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A METHOD FOR COUPLING A DIRECT CURRENT POWER SOURCE ACROSS A NEARLY FRICTIONLESS HIGH-SPEED ROTATION BOUNDARY

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

[0002] None.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0003] The present invention relates to power transmission and more specifically to a method for coupling a direct current across a high-speed rotation boundary.

(2) Description of the Prior Art

[0004] Sensor systems located at the end of towed tethers require Direct Current (DC) power for operation. Rotary joints are positioned along a tether to prevent twisting and breakage of the tether. A problem arises in connection with electronic circuits for sensing or control that are placed on a rotating platform.

[0005] As such, an ongoing need exists to permit DC power to be transmitted across rotary joints and to permit signals to be sent to a tethered sensor system and data to be retrieved from the sensor system.

[0006] A number of commercial applications may also exist. For example, an application may be transferring power to sensors in the rotating wheels of vehicles using a long-life frictionless connection.

SUMMARY OF THE INVENTION

[0007] It is, therefore, a general purpose and primary object of the present invention to provide a method for coupling a direct current power source across a rotating boundary.

[0008] It is a further object of the present invention to provide a method for coupling a DC power source across a nearly frictionless and high speed rotating boundary.

[0009] To attain the objects described, a method is disclosed for coupling DC power across a rotating boundary, in which the boundary may be operating at a high speed of rotation. The method incorporates balanced concentric cylinders separated by a dielectric medium that form capacitor couplings. However, anyone skilled in the art will recognize that the method can also be realized by a dual method wherein a magnetic coupling mechanism is effected by placing coupled coils on topologically opposite sides of a non-magnetic rotating boundary. While this application will focus on capacitive coupling in order to teach the method, the dual magnetically coupled mode is claimed implicitly. The dielectric medium can be a vacuum, a gas, or a non-conducting liquid.

[0010] If the dielectric medium is a vacuum or a gas, then the method would be nearly frictionless and no presently measurable mechanical or electrical friction losses would result. A liquid dielectric, which would introduce more friction, may allow application of the method in cases involving rotary joints that penetrate a sealed environment.

[0011] The disclosed method also permits external control of a DC field current without the need for brushes or wiper contacts. Brushes and wiper contacts introduce friction, which is a potential for intermittent contact. Contact also requires regular maintenance of the equipment impacted. Many rotating field alternators are in use today in power generation systems.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Other objects, features and advantages of the present invention will become apparent upon reference to the following description of the preferred embodiments and to the drawings wherein:

[0013] **FIG. 1** depicts a Thevenin-Equivalent square-wave source;

[0014] **FIG. 2** depicts a loaded square-wave source;

[0015] **FIG. 3** depicts a square-wave source, positive half period;

[0016] **FIG. 4** depicts a square-wave source, negative half period;

[0017] **FIG. 5** depicts an energy efficient square-wave generator;

[0018] **FIG 6** depicts a square-wave generator, steady-state, OPEN switch;

[0019] **FIG. 7** depicts a square-wave generator, steady-state, CLOSED switch;

[0020] **FIG. 8** depicts a square-wave generator, steady-state energy exchange;

[0021] **FIG. 9** depicts an energy efficient [square-wave]-to-DC converter circuit;

[0022] **FIG. 10** depicts a [square-wave]-to-DC converter, POSITIVE half period;

[0023] **FIG. 11** depicts a [square-wave]-to-DC converter, NEGATIVE half period;

[0024] **FIG. 12** depicts a DC converter, steady-state energy exchange;

[0025] **FIG. 13** depicts a power transmission model; and

[0026] **FIG. 14** depicts coupling DC power to electrical circuits on a rotating structure using a frictionless coupler.

DETAILED DESCRIPTION OF THE INVENTION

[0027] Generally, the disclosure describes a method for transmitting DC power over a uniform transmission line of any length using two circuits that work together to provide the power to loads that are remotely located with respect to the sources of the power.

[0028] The first circuit, a square-wave generator, uses a DC source to generate a square-wave. The generator uses an inductor, a capacitor, and a switch, which may be implemented using a single transistor and a drive circuit. The second circuit, a square-wave converter, converts a square-wave source into a DC source. The converter uses an inductor, a capacitor, and a P-N junction diode.

[0029] The square-wave generator and square-wave converter each provide a matched termination to a uniform transmission line so that energy is not reflected from the converter back toward the generator. Thus, the transmission line can be many wavelengths long without affecting the efficiency of power transmission. Typically, power is lost and a voltage drop occurs as a result of transmission line Ohmic losses. Using transmission line transformers to increase voltage and to decrease current on the transmission line can reduce these Ohmic losses.

[0030] The transmission efficiency of the disclosed method is determined by departures from an ideal of the parameters of the components used. If the switch, diode, inductors, capacitors, and transmission line were all ideal and lossless, then the transmission efficiency would be one hundred percent.

[0031] A small amount of DC power is required to energize the disclosed switch driver circuits; however, the switch driver is located at the DC source where, presumably, DC power is plentiful. Therefore, the issue of switch driver power is minimized when discussing the transmission efficiency of the disclosed method. That is the DC power delivered to the load would be equal to the DC power available from the source.

[0032] In practice, system considerations and the non-ideal nature of the components affect the actual efficiency of the method. However, for the purposes of this disclosure, the components are assumed to be ideal and, therefore, the predicted DC transmission efficiency is approximately one hundred percent.

[0033] There is also a limitation on the amount of power that can be delivered to a load using the disclosed method. The limitation is fixed by the non-linear properties of the diode used in the converter circuit. The maximum current that can be delivered to a load is one-half of the maximum forward current that the diode can safely carry. The maximum voltage that can be delivered to a load is one-half of the breakdown voltage of the diode. The maximum DC power that can be delivered to a load is the product of one-half of the maximum forward current and one-half of the breakdown voltage. For example, a diode with a reverse breakdown voltage of one hundred Volts may be able to support a maximum forward current of one ampere. Then, the maximum power that could be delivered to a resistive load by a converter that uses the diode would be 25 Watts (50 Volts X 500 mA).

[0034] The disclosed method uses inductors and capacitors for energy storage. It is known in the art that energy is lost when an abrupt change in capacitor voltage or an abrupt change in inductor current is required by circuit operation. Within the disclosed method and under steady-state operating conditions, inductor current and capacitor voltage remain essentially constant.

[0035] A "steady-state" operating condition is an operating condition under which the circuits would normally be used. When the circuits used in the method are energized and the switch begins operation, the current through the inductors and the voltage across the capacitors are both zero. A transient state exists until the inductor currents and capacitor voltages have become periodically stable. At this time of stability, the operating conditions are described as "steady-state". However, the inductor voltage and the capacitor current are each subjected to abrupt changes as the square-wave polarity changes. Even though these changes are allowable with ideal components, the parasitic capacitance of the inductors and the parasitic inductance of the capacitors will degrade the ideal operation of the method and decrease the observed efficiency. These parasitic effects are not addressed in this disclosure because, in good engineering practice, these effects only minimally degrade performance.

Introduction to the Disclosed Method

[0036] In **FIG. 1,** a Thevenin-Equivalent square-wave source **2** is shown. In the figure, voltage **4** of a signal generator **6** switches between a positive-value state, $+V_S$, and a negative-value state, $-V_S$, in which the states have the same magnitude but opposite polarity. The switching operation is periodic with a period, T_S, and with equal dwell times in each state. Thus, the average value of the voltage **4** is zero. Furthermore, the time required to switch between the two states is negligible and is assumed to be zero.

[0037] The characteristic impedance of the generator **6** is Z_0, a positive real number. In general, a Thevenin-Equivalent source impedance can be complex and may, under certain circumstances, have a negative real part. However, for the purpose of this disclosure, only positive real values of Z_0 are considered. This restriction is consistent with practical applications of the disclosed method.

[0038] If an equivalent circuit were used to drive a transmission line with a characteristic impedance also equal to Z_0, then the equivalent circuit for the output of the transmission line would be identical to the illustration in **FIG. 1**, regardless of the length of the transmission line.

[0039] The maximum power available from the Thevenin-Equivalent circuit of **FIG. 1** is equal to the power that would be delivered to a load resistor equal to Z_0, as illustrated in **FIG. 2**. In the figure, maximum power transfer occurs when a generator **10** is driving a load **12**. The load **12** is Z_0, which is equal to impedance **14** of the generator **10**. Under these conditions, the voltage across the load **12** is one-half the voltage of the generator **10** and the current is one-half of the short-circuit current available from the Thevinin-Equivalent generator.

[0040] During the positive state of the generator **10**, illustrated in **FIG. 3**, a current **16** passing through the load (**12**), Z_0, is $V_S/2Z_0$ so that the instantaneous power delivered to the load is $V_S^2/4Z_0$. During a positive half period **24** of the square-wave cycle, the current **16** is positive and equal to the peak voltage, V_S, divided by the total circuit resistance $2Z_0$, and a voltage **26** across the load **12** is just one half the peak voltage V_S.

[0041] During a negative state, illustrated in **FIG. 4**, the instantaneous power delivered to the load, Z_0, is the same, $(V_S)^2/4Z_0$, even though the current **16** flows in the opposite direction. During a negative half period **29** of the square-wave cycle, the current **16** is positive and is equal to the peak voltage, V_S, divided by the total circuit resistance $2Z_0$ and a voltage across the load is one-half of the peak voltage, V_S.

[0042] The average power is equal to the instantaneous power and is defined as $P_{MAX}=(V_S)^2/4Z_0$, which is the maximum power available from the source. Thus terminated, the generator is optimally loaded because the generator is delivering maximum available power to the load, Z_0.

