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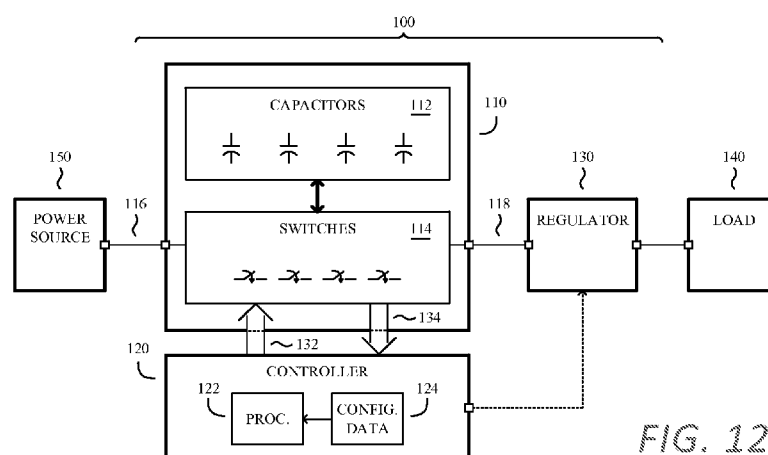


FIG. 12

(57) Abstract: An apparatus for coupling to capacitors to form a charge pump includes first and second sets of switch elements, and a controller. Switches in the first set couple terminals of capacitors to permit charge transfer between them. Switches in the second set couple terminals of at least some of the capacitors to either a high-voltage or a low-voltage terminal. The controller causes the switches to cycle through a sequence of states, each defining a corresponding configuration of the switch elements. At least three of the states define different configurations permitting charge transfer either between a first capacitor and a second capacitor, or between a first capacitor and one of the terminals. The configured cycle of states causes voltage conversion between the two terminals.

CHARGE BALANCED CHARGE PUMP CONTROL

RELATED APPLICATIONS

This application claims the benefit of the March 14, 2014 priority date of U.S. Provisional Application 61/953,270, the contents of which are herein incorporated by reference.

FIELD OF INVENTION

This invention relates to control for charge pumps to balance charge.

BACKGROUND

Patent Publication WO 2012/151466, published on November 8, 2012, and incorporated herein by reference, describes configurations of charge pumps, also known as switched capacitor converters, in which the source and/or load comprise regulating/regulator circuits. In some examples, the load can effectively comprise a current source and/or load rather than present a constant voltage in an example of what is referred to as “adiabatic” operation of a charge pump. Regulating/regulator circuits, such as switch-mode power converters, behave as current loads/sources. Therefore, current loads/sources and regulating/regulator circuits are interchangeable for the purpose of this disclosure.

Although use of a current-based load (and/or source) may improve efficiency as compared to a purely or substantially voltage-based load (and/or source), internal energy losses may remain, for example, due to redistribution of charges within the charge pump.

SUMMARY

One effect of using a current-based load (and/or source) with a charge pump is that there may be situations in which a conventional switch timing used with voltage-based loads and/or sources results in charge imbalance across capacitors, which can result in loss of efficiency, for example, due to charge redistribution immediately after switching between configurations in the charge pump.

In one aspect, in general, an approach to improving efficiency of a charge pump using adiabatic charge transfer makes use of three or more states, each corresponding to a

configuration of switches coupling capacitors to one another and/or the input and output terminals of the charge pump. By introducing an appropriate sequence of more than two states in which charge is transferred to or from capacitors, and selecting the duration those states are occupied in each operating cycle of the charge pump, charge transfer in and out of each capacitor is balanced over the operating cycle, thereby avoiding or greatly reducing charge redistribution at state transitions and its associated power losses that lead to inefficiency.

In one aspect, the invention features an apparatus for coupling to capacitors to form a charge pump circuit. Such an apparatus includes a first and second set of switch elements and a controller circuit. The first set of switch elements comprises switch elements that are configured to couple terminals of capacitor elements to permit charge transfer between the capacitors. The second set of switch elements comprises switch elements that are configured to couple terminals of at least some of the capacitor elements to a first terminal, which is either a high voltage terminal or a low voltage terminal. The controller circuit is coupled to the switch elements and configured to cycle the switch elements through a sequence of states. Each state defines a corresponding configuration of the switch elements. At least three of the states define different configurations of the switch elements permitting charge transfer between a pair of elements. The pair of elements is either a pair of capacitors, or a capacitor and a terminal. The configured cycle of states provides a voltage conversion between the high voltage terminal and the low voltage terminal.

In some embodiments, there are terminals for coupling the switch elements to the capacitors.

Other embodiments include the capacitors themselves. In these embodiments, the capacitors, when coupled to the switch elements, define a charge pump circuit.

Some embodiments comprise an integrated circuit. In these embodiments, at least part of the charge pump circuit and at least part of the controller circuit are formed in a single integrated circuit.

Also among the embodiments are those that include a regulator circuit. In these embodiments, the regulator circuit is coupled to at least one of the high voltage terminal and the low voltage terminal of the charge pump circuit. In some of these embodiments, the regulator circuit is configured to provide a current load at the low voltage terminal of the charge pump circuit. In others, the regulator circuit is configured to operate as a current source at the low voltage terminal of the charge pump circuit. In yet others, the regulator circuit is configured to provide a current load at the high voltage terminal of the charge pump circuit, or to operate as a current source at the high voltage terminal of the charge pump circuit, or to cause a pulsed current to pass between the regulator circuit and the charge pump circuit. In the latter case, the charge pump operates in a pulse cycle having a first fraction, during which the pulsed current is a first constant current, and a second fraction, during which the pulsed current is greater in magnitude than the second constant current. In many cases, the second constant current is substantially zero or even equal to zero. Typically, the first constant current is substantially larger than the second constant current.

In some embodiments, a regulator circuit is configured to control an average current passing between the regulator circuit and the charge pump circuit.

In those embodiments that feature a regulator, a great many regulator types can be used. These include regulators that are switch-mode power converters, or buck converters, or even magnetic filters.

In some embodiments, the controller is configured to maintain each state for a corresponding duration of a fraction of a charge pump cycle time. The durations of these states are selected to maintain a balanced charging and discharging of each of the capacitors through the sequence of states of each cycle.

In other embodiments, the controller is configured to select durations of the states to reduce redistribution of charge among the capacitors upon state transitions.

When coupled to the terminals of the capacitor elements, the switch elements define any of a variety of charge pump circuits. Examples include a multi-phase charge pump, a single-phase charge pump, a multi-stage charge pump, and a cascade multiplier.

Also among the embodiments are those in which the controller is configured to receive sensor signals from at least one of the first and second sets of switch elements and to adaptively adjust cycling of the switch elements through the sequence of states based at least in part on the sensor signals.

In some embodiments, there are two regulator circuits. A regulator circuit is coupled to the high voltage terminal of the charge pump circuit. Meanwhile, a second regulator circuit is coupled to the low voltage terminal of the charge pump circuit. Either the first or second regulator can be a magnetic filter. Among these embodiments are those in which the controller is configured to receive sensor signals from at least one of the first and second sets of switch elements and to adaptively adjust cycling of the switch elements through the sequence of states based at least in part on the sensor signals.

In another aspect, the invention features a method for operating a charge pump in which switch elements from a first set of switch elements are configured to couple terminals of capacitor elements to permit charge transfer between the capacitors, and in which switch elements from a second set of switch elements are configured to couple terminals of capacitor elements to either a high voltage terminal or a low voltage terminal. Such a method includes causing a voltage conversion between the high voltage terminal and the low voltage terminal. Causing this voltage conversion includes cycling the switch elements through a sequence of states. Each state defines a corresponding configuration of the switch elements. At least three of the states define different configurations of the switch elements permitting charge transfer between a pair of elements. The pair of elements is either a pair of capacitors or a capacitor and a one of the terminals.

Some practices of the invention include maintaining an average current passing between a regulator circuit and the charge pump circuit. Others include regulating a

current at the first terminal, thereby maintaining an average current passing between a regulator circuit and the charge pump circuit.

In other practices, cycling the switch elements through a sequence of states includes maintaining each state for a corresponding duration of a fraction of a charge pump cycle time. This can also include selecting the durations of the states are selected to maintain a balanced charging and discharging of each of the capacitors through the sequence of states of each cycle.

Some practices of the invention include controlling an average current between a regulator circuit and the charge pump circuit.

Other practices include coupling a regulator circuit to the first terminal. Among these are practices that include causing the regulator circuit to provide a current load at the low voltage terminal of the charge pump circuit, causing the regulator circuit to provide a current load at the high voltage terminal of the charge pump circuit, causing the regulator circuit to operate as a current source at the low voltage terminal of the charge pump circuit, causing the regulator circuit to operate as a current source at the high voltage terminal of the charge pump circuit, and causing a pulsed current to pass between a regulator circuit and the charge pump circuit.

Some practices include coupling the switch elements from the first and second sets of switch elements to the terminals of the capacitor elements. This can result in forming a multi-phase charge pump, a single-phase charge pump, a multi-stage charge pump, or a cascade multiplier.

