circuit by battery 14 (Figure 5C); the opening and closing of switches S1 and S3 (Figure 5D); the opening and closing of switches S2 and S4 (Figure 5E); the opening and closing of switch S5 (Figure 5F); and the opening and closing of switch S6 (Figure 5G), as a function of time.

Once capacitor C_1 is pre-charged, the circuit is switched on by closing switches S1 and S3 from time t_0 to time t_1. Closing switches S1 and S3 forms the circuit shown in bold in Figure 3A and the equivalent circuit as shown in Figure 4A. In this circuit configuration, battery 14 is connected in series with capacitor C_1 aids in supplying a voltage V_B having the same polarity as the voltage across capacitor C_1. This results in a current I_R flowing through the circuit along the conduction path shown in bold in Figure 3A. As current begins to flow through the circuit, capacitor C_1 begins to discharge such that the voltage across capacitor C_1 begins to drop. The voltage V_C across capacitor C1 and the current I_R through resistor are graphically represented in Figures 5A and 5B, respectively. As shown in Figures 5A and 5B, the current I_R lags behind the voltage V_C by ninety degrees. Switch S6 is also closed with switches S1 and S3 between times t_0 and t_1, but does not provide a conductive path due to the diode D_2.

At time t_1, switches S1 and S3 are placed in the open position by logic circuit 18, thereby forming the circuit as shown in Figure 3B and the equivalent circuit of Figure 4B. This internal closed and isolated circuit remains in place from time t_1 to time $T_0/2$. In this configuration, the battery is isolated from, and provides no power to, the circuit. However, capacitor C_1 continues to discharge, providing additional power to the circuit. In addition, inductor L_1 attempts to maintain the current in the circuit. As a result of the combination of the action of capacitor C_1 and inductor L_1, the current I_R continues to build and flow through the circuit in the same direction, as shown by arrow 60 in Figure 3B, without the aid of battery 14. As a result of the inductor L_1 attempting to sustain the current I_R through the circuit, the polarity of the voltage across capacitor C_1 reverses as the current I_R peaks at time $T_0/4$, which is graphically illustrated in Figure 5A. Between times $T_0/4$ and $T_0/2$, capacitor C_1 begins recharging, and the voltage V_C across capacitor C_1 begins to build, but this time with the opposite polarity, and the current I_R begins to decline. This continues until the voltage across capacitor C_1 reaches its maximum negative value and the current I_R is reduced to zero at time $T_0/2$.

At time $T_0/2$, logic circuit 18 causes switch S6 to open and causes switches S2, S4, and S5 to close, resulting in the circuit path as shown in bold in Figure 3C with equivalent circuit model shown in Figure 4C. The circuit remains in this configuration from time $T_0/2$ until time t_2. With switches S2 and S4 closed, battery 14 is once again coupled to, and supplies power to, the circuit and again aids capacitor C_1 which is now in a different polarity (negative). Although switch S5 is also closed, no current flows through that circuit path due to diode D_1 and, consequently, it has no appreciable effect on the circuit between time $T_0/2$ and time t_2.

With the circuit in this configuration, the operation and interaction of the various components is exactly the same as described above between time t_0 and t_1 except that all of the polarities are exactly the opposite. Specifically, battery 14 is connected in series with capacitor C_1 and aids in supplying a voltage V_B having the same polarity as the voltage across capacitor C_1. This results in a current I_R flowing through the circuit along the conduction path shown in bold in Figure 3C. As current begins to flow through the circuit, capacitor C_1 begins to discharge such that the voltage across capacitor C_1 begins to drop. The voltage V_C across capacitor C_1 and the current I_R through resistor are graphically represented in Figures 5A and 5B, respectively. As shown in Figures 5A and 5B, the current I_R lags behind the voltage V_C by ninety degrees.

At time t_2, logic circuit 18 opens switches S2 and S4, while switch S5 remains closed. Battery 14 is again isolated from the circuit while an internal circuit is completed as illustrated in Figure 3D, with a pair of equivalent circuit models illustrated in Figure 4D. The circuit remains in this configuration between time t_2 and time T. Here, again, the operation of the circuit, as well as the interaction of the various circuit components, in this configuration is exactly the same as that described above between time t_1 and time $T_0/2$, exactly that the polarity is exactly opposite. Specifically, the battery is again isolated from, and provides no power to, the circuit. However, capacitor C_1 continues to discharge, providing additional power to the circuit. In addition, inductor L_1 attempts to maintain the current in the circuit. As a result of the combination of and the interaction between capacitor C_1 and inductor L_1, the current I_R continues to build and flow through the circuit in the same direction, as shown by arrow 60 in Figure 3B, without the aid of battery 14. As a result of the inductor L_1 attempting to sustain the current I_R through the circuit, the polarity of the voltage across capacitor C_1 again reverses, this time from negative to positive, as the current I_R reaches its maximum negative value at time $3T_0/4$, which is graphically illustrated in graph A of Figure 5. Between time $3T_0/4$ and time T_0, capacitor C_1 begins recharging, and the voltage V_C across capacitor C_1 begins to build, but this time with the opposite polarity, and the current I_R begins to decline. This continues until the voltage across capacitor C_1 reaches its maximum positive value and the current I_R is returns to zero at time T_0, completing one complete cycle.

The cycle repeats itself and maintains the energy initially placed into the tuned circuit on the pre-charged capacitor and provides a current flow through the load R_1. Those skilled in the art will readily appreciate that the present invention essentially functions as a digital power converter, converting the DC power supplied by battery 14 into an AC voltage source. It should also be apparent that, while not specifically shown in the drawing, the resulting AC power output could readily be passed through a bridge rectifier and related circuitry before being applied to a DC load.

In the presently preferred embodiment of the invention, the time interval between time t_1 and time t_0 is equal to $T_0/8$. Similarly, in the presently preferred embodiment of the invention, the time interval between time $T_0/2$ and time t_2 is equal to $T_0/8$.