<u>Energy-Efficient Square-Wave Generator</u>

[0043] The circuit illustrated in **FIG. 5** can be used to convert a DC source **50** into a square-wave driving an impedance of a load resistor **54** which is equal to an internal impedance **56** of the DC source. Assuming ideal components, an inductor **58** and a capacitor **59**, the efficiency of the conversion is one hundred percent because the average square-wave power delivered to the impedance of the load resistor **54** is equal to the maximum DC power available from the DC source **50**. A square-wave is created by the periodic operation of a switch **60** that changes state once each period (**62**) T_S, of the square-wave. The two states of the switch **60** are defined as follows: (1) when the switch is OPEN, the current through the branch containing the switch is identical to zero while the voltage across the branch may assume any value, and (2) when the switch is CLOSED, the voltage across the branch containing the switch is identical to zero while the current through the branch may assume any value. The dwell time in each of the two switch states is the same.

[0044] In **FIG. 5**, the switch **60** opens and closes periodically causing a square-wave of current to pass through the load resistor, Z_0 (**54**). A transient state occurs when the action of the switch **60** is initialized. The transient state lasts until the voltage across the capacitor **59** and the current through the inductor **58** each reach a steady-state condition.

[0045] A steady-state OPEN condition of the switch **60** is illustrated in **FIG. 6**. During this half period, $T_S/2$, energy is delivered to the circuit by the inductor **58** while a stored energy of the capacitor **59** is increasing. The average, steady-state, energy stored on the inductor **58** is $E_{AVG} = \{L(V_{DC})^2\}/8(Z_0)^2$ in which "L" is the inductance of the inductor.

[0046] The energy delivered to the circuit by the inductor **58** during each OPEN condition half period is $E_{DEL} = T_S(V_{DC})^2/8Z_0$. The choice of value of the inductor **58** is made by observing that the exchanged or delivered energy, E_{DEL} should be a fraction of the average energy, E_{AVG}. This will be true if the inductance is much greater than the product, Z_0T_S. Thus, $L \gg Z_0T_S$ is required. During the OPEN condition, the voltage across the branch of the switch **60** is V_{DC}.

[0047] During this half period, the switch **60** is OPEN so that the current through the branch of the switch is zero. A steady-state current **64** equal to $V_{DC}/2Z_0$ passes through the load, Z_0, producing a voltage, $V_{DC}/2$. During this half period, energy is supplied to the circuit by the inductor **58** while energy is being stored in the capacitor **59**. The voltage across the open switch **60** is V_{DC}.

[0048] A steady-state switch CLOSED condition is illustrated in **FIG. 7**. During this half period, the switch **60** is CLOSED so that the voltage across the switch branch is zero. The steady-state current **64** reverses through the load, Z_0, producing a voltage, $- V_{DC}/2$. During this half period, energy is supplied to the circuit by the capacitor **59** while energy is being stored in the inductor **58**. The current through the CLOSED switch **60** is V_{DC}/Z_0 which is twice the steady-state DC current supplied by the DC source **50**.

[0049] During this half period, $T_S/2$, energy is delivered to the circuit by the capacitor **59** while stored energy of the inductor **58** increases. The average, steady-state, energy stored on the capacitor **59** is $E_{AVG} = C(V_{DC})^2/8$ in which "C" is the capacitance of the capacitor. The energy delivered to the circuit by the capacitor **59** during each CLOSED condition half period is $E_{DEL} = T_S(V_{DC})^2/8Z_0$, which is the same as that delivered by the inductor **58** during each OPEN condition half period.

[0050] The choice of value of the capacitor **59** is made by observing that the delivered energy, E_{DEL}, should be a fraction of the average energy, E_{AVG}. This will be true if the capacitance is much greater than the ratio T_S/Z_0. Thus, $C >> T_S/Z_0$ is required. During the CLOSED condition of the switch **60**, the current through the switch is V_{DC}/Z_0, which is twice the current through the DC source **50**.

[0051] Energy balance is achieved if the ratio of the element values, L and C, are chosen such that $(L/C)=(Z_0)^2$. Then, the average energy stored on each element is the same. The energy exchange during each period of steady-state operation is illustrated in **FIG. 8**.

[0052] In **FIG. 8**, the figure depicts the time variation of the energy stored on the inductor and capacitor components in the square-wave generator illustrated in **FIG. 5, FIG. 6,** and **FIG. 7.** During each half period, energy is delivered to the circuit by either the inductor or the capacitor while the energy on the other component is increasing. During the next half period, the process reverses. The graph is based on an assumed condition that $E_{DEL} << E_{AVG}$. Only one period is illustrated because, in the steady-state condition, each period is identical to every other period.

[0053] By comparing **FIG. 6** with **FIG. 7**, the effects caused by the CLOSING operation of the switch **60** are seen. The instant that the switch **60** closes, the voltage across the inductor **58** changes polarity, but not magnitude, while the current through the capacitor **59** and a load impedance **70** changes direction, but not magnitude. Both of these instantaneous changes are permissible by the boundary conditions imposed by the circuit components and no transient behavior occurs as a result of the CLOSING operation of the switch **60**. The current through the inductor **58** and the voltage across the capacitor **59** do not change when the switch **60** CLOSES and this is also required by the respective boundary conditions.

[0054] In one embodiment, the switch **60** used to implement this square-wave generator circuit would be a transistor collector-emitter circuit. A small amount of energy would be necessary to power a switch driver to provide the base-emitter drive current, which may be more than one hundred times less than the peak collector-emitter current, V_{DC}/Z_0, when the switch **60** is CLOSED.

Energy Efficient [Square-wave]-to-DC Converter

[0055] In **FIG. 9**, a [square-wave]-to-DC converter circuit is shown. The passive circuit requires a capacitor and an inductor for energy exchange and a single diode. A square-wave source **90** and a source impedance **91** represent the Thevenin-Equivalent, as previously described in the "Introduction to the Disclosed Method" section, of a transmission line being driven by a square-wave generator, as previously described in the "Energy-Efficient Square-Wave Generator" section. If an inductor **92**, a capacitor **93**, and a diode **94** of the converter circuit are assumed to be ideal, then the efficiency of the converter circuit is one hundred percent. That is, the DC power delivered to a load resistor **95** is equal to the maximum power available from the Thevenin-Equivalent generator.

[0056] The square-wave is converted to DC power by a non-linear property of the diode **94** that, in one state, permits an undefined current to flow through the diode in only one direction while the voltage across the branch containing the diode is zero and that, in a second state, permits an undefined voltage across the branch for the diode in only one polarity while the current through the branch for the diode is zero. The operation of the converter circuit in steady-state can best be described by observing each non-linear state separately. When the diode polarity is as illustrated in **FIG. 9**, the two states correspond to the NEGATIVE half period of the square-wave and to the POSITIVE half period of the square-wave, respectively.

[0057] The square-wave source **90** switches periodically between a positive voltage, $+V_S$, and a negative voltage, $-V_S$. After a steady-state condition is reached, the inductor **92** acts as a constant current source delivering a positive current to the load resistor **95**. A transient state occurs when the square-wave source is first initialized. A transient state lasts until the voltage across the capacitor **93** and the current through the inductor **92** each reach a steady-state condition.

[0058] A converter circuit steady-state operation during the POSITIVE half period is illustrated in **FIG. 10**. In the figure, the current through a branch with the diode **94** is zero. Thus, a current **101** driven by the generator **90** flows through the inductor **92**, the capacitor **93** and the load resistor **95**. During this half period, energy is delivered to the circuit by the capacitor **93** while the stored energy of the inductor **92** is increasing. The average, steady-state, energy stored on the **93** is $E_{AVG} = C(V_S)^2/8$ in which "C" is the capacitance of the capacitor. The energy delivered to the circuit by the capacitor during each POSITIVE half period is $E_{DEL} = T_S(V_S)^2/8Z_0$. The choice of value of the capacitor **93** is made by observing that the delivered energy, E_{DEL}, should be a fraction of the average energy, E_{AVG}. This will be true if the capacitance is much greater than the ratio T_S/Z_0. Thus, $C >> T_S/Z_0$ is required. During the POSITIVE half periods of the square-wave, the voltage across the branch of the diode **94** is V_S with a polarity that reverse-biases the diode junction so that no current can flow in the branch.

[0059] During this half period, the square-wave source **90** (generator) presents a positive voltage, V_S, to the circuit causing a current $V_S/2Z_0$ to flow in the circuit. The diode **94** is reverse-biased by a voltage equal to V_S so that no current flows in the branch containing the diode. Thus, the current, I_S, flows through the load, Z_0, generating a voltage $V_S/2$ across the load. During this half period, the capacitor **93** supplies energy to the circuit while the inductor **92** is storing energy.

[0060] The steady-state operation of the converter circuit during a polarity change **102** of a NEGATIVE half period is illustrated in **FIG. 11.** In the figure, the voltage across a branch of the diode **94** is zero and the current through the branch is V_S/Z_0, which is twice the current **101** driven by the square-wave source **90**. During this half period, $T_S/2$, energy is delivered to the circuit by the inductor **92** while the stored energy of the capacitor **93** is increasing. The average, steady-state, energy stored on the inductor **92** is $E_{AVG} = \{L(V_S)^2\}/8(Z_0)^2$ in which "L" is the inductance of the inductor. The energy delivered to the circuit by the inductor **92** during each NEGATIVE half period is $E_{DEL} = T_S(V_S)^2/8Z_0$. The choice of value of the inductor **92** is made by observing that the delivered energy, E_{DEL}, should be a fraction of the average energy, E_{AVG}. This will be true if the inductance is much greater than the product, Z_0T_S. Thus, $L >> Z_0T_S$ is required.

[0061] During this half period, the square-wave source **90** presents a negative voltage, $-V_S$, to the circuit causing a current, $-V_S/2Z_0$, to flow in the circuit. The diode **94** is forward-biased by a current equal to V_S/Z_0 and the voltage containing the diode is about zero. A current, I_s, flows through the load, Z_0, generating a voltage, $V_S/2$, across the load. During this half period, the capacitor **93** is storing energy while the inductor **92** supplies energy to the circuit.

[0062] Energy balance is achieved if the ratio of the element values, L and C, are chosen such that $(L/C)=(Z_0)^2$. Then, the average energy stored on each element is the same. The energy exchange during each period of steady-state operation is illustrated in **FIG. 12**.