Those practices that involve a regulator include selecting the type of regulator. This can include selecting the regulator to be a switch-mode power converter, selecting the regulator to be a buck converter, or selecting the regulator to be a magnetic filter.

Some practices also include receiving sensor signals from at least one of the first and second sets of switch elements and adaptively adjusting the cycling of the switch elements through the sequence of states based at least in part on the sensor signals.

Some practices involve the use of two regulators. These practices further include coupling a first regulator to the high voltage terminal, and coupling a second regulator to the low voltage terminal. One of the regulators can be a magnetic filter while the other is a converter. Among these practices are those that also include controlling least one of the first and second sets of switch elements and adaptively adjusting the cycling of the switch elements through the sequence of states based at least in part on sensor signals received from at least one of said first and second sets of switch elements.

Other features and advantages of the invention are apparent from the following description, and from the claims.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a single-phase 5:1 charge pump with a voltage source and a current load.

FIGS. 2A – 2B are schematic diagrams of the circuit of FIG. 1 in states 1 and 2, respectively, of the switch configuration.

FIGS. 3A – 3C are schematic diagrams of the circuit of FIG. 1 in states *1a*, *1b*, and 2, respectively.

FIG. 3D is a set of waveforms showing the voltage across each capacitor in FIGS. 3A – 3C during the operation of the charge pump.

FIGS. 4A – 4C are schematic diagrams of the circuit of FIG. 1 in alternative definitions of states *1a*, *1b*, and 2, respectively.

FIG. 4D is a set of waveforms showing the voltage across each capacitor in FIGS. 4A – 4C during the operation of the charge pump.

FIG. 5 is a schematic diagram of a single-phase 6:1 charge pump with a voltage source and a current load.

FIGS. 6A – 6D are schematic diagrams of the circuit of FIG. 5 in states *1a*, *1b*, *2a*, and *2b*, respectively.

FIG. 7 is a schematic diagram of a two-phase 5:1 charge pump with a voltage source and a current load.

FIGS. 8A – 8B are schematic diagrams of the circuit of FIG. 7 in states *1a* and *1b*, respectively.

FIG. 9 is a schematic of a two-phase 3:1 series-parallel charge pump with a voltage source and a current load.

FIGS. 10A – 10D are schematic diagrams of the circuit of FIG. 9 in states *1a*, *1b*, *2a*, and *2b*, respectively.

FIGS. 11A – 11B are schematic diagrams of the circuit of FIG. 7 in states *1a* and *1b*, respectively with current skew.

FIGS. 12 – 14 are block diagrams of power converters.

DETAILED DESCRIPTION

A first example charge pump **110** is shown in FIG. 1 to illustrate a source of charge imbalance in the operation of such a charge pump. The charge pump **110** is a cascade multiplier configured to nominally provide a 5:1 (i.e., $M = 5$) step-down in voltage such that an output voltage V_{OUT} (volts) is one-fifth of an input voltage V_{IN} (volts). Four capacitors (labeled C_1 to C_4) are used with switches (labeled S_1 to S_9) on both terminals of each capacitor to store a fraction of the input voltage V_{IN} and transfer charge from one capacitor to the next. The capacitors closest to the V_{IN} and V_{OUT} terminals are labeled C_1 and C_4 , respectively, and are referred to below as the “outer” capacitors, while the remaining capacitors labeled C_2 and C_3 are referred to below as the “inner” capacitors. As further notation, the voltage and charge on a capacitor C_k are denoted V_k and Q_k , respectively. Unless otherwise indicated, the capacitors are treated as ideally having identical capacitance C (Farads).

The charge pump **110** is operated by controlling a set of switches (S_1 through S_9) that cause charge to pass between the capacitors and between the terminals and the capacitors. The control of the switches of the charge pump **110** can be represented as a cycle through a series of states, where each state is associated with a particular

configuration of the set of switches (i.e., a particular setting of open-circuit (non-conducting) and closed-circuit (conducting) configuration of each of the switches).

One mode of operation of the charge pump **110** shown in FIG. 1 uses a cycle of two states. In a state 1, the switches labeled “1” (i.e., S_1 , S_3 , S_5 , S_7 , S_8) are closed and the switches labeled “2” (i.e., S_2 , S_4 , S_6 , S_9) are open. In a state 2, the switches labeled “1” are open and the switches labeled “2” are closed. These configurations of switches are shown in tabular form (“1” indicating the switch is closed and “0” indicating that the switch is open) as follows:

State	Switch								
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
State 1	1	0	1	0	1	0	1	1	0
State 2	0	1	0	1	0	1	0	0	1

Note that in practice, additional states may be needed in which all or a sufficient set of switches are open such that charge is not passing to or from the capacitors without affecting the overall function of the charge pump **110**, for example, in a “break before make” approach to avoid the necessity of truly instantaneous switching. However, for the analysis of the ideal behavior below, such additional states are not generally considered because these additional states do not involve a transfer of charge and will not affect the outcome of the analysis.

A complete cycle of the charge pump **110** has a sequence of two states, state 1 followed by state 2. A first phase node P_1 couples with the negative terminal of the capacitors C_1 , C_3 , and a second phase node P_2 couples with the negative terminal of the capacitors C_2 , C_4 . The voltage at the first phase node P_1 alternates between ground and the output voltage V_{OUT} , and the voltage at the second phase node P_2 is out of phase with the first phase node P_1 .

In steady-state operation, the capacitors C_1 to C_4 have nominal voltages across their terminals that are multiples of the nominal output voltage:

$$\begin{aligned}
V_1^{(nom)} &= 4 * V_{OUT}^{(nom)} = (4 / 5) * V_{IN} \\
V_2^{(nom)} &= 3 * V_{OUT}^{(nom)} = (3 / 5) * V_{IN} \\
V_3^{(nom)} &= 2 * V_{OUT}^{(nom)} = (2 / 5) * V_{IN} \\
V_4^{(nom)} &= 1 * V_{OUT}^{(nom)} = (1 / 5) * V_{IN}
\end{aligned}$$

For example, when the input voltage V_{IN} equal to 25.0 (volts), the nominal voltages across the capacitors $C_1 - C_4$ are 20.0, 15.0, 10.0, and 5.0 (volts), respectively, and the nominal output voltage V_{OUT} is 5.0 (volts). The actual voltages across the capacitors vary around these nominal values (i.e., the voltage exhibits “ripple”) during a cycle of the successive states of operation of the charge pump **110**, denoted as

$$V_k = V_k^{(nom)} + v_k \quad .$$

In this example, the output terminal of the charge pump **110** is treated as being coupled to a current load, with current I_{OUT} . In some examples, this current is assumed constant. More generally, as discussed further below, the current may be pulsed with a constant average $\bar{I}_{OUT} = D * I_{OUT}^{(peak)}$, where D is the duty cycle (a fraction between zero and one) of the pulsed current load; this is a good representation of the behavior of a buck converter. In general, the frequency of the current load switching is a multiple times the frequency of the charge pump **110** switching (e.g., 2x, 3x, 10x, 100x). In some examples, the current may be constant during each state, but have different values during each state. Furthermore, state transition instants are preferably chosen to occur during the zero-current part of the output current duty cycle, thereby reducing switching losses with non-ideal (e.g., transistor) switches. But for the sake of discussion of this first example, only the constant current case is considered.

Referring to FIGS. 2A – 2B, the equivalent circuits of the charge pump **110** in FIG. 1 are shown for state 1 and state 2, respectively. Generally, in state 1, energy is transferred from the V_{IN} terminal to the outer capacitor C_1 , between the inner capacitors C_2 , C_3 , and from the outer capacitor C_4 to the V_{OUT} terminal. In state 2, energy is transferred between the capacitors and to the load at the V_{OUT} terminal.

During state 1, the outer capacitors C_1, C_4 carry a current of $0.4 * I_{OUT}$ while the inner capacitors C_2, C_3 each carry a current of $0.2 * I_{OUT}$, which is half the current through the outer capacitors C_1, C_4 . Therefore, if state 1 has a state duration time t_1 , then the change in charge on the outer capacitors C_1, C_4 , denoted $\Delta Q_{k,j}$ as the change in charge on capacitor C_k during state j , satisfy

$$+\Delta Q_{1,1} = -\Delta Q_{4,1} = t_1 * 0.4 * \bar{I}_{OUT}$$

while the change in charge on the inner capacitors C_2, C_3 during state 1 satisfy

$$-\Delta Q_{2,1} = +\Delta Q_{3,1} = t_1 * 0.2 * \bar{I}_{OUT}.$$

Note that the inner capacitors C_2, C_3 are connected in series while the outer capacitors C_1, C_4 are the only elements in their respective paths, causing the current to divide accordingly by the number of series capacitors.

During state 2, every capacitor carries a current of $0.5 * I_{OUT}$. The inner capacitors C_2, C_3 are always in a series connection with another capacitor in either state while the outer capacitors C_1, C_4 have a similar series connection only during state 2. The current flow polarity through each capacitor changes back and forth from one state to the next state as needed to charge and discharge the capacitor and maintain a constant average voltage across the capacitor.