As alluded to above, the operation of switches S1-S6 is controlled and coordinated by logic circuit 18. Logic circuit 18 can be implemented in any number of ways well within the knowledge of those skilled in the art and, therefore, will not be discussed in detail. Suffice it to say that standard logic components may be used to create four control outputs, one each to control switches S1 and S3, S2 and S4, S5, and S6, respectively, by generating control pulses having the shape and timing illustrated in Figures 5D through 5G.

The circuit described above can be readily and easily adapted for use in a variety of different applications. The actual values of the components of tuned circuit 12 must be selected, however, based on the particular requirements of each application. To select specific values of the components of the tuned circuit, first assume a circuit generalized by the schematic illustrated in Figure 6. Next, require that capacitor C_1 is initially charged to an initial static voltage of V_{C0} volts and switch K is at position A, or open circuit. The switch K then goes to position B, so that battery V_B is connected. The initial polarity of the voltage across capacitor C_1 is such to aid the battery V_B, so that a clockwise current i(t) may flow throughout one-half cycle, relating to the damped frequency of oscillation, f_0, of L_1, C_1 and R_1.

The values of L_1 and C_1 should be chosen such that their resonant frequency f is such that the corresponding period T_0, which is equal to $1/f_0$, is sufficiently long that the switching times (including rise, fall and decay) of switches S1-S6 are insignificant compared to the period T_0. For a given period T_0, the values of L_1 and C_1 can be determined. First, a convenient value of capacitor C_1 is selected. Capacitor C_1 is preferably a nonpolarized, very low loss type capacitor, such as a polypropylene capacitor. The value of inductor L_1 can then be determined from the following relationship:

$$L_1 \cong \frac{1}{(2\pi f_0)^2 C_1}$$

Next a Q value for inductor L_1 is selected. The Q value should preferably be sufficiently low to provide a relatively wide operating range of load resistance values, yet should at least be greater than 0.5. The Q value of an inductor is defined to be the ratio of the amount of energy stored in the system to the amount of energy lost (to the load resistance). Q is also equal to $1/2\zeta$, where ζ is the damping ratio, and $\zeta = R_1/2\ (\sqrt{C_1/L_1})$. From this relationship R_1 can be determined, as $R_1 = 2\zeta/(\sqrt{C_1/L_1})$ ohms, which is the proper value of resistance to be seen by the resonant system of resistor R_1, inductor L_1, and capacitor C_1. Also, resistor R_1 must be such that the system is underdamped, as demanded by the value of Q to be greater than 0.5.

Assuming a power P to be required by, and dissipated in, the load resistance R_1 for a particular application, the energy E associated with each half-period is equal to E = P (T/2), which represents the energy, expressed in Joules, that will be passed to the load R_1 during each half cycle. Since the capacitor C_1 has an initial condition of charge equal to V_{C0} and since the energy E stored per half period in the capacitor C_1 will be equal to $\frac{1}{2}C_1V_C^2$ joules, then the value of V_{C0} can be determined from the following relationship:

$$Q = \pi \frac{(\frac{1}{2}C_1V_C^2)}{P \cdot (T/2)}, \quad So\ V_C = \frac{\sqrt{PTQ}}{C_1}\ volts.$$

Referring to Figure 1, and solving for the variable I(t), it can be shown that through a LaPlace Transform process $I(s) = (V_B/s + V_C/s)/(R_1 + 1/C_1s + L_1s)$, and the inverse LaPlace Transform will yield i(t) in the form of $Ae^{-\gamma t}\sin(2\pi f_0 t)$. This will be the series circulating current for the first quarter of the half period, and V_C will be 90° out of phase, or a cosine function, with respect to I_R. Then the battery voltage V_B will be disconnected, so for the duration of the half period, I(s) will equal $(V_C/s)/(R_1 + 1/C_1s + L_1s)$, where V_C will continue with the initial condition of voltage, namely that value V_{C0} at the instant of the disconnection of the battery voltage, as depicted in Figure 7. The capacitor voltage will reverse polarity at approximately $T_0/4$ and will be opposite in magnitude at $T_0/2$, relative to its value at initiation.

Thus, at $T_0/2$, the battery V_B is again connected in the opposite direction, so that the battery, along with V_C aiding, can repeat the process just described.

The stored energy $\frac{1}{2} C_1 V_C^2$ is transported through the series connected to load R_1 to the inductor L_1, which develops a stored energy value $\frac{1}{2} L_1 I^2$.

The energy dissipated in R_1 is equal to $I^2 R_1 t$. Because the Law of Conservation of Momentum applies in this case, the total energy stored (or that from momentum) in three quarters of each half cycle (*e.g.*, between $T_0/8$ and $T_0/2$, and between $5T_0/8$ and T_0) is available to be directed through the load R_1, which is in series, and intercepting the current i(t). The battery voltage V_B is applied, having sufficient energy to keep the system in equilibrium, without decay.

By taking the integral of ${}_0\int^{\pi} P\,dt$ where P is power, in this case I^2R, it is possible to derive the value of energy that is normally or otherwise stored in the reactances and that contributed by the battery, V_B. The energy relationships can be depicted as illustrated in Figure 8. The energy ratio can be determined, per half cycle, according to the following formula:

$$G = \frac{R_1[{}_0\int^{\pi} i(t)dt]^2}{R_1[{}_0\int^{\pi/4} i(t)dt]^2} = \frac{[{}_0\int^{\pi} i(t)dt]^2}{[{}_0\int^{\pi/4} i(t)dt]^2}$$

As used herein, the term "energy ratio" means the total amount of energy delivered to the load (the energy contributed by the battery plus the energy extracted from the other circuit components) in comparison to the amount of energy contributed by the battery alone.

