Office de la Propriété Intellectuelle du Canada
Un organisme d'Industrie Canada

Canadian Intellectual Property Office
An agency of Industry Canada

CA 2945016 A1 2015/10/15

(21) **2 945 016**

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) **A1**

(86) Date de dépôt PCT/PCT Filing Date: 2015/04/07
(87) Date publication PCT/PCT Publication Date: 2015/10/15
(85) Entrée phase nationale/National Entry: 2016/10/05
(86) N° demande PCT/PCT Application No.: US 2015/024723
(87) N° publication PCT/PCT Publication No.: 2015/157290
(30) Priorité/Priority: 2014/04/07 (US61/975,997)

(51) Cl.Int./Int.Cl. *H03K 4/06* (2006.01)
(71) Demandeur/Applicant:
LOCKHEED MARTIN CORPORATION, US
(72) Inventeurs/Inventors:
KRAUSE, JAMES MICHAEL, US;
MABRY, JAMES P., US;
PEPA, ELTON, US
(74) Agent: GOWLING WLG (CANADA) LLP

(54) Titre : CIRCUIT GENERATEUR DE CHAMP MAGNETIQUE A COMMANDE ORIENTEE VERS L'EFFICACITE ENERGETIQUE

(54) Title: ENERGY EFFICIENT CONTROLLED MAGNETIC FIELD GENERATOR CIRCUIT

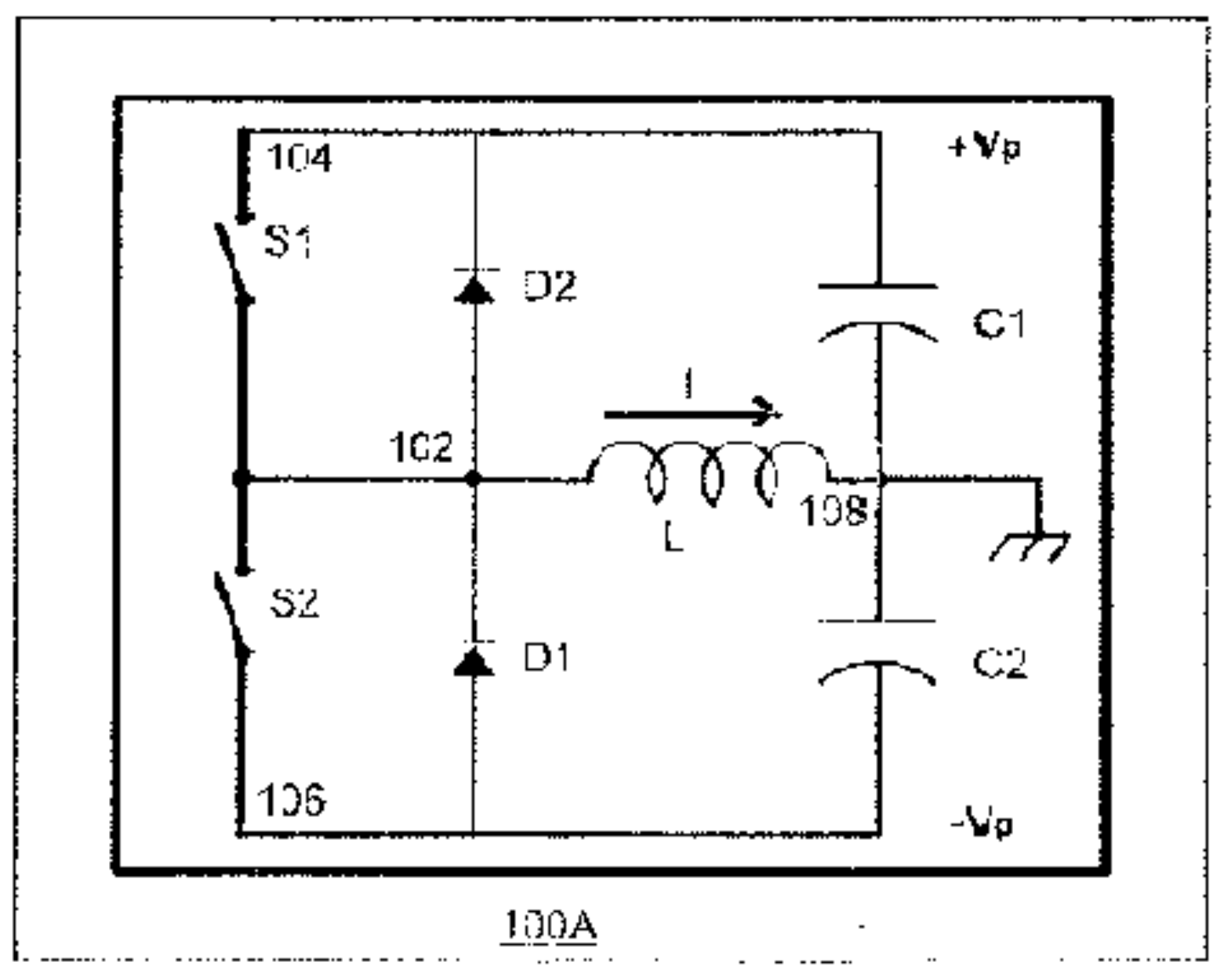

FIG. 1A

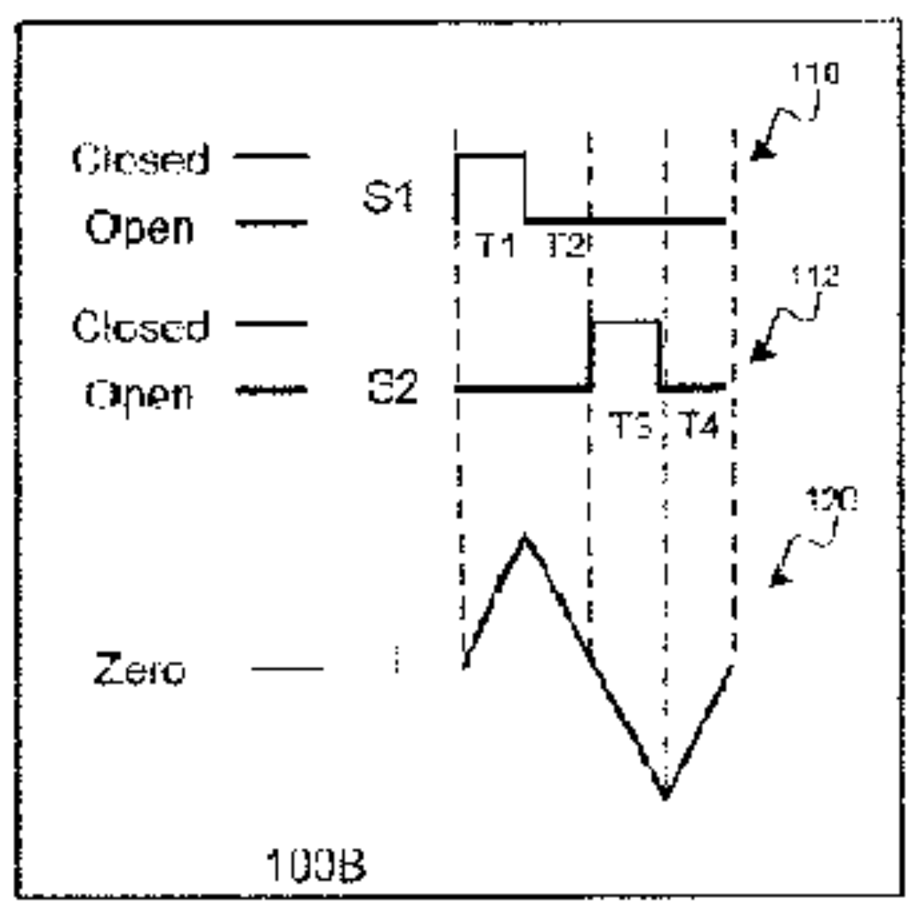

FIG. 1B

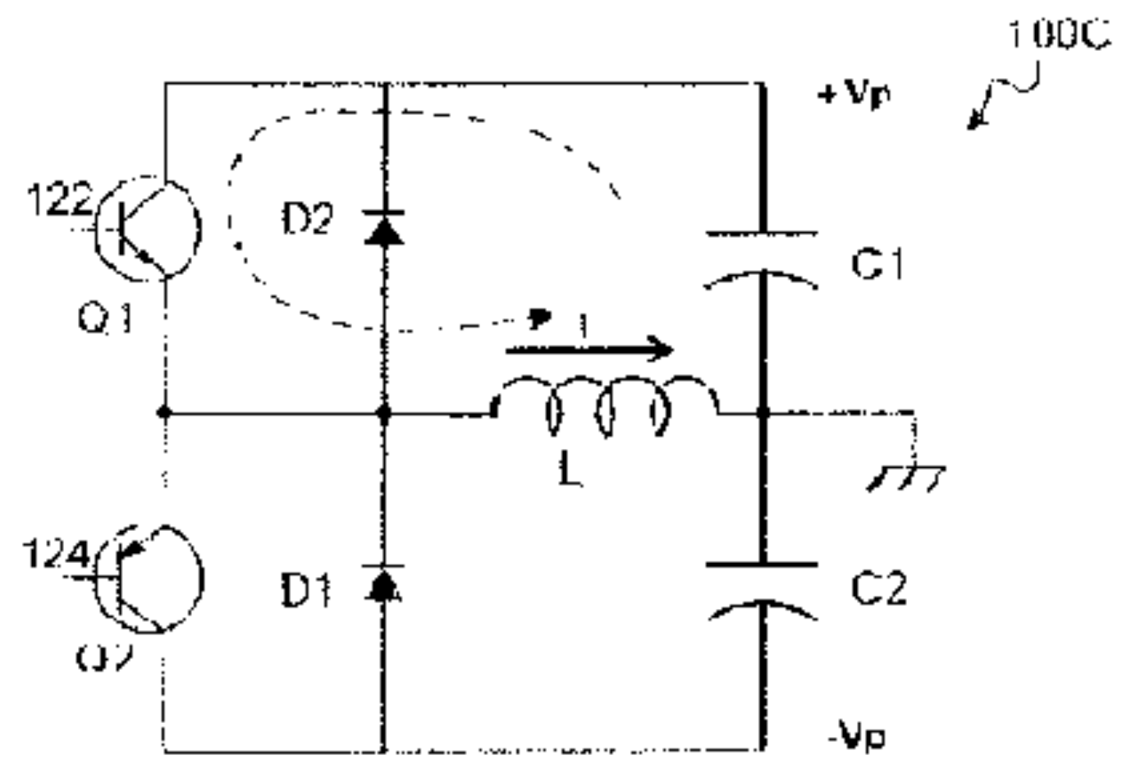

FIG. 1C

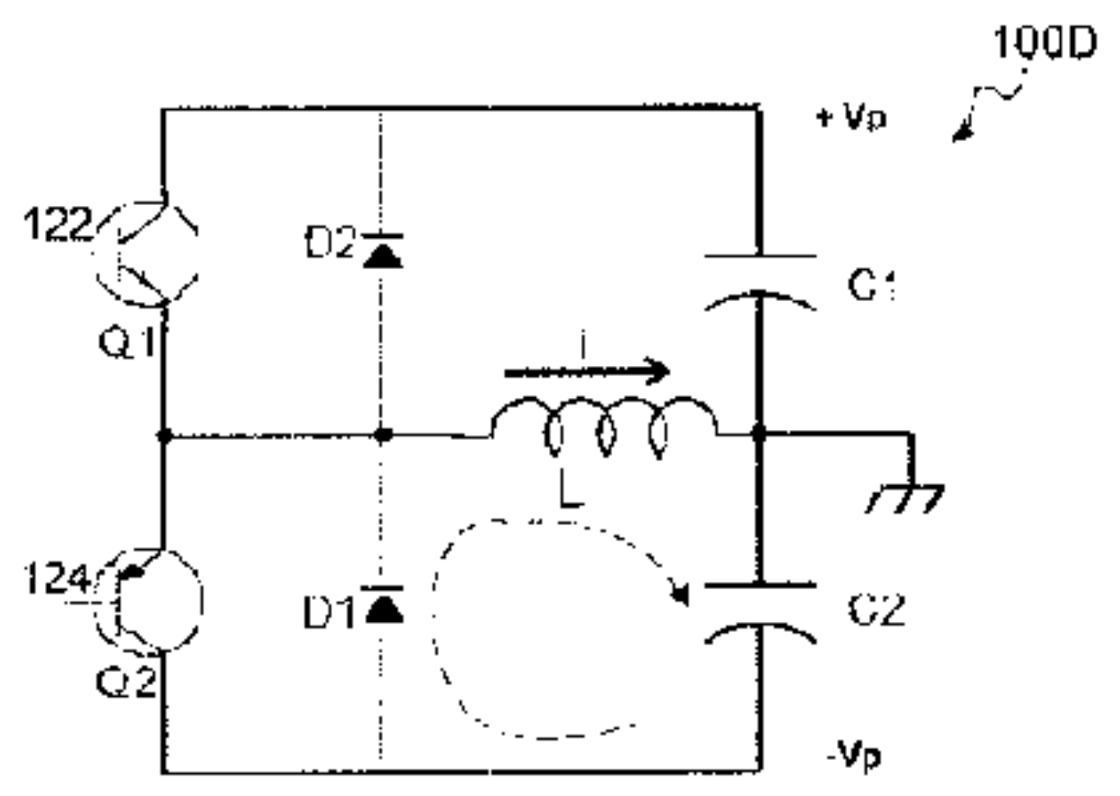

FIG. 1D

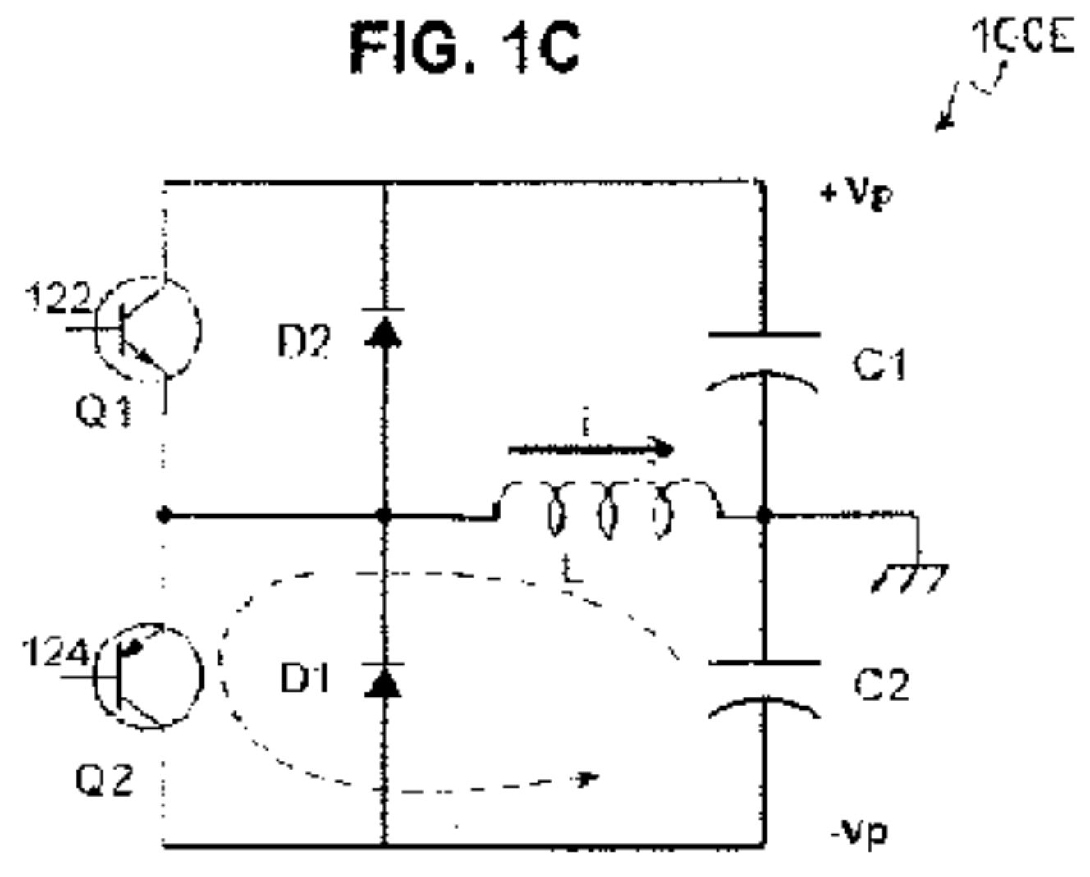

FIG. 1E

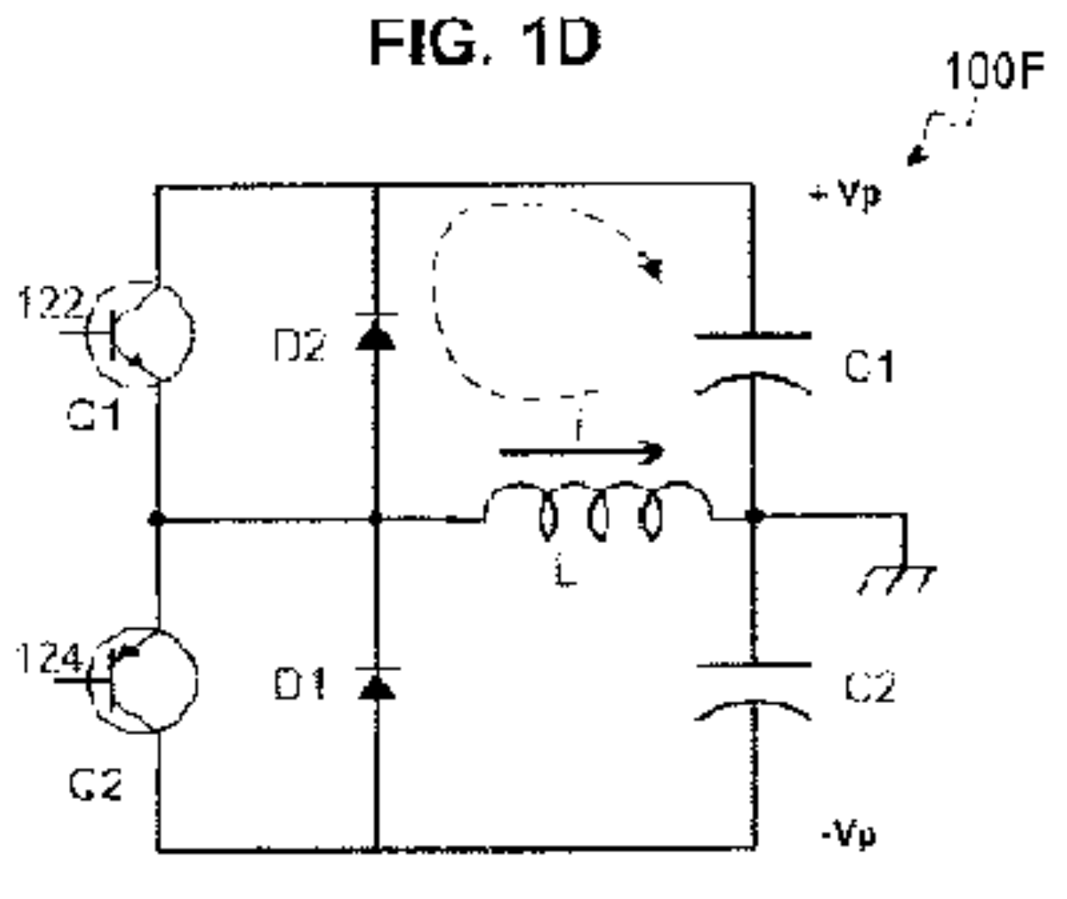

FIG. 1F

(57) Abrégé/Abstract:

A magnetic waveform generator circuit includes a first switch coupled to a first rectifier element at a first node, a first capacitor coupled, at a second node to the first switch, and to a fourth node, a second capacitor coupled, at a third node to the first rectifier element, and to the fourth node, and an inductor coupled between the first and the fourth nodes. The first switch is operable to be in an ON state during a first time period and in an off state during a second time period. The first switch and the first rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
15 October 2015 (15.10.2015)

(10) **International Publication Number**
WO 2015/157290 A1

(51) **International Patent Classification**:
H02M 7/12 (2006.01)

(21) **International Application Number**:
PCT/US2015/024723

(22) **International Filing Date**:
7 April 2015 (07.04.2015)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
61/975,997 7 April 2014 (07.04.2014) US

(71) **Applicant**: **LOCKHEED MARTIN CORPORATION** [US/US]; 6801 Rockledge Drive, Bethesda, MD 20817-1877 (US).

(72) **Inventors**: **KRAUSE, James Michael**; 5651 Parnell Avenue NE, Saint Michael, MN 55376 (US). **MABRY, James P.**; 2015 Approach Lane, Reston, VA 20191 (US). **PEPA, Elton**; 4309 Fallstone Place, Dumfries, VA 22025 (US).

(74) **Agent**: **ITRI, Mark J.**; Mcdermott Will & Emery LLP, 4 Park Plaza, Suite 1700, Irvine, CA 92614 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

[Continued on next page]

(54) Title: ENERGY EFFICIENT CONTROLLED MAGNETIC FIELD GENERATOR CIRCUIT

(57) **Abstract**: A magnetic waveform generator circuit includes a first switch coupled to a first rectifier element at a first node, a first capacitor coupled, at a second node to the first switch, and to a fourth node, a second capacitor coupled, at a third node to the first rectifier element, and to the fourth node, and an inductor coupled between the first and the fourth nodes. The first switch is operable to be in an ON state during a first time period and in an off state during a second time period. The first switch and the first rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