If the charge pump **110** were controlled at a 50% duty cycle with $t_1=t_2=0.5 * T_{SW}$, where T_{SW} is the total duration of the switching cycle, the net charge across each cycle of two states on each capacitor C_k , $\Delta Q_k = \Delta Q_{k,1} + \Delta Q_{k,2}$ is not zero. A consequence of this is that the net charge and average voltage on the capacitors may drift over successive cycles, and/or may cause a sizeable redistribution of charge at each state transition, neither of which may be desirable.

An alternative three-state control of the charge pump **110** shown in FIG. 1 uses states labeled “1a”, “1b”, and “2”. The configuration of the switches in these states is shown in tabular form as follows:

State	Switch								
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
State 1a	1	0	0	0	1	0	1	1	0
State 1b	0	0	1	0	0	0	1	1	0
State 2	0	1	0	1	0	1	0	0	1

The equivalent circuits in each of these states are shown in FIGS. 3A – 3C, respectively. Note that in state 1a, a current of $0.5 \cdot I_{OUT}$ passes through each of the capacitors C_1 , C_4 (with opposite voltage polarities), in state 1b, a current of $1.0 \cdot I_{OUT}$ passes through the capacitors C_2 , C_3 , and in state 2, a current of $0.5 \cdot I_{OUT}$ passes through all four capacitors. A suitable selection of state durations times t_{1a} , t_{1b} , t_2 to balance the total change in charge in each cycle must satisfy the set of equations:

$$\begin{aligned}\Delta Q_1 &= 0 = +0.5t_{1a} && -0.5t_2 \\ \Delta Q_2 &= 0 = && -1.0t_{1b} + 0.5t_2 \\ \Delta Q_3 &= 0 = && +1.0t_{1b} - 0.5t_2 \\ \Delta Q_4 &= 0 = -0.5t_{1a} && +0.5t_2\end{aligned}$$

$$T_{SW} = +1.0t_{1a} + 1.0t_{1b} + 1.0t_2$$

where the set of equations are satisfied with

$$\begin{aligned}t_{1a} &= 0.4 \cdot T_{SW} \\ t_{1b} &= 0.2 \cdot T_{SW} \\ t_2 &= 0.4 \cdot T_{SW}\end{aligned}$$

Assuming the state duration times above, FIG. 3D illustrates the voltages $V_1 - V_4$ across the capacitors $C_1 - C_4$ in FIGS. 3A – 3C when the charge pump **110** has an input voltage V_{IN} equal to 25.0 volts. This yields an output voltage V_{OUT} with average voltage of approximately 5.0 volts as shown in the FIG. 3D.

Another three-state approach to controlling the charge pump **110** of FIG. 1 uses a different sequence of states with switch configurations and corresponding equivalent circuits shown in FIGS. 4A – 4C, respectively. The configuration of switches in the three states is shown in tabular form as:

State	Switch								
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
State 1a	1	0	1	0	1	0	1	1	0
State 1b	0	0	1	0	0	0	1	1	0
State 2	0	1	0	1	0	1	0	0	1

An analysis as presented above applied to this definition of the states yields state duration times that satisfy the charge balance equations of

$$t_{1a} = 0.5 * T_{SW}$$

$$t_{1b} = 0.1 * T_{SW}$$

$$t_2 = 0.4 * T_{SW}$$

Assuming the state duration times above, FIG. 4D illustrates the voltages $V_1 - V_4$ across the capacitors $C_1 - C_4$ in FIGS. 4A – 4C when the charge pump **110** has an input voltage V_{IN} equal to 25.0 volts. This yields an output voltage V_{OUT} with average voltage of approximately 5.0 volts as shown in FIG. 4D. Notice how the shape of the waveforms in FIG. 4D differ from those in FIG. 3D.

A consideration of the sum of the RMS (root mean squared) currents through the capacitors shows that these state definitions yield a lower value than that of the previously described three-state configuration (FIGS. 3A – 3C). In a non-ideal implementation of the charge pump **110**, in which resistances including resistances in series with the capacitors cause power loss, a lower RMS current is associated with smaller power loss. Therefore, these state configurations may be preferable.

Note that different sequences of states can still result in charge balance over the repeating cycle. For example, the state sequence 1a-1b-2-1a-1b-2... can be replaced with the sequence 1b-1a-2-1b-1a-2... using the same state duration times as determined above.

Other state definitions and timing also follow the approach outlined above. For instance, two additional approaches for the $M = 5$ case are shown below in tabular form:

State	Switch	Duration
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	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	
State 1a	0	0	1	0	1	0	1	1	0	$0.3 * T_{SW}$
State 1b	1	0	1	0	0	0	1	1	0	$0.3 * T_{SW}$
State 2	0	1	0	1	0	1	0	0	1	$0.4 * T_{SW}$

and

State	Switch									Duration
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	
State 1a	1	0	0	0	0	0	1	X	0	$0.2 * T_{SW}$
State 1b	0	0	0	0	1	0	X	1	0	$0.2 * T_{SW}$
State 1c	0	0	1	0	0	0	1	1	0	$0.2 * T_{SW}$
State 2	0	1	0	1	0	1	0	0	1	$0.4 * T_{SW}$

where X indicates that the switch can either be open or closed.

The multi-state approach presented above for the $M = 5$ circuit of FIG. 1 may be extended directly to other odd values of M . Generally, in state 1a, capacitor C_1 is in parallel with capacitor C_{M-1} , and when $M \geq 5$ in parallel with series connections of C_2 and C_3 , through C_{M-3} and C_{M-2} . State 1b has the parallel connection of the series of C_2 and C_3 , through C_{M-3} and C_{M-2} , and state 2 has the parallel connection of the series C_1 and C_2 through C_{M-2} and C_{M-1} . A closed form of the state duration times for general odd M can then be expressed as

$$t_{1a} = (M + 5) / (4M) * T_{SW}$$

$$t_{1b} = (M - 3) / (4M) * T_{SW}$$

$$t_2 = (M - 1) / (2M) * T_{SW}$$

A similar approach can be applied to situations where M is even. Referring to FIG. 5, a 6:1 ($M = 6$) cascade multiplier type charge pump **110** is shown that includes ten switches labeled S_1 to S_{10} and five capacitors labeled C_1 to C_5 . The configurations for the

switches in each of four states: 1a, 1b, 2a, and 2b, are shown in the table below. The equivalent circuits in each of these states are shown in FIGS. 6A – 6D, respectively.

State	Switch									
	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}
State 1a	1	0	1	0	1	0	0	1	1	0
State 1b	0	0	1	0	1	0	0	1	1	0
State 2a	0	1	0	1	0	1	1	0	0	1
State 2b	0	1	0	1	0	0	1	0	0	1

Applying the type of analysis described above, the state duration times to achieve a balancing of charge transfer through the cycle of states yields:

$$t_{1a} = 1/3 * T_{SW}$$

$$t_{1b} = 1/6 * T_{SW}$$

$$t_{2a} = 1/3 * T_{SW}$$

$$t_{2b} = 1/6 * T_{SW}$$

As with M being an odd case, a general solution for arbitrary M being even yields the solution:

$$t_{1a} = (M - 2) / (2M) * T_{SW}$$

$$t_{1b} = 1 / M * T_{SW}$$

$$t_{2a} = (M - 2) / (2M) * T_{SW}$$

$$t_{2b} = 1 / M * T_{SW}$$

The approach described above is applicable to multi-phase charge pumps as well. For example, FIG. 7 shows a two-phase $M = 5$ cascade multiplier type charge pump **110** that includes fourteen switches labeled S_{1a} to S_{7b} and eight capacitors labeled C_{1a} to C_{4b} . The configurations for the switches in one possible four-state approach (with states labeled 1a, 1b, 2a, 2b) are shown in the table below:

State	Switch													
	S_{1a}	S_{1b}	S_{2a}	S_{2b}	S_{3a}	S_{3b}	S_{4a}	S_{4b}	S_{5a}	S_{5b}	S_{6a}	S_{6b}	S_{7a}	S_{7b}
State 1a	1	0	0	1	0	1	0	1	0	0	0	1	1	0
State 1b	0	0	0	1	0	1	0	1	0	1	0	1	1	0
State 2a	0	1	1	0	1	0	1	0	0	0	1	0	0	1
State 2b	0	0	1	0	1	0	1	0	1	0	1	0	0	1

FIGS. 8A – 8B show the equivalent circuits for states 1a and 1b, respectively. The circuits for states 2a and 2b are equivalent (i.e., interchanging the “a” and “b” elements of the circuit). Applying the charge balance constraints for this circuit yields the state duration times of $0.25 * T_{SW}$ for each of the four states as shown below:

$$t_{1a} = t_{2a} = 0.25 * T_{SW}$$

$$t_{1b} = t_{2b} = 0.25 * T_{SW}$$

Note that in this example, the input current from the V_{IN} terminal is zero during states 1b and 2b while non-zero during states 1a and 2a at a current of $0.4 * I_{OUT}$, yielding an average input current of $0.2 * \bar{I}_{OUT} = \bar{I}_{OUT} / M$ as expected.