Starting from the plot of i(t) over one half period, the mean value of current (assuming a peak of amplitude of 1) is first determined. Thus, the normalized mean value is determined from the following formula:

$$i = \frac{\int_0^{\pi} \sin\theta \; d\theta}{\pi} = 0.637$$

Similarly, the mean value of current of this same sine wave over the range of 0 to $\pi/4$ (the time that the battery is connected) is determined from the following equation:

$$i = \frac{\int_0^{\pi/4} \sin\theta \; d\theta}{\pi/4} = 0.373$$

Thus, the energy ratio is then given by

$$G = \frac{[i]^2 R \cdot \pi}{[i_B]^2 R \cdot (\pi/4)} = \frac{(0.637)^2}{(0.373)^2}(4) = 11.67$$

The ratio value above assumes a pure sine wave and no other losses (such as switching). The wave, in fact, is modified slightly by an exponential coefficient $e^{\alpha t}$. Through empirical and experimental tests, it has been determined through numerical integration that the actual gain ratios on the order of 6 to 1 through the use of the present invention. Thus, the present invention can extend the effective operating time of battery 14 by up to six times.

Based on the foregoing principles, further details of the present invention will now be discussed in relation to the circuit illustrated in Figure 9, which is one particular implementation of the presently preferred embodiment of the present invention. It should be understood, however, that the circuit shown in Figure 9 and discussed below is provided merely by way of a representative example of one particular implementation of the present invention and should not be construed as limiting the scope of the present invention.

Following the methodology for implementing a circuit for a specific application in accordance with the present invention, the circuit illustrated in Figure 9 is based on a power requirement of 25 watts and a full cycle period T_0 equal to 1 millisecond. The major functional components of circuit 10 are identified with dashed blocks, which correspond to the functional blocks contained in the block diagram illustrated in Figure 1. Thus, circuit 10 consists primarily of tuned circuit 12, battery 14, load 16, logic circuit 18, and pre-charging circuit 20. Circuit 10 also has an operational amplifier U_1 and associated components R_2 and C_2. Operational amplifier U_1 is configured, and the values of R_2 and C_2 are selected, so that operational amplifier U_1 outputs a square wave having a frequency equal to 4 times the resonant frequency f_0 of tuned circuit 12. In this particular embodiment, R_2 is preferably 1 kΩ and C_2 is preferably 0.001 μF. The output of operational amplifier U_1 is coupled to, and provides an input signal to both logic circuit 18 and pre-charging circuit 20. Logic circuit 18 and pre-charging circuit 20 are actually coupled to the output of operational amplifier U_1 through switch S7, which, in this particular implementation, is a manual multiple pole, double throw switch. With switch S7 in the position illustrated in Figure 9 (the lower position), the output of operational amplifier U_1 is applied as an input signal to logic circuit 20. With switch S7 in the intermediate position, the output of operational amplifier U_1 is applied to the input of pre-charging circuit 20 and, at the same time, the output of pre-charging circuit 20 is coupled to capacitor C_1 of tuned circuit 12 so as to pre-charge capacitor C_1 to an initial voltage V_{CO} prior to initial steady state operation of circuit 10. With switch S7 in the upper position, the entire circuit 10 is disabled.

Logic circuit 18 coordinates and controls the operation of switches S1-S6 of tuned circuit 12. Logic circuit 18 provides four outputs, graphically represented at connectors W, X, Y and Z, which are coupled to switches S1 and S3, S2 and S4, S5, and S6, respectively. More specifically, logic circuit 18 converts the input signal received from operational amplifier U_1 into: a first output W, which has a waveform of that illustrated in Figure 5D and which is coupled to and controls the operation of switches S1 and S3; a second output X, which has a waveform of that illustrated in Figure 5E and which is coupled to and controls the operation of switches S2 and S4; a third output Y, which has a waveform of that illustrated in Figure 5F and which is coupled to and controls the operation of switch S5; and a fourth output Z, which has a waveform of that illustrated in Figure 5G and which is coupled to and controls the operation of switch S6. In this example, IRF-740 were selected for use as switches S1-S6. However, as previously mentioned, switches S1-S6 can be constructed using any standard semiconductors, such as IGFETs or MOSFETs, as well as more rugged componentry, such as SCRs, depending on the requirements and characteristics of the particular implementation. Inherent in all switching are switching times, including rise time, fall time, and delay time. The faster such switching times can be made, the more efficient the operation of the present invention.

Pre-charging circuit 20 is made up of a transistor Q_1, a transformer T_1, rectifier bridge RB_1, resistors R_4, R_5 and R_6, and diode D_3. For this particular implementation, the component values used in pre-charging circuit 20 are preferably as follows: Q_1 is an NPN type transistor, transformer T_1 is a 10:1 transformer, rectifier bridge RB_1 is 2 amp standard type rectifier bridge, resistor R_3 is 10kΩ, resistor R_4 is 300Ω, R_5 is 480 kΩ, and R_6 is 2.2 kΩ, and D_3 is a fast recovery type rectifier, such as MUR160. When switch S7 is positioned in the middle position, the output of operational amplifier U_1 is coupled through resistor R_3 to the base of, and drives transistor Q_1. Placement of switch S7 in the middle position also couples one side of resistor R_4 to battery 14, which supplies a voltage V_B to pre-charging circuit 20, and also couples the output of pre-charging circuit O and O' to opposite sides of capacitor C_1.

Whenever the output of operational amplifier U_1 is at a high asserted level, this causes transistor Q_1 to turn on, allowing current to flow through resistor R_4, the primary of transformer T_1, and through transistor Q_1. The current flowing through the primary of transformer T_1, in turn, induces a current in the secondary of transformer T_1, which then flows through rectifier bridge RB_1, resistor R_6 and capacitor C_1, thereby charging capacitor C_1. Once the voltage across capacitor C_1 reaches V_{C0}, switch S7 is moved to the lower position, thereby enabling logic control circuit 18 and, at the same time, isolating pre-charging circuit 20 from the remainder of circuit 10.

Tuned circuit 12 consists of the load 16, which in this case as modeled as resistor R_1, capacitor C_1, inductor L_1, switches S1-S6, diodes D_1 and D_2. Capacitors C_3 and C_4 are also provided to filter out transients, and rectifiers D_4 and D_5 are used to couple tuned circuit 12 to battery supply 14. Resistor R_7, diode D_6 and capacitor C_4 are also provided to isolate tuned circuit 12 from pre-charging circuit 20. In this particular implementation of the present invention, capacitors C_3 and C_4 are preferably 0.01 μF and 0.1 μF, respectively, rectifiers D_4 and D_5 are preferably fast recovery type rectifiers, such as MUR160, resistor R_7 is preferably 82 Ω, and diode D_6 is preferably a fast recovery type rectifier, such as MUR160.