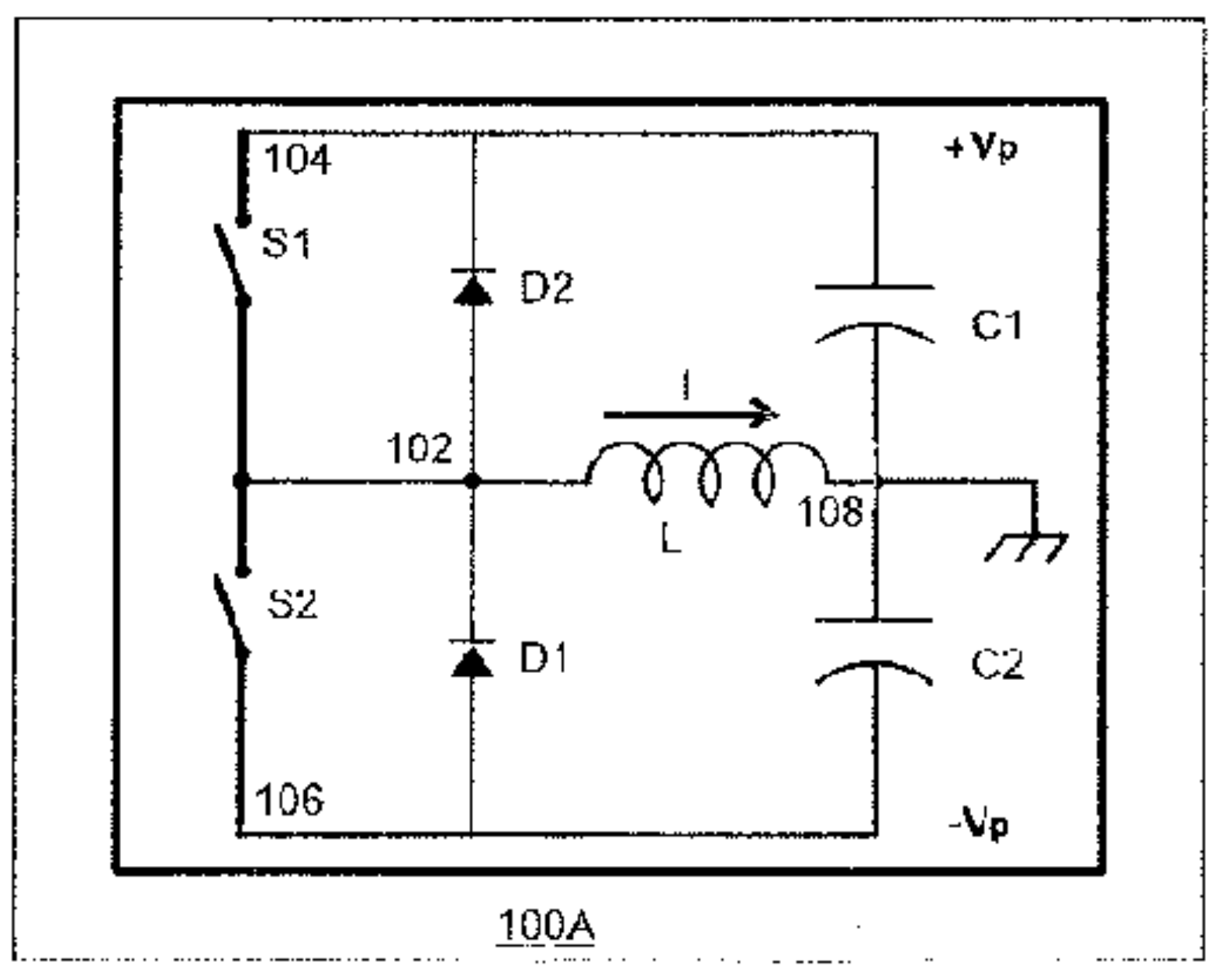

FIG. 1A

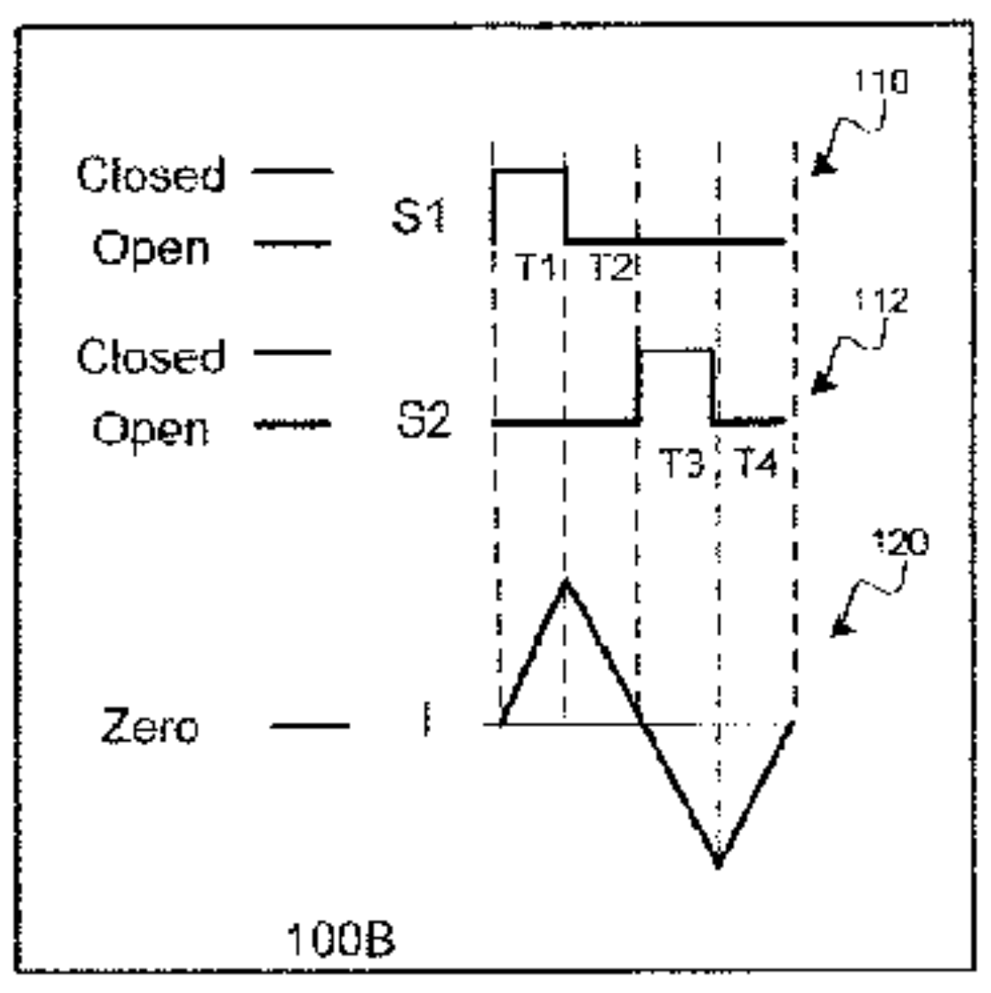

FIG. 1B

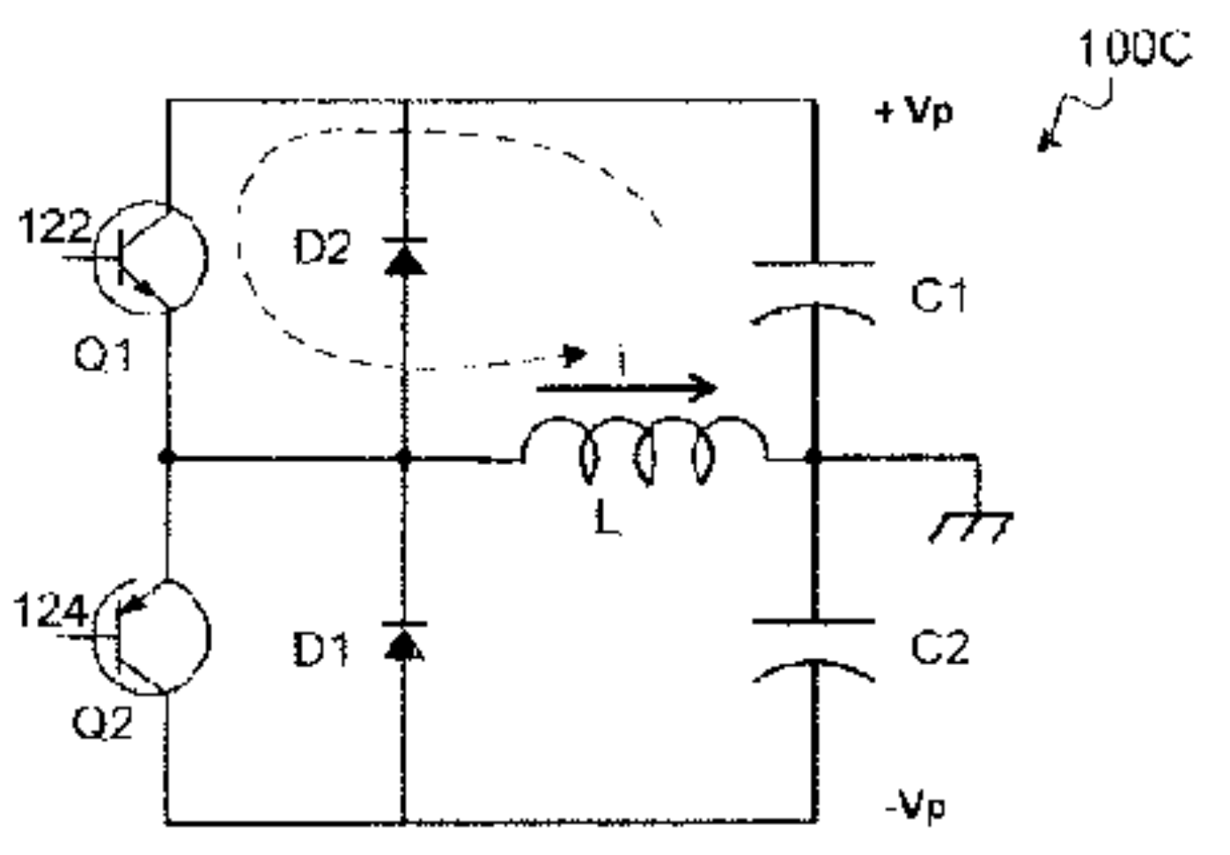

FIG. 1C

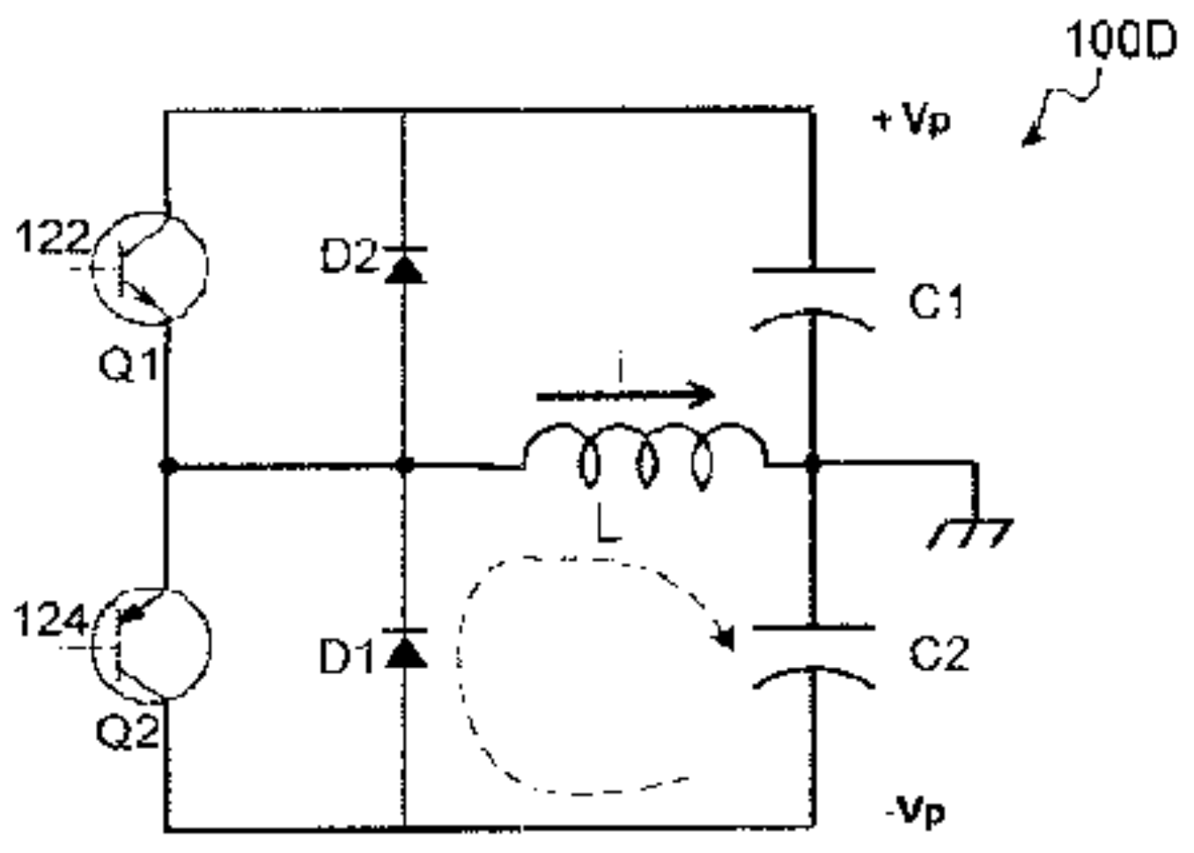

FIG. 1D

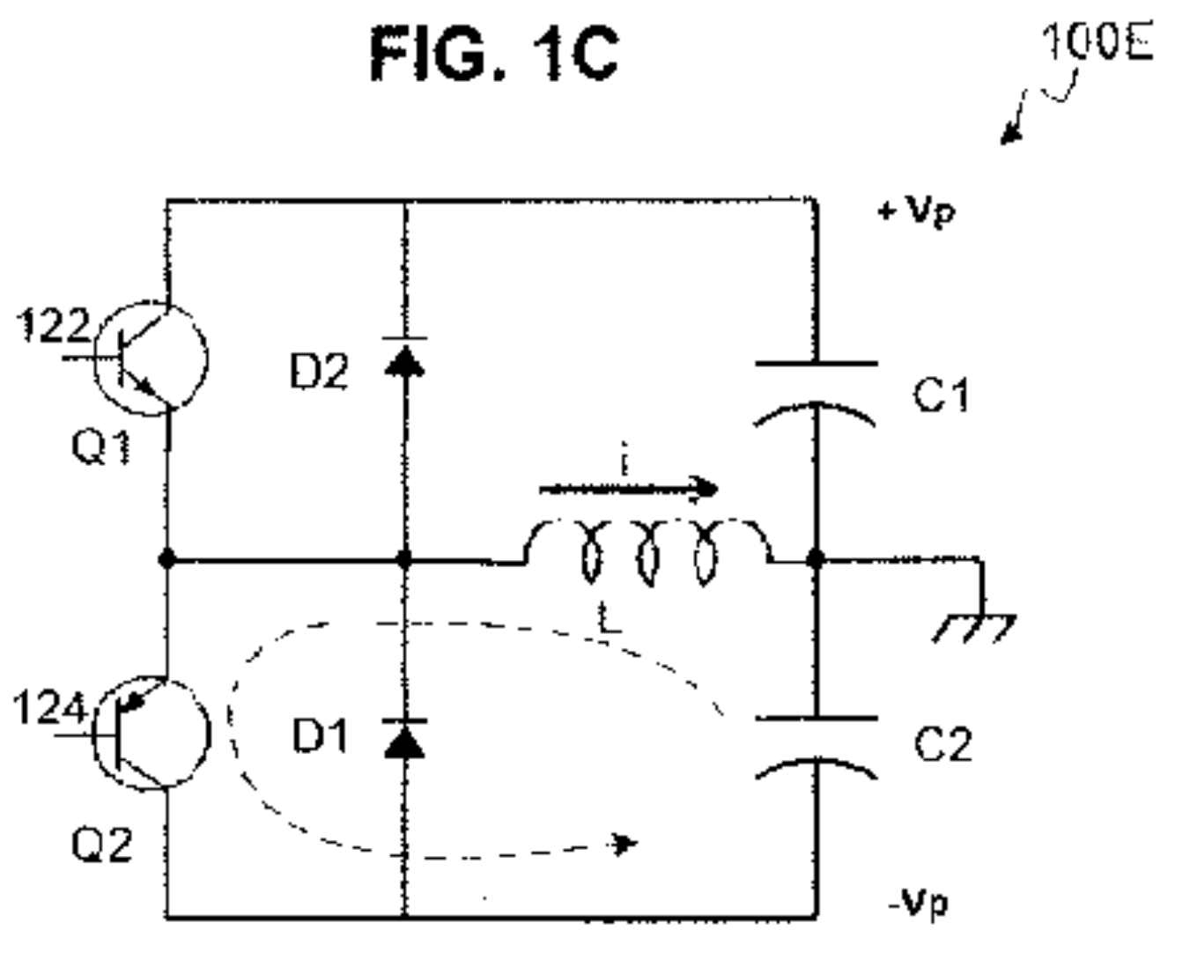

FIG. 1E

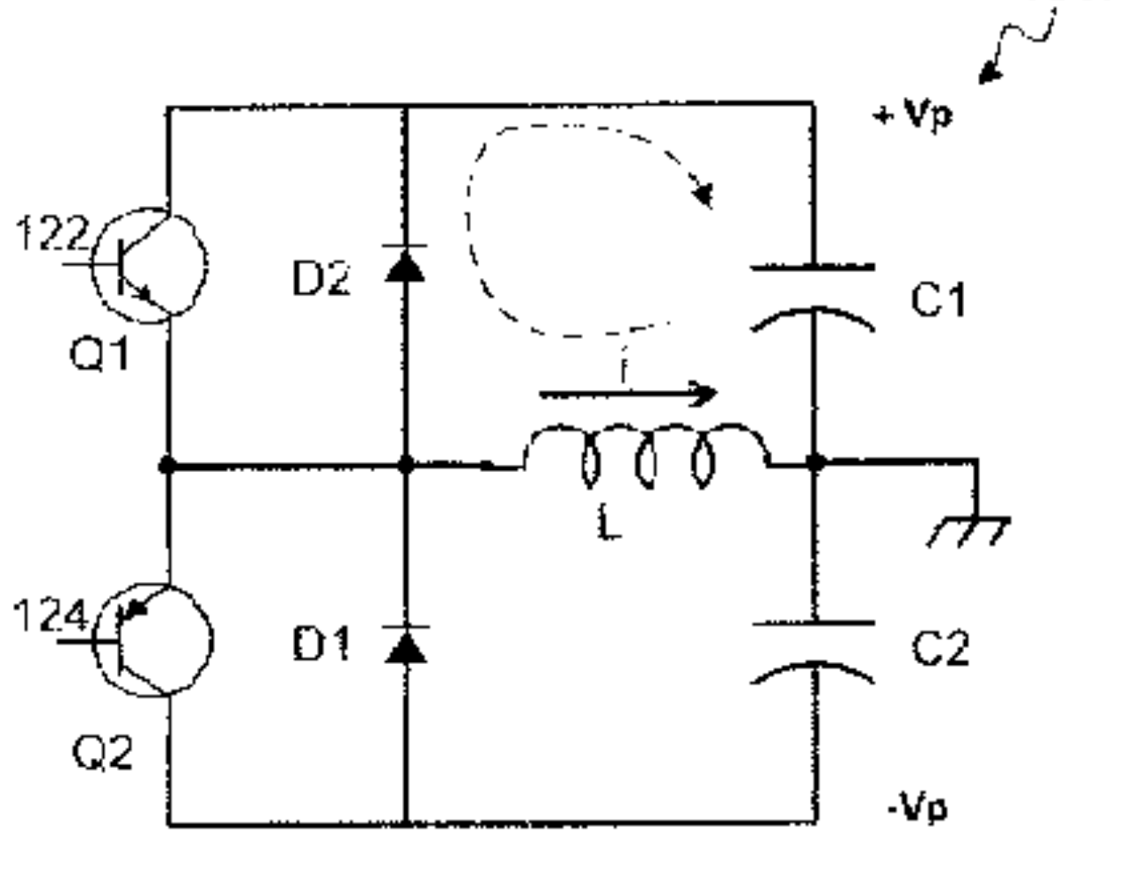

FIG. 1F

WO 2015/157290 A1

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

ENERGY EFFICIENT CONTROLLED MAGNETIC FIELD GENERATOR CIRCUIT

CROSS-REFERENCE TO RELATED APPLICATIONS

[001] This application claims the benefit of priority under 35 U.S.C. § 119 from United States Provisional Patent Application 61/975,997, filed April 07, 2014, which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[002] The present invention generally relates to signal generators, more particularly, to an energy efficient controlled magnetic field generator circuit.

BACKGROUND

[003] As radio-frequency (RF) and optical electromagnetic signals do not propagate well under the ocean surface or through land, alternative communication methods are to be used for these environments. There are multiple alternative options, each having advantages and disadvantages. Therefore, different approaches may be taken depending on applications. For example, some applications may use a tether to communicate by wire or optical fiber, which can impose maneuvering limits or hazards involving physical contact with vehicles or structures. As another example, acoustic communications are often used, but are affected by multipath and shallow-water resonances, with the consequence that robust acoustic communications have a very low bit rate. Yet, another candidate can be near-field magnetic communications, which works with low-frequency signals, to be measurable at longer ranges thereby limiting bit rate, and signals which have a rapid drop off in signal strength at longer ranges.

[004] Recent undersea systems research has shown that manipulating the shape of the magnetic field changes over time can provide more information, either for higher bit-rate communications or for difficult-to-counter short-term magnetic pings. This is a departure from traditional magnetic field signal shapes, which are sinusoidal and involve a number of cycles because LC circuit techniques can be used to efficiently vary the magnetic field through a resonance of the LC circuit. Achieving similar energy efficiency in a magnetic field drive circuit and allowing the shape of each cycle of the waveform to be controlled, for example, amplitude modulated, are desired.

SUMMARY

[005] In some aspects, a magnetic waveform generator circuit includes a first switch coupled to a first rectifier element at a first node, a first capacitor coupled, at a second node to the first switch, and to a fourth node, a second capacitor coupled, at a third node to the first rectifier element, and to the fourth node, and an inductor coupled between the first and the fourth nodes. The first switch is operable to be in an ON state during a first time period and in an off state during a second time period. The first switch and the first rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

[006] In another aspect, a method for providing a magnetic waveform generator includes coupling, at a first node, a first switch to a first rectifier element, A first capacitor may be coupled, at a second node to the first switch, and to a fourth node. A second capacitor may be coupled, at a third node to the first rectifier element, and to the forth node. An inductor may be coupled between the first and the fourth nodes. The first switch is operable to be in an ON state during a first time period and in an off state during a second time period. The first switch and the first rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

[007] In yet another aspect, A magnetic waveform generator circuit includes a first switch coupled to a first rectifier element at a first node, a second switch coupled to a second rectifier element at a second node, and a first capacitor coupled, at a third node to the first switch, and to a fifth node. The magnetic waveform generator circuit further includes a second capacitor coupled, at a fourth node to the second switch, and to the fifth node, and an inductor coupled between the first and the second nodes. The first switch and the second switch are operable to be in an ON state during a first time period and in an off state during a second time period. The first switch, the second switch, the first rectifier element, and the second rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

[008] The foregoing has outlined rather broadly the features of the present disclosure in order that the detailed description that follows can be better understood. Additional features and advantages of the disclosure will be described hereinafter, which form the subject of the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[009] For a more complete understanding of the present disclosure, and the advantages thereof, reference is now made to the following descriptions to be taken in conjunction with the accompanying drawings describing specific embodiments of the disclosure, wherein:

[010] FIGs. 1A through 1F are diagrams illustrating examples of a magnetic waveform generator circuit, a corresponding timing diagram, and various operational phases of the magnetic waveform generator circuit, according to certain embodiments;

[011] FIGs. 2A-2B are diagrams illustrating examples of a magnetic waveform generator circuit with amplitude modulation capability and corresponding timing diagrams, according to certain embodiments;