Referring to FIG. 7, a parallel arrangement of two sections as shown in FIG. 1; the timing of each section is 90° out of phase, such that one section has the switch configuration of state 1a while the other section has the switch configuration of state 1b, and so forth. Note that in this parallel arrangement, the average input current is $0.2 * \bar{I}_{OUT} = \bar{I}_{OUT} / M$ in each cycle of operation.

The approaches described above are applicable to a wide range of charge pump topologies. As a further example, an FIG. 9 shows a $M = 3$ two-phase series-parallel charge pump **110** that includes fourteen switches labeled S_{1a} to S_{7b} and four capacitors labeled C_{1a} to C_{2b} . The configuration of switches in the four states is shown in tabular form as:

State	Switch													
	S_{1a}	S_{1b}	S_{2a}	S_{2b}	S_{3a}	S_{3b}	S_{4a}	S_{4b}	S_{5a}	S_{5b}	S_{6a}	S_{6b}	S_{7a}	S_{7b}
State 1a	1	0	1	0	1	0	0	1	0	1	0	0	0	0
State 1b	1	0	1	0	1	0	0	0	0	0	0	1	0	1
State 2a	0	1	0	1	0	1	1	0	1	0	0	0	0	0
State 2b	0	1	0	1	0	1	0	0	0	0	1	0	1	0

Equivalent circuits for the four states are shown in FIGS. 10A – 10D. Charge balance is achieved with a state duration time of $0.25 \cdot T_{SW}$ for each state, yielding an average input current from V_{IN} in each state and cycle of $(1/3) \cdot \bar{I}_{OUT}$.

In the analysis above, the average current $\bar{I}_{OUT}$ is assumed to be the same during all state duration times, therefore, the charge transfers are proportional to $t_j \cdot \bar{I}_{OUT}$. In an alternative approach, the average output current may be controlled to be different for different states so that the charge transfers in state j are proportional to $t_j \cdot \bar{I}_{OUT,j}$ where both the state duration time t_j and the average current $\bar{I}_{OUT,j}$ are determined according to the constraint equations. In some examples, the state duration times may be further (fully or partially) constrained for other considerations, for example, to avoid short state duration times which might cause EMI (electro-magnetic interference). An example, where such variable and periodic control of output current may be effective is when driving one or more LEDs (light emitting diode) in series or in parallel, where the variation in current does not appreciably cause perceptible variation in light output.

The approach described above can be applied to the two-phase $M = 5$ cascade multiplier type charge pump **110** of FIG. 7. One possible four-state approach (with states labeled 1a, 1b, 2a, 2b) has equivalent circuits as shown in FIGS. 11A – 11B for states 1a and 1b, respectively. The circuits for states 2a and 2b are equivalent (i.e. interchanging the “a” and “b” elements of the circuit). The configuration of switches in the four states is shown in tabular form as:

State	Switch													
	S_{1a}	S_{1b}	S_{2a}	S_{2b}	S_{3a}	S_{3b}	S_{4a}	S_{4b}	S_{5a}	S_{5b}	S_{6a}	S_{6b}	S_{7a}	S_{7b}
State 1a	1	0	0	0	0	0	0	0	0	1	0	1	1	0
State 1b	0	0	0	1	0	1	0	1	0	0	0	1	1	0
State 2a	0	1	0	0	0	0	0	0	1	0	1	0	0	1
State 2b	0	0	1	0	1	0	1	0	0	0	1	0	0	1

With state duration times of $0.25 \cdot T_{SW}$ for each of the four states, it becomes necessary to apply a current skew, I_{SKEW} , to the output load in each state to achieve charge balance over a cycle of the four states. In this example, a negative current skew of $0.2 \cdot I_{OUT}$ during states 1a and 2a, and a positive current skew of $0.2 \cdot I_{OUT}$ during states 1b and 2b will achieve charge balance in all capacitors over a cycle, where the average output current across each cycle of four states is I_{OUT} . In other words, the output load current during states 1a and 2a is $0.8 \cdot I_{OUT}$ and the output load current during states 1b and 2b is $1.2 \cdot I_{OUT}$. The magnitude of the applied current skew is the same in all four states, but the polarity of the current skew changes back and forth between positive and negative from one state to the next. For a two-phase charge pump with this four-state approach and $0.25 \cdot T_{SW}$ state duration times, a general solution for arbitrary M yields the following solution for the magnitude of the applied current skew, I_{SKEW} :

$$I_{SKEW} = \left| \frac{4 - M}{M} \right| I_{OUT}$$

It should be understood that the description above focuses on analysis of idealized circuits with ideal switches, ideal current, voltage sources, and resistance-free circuit paths. In practice, switches are implemented, for instance, with transistors, which generally exhibit internal resistance and capacitive characteristics. The output current load may be implemented using an inductor such that during the part of the duty cycle modeled as a constant current, the current in fact fluctuates as energy is transferred from the charge pump to the inductor. Physical capacitors may have slightly different capacitances, and therefore the ideal analysis for charge balancing may not be exactly correct. Nevertheless, the approach presented above is applicable to non-ideal implementations of the approach, either exactly, or accounting for the non-ideal nature of

the circuit for example, determining the state durations to achieve charge balance in a real rather than an ideal circuit, for example, using numerical circuit simulation techniques.

Implementations of a charge pump controlled according to one or more of the approaches described above may use a controller that is configured to follow a state sequence as described and to set the switches accordingly. Referring to FIG. 12, an example of a power converter **100** includes a charge pump **110** coupled to a controller **120** providing control signals on path **132** and receiving sensor signals on path **134**. The charge pump **110** includes capacitors **112** and switches **114**. A terminal **116** (e.g., a high voltage terminal) couples the charge pump **110** to a power source **150**, for example, to a voltage source (e.g., at 25 volts). Another terminal **118** couples the charge pump **110** to a first regulator circuit **130**, which is coupled to a load **140**. A controller **120** includes a programmable processor **122** configured with configuration data **124** (and/or processor instructions), which impart functionality on the controller **120**.

In some examples, the controller **120** also controls the first regulator circuit **130**, for example, to maintain a common underlying clocking rate for both the charge pump **110** and the first regulator circuit **130** (e.g., switching the first regulator circuit **130** at a multiple 2x, 4x, 10x, 100x, etc. of the cycle frequency of the charge pump **110**). In some implementations, the controller **120** is integrated in whole or in part in an integrated device that includes at least some of the switches **114** (e.g., transistors).

An alternative power converter **101** is illustrated in FIG. 13, where a second regulator circuit **160** is coupled between the power source **150** and the charge pump **110** instead of between the load **140** and the charge pump **110** as in FIG. 12. In some examples, the controller **120** controls the load **140** to facilitate charge balancing of the capacitors **112** within the charge pump **110**. In other examples, the controller **120** controls the second regulator circuit **160** and in even other examples, the controller **120** controls both the load **140** and the second regulator circuit **160**.

One more alternative power converter **102** is illustrated in FIG. 14. This example is a combination of the power converters **100**, **101**. In this implementation, there is a first regulator circuit **130** coupled between the load **140** and the charge pump **110**; and a

second regulator circuit **160** coupled between the power source **150** and the charge pump **110**. In some examples the controller **120** controls at least the first regulator circuit **130** or the second regulator circuit **160**, to maintain a common underlying clocking.

In other examples, either the first regulator circuit **130** or the second regulator circuit **160** is a magnetic filter, such as an LC filter, instead of a converter. If the first regulator circuit **130** is a magnetic filter, then the regulation capability of the power converter **102** is only accomplished by the second regulator circuit **160** and adiabatic operation is in part possible due to the first regulator circuit **130** acting as a current load. Similarly, if the second regulator circuit **160** is a magnetic filter, then the regulation capability of the power converter **102** is only accomplished by the first regulator circuit **130** and adiabatic operation is in part possible due to the second regulator circuit **160** acting as a current source.

It should be understood that in practice, the devices are not ideal, for example, with the capacitors **112** not necessarily having identical capacitances, and with non-zero resistances in circuit paths and through the switches **114** in the charge pump **110**. In some examples, the controller **120** controls the switches **114** according to the idealized analysis. In other examples, the effect of non-idealized characteristics are taken into account in determining the state durations, for example, by explicit circuit analysis (e.g., simulation) or adaptively by adjusting the relative state durations to achieve charge balance during state cycles based upon sensor signals on path **134**. In some examples, the controller **120** is software configurable, for example, allowing specific state timing to be configured after the device is fabricated. In some examples, the controller **120** is fully or at least partially implemented in application-specific logic that is specified with the other circuit components of the device.

The charge pump **110** can be implemented using many different charge pump topologies such as Ladder, Dickson, Series-Parallel, Fibonacci, and Doubler. Similarly, suitable converters for the regulator circuits **130**, **160** include Buck converters, Boost converters, Buck-Boost converters, non-inverting Buck-Boost converters, Cuk converters, SEPIC converters, resonant converters, multi-level converters, Flyback converters, Forward converters, and Full Bridge converters.