As disclosed above, the values of resistor R_1, capacitor C_1 and inductor L_1 depend on the requirements of the particular application. In this particular implementation of the present invention, the following selections were made: the power requirements were assumed not to exceed 25 watts, the full cycle period was selected to be equal to 1 millisecond, and a convenient value of 3 μF was selected for capacitor C_1. From this the values of resistor R_1 and inductor L_1 can be calculated in the manner described above, which results in a value for resistor R_1 equal to 10.58 Ω and a value for inductor L_1 of 8.4 mH with a Q value of 5.

The circuit operates generally in the manner previously described. Switches S1-S6 are coupled to, and their operation is controlled and coordinated by, logic circuit 18 through control lines W-Z. During steady state operation, battery 14 delivers power to the circuit and the load only for one-fourth of each half-cycle; the power for the circuit, including the load, being derived for the remainder of each half-cycle from the energy stored in capacitor C_1 and inductor L_1. In this manner, the present invention reduces the power drawn from battery 14 by a factor of approximately 6, thereby extending the effective life or operating time of battery 14. In addition, circuit 10 converts the DC input from battery 14 to a sinusoidal AC output to drive the load 16.

Thus, the present invention provides a relatively simple and inexpensive circuit that will significantly prolong the operating time of any battery, regardless of type or chemistry, and that is readily adaptable to provide the voltages and power consumption requirements of a wide variety of applications.

Those skilled in the art will appreciate that the invention may be embodied in many other forms, and the scope of the invention is intended to include all equivalent circuits and implementations, whether implemented in analog or digital form.

What is claimed is:

1. A power source to load switching circuit for extending the operating life of a power source with respect to a load, the circuit comprising:

a capacitive means;

an inductive means, wherein the load, the capacitive means, and the inductive means together form a RLC circuit having a natural frequency f_0 and a cycle time period T_0; and

a switching means for alternately connecting the power source to the RLC circuit and isolating the power source from the RLC circuit and for providing an alternate conduction path for the RLC circuit while the power source is isolated from the RLC circuit to allow continued oscillation of voltage and current.

2. A circuit as recited in claim 1 wherein the switching means comprises:

a switching matrix interposed between the power source and the RLC circuit, the switching matrix comprising a plurality of solid state switches;

a pair of switched shunts coupled to the RLC circuit, wherein each shunt comprises a solid state switch connected in series with a diode; and

controller means for controlling and coordinating the opening and closing of the switches of the switching matrix and the shunts.

3. A circuit as recited in claim 2 wherein the switching means connects the power source to the RLC circuit for a predetermined portion of each half-cycle, disconnects and isolates the power source from the RLC circuit and provides an alternate conduction path for the RLC circuit for the remainder each half-cycle, and reverses the polarity of the power source relative to the RLC circuit during each successive half-cycle.

4. A circuit as recited in claim 3 wherein the predetermined portion of the half-cycle is less than $T_0/4$.

5. A circuit as recited in claim 3 wherein the predetermined portion of the half-cycle is about $T_0/8$.

6. A circuit as recited in claim 3 wherein the capacitive means is precharged to an initial voltage V_{C0} prior to initial operation of the circuit.

7. A circuit as recited in claim 6 wherein the initial voltage V_{C0} is within the range from 0 to 300 volts.

8. A circuit as recited in claim 6 wherein the initial voltage V_{C0} is within the range from 50 to 150 volts.

9. A circuit as recited in claim 6 wherein the initial voltage V_{C0} is approximately 100 volts.

10. A circuit as recited in claim 3 wherein the cycle time period T_0 is about 1 microsecond.

11. A circuit as recited in claim 3 wherein the cycle time period T_0 is in the range of 500 microseconds to 2 milliseconds.

12. A circuit as recited in claim 3 wherein the RLC circuit has a Q value greater than .5.

13. A circuit as recited in claim 3 wherein the RLC circuit has a Q value in the range of 3 to 5.

14. A circuit as recited in claim 3 wherein the RLC circuit has a Q value of about 4.

15. A method for extending the operating time of a power source as applied to a load, the method comprising the steps of:

precharging a capacitive means;

connecting the precharged capacitive means to an inductive means and the load, wherein the load, the capacitive means, and the inductive means together form a RLC circuit having a natural frequency f_0 and a cycle time period T_0;

alternately connecting the power source to the RLC circuit and isolating the power source from the RLC circuit; and

providing an alternate conduction path for the RLC circuit to allow continued oscillation of voltage and current during the time the power source is isolated from the RLC circuit.

16. A circuit as recited in claim 15 wherein the power source is connected to the RLC circuit for a predetermined portion of each half-cycle and is disconnected and isolated from the RLC circuit for the remainder of each half-cycle.

17. A circuit as recited in claim 16 wherein an alternate conduction path for the RLC circuit is provided for the remainder each half-cycle.

18. A circuit as recited in claim 17 wherein the polarity of the power source is reversed relative to the RLC circuit during each successive half-cycle.

19. A method as recited in claim 18 wherein the predetermined portion each half-cycle is less than $T_0/4$.

20. A method as recited in claim 18 wherein the predetermined portion of each half-cycle is about $T_0/8$.

21. A method as recited in claim 18 wherein the cycle time period T_0 is about 1 microsecond.

22. A method as recited in claim 18 wherein the cycle time period T_0 is in the range of 500 microseconds to 2 milliseconds.

23. A method as recited in claim 18 wherein the switching occurs twice during the cycle time period T_0, once at the beginning of each cycle and once at $T_0/2$.