[012] FIGs. 3A-3B are diagrams illustrating examples of an H-bridge magnetic waveform generator circuit and an H-bridge magnetic waveform generator circuit with amplitude modulation capability, according to certain embodiments; and

[013] FIG. 4 is a diagram illustrating an example of a method for providing a magnetic waveform generator circuit, according to certain embodiments.

DETAILED DESCRIPTION

[014] The detailed description set forth below is intended as a description of various configurations of the subject technology and is not intended to represent the only configurations in which the subject technology may be practiced. The appended drawings are incorporated herein and constitute a part of the detailed description. The detailed description includes specific details for the purpose of providing a thorough understanding of the subject technology. However, it will be clear and apparent to those skilled in the art that the subject technology is not limited to the specific details set forth herein and may be practiced without these specific details. In some instances, well-known structures and components are shown in block diagram form in order to avoid obscuring the concepts of the subject technology.

[015] The present disclosure is directed, in part, to an energy efficient controlled magnetic field generator circuit. The subject technology uses a coil electromagnet to establish a variable magnetic field that reaches out a significant distance. This subject solution transfers energy between energy storage devices (e.g., inductors and capacitors) using a switching scheme that enables the control of the ramp rate and duration of each cycle of the magnetic field waveform. The ramp rate is the rate of change of the magnetic field, and by varying the ramp rate, among other things, a triangle wave of selectable amplitude, can be created. The subject technology provides a family of circuits that can accomplish the energy transfer with substantially low energy consumption. Ideally, the disclosed circuits use no energy if lossless devices such as switches, capacitors, and inductors were used. In practice, no device is perfectly lossless, so the circuits do draw energy. However, the energy consumption of the disclosed circuits is substantially low compared to the generated magnetic field strength.

[016] Traditionally, an efficient approach to generate a magnetic field is using a series LC resonators circuit that generates a sinusoidal waveform. There are techniques for varying the average amplitude and /or frequency of the resonance. These techniques are not single-cycle control techniques. It is understood that resonant LC circuits that work with many cycles of the waveform to deliver information have a lower rate of information delivery. By being able to modulate each cycle of the waveform, more bits per second can be delivered. In addition, by achieving the control through ramp rate control, the waveform can have a triangle shape which can have higher amplitude, and more importantly, a higher L2-norm than a sine wave with the same peak slope. The peak slope corresponds to the maximum voltage that the circuit can tolerate. The triangular waveform can achieve a higher signal-to-noise ratio (SNR) for a given maximum voltage in the drive circuit. For sensing applications (e.g., magnetic ping), single cycle control can perform identification with a shorter signal duration, requiring higher sophistication and cost on the part of the adversary to cancel, and also allowing a shorter duty cycle and thus more stealth and energy efficiency.

[017] FIGs. 1A through 1F are diagrams illustrating examples of a magnetic waveform generator circuit 100A, a corresponding timing diagram 100B, and various operational phases 100C through 100F of the magnetic waveform generator circuit, according to certain embodiments. The magnetic waveform generator circuit 100A (hereinafter "circuit 100A") includes a first switch S1 coupled between a first node 102 (hereinafter "node102") and a second node 104 (hereinafter "node104"), a second switch S2 coupled between node 102 and a third node 106 (hereinafter "node106"), a first rectifier element D1 coupled in parallel to the switch S2, and a second rectifier element D2 coupled in parallel to the switch S1. The circuit 100A further includes an inductor L coupled between node 102 and a fourth node 108 (hereinafter "node108"), a first capacitors C1 coupled between nodes 104 and 108, and a second capacitors C2 coupled between nodes 108 and 106. Node 108 is coupled to ground potential and capacitors C1 and C2 are precharged to +Vp (e.g., 100V) and -Vp (e.g., -100V).

[018] In one or more implementations, the switches S1 and S2 can be implemented with semiconductor switches such as transistors (e.g., bipolar junction transistor (BJT), field-effect transistor (FET)) or other types of switches). The rectifier elements D1 and D2 can be semiconductor diodes (e.g., silicon diodes) or other rectifier elements. The inductor L is a magnetic coil of the magnetic waveform generator and can have an inductance value of the order of hundreds of micro-Henry (μH), for example, 300 μH, and capacitance values of the capacitors C1 and C2 can be of the order of hundreds of micro-farad (μF). The circuit 100A can generate a current i in the in inductor L that has an optimized waveform, for example, a triangular waveform, by controlling the switches S1 and S2, as shown in the timing diagram 100B of FIG. 1B.