It is to be understood that the foregoing description is intended to illustrate and not to limit the scope of the invention, which is defined by the scope of the appended claims. Other embodiments are within the scope of the following claims.

CLAIMS

1. An apparatus for coupling to capacitors to form a charge pump circuit, said apparatus comprising: a first set of switch elements, a second set of switch elements, and a controller circuit, wherein the first set of switch elements comprises switch elements that are configured to couple terminals of capacitor elements to permit charge transfer between the capacitors, wherein the second set of switch elements comprises switch elements that are configured to couple terminals of at least some of the capacitor elements to a first terminal, wherein the first terminal is selected from the group consisting of a high voltage terminal and a low voltage terminal, wherein the controller circuit is coupled to the switch elements and configured to cycle the switch elements through a sequence of states, wherein each state defines a corresponding configuration of the switch elements, wherein at least three of the states define different configurations of the switch elements permitting charge transfer between a pair of elements, wherein the pair of elements is selected from the group consisting of a first capacitor and a second capacitor, and a first capacitor and the first terminal, and wherein the configured cycle of states provides a voltage conversion between the high voltage terminal and the low voltage terminal.
2. The apparatus of claim 1, further comprising terminals for coupling switch elements to the capacitors.
3. The apparatus of claim 1 or 2 further comprising the capacitors, wherein the capacitors, when coupled to the switch elements, define a charge pump circuit.
4. The apparatus of claim 1, 2, or 3 further comprising an integrated circuit, wherein at least part of the charge pump circuit and at least part of the controller circuit are formed in a single integrated circuit.
5. The apparatus of any of the preceding claims, further comprising a regulator circuit, wherein the regulator circuit is coupled to at least one of the high voltage terminal and the low voltage terminal of the charge pump circuit.

6. The apparatus of claim 5, wherein the regulator circuit is configured to provide a current load at the low voltage terminal of the charge pump circuit.
7. The apparatus of claim 5, wherein the regulator circuit is configured to operate as a current source at the low voltage terminal of the charge pump circuit.
8. The apparatus of claim 5, wherein the regulator circuit is configured to provide a current load at the high voltage terminal of the charge pump circuit.
9. The apparatus of claim 5, wherein the regulator circuit is configured to operate as a current source at the high voltage terminal of the charge pump circuit.
10. The apparatus of claim 5, wherein the regulator circuit is configured to cause a pulsed current to pass between the regulator circuit and the charge pump circuit.
11. The apparatus of claim 10, wherein charge pump operates in a pulse cycle having a first fraction and a second fraction, wherein the pulsed current comprises a first constant current during the first fraction and a second constant current in the second fraction, wherein the first constant current is greater in magnitude than the second constant current.
12. The apparatus of any of the preceding claims, further comprising a regulator circuit, wherein the regulator circuit is configured to control an average current passing between the regulator circuit and the charge pump circuit.
13. The apparatus of any of claims 5-12, wherein the regulator is a switch-mode power converter.
14. The apparatus of any of claims 5-12, wherein the regulator is a buck converter.
15. The apparatus of claim any of the preceding claims, wherein the controller is configured to maintain each state for a corresponding duration of a fraction of a charge pump cycle time, wherein the durations of the states are selected to maintain a balanced charging and discharging of each of the capacitors through the sequence of states of each cycle.

16. The apparatus of any of the preceding claims, wherein the controller is configured to select durations of the states to reduce redistribution of charge among the capacitors upon state transitions.
17. The apparatus of any of the preceding claims, wherein the switch elements when coupled to the terminals of the capacitor elements, define the charge pump circuit.
18. The apparatus of claim 17, wherein the charge pump circuit comprises a multi-phase charge pump.
19. The apparatus of claim 17, wherein the charge pump circuit comprises a single-phase charge pump.
20. The apparatus of claim 17, wherein the charge-pump circuit comprises a cascade multiplier.
21. The apparatus of any of the preceding claims, wherein the controller is configured to receive sensor signals from at least one of the first and second sets of switch elements and to adaptively adjust cycling of the switch elements through the sequence of states based at least in part on the sensor signals.
22. The apparatus of claim 1, further comprising a first regulator circuit and a second regulator circuit, wherein the regulator circuit is coupled to the high voltage terminal of the charge pump circuit and wherein the second regulator circuit is coupled to the low voltage terminal of the charge pump circuit.
23. The apparatus of claim 22, wherein the controller is configured to receive sensor signals from at least one of the first and second sets of switch elements and to adaptively adjust cycling of the switch elements through the sequence of states based at least in part on the sensor signals.
24. The apparatus of claim 22, wherein the first regulator circuit comprises a magnetic filter.

25. The apparatus of claim 22, wherein the second regulator circuit comprises a magnetic filter.
26. The apparatus of claim 17, wherein the charge-pump circuit comprises a multi-stage charge pump.
27. A method for operating a charge pump in which switch elements from a first set of switch elements are configured to couple terminals of capacitor elements to permit charge transfer between the capacitors, and in which switch elements from a second set of switch elements are configured to couple terminals of capacitor elements to a first terminal selected from the group consisting of a high voltage terminal and a low voltage terminal, the method comprising causing a voltage conversion between the high voltage terminal and the low voltage terminal, wherein causing the voltage conversion comprises cycling the switch elements through a sequence of states, each state defining a corresponding configuration of the switch elements, at least three of the states defining different configurations of the switch elements permitting charge transfer between a pair of elements, wherein the pair of elements is selected from the group consisting of a first capacitor and a second capacitor, and a first capacitor and the first terminal.
28. The method of claim 27, further comprising maintaining an average current passing between a regulator circuit and the charge pump circuit.
29. The method of any of the preceding claims, further comprising regulating a current at the first terminal, thereby maintaining an average current passing between a regulator circuit and the charge pump circuit.
30. The method of any of the preceding claims, wherein cycling the switch elements through a sequence of states includes maintaining each state for a corresponding duration of a fraction of a charge pump cycle time.
31. The method of any of the preceding claims, wherein the durations of the states are selected to maintain a balanced charging and discharging of each of the plurality of capacitors through the sequence of states of each cycle.

32. The method of any of the preceding claims, further comprising controlling an average current between a regulator circuit and the charge pump circuit.
33. The method of any of the preceding claims, further comprising coupling a regulator circuit to the first terminal.
34. The method of claim 33, further comprising causing the regulator circuit to provide a current load at the low voltage terminal of the charge pump circuit.
35. The method of claim 33, further comprising causing the regulator circuit to provide a current load at the high voltage terminal of the charge pump circuit.
36. The method of claim 33, further comprising causing the regulator circuit to operate as a current source at the low voltage terminal of the charge pump circuit.
37. The method of claim 33, further comprising causing the regulator circuit to operate as a current source at the high voltage terminal of the charge pump circuit.
38. The method of claims 33-37, further comprising causing a pulsed current to pass between a regulator circuit and the charge pump circuit.
39. The method of any of the preceding claims, further comprising coupling the switch elements from the first and second sets of switch elements to the terminals of the capacitor elements.
40. The method of claim 39, wherein coupling the switch elements comprises forming a multi-phase charge pump.
41. The method of claim 39, wherein coupling the switch elements comprises forming a single-phase charge pump.
42. The method of claim 39, wherein coupling the switch elements comprises forming a multi-stage charge pump.
43. The method of claim 39, wherein coupling the switch elements comprises forming a cascade multiplier.

44. The method of any of the preceding claims, further comprising selecting the regulator to be a switch-mode power converter.
45. The method of any of the preceding claims, further comprising selecting the regulator to be a buck converter.
46. The method of any of the preceding claims, further comprising receiving sensor signals from at least one of the first and second sets of switch elements and adaptively adjusting the cycling of the switch elements through the sequence of states based at least in part on the sensor signals.
47. The method of claim 27, further comprising coupling a first regulator to the high voltage terminal, and coupling a second regulator to the low voltage terminal.
48. The method of claim 47, further comprising selecting said second regulator to be a magnetic filter and selecting said first regulator to be a converter.
49. The method of claim 47, further comprising selecting said first regulator to be a magnetic filter and selecting said second regulator to be a converter.
50. The method of claim 47, further comprising controlling least one of the first and second sets of switch elements and adaptively adjusting the cycling of the switch elements through the sequence of states based at least in part on sensor signals received from at least one of said first and second sets of switch elements.