[0063] **FIG. 12** depicts the time variation of the energy stored on the inductor and capacitor components in the DC converter illustrated in **FIG. 9**, **FIG. 10** and **FIG. 11**. During each half period, energy is delivered to the circuit by either the inductor or the capacitor while the energy stored on the other component is increasing. During the next half period, the process reverses. **FIG. 12** is based on a condition that $E_{DEL} << E_{AVG}$. Only one period is illustrated because, in the steady-state condition, each period is identical to every other period.

[0064] By comparing **FIG. 10** with **FIG. 11,** the effects caused by the instantaneous change in square-wave polarity from POSITIVE to NEGATIVE are seen. The instant that the square-wave polarity changes, the voltage across the inductor **92** also changes polarity, but not magnitude, while the current through the capacitor **93** changes direction, but not magnitude. Both of these instantaneous changes are permissible by the boundary conditions imposed by the circuit components and no transient behavior occurs as a result of the polarity change. The current through the inductor **92** and the voltage across the capacitor **93** do not change when the square-wave polarity changes and this is also required by their respective boundary conditions. The current through a load **107** is the same as the current through the inductor **92** and does not change in either polarity or magnitude. Thus, as predicted, the load **107** experiences direct current (DC).

[0065] By comparing **FIG. 10** with **FIG. 3** and **FIG. 11** with **FIG. 4**, the converter circuit is indistinguishable from a resistive termination, Z_0. Consider a boundary **108** shown in **FIG. 10** and a boundary **27** shown in **FIG. 3**.

- The generator **90** and a Thevenin-Equivalent circuit **109** to the left of the boundary **108** in **FIG. 10** is identical to the generator **10** and a Thevenin-Equivalent circuit **28** to the left of the boundary **27** in **FIG. 3**.
- The current **101** crossing the boundary **108**, from the generator **90** to the converter circuit is identical to the current **16** crossing the boundary **27** from the generator **10** to the matched termination, Z_0 in **FIG. 3**.
- The voltage across the boundary **108** is $V_S/2$, which is identical to the voltage across the boundary **27**.

[0066] Thus, during the POSITIVE half cycle of a square-wave, the converter circuit is indistinguishable from a resistor having a value Z_0.

[0067] Consider the boundary **108** shown in **FIG. 11** and the boundary **27** shown in **FIG. 4**.

- The generator **90** and the Thevenin-Equivalent circuit **109** to the left of the boundary **108** in **FIG. 11** is identical to the generator **10** and a Thevenin-Equivalent circuit **28** to the left of the boundary **27** in **FIG. 4**.
- The current **101** crossing the boundary **108**, from the converter circuit to the Thevenin-Equivalent generator is identical to the current **22** crossing the boundary **27** from the

matched termination, Z_0, of **FIG. 4**, to the Thevenin-Equivalent generator.

- The voltage across the boundary **108** is $-V_S/2$, which is identical to the voltage across the boundary **27**.

[0068] Thus, during a NEGATIVE half cycle of a square-wave **110**, **45**, the converter circuit is indistinguishable from a resistor having a value, Z_0.

[0069] An important property of the converter circuit is demonstrated in that after reaching a steady-state condition, the disclosed converter circuit is indistinguishable from a resistive termination, Z_0, when driven by a square-wave. This property allows the converter circuit to be used as a matched termination for a uniform transmission line of any length with a transmission line characteristic impedance equal to Z_0 when the uniform transmission line is driven by a square-wave source. This property is illustrated in **FIG. 13**.

[0070] In **FIG. 13**, power from a DC source **130** is transmitted over a distance, L_T, by using an energy efficient square-wave generator **132** and an energy efficient [square-wave]-to-DC converter **133**. The source impedance **134** of a generator, the characteristic impedance of a transmission line **135** and the DC load impedance are each equal to Z_0. The transmission line **135** can be comparatively long since the converter **133** presents a matched termination to the transmission line. The matched termination insures that there are no reflections or standing waves on the line that would corrupt the operation of the system.

A Method for Efficiently Coupling a DC Power Source Across a Nearly Frictionless High Speed Rotation Boundary

[0071] In **FIG. 14,** an energy-efficient square-wave generator **140** is schematically shown in which the generator is connected through a transformer **141** to stator rings **142** of a nearly frictionless capacitor coupling with rotor rings **143** which are capable of operating at high speeds of rotation. The rings **142** and **143** form nearly frictionless capacitor couplings. The transformers **141**, **144** of the transmission line step up the impedance level at the capacitor couplings to increase the time constant of the capacitor circuit. The wideband transformers **141** and **144** raise the impedance level at the dielectric boundary by a factor of K in order to increase the transmission efficiency across the rotation boundary.

[0072] Wideband transmission-line transformers and baluns are extensively used in circuit applications covering a few MHz to a few GHz. Multiple designs have been described in literature covering transformation ratios up to approximately 64:1. In general, any impedance ratio of the form (M^2/N^2), in which M and

N are integers, can be realized using the wideband transmission-line concepts.

[0073] In principal, the impedance level, KZ_0, can be comparatively large. However, practical circuit limitations will usually constrain KZ_0 to a maximum of approximately 600 Ohms. Assuming that the coupling capacitance between the concentric rotor ring **143** and the stator ring **145** is 10 pico-Farad (pF), the period T_S of the square-wave generator **140** will be constrained by $T_S < 2RC$, or $T_S < 2[(600) \times (10^{-11})]$, or $T_S < 12$ nano-seconds. Thus, the frequency of the square-wave would be about 50 MHz, which is well within the practical limitations of the disclosed method. A coupling capacitance of approximately 10 pF would correspond to a concentric cylinder mean diameter of two centimeters (cm), a cylindrical height of two cm, and a separation between the concentric cylinders of one millimeter. The calculation assumes that the medium separating the concentric cylinders has a relative dielectric constant of unity, which would correspond to dry air or a vacuum.

[0074] In the embodiment illustrated in **FIG. 14**, the generator **140** converts a DC source **147** with internal impedance Z_0, to a zero average value square-wave source at the impedance level, Z_0. The output of the generator **140** drives the wideband transmission-line transformer **141** that raises the impedance level of the square-wave source to KZ_0. The output of the transmission line of the transformer **141** is connected to the stator rings **142** and **145** of a rotary coupling mechanism comprising the capacitance between the concentric rings **143**. The rotating inner rings **143** form the output circuit of the coupling mechanism. For the purposes of illustration, the inner rings **143** are assumed to rotate while the outer stator rings **142** and **145** remain stationary. In practice, either ring **142** or **145** could operate like the rotating ring **143** without affecting the operation of the disclosed method. In some instances, all of the rings may rotate simultaneously.

[0075] The inner rotor rings **143** are connected to the transmission line transformer **144** that reduces the impedance level of the square-wave to Z_0. The output of the second transmission line transformer **144** feeds a converter **148** that converts the square-wave to a direct current, which feeds a load resistor, Z_0 (**149**). In this embodiment, the load at the load resistor **149**, the converter **148**, and the transformer **144** are assumed to be mounted on a rotor-mounted component **200**, which may, for example, be the wheel of a vehicle, the rotating field of an electromechanical device, the propeller of a boat, or other free-to-rotate structure. Stator mounted components include the step-up transformer **141**, the square-wave generator **140**, and the DC source **147**.

[0076] The practical usefulness of the disclosed method can be related to the power that can be delivered to the rotating platform; however, there is a limitation on the amount of power that can be delivered to a load using the disclosed method. The limitation is fixed by the non-linear properties of the diode used in the converter circuit. The maximum current that can be delivered to a load is one-half of the maximum forward current that the diode can safely carry. The maximum voltage that can be delivered to a load is one-half of the breakdown voltage of the diode. The maximum DC power that can be delivered to a load is the product of one-half of the forward current and one-half of the breakdown voltage. For example, a diode with a reverse breakdown voltage of 100 Volts may be able to support a maximum forward current of one ampere. Then, the maximum power that could be delivered to a resistive load by a converter that uses this diode would be 25 Watts (50 Volts X 500 mA).

[0077] Furthermore, the switching speed of the converter diode is limited by a junction capacitance of the converter diode, which also determines the current handling capacity of the junction. The switching speed should be less than ten percent of the square-wave period, T_S. Thus, as the coupling capacitance of the concentric-cylinder coupling mechanism is increased, the square-wave period can be proportionately increased. Then, because the required diode switching speed can be increased, the converter diode junction area can be proportionately increased, which results in a proportionately higher current-handling capability and proportionately higher power can be delivered to the load. In principal, the disclosed method is scalable to the large power levels that would be needed to power air compressors on the wheels of a moving vehicle.

[0078] It will be understood that many additional changes in details, materials, steps and arrangement of parts which have been described herein and illustrated in order to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention as expressed in the appended claims. Further, those skilled in the art will recognize that a dual coupling mechanism using magnetically coupled coils is an obvious extension of the disclosed method and is implicitly included in the principle and scope of the invention.

ABSTRACT

A system and method is provided for coupling a power source across a rotation boundary. A generator converts a DC source on the stationary side of a rotation boundary to a square-wave at a determined frequency. The generator output connects through a transmission line and a first transformer to a set of stator rings. A set of rotor rings form a set of coupling capacitors with the stator rings. The rotor rings connect through a second transformer and a transmission line to a non-linear circuit capable of converting the square-wave to a DC voltage and current that can power a load on the rotating side of the rotating boundary in which the power is nearly equal to the power available from the source on the stationary side of the rotation boundary.

