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62/132,934 13 March 2015 (13.03.2015) US(71) Applicant: ARCTIC SAND TECHNOLOGIES, INC.
[US/US]; 150 CambridgePark Drive, Suite 705, Cambridge, Massachusetts 02140 (US).

(72) Inventor: GIULIANO, David; 12 Parkway Road, Brookline, Massachusetts 02445 (US).

(74) Agent: LICHAUCO, Faustino A.; Occhiuti & Rohlicek LLP, 321 Summer Street, Boston, Massachusetts 02210 (US).

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(54) Title: DC-DC TRANSFORMER WITH INDUCTOR FOR THE FACILITATION OF ADIABATIC INTER-CAPACITOR CHARGE TRANSPORT

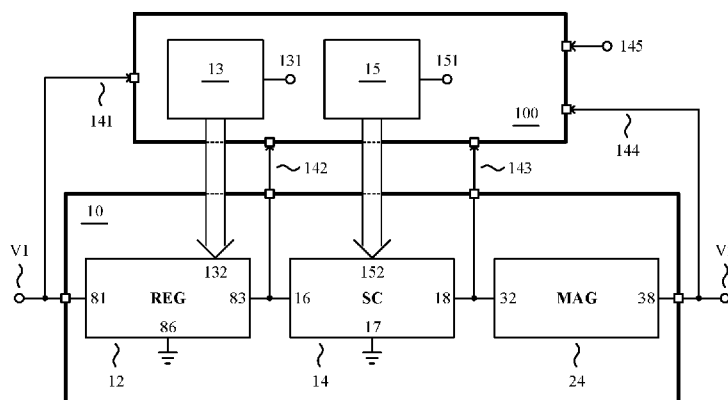


FIG. 1

(57) Abstract: An apparatus for power transformation includes a power converter having a charge pump, a first regulator that regulates the power provided by the power converter, and a magnetic filter connected to a terminal of the charge pump. The particular terminal to which the magnetic filter is connected is selected to facilitate adiabatic inter-capacitor charge transport within the charge pump.

1 **DC-DC TRANSFORMER WITH INDUCTOR FOR THE FACILITATION OF**
2 **ADIABATIC INTER-CAPACITOR CHARGE TRANSPORT**

3
4 **CROSS REFERENCE TO RELATED APPLICATION**

5 This application claims the benefit of the priority date of U.S. Provisional
6 Application No.: 62/132,934, filed March 13, 2015. The contents of which are
7 incorporated herein in their entirety.

8 **FIELD OF DISCLOSURE**

9 This disclosure relates to power conversion, and in particular, to DC power
10 conversion.

11 **BACKGROUND**

12 A known power converter is obtained by placing a regulator in series with a
13 charge pump. An example of such a regulator operates by switching an inductor into one
14 state and into a second state according to some switch duty cycle. The inductor in this
15 regulator performs two functions. One is to control the output voltage of the converter.
16 The other is to promote adiabatic charge transfer among the capacitors within the charge
17 pump.

18 Known power converters operating according to the above principles are
19 described in U.S. Patent No. 8,860,396, U.S. Patent No. 8,743,553, U.S. Patent No.
20 8,503,203, U.S. Patent No. 8,693,224, U.S. Patent No. 8,339,184, U.S. Patent No.
21 8,619,445, U.S. Patent No. 8,723,491, and U.S. Patent No. 8,817,501, the contents of
22 which are all herein incorporated by reference in their entirety.

23 **SUMMARY**

24 The invention is based on the recognition that the regulator's dual function of
25 regulation and promoting adiabatic charge transfer can be carried out by different
26 components.

27 The invention includes reducing the functionality of a component that has always
28 been used to carry out two functions, and relocating it so that it can no longer carry out
29 one of those functions. A new circuit component is added to carry out the function that
30 used to be carried out by the existing component. The invention thus achieves a more
31 complex circuit with an additional component that was not needed in the prior art.

1 The invention also reduces the die area required for the circuit by increasing the
2 number of components that have to be placed on the die.

3 In addition to reducing chip area, the invention described herein also fills in
4 certain holes in the performance of the overall power converter and makes it possible to
5 carry out more of the voltage transformation within the charge pump, where it can be
6 done most efficiently.

7 In a general aspect, one or more arrangements of a power converter are made up
8 of a combination of an interconnection of sections, including at least a “voltage
9 transformer,” a “magnetic filter,” and a “current regulator,” wherein these denotations
10 have no further implicit connotations.

11 The power converter has terminals that include a first pair of terminals and a
12 second pair of terminals, also referred to as the “controller” pair of terminals. In at least
13 some embodiments, an operating power converter controls a voltage measured between
14 the controlled pair of terminals. Typically, the power converter accepts power at the first
15 pair of terminals from a power source (e.g., an unregulated voltage source), referred to as
16 the “powered” pair of terminals, and provides power at a controlled voltage at the second
17 pair of terminals (e.g., to a substantially resistive load), referred to as the “load” pair of
18 terminals. It should be understood, however, that other arrangements can be used.

19 The voltage transformer, which is not to be confused with a conventional
20 magnetic core alternating current “transformer,” has at least three terminals and comprises
21 a switched arrangement of capacitors. Generally, sequential operation of switches in the
22 voltage transformer causes a voltage transformation, generally by a rational multiple,
23 between a first pair of terminals of the voltage transformer and a second pair of terminals
24 of the voltage transformer. In general, one pair of terminals is associated with a higher
25 voltage than the other pair. These pairs of terminals are hereinafter referred to as the
26 “high voltage” pair of terminals and the “low voltage” pair of terminals, respectively.

27 The sequential operation of the switches causes charge to transfer between
28 capacitors of the voltage transformer. The rate of charge transfer is constrained by a
29 current through at least one of the terminals of the voltage transformer. This terminal will
30 be referred to as a “charge transfer rate constraint” terminal.

1 When the rate of charge transfer between capacitors in at least one capacitor of
2 the voltage transformer is constrained for at least some of the time, for example, by the
3 current at the charge transfer rate constraint terminals, the voltage transformer is deemed
4 to be “adiabatic.” If at least some but not necessarily all of the charge transfers are
5 controlled, the voltage transformer is termed “partially adiabatic.” Otherwise the voltage
6 transformer is “fully adiabatic.”

7 The magnetic filter comprises two terminals coupled in a circuit path without any
8 switching activity. The magnetic filter opposes changes in the current flowing through at
9 least one of the terminals, hereinafter referred to as the “filtered terminal(s)” of the
10 magnetic filter, and generally maintains a substantially constant current through the
11 filtered terminal(s) during steady state operation of the power converter. In some
12 examples, the circuit path joining the terminals includes a passive inductor. In any case,
13 because the path between the two terminals does not require a switch, there is no switch
14 on the path that must be sized or selected to accommodate the maximum voltage or
15 current that may be present on the path during operation.

16 The current regulator has at least two terminals and comprises a switched
17 arrangement of at least one inductor. Generally, controlled sequential operation of one or
18 more switches of the current regulator controls current flow through a least one of the
19 terminals, hereinafter referred to as a “controlled terminal,” of the current regulator. In
20 general, although the current regulator may regulate current flow, the regulation of
21 current flow may be based on the output voltage (e.g., a time average voltage), which
22 may be measured between a pair of terminals of the current regulator, or between other
23 terminals within or at the interface of the power converter.

24 A common feature of a number of embodiments is that the arrangement of the
25 voltage transformer, magnetic filter, and current regulator of the power converter is that a
26 filtered terminal of the magnetic filter is directly coupled (i.e., without intervening
27 switches) to a first terminal of the voltage transformer, with this first terminal being a
28 charge transfer control terminal. Preferably, the magnetic filter is so coupled to a low
29 voltage pair of terminals, recognizing that generally, the magnitude of current flow is
30 higher at the low voltage terminals than at the high voltage terminals of the voltage
31 transformer.

1 Another common feature is that the controlled terminal of the current regulator is
2 directly coupled (i.e., without intervening switches) to a second terminal (different than
3 the first terminal) of the voltage transformer. The second terminal may be, but is not
4 necessarily, a charge transfer rate control terminal of the voltage transformer.

5 In some examples, the current regulator is coupled to multiple terminals of the
6 voltage transformer, or to multiple separate voltage transformer sections of the power
7 converter. In other examples, multiple current regulators, or current regulators having
8 multiple separate controlled terminals, are coupled to multiple terminals of the voltage
9 transformer or to multiple separate voltage transformers.

10 In operation of the power converter, the current regulator is controlled to achieve
11 a controlled voltage at the controlled terminals of the power converter.

12 A number of configurations of the voltage transformer, magnetic filter, and
13 current regulator can be grouped into (possibly overlapping) classes referred to as
14 “series,” “sigma,” and “pseudo series,” without connoting any particular attributes by
15 these names.

16 The series class of configurations includes configurations in which the current
17 regulator, the voltage transformer, and the magnetic filter are connected in series between
18 the first pair and the second pair of terminals of the power converter. In at least some of
19 these configurations, the magnetic filter is coupled to a controlled/load terminals of the
20 power converter, and the current regulator is coupled to a powered terminal of the
21 regulator. In at least other of these configurations, the magnetic filter is coupled to a
22 powered terminal of the power converter and the current regulator is coupled to a
23 controlled terminal of the power converter.

24 The sigma class and the pseudo series class of configurations include
25 configurations in which one controlled terminal of the current regulator is coupled to a
26 controlled terminal of the power converter. The voltage transformer is also coupled to the
27 same (or potentially a different) controlled terminal of the power converter via the
28 magnetic filter such that the magnetic filter provides a path from a charge transfer rate
29 control terminal of the voltage transformer to the controlled terminal. In at least some
30 configurations of the sigma class, another terminal of the current regulator is coupled to
31 the voltage transformer, such that in operation, control of the current regulator affects a

1 voltage on the first pair or the second pair of terminals of the voltage transformer. For
2 example, if a terminal of the first pair of terminals of the voltage transformer is coupled
3 via the magnetic filter to a controlled terminal of the power converter to which a
4 controlled terminal of the current regulator is also coupled, then another terminal of the
5 current regulator is coupled to a terminal of the second pair of terminals of the voltage
6 transformer.

7 The sigma class of configurations includes configurations in which there exists a
8 path from a terminal of the first pair of terminals of the power converter to a terminal of
9 the second pair of terminals of the power converter that passes through the current
10 regulator without passing through the voltage transformer.

11 The pseudo series class of configurations includes configurations in which the
12 voltage transformer is coupled to a controlled terminal of the power converter through a
13 first path that passes via the magnetic filter but not the current regulator, as well as via a
14 second path that that passes via the current regulator but not the magnetic filter.

15 An advantage of at least some configurations of the sigma and the pseudo parallel
16 classes is that some of the power flow through the power converter passes through the
17 magnetic filter but not the current regulator. Because the magnetic filter does not
18 introduce a switch on power flow path though the magnetic filter, power losses (e.g.,
19 resistive and capacitive losses in a switch) are reduced and overall efficiency of the
20 power converter is improved.

21 An advantage of at least some configurations of any of the classes are that the
22 number or range of combinations of terminal voltages supported by the power converted
23 can be increases as compared to other configurations that are affected by limitations on
24 voltage differences between pair of its terminals of the current regulator that differ by less
25 than a threshold voltage.

26 Another advantage of at least some configurations is that voltage or current
27 handling requirements of switches of the voltage transformed and/or the current regulator
28 can be reduced as compared to other configurations. These reduced requirements can
29 result in physically smaller semiconductor devices, which can reduce the size of an
30 integrated circuit implementation of some or all of the power converter.

1 In one aspect, the invention features an apparatus for power transformation. Such
2 an apparatus includes a power converter having a charge pump, a first regulator that
3 regulates the power provided by the power converter, and a magnetic filter connected to a
4 terminal of the charge pump. The particular terminal to which the magnetic filter is
5 connected is selected to facilitate adiabatic inter-capacitor charge transport within the
6 charge pump.

7 Embodiments include those in which the charge pump has a first terminal and a
8 second terminal. In operation the first terminal is maintained at a first voltage and the
9 second terminal is maintained at a second voltage that is lower than the first. In these
10 embodiments, the magnetic filter is connected to the second terminal, which is the
11 terminal that has the lower voltage.

12 In other embodiments, the first regulator is disposed to intercept a first portion of
13 power provided by the power converter. Meanwhile, the charge pump is disposed to
14 intercept a second portion power provided by the power converter. The magnetic filter
15 too is disposed to intercept the second portion. The second portion is greater in
16 magnitude and the first portion.

17 In other embodiments, the first regulator is disposed to intercept a first portion of
18 power provided by the power converter. Meanwhile, the charge pump is disposed to
19 intercept a second portion power provided by the power converter. The magnetic filter
20 two is disposed to intercept the second portion. The first and second portions are
21 combined at an output of the power converter.

22 In another embodiment, both the magnetic filter and the first regulator are
23 connected to an output of the power converter. In this embodiment, the first regulator is
24 connected to the first terminal. Also among these embodiments are those in which the
25 first regulator includes a ground terminal that is also connected to the first terminal.

26 In another embodiment, the charge pump includes first and second charge-
27 transport paths. In these embodiments, first regulator is connected to the first charge
28 transport path, and the magnetic filter is connected to the second charge transport pass.
29 Among these are embodiments in which the second charge-transport path has greater
30 current than the first charge-transport path, and embodiments in which the first charge-
31 transport path has greater current than the second charge-transport path. Also among

1 these are embodiments in which there is a second regulator, and the magnetic filter is a
2 constituent part of the second regulator. In some of these embodiments, the first regulator
3 operates at a first duty cycle, and the second regulator operates at a second duty cycle that
4 is controlled independently of the first duty cycle.

5 Some embodiments include a controller for controlling operation of the regulator
6 based on an output of the power converter. Others include a clock configured to provide a
7 clock signal to either the regulator or the charge pump.

8 Also among the embodiments are those that have a control system configured to
9 control operation of the power converter based on a measured output of the power
10 converter. Among these are those that have a controller to control the regulator, those that
11 have a controller to control the charge pump, those that have both, those that have a clock
12 signal input that can receive a clock signal, those in which the controller has digital
13 inputs, those in which the controller has analog inputs, and any combination of the
14 foregoing.

15 A variety of charge pumps and regulators can be used. For example, among the
16 embodiments are those that have a multi-phase charge pump, those that have a single-
17 phase charge pump, those that have a multi-stage charge pump, those have a two-phase
18 charge pump, those that have a resonant power converter, those that have a switch mode
19 power converter, those that have a buck converter, those that have a bidirectional
20 regulator, and those that a multi-phase regulator.

21 In some embodiments, the charge pump comprises capacitors interconnected by
22 sets of switches. During operation, switches in the first set are opposite in state to
23 switches in the second set.

24 In some embodiments, the charge pump is a reconfigurable charge pump. Among
25 these are embodiments in which the regulator is configured to transition from providing a
26 first voltage to providing a second voltage during reconfiguration of the charge pump.

27 In another aspect, the invention features an apparatus for power transformation.
28 Such an apparatus includes a power converter having a charge pump, a first regulator that
29 regulates the power provided by the power converter, and a magnetic filter connected to a
30 terminal of the charge pump. The particular terminal to which the magnetic filter is

1 connected is selected to facilitate causing a constraint in inter-capacitor charge transport
2 within the charge pump.

3 In another aspect, the invention features a non-transitory computer-readable
4 medium that stores a data structure that is to be operated upon by a program executable
5 on a computer system, wherein, when operated upon by such a program, the data
6 structure causes at least a portion of a process for fabricating an integrated circuit that
7 includes circuitry described by the data structure, wherein the circuitry described by the
8 data structure includes a switching network that has been configured to be used with a
9 power converter that comprises a charge pump, a first regulator that is configured to
10 regulate power provided by said power converter, and a magnetic filter that is connected
11 to a terminal of said charge pump and that is selected to facilitate adiabatic inter-capacitor
12 charge transport within said charge pump.

13 These and other features of the invention will be apparent from the following
14 detailed description, and the accompanying figures, in which:

15 **BRIEF DESCRIPTION OF THE DRAWINGS**

16 FIG. 1 shows one embodiment of a power converter;

17 FIG. 2 shows a switched-capacitor charge pump for use with a power converter such as
18 that shown in FIG. 1;

19 FIG. 3A shows terminals that connect to the various capacitor networks that will be
20 formed and unformed as the charge pump of FIG. 2 transitions through its various
21 states;

22 FIG. 3B shows a first capacitor network corresponding to a first configuration of switches
23 for the charge pump of FIG. 2;

24 FIG. 3C shows a second capacitor network corresponding to a second configuration of
25 switches for the charge pump of FIG. 2;

26 FIG. 4 shows a block diagram of the 4-terminal charge pump of FIG. 2;

27 FIG. 5 shows a block diagram of the 3-terminal charge pump of FIG. 3A;

28 FIG. 6A shows the components of a typical regulator that can be used in a power
29 converter such as that shown in FIG. 1;

30 FIGS. 6B – 6D show alternative regulators for use with a power converter such as that
31 shown in FIG. 1;

1 FIGS. 7A – 7B show magnetic filters that can be used in the embodiment of FIG. 1;
2 FIG. 8 shows an embodiment in which a diode is used to conduct current in a magnetic
3 filter that has no place to go during the dead time of the charge pump;
4 FIG. 9 shows the power converter of FIG. 1 but with parallel charge pumps and parallel
5 magnetic filters.
6 FIG. 10 shows the power converter of FIG. 9 but with the magnetic filters sharing a
7 common inductor;
8 FIG. 11 shows the power converter of FIG. 1 but with the regulator having switches that
9 share a common inductor;
10 FIG. 12 shown an embodiment similar to that shown in FIG. 1 but with a four-terminal
11 charge pump;
12 FIG. 13 shows an embodiment having a bifurcated power path through the power
13 converter;
14 FIG. 14A shows a circuit that implements the bifurcated power path of FIG. 13, with the
15 input voltage split so that the voltage presented to the regulator is twice that
16 presented to the charge pump;
17 FIG. 14B shows a circuit that implements the bifurcated power path of FIG. 13, with the
18 input voltage split so that the voltage presented to the regulator is half that
19 presented to the charge pump;
20 FIG. 15A, shows another embodiment having a bifurcated power path through a power
21 converter;
22 FIG. 15B shows a circuit that implements the bifurcated power path of FIG. 15A;
23 FIGS. 16A shows an isolated charge pump that is suitable for use with the architecture
24 shown in FIG. 15A;
25 FIG. 16B shows a single-phase implementation of the isolated charge pump shown in
26 FIG. 16A;
27 FIG. 16C shows a two-phase implementation of the isolated charge pump shown in FIG.
28 16A;
29 FIGS. 17A – 17D show variants of the architecture shown in FIG. 15A;
30 FIGS. 18A – 18C show circuit topologies having bifurcated power paths with grounded
31 charge pumps.

FIGS. 19A – 19C show circuit topologies similar to those in FIGS. 18A – 18C except with grounded regulators instead of charge pumps.

FIG. 20 shows a power converter that shows features common to the embodiments of FIGS. 1, 12, 13, and 15A;

FIG. 21A shows a regulated charge pump;

FIGS. 21B – 21C show the switch configurations and network states for the regulated charge pump of FIG. 21A;

FIG. 22A shows a regulated charge pump of FIG. 21A with a switch having been eliminated;

FIG. 22B shows the switch configurations for the regulated charge pump of FIG. 22A;

FIG. 23A shows the regulated charge pump of FIG. 22A with a stabilizing capacitor;

FIGS. 23B – 23C show the switch configurations and network states for the regulated charge pump of FIG. 23A;

FIG. 24A shows a regulated charge pump in which both switches of the regulator have been removed;

FIG. 24B shows the switch configurations for the regulated charge pump of FIG. 24A;

FIGS. 25A – 26B show, for the regulated charge pump of FIG. 24A, additional switch configurations and network states in which there are only three states and configurations needed to operate the charge pump;

FIG. 27A is a two-phase implementation of the regulated charge pump of FIG. 24A; and

FIG. 27B shows the network states for the regulated charge pump of FIG. 27A.

DETAILED DESCRIPTION

A charge pump has a high-voltage terminal and a low-voltage terminal. Because of conservation of energy, the high-voltage terminal is associated with a lower current, whereas the low-voltage terminal is associated with a higher current. The regulator can, in principle, be placed at either end.

However, in order to allow the inductor in the regulator to participate in the adiabatic charging of all capacitors in the charge pump, it is important that the regulator be connected to the low-voltage side. There are two disadvantages to this configuration: one physical and the other operational.

1 The physical disadvantage arises from the fact that the low-voltage terminal of the
2 charge pump has a great deal of current coming out of it. This means that the switch
3 within the regulator must be able to accommodate very high currents. This is most often
4 achieved by making the transistor that implements the switch physically larger, so that
5 the current density at any point within the transistor will be smaller. Unfortunately, with
6 this switch consuming so much of the die area, it can become necessary to use a larger
7 die. This increases cost of manufacture, as well as size of the power converter as a whole.

8 The operational disadvantage arises from the fact that charge pumps are generally
9 more efficient at executing a voltage transformation than regulators. Although the
10 regulator can also transform voltage, it is not particularly efficient at doing so. Where it
11 excels is in providing fine control over voltage and suppressing current ripple. Thus,
12 when a power converter is asked to transform a first voltage into a second voltage, it is
13 preferable that the charge pump carry out as much of the voltage transformation as
14 possible, and that the regulator do as little of the voltage transformation as possible.

15 There are two constraints that militate against achieving this. The first constraint
16 is that charge pumps are designed around a particular integer ratio, n/m . Thus, for a given
17 input voltage V_{in} , the output voltage V_{out} of a charge pump is $V_{in} * (n/m)$. This ratio is fixed
18 for a particular configuration of the charge pump. Among the regulator's functions is to
19 bridge the gap between the overall factor required to reach a target value of voltage and
20 the factor (n/m) that the charge pump contributes.

21 The second constraint that arises in known designs is that a minimum voltage
22 margin must exist between the input and output of the regulator. If the regulator is placed
23 at the low-voltage terminal of the charge pump, it is quite possible that the voltage at the
24 output of the charge pump and the target voltage will differ by less than this minimum
25 voltage margin.

26 For example, if the desired power converter output is 1.0 volt, and V_{in} is 4.2 volts,
27 one can use a charge pump designed with $m/n=3$ to maintain 1.4 volts at the low voltage
28 output. Although this slightly exceeds the target voltage, the regulator is intended to
29 bridge the gap between the 1.4 volts and the desired 1.0 volts. This is desirable because a
30 large fraction of the required voltage transformation will have been carried out by the
31 more efficient charge pump.