[019] The timing diagram 100B includes control pulses 110 and 112 applied to the switches S1 and S2, and a triangular waveform 120 for the current i of the inductor L of FIG. 1A. During a time period T1, switch S1 is closed and switch S2 is open. During a time period T2, both switches S1 and S2 are open, and during a time period T3, switch S1 is open and switch S2 is closed, and during a time period T4, both switches S1 and S2 are open again. The four phases of switches S1 and S2 can cause the current i of the inductor L run through the ramp-up and ramp-down cycles to create a full cycle of the triangular waveform 120. More detailed operational descriptions of the circuit 100A are provided below with respect to FIGs. 1C through 1F.

[020] The operational phase 100C shown in FIG. 1C depicts the operation of the circuit 100A of FIG. 1A during the time period T1 of FIG. 1B. Transistors Q1 (e.g., an NPN transistor) and Q2 (e.g., a PNP transistor) are example implementations of the switches S1 and S2 of FIG. 1A. During the operational phase 100C, the transistor Q1 is on and the transistor Q2 is off, and diodes D1 and D2 are both reverse biased by the initial voltage (e.g., 100V) of the capacitors C1 and C2. The capacitor C1 discharges through the transistor Q1 and the inductor L, thereby passing a positive up-ramping (increasing) current i in the inductor L, which forms the first quarter cycle, corresponding to the time period T1, of the triangular waveform 120 of FIG. 1B. In practice, the current i ramps up in a manner which can be closely approximated with a linear ramp when the capacitor sizing and switch closure interval are such that the capacitor voltage remains nearly constant during discharging or recharging intervals.

[021] The operational phase 100D shown in FIG. 1D depicts the operation of the circuit 100A of FIG. 1A during the time period T2 of FIG. 1B. During the operational phase 100D, both transistors Q1 and Q2 and diode D2 are off. The stored energy in the inductor L during the phase 100C, is delivered to capacitor C2 and charges this capacitor through the diode D1 and the inductor L, thereby passing a positive down- ramping (decreasing) current i in the inductor L, which forms the second quarter cycle, corresponding to the time period T2, of the triangular waveform 120 of FIG. 1B.

[022] The operational phase 100E shown in FIG. 1E depicts the operation of the circuit 100A of FIG. 1A during the time period T3 of FIG. 1B. During the operational phase 100E, the transistors Q2 is on and the transistor Q1 and both diodes D1 and D2 are off. During this phase, capacitor C2 discharges through the transistor Q2 and the inductor L and induces a negative increasing current in the inductor L, which continues the down-ramping leg of the triangular waveform 120 until the end of period T3.

[023] The operational phase 100F shown in FIG. 1F depicts the operation of the circuit 100A of FIG. 1A during the time period T4 of FIG. 1B. During the operational phase 100F, both transistors Q1 and Q2 and diode D1 are off, and the capacitor C1 is charged through diode D2 and the inductor L. The current i of the inductor L is negative and decreasing and reaches zero as the capacitor C1 is charged nearly to its initial voltage. In the circuits 100A and 100C through 100F, the drive circuitry, protection circuitry, power supplies, and internal resistors (e.g., for the inductor L) are not shown for simplicity. With ideal lossless circuit elements, at the completion of the four switching periods (T1 through T4), the capacitors would have exactly the same voltage as they had at the beginning of the four periods. However, because of internal resistors and non-ideal switches and rectifiers, there is some energy loss, with the result that the capacitors do not have exactly their original voltage after the sequence of four switching periods. To compensate for this energy loss, some means of recharging (e.g., a trickle charge or a rapid charge with the inductor disengaged) the capacitors can be employed to prevent any operation failure due to the non-idealities. The effect of this deviation from the ideal straight line in the triangular waveform may be compensated for by using, in the receiver, a demodulator that is matched with the non-ideal waveform.

[024] FIGs. 2A-2B are diagrams illustrating examples of a magnetic waveform generator circuit 200A with amplitude modulation capability and corresponding timing diagrams 210, 212, 214, 216, and 220, according to certain embodiments. The magnetic waveform generator circuit 200A is similar to the circuit 100A of FIG. 1A, except for the additional switches S3 and S4 and capacitors C3 and C4. The addition of the switches S3 and S4 and capacitors C3 and C4 enable circuit 200A to generate a current i in the inductor L with a triangular waveform that can be amplitude modulated. The switches S3 and S4 are dipole switches that can be set to be connecting at either of two positions A or B. When set to be at position A, the switches S3 and S4, allow the capacitors C3 and C4 to be connected in series with the capacitors C1 and C2, respectively. When switches S3 and S4 are set to be connecting at position B, the circuit 200 becomes similar and operates similarly to the circuit 100A. The switches S3 and S4 can be implemented as semiconductor dipole switches using known transistor or diode switch circuitry.

[025] When the switches S3 and S4 are set to be connecting at position A, as mentioned above, capacitors C3 and C4 are connected in series with capacitors C1 and C2 to provide a higher voltage for driving the current i through the inductor L, which can form the high current amplitude of the amplitude modulated waveform, as shown in the timing diagram 220 of FIG. 2B. In the circuit 200A, the drive circuitry, protection circuitry, power supplies, and internal resistors (e.g., for the inductor L) are not shown for simplicity

[026] The timing diagrams 210, 212, 214, 216 shown in FIG. 2B are control pulses applied to switches S1 through S4. The timing diagrams are shown for five consecutive cycles (e.g., periods) P1 P2 ... P5. During the first cycle P1, switches S1 and S2 are toggled as explained with respect to phases 100C through 100F of FIGs. 1C through 1F, and the switches S3 and S4 are set at position A, to allow capacitors C3 and C4 be connected in series with the capacitors C1 and C2, thereby providing the high amplitude triangular waveform, as shown by waveform 222. The amplitude of the triangular waveform may be reduced by removing the capacitors C3 and C4 from the circuit 200A, thereby providing smaller voltage to drive the inductor current through the inductor L. This is done at cycle P2, where the switches S3 and S4 are both set to position B and switches S1 and S2 go through the phases to generate a triangular waveform as explained above. The ratio of amplitudes of the waveforms 222 and 224 depend on the capacitance values of the capacitors C1, C2, C3, and C4. For example, if the capacitance values of the capacitors C1, C2, C3, and C4 are the same, the amplitude of the waveform 224 would be half of the amplitude of the waveform 222. Other amplitude ratios can be achieved by suitably selecting the capacitance values of the capacitors C1, C2, C3, and C4.

[027] During the third cycle P3, switches S1 and S2 are open and switches S3 and S4 are set at position B, and the charged capacitors C1 have no path for driving current into the inductor L. Therefore, during cycle -P3, zero current passes through the inductor L. During this cycle, a recharge circuit (not shown for simplicity) can return the voltages of capacitors C1 and C2 to their desired level, correcting for resistive losses, without generating a current in the inductor L and therefore without affecting the magnetic field. During the cycles P4 and P5, the setting of switches S3 and S4 are the same as cycles P1 and P2, but the status of switches S1 and S2 in cycles P4 and P5 are reversed relative to cycles P1and P2, respectively. As a consequence, the direction of currents in the inductor L are also reversed, resulting in waveforms 226 and 228, which have the same amplitudes as their respective waveforms 222 and 224, but with opposite polraities.

[028] The waveforms 222, 224, 226, and 228 can be used to represent, for example, binary symbols 11, 10, 01, and 00 by a magnetic communications transmitter using the circuit 200A as the magnetic field generator. The cycle P3, which has no signal, can be used as the OFF symbol to allow for calibration, synchronization, and background cancellation in the receiver side.

[029] FIGs. 3A-3B are diagrams illustrating examples of an H-bridge magnetic waveform generator circuit 300A and an H-bridge magnetic waveform generator circuit 300B with amplitude modulation capability, according to certain embodiments. The bridge magnetic waveform generator circuit 300A (hereinafter "circuit 300A") is similar to circuit 100A of FIG. 1A, except for the additional switches S3 and S2 and diodes D2 and D3 and the fact that node 308 of the inductor L is not connected to the ground potential. The switch S3 is coupled between nodes 304 and 308, and switch S2 is coupled between nodes 308 and 306. Diodes D2 and D3 are coupled in parallel with switches S3 and S2, respectively. The capacitors C1 and C2 join at node 310 that is coupled to ground potential. In the circuit 300A, the drive circuitry, protection circuitry, power supplies, and internal resistors (e.g., for the inductor L) are not shown for simplicity. Switches S2 and S3 and diodes D2 and D3 can be implemented in the same semiconductor chip using transistor switches and semiconductor (e.g., silicon) diodes.

[030] The configuration of FIG. 300A has the advantageous feature that allows using lower supply voltage values. For example, the capacitors C1 and C2 can each be precharged to 50V (instead of 100V for circuit100A) and the circuit 300A still provides the same amplitude triangular waveform for the current in the inductor L. The operation of the circuit 300A includes four phases, during which status of switches S1, S2, S3, and S4 are controlled to be different to allow suitable paths for flow of current from or to the capacitors C1 and C2 through the inductor L.

[031] During a first phase, switches S1 and S2 are closed and switches S3 and S4 are open, and diodes D1 and D2 are reverse biased. During the first phase, the capacitors C1 and C2 discharge to drive a positive increasing (up-ramping) current through the switches S1 and S2 and the inductor L. This current provides the first quarter-cycle of a triangular current waveform (e.g., 120 of FIG. 1B). During a second phase, switches S1, S2, S3, and S4 are open, and diodes D1 and D2 are forward biased and conduct current. During this phase, the capacitors C1 and C2 recharge, which causes driving a positive decreasing (down-ramping) current through the diodes D1 and D2 into the inductor L. This current provides the second quarter-cycle of the triangular current waveform.

[032] During a third phase, switches S3 and S4 are closed and switches S1 and S2 are open, and diodes D1 and D2 are reverse biased. During this phase, the capacitors C1 and C2 discharge to drive a negative (e.g., with revered direction) increasing amplitude current through the switches S3 and S4 and the inductor L. This current provides the third quarter-cycle of the triangular current waveform. During a fourth phase, switches S1, S2, S3, and S4 are open, and diodes D3 and D4 are forward biased and conduct current. During this phase, the capacitors C1 and C2 recharge and cause driving a negative decreasing current into the inductor L through diodes D3 and D4. This current provides the fourth quarter-cycle of the triangular current waveform. The circuit 300A can be modified to provide amplitude modulation as discussed herein.

[033] The H-bridge magnetic waveform generator circuit 300B (hereinafter "circuit 300B") shown in FIG. 3B has amplitude modulation capability. The circuit 300B has a portion 350 that is similar to the circuit 300A and an additional portion 352 including an inductor L2, diodes D5 and D6, and switches S5 and S6. Here, the inductor L2 does not create an external magnetic field at long distances as, for example, a toroidal inductor. Whereas the inductor L1 creates an external magnetic waveform as, for example, a magnetic coil. The operation of portion 350 is also similar to the operation of circuit 300A, as discussed above. The portion 350 is used to generate a high (e.g., maximum)-amplitude triangular current waveform (e.g., 222 of FIG. 2B), during the four phased as discussed above with respect to FIG. 3A. During these phases switches S5 and S6 are open. When generating a low-amplitude triangular current waveform (e.g., 224 of FIG. 2B), the portion 352 comes into the play and switches S5 and S6 are suitably opened or closed (while S1 and S4 are kept open) to allow driving currents in two different directions, as explained above, into series connected inductors L1 and L2. The series connection of inductors L1 and L2 increases the impedance in the path of the current and thereby decrease the amplitude of the current passing through the inductors L1 and L2. The ratio of amplitudes of the low-amplitude and high-amplitude waveforms depend on the inductance values of the inductors L1 and L2. For example, if the inductance values of the inductors L1 and L2 are the same, the amplitude of the low-amplitude waveform would be half of the amplitude of the high-amplitude waveform. Other amplitude ratios can be achieved by suitably selecting the inductance values of the inductors L1 and L2.

[034] FIG. 4 is a diagram illustrating an example of a method 400 for providing a magnetic waveform generator circuit, according to certain embodiments. According to the method 400, a first switch (e.g., S1 of FIG. 1A) is coupled, at a first node (e.g., 102 of FIG. 1A), to a first rectifier element (e.g., D1 of FIG. 1A) (410). A first capacitor (e.g., C1 of FIG. 1A) is coupled, at a second node (e.g., 104 of FIG. 1A) to the first switch, and to a fourth node (e.g., 108 of FIG. 1A) (420). A second capacitor may be coupled, at a third node (e.g., 106 of FIG. 1A) to the first rectifier element, and to the forth node (430). An inductor (e.g., L of FIG. 1A) may be coupled between the first and the fourth nodes (440). The first switch is operable to be in an ON state during a first time period (e.g., T1 of FIG. 1B) and in an off state during a second time period (e.g., T2 of FIG. 1B). The first switch and the first rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform (e.g., 120 of FIG. 1B).

[035] Although the invention has been described with reference to the disclosed embodiments, one having ordinary skill in the art will readily appreciate that these embodiments are only illustrative of the invention. It should be understood that various modifications can be made without departing from the spirit of the invention. The particular embodiments disclosed above are illustrative only, as the present invention may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular illustrative embodiments disclosed above may be altered, combined, or modified and all such variations are considered within the scope and spirit of the present invention. While compositions and methods are described in terms of “comprising,” “containing,” or “including” various components or steps, the compositions and methods can also “consist essentially of” or “consist of” the various components and operations. All numbers and ranges disclosed above can vary by some amount. Whenever a numerical range with a lower limit and an upper limit is disclosed, any number and any subrange falling within the broader range is specifically disclosed. Also, the terms in the claims have their plain, ordinary meaning unless otherwise explicitly and clearly defined by the patentee. If there is any conflict in the usages of a word or term in this specification and one or more patent or other documents that may be incorporated herein by reference, the definitions that are consistent with this specification should be adopted.

CLAIMS

What is claimed is the following:

1. A magnetic waveform generator circuit, the circuit comprising:

a first switch coupled to a first rectifier element at a first node;

a first capacitor coupled, at a second node to the first switch, and to a fourth node;

a second capacitor coupled, at a third node to the first rectifier element, and to the fourth node; and

an inductor coupled between the first and the fourth nodes,

wherein:

the first switch is operable to be in an ON state during a first time period and in an off state during a second time period, and

the first switch and the first rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

2. The circuit of claim 1, wherein the first switch is configured to allow the first capacitor to discharge through the inductor in the first time period and the rectifier element is configured to allow the second capacitor to charge through the inductor in the second time period.

3. The circuit of claim 1, further comprising a second switch coupled to a second rectifier element at the first node, wherein the first switch is coupled in parallel to the second diode and the second switch is coupled in parallel to the first diode.

4. The circuit of claim 3, wherein the second switch and the second rectifier element are configured to enable the inductor to generate, during a third and a fourth time periods, a magnetic field having a waveform resembling a negative half-cycle of the triangular waveform.

5. The circuit of claim 4, wherein the second switch is operable to be in an ON state during the third time period to allow the second capacitor to discharge through the inductor in the third time period, wherein the second rectifier element is configured to

allow the first capacitor to charge through the inductor in the fourth time period, wherein the first and second switches comprise transistor switches and the rectifier elements comprise diodes, and wherein the first and second switches comprise semiconductor switches and the rectifier elements comprise semiconductor diodes.

6. The circuit of claim 4, further comprising a first and a second dipole switch and a third and fourth capacitor, wherein the first dipole switch is operable, in a first state, to couple the second node through the third capacitor to the first capacitor, and the second dipole switch is operable, in a first state, to couple the third node through the fourth capacitor to the second capacitor to allow generation of a high amplitude triangular magnetic field waveform.

7. The circuit of claim 6, wherein the first dipole switch and the second dipole switch are operable, in second states, to isolate the third and fourth capacitors to allow a low amplitude triangular magnetic field waveform, and wherein the low amplitude triangular magnetic field waveform has an amplitude that is one-third of the high amplitude triangular magnetic field waveform.

8. A method for providing a magnetic waveform generator, the method comprising:

coupling, at a first node, a first switch to a first rectifier element;

coupling a first capacitor, at a second node to the first switch, and to a fourth node;

coupling a second capacitor, at a third node to the first rectifier element, and to the fourth node; and

coupling an inductor coupled the first and the fourth nodes,

wherein:

the first switch is operable to be in an ON state during a first time period and in an off state during a second time period, and

the first switch and the first rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

9. The method of claim 8, further comprising configuring the first switch to allow the first capacitor to discharge through the inductor in the first time period and configuring the rectifier element to allow the second capacitor to charge through the inductor in the second time period.