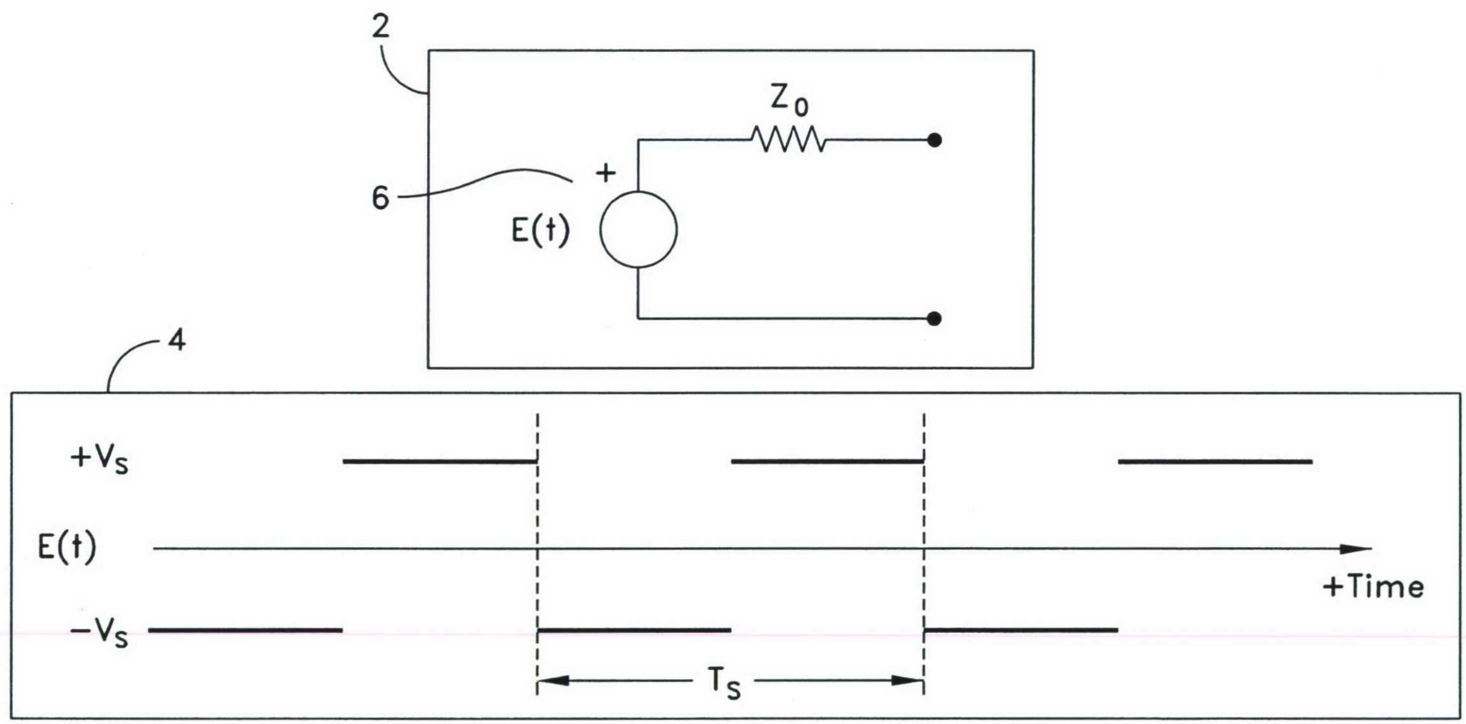


FIG. 1

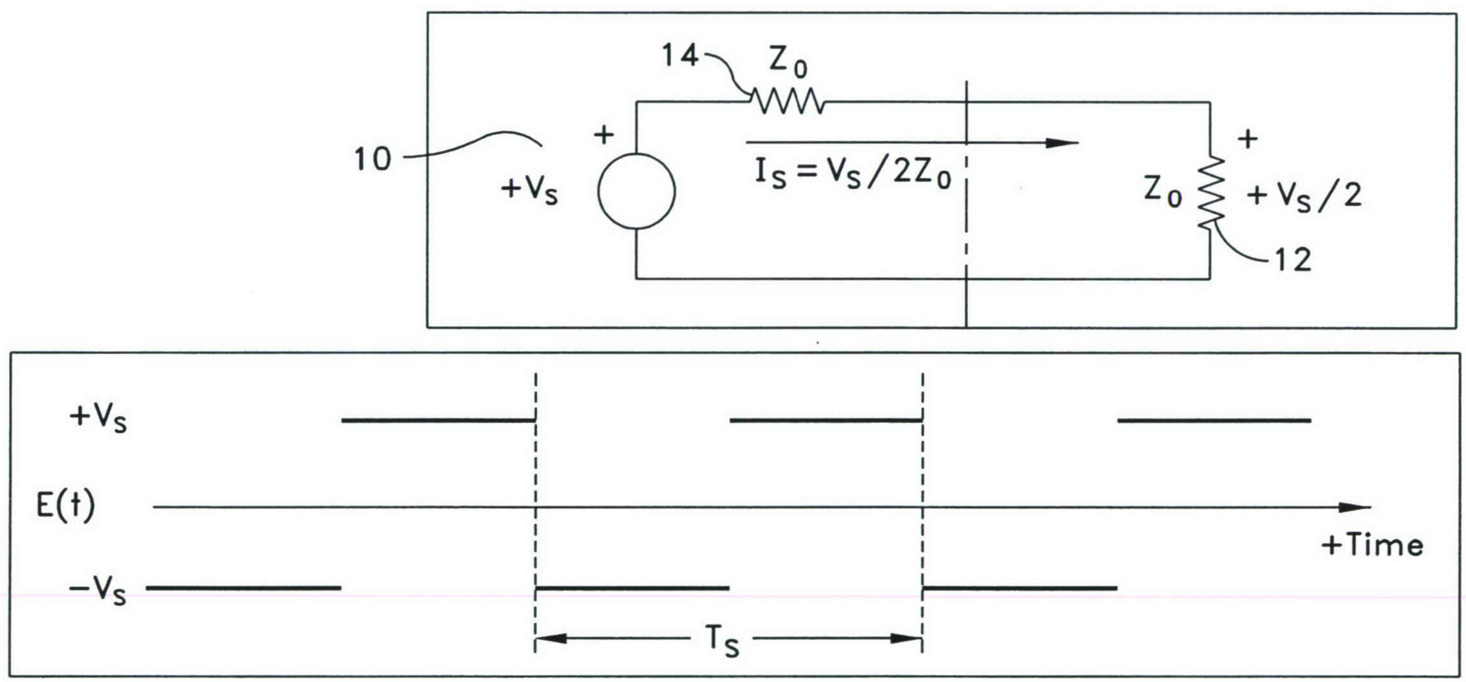


FIG. 2

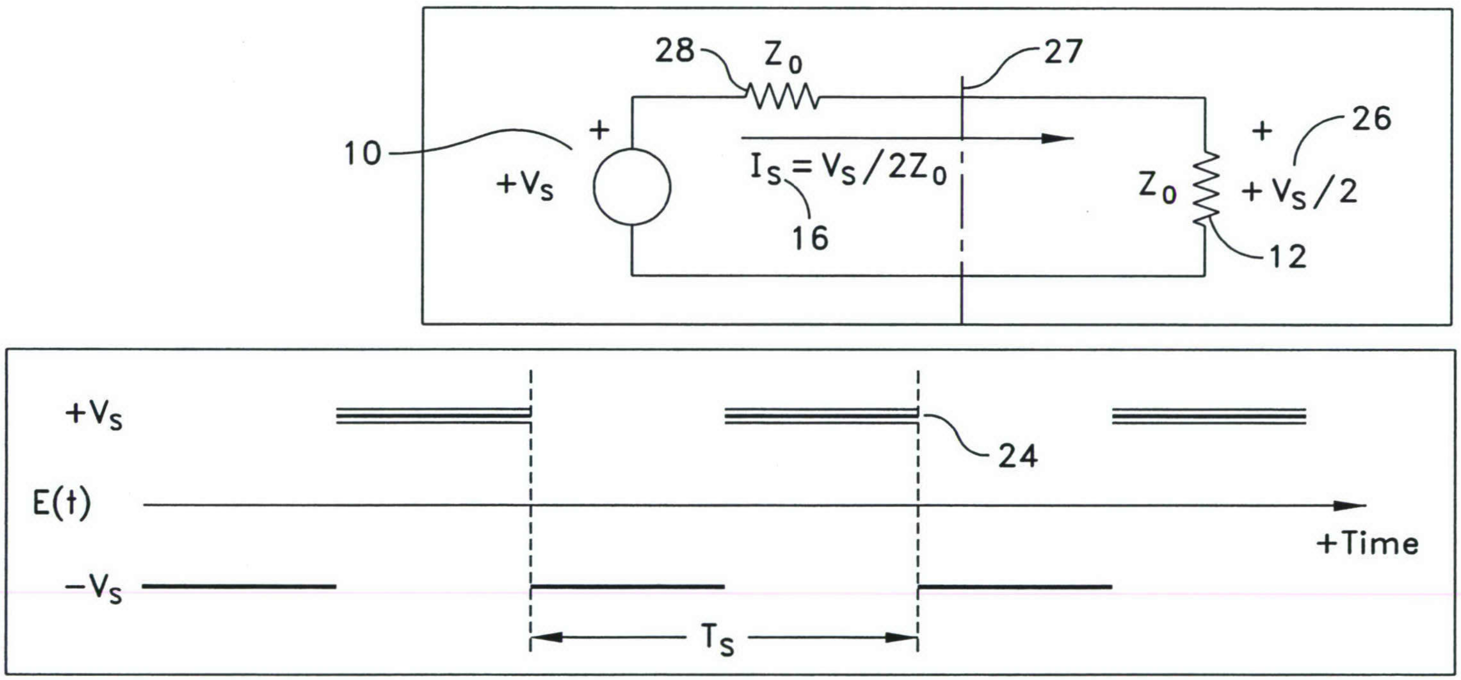