1 However, if this output is provided to a regulator that requires, for example, a 0.6
2 volt minimum voltage margin, then it will not be possible to output 1.0 volts. This creates
3 what amounts to a gap in the performance of the power converter.

4 Of course, this problem can easily be solved by using a charge pump designed
5 with $m/n=2$ instead. If this is done, the output of the charge pump will be 2.1 volts, which
6 will be enough to provide the 0.6 voltage margin. However, the job of transforming the
7 2.1 volts into the desired 1.0 volt must now be carried out by the regulator, which is not
8 particularly efficient at doing so.

9 In a first embodiment, shown in FIG. 1, a power converter **10** transforms a first
10 voltage **V1** into a second voltage **V2**. The power converter **10** includes a regulator **12** and
11 a 3-terminal charge pump **14** in series. The 3-terminal charge pump **14** has a first CP-
12 terminal **16**, a second CP-terminal **18**, and a third CP-terminal **17**.

13 A regulator controller **13** connected to a regulator-control output **132** controls the
14 switching activity of the regulator **12** based at least in part on feedback from a feedback
15 line **144** connected to the second voltage **V2**. The regulator controller **13** can, however,
16 rely on other inputs such as a feed-forward line **141**, a first intermediate feedback line
17 **142**, and a second intermediate feedback line **143**. A regulator-control input **131**, which
18 can be a digital input or an analog input, enables one to enter a set point for operation of
19 the regulator **12**.

20 Meanwhile, a charge-pump controller **15** that is connected to a charge-pump-
21 control output **152** controls the switching activity of the 3-terminal charge pump **14**. A
22 charge-pump-control input **151**, which can be a digital input or an analog input, enables
23 one to enter a set point for operation of the 3-terminal charge pump **14**.

24 The power converter **10** further includes a clock **145** connected to both the
25 charge-pump controller **15** and the regulator controller **13** to ensure that switches open
26 and close at the correct time and in synchrony.

27 For the sake of clarity, the regulator controller **13**, the charge-pump controller **15**,
28 and the clock **145** have been omitted from certain figures. However, it is understood that
29 they are always implicitly present.

30 During operation of the 3-terminal charge pump **14**, the regulator **12** maintains the
31 first CP-terminal **16** at a high voltage, but has a low current passing through it. The

second CP-terminal **18** is maintained at a relatively low voltage by the action of the 3-terminal charge pump **14**. Both the first and second CP-terminals **16**, **18** share a common ground reference at the third CP-terminal **17**.

In particular, for an input voltage V_h , at the first CP-terminal **16**, the voltage at the second CP-terminal **18** is $V_h \cdot (m/n)$ where m/n is the defining voltage transformation ratio of the particular charge pump. The second CP-terminal **18** will, however, also have a higher current passing through it. In the ideal case, with no loss, the power entering the 3-terminal charge pump **14** should be equal to the power leaving the 3-terminal charge pump **14**. This means that the product of high current and low voltage at the second CP-terminal **18** should be equal to the product of high voltage and low current at the first CP-terminal **16**.

The 3-terminal charge pump **14** can be implemented using many different charge pump topologies such as Ladder, Dickson, Series-Parallel, Fibonacci, and Doubler. Some of these topologies can be configured such that the ground reference associated with the first CP-terminal **16** and the ground reference associated with the second CP-terminal **18** are different, resulting in a 4-terminal charge pump **74** with four terminals.

FIG. 2 illustrates a 4-terminal charge pump **74** that is a two-phase variant of the Dickson charge pump, also known as a cascade multiplier. In addition to the first and second CP-terminals **16**, **18**, the 4-terminal charge pump **74** also includes fourth and fifth CP-terminals **116**, **118**. Unlike in the 3-terminal charge pump **14**, the first and second CP-terminals **16**, **18** in the 4-terminal charge pump **74** do not share a common ground reference. Instead, the first CP-terminal **16** has its own ground reference at the fourth CP-terminal **116** and the second CP-terminal **18** has its own ground reference at the fifth CP-terminal **118**.

The 4-terminal charge pump **74** features a switching network that causes transitions between first and second states. A switched-capacitor network **21** inside of the 4-terminal charge pump **74** alternates between first and second states depending on which of these switches are open and which ones are closed. A first switch configuration causes the switched-capacitor network **21** to transition from the first state to the second state. A second switch configuration causes the switched-capacitor network **21** to transition from

1 the second state to the first state. Charge pumping action arises as a result of the switches
2 causing the switched-capacitor network **21** to switch between these states.

3 In operation, different amounts of current will flow through different switches. It
4 is therefore useful to size the switches in a manner appropriate to the currents that will be
5 flowing through them. For example, the switches connected to the second and fifth CP-
6 terminals **18**, **118** carry more current than the other switches in FIG. 2. By making these
7 switches larger than the other switches one avoids the need to have unnecessarily large
8 switches and thus results in a smaller circuit footprint. This also avoids unnecessary
9 additional capacitive losses, which are proportional to the size of the switch.

10 FIG. 3A shows the terminals that will connect to a switched-capacitor network **21**
11 of the 4-terminal charge pump **74**. The 4-terminal charge pump **74** is constantly
12 transitioning between states, each of which is a different capacitor network. In the
13 discussion that follows, the switched-capacitor network **21** shown in FIG. 2 will only be
14 shown in one state or the other. As a result, the proliferation of switches shown in FIG. 2
15 will no longer need to be shown.

16 Of course, no one state can be said to actually define the 4-terminal charge pump
17 **74** any more than it is possible to identify one frame that defines a movie. In recognition
18 of this, the switched-capacitor network **21** is shown as a blank screen in FIG. 3A. Either a
19 first state **21A** or a second state **21B** will be projected into this blank screen. The actual
20 switched capacitor network that exists in FIG. 3A will depend on exactly when one looks
21 at it. Sometimes, the switched-capacitor network **21** will be in its first state **21A**, as
22 shown in FIG. 3B, and sometimes it will be in its second state **21B**, as shown in FIG. 3C.

23 The first and second states **21A**, **21B** are essentially symmetric. Although the
24 topology appears the same, a close examination of FIGS. 3B and 3C will reveal that the
25 capacitors have switched places. This switching places is what the switches shown in
26 FIG. 2 accomplish.

27 In the 4-terminal charge pump **74** shown in FIG. 4, there are three internal charge-
28 transport paths. A first charge-transport path, between the fifth CP-terminal **118** and the
29 second CP-terminal **18** carries a first current, i_P . This first charge-transport path carries
30 the highest current. A second charge-transport path between the first CP-terminal **16** and
31 the second CP-terminal **18** carries a second current, i_H . A third charge-transport path

1 between the fifth CP-terminal **118** and the fourth CP-terminal **116** carries a third current,
 2 i_L . The current present at the second CP-terminal **18** is thus the sum (i_P+i_H) . This is
 3 approximately equal to $N*i_H$, where N depends on the topology of the switched-capacitor
 4 network **21**. In this embodiment, the grounds are not completely isolated because there is
 5 a charge-transport path between them.

6 The 3-terminal charge pump **14** can be created from the 4-terminal charge pump
 7 **74** by shorting the fourth CP-terminal **116** to the second CP-terminal **18** and by shorting
 8 the fifth CP-terminal **118** to the third CP-terminal **17** of the 3-terminal charge pump **14**. A
 9 block diagram of the resulting charge pump is shown in FIG. 5.

10 It is apparent from FIG. 5 that there are two internal charge-transport paths within
 11 the 3-terminal charge pump **14**. A first charge-transport path, between the third CP-
 12 terminal **17** and the second CP-terminal **18** carries a first current, i_P+i_L . This first charge-
 13 transport path carries the highest current. A second charge-transport path between the
 14 first CP-terminal **16** and the second CP-terminal **18** carries a second current, i_H . The
 15 current present at the second CP-terminal **18** is thus the sum $(i_P+i_H+i_L)$. This is
 16 approximately equal to $(N+1)i_H$, wherein N depends on the topology of the switched-
 17 capacitor network **21**.

18 In the embodiment shown in FIG. 1, the regulator **12** is placed between the first
 19 voltage **V1** to be transformed and the first CP-terminal **16** of the 3-terminal charge pump
 20 **14**. This hinders the regulator's ability to promote adiabatic inter-capacitor charge
 21 transport among the capacitors in the 3-terminal charge pump **14**. To improve this ability,
 22 it is preferable to connect the regulator **12** to the second CP-terminal **18**.

23 The desirability of placing the regulator **12** at the second CP-terminal **18** is
 24 apparent from FIGS. 3B – 3C. An examination of the network topology reveals that an
 25 inductor coupled to the second CP-terminal **18** would be coupled to all capacitors in the
 26 switched-capacitor network **21**. Therefore, it will be able to influence all three charge-
 27 transport paths simultaneously. In contrast, an inductor coupled to the first CP-terminal
 28 **16** will only be able to affect the second charge-transport path between the first CP-
 29 terminal **16** and the second CP-terminal **18**. To make matters worse, the second charge-
 30 transport path does not carry nearly as much current as the first charge-transport path

1 between the fifth CP-terminal **118** and the second CP-terminal **18**. Thus, to reduce loss, it
 2 is more important to influence the first charge transport path.

3 In the configuration shown in FIG. 1, the regulator **12** has been partially side-
 4 lined. It can still regulate the current at the second CP-terminal **18**. But it has lost its
 5 ability to promote adiabatic inter-capacitor charge transport.

6 However, having the regulator **12** connected to the first CP-terminal **16** instead of
 7 the second CP-terminal **18** is not without its advantages. In particular, at the first CP-
 8 terminal **16**, only a small current, i_H , flows through regulator **12**. This means that the
 9 various components in the regulator **12** no longer have to be sized to accommodate the
 10 larger current, $(i_H + i_P)$, present at the second CP-terminal **18**.

11 In particular, in a common embodiment of a regulator **12**, such as that shown in
 12 FIG. 6A, a switch **20** periodically connects an inductor **22** into a first state and into a
 13 second state according to a duty cycle. This switch **20** ultimately bears the full brunt of
 14 the current passing through the regulator **12**. Since practical switches **20** are implemented
 15 with semiconductor materials, there is some risk that the switch **20** will overheat. Since
 16 the heat produced in a bulk material is the product of resistivity and current density, one
 17 way to reduce excessive heating of a semiconductor switch **20** so that it can
 18 accommodate large amounts of current is to simply spread the current over a larger area
 19 of semiconductor material, thus lowering the current density. However, this results in a
 20 switch **20** that consumes a great deal of area on a semiconductor die.

21 Many other regulator configurations have such a switch **20** that periodically
 22 connects an inductor into a first state and into a second state to regulate. Other examples
 23 are shown in FIGS. 6B - 6D, which features a boost converter in FIG. 6B, a boost-buck
 24 converter in FIG. 6C, and a Flyback converter in FIG. 6D. Although these regulators are
 25 somewhat different in topology, they all feature a switch **20** that modulates an inductor
 26 **22** (or transformer). Other suitable regulators not shown, include Flyback converters,
 27 quasi-resonant Flyback converters, active-clamp Flyback converters, interleaved Flyback
 28 converters, Cuk converters, SEPIC converters, resonant converters, multi-level
 29 converters, Forward converters, two-switch Forward converters, active-clamp Forward
 30 converters, interleaved Forward converters, multi-Resonant Forward converters, Half-

1 Bridge converters, asymmetric Half-Bridge converters, multi-resonant Half-Bridge
2 converters, LLC resonant Half-Bridge converters, and Full-Bridge converters.

3 As a result of having connected the regulator **12** to the first CP-terminal **16** as
4 shown in FIG. 1, the switch **20** needs only to accommodate a smaller current than it
5 would have had to accommodate had it been connected to the second CP-terminal **18**. Of
6 course, the switch **20** may need to be designed to accommodate the high voltage at the
7 first CP-terminal **16**. However, this trade-off is usually favorable in most designs.

8 Another advantage of connecting the regulator **12** to the first CP-terminal **16** is
9 that the inductor **22** does not need as large of an inductance as it would have had it been
10 connected to the second CP-terminal **18**. This reduces the dc resistance of the inductor **22**
11 and thus reduces energy losses associated with the current through the inductor **22**.

12 Adiabatic inter-capacitor charge transport remains desirable no matter where the
13 regulator **12** is placed. With the inductor **22** within the regulator **12** no longer available
14 for this purpose, it is necessary to add another component to the power converter **10**. This
15 results in an increase in the component count and a resultant increase in circuit
16 complexity.

17 To promote adiabatic intra-capacitor charge transport within the 3-terminal charge
18 pump **14**, the illustrated embodiment in FIG. 1 features a magnetic filter **24** that is
19 connected to the second CP-terminal **18**. The magnetic filter **24** includes an inductor that
20 tends to promote adiabatic inter-capacitor charge transport within the 3-terminal charge
21 pump **14**.

22 The switches shown in FIG. 2 will transition between states at some switching
23 frequency. It is desirable that, in order to reduce loss, the charge pump **14** operate
24 adiabatically at that switching frequency. One way to ensure that this is the case is to
25 choose the resistances of the switches such that they are so large that the RC time
26 constant of the charge transfer between the capacitors is similar if not longer than the
27 switching frequency. Unfortunately, this increases the resistive losses. The magnetic filter
28 **24**, allows us to reduce the resistance of the switches without incurring substantial
29 redistribution loss and thereby operate adiabatically. Therefore, the switches can be
30 optimally sized for the highest efficiency without worrying about redistribution loss. The

1 optimal size for each switch is chosen by balancing the resistive and capacitive losses in
2 each switch at a given switching frequency and at a given current.

3 Yet another advantage of connecting the regulator **12** to the first CP-terminal **16**
4 arises with certain dynamically reconfigurable charge pumps.

5 In some cases, it is possible for the first voltage **V1** shown in FIG. 1 to fluctuate
6 considerably. There may be times, for example, where the voltage drops enough so that
7 the voltage across the regulator **12** is insufficient for proper operation. This requires
8 reducing the voltage transformation ratio of the 3-terminal charge pump **14**, thus
9 providing enough slack voltage for the regulator **12** to work with. Such dynamic
10 reconfiguration can be carried out using charge pumps, such as those described in U.S.
11 Patent No. 8,817,501.

12 When a charge pump is in a new configuration, the voltages across the capacitors
13 in the charge pump may have to change to be appropriate to the new configuration. This
14 change often has to occur rapidly. A rapid change in capacitor voltage requires a very
15 large current.

16 For some charge pumps, the capacitor voltages are set by whatever is present at
17 the second CP-terminal **18**. An example of such a configuration is the one shown in
18 FIGS. 3A-3C, where it is apparent that the voltage across the capacitors is a function of
19 the voltage between the second CP-terminal **18** and the third CP-terminal **17**. For these
20 charge pump configurations, a dynamic reconfiguration may draw considerable current
21 through the first CP-terminal **16** as the charge pump begins to operate in its new
22 configuration.

23 Placing the regulator **12** before the 3-terminal charge pump **14** as illustrated in
24 FIG. 1, and carefully synchronizing the operation of the regulator **12** with the dynamic
25 reconfiguration of the 3-terminal charge pump **14**, can avoid this disturbance. In
26 particular, while the 3-terminal charge pump **14** is in the old configuration, the regulator
27 **12** supplies a first intermediate voltage to the 3-terminal charge pump **14** via the first CP-
28 terminal **16**. Then, during the brief interval that reconfiguration is actually taking place,
29 the regulator **12** is quickly adjusted so that instead of providing the first intermediate
30 voltage, it provides a second intermediate voltage that is more appropriate for the charge
31 pump's new configuration. Once dynamic reconfiguration is complete, the 3-terminal

1 charge pump **14** resumes operation. However, by this time, the regulator **12** is already
2 ready and waiting to supply it with the correct second intermediate voltage at the first
3 CP-terminal **16**.

4 The magnetic filter **24** can be created in many different ways. FIG. 7A shows one
5 implementation of the magnetic filter **24** that features a first inductor **26** and, optionally, a
6 capacitor **28**.

7 FIG. 7B shows an alternative magnetic filter **24** that features an a second inductor
8 **27** in addition to the first inductor **26** and the capacitor **28**. This embodiment of the
9 magnetic filter **24** is a third order low pass filter and therefore, more effective than the
10 magnetic filter **24** in FIG. 7A at attenuating high frequencies.

11 A charge pump is constantly opening and closing one or more switches. It is
12 important, particularly when an inductor is present in a circuit, that whenever a switch is
13 opened, current flowing in the circuit have someplace to go. Otherwise it may damage the
14 switch.

15 Between the first state and the second state of a charge pump (e.g., the 3-terminal
16 charge pump **14**), there is a dead-time interval during which all of the switches in the
17 switched-capacitor network **21** are open. Although not, in principle, required, this dead-
18 time interval is a practical necessity because switches do not transition instantaneously.
19 Thus, it is necessary to provide a margin to avoid the undesirable result of having
20 switches closed at the same time.

21 In a preferred embodiment, a magnetic filter **24** connected to the second CP-
22 terminal **18** in a power converter **10** is modified to include a circuit element to safely
23 shunt current that would otherwise have no place during the dead-time of the 3-terminal
24 charge pump **14**. In one such embodiment shown in FIG. 8, a shunt diode **29** is used to
25 direct such current. Alternatively, if the dead-time interval in the switched-capacitor
26 network **21** does not last too long, a shunt capacitor can be connected to ground to
27 temporarily store excess charge during that interval and to release it once the switches
28 have been properly reconnected. In some cases, a switch is placed in series with the shunt
29 capacitor so that the shunt capacitor can be disconnected from the circuit when it is not
30 needed. This avoids having the shunt capacitor interfere with circuit operation.

FIG. 9 shows a variant of the power converter **10** in FIG. 1 in which the output of a regulating circuit **12** connects to multiple 3-terminal charge pumps **14** in parallel. Each 3-terminal charge pump **14** has a corresponding magnetic filter **24** at its second CP-terminal **18**. The outputs of each magnetic filter **24** are then combined at a common node, which is a second voltage **V2** of a power converter **10**.

FIG. 10 shows a variant of the embodiment in FIG. 9 in which the magnetic filters **24** are constructed using a coupled inductor **26**. The coupled inductor **26** is constructed by having two windings sharing a common core.

The idea of a coupled inductor as shown in FIG. 10 can also be used in the regulator **12**. This is shown in FIG. 11, in which a regulator **12** such as that shown in FIG. 6A is opened up to reveal a coupled inductor **22** shared by two switches **20**.

FIG. 12 illustrates yet another embodiment in which a regulator **12**, a 4-terminal charge pump **74**, and a magnetic filter **24** are connected in series. However, unlike the embodiment in FIG. 1, the 4-terminal charge pump **74** is used instead of the 3-terminal charge pump **14**. This 4-terminal charge pump **74** is a four-terminal charge pump, rather than a three-terminal charge pump **14** as shown in FIG. 1. Since there are more terminals, there are more options for interconnection. For example, in the particular example shown, as a result of the orientation of the grounds, the first and second voltages **V1**, **V2** are of opposite polarity. This provides a simple way to change the polarity of an input voltage without having any additional stages (e.g, a polarity inverting stage).

In the embodiments discussed thus far, all power that passes through the power converter **10** flows through both the regulator **12** and the 3-terminal charge pump **14**. However, in certain embodiments, the power path is bifurcated within the power converter so that some of the power bypasses the regulator **12** altogether.

FIG. 13 shows one embodiment that achieves a bifurcated power path, one of which carries more power than the other. In FIG. 13, a first power path **30** and a second power path **32** traverse the power converter **10**. The heavier line on the second power path **32** indicates that it carries the higher of the two powers. Conversely, the lighter line on the first power path **30** indicates that this path carries the lower of the two powers.

The second power path **32** carries power that goes through the 3-terminal charge pump **14**. Meanwhile, the first power path **30** passes through the regulator **12**, bypassing

1 the 3-terminal charge pump **14** in the process. Because the 3-terminal charge pump **14** is
2 more efficient at executing a voltage transformation, it is desirable for most of the power
3 to use the second power path **32**.

4 An additional advantage to a bifurcated power path is that the regulator **12** can be
5 used to provide an additive offset to the voltage difference across the first CP-terminal **16**
6 and third CP-terminal **17** of the 3-terminal charge pump **14**. As a result, there is an extra
7 degree of freedom available for controlling the voltage at the output of the power
8 converter **10**. This provides greater flexibility and thus fewer voltage ranges at which the
9 power converter **10** will not be able to provide a desired output voltage.

10 In the embodiment shown in FIG. 13, the voltage at an output **83** of the regulator
11 **12** is the same as that at the output **38** of the magnetic filter **24**. This is achieved by
12 connecting the ground terminal **86** of the regulator **12** to the first CP-terminal **16** of the 3-
13 terminal charge pump **14**. The output **83** of the regulator **12** that was connected to the
14 first CP-terminal **16** in FIG. 1 is then connected to the output **38** of the magnetic filter **24**
15 instead.

16 FIG. 14A shows an exemplary circuit that uses the configuration of FIG. 13 to
17 transform a 12-volt input voltage into a 1-volt output at a load **40**. A 4-volt input is
18 provided at the first CP-terminal **16** of the 3-terminal charge pump **14**. The 3-terminal
19 charge pump **14**, being a 4:1 charge pump, outputs 1 volt at its second CP-terminal **18**.

20 Meanwhile, the remaining 8 volts is presented across the input terminal **81** and
21 ground terminal **86** of the regulator **12**, which presents -3 volts at the output **83** of
22 regulator **12**. However, this -3 volts is measured relative to the ground of the regulator
23 **12**, which is not the same as that of the 3-terminal charge pump **14**. Because the ground
24 terminal **86** of the regulator **12** is connected to the first CP-terminal **16** of the 3-terminal
25 charge pump **14**, it too must be at 4 volts. Therefore, the voltage measured at the output
26 **83** of the regulator **12** would actually be 1 volt (i.e. 4-3) when measured relative to the
27 ground of the 3-terminal charge pump **14**. As a result, the voltage at the output **83** of the
28 regulator **12** and the output **38** of the magnetic filter **24** will be the same at the load **40**, as
29 they should be.

30 FIG. 14B shows the circuit of FIG. 14A being used to transform a 12-volt input
31 voltage into a 2-volt output at a load **40**. Unlike the circuit in FIG. 14A, the voltage

1 presented to the regulator **12** is half that presented to the 3-terminal charge pump **14**
2 instead of the other way around.