AMENDED CLAIMS**received by the International Bureau on 18 August 2015 (18.08.2015)**

1. An apparatus for coupling to capacitors to form a charge pump circuit, said apparatus comprising: a first set of switch elements, a second set of switch elements, and a controller circuit, wherein the first set of switch elements comprises switch elements that are configured to couple terminals of capacitor elements to permit charge transfer between the capacitors, wherein the second set of switch elements comprises switch elements that are configured to couple terminals of at least some of the capacitor elements to a first terminal, wherein the first terminal is selected from the group consisting of a high-voltage terminal and a low-voltage terminal, wherein the controller circuit is coupled to the switch elements and configured to cycle the switch elements through a sequence of states, wherein each state defines a corresponding configuration of the switch elements, wherein at least three of the states define different configurations of the switch elements permitting charge transfer between a pair of elements, wherein the pair of elements is selected from the group consisting of a first capacitor and a second capacitor, and a first capacitor and the first terminal, and wherein the configured cycle of states provides a voltage conversion between the high-voltage terminal and the low-voltage terminal.
2. The apparatus of claim 1, further comprising terminals for coupling switch elements to the capacitors.
3. The apparatus of claim 1, further comprising the capacitors, wherein the capacitors, when coupled to the switch elements, define a charge pump circuit.

4. The apparatus of claim 1, further comprising an integrated circuit, wherein at least part of the charge pump circuit and at least part of the controller circuit are formed in a single integrated circuit.
5. The apparatus of claim 1, further comprising a regulator circuit, wherein the regulator circuit is coupled to at least one of the high-voltage terminal and the low-voltage terminal of the charge pump circuit.
6. The apparatus of claim 5, wherein the regulator circuit is configured to provide a current load at the low-voltage terminal of the charge pump circuit.
7. The apparatus of claim 5, wherein the regulator circuit is configured to operate as a current source at the low-voltage terminal of the charge pump circuit.
8. The apparatus of claim 5, wherein the regulator circuit is configured to provide a current load at the high-voltage terminal of the charge pump circuit.
9. The apparatus of claim 5, wherein the regulator circuit is configured to operate as a current source at the high-voltage terminal of the charge pump circuit.
10. The apparatus of claim 5, wherein the regulator circuit is configured to cause a pulsed current to pass between the regulator circuit and the charge pump circuit.
11. The apparatus of claim 10, wherein charge pump operates in a pulse cycle having a first fraction and a second fraction, wherein the pulsed current comprises a first constant current during the first fraction and a second

constant current during the second fraction, wherein the first constant current is greater in magnitude than the second constant current.

12. The apparatus of claim 1, further comprising a regulator circuit, wherein the regulator circuit is configured to control an average current passing between the regulator circuit and the charge pump circuit.
13. The apparatus of any of claims 12, wherein the regulator circuit is a switch-mode power converter.
14. The apparatus of any of claims 12, wherein the regulator circuit is a buck converter.
15. The apparatus of claim 1, wherein the controller circuit is configured to maintain each state for a corresponding duration of a fraction of a charge pump cycle time, wherein the durations of the states are selected to maintain a balanced charging and discharging of each of the capacitors through the sequence of states of each cycle.
16. The apparatus of claim 1, wherein the controller circuit is configured to select durations of the states to reduce redistribution of charge among the capacitors upon state transitions.
17. The apparatus of claim 1, wherein the switch elements when coupled to the terminals of the capacitor elements, define the charge pump circuit.
18. The apparatus of claim 17, wherein the charge pump circuit comprises a multi-phase charge pump.

19. The apparatus of claim 17, wherein the charge pump circuit comprises a single-phase charge pump.
20. The apparatus of claim 17, wherein the charge-pump circuit comprises a cascade multiplier.
21. The apparatus of claim 1, wherein the controller circuit is configured to receive sensor signals from at least one of the first and second sets of switch elements and to adaptively adjust cycling of the switch elements through the sequence of states based at least in part on the sensor signals.
22. The apparatus of claim 1, further comprising a first regulator circuit and a second regulator circuit, wherein the first regulator circuit is coupled to the high-voltage terminal of the charge pump circuit, and wherein the second regulator circuit is coupled to the low-voltage terminal of the charge pump circuit.
23. The apparatus of claim 22, wherein the controller circuit is configured to receive sensor signals from at least one of the first and second sets of switch elements and to adaptively adjust cycling of the switch elements through the sequence of states based at least in part on the sensor signals.
24. The apparatus of claim 22, wherein the first regulator circuit comprises a magnetic filter.
25. The apparatus of claim 22, wherein the second regulator circuit comprises a magnetic filter.

26. The apparatus of claim 17, wherein the charge-pump circuit comprises a multi-stage charge pump.
27. A method for operating a charge pump in which switch elements from a first set of switch elements are configured to couple terminals of capacitor elements to permit charge transfer between the capacitors, and in which switch elements from a second set of switch elements are configured to couple terminals of capacitor elements to a first terminal selected from the group consisting of a high-voltage terminal and a low-voltage terminal, the method comprising causing a voltage conversion between the high-voltage terminal and the low-voltage terminal, wherein causing the voltage conversion comprises cycling the switch elements through a sequence of states, each state defining a corresponding configuration of the switch elements, at least three of the states defining different configurations of the switch elements permitting charge transfer between a pair of elements, wherein the pair of elements is selected from the group consisting of a first capacitor and a second capacitor, and a first capacitor and the first terminal.
28. The method of claim 27, further comprising maintaining an average current passing between a regulator circuit and the charge pump circuit.
29. The method of claim 27, further comprising regulating a current at the first terminal, thereby maintaining an average current passing between a regulator circuit and the charge pump circuit.
30. The method of claim 27, wherein cycling the switch elements through a sequence of states includes maintaining each

state for a corresponding duration of a fraction of a charge pump cycle time.

31. The method of claim 30, wherein the durations of the states are selected to maintain a balanced charging and discharging of each of the plurality of capacitors through the sequence of states of each cycle.
32. The method of claim 27, further comprising controlling an average current between a regulator circuit and the charge pump circuit.
33. The method of claim 27, further comprising coupling a regulator circuit to the first terminal.
34. The method of claim 33, further comprising causing the regulator circuit to provide a current load at the low-voltage terminal of the charge pump circuit.
35. The method of claim 33, further comprising causing the regulator circuit to provide a current load at the high-voltage terminal of the charge pump circuit.
36. The method of claim 33, further comprising causing the regulator circuit to operate as a current source at the low-voltage terminal of the charge pump circuit.
37. The method of claim 33, further comprising causing the regulator circuit to operate as a current source at the high-voltage terminal of the charge pump circuit.
38. The method of claims 33, further comprising causing a pulsed current to pass between the regulator circuit and the charge pump circuit.

39. The method of claim 27, further comprising coupling the switch elements from the first and second sets of switch elements to the terminals of the capacitor elements.
40. The method of claim 39, wherein coupling the switch elements comprises forming a multi-phase charge pump.
41. The method of claim 39, wherein coupling the switch elements comprises forming a single-phase charge pump.
42. The method of claim 39, wherein coupling the switch elements comprises forming a multi-stage charge pump.
43. The method of claim 39, wherein coupling the switch elements comprises forming a cascade multiplier.
44. The method of claim 29, further comprising selecting the regulator circuit to be a switch-mode power converter.
45. The method of claim 29, further comprising selecting the regulator circuit to be a buck converter.
46. The method of claim 27, further comprising receiving sensor signals from at least one of the first and second sets of switch elements and adaptively adjusting the cycling of the switch elements through the sequence of states based at least in part on the sensor signals.
47. The method of claim 27, further comprising coupling a first regulator to the high-voltage terminal, and coupling a second regulator to the low-voltage terminal.
48. The method of claim 47, further comprising selecting said second regulator to be a magnetic filter and selecting said first regulator to be a converter.

49. The method of claim 47, further comprising selecting said first regulator to be a magnetic filter and selecting said second regulator to be a converter.
50. The method of claim 27, further comprising controlling least one of the first and second sets of switch elements and adaptively adjusting the cycling of the switch elements through the sequence of states based at least in part on sensor signals received from at least one of said first and second sets of switch elements.