10. The method of claim 8, further comprising coupling a second switch to a second rectifier element at the first node, and coupling the first switch in parallel to the second diode and the second switch in parallel to the first diode.

11. The method of claim 10, further comprising configuring the second switch and the second rectifier element to enable the inductor to generate, during a third and a fourth time periods, a magnetic field having a waveform resembling a negative half-cycle of the triangular waveform.

12. The method of claim 11, further comprising configuring the second switch to be operable to be in an ON state during the third time period to allow the second capacitor to discharge through the inductor in the third time period, and configuring the second rectifier element to allow the first capacitor to charge through the inductor in the fourth time period.

13. The method of claim 11, further comprising providing a first and a second dipole switch and a third and a fourth capacitor; configuring the first dipole switch to be operable, in a first state, to couple the second node through the third capacitor to the first capacitor; and configuring the second dipole switch to be operable, in a first state, to couple the third node through the fourth capacitor to the second capacitor to allow generation of a high amplitude triangular magnetic field waveform.

14. The method of claim 13, further comprising configuring the first dipole switch and the second dipole switch to be operable, in second states, to isolate the third and fourth capacitors to allow a low amplitude triangular magnetic field waveform, and wherein the low amplitude triangular magnetic field waveform has an amplitude that is one-third of the high amplitude triangular magnetic field waveform.

15. A magnetic waveform generator circuit, the circuit comprising:

a first switch coupled to a first rectifier element at a first node;

a second switch coupled to a second rectifier element at a second node

a first capacitor coupled, at a third node to the first switch, and to a fifth node;

a second capacitor coupled, at a fourth node to the second switch, and to the fifth node; and

an inductor coupled between the first and the second nodes,

wherein:

the first switch and the second switch are operable to be in an ON state during a first time period and in an off state during a second time period, and

the first switch, the second switch, the first rectifier element, and the second rectifier element are configured to enable the inductor to generate, during the first and the second time periods, a magnetic field having a waveform resembling a positive half-cycle of a triangular waveform.

16. The circuit of claim 15, wherein the first switch and the second switch are configured to allow the first capacitor and the second capacitor to discharge through the inductor in the first time period and the first rectifier element and the second rectifier element are configured to allow the first capacitor and the second capacitor to charge through the inductor in the second time period.

17. The circuit of claim 15, further comprising a third switch coupled between the third node and the second node and, a fourth switch coupled between the first node and the fourth node, a third rectifier element coupled in parallel with the second switch, and a fourth rectifier element coupled in parallel to the first switch.

18. The circuit of claim 17, wherein the third switch, the fourth switch, the second rectifier element, and the first rectifier element are configured to enable the inductor to generate, during a third and a fourth time periods, a magnetic field having a waveform resembling a negative half-cycle of the triangular waveform.

19. The circuit of claim 18, wherein the third switch and the fourth switch are operable to be in an ON state during the third time period to allow the first capacitor and

the second capacitor to discharge through the inductor in the third time period, wherein the third rectifier element and the fourth rectifier element are configured to allow the first capacitor and the second capacitor to charge through the inductor in the fourth time period, and wherein switches comprise semiconductor switches and rectifier elements comprises semiconductor diodes.

20. The circuit of claim 18, further comprising a fifth switch coupled between the third and a sixth node, a sixth switch coupled between the fourth node and the sixth node, a fifth rectifier element coupled in parallel to the sixth switch, and a sixth rectifier element coupled in parallel to the fifth switch, and a second inductor coupled between the sixth node and the first node, wherein addition of the fifth switch, fifth rectifier element, the sixth switch, and the sixth rectifier element allows generation of amplitude modulated triangular waveform magnetic field.

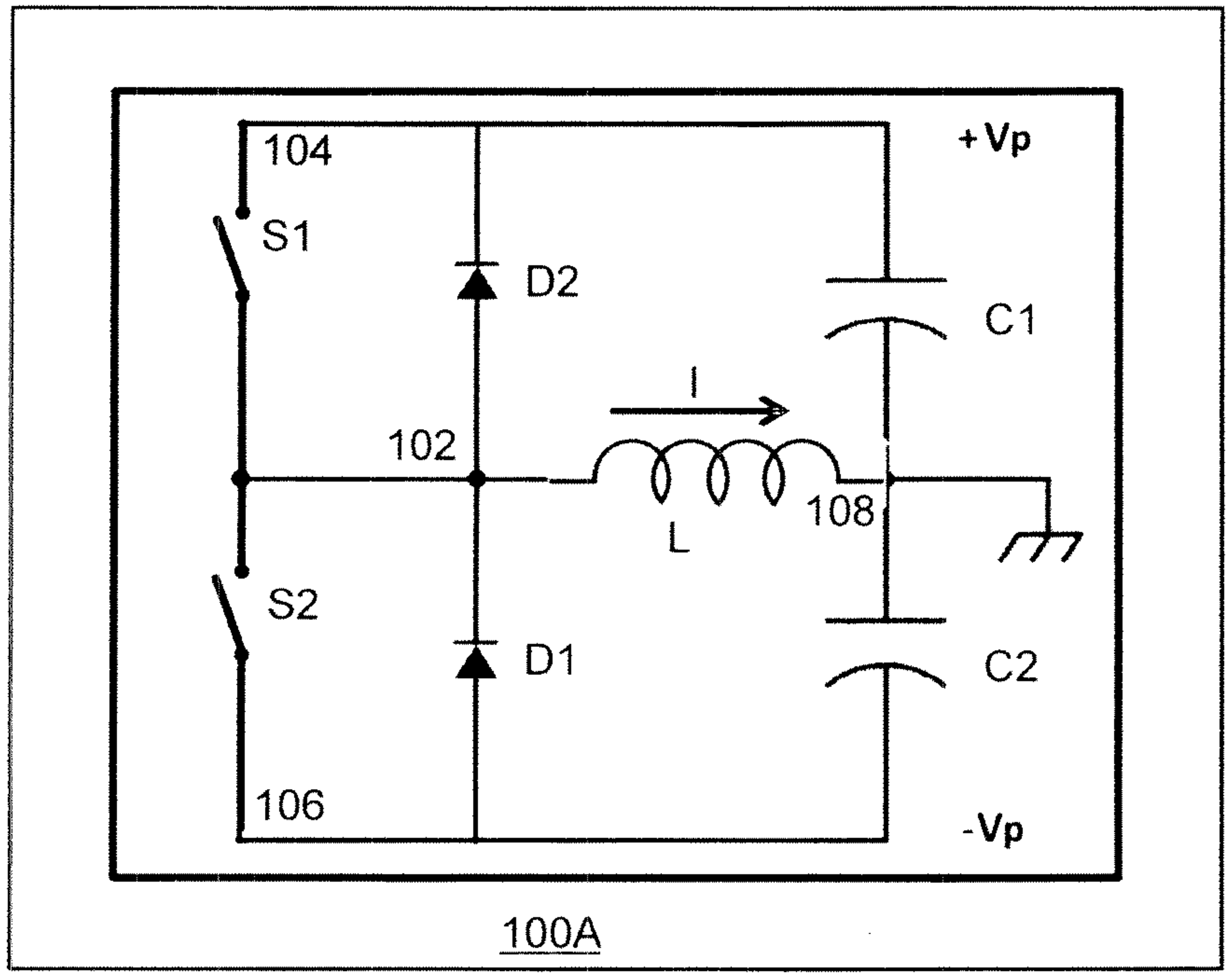
104
+Vp
S1
D2
C1
I
102
L
108
S2
D1
C2
106
-Vp
100A

FIG. 1A

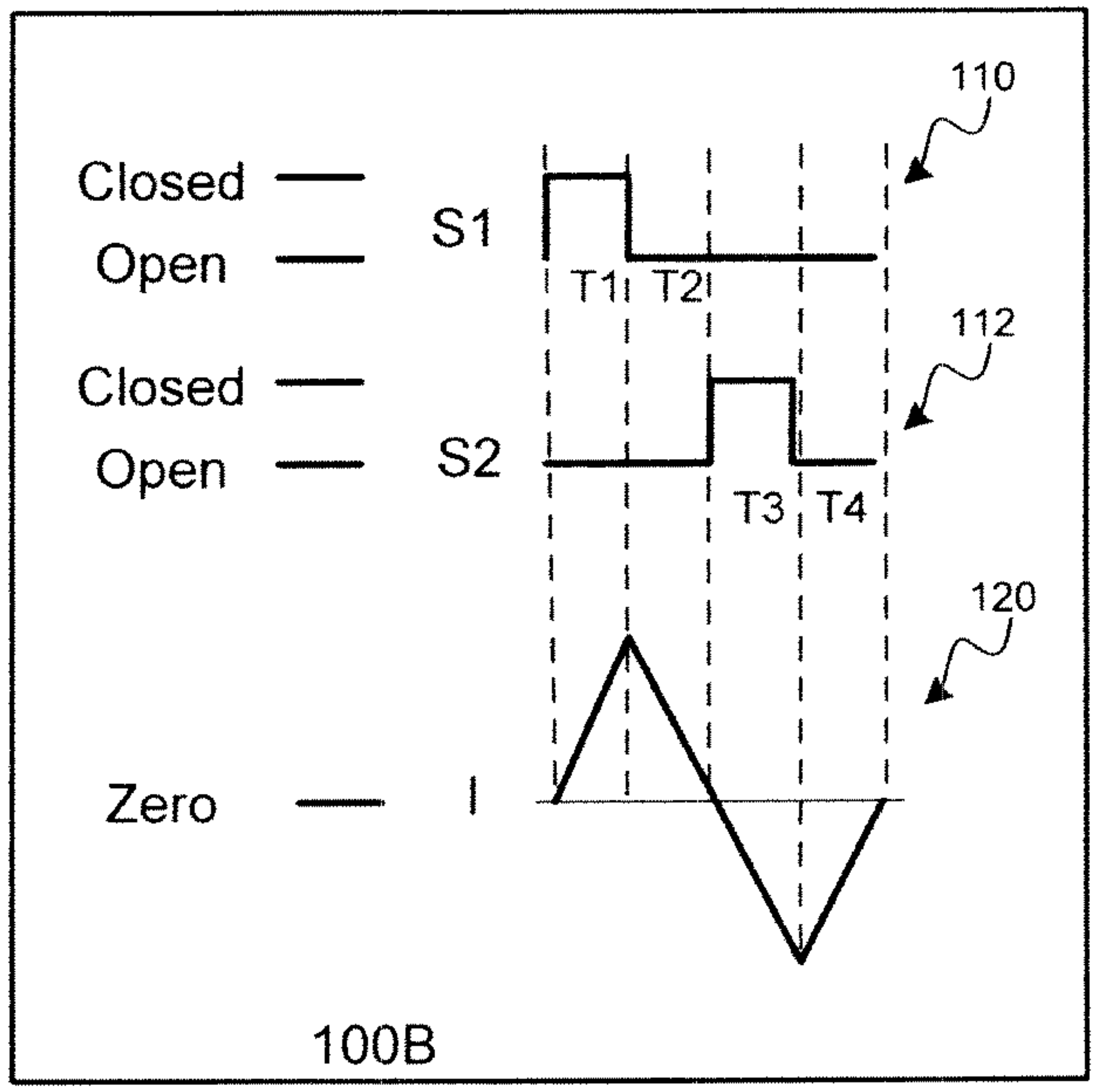
110
Closed
Open
S1
T1
T2
112
Closed
Open
S2
T3
T4
120
Zero
I
100B