3 In operation, an 8-volt input is provided at the first CP-terminal **16** of the 3-
4 terminal charge pump **14**. The 3-terminal charge pump **14**, being a 4:1 charge pump,
5 outputs 2 volts at its second CP-terminal **18** as required.

6 Meanwhile, the remaining 4 volts is presented across the input terminal **81** and
7 ground terminal **86** of the regulator **12**, which presents -6 volts at the output **83** of the
8 regulator **12**. However, this -6 volts is measured relative to the ground of the regulator
9 **12**, which is not the same as that of the 3-terminal charge pump **14**. Because the ground
10 terminal **86** of the regulator **12** is connected to the first CP-terminal **16** of the 3-terminal
11 charge pump **14**, it too must be at 8 volts. Therefore, the voltage measured at the output
12 **83** of the regulator **12** would actually be 2 volts (i.e. 8-6) when measured relative to the
13 ground of the 3-terminal charge pump **14**. As a result, the voltages at the output **83** of the
14 regulator **12** and the output **38** of the magnetic filter **24** at the load **40** will be the same, as
15 they should be.

16 With isolated charge pumps, such as a 4-terminal charge pump **74**, it becomes
17 possible to create alternative architectures for bifurcating the power path where only a
18 portion of the total power passes through the regulator **12**. FIG. 15 shows such an
19 architecture.

20 Referring to FIG. 15A, the first power path **30** starts at the fourth CP-terminal **116**
21 and leads to the input terminal **81** of the regulator **12** while the second power path **32**
22 starts at the second CP-terminal **18** and leads to a magnetic filter **24**. The bulk of the
23 power goes through the second power path **32**. This configuration is advantageous
24 because the regulator **12** no longer has to bear the brunt of carrying all the power that
25 goes through the power converter **10**. As was the case in FIG. 13, the output **83** of the
26 regulator **12** and the output **38** of the magnetic filter **24** meet at a common node, a second
27 voltage **V2** of the power converter **10**, to which a load **40** will be connected.

28 FIG. 15B is an implementation of the embodiment shown in FIG. 15A. The
29 configuration shown is analogous to that shown in FIG. 14B except that in FIG. 15B, it is
30 the regulator that is grounded and the charge pump that floats.

Embodiments of the type shown in FIG. 15A require that the regulator **12** and 4-terminal charge pump **74** have separate grounds. This requires a fully-isolated version of the 4-terminal charge pump **74**, an example of which is shown in FIG. 16A.

In operation, the fully-isolated version of the 4-terminal charge pump **74** shown in FIG. 16A transitions between a first state and a second state. During the first state, switches in a first switch-set **1** open and switches in a second switch-set **2** close. During the second state, switches in the second switch-set **2** open and switches in the first switch-set **1** close.

While the 4-terminal charge pump **74** is in its first state, a coupling capacitor C_c that stores charge sufficient for maintaining the voltage across the first CP-terminal **16** and the fourth CP-terminal **116**. Then, when the charge pump **74** transitions into its second state, the coupling capacitor C_c presents its maintained voltage to the 3-terminal charge pump **14** contained within the 4-terminal charge pump **74**.

This method will work for any type of charge pump topology, two examples of which are shown in FIGS. 16B and 16C.

In particular, FIG. 16B shows the architecture of the charge pump **74** in FIG. 16A in use with a cascade multiplier type similar to the charge pump in FIGS. 3A-3C, the difference being that the voltage transformation ratio is different and the number of phases is different.

FIG. 16C is a two-phase version of the 4-terminal charge pump **74** in FIG. 16B. In contrast to the implementation shown in FIG. 16B, this implementation can draw continuous input current. This results in the ability to reduce the size of first and second DC capacitors C_{DC1} , C_{DC2} in FIG. 15B.

The particular implementations shown in FIGS. 16B and 16C have switch pairs with switches that belong to the same switch set and that are in series. For example, the embodiment in FIG. 16B has one such switch pair between the coupling capacitor C_c and pump capacitor C_1 . Since the switches in each of these switch pairs belong to the first switch-set **1**, they always open and close together. Thus, it is possible to eliminate additional switches by merging the switches in each switch pair. The embodiment in FIG. 16C has two such switch pairs in a similar location, but were merged in the figure.

FIGS. 17A – 17D show four possible variants of configurations for the architecture of FIG. 15. These differ in whether or not they use a magnetic filter **24** at all, and if so, which charge-pump terminal is connected to it.

In a first configuration **42**, shown in FIG. 17A, the regulator **12** is connected to the second CP-terminal **18** of the 4-terminal charge pump **74**, while the magnetic filter **24** is connected to the fourth CP-terminal **116** of the 4-terminal charge pump **74**. A suitable regulator for this configuration is a boost converter.

A second configuration **44**, shown in FIG. 17B, is the converse of the first configuration **42**. This second configuration **44** is particularly advantageous because most of the current flows through the second CP-terminal **18**. Thus, the regulator **12** is placed at the lower current terminal, and therefore accrues all the advantages associated with such placement as already discussed.

A third configuration **46**, shown in FIG. 17C, dispenses with a magnetic filter **24** altogether and just has a regulator **12** connected to the second and fourth CP-terminals **18**, **116** of the 4-terminal charge pump **74**.

A fourth configuration **48**, shown in FIG. 17D, also dispenses with the magnetic filter **24** but uses a separate regulator **12** at the second and fourth CP-terminals **18**, **116**. This fourth configuration offers considerable flexibility since the duty cycles of each regulator **12** can be controlled independently of each other.

In the third configuration **46**, shown in FIG. 17C, there is only multiplicative control over a second voltage **V2**. In particular, the second voltage **V2** is given by the product of the first voltage **V1** and $((N+1)/(D+1))$, where N is the number of stages in the 4-terminal charge pump **74** and D is the duty cycle of the regulator **12**, with $D=1$ corresponding to a permanently closed switch.

On the other hand, the first and second configurations **42**, **44**, shown in FIGS. 17A and 17B, offer a combination of additive and multiplicative control over the second voltage **V2**.

In particular, in the first configuration **42**, shown in FIG. 17A, the second voltage **V2** is given by the product of the first voltage **V1** and $(1+N/(1-D))$.

1 In the second configuration **44**, shown in FIG. 17B, the second voltage **V2** is
2 given by the product of the first voltage **V1** and $(N+1/(1-D))$. This provides greater
3 flexibility because the additive and multiplicative control is decoupled.

4 The fourth configuration **48**, shown in FIG. 17D, provides greater flexibility in
5 control because of the presence of another degree of freedom. In the fourth configuration
6 **48**, the second voltage **V2** is given by the product of the first voltage **V1** and $((1/(1-$
7 $D2))+(N/(1-D1)))$, where $D1$ and $D2$ are duty cycles for the two regulators shown in the
8 FIG. 17D.

9 The circuits described above are representative of a variety of topologies that
10 provide parallel power paths. However, many others are shown in FIGS. 18A–18C and
11 FIGS. 19A–19C.

12 FIGS. 18A–18C show three topologies in which the 4-terminal charge pump **74**
13 has a ground that is separate from that of the regulator **12**. The terms “down” and “up”
14 indicate the direction of voltage transformation. Thus, a circuit element identified by
15 “down” will have its output be at a lower voltage than its input. In contrast, a circuit
16 element identified by “up” will have its output be at a higher voltage than its input.

17 FIGS. 19A–19C show topologies in which the regulator **12**, rather than the 3-
18 terminal charge pump **14**, has been isolated. These topologies require a regulator that
19 incorporates a transformer, such as a flyback converter. As was the case with FIGS. 18A–
20 18C, the regulator and charge pump can work in tandem or in opposite directions.

21 FIG. 20 consolidates and summarizes the embodiments shown in FIGS. 1, 12, 13,
22 and 15A, and in particular, draws attention to the fundamental modularity of the concepts
23 described herein. The three general classes of components described herein, namely the
24 regulator **12** (either isolated or non-isolated versions are applicable), the 4-terminal
25 charge pump **74** (either isolated or non-isolated versions are applicable), and the
26 magnetic filter **24**, can be mixed and matched in various ways to achieve a variety of
27 technical goals. What the embodiments have in common however is the ability to split
28 the task of regulation from the task of promoting adiabatic charge transfer within the 3-
29 terminal charge pump **14**.

30 The circuit topologies described herein thus enable one to eliminate the large
31 switch associated with having a regulator connected to a terminal of a charge pump that

1 has a low voltage and a high current. Instead, an inductor replaces the regulator. The
2 inductor is able to carry out one of the regulator's functions in the prior art, namely that
3 of facilitating adiabatic inter-capacitor charge transport within the charge pump.
4 However, it was precisely this function that pinned the regulator to the low-voltage
5 second CP-terminal **18** of the charge pump. The fact that the regulator was pinned to the
6 second CP-terminal **18** resulted in a great many technical problems, including the
7 introduction of dead zones that may be inconveniently located, and the need to allocate a
8 great deal of die space to the oversized switches that were necessary at that location.
9 Having been liberated from its location at the second CP-terminal **18** of the charge pump,
10 the regulator can now be placed in a variety of other locations. This, in turn, enables the
11 circuit designer to adjust the locations of the dead zones of operation based on the
12 requirements of the power converter. It also results in the ability to use a more modestly
13 sized switch in the regulator, and to thereby save considerable die space.

14 In some embodiments described thus far, the regulator **12** connects to the first CP-
15 terminal **16** of the 3-terminal charge pump **14**. This means that less current will flow
16 through the switch **20** in the regulator **12**. As a result, it is possible to reduce the size of
17 the switch **20**. However, these embodiments have the disadvantage of still having a
18 switch size greater than zero.

19 In other embodiments described thus far, the power path is bifurcated so that the
20 majority of the current bypasses the regulator **12**, and hence the switch **20**, altogether.
21 This approach also permits making the switch **20** smaller. However, this approach suffers
22 from the disadvantage that some current still goes through the switch **20**.

23 In another embodiment, the switch size is reduced to zero, effectively eliminating
24 the problem altogether, but without giving up the regulating function of the regulator **12**.
25 The resulting circuit, which is referred to as a "regulated charge pump," minimizes loss
26 due to the switch **20** by causing the 3-terminal charge pump **14** and regulator **12** to share
27 a common switch set, none of which will carry the full brunt of all the current that passes
28 through the power converter **10**.

29 As a first example, FIG. 21A shows a buck converter **12** and a 3-terminal charge
30 pump **14** that have been merged to create a first regulated charge pump **41**. The first
31 regulated charge pump **41** still has the switch **20** that was originally in the regulator **12**.

1 This switch **20** carries considerable current. Operation of the first regulated charge pump
2 **41** includes cycling the circuit through a first set of network states **51** using a first set of
3 switch configurations **61**, as shown in FIGS. 21B – 21C. A disadvantage of the first
4 regulated charge pump **41** is therefore that the switch **20** is still present.

5 A second regulated charge pump **42**, shown in FIG. 22A, eliminates the switch
6 **20**. In effect, the functionality of the switch **20** has been incorporated into the 3-terminal
7 charge pump **14**. Operation of this second regulated charge pump **42** includes attaining
8 the same first set of network states **51** but using a different, second set of switch
9 configurations **62**, shown in FIG. 22B.

10 A disadvantage of the second regulated charge pump **42** is that all switches must
11 run at the same frequency. This can be inconvenient because the capacitors and the
12 inductor tend to have different energy densities. However, for cases in which the current
13 is quite high, the advantage associated with eliminating the switch **20** can outweigh this
14 disadvantage.

15 Another disadvantage of the second regulated charge pump **42** is that the overall
16 circuit can potentially become an unstable oscillator. To reduce the likelihood of this
17 occurring, a third regulated charge pump **43**, shown in FIG. 23A, introduces a stabilizing
18 capacitor **94** and a stabilizing switch **96**. The loss arising from the stabilizing switch **96** is
19 minimal because only a small amount of current has to flow into the stabilizing capacitor
20 **94**. Operation of this third regulated charge pump **43** involves cycling through a second
21 set of network states **53** using a third set of switch configurations **63**, as shown in FIGS.
22 23B – 23C.

23 In the regulated charge pumps thus far, although a first switch **20** of the regulator
24 **12** has been eliminated, a second switch remains. In a fourth regulated charge pump **44**,
25 shown in FIG. 24A, even this switch is eliminated. The resulting circuit is essentially a 3-
26 terminal charge pump **14** with an LC circuit **98** at its output end. Operation of this fourth
27 regulated charge pump **44** involves cycling through the first set of network states **51**
28 using a fourth set of switch configurations **64**, as shown in FIG. 21B and FIG. 24B,
29 respectively.

30 The fourth regulated charge pump **44** can also be operated by cycling through
31 three network states instead of four. This reduces switching loss associated with each

1 switch transition because there are fewer switch transitions per cycle. The two
2 alternatives are represented by third and fourth sets of network states **58, 59**, each of
3 which consists of three rather than four states, and corresponding fifth and sixth sets of
4 three switch configurations **68, 69**, as shown in FIGS. 25A – 26B.

5 The technique used to eliminate both switches from the regulator **12** that was used
6 in connection with the fourth regulated charge pump **44**, shown in FIG. 24A, can be used
7 to implement a two-phase version, which is the fifth regulated charge pump **45** shown in
8 FIG. 27A.

9 Operation of this fifth regulated charge pump **45** involves cycling through a fifth
10 set of network states **55** using the fourth set of switch configurations **64**, as shown in FIG.
11 27B and FIG. 24B, respectively.

12 In some implementations, a computer accessible storage medium includes a
13 database representative of one or more components of the converter. For example, the
14 database may include data representative of a switching network that has been optimized
15 to promote low-loss operation of a charge pump.

16 Generally speaking, a computer accessible storage medium may include any non-
17 transitory storage media accessible by a computer during use to provide instructions
18 and/or data to the computer. For example, a computer accessible storage medium may
19 include storage media such as magnetic or optical disks and semiconductor memories.

20 Generally, a database representative of the system may be a database or other data
21 structure that can be read by a program and used, directly or indirectly, to fabricate the
22 hardware comprising the system. For example, the database may be a behavioral-level
23 description or register-transfer level (RTL) description of the hardware functionality in a
24 high level design language (HDL) such as Verilog or VHDL. The description may be
25 read by a synthesis tool that may synthesize the description to produce a netlist
26 comprising a list of gates from a synthesis library. The netlist comprises a set of gates
27 that also represent the functionality of the hardware comprising the system. The netlist
28 may then be placed and routed to produce a data set describing geometric shapes to be
29 applied to masks. The masks may then be used in various semiconductor fabrication steps
30 to produce a semiconductor circuit or circuits corresponding to the system. In other

1 examples, Alternatively, the database may itself be the netlist (with or without the
2 synthesis library) or the data set.

3 Having described the invention, and a preferred embodiment thereof, what is
4 claimed as new, and secured by letters patent is:

CLAIMS

- 1
2 **1.** An apparatus for power transformation, said apparatus comprising a power
3 converter, said power converter comprising a charge pump, a first regulator, and a
4 magnetic filter, wherein said magnetic filter is connected to a terminal of said
5 charge pump, wherein said terminal is selected to facilitate adiabatic inter-
6 capacitor charge transport within said charge pump, and wherein said first
7 regulator is configured to regulate power provided by said power converter.
- 8 **2.** The apparatus of claim 1, wherein said charge pump comprises a first terminal
9 and a second terminal, wherein, in operation, said first terminal is maintained at a
10 first voltage and said second terminal is maintained at a second voltage, wherein
11 said second voltage is lower than said first voltage, and wherein said magnetic
12 filter is connected to said second terminal.
- 13 **3.** The apparatus of claim 2, wherein said first regulator is connected to said first
14 terminal.
- 15 **4.** The apparatus of claim 1, wherein said first regulator is disposed to intercept a
16 first portion of power provided by said power converter, wherein said charge
17 pump is disposed to intercept a second portion of power provided by said power
18 converter, wherein said magnetic filter is disposed to intercept said second
19 portion, wherein said second portion is greater than said first portion, and wherein
20 said first and second portions are combined at an output of said power converter.
- 21 **5.** The apparatus of claim 1, wherein said magnetic filter is connected to an output of
22 said power converter, wherein said first regulator is connected to said output, and
23 wherein said first regulator is connected to said first terminal.
- 24 **6.** The apparatus of claim 5, wherein said first regulator comprises a ground
25 terminal, and wherein said ground terminal is connected to said first terminal.
- 26 **7.** The apparatus of claim 1, said charge pump comprises first and second charge-
27 transport paths, wherein said first regulator is connected to said first charge-
28 transport path, and wherein said magnetic filter is connected to said second
29 charge-transport path.
- 30 **8.** The apparatus of claim 7, wherein, in operation, said second charge-transport path
31 has greater current than said first charge-transport path.

- 1 **9.** The apparatus of claim 7, wherein, in operation, said first charge-transport path
2 has greater current than said second charge-transport path.
- 3 **10.** The apparatus of claim 7, further comprising a second regulator, wherein said
4 magnetic filter is a constituent part of said second regulator.
- 5 **11.** The apparatus of claim 9, wherein said first regulator operates at a first duty cycle,
6 wherein said second regulator operates at a second duty cycle, and wherein said
7 first and second duty cycles are controlled independently of each other.
- 8 **12.** The apparatus of claim 1, further comprising a controller for controlling operation
9 of said regulator based on an output of said power converter.
- 10 **13.** The apparatus of claim 1, further comprising a clock configured to provide a
11 clock signal to at least one of said regulator and said charge pump.
- 12 **14.** The apparatus of claim 1, further comprising a control system configured to
13 control operation of said power converter based on a measured output of said
14 power converter.
- 15 **15.** The apparatus of claim 14, wherein said control system comprises a controller to
16 control said regulator.
- 17 **16.** The apparatus of claim 14, wherein said control system comprises a controller to
18 control said charge pump.
- 19 **17.** The apparatus of claim 14, further comprising a clock, wherein said control
20 system comprises a clock signal input for receiving a signal from said clock.
- 21 **18.** The apparatus of claim 14, wherein said control system comprises analog inputs.
- 22 **19.** The apparatus of claim 14, wherein said control system comprises digital inputs.
- 23 **20.** The apparatus of claim 1, wherein said charge pump comprises a multi-phase
24 charge pump.
- 25 **21.** The apparatus of claim 1, wherein said charge pump comprises a single-phase
26 charge pump.
- 27 **22.** The apparatus of claim 1, wherein said charge pump comprises a multi-stage
28 charge pump.
- 29 **23.** The apparatus of claim 1, wherein said charge pump comprises a two-phase
30 charge pump.

- 1 **24.** The apparatus of claim 1, wherein said charge pump comprises a resonant power
2 converter.
- 3 **25.** The apparatus of claim 1, wherein said charge pump comprises a switch mode
4 power converter.
- 5 **26.** The apparatus of claim 1, wherein said first regulator comprises a buck converter.
- 6 **27.** The apparatus of claim 1, wherein said first regulator comprises a bidirectional
7 regulator.
- 8 **28.** The apparatus of claim 1, wherein said first regulator comprises a multi-phase
9 regulator.
- 10 **29.** The apparatus of claim 1, wherein said charge pump comprises a plurality of
11 capacitors interconnected by a plurality of sets of switches, wherein, during
12 operation, switches in said first set are opposite in state to switches in said second
13 set.
- 14 **30.** The apparatus of claim 1, wherein said charge pump is a reconfigurable charge
15 pump.
- 16 **31.** The apparatus of claim 30, wherein said regulator is configured to transition from
17 providing a first voltage to providing a second voltage during reconfiguration of
18 said charge pump.
- 19 **32.** An apparatus for power transformation, said apparatus comprising a power
20 converter, said power converter comprising a charge pump, a first regulator, and a
21 magnetic filter, wherein said magnetic filter is connected to a terminal of said
22 charge pump, wherein said terminal to which said magnetic filter is connected is
23 selected to facilitate causing a constraint in inter-capacitor charge transport within
24 said charge pump, and wherein said first regulator is configured to regulate power
25 provided by said power converter.
- 26 **33.** A method for power transformation includes connecting a magnetic filter to a
27 terminal of a charge pump, with the terminal having been selected to facilitate
28 adiabatic inter-capacitor charge transport within a charge pump, and connecting a
29 regulator to regulate power provide by the power converter.
- 30 **34.** The method of claim 33, wherein said charge pump comprises a first terminal and
31 a second terminal, wherein, in operation, said first terminal is maintained at a first

1 voltage and said second terminal is maintained at a second voltage, wherein said
2 second voltage is lower than said first voltage, and wherein said method
3 comprises connecting said magnetic filter to said second terminal.

4 **35.** The method of claim **34**, further comprising connecting said first regulator to said
5 first terminal.

6 **36.** The method of claim **33**, further comprising disposing said first regulator to
7 intercept a first portion of power provided by said power converter, disposing said
8 charge pump to intercept a second portion of power provided by said power
9 converter, disposing said magnetic filter to intercept said second portion, wherein
10 said second portion is greater than said first portion, and wherein said first and
11 second portions are combined at an output of said power converter.

12 **37.** A non-transitory computer-readable medium that stores a data structure that is to
13 be operated upon by a program executable on a computer system, wherein, when
14 operated upon by such a program, the data structure causes at least a portion of a
15 process for fabricating an integrated circuit that includes circuitry described by
16 the data structure, wherein the circuitry described by the data structure includes a
17 switching network that has been configured to be used with a power converter
18 that comprises a charge pump, a first regulator that is configured to regulate
19 power provided by said power converter, and a magnetic filter that is connected to
20 a terminal of said charge pump and that is selected to facilitate adiabatic inter-
21 capacitor charge transport within said charge pump.