FIG. 3

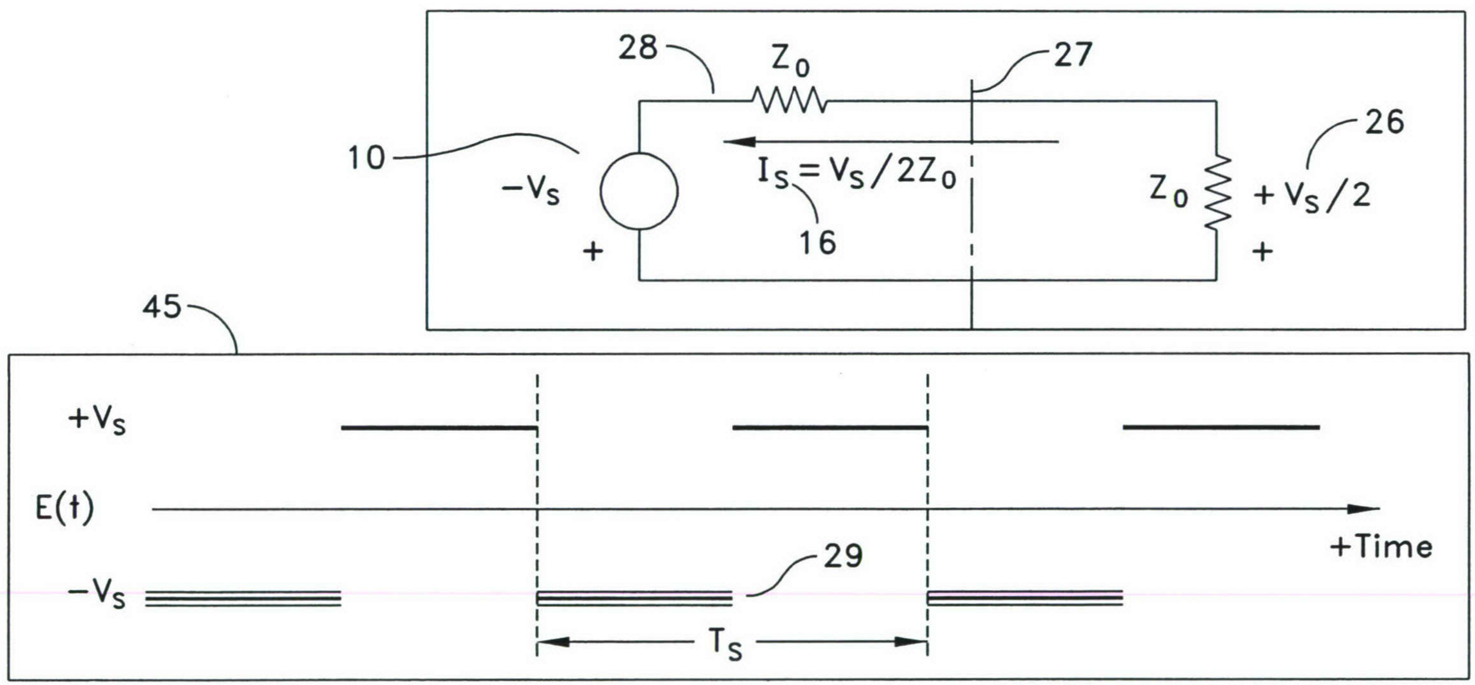
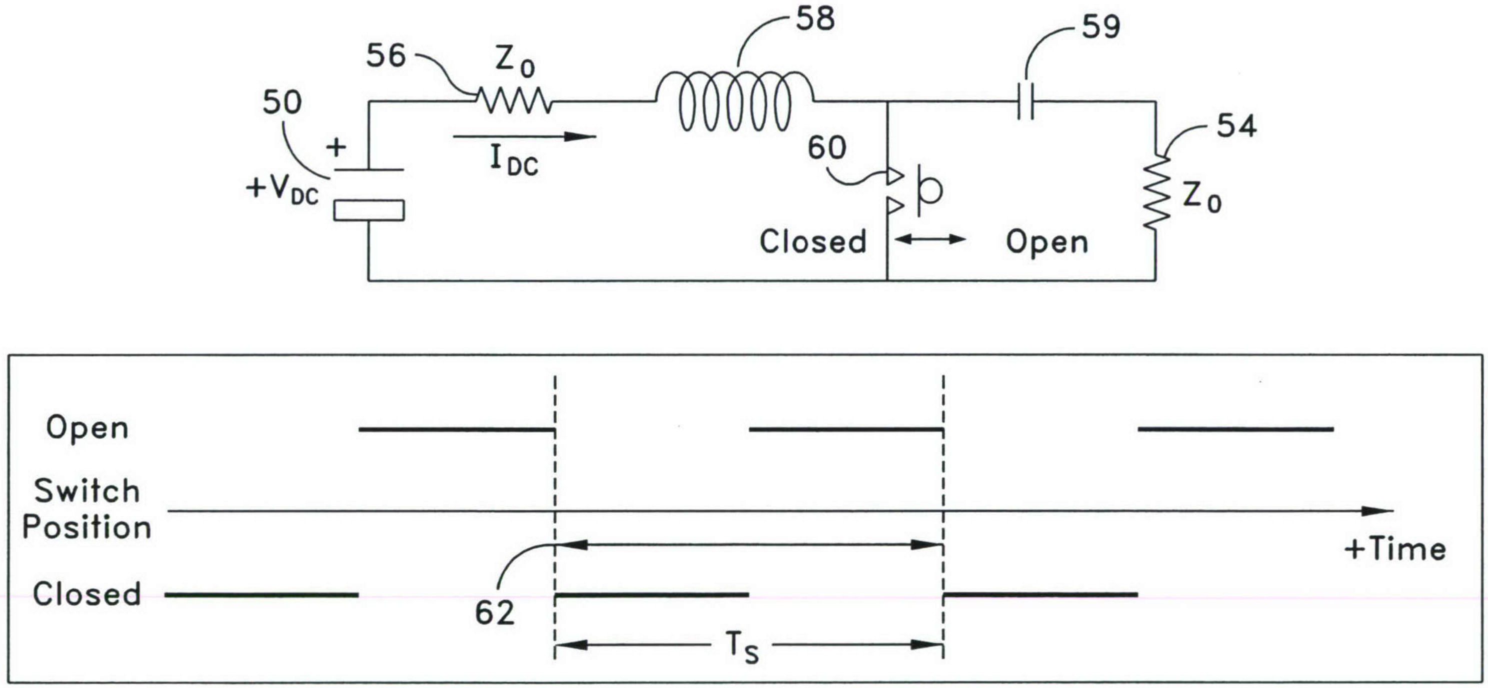
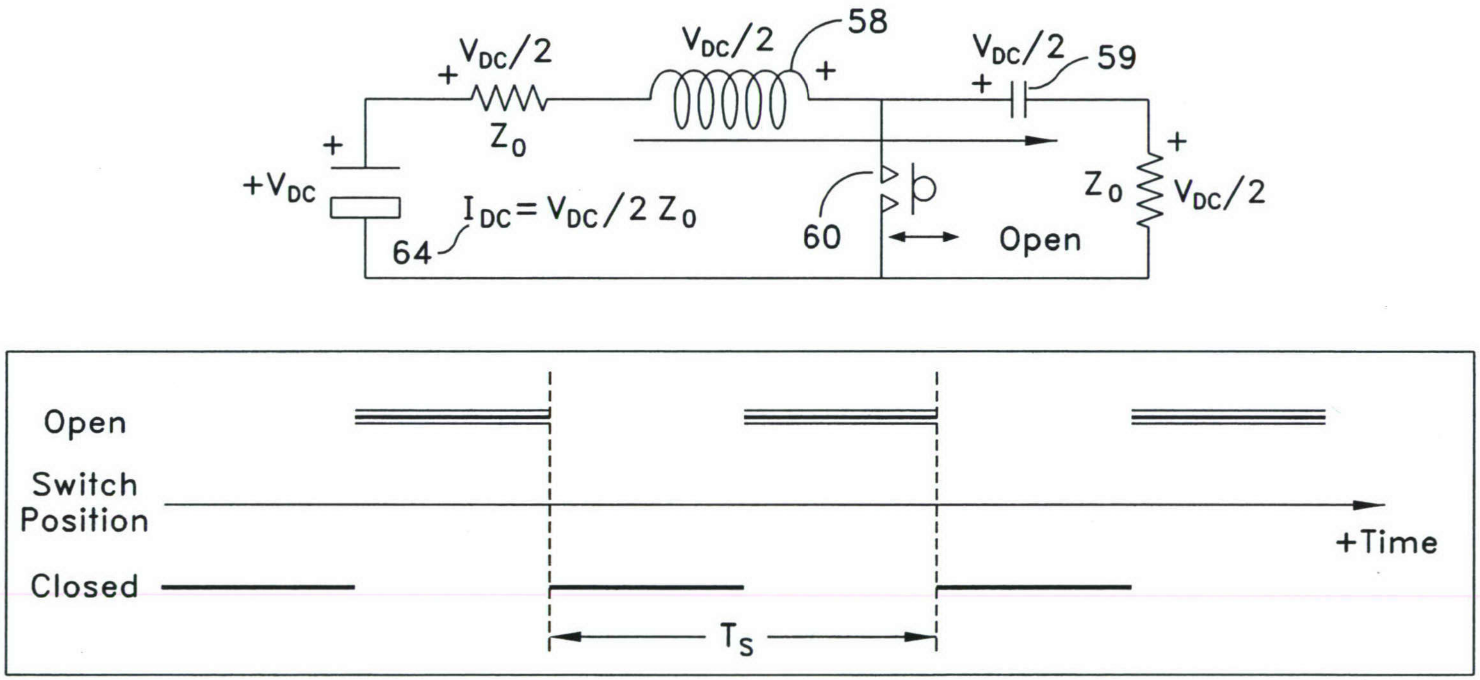