FIG. 1B

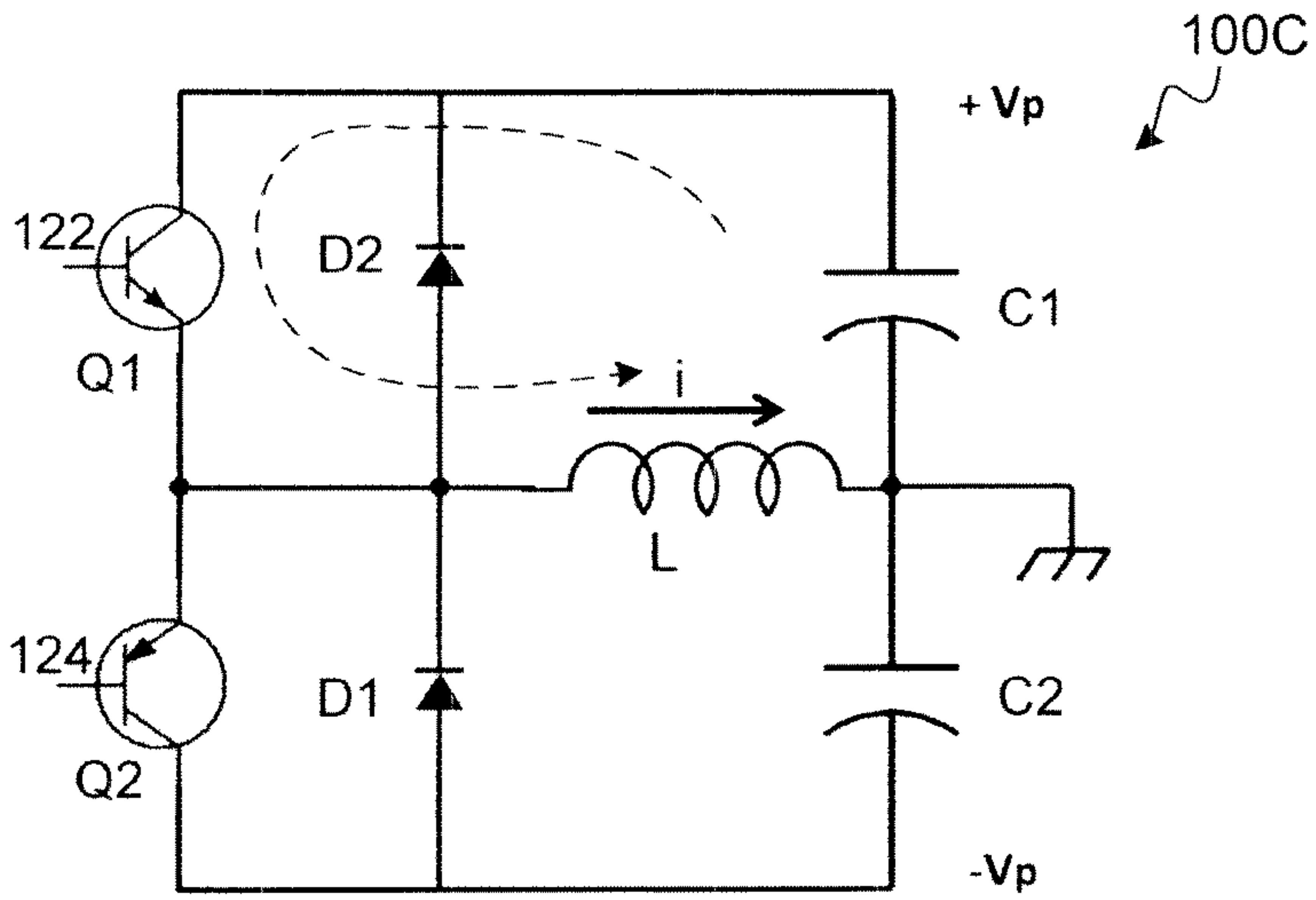

FIG. 1C

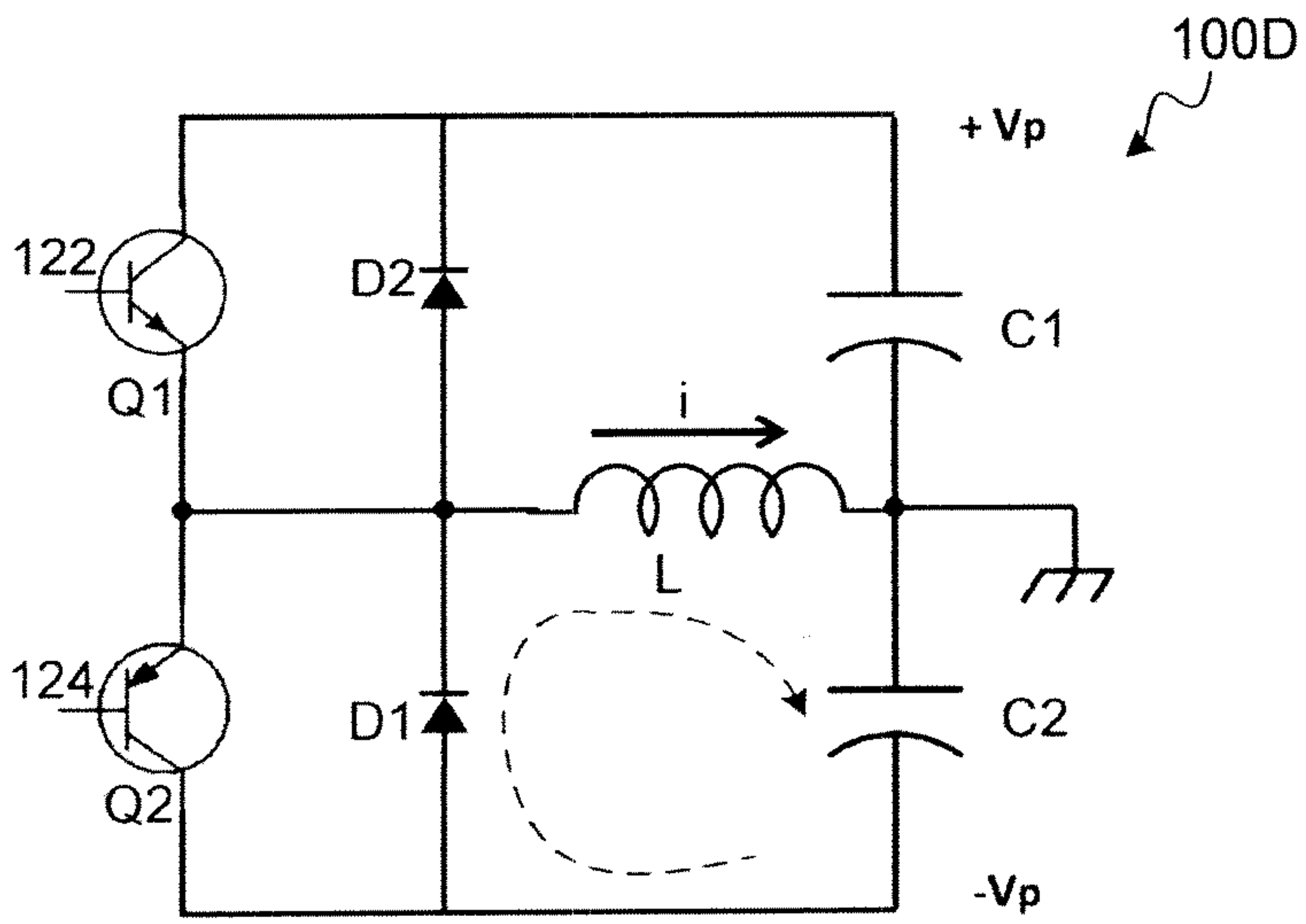

FIG. 1D

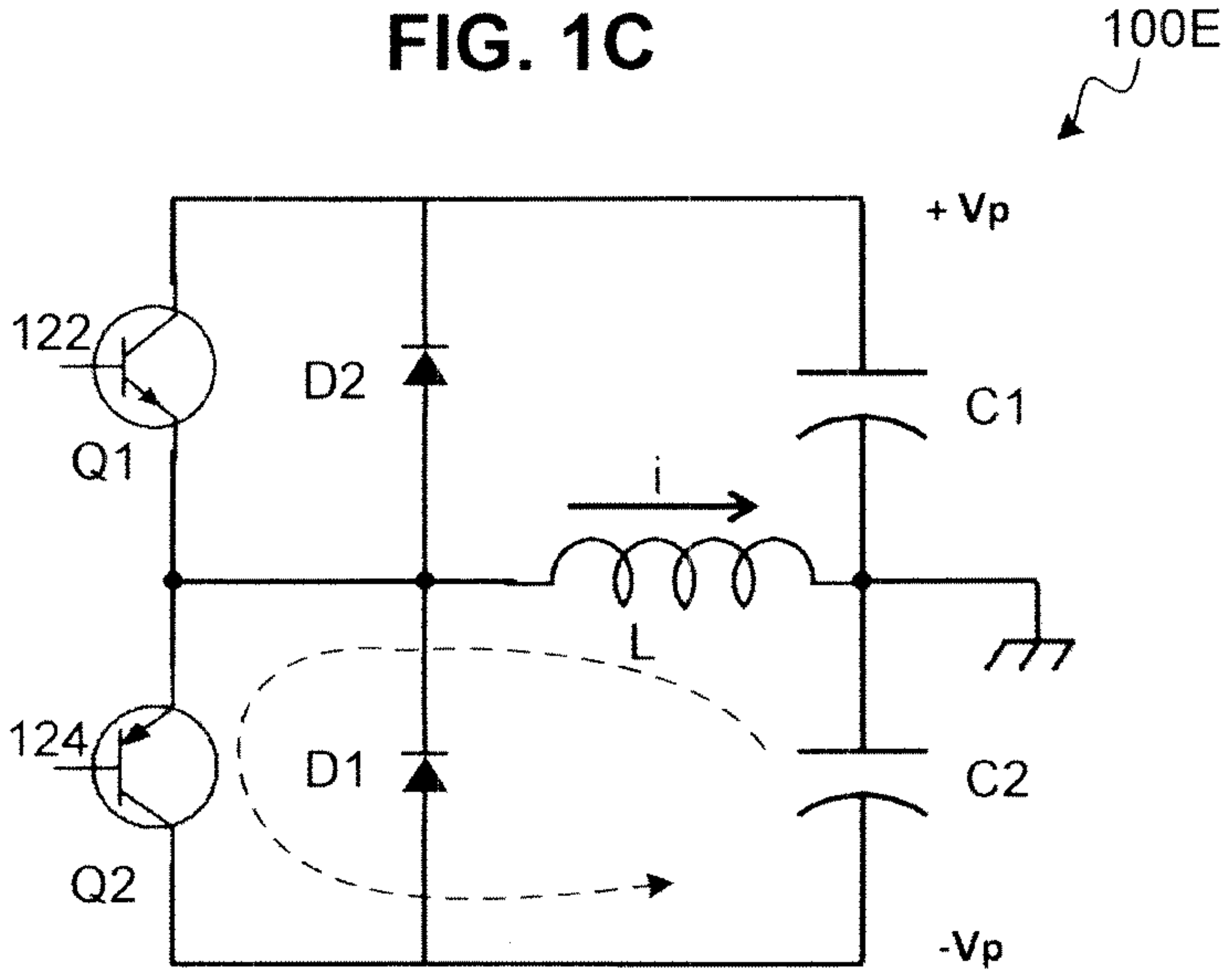

FIG. 1E

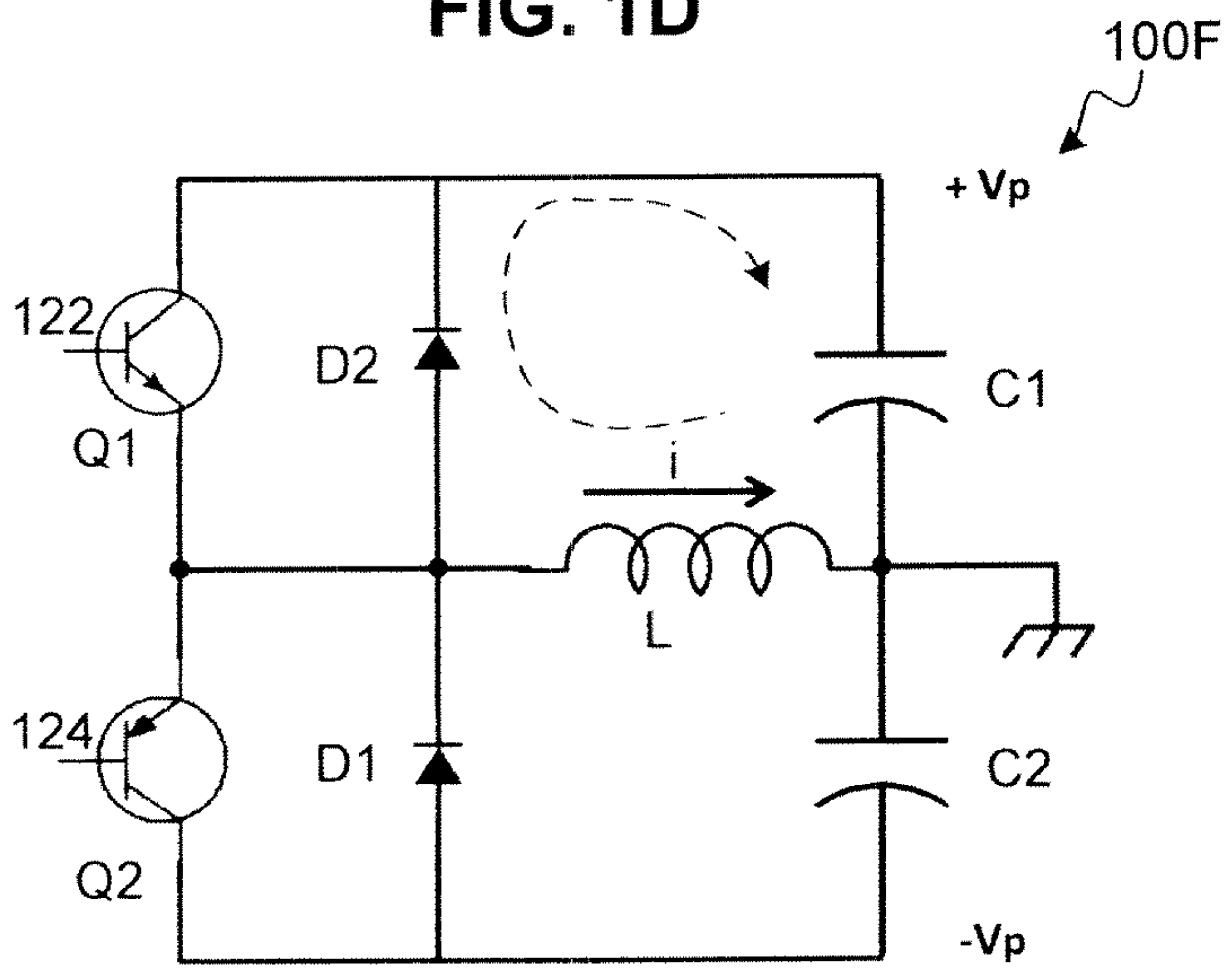

FIG. 1F

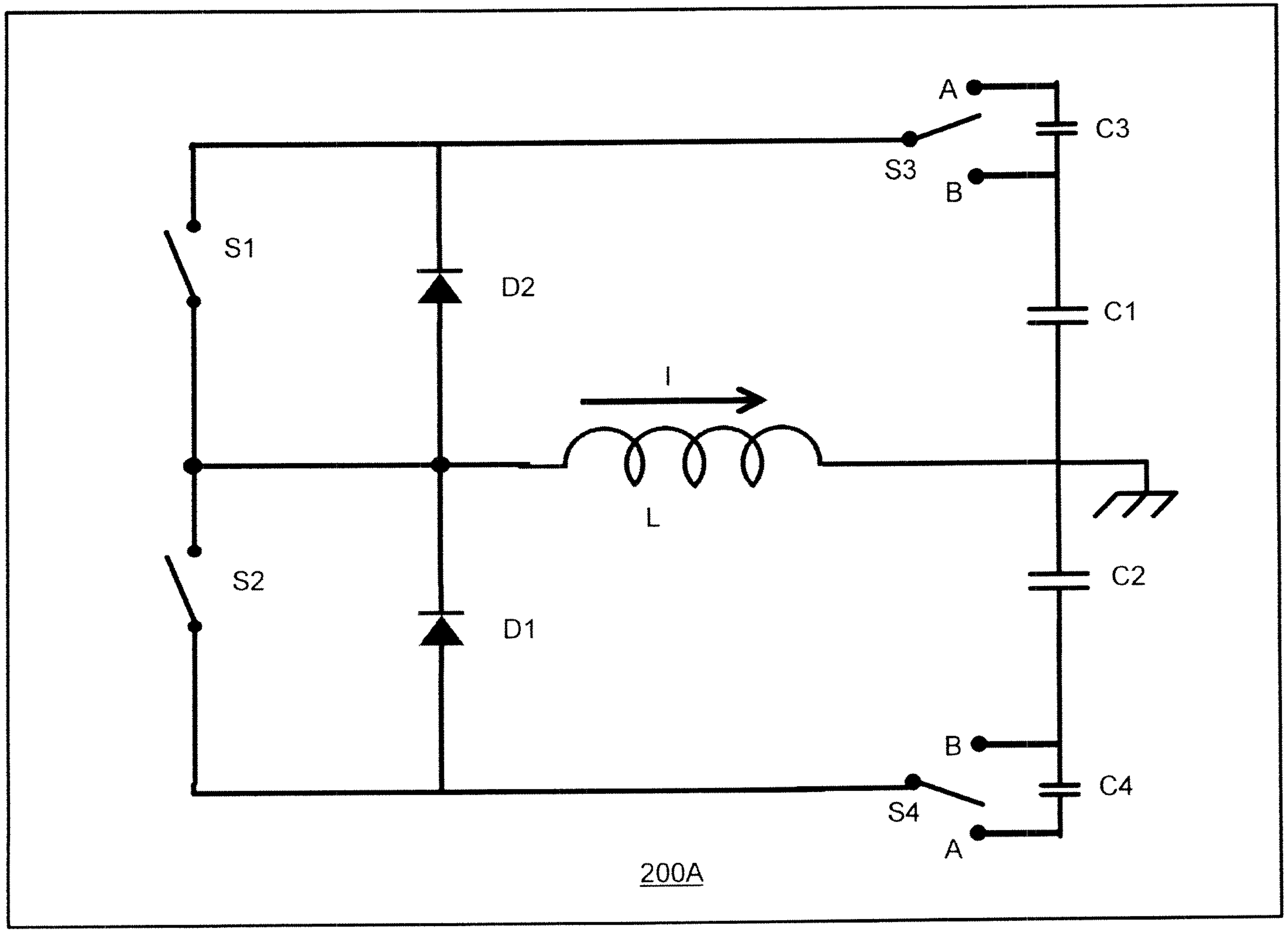

FIG. 2A

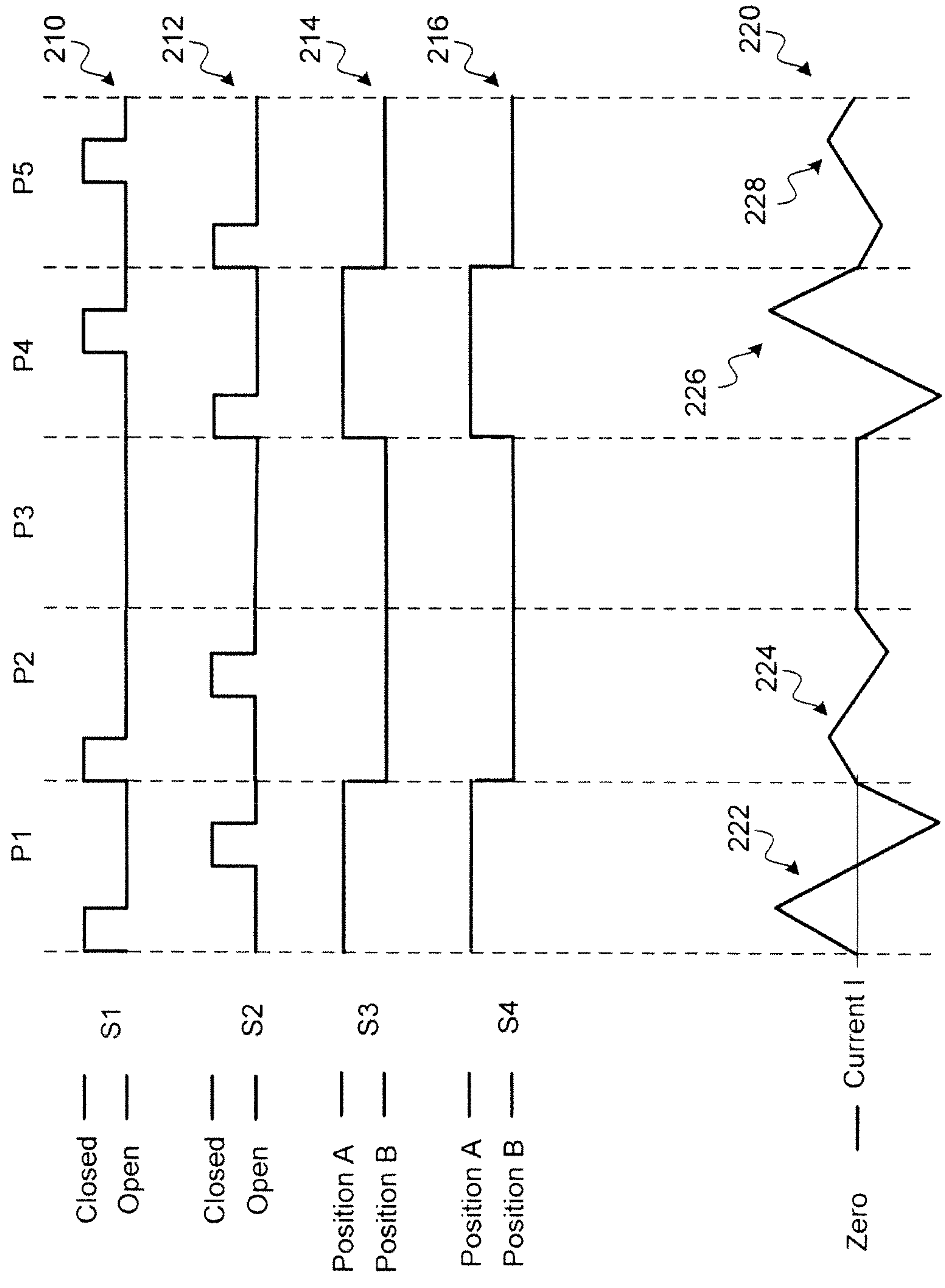
P1
P2
P3
P4
P5
210
212
214
216
220
222
224
226
228
Closed
Open
S1
Closed
Open
S2
Position A
Position B
S3
Position A
Position B
S4
Zero
Current I