22

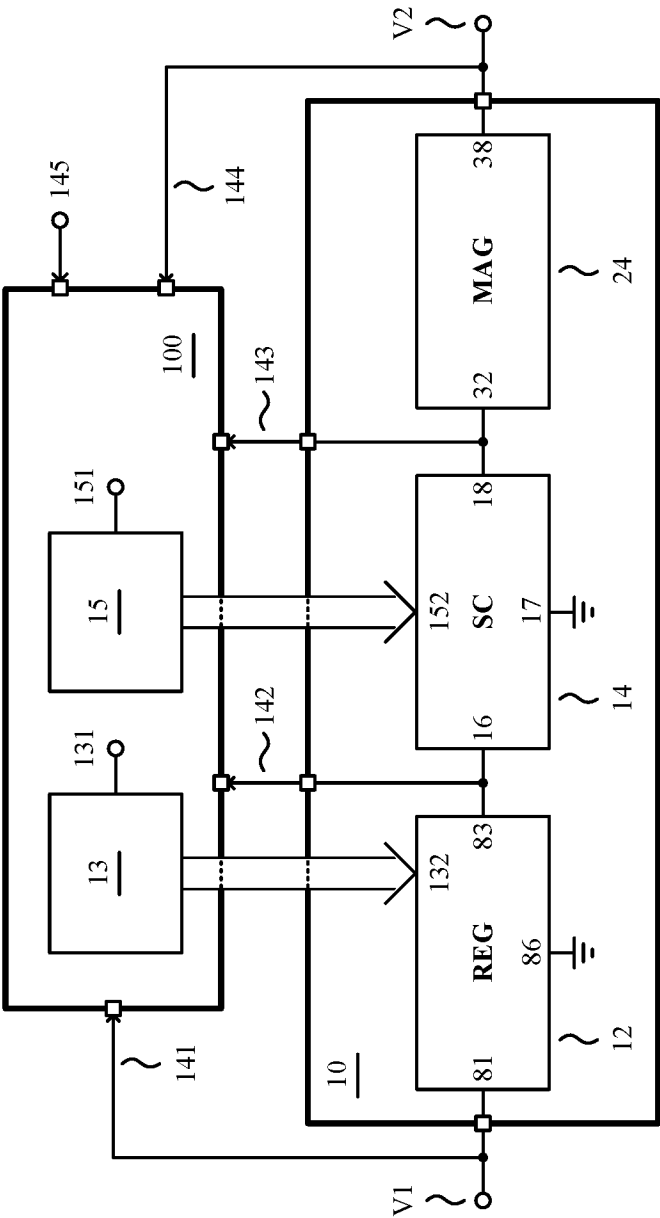


FIG. 1

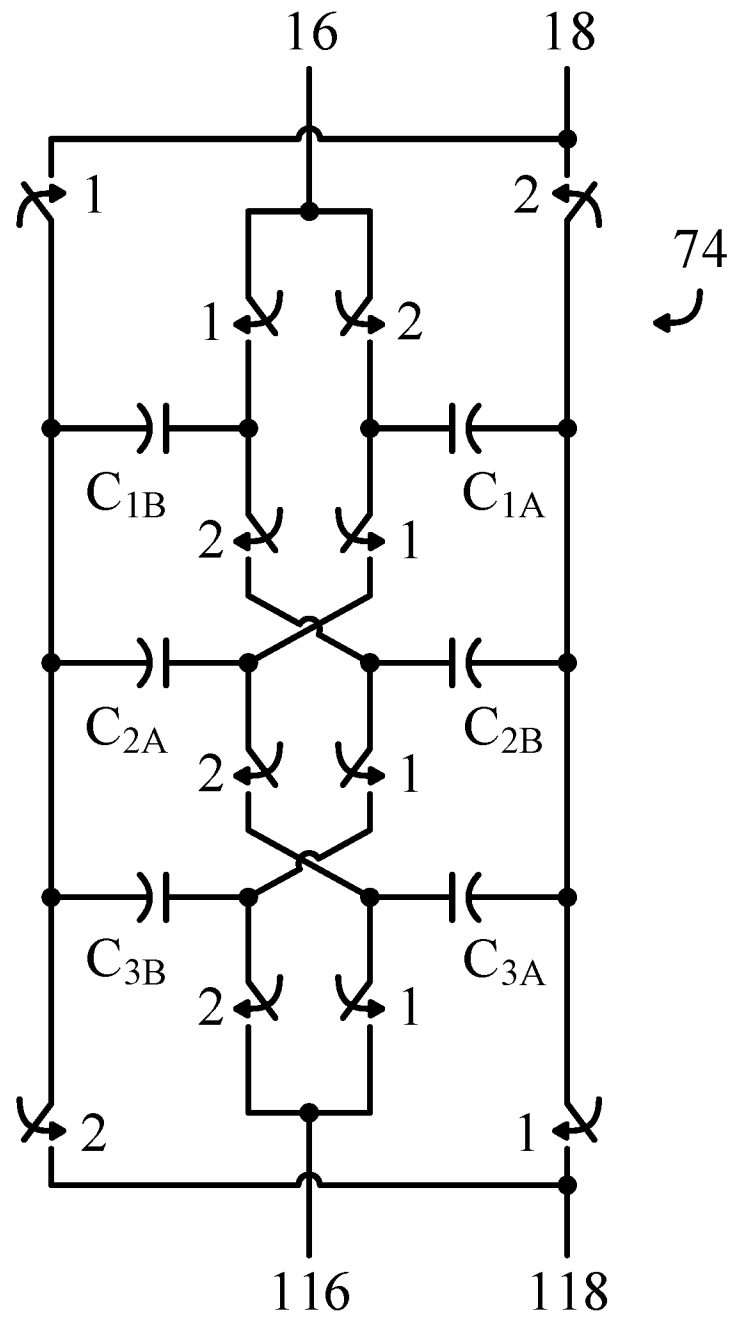


FIG. 2

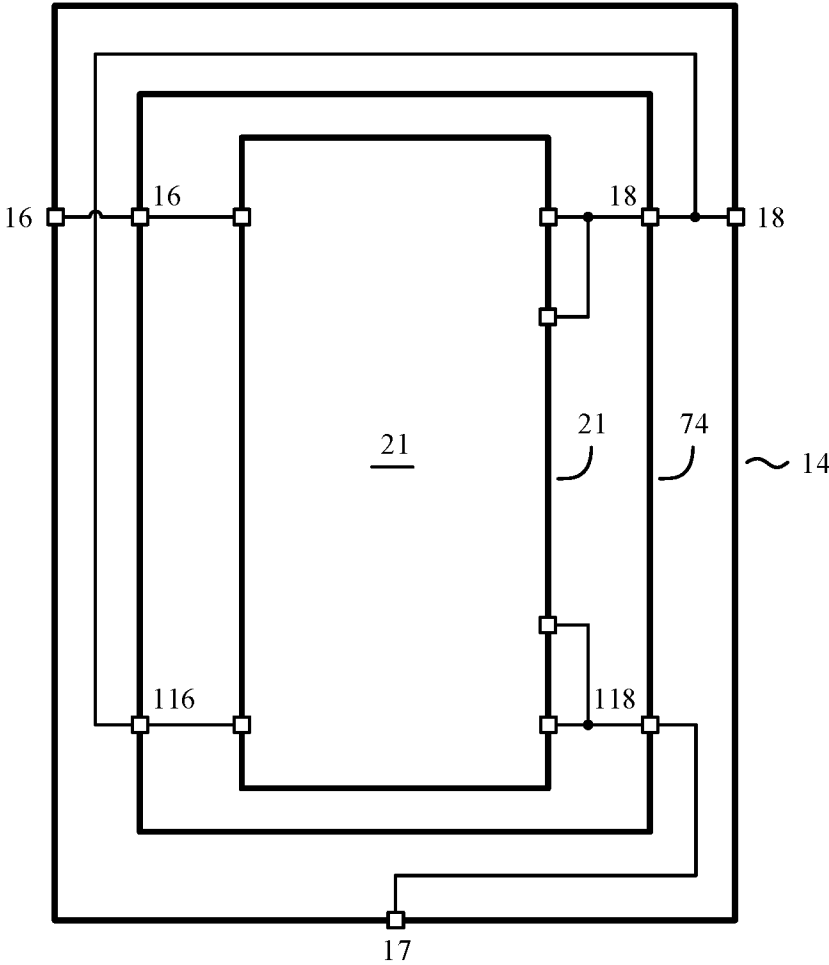


FIG. 3A

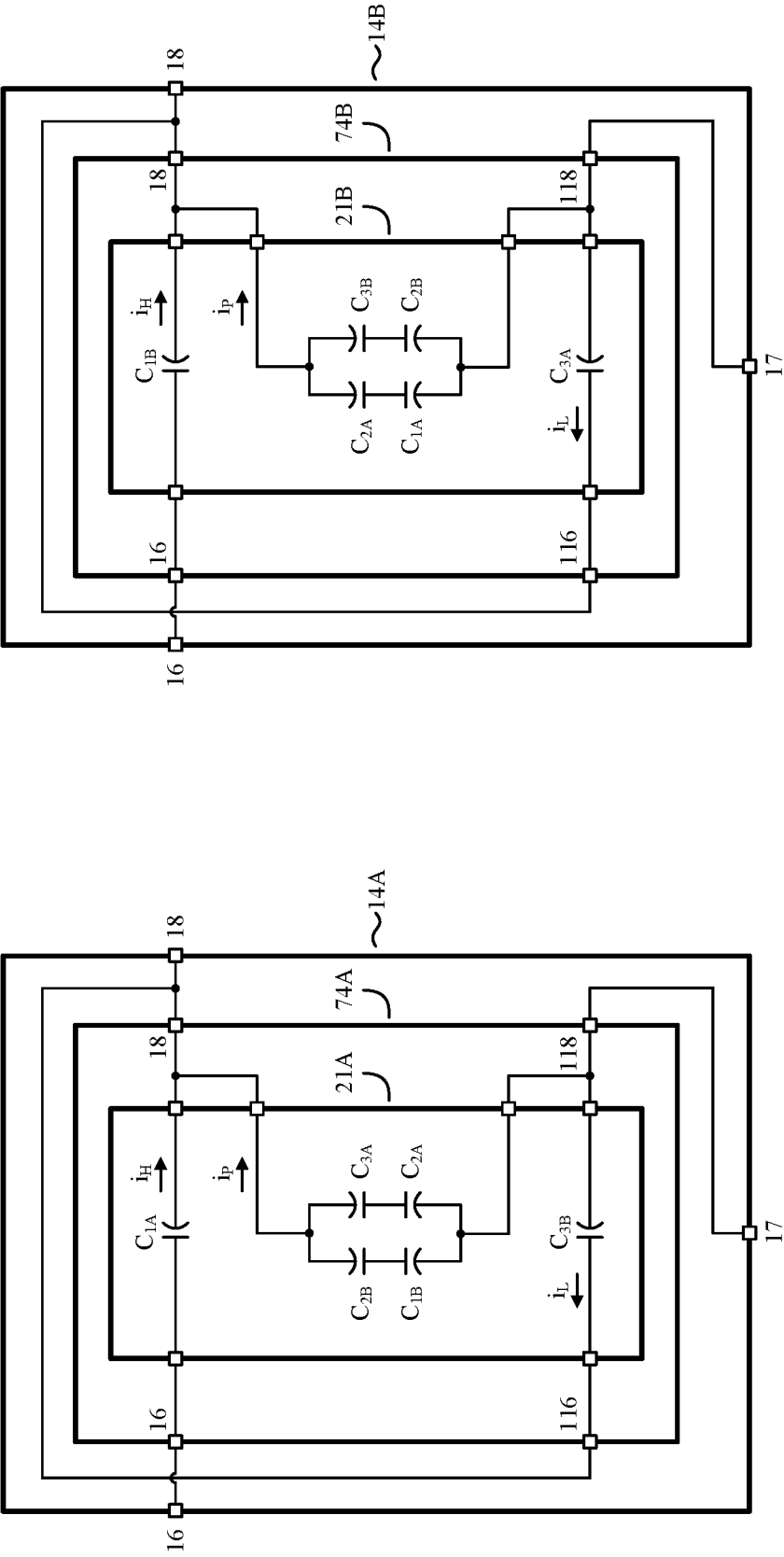


FIG. 3C

FIG. 3B

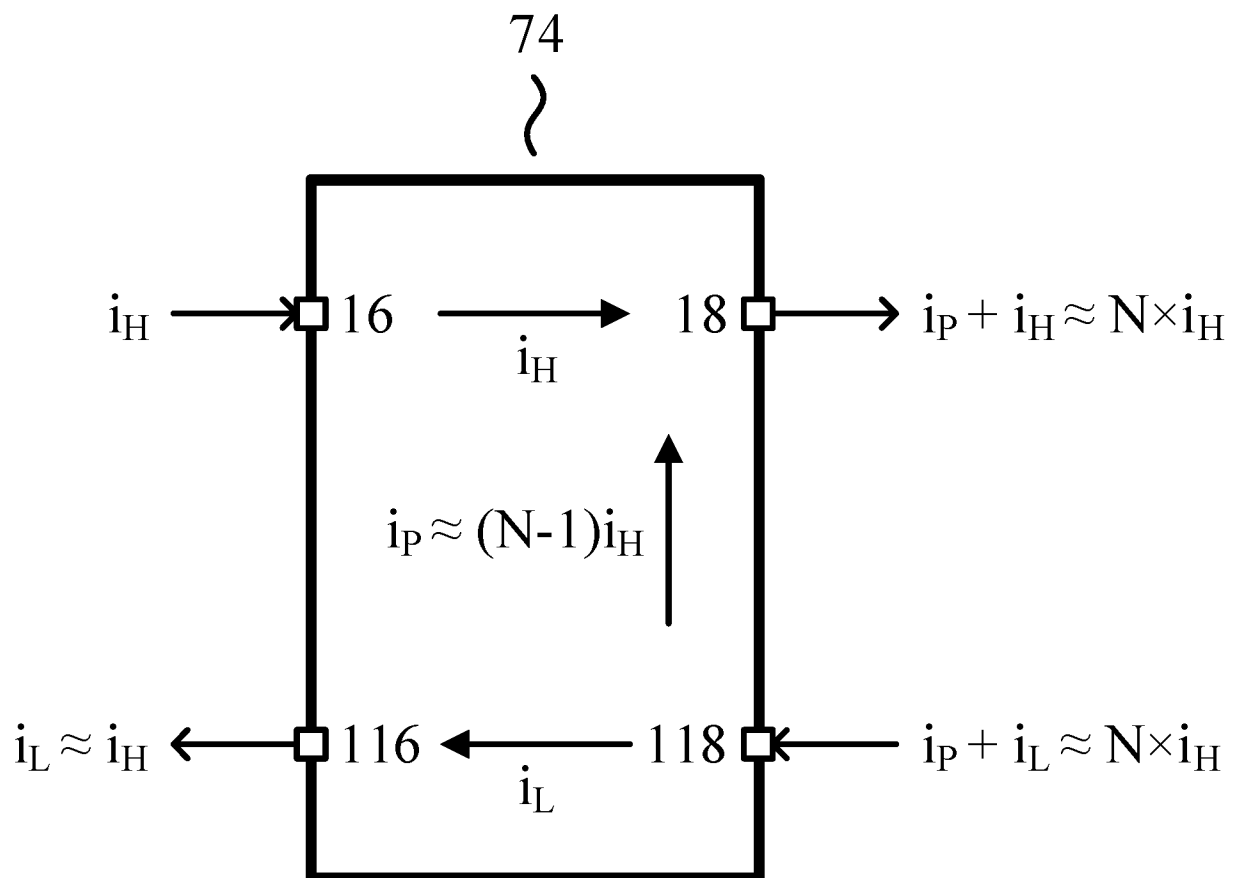


FIG. 4

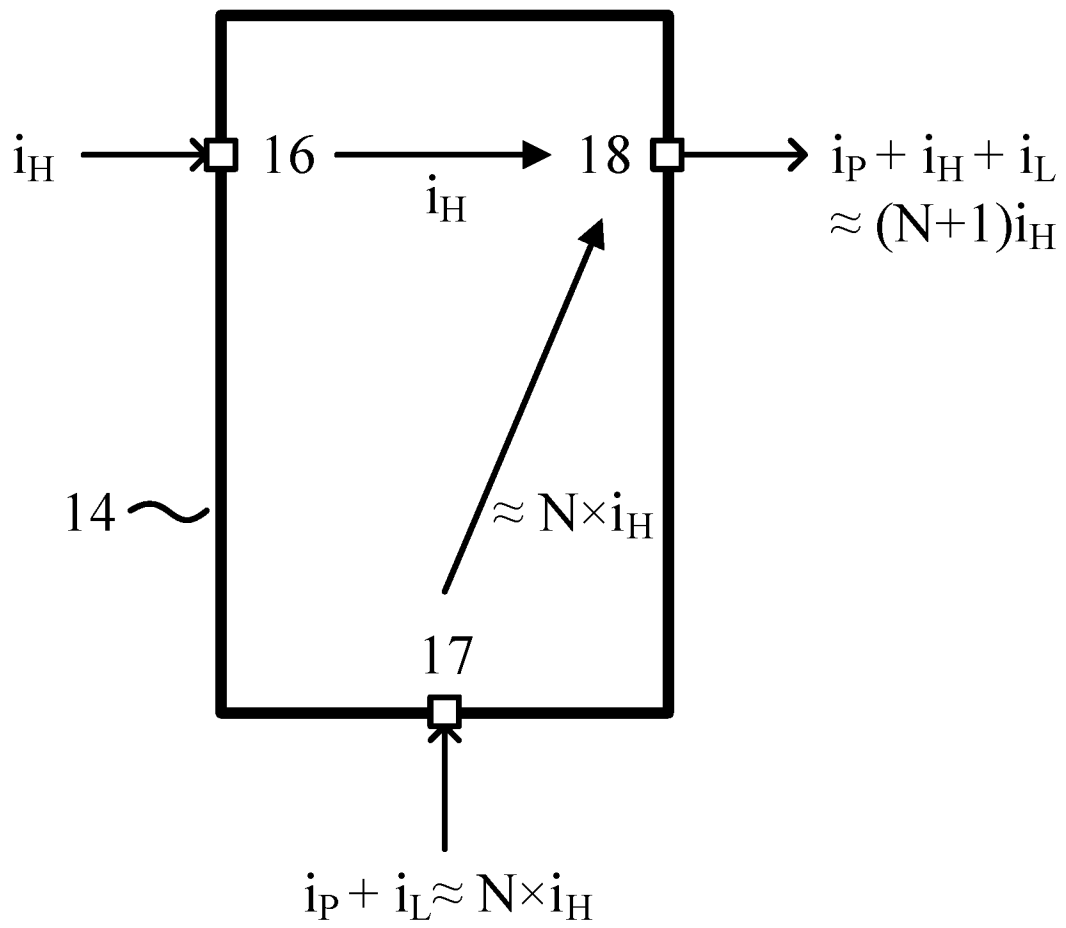


FIG. 5

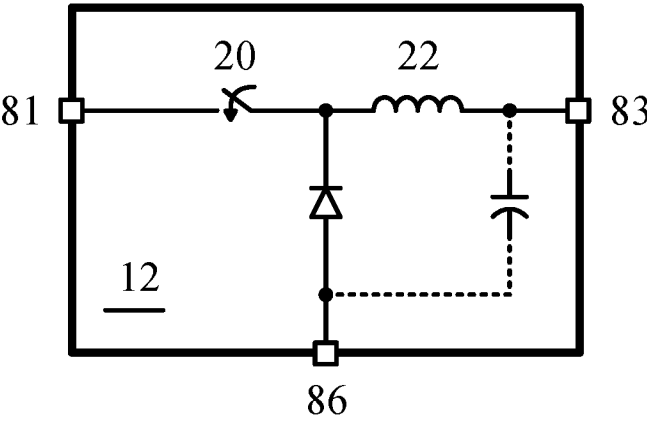


FIG. 6A

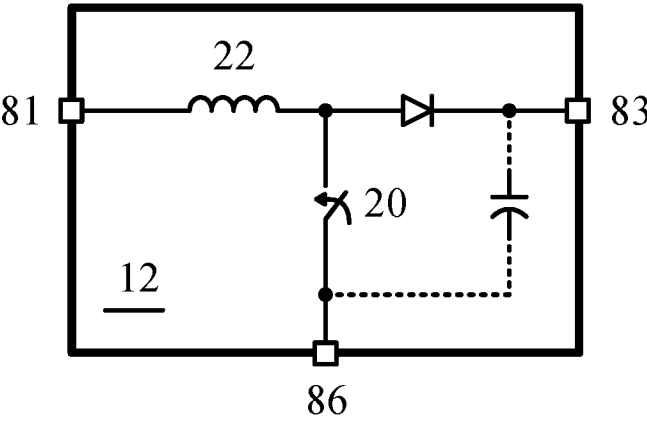


FIG. 6B

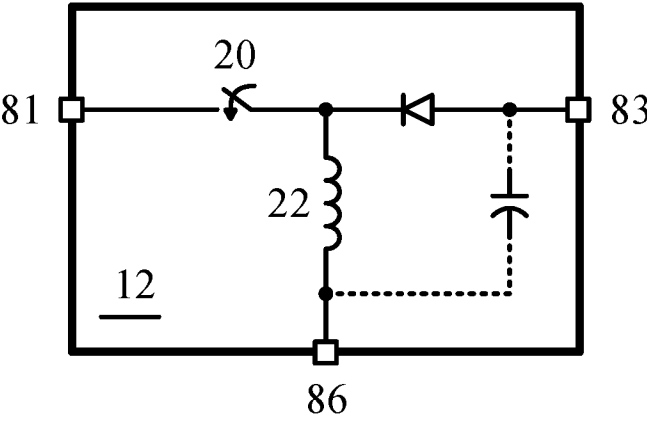