FIG. 4



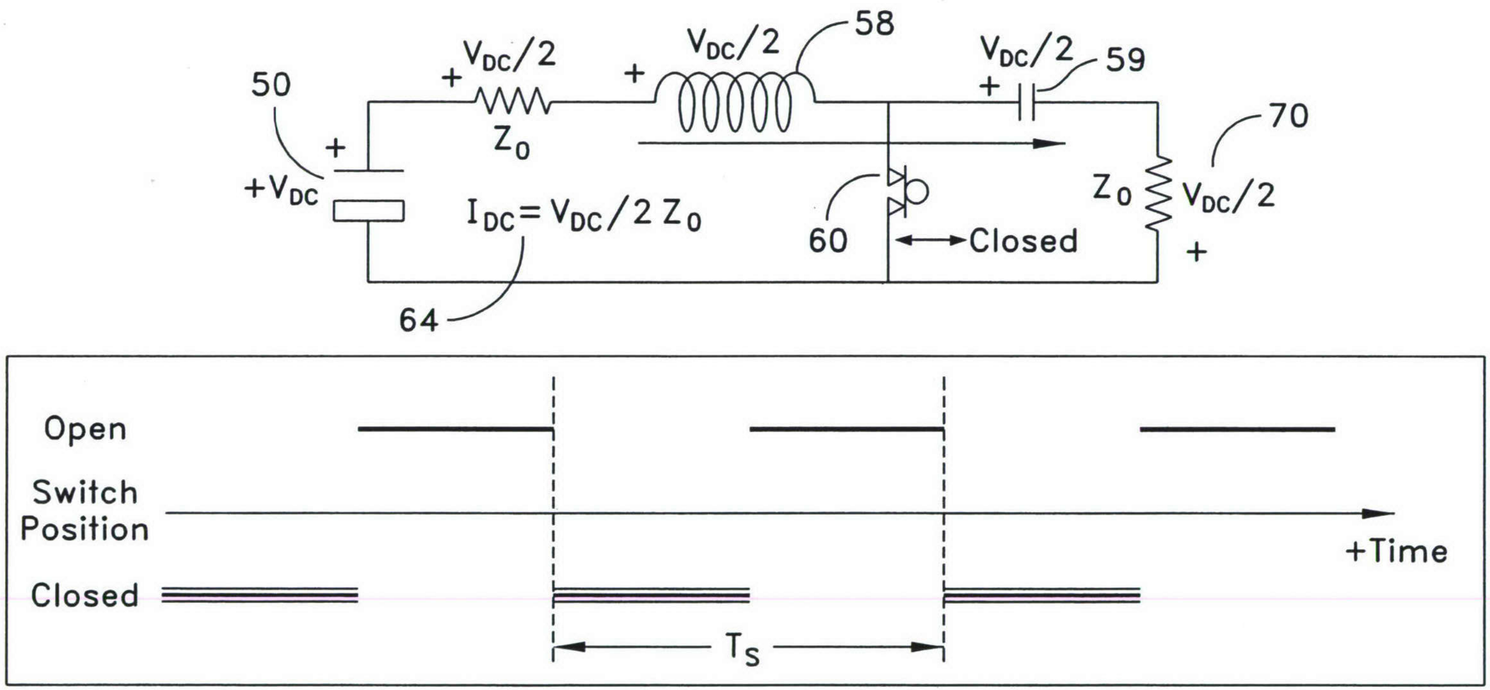
50
+V_DC
+
56
Z0
I_DC
58
60
Closed
Open
59
54
Z0
Open
Switch
Position
Closed
62
T_S
+Time

FIG. 5



+VDC
+
VDC/2
Z0
VDC/2
58
+
VDC/2
59
IDC = VDC/2 Z0
64
60
Open
Z0
VDC/2
Open
Switch
Position
Closed
+Time
TS

FIG. 6



50
+
$+V_{DC}$
$V_{DC}/2$
+
Z_0
$V_{DC}/2$
+
58
$V_{DC}/2$
+
59
70
Z_0
$V_{DC}/2$
+
$I_{DC}=V_{DC}/2\,Z_0$
64
60
Closed
Open
Switch
Position
Closed
+Time
T_S

FIG. 7

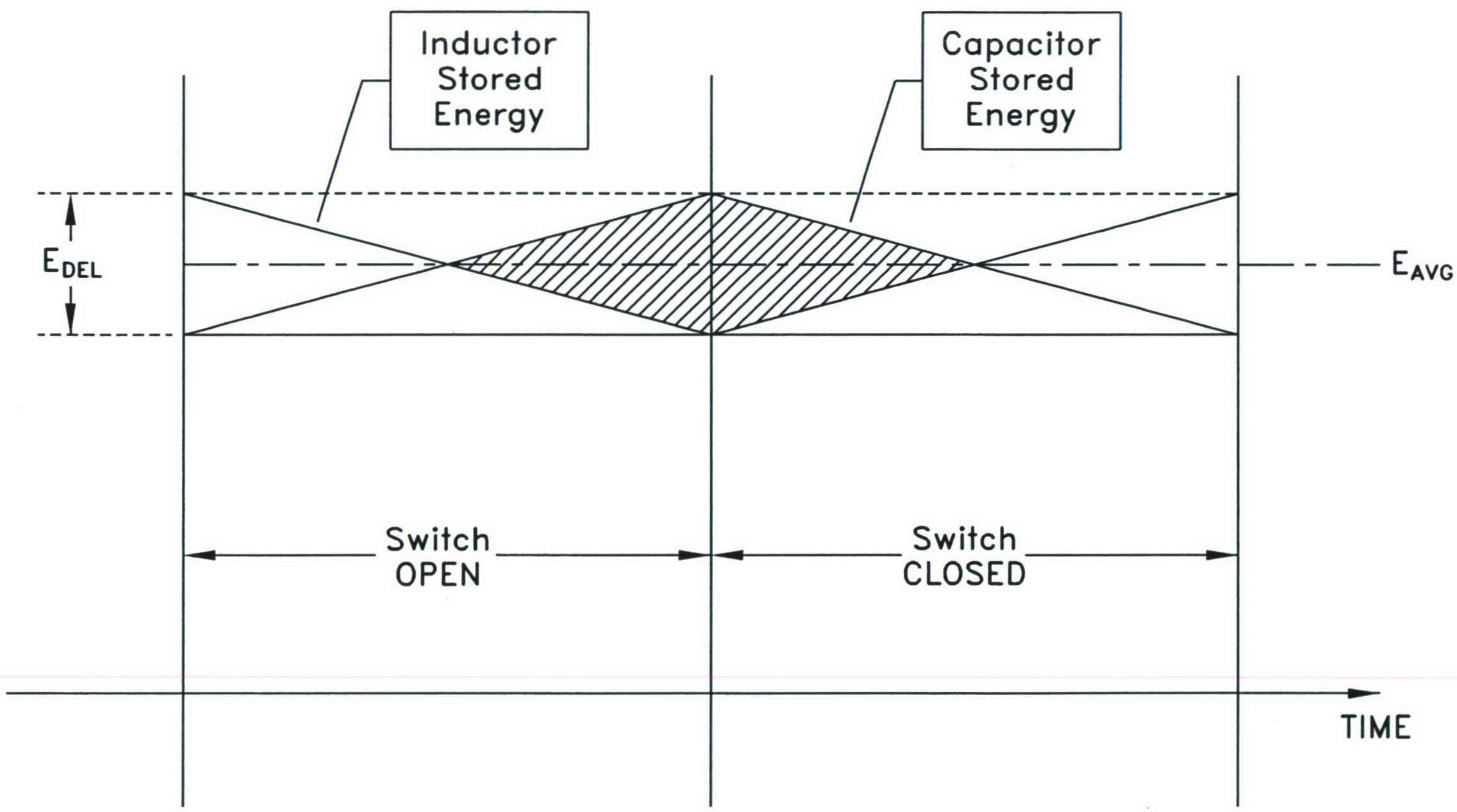

Inductor Stored Energy
Capacitor Stored Energy
EDEL
EAVG
Switch OPEN
Switch CLOSED
TIME