FIG. 2B

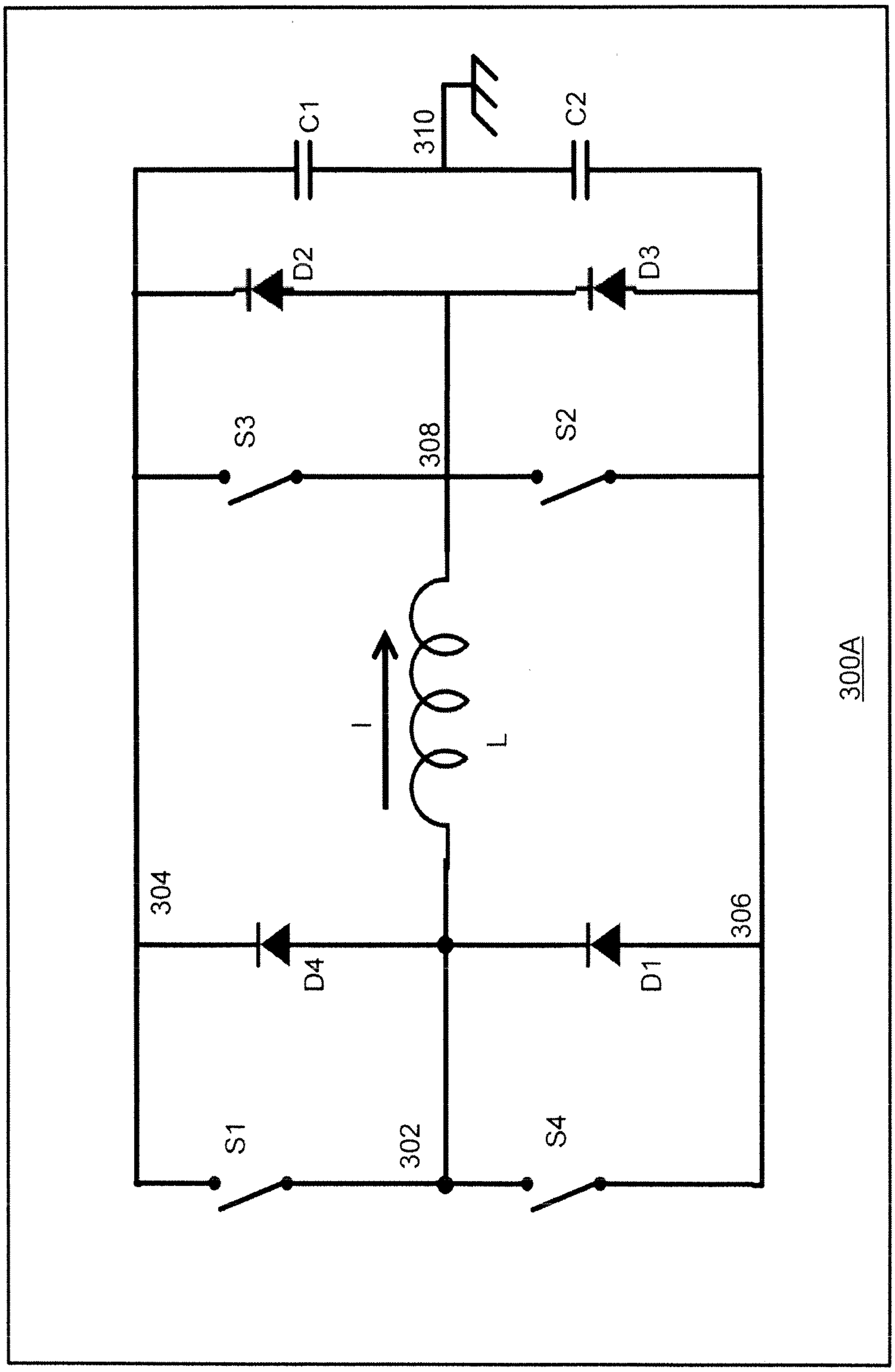

FIG. 3A

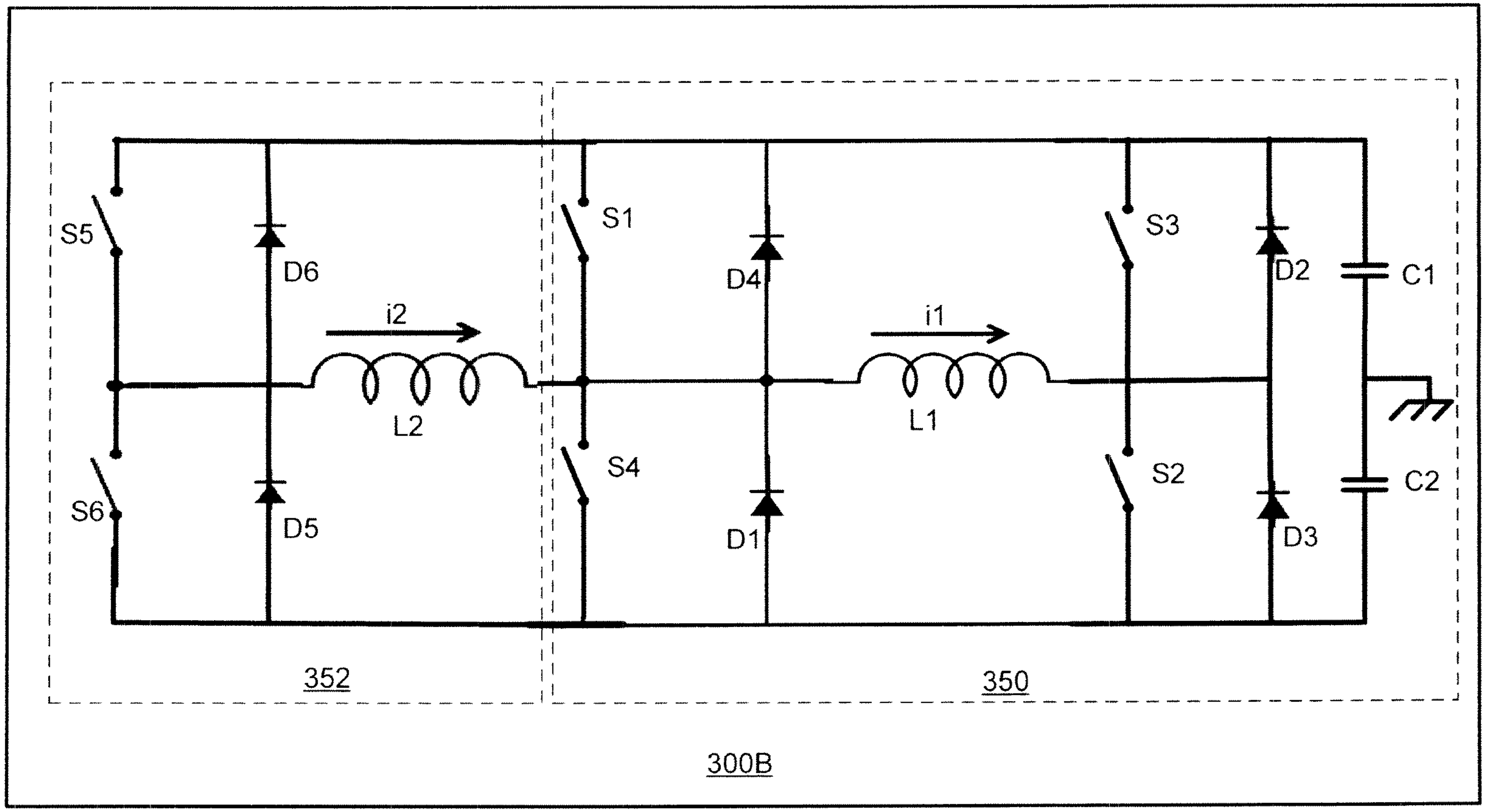

FIG. 3B

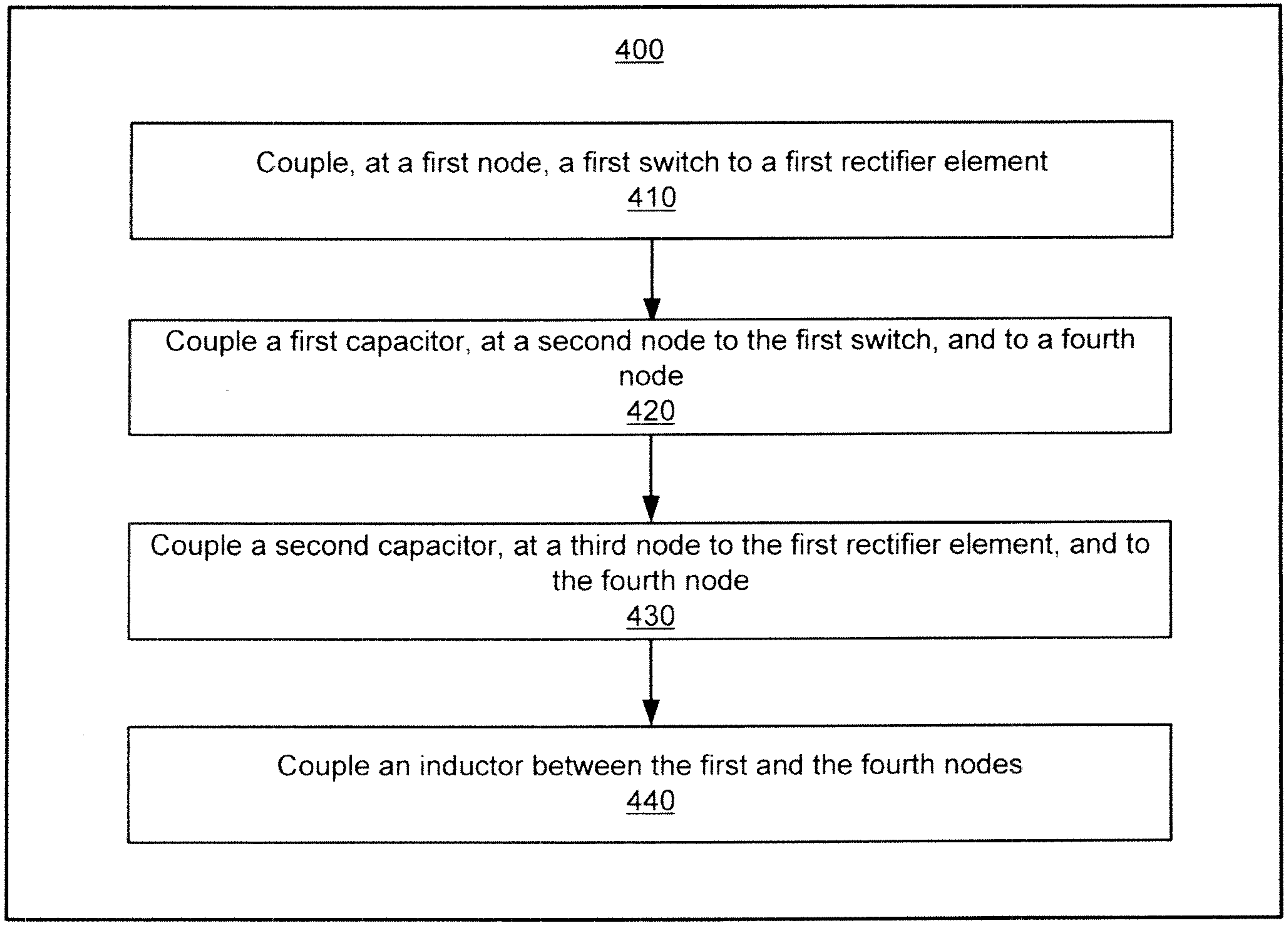
400
Couple, at a first node, a first switch to a first rectifier element
410
Couple a first capacitor, at a second node to the first switch, and to a fourth node
420
Couple a second capacitor, at a third node to the first rectifier element, and to the fourth node
430
Couple an inductor between the first and the fourth nodes
440