FIG. 6C

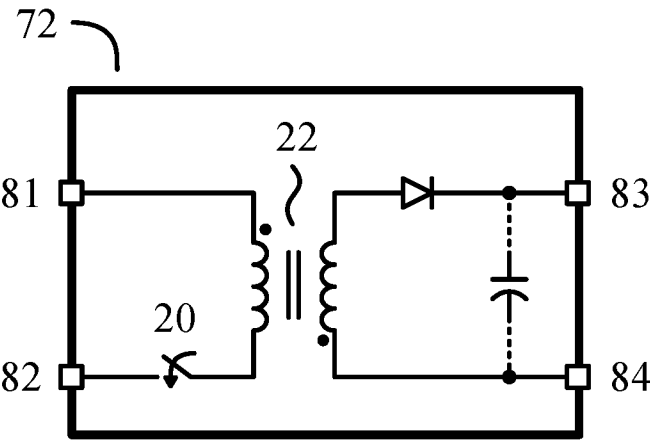


FIG. 6D

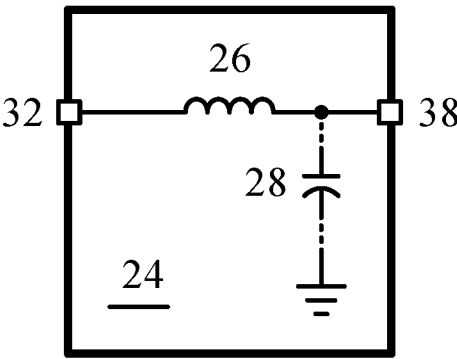


FIG. 7A

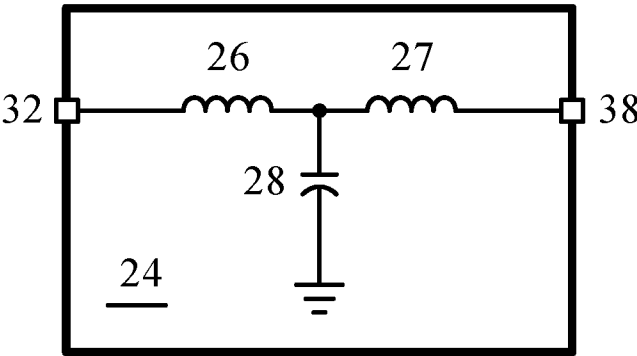


FIG. 7B

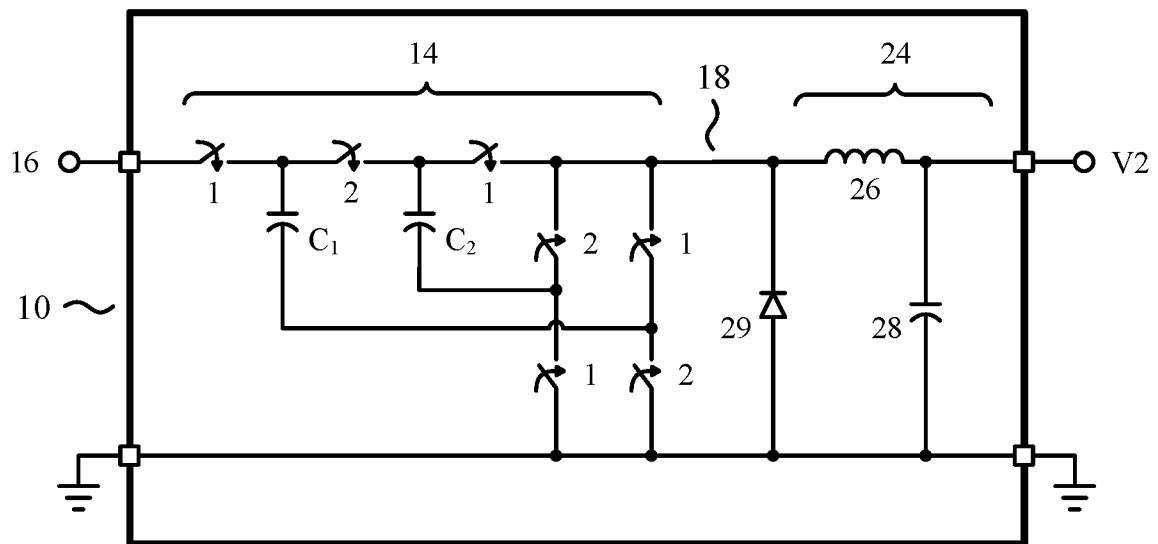


FIG. 8

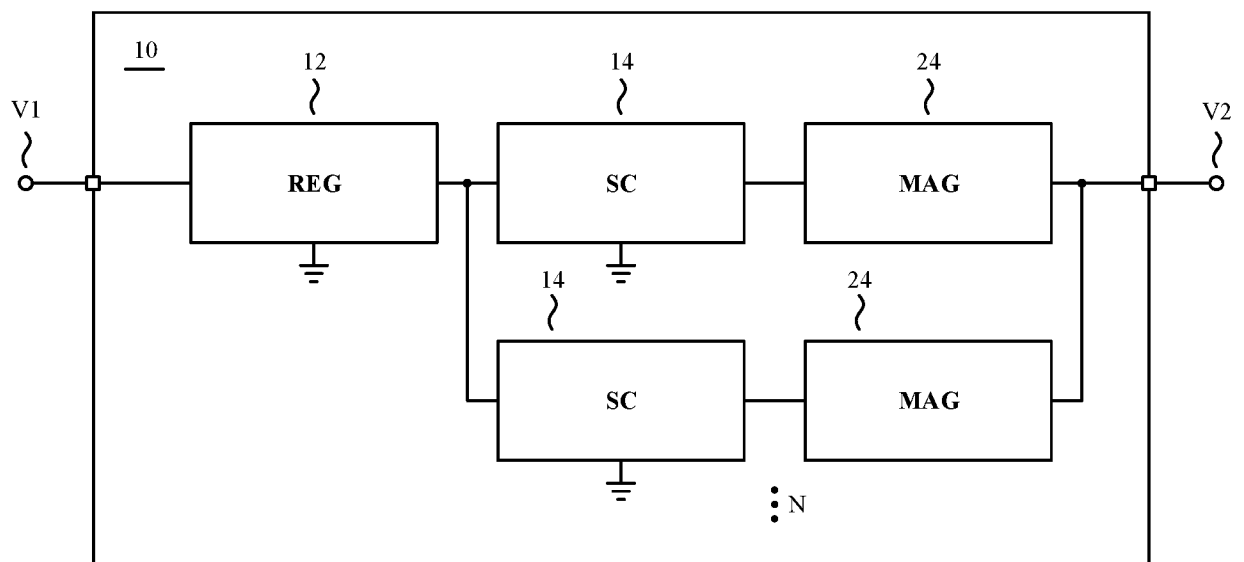


FIG. 9

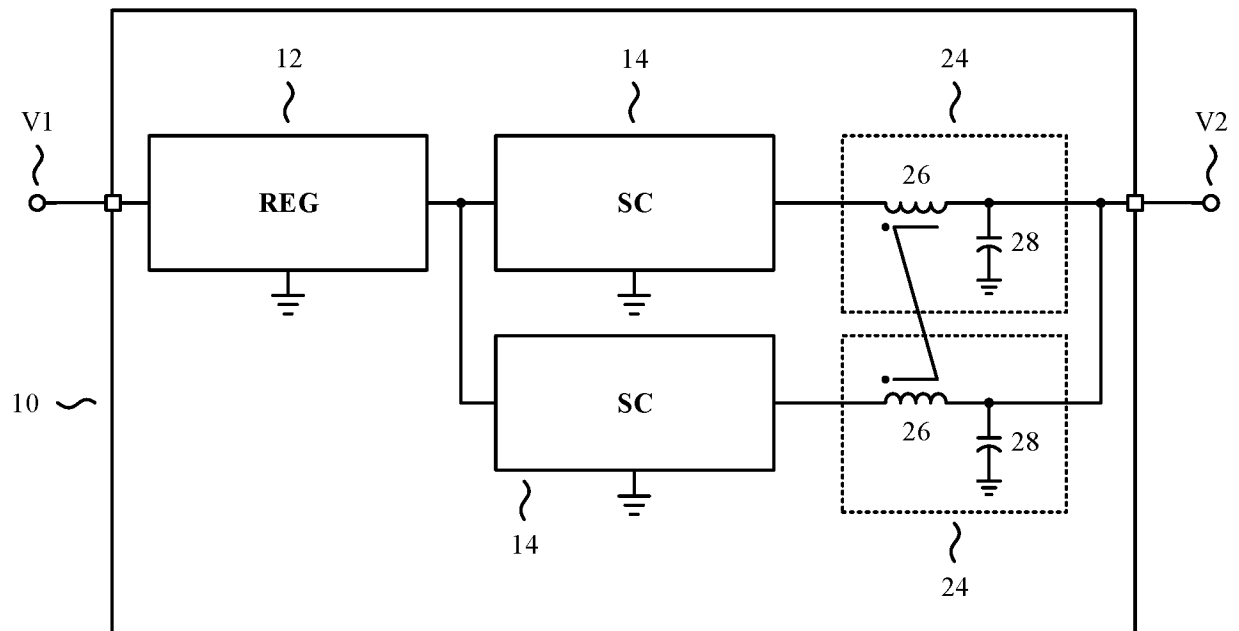


FIG. 10

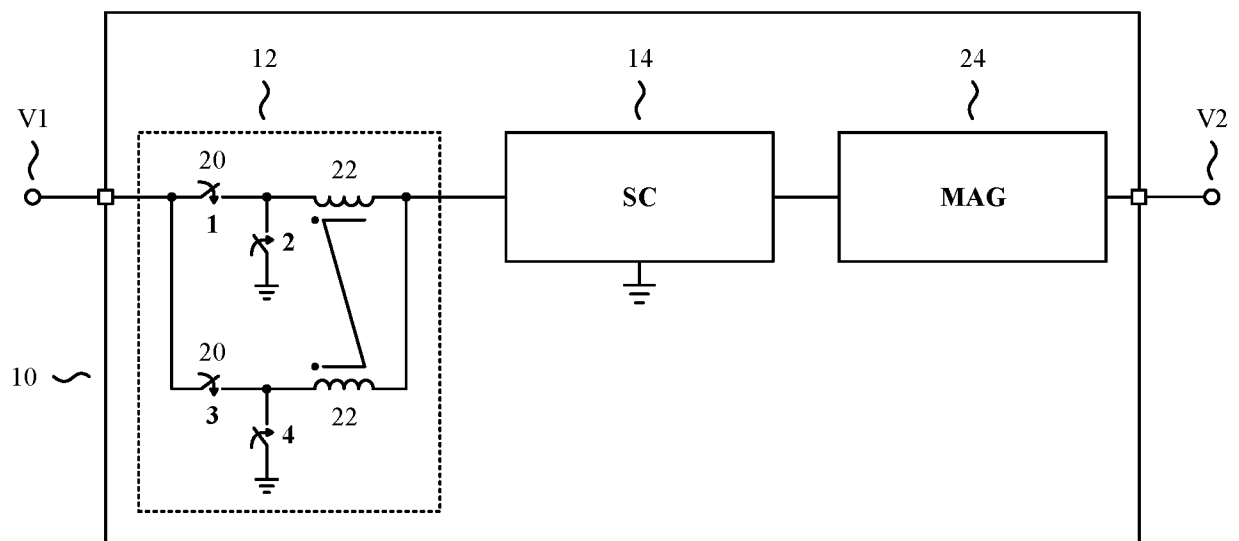


FIG. 11

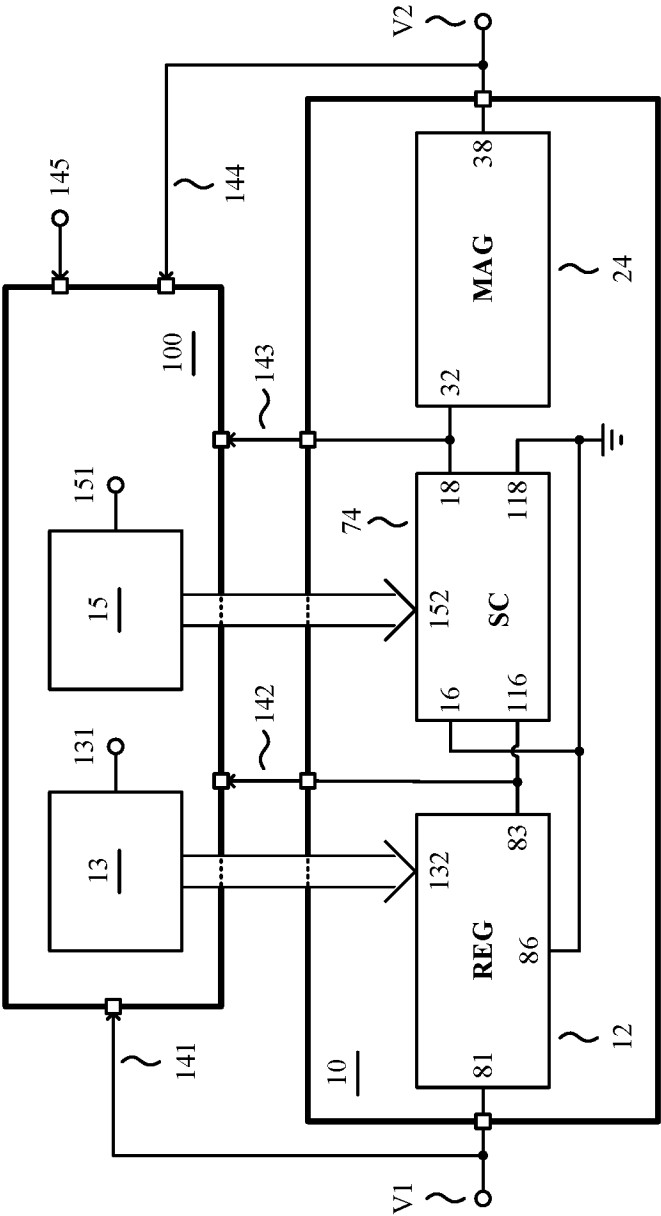
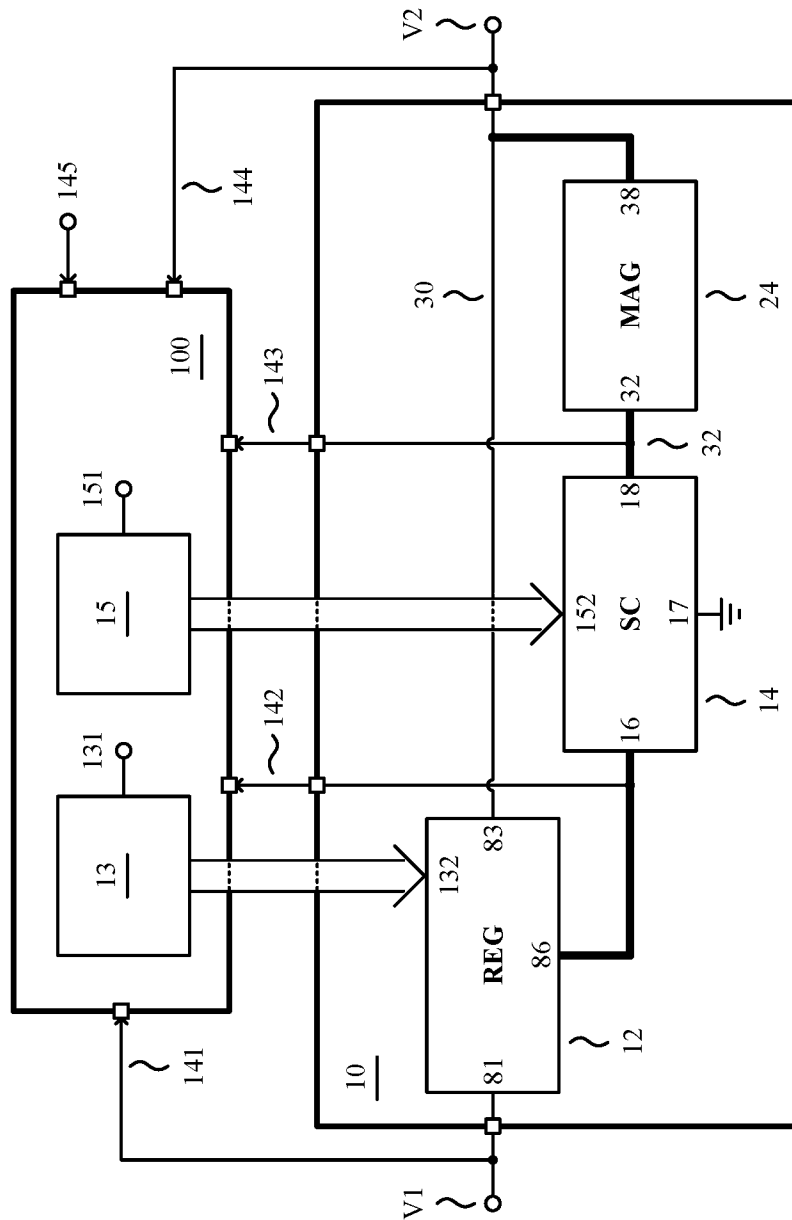