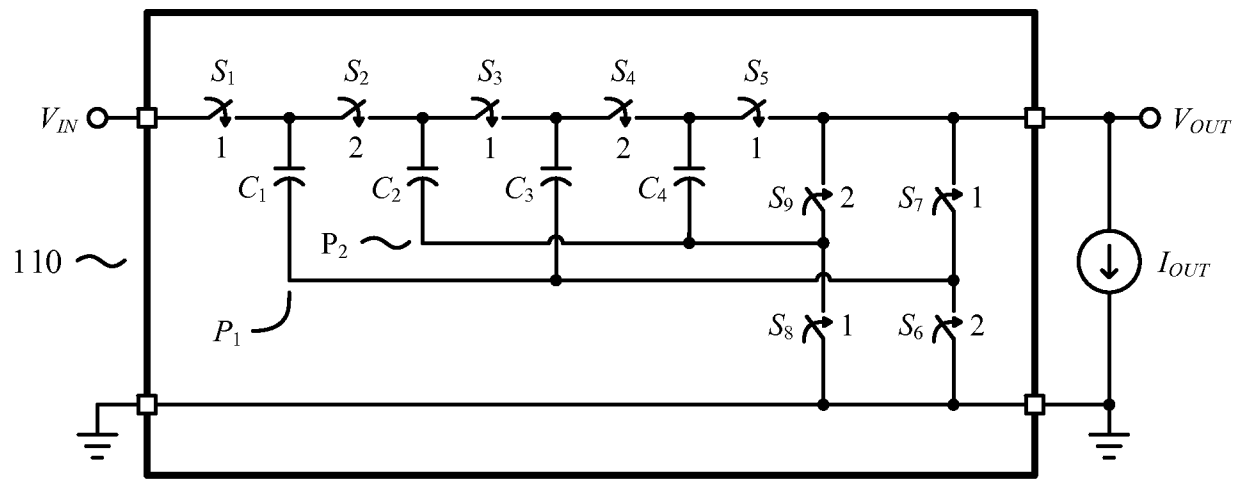


FIG. 1

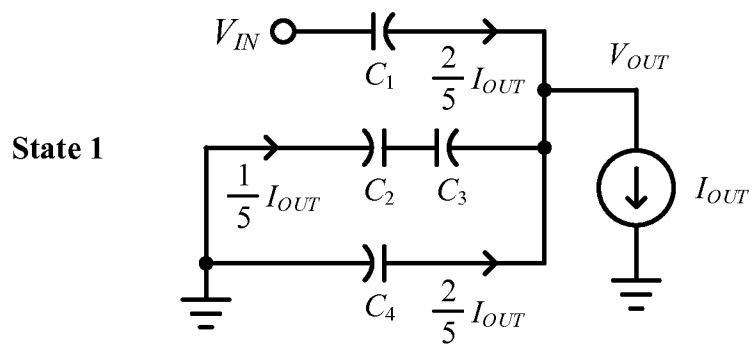


FIG. 2A

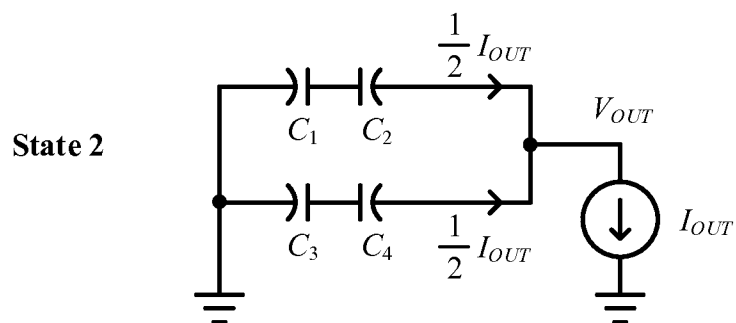


FIG. 2B

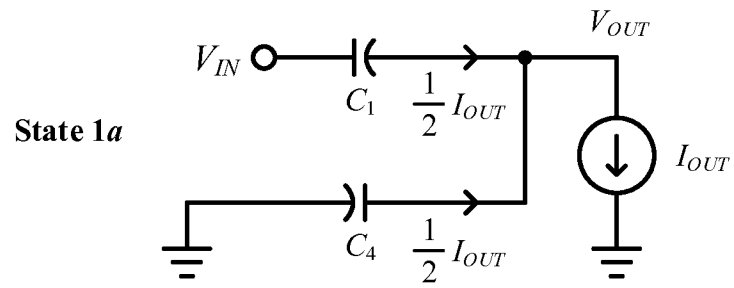


FIG. 3A

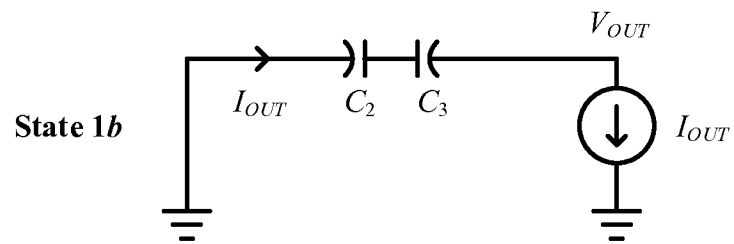


FIG. 3B

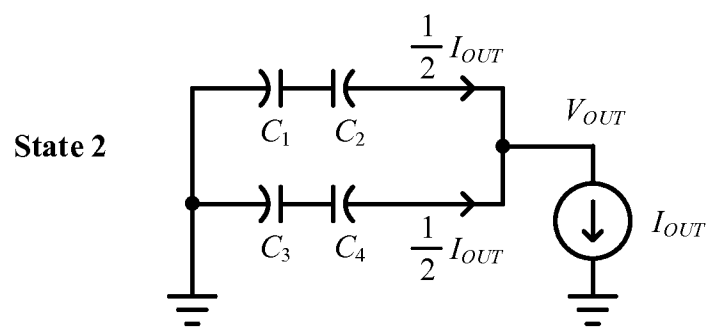


FIG. 3C

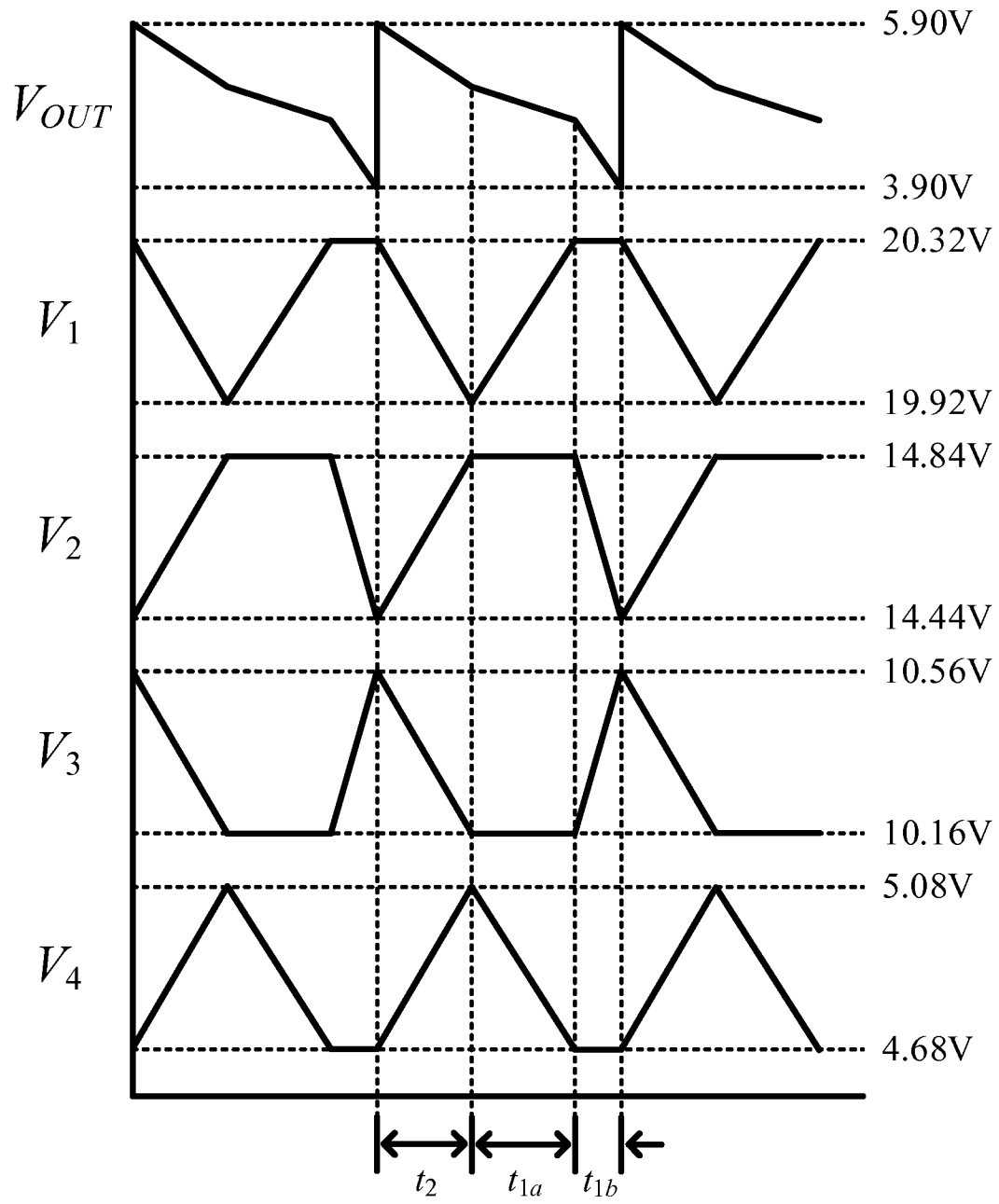


FIG. 3D