FIG. 4

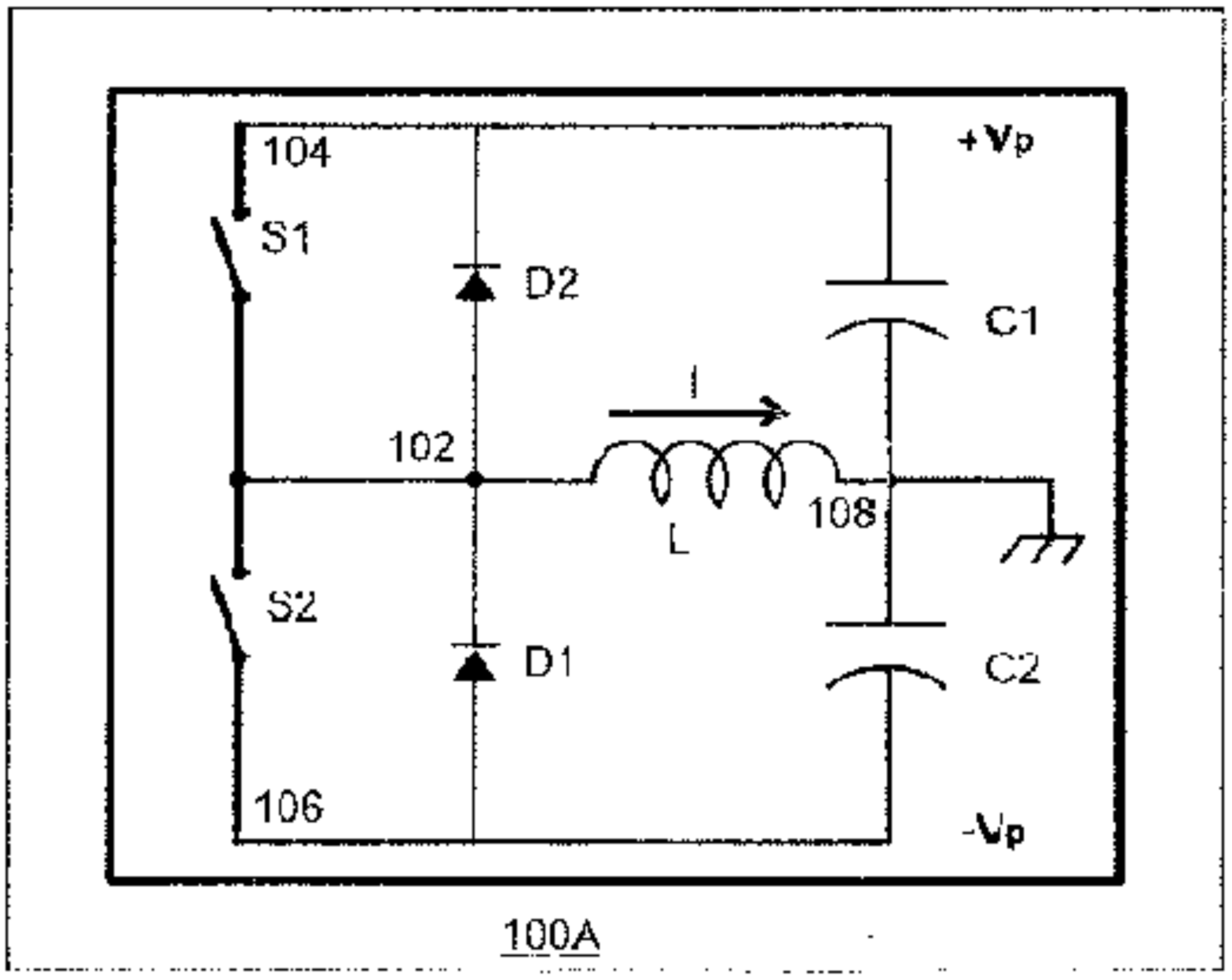

FIG. 1A

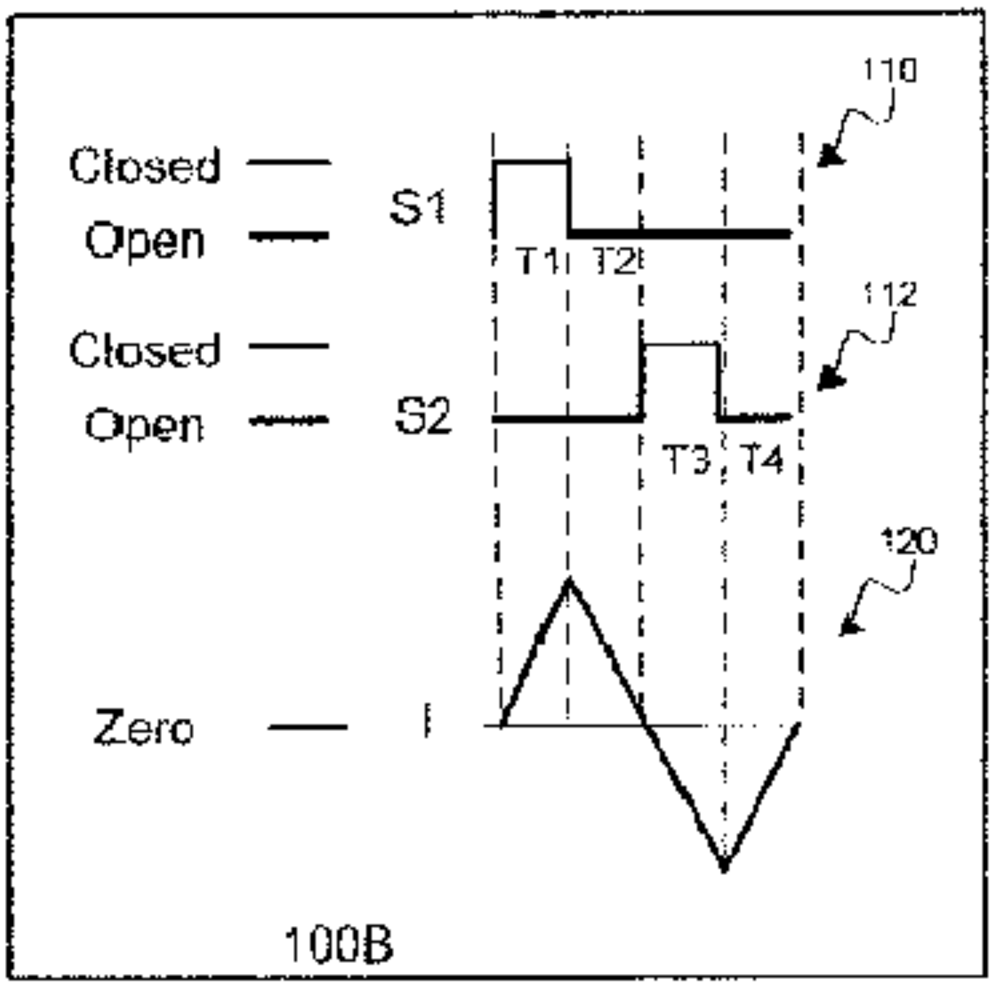

FIG. 1B

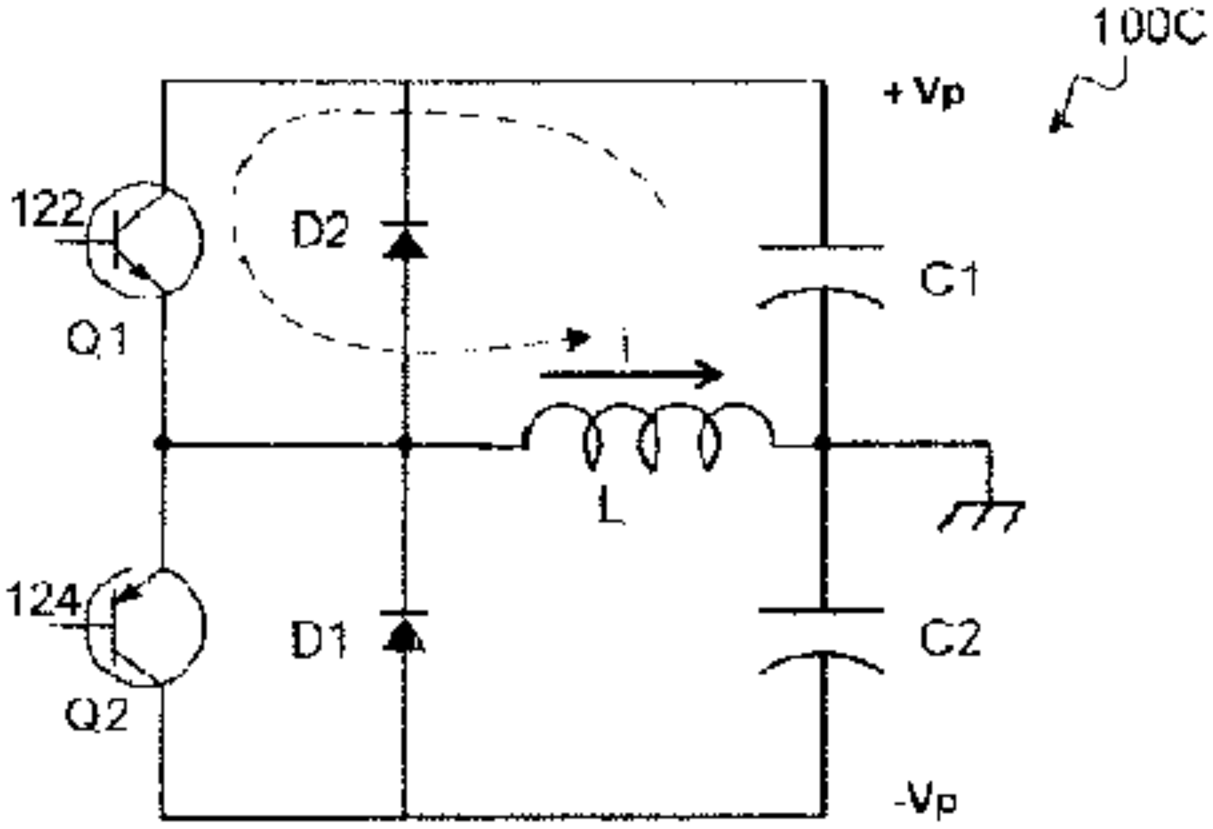

FIG. 1C

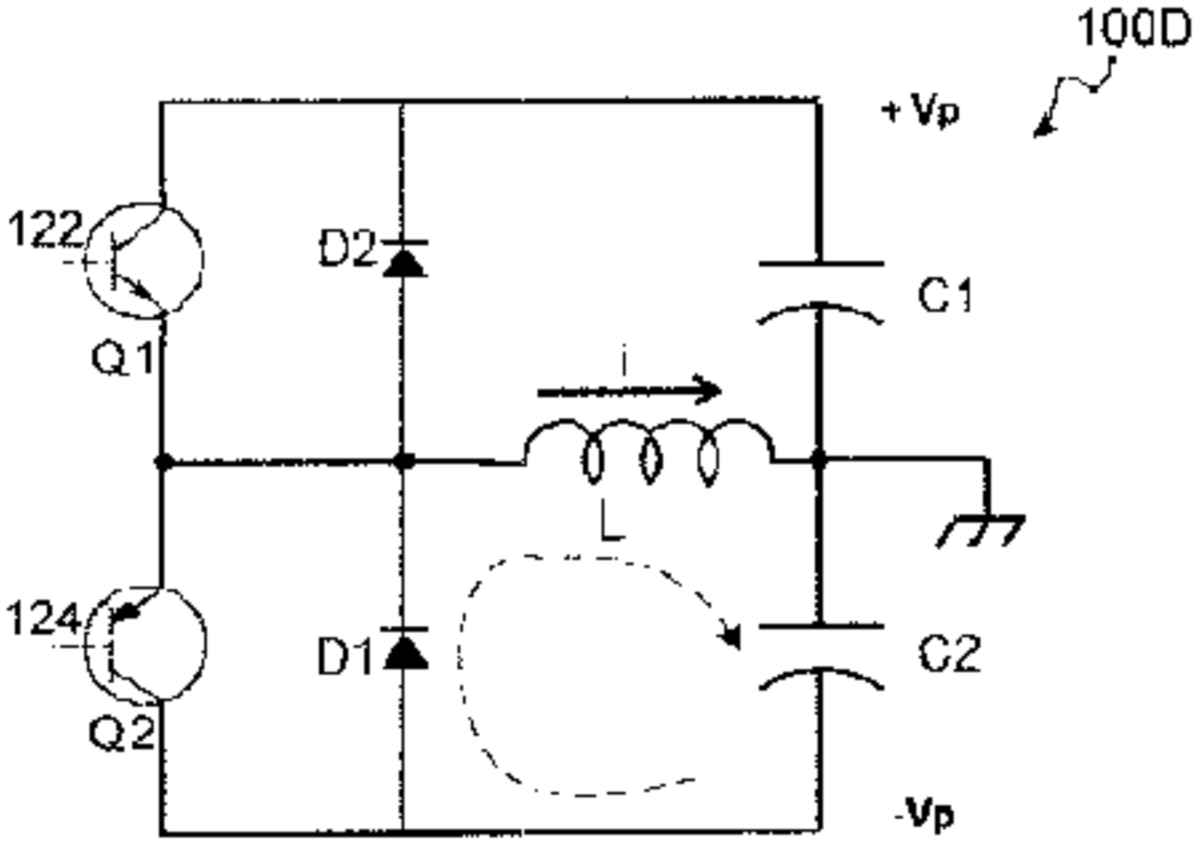

FIG. 1D

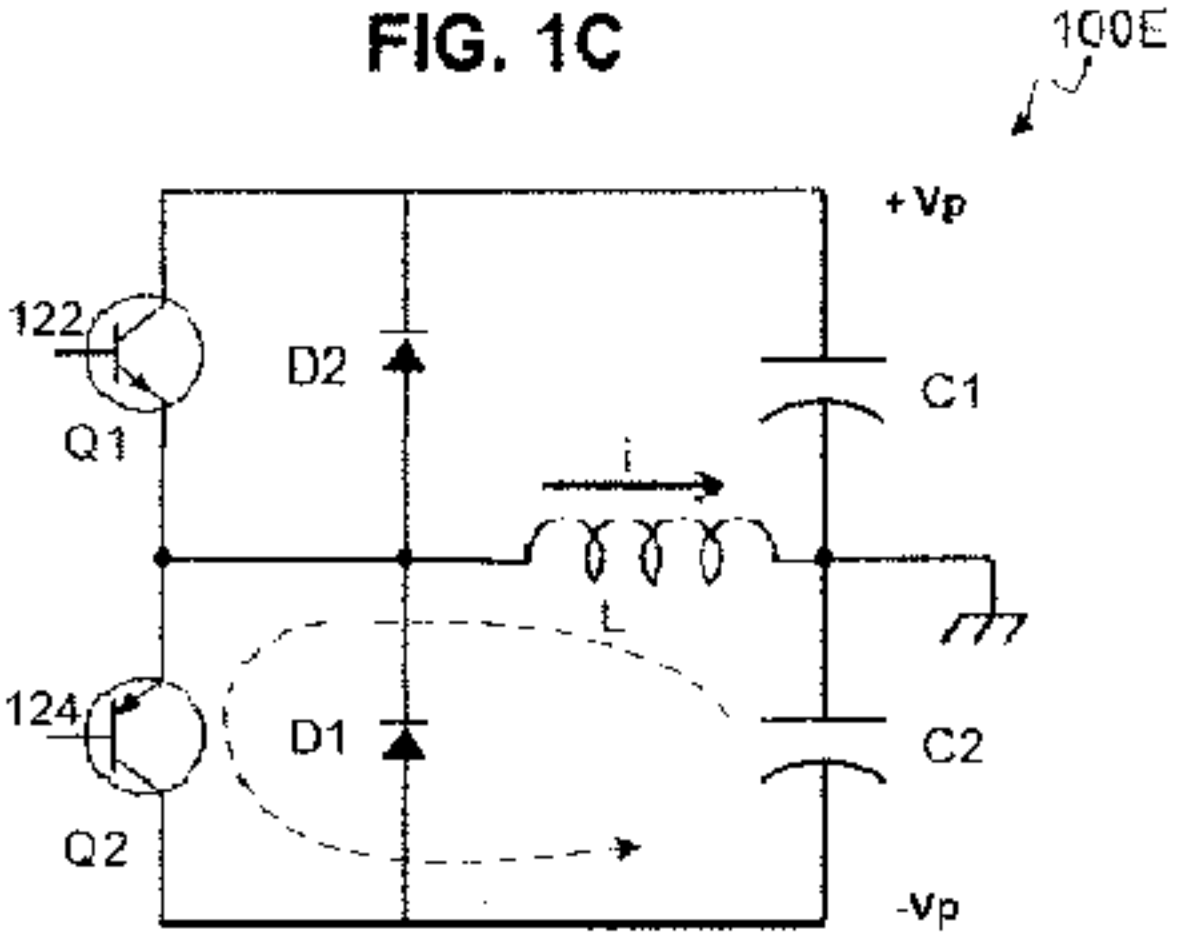

FIG. 1E

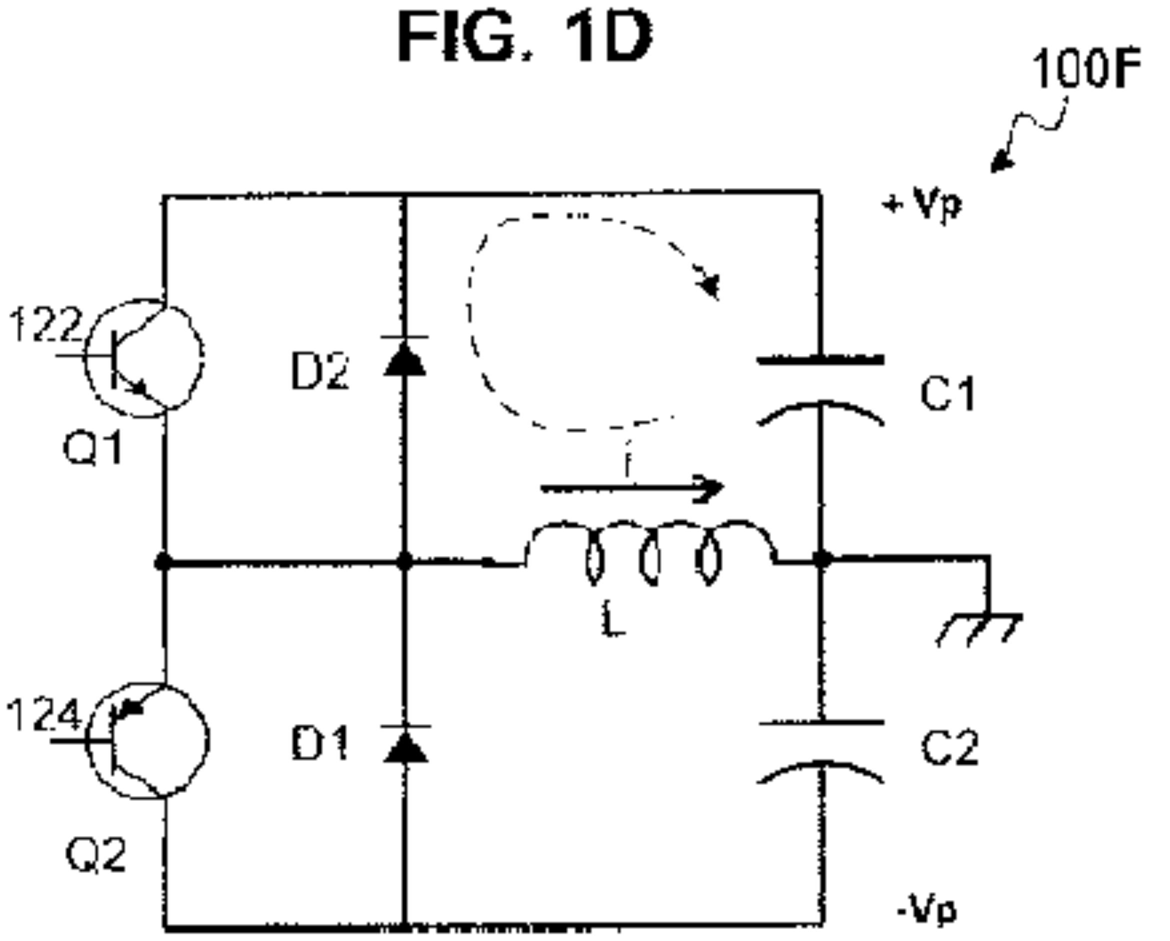

FIG. 1F