FIG. 12



3454

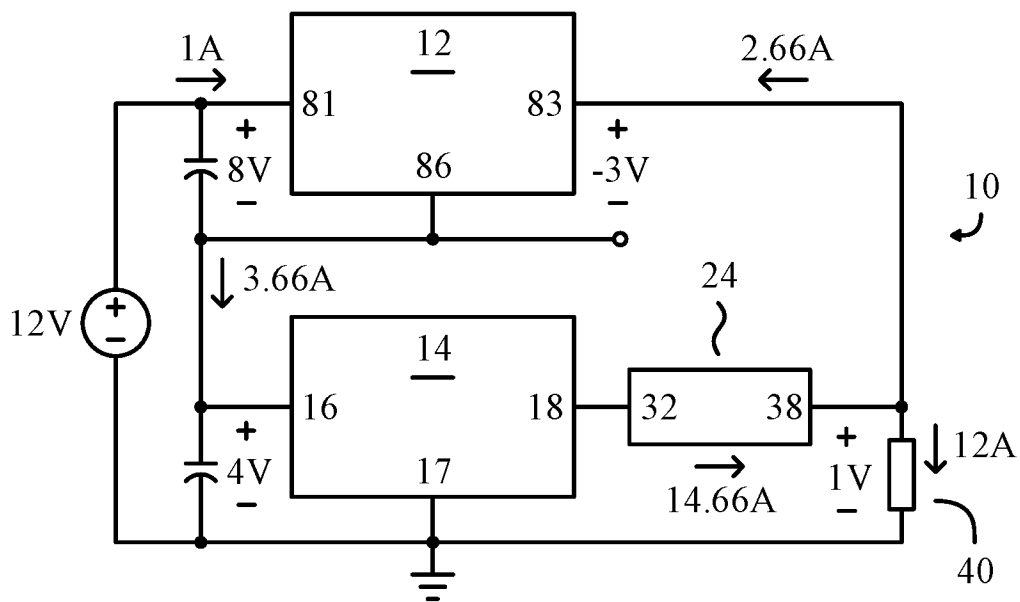


FIG. 14A

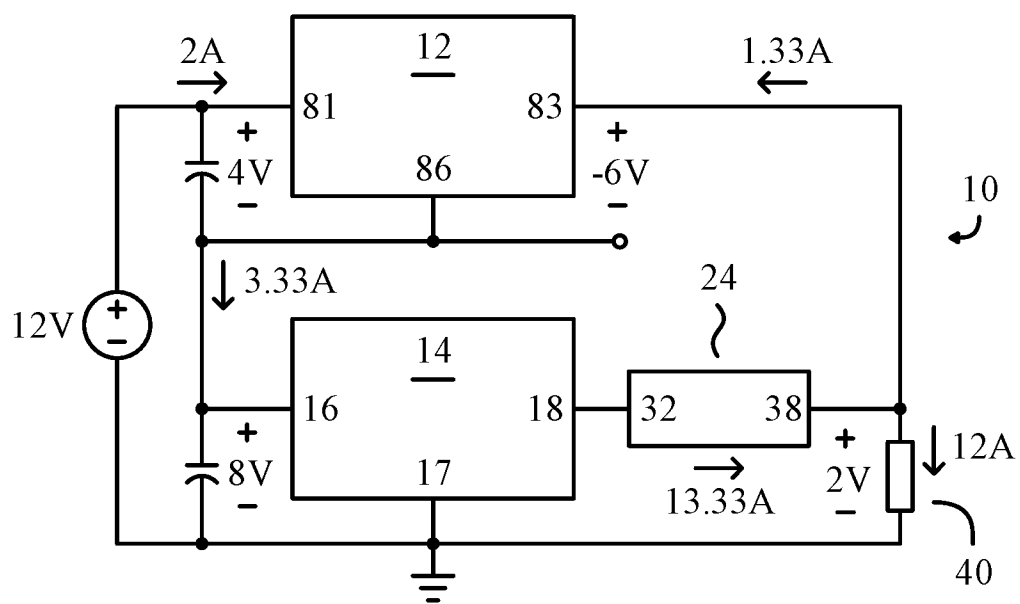


FIG. 14B

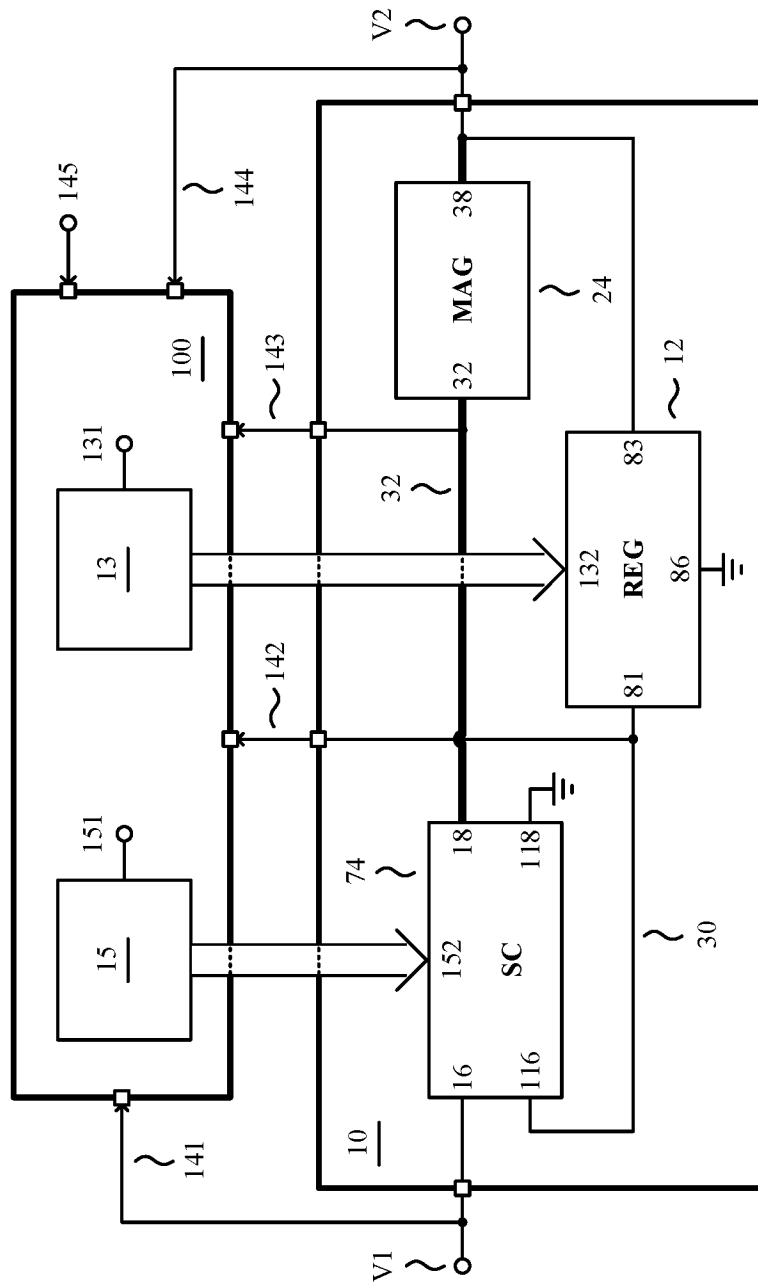


FIG. 15A

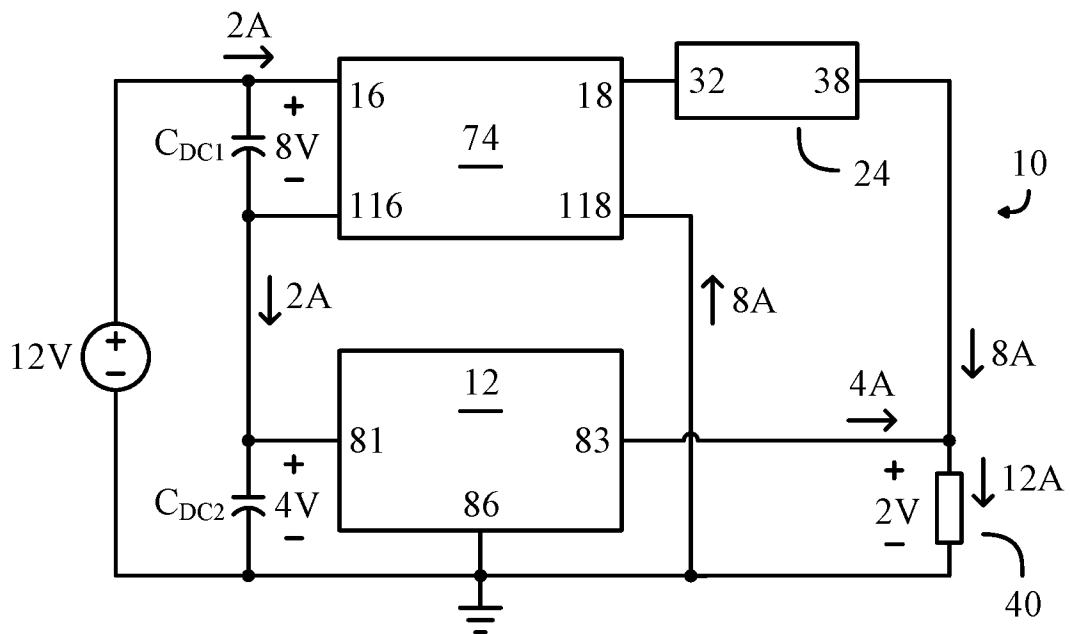


FIG. 15B

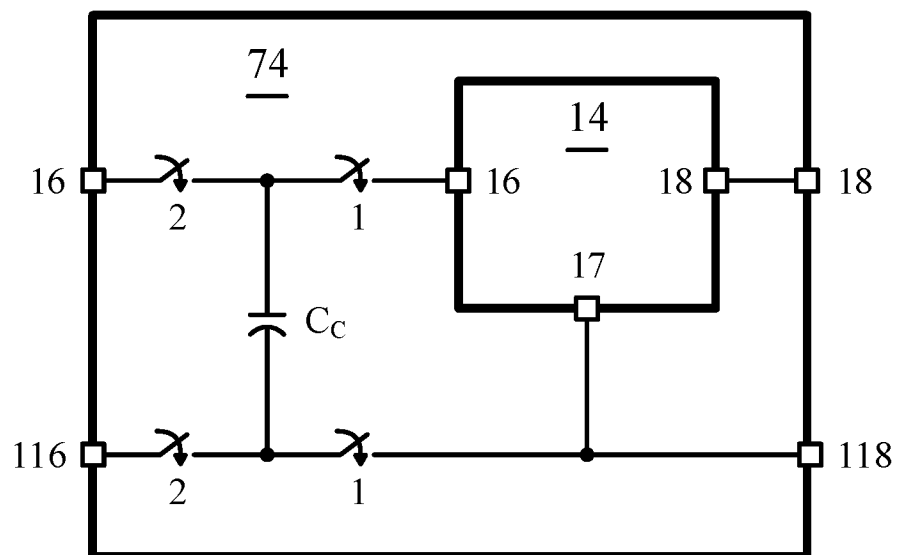


FIG. 16A

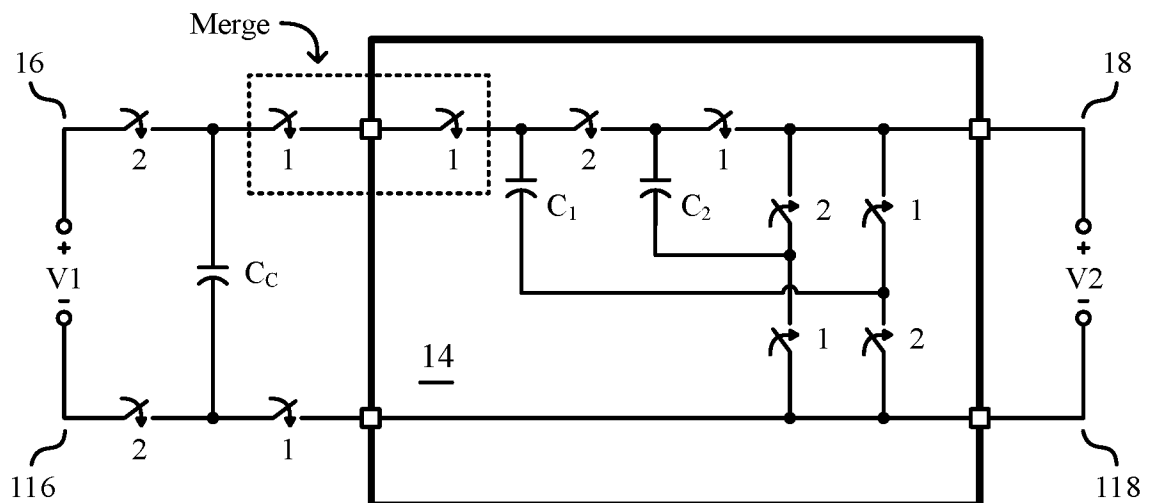


FIG. 16B

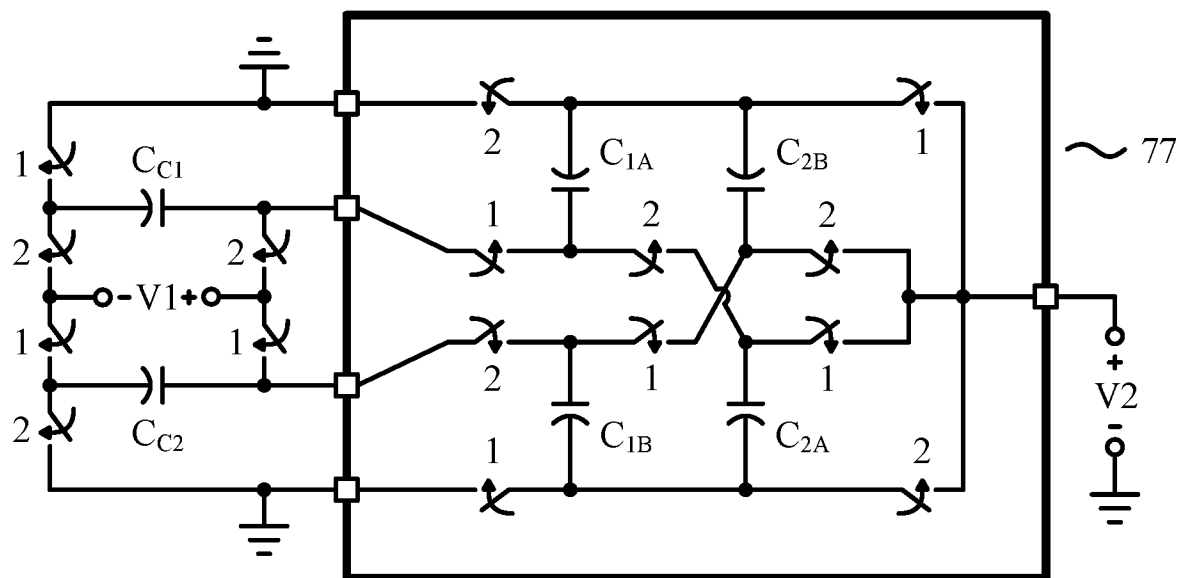


FIG. 16C

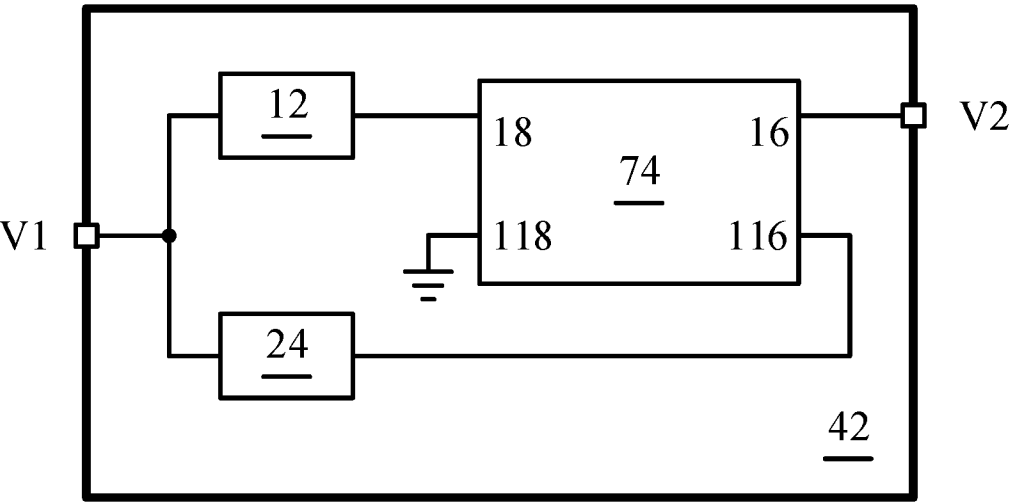


FIG. 17A

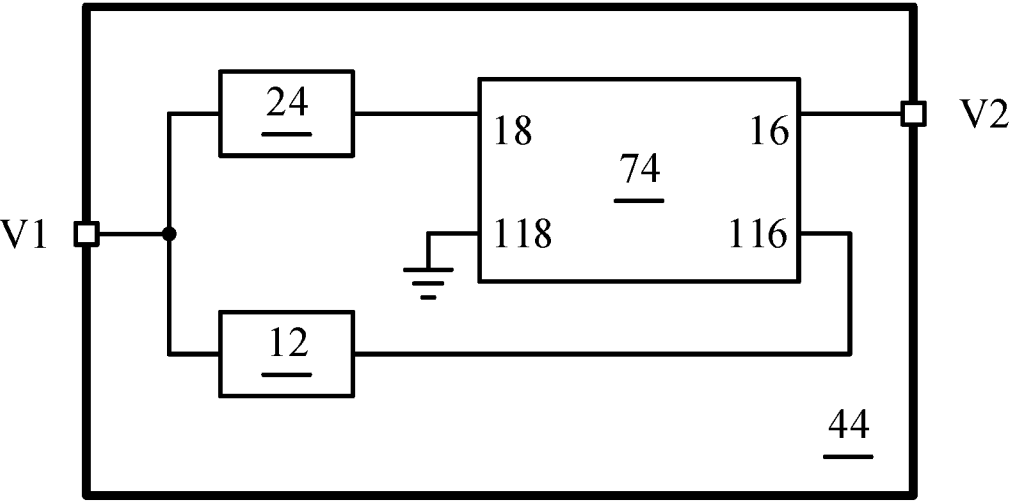


FIG. 17B

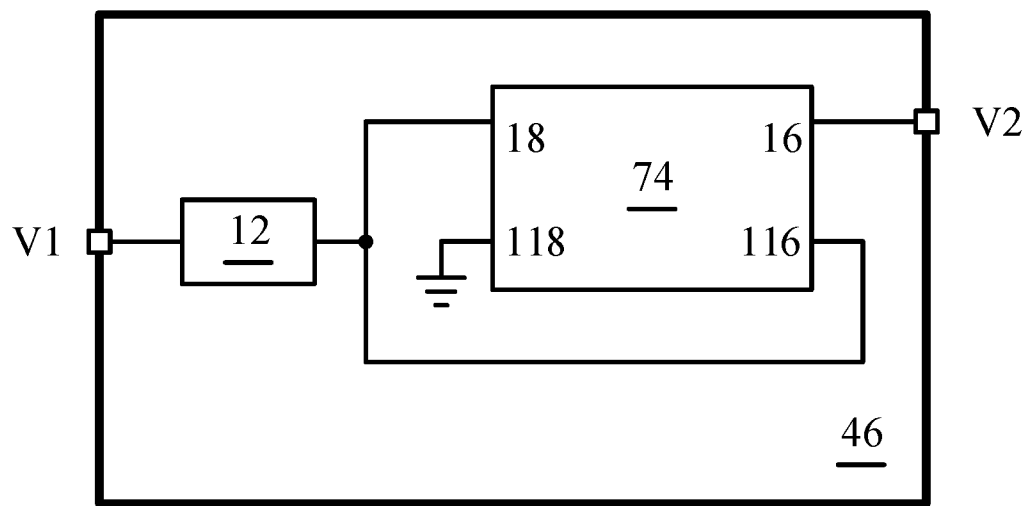


FIG. 17C

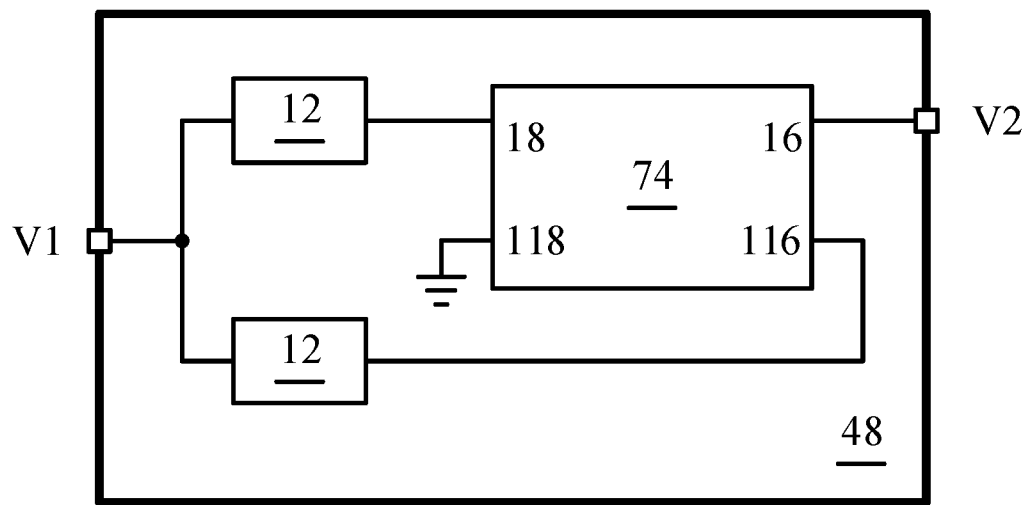


FIG. 17D

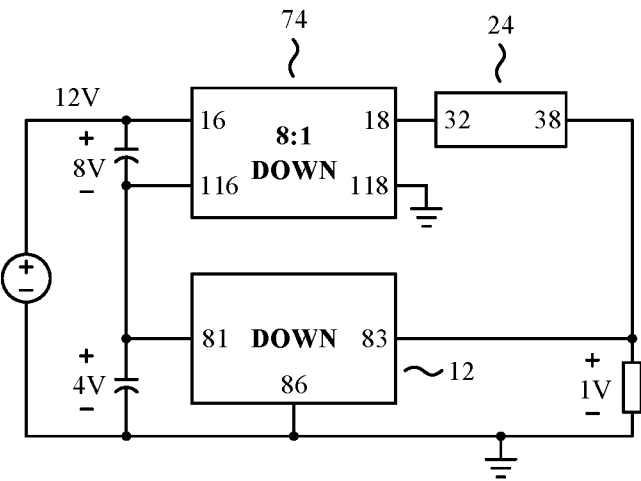


FIG. 18A