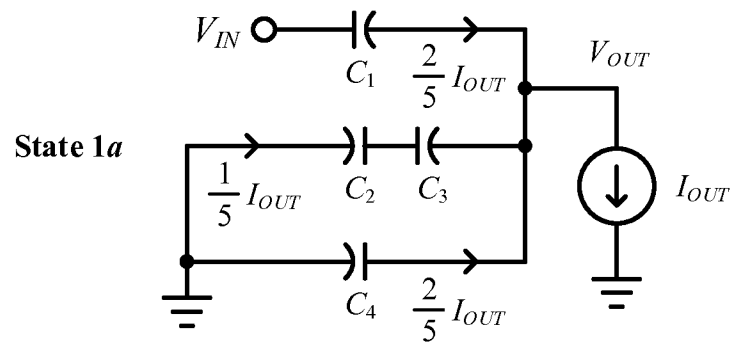


FIG. 4A

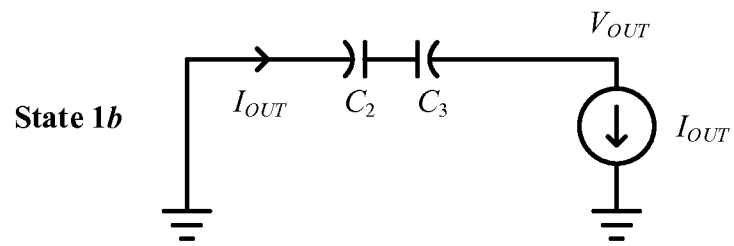


FIG. 4B

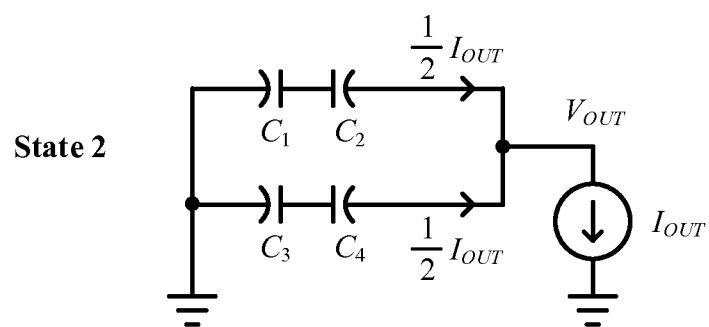


FIG. 4C

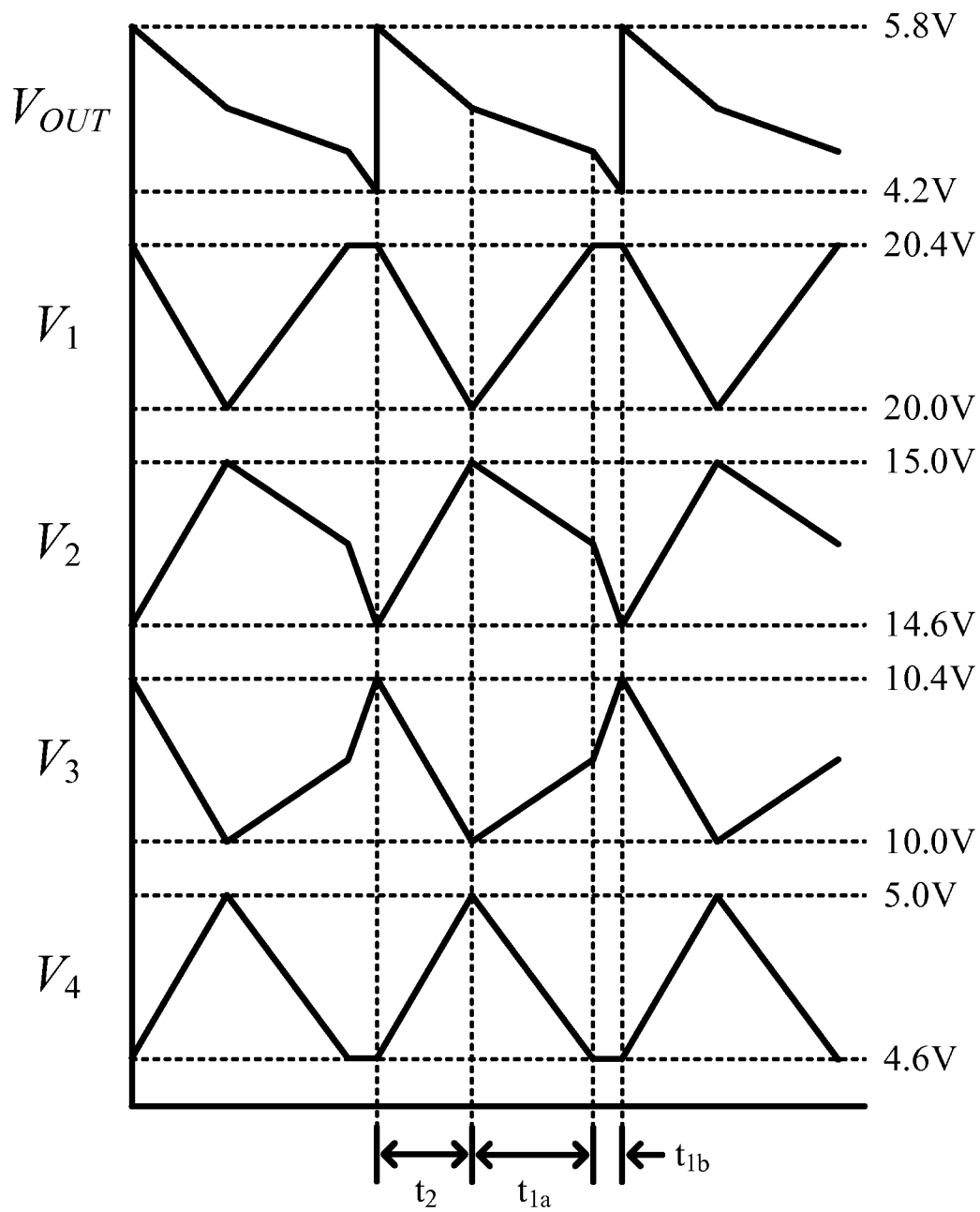


FIG. 4D

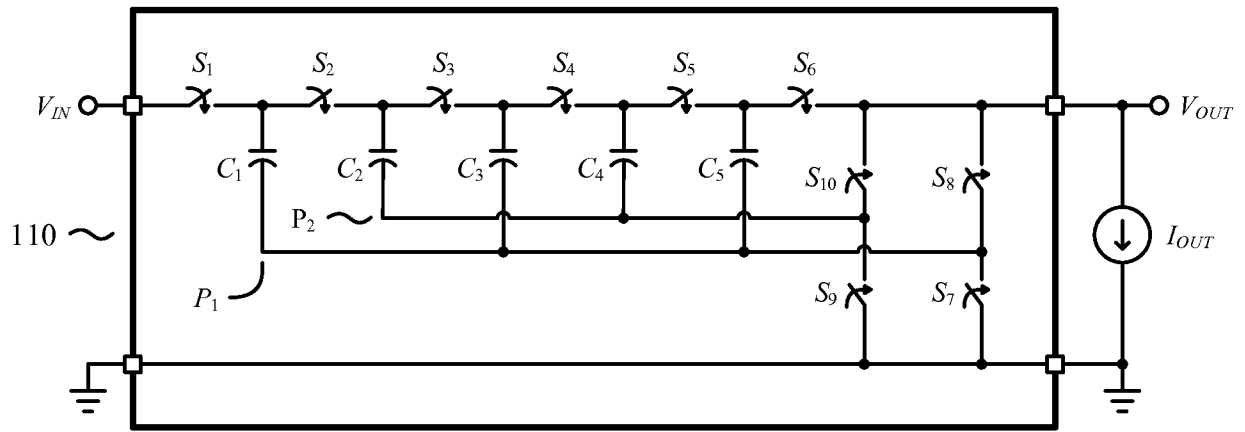


FIG. 5

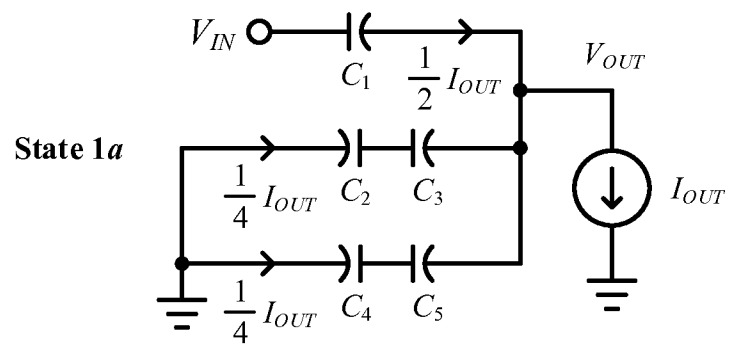


FIG. 6A

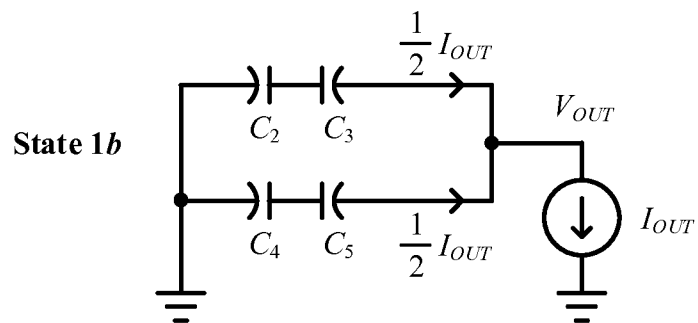


FIG. 6B