24. A method as recited in claim 18 wherein the RLC circuit has a Q value greater than .5.

25. A method as recited in claim 18 wherein the RLC circuit has a Q value in the range of 3 to 5.

26. A method as recited in claim 18 wherein the RLC circuit has a Q value of about 4.

27. A power source to load switching circuit for extending the operating time of a power source with respect to a load, the circuit comprising:

a pre-charged capacitive;

an inductive means, wherein the load, the capacitive means, and the inductive means together form a RLC circuit having a natural frequency f_0 a cycle time period T_0;

a first switching means for alternately connecting the power source to the RLC circuit for a predetermined portion of each half-cycle and for isolating the power source from the RLC circuit during the remainder of each half cycle; and

a second switching means for providing an alternate conduction path for the RLC circuit during the time the power source is isolated from the RLC circuit to allow continued oscillation of voltage and current.

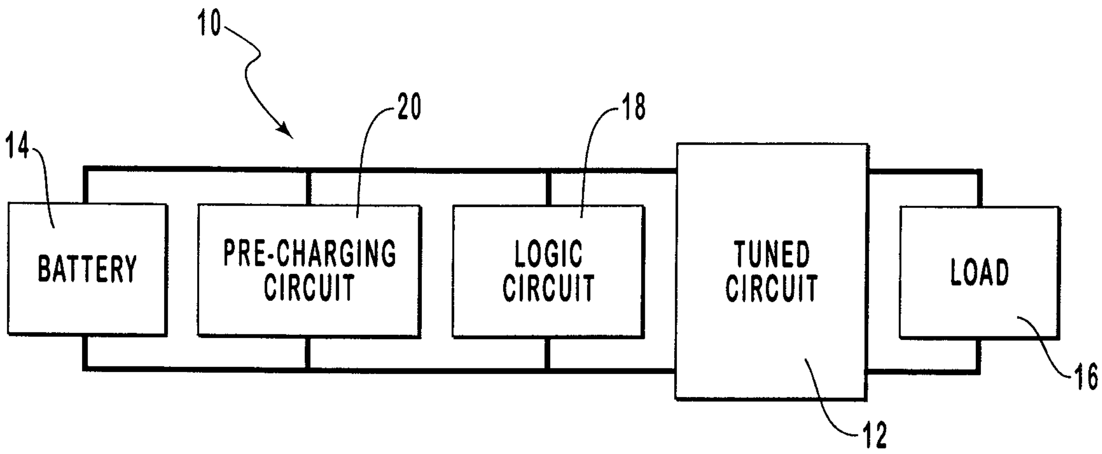

10
14
20
18
BATTERY
PRE-CHARGING CIRCUIT
LOGIC CIRCUIT
TUNED CIRCUIT
LOAD
16
12

FIG. 1

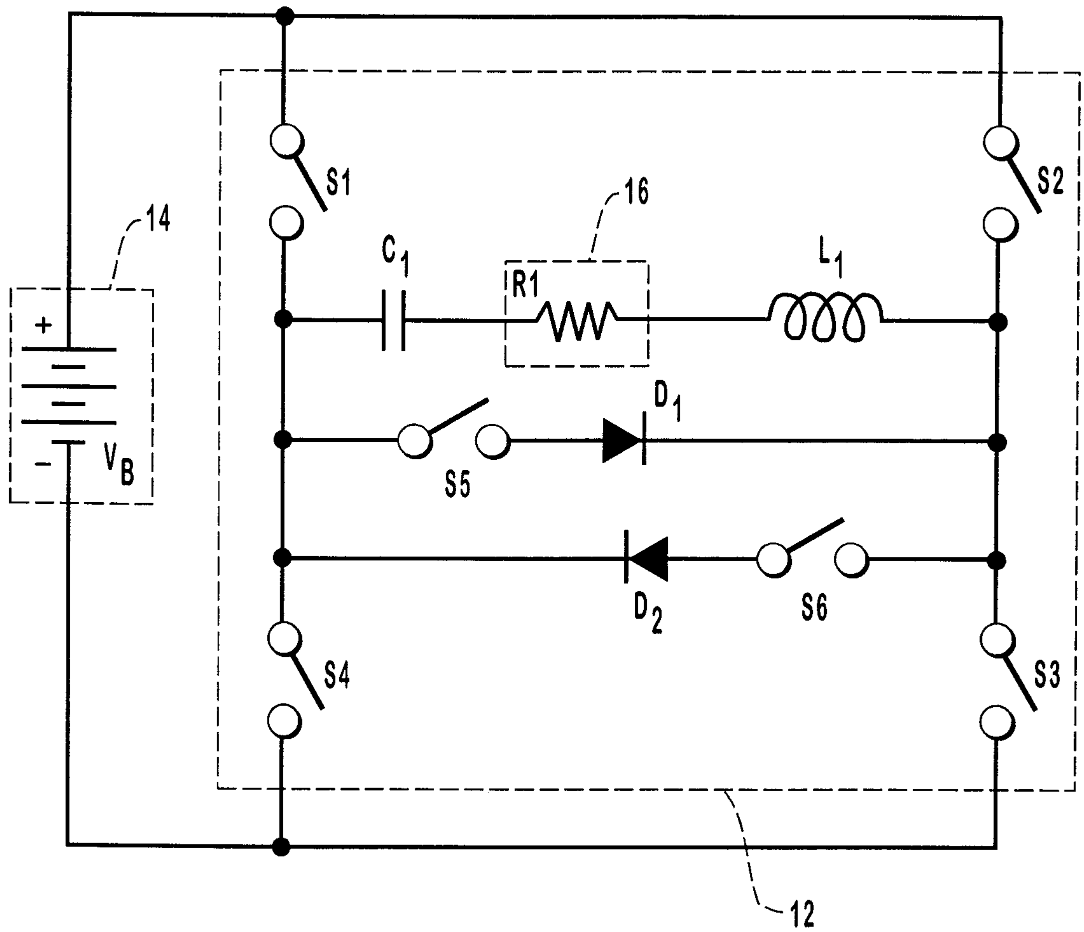

S1
S2
14
16
C_1