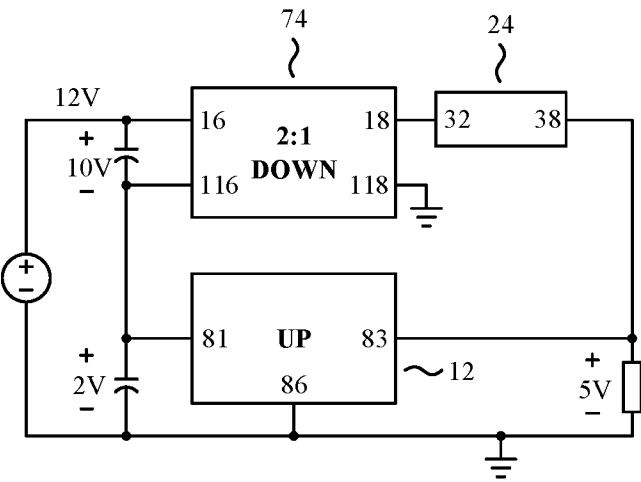


FIG. 18B

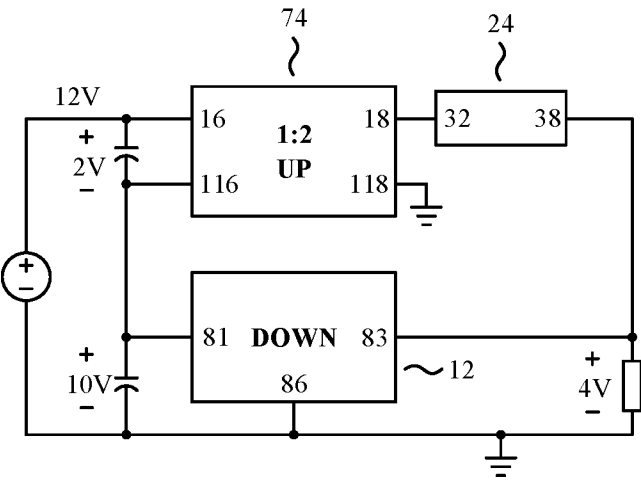


FIG. 18C

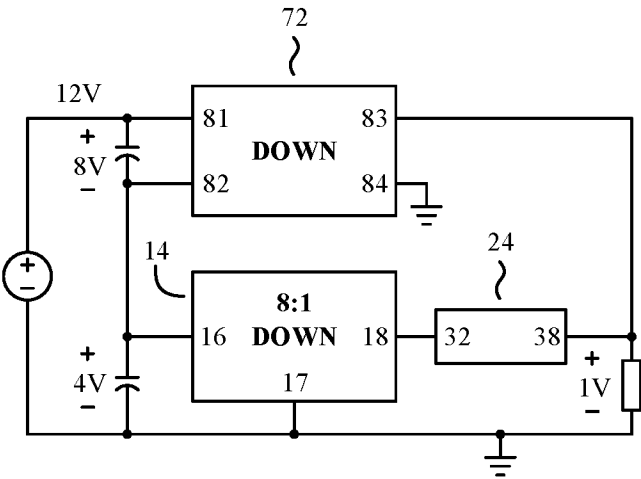


FIG. 19A

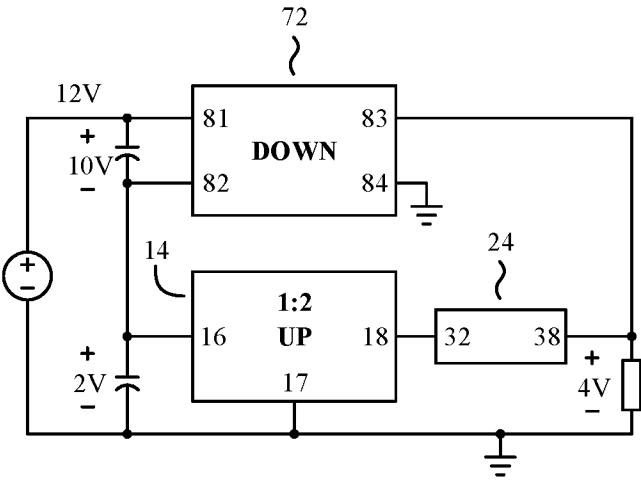


FIG. 19B

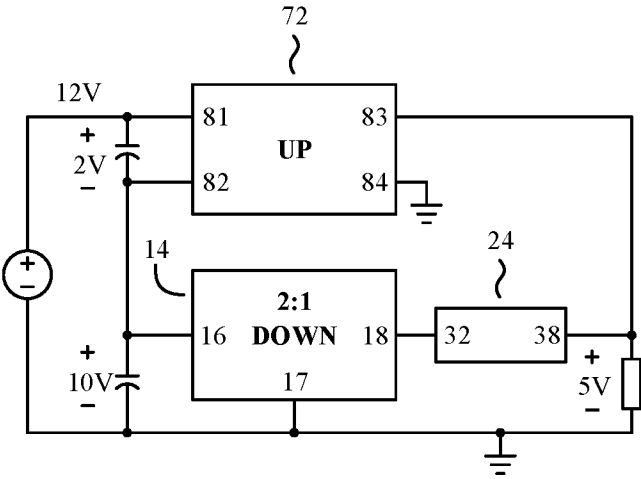


FIG. 19C

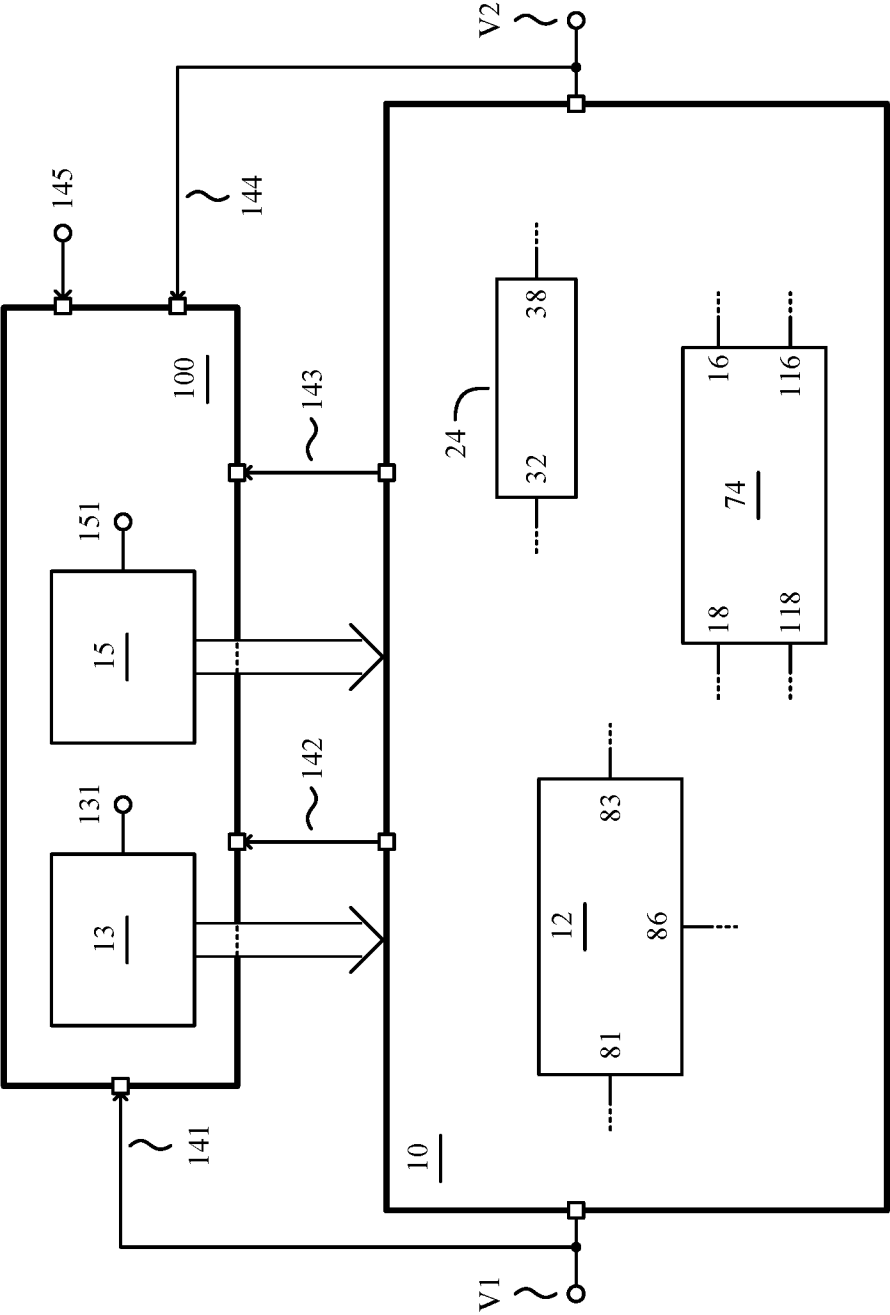


FIG. 20

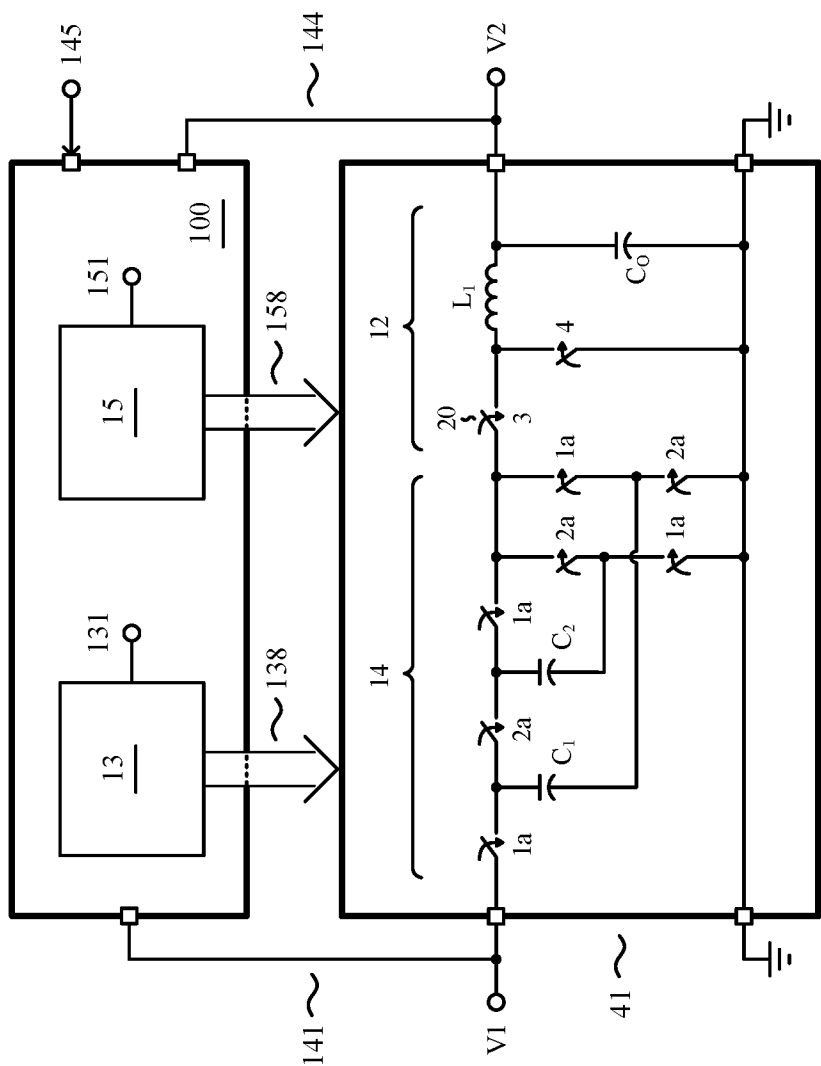
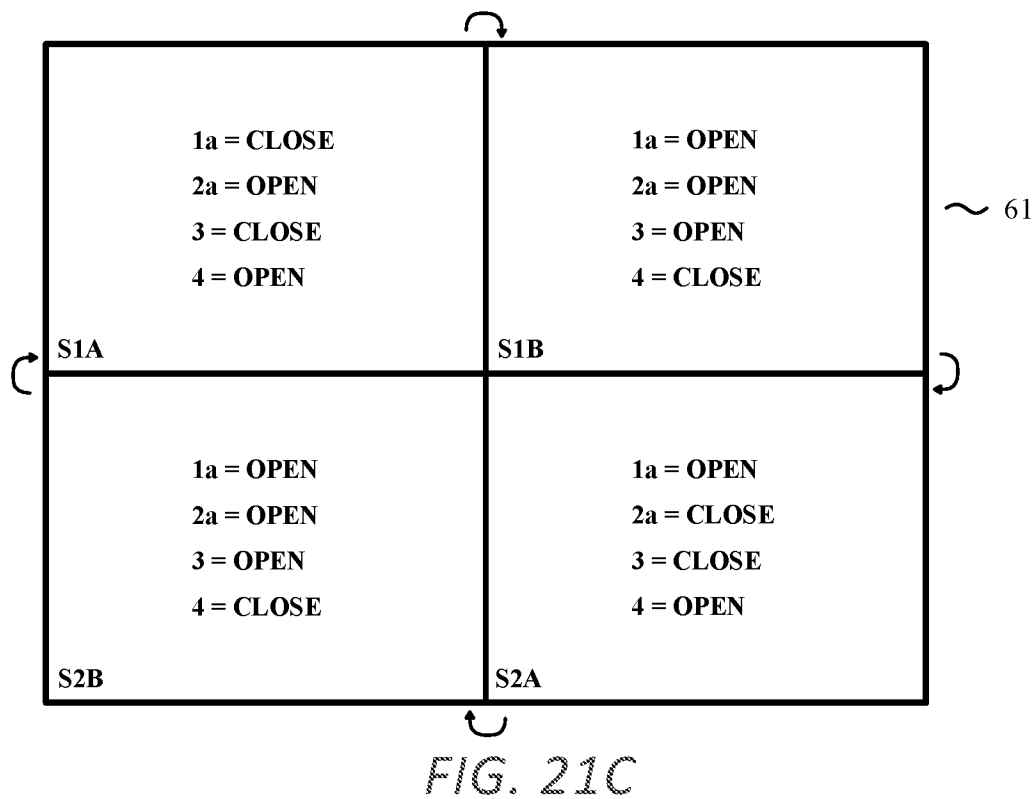
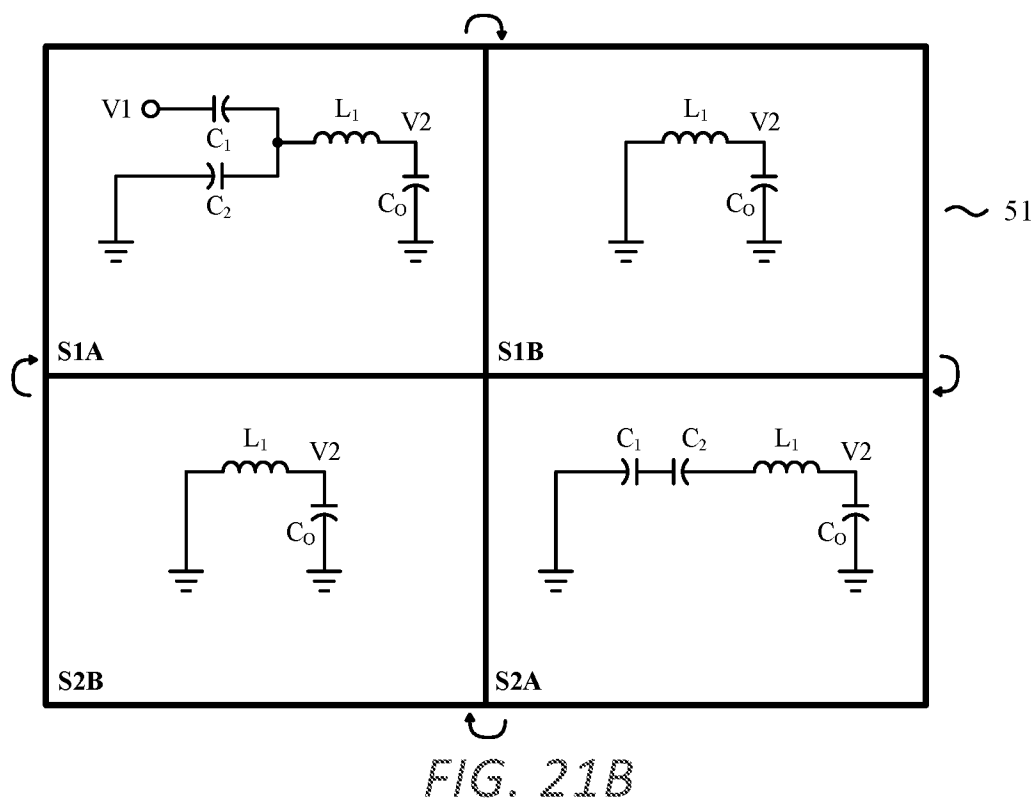


FIG. 21A



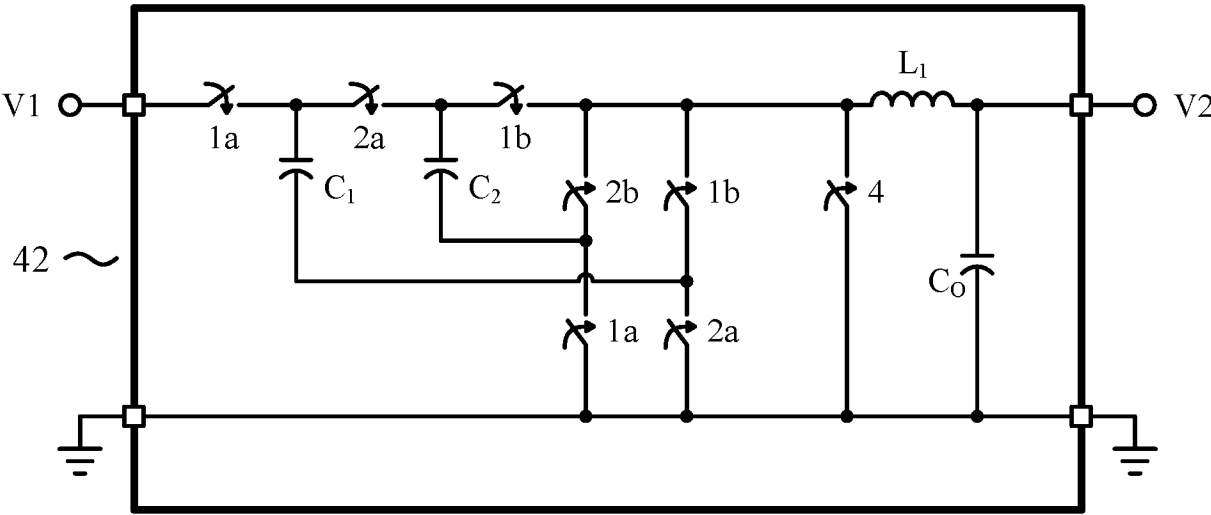


FIG. 22A

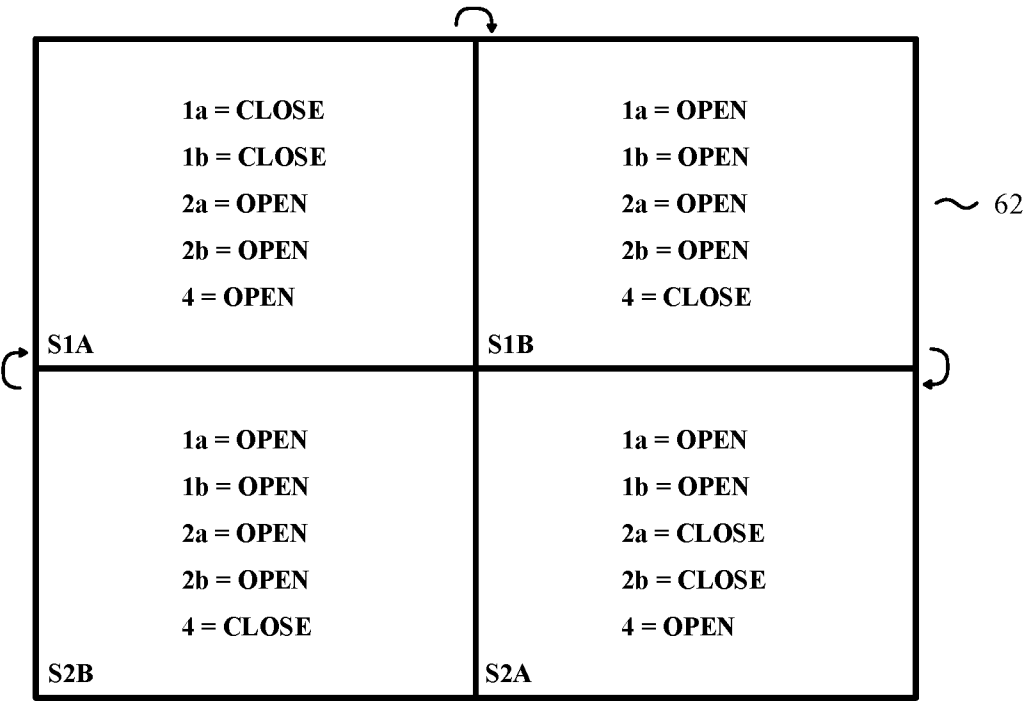


FIG. 22B

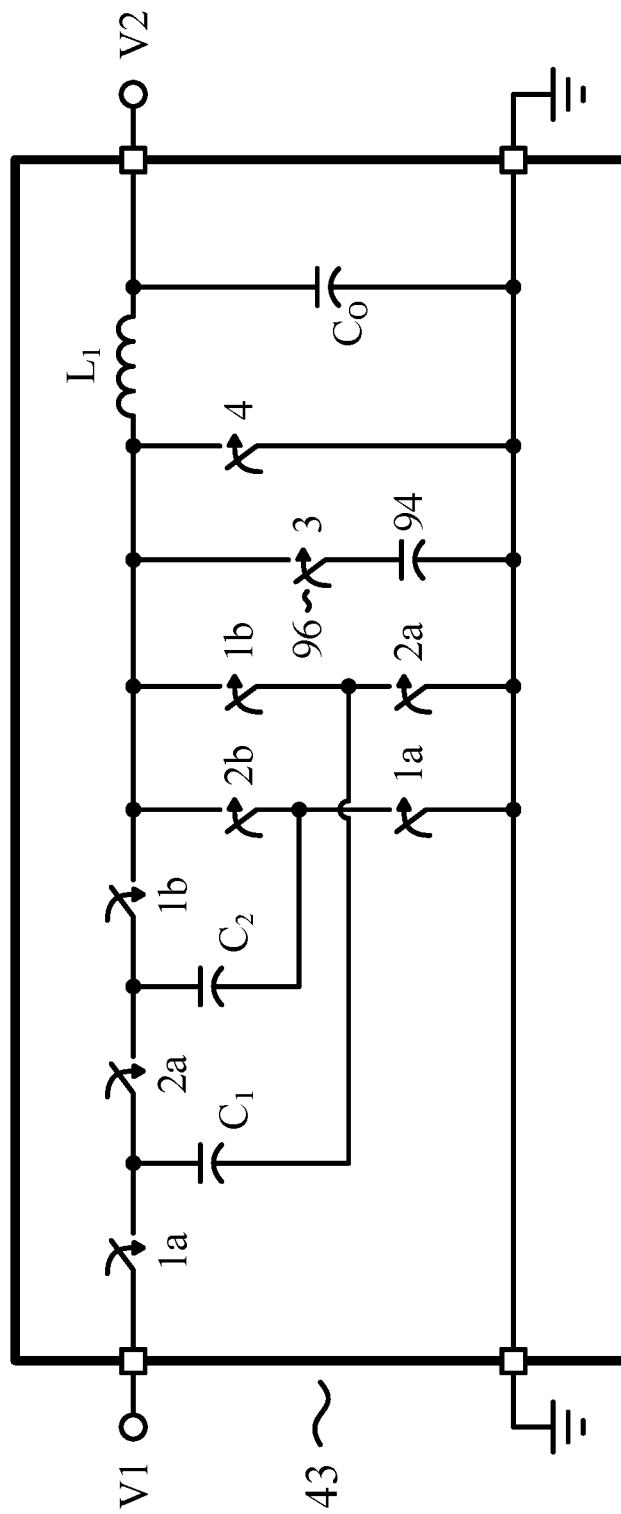
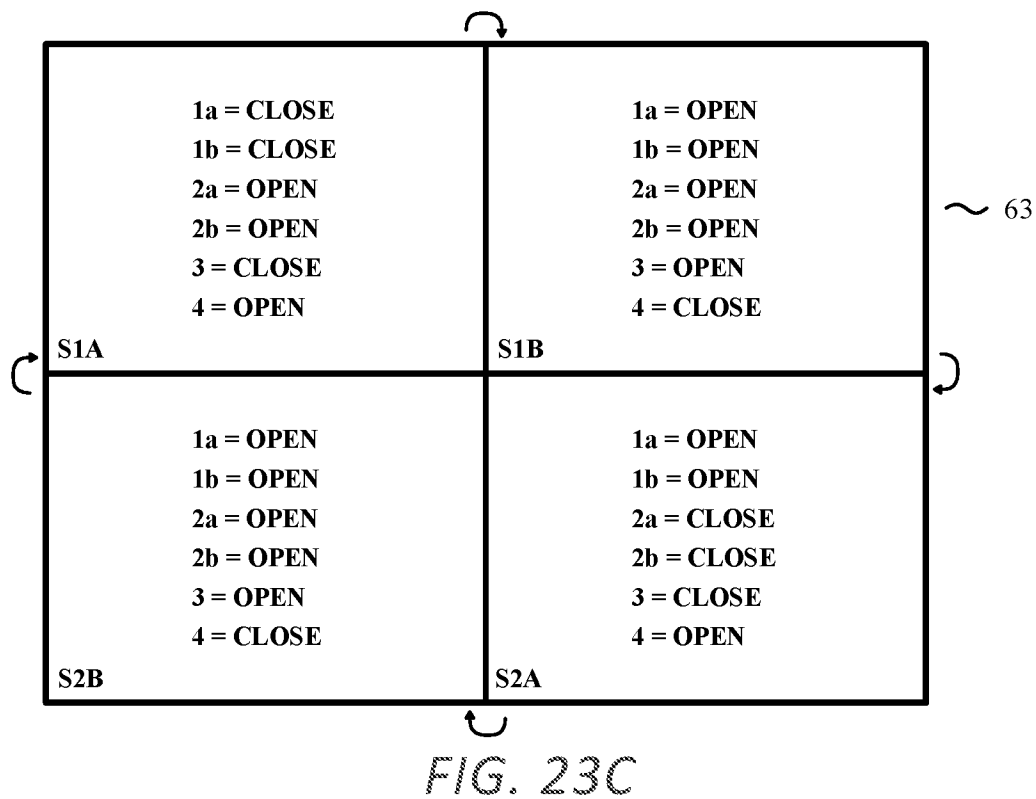
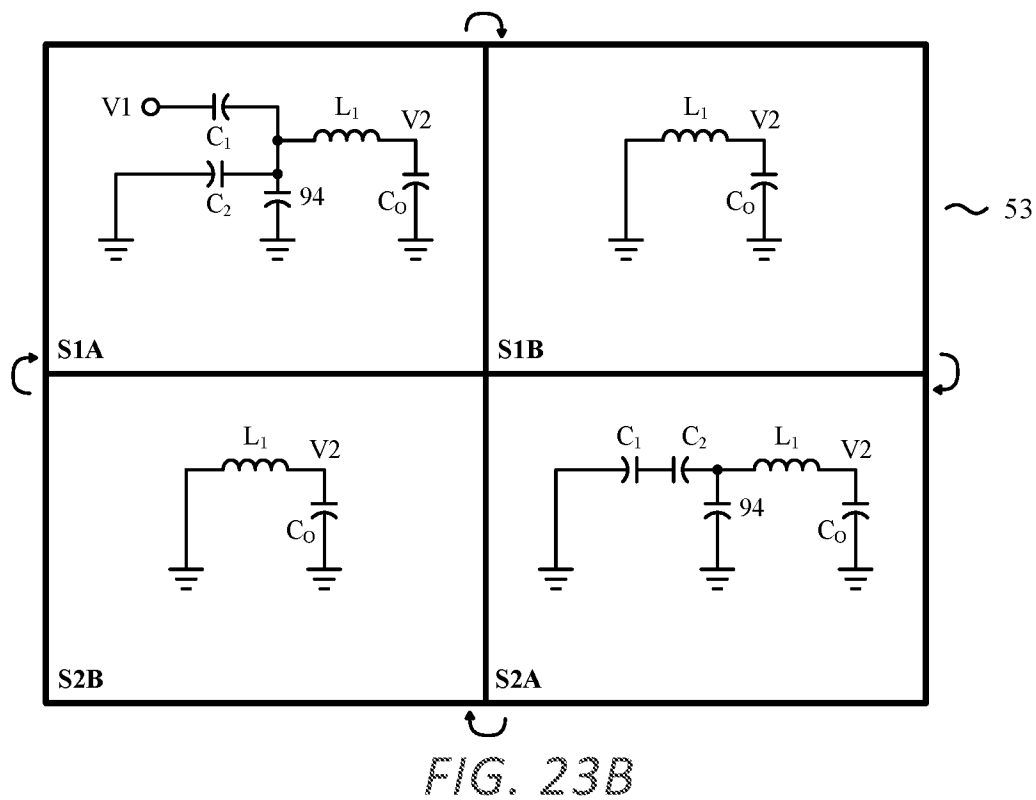