FIG. 8

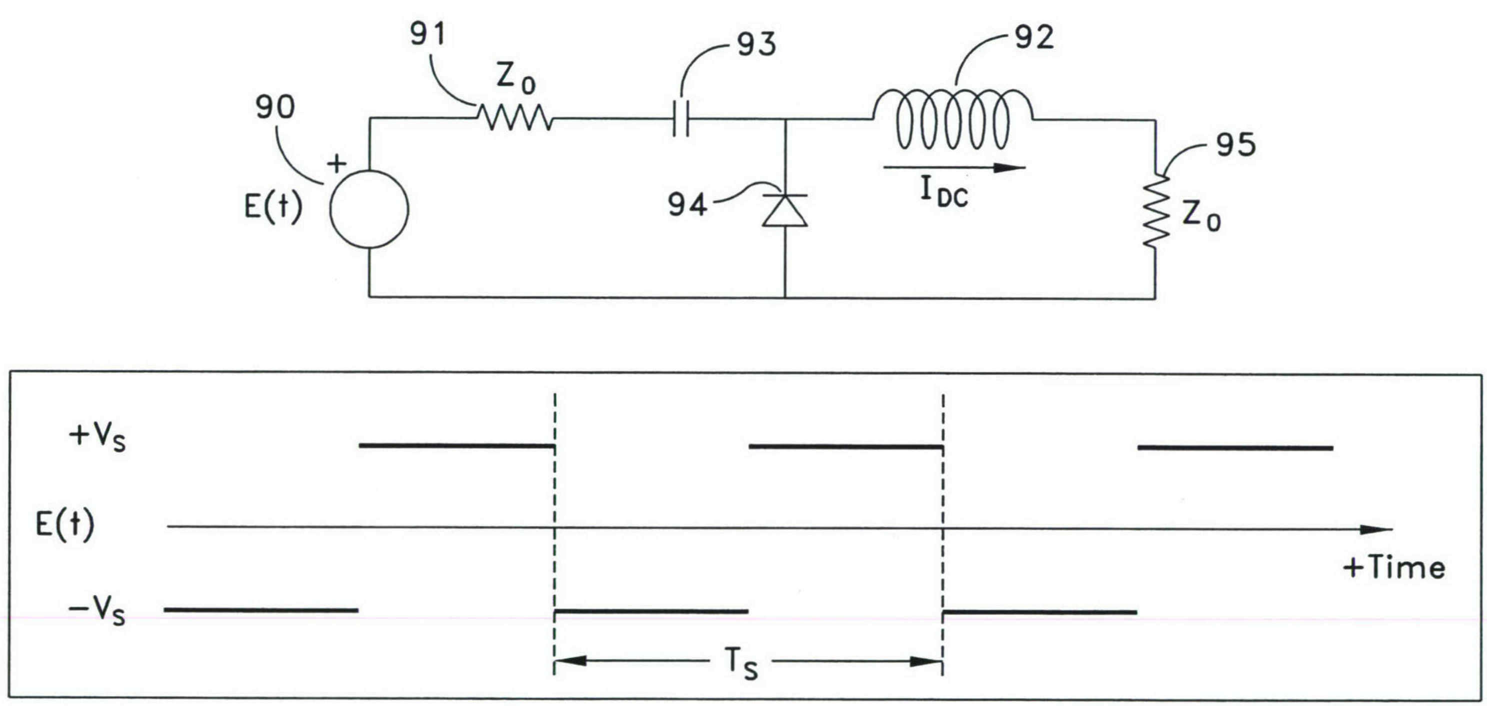
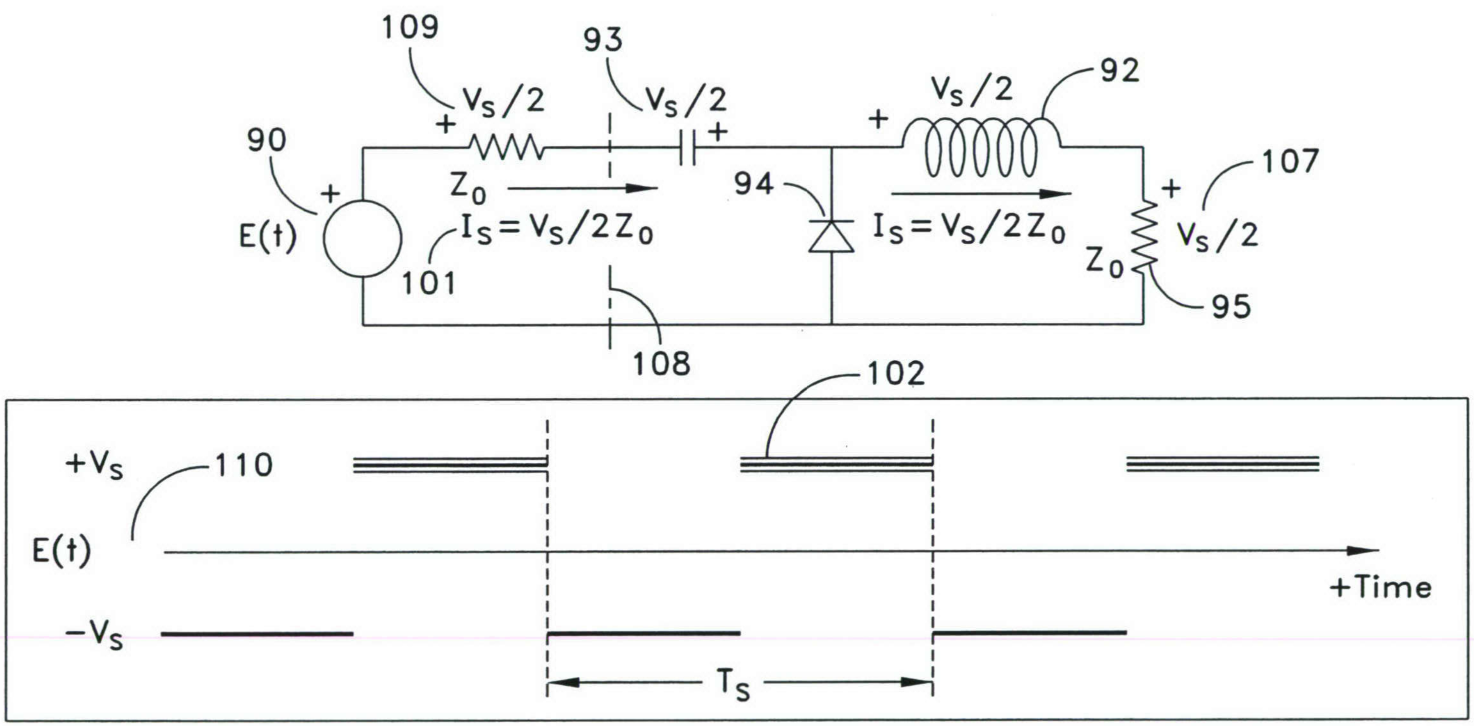


FIG. 9



109
93
92
90
+
Vs/2
Vs/2
+
+
Vs/2
Z0
Is=Vs/2Z0
94
Is=Vs/2Z0
107
+
Vs/2
E(t)
101
Z0
95
108
102
+Vs
110
E(t)
+Time
−Vs
Ts

FIG. 10

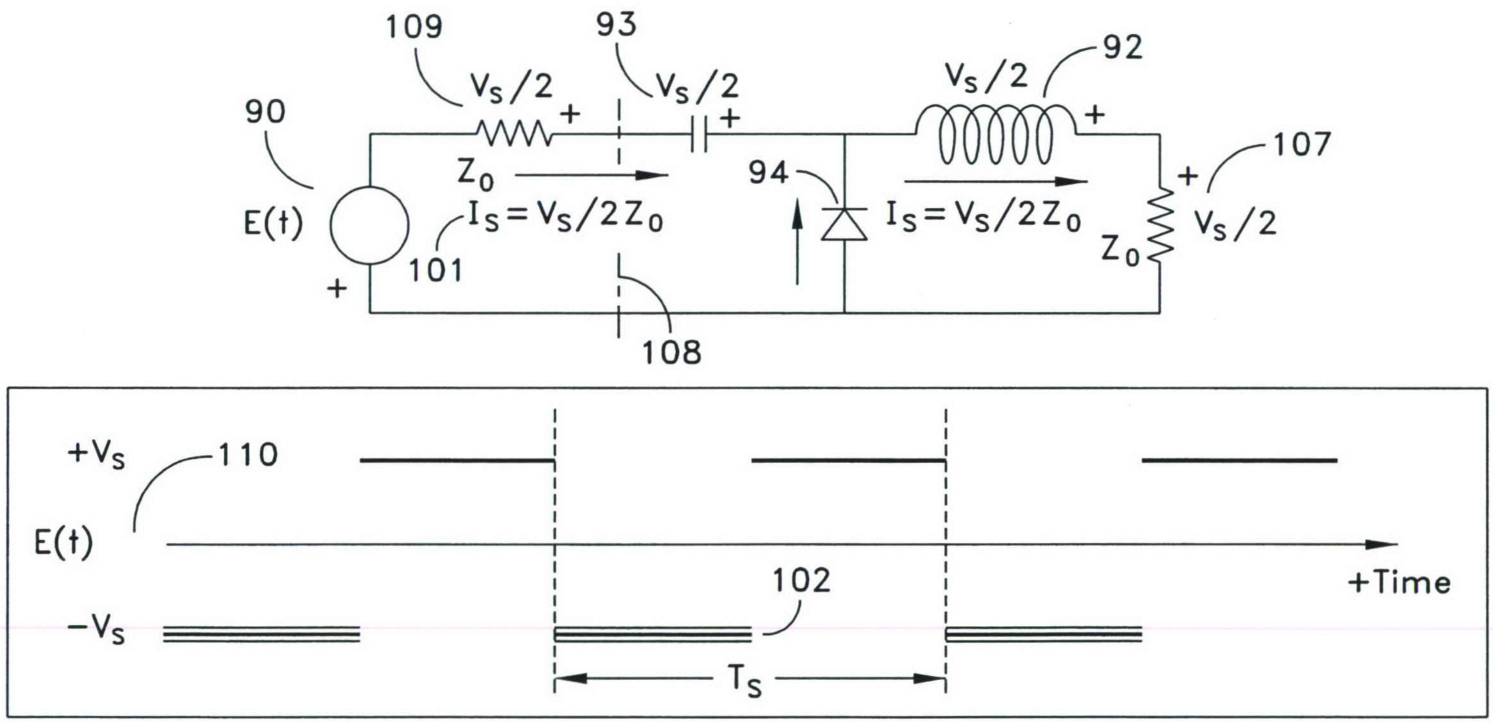

109
93
92
90
Vs/2
Vs/2
Vs/2
+
+
+
Z0
E(t)
Is=Vs/2Z0
101
94
Is=Vs/2Z0
107
+
Vs/2
Z0
+
108
+Vs
110
E(t)
+Time
102
−Vs
Ts