R1
L_1
+
-
V_B
D_1
S5
D_2
S6
S4
S3
12

FIG. 2

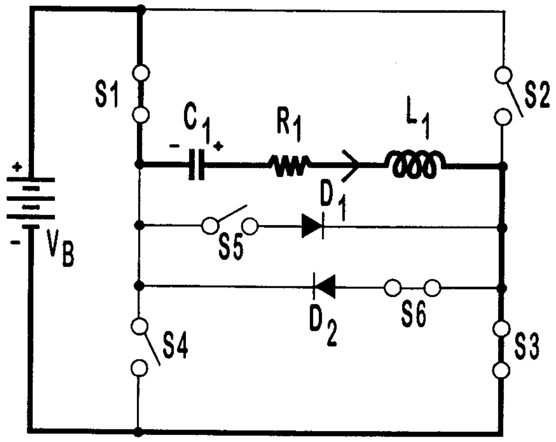


FIG. 3A

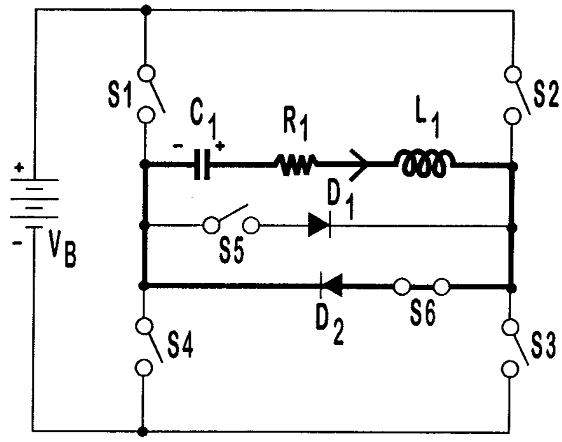


FIG. 3B

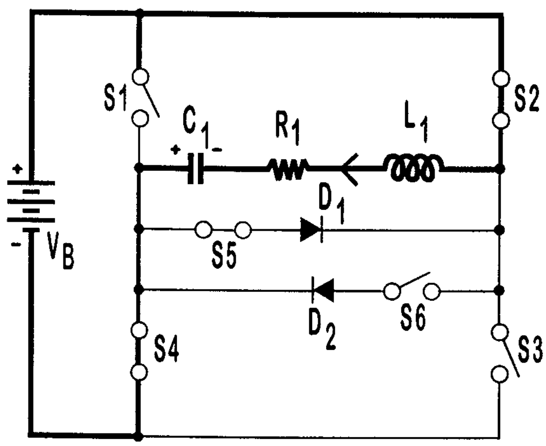


FIG. 3C

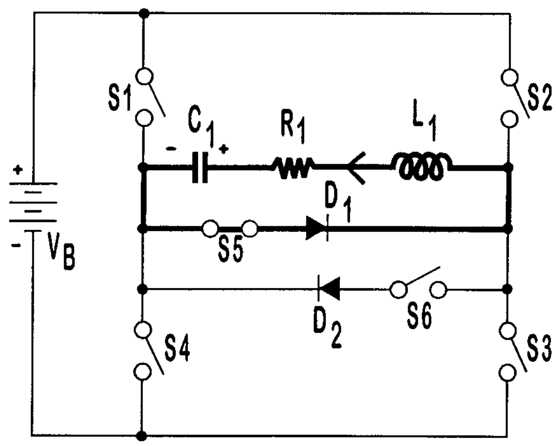


FIG. 3D

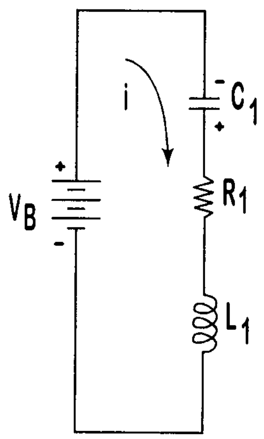


FIG. 4A

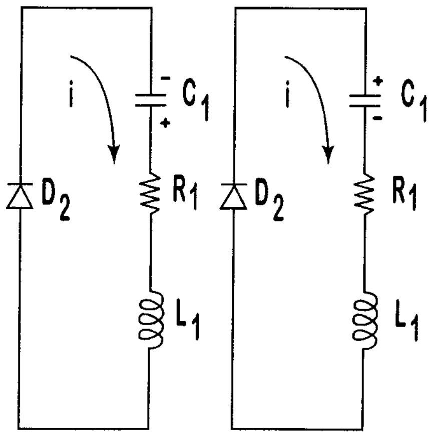


FIG. 4B

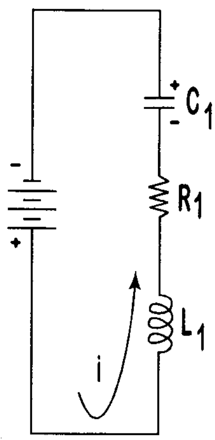


FIG. 4C

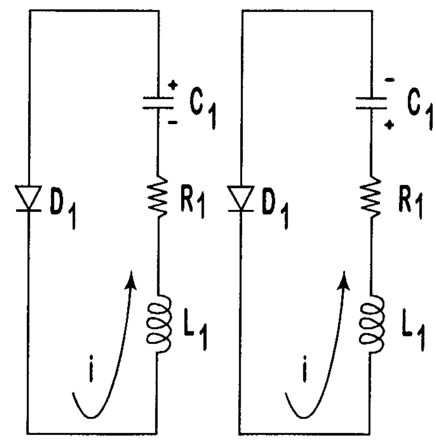
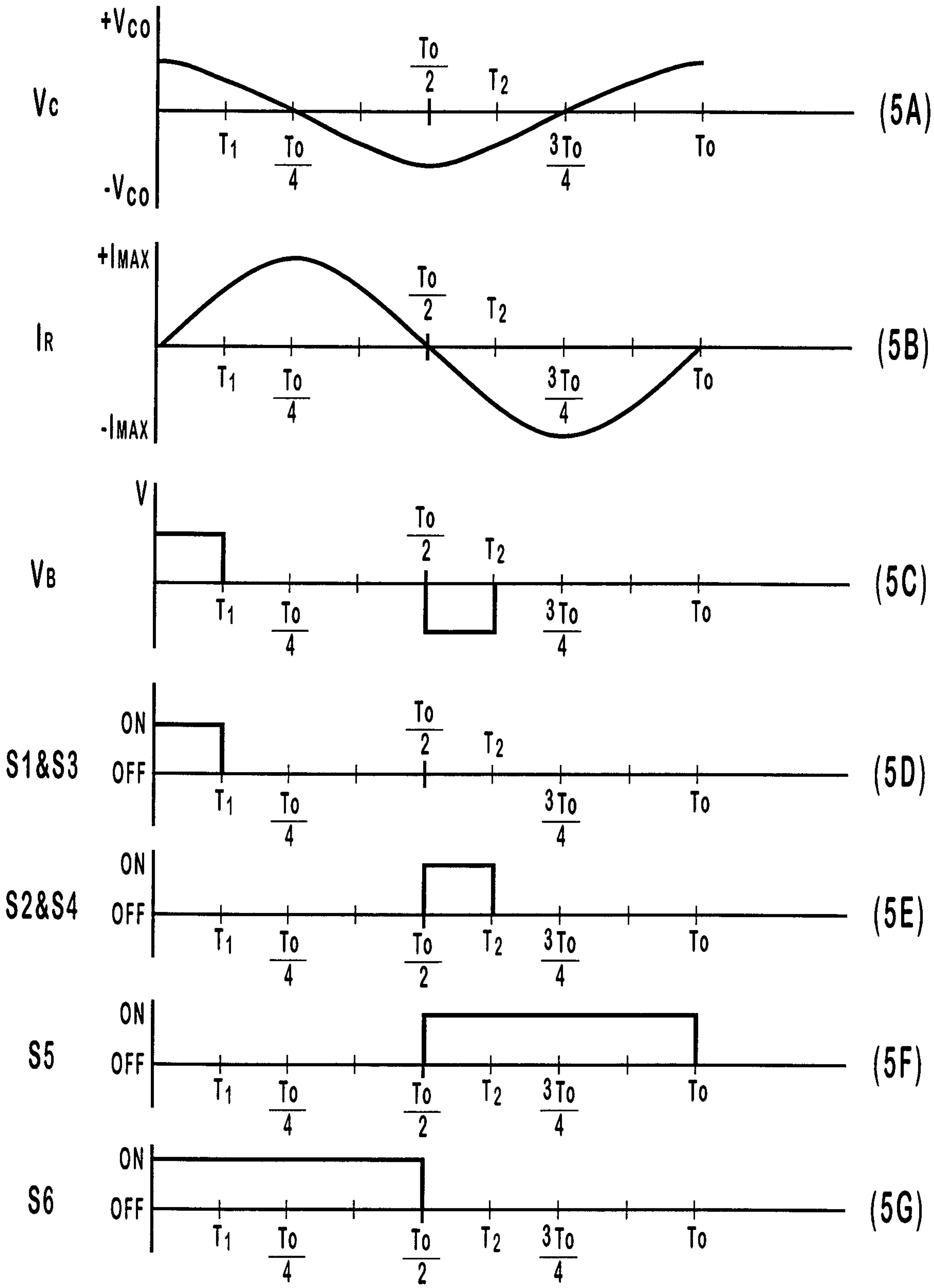


FIG. 4D



+Vco
-Vco
Vc
To/2
T2
T1
To/4
3To/4
To
(5A)
+IMAX
-IMAX
IR
(5B)
V
VB
(5C)
ON
OFF
S1&S3
(5D)
S2&S4
(5E)
S5
(5F)
S6
(5G)