FIG. 23A



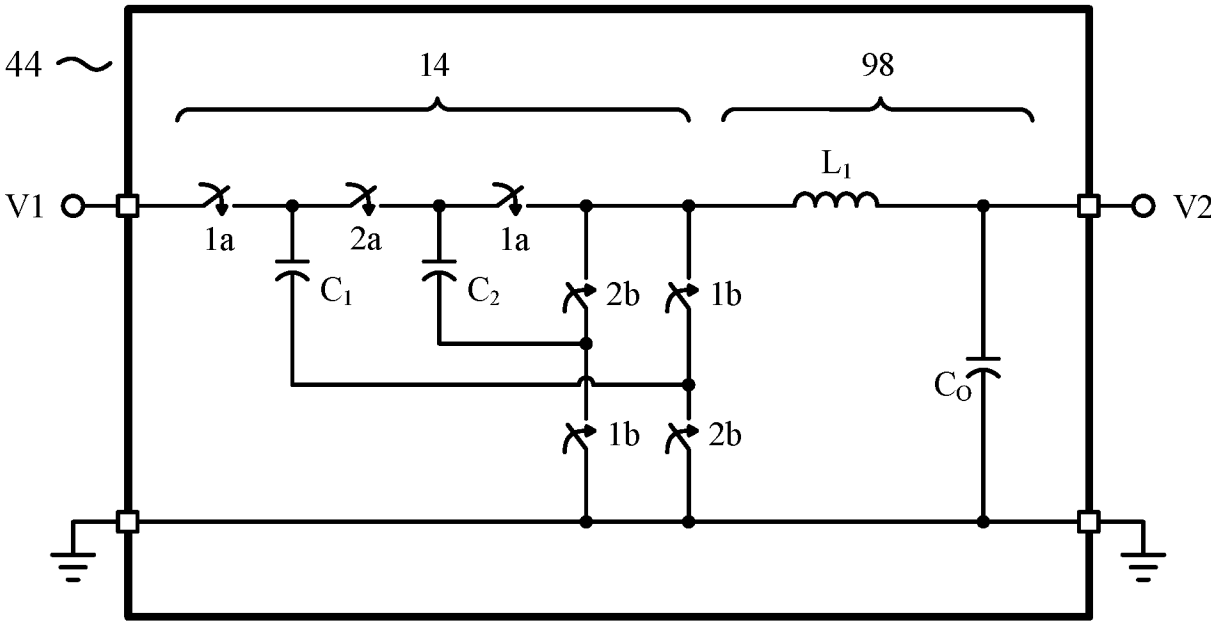


FIG. 24A

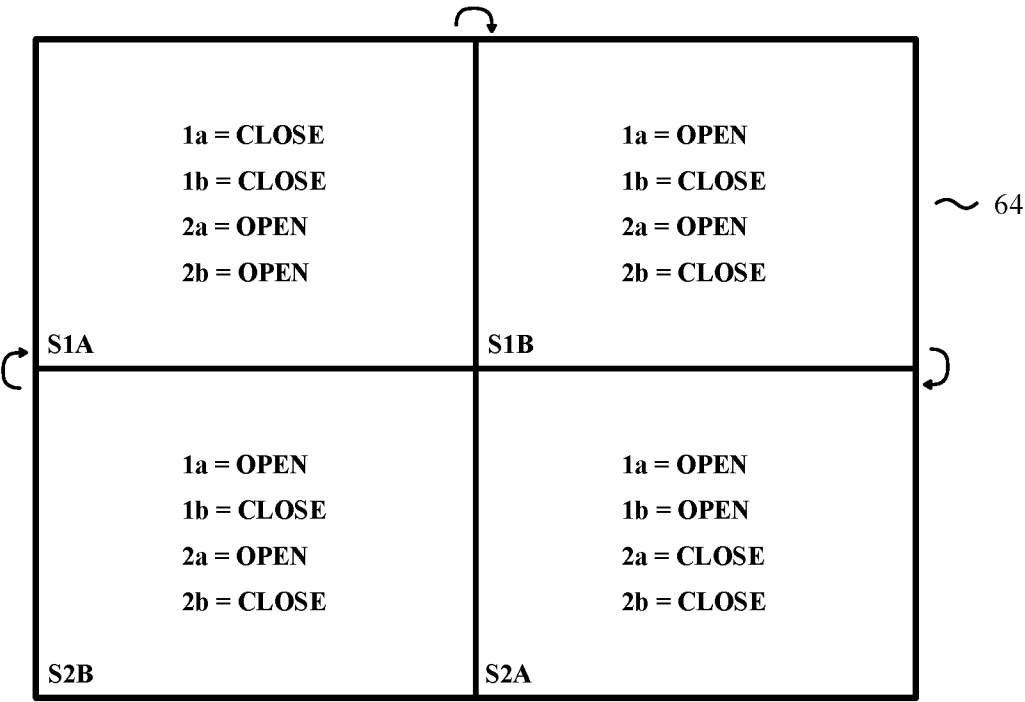


FIG. 24B

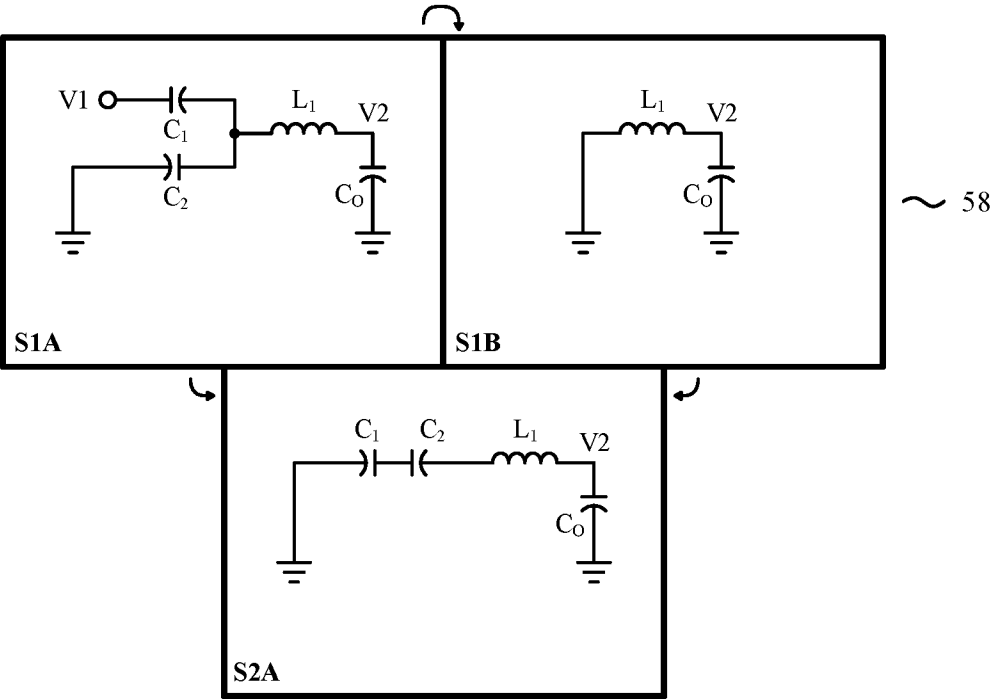


FIG. 25A

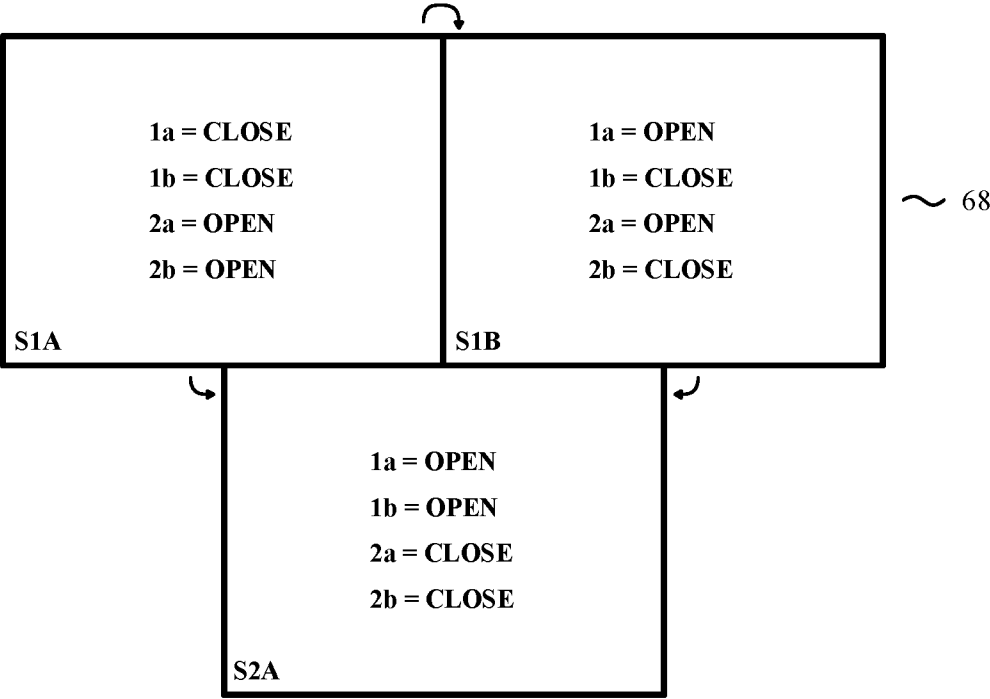
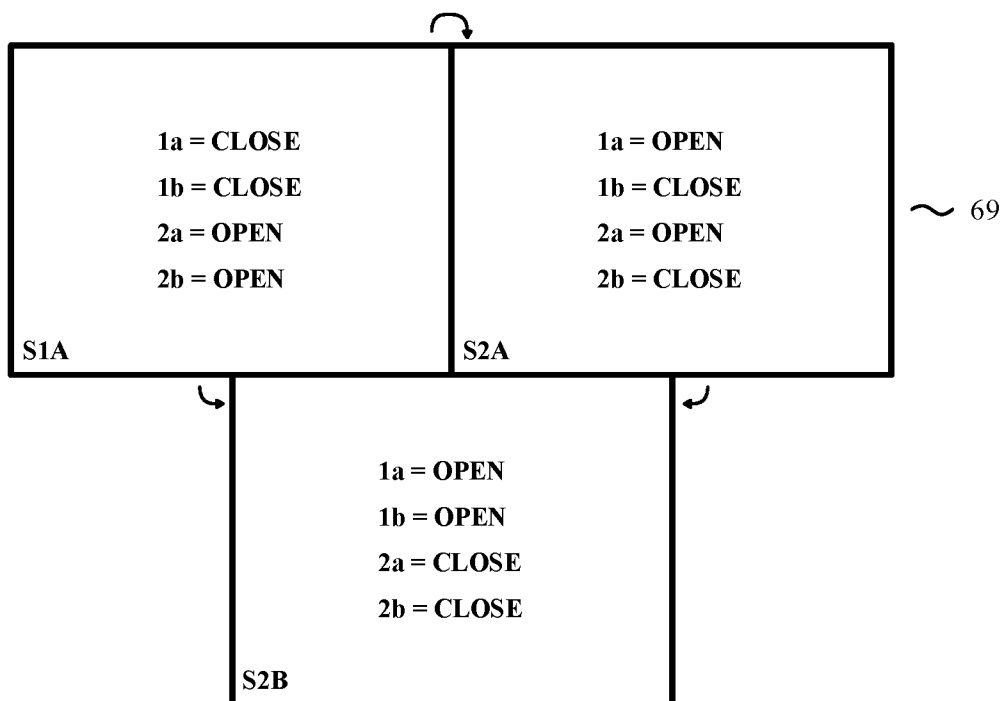
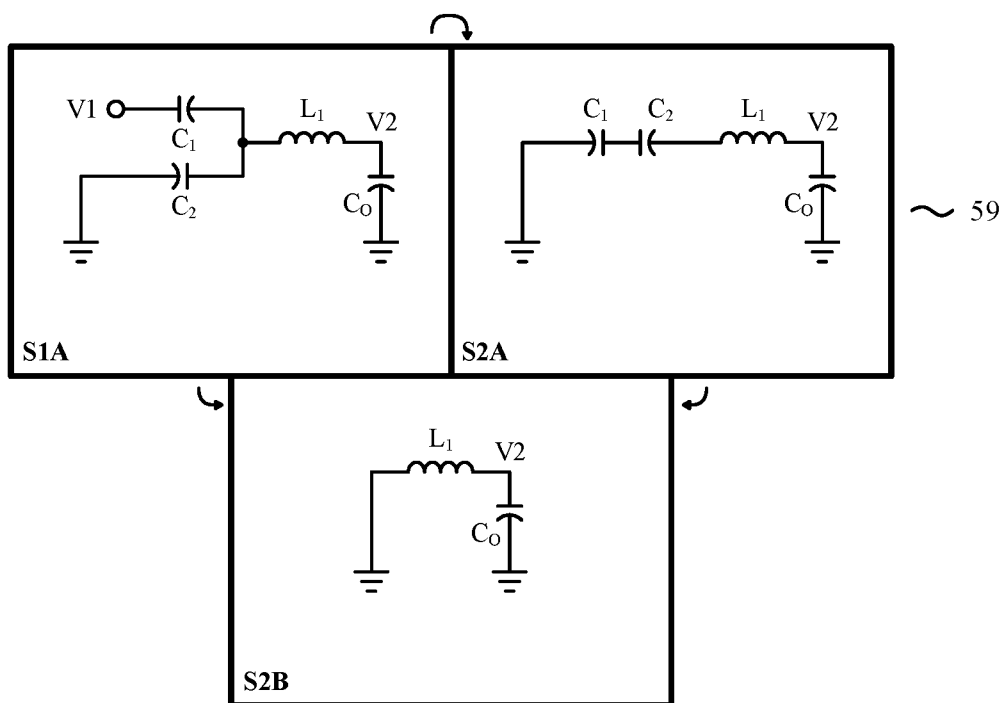


FIG. 25B



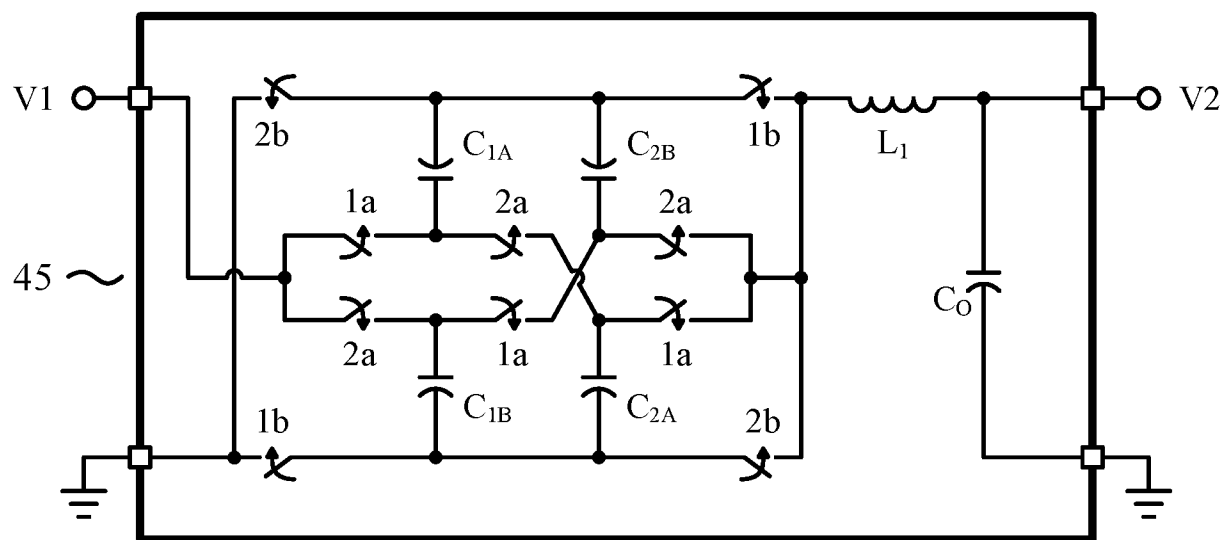


FIG. 27A

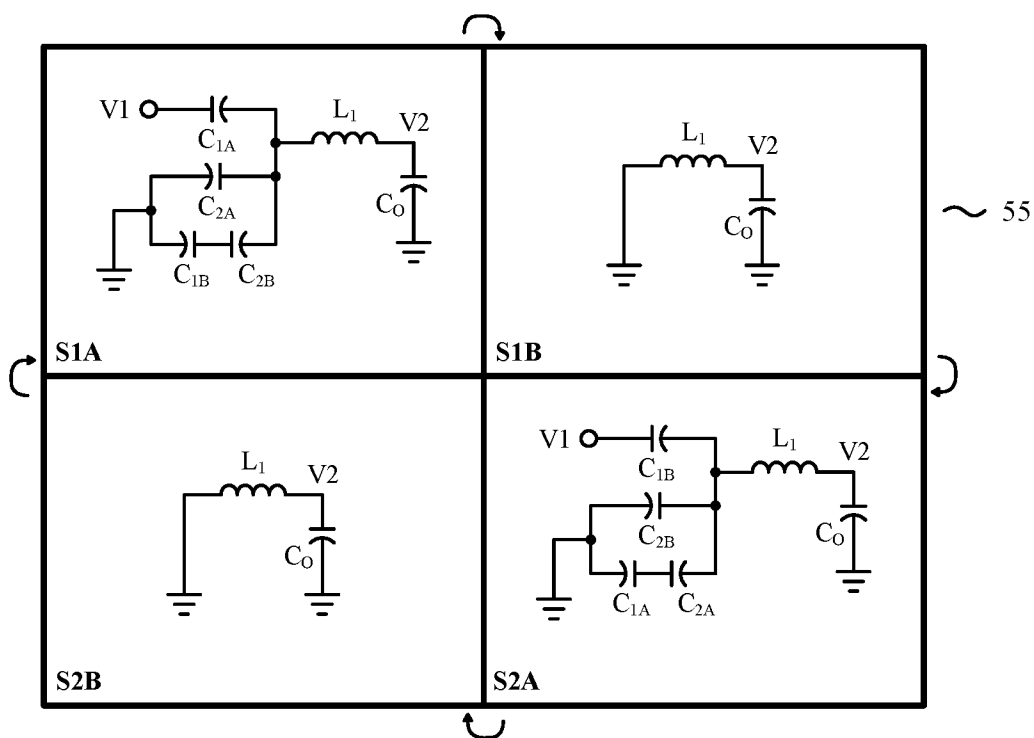


FIG. 27B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/021920**A. CLASSIFICATION OF SUBJECT MATTER****H02M 3/06(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H02M 3/06; H02M 3/155; H02M 7/5387; H02M 3/00; H02M 3/07

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: controller, capacitor, charge, switch, adiabatic, regulator, magnetic, filter, inductor, transport

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2013-0229841 A1 (ARCTIC SAND TECHNOLOGIES, INC.) 05 September 2013 See abstract, paragraphs 56-121 and figures 1-36.	1-37
A	US 2014-0177300 A1 (THALES) 26 June 2014 See abstract, paragraphs 56-192 and figures 1-10.	1-37
A	JP 2002-233139 A (MATSUSHITA ELECTRIC IND. CO., LTD.) 16 August 2002 See abstract, claims 1-7 and figures 1-6.	1-37
A	JP 2009-022093 A (RICOH CO., LTD.) 29 January 2009 See abstract, paragraphs 22-48 and figures 1-3.	1-37
A	KR 10-2010-0023304 A (LG INNOTEK CO., LTD.) 04 March 2010 See abstract, claims 1-7 and figures 1-4.	1-37



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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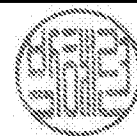
189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea

Facsimile No. +82-42-481-8578

Authorized officer

PARK, Hye Lyun

Telephone No. +82-42-481-3463



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/021920

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013-0229841 A1	05/09/2013	CN 103650313 A EP 2705597 A2 EP 2705597 A4 GB 2505371 A KR 10-1556838 B1 KR 10-2014-0015528 A KR 10-2015-0085072 A US 2015-0102798 A1 US 8860396 B2 WO 2012-151466 A2 WO 2012-151466 A3	19/03/2014 12/03/2014 18/03/2015 26/02/2014 13/10/2015 06/02/2014 22/07/2015 16/04/2015 14/10/2014 08/11/2012 28/02/2013
US 2014-0177300 A1	26/06/2014	CN 103887979 A EP 2747266 A1 FR 3000323 A1	25/06/2014 25/06/2014 27/06/2014
JP 2002-233139 A	16/08/2002	None	
JP 2009-022093 A	29/01/2009	CN 101542879 A CN 101542879 B KR 10-1243595 B1 KR 10-2009-0038929 A TW 200908525 A TW I462452 B US 2010-0237833 A1 US 8102157 B2 WO 2009-008223 A1	23/09/2009 04/07/2012 20/03/2013 21/04/2009 16/02/2009 21/11/2014 23/09/2010 24/01/2012 15/01/2009
KR 10-2010-0023304 A	04/03/2010	KR 10-0986183 B1	07/10/2010