FIG. 11

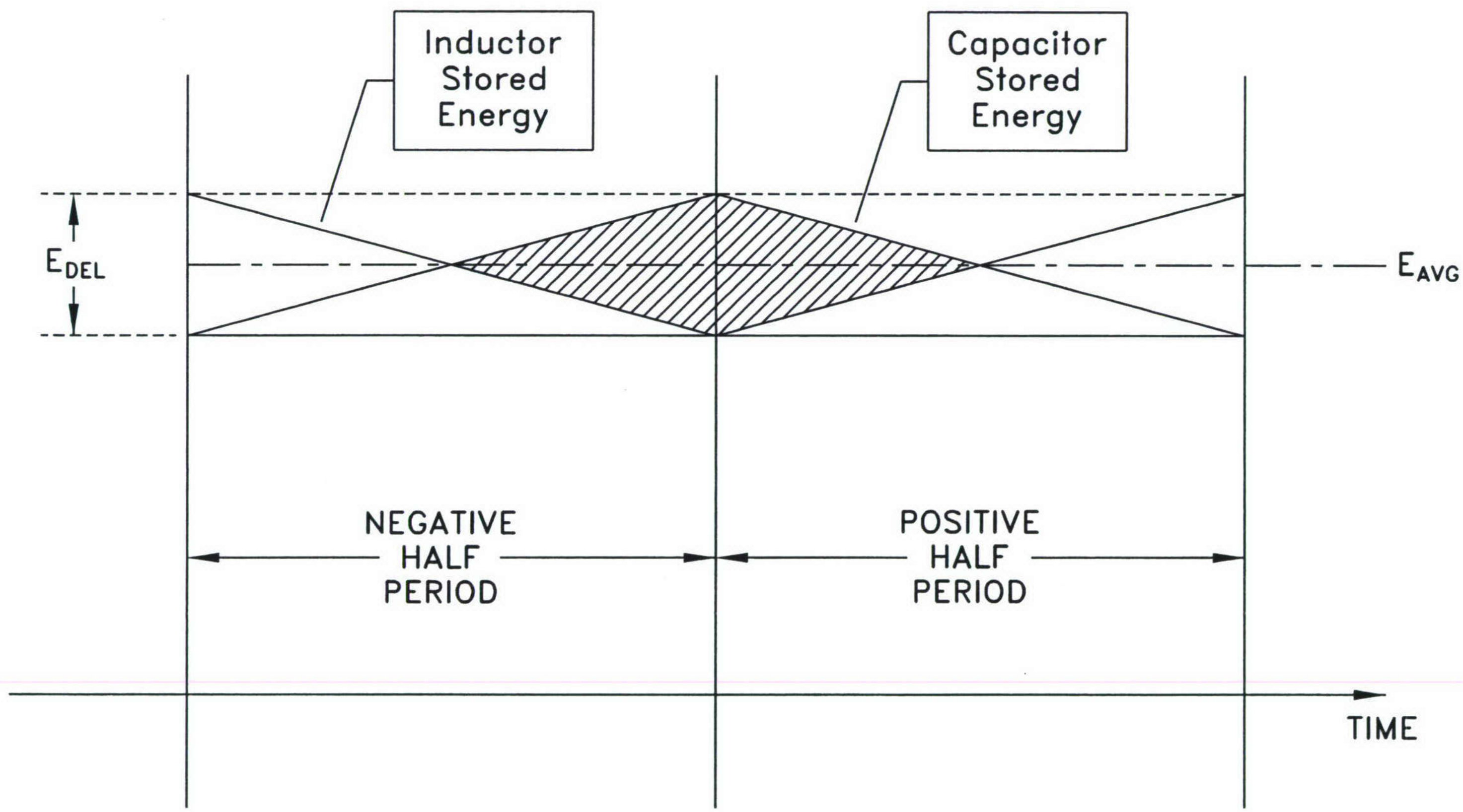

Inductor Stored Energy
Capacitor Stored Energy
E_{DEL}
E_{AVG}
NEGATIVE HALF PERIOD
POSITIVE HALF PERIOD
TIME

FIG. 12

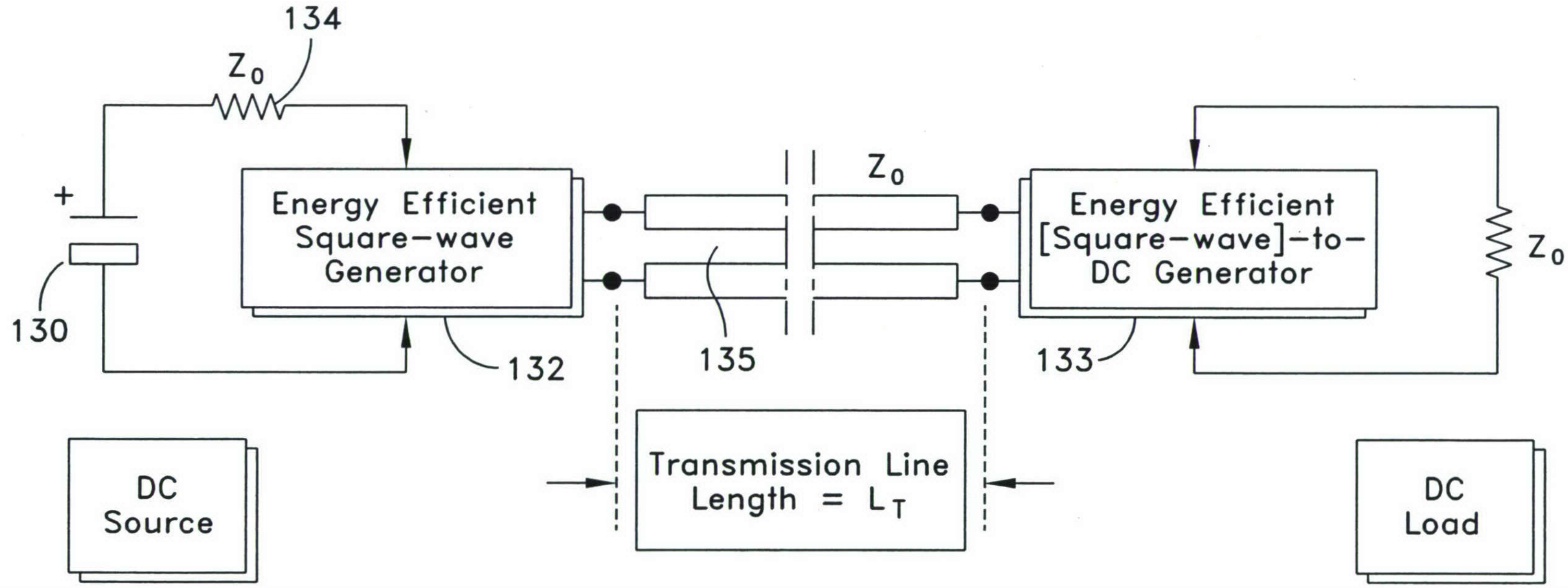

134
Z0
+
130
Energy Efficient
Square-wave
Generator
132
135
Z0
Energy Efficient
[Square-wave]-to-
DC Generator
133
Z0
DC
Source
Transmission Line
Length = LT
DC
Load

FIG. 13

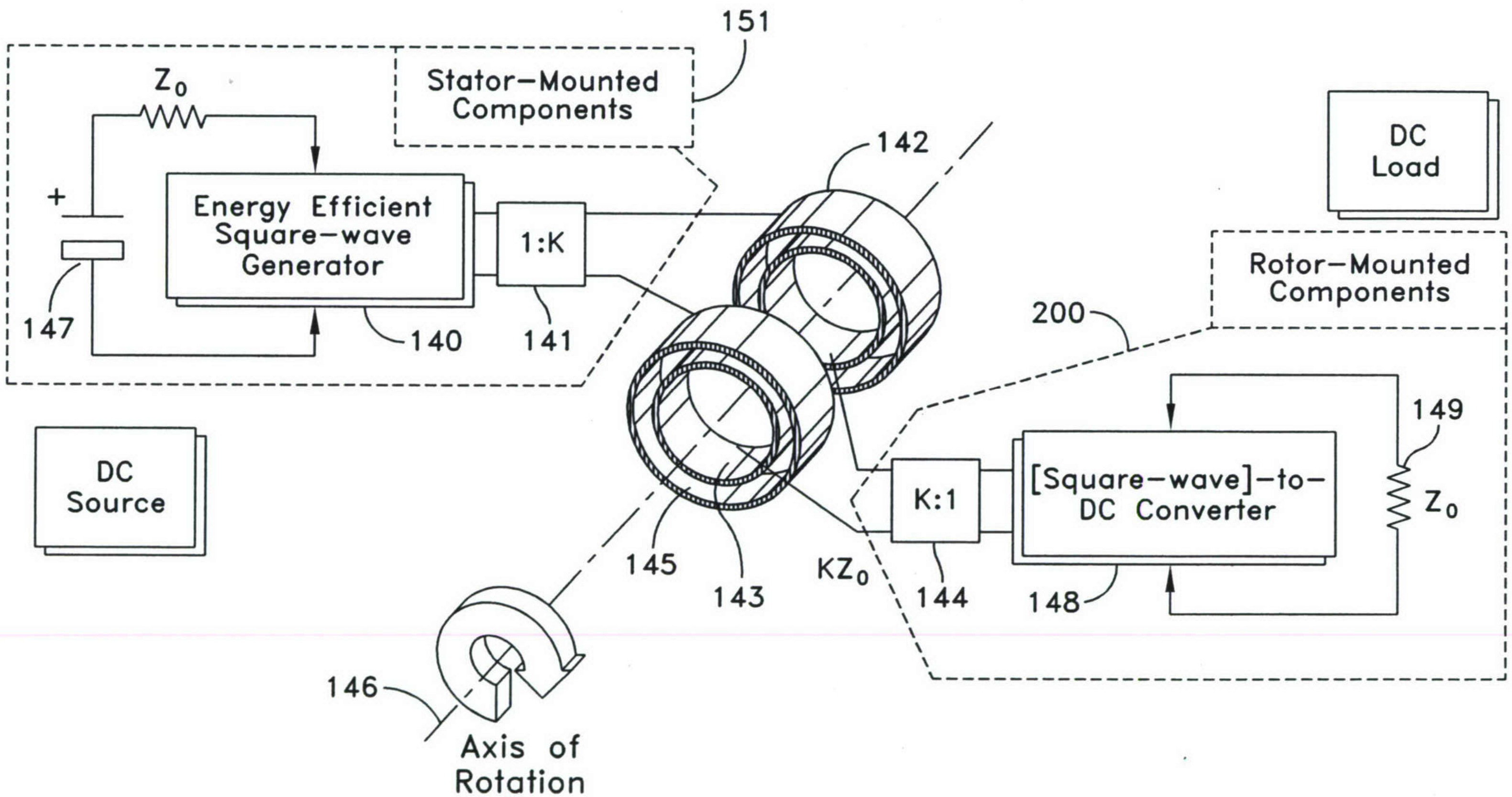

151
Stator–Mounted Components
Z_0
+
Energy Efficient Square–wave Generator
1:K
147
140
141
142
DC Load
Rotor–Mounted Components
200
149
[Square–wave]–to–DC Converter
Z_0
K:1
DC Source
145
143
KZ_0
144
148
146
Axis of Rotation

FIG. 14