FIG. 5

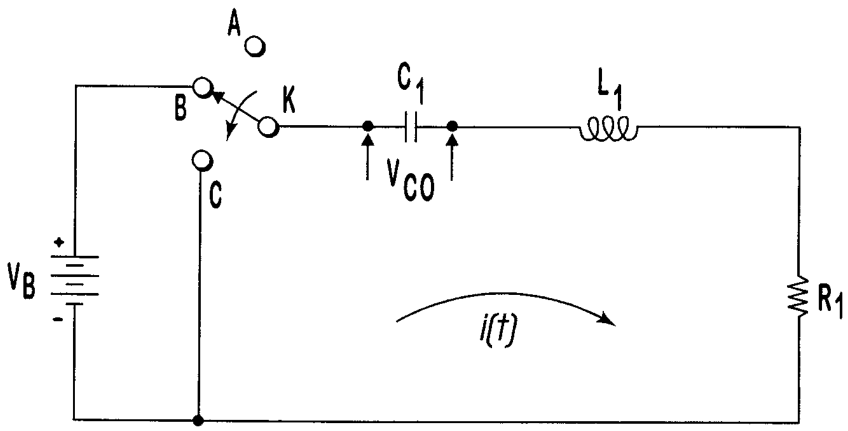


FIG. 6

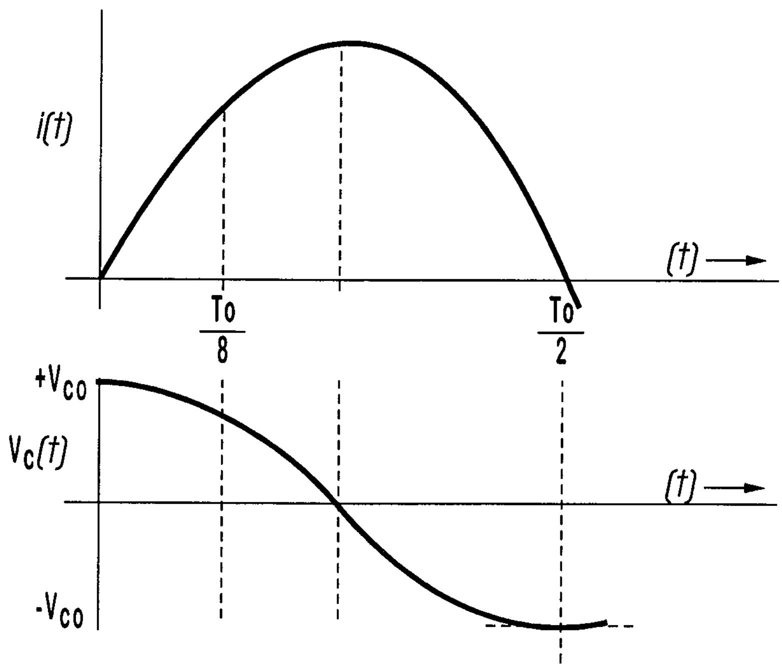


FIG. 7

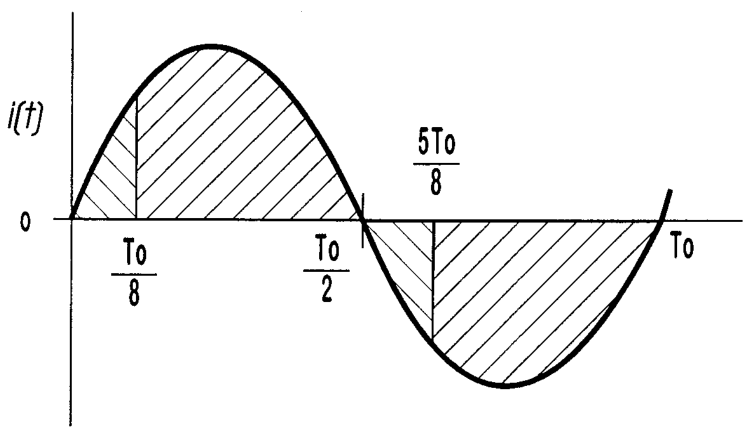


FIG. 8

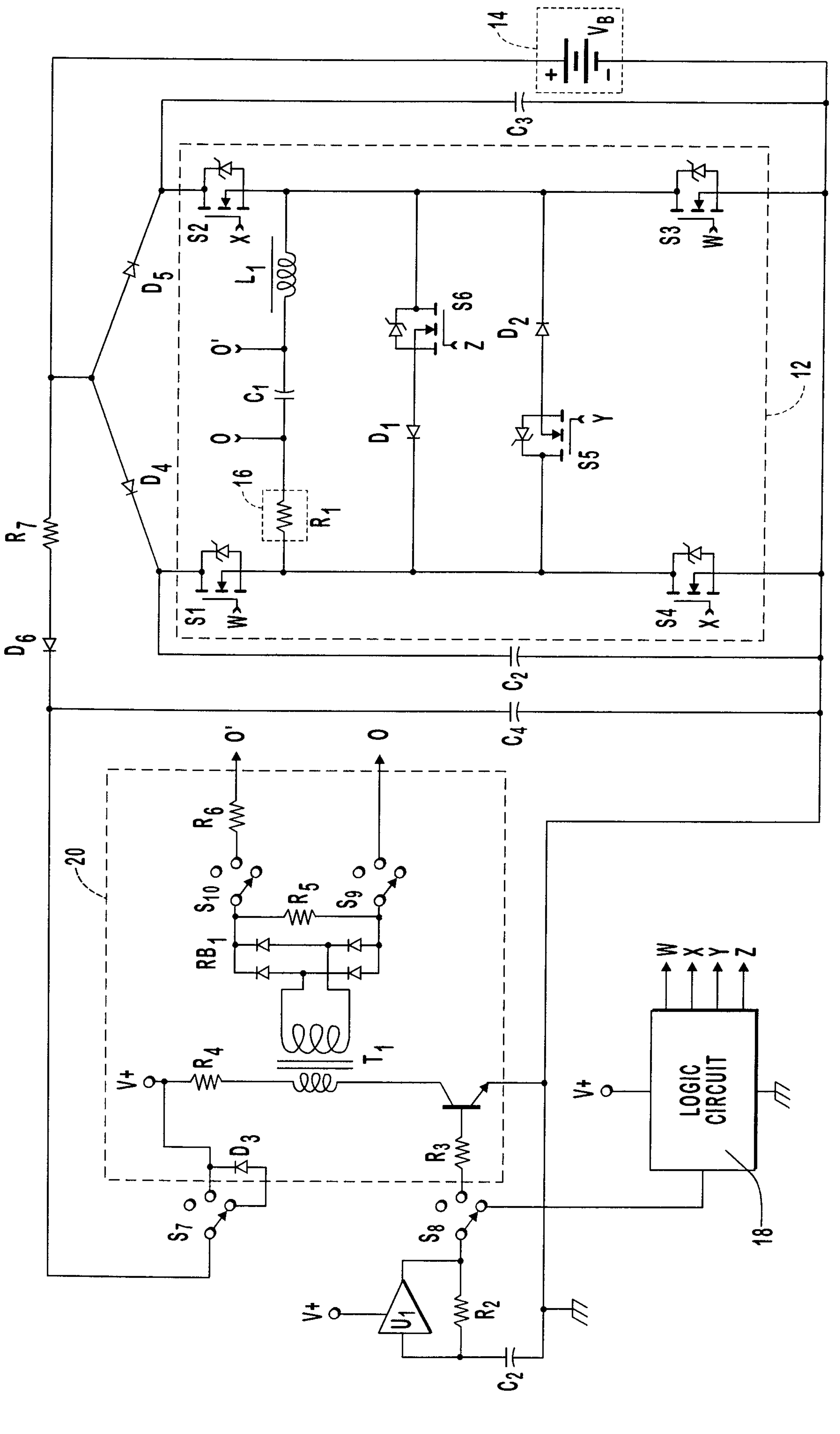

14
V_B
+
-
C_3
R_7
D_5
D_4
D_6
S2
X
S1
W
S3
W
S4
X
L_1
O'
C_1
O
16
R_1
S6
Z
D_2
D_1
S5
Y
12
C_2
C_4
O'
O
R_6
20
S_{10}
R_5
S_9
RB_1
V+
R_4
T_1
D_3
R_3
S_7
S_8
W
X
Y
Z
V+
LOGIC
CIRCUIT
18
V+
U_1
R_2
C_2

FIG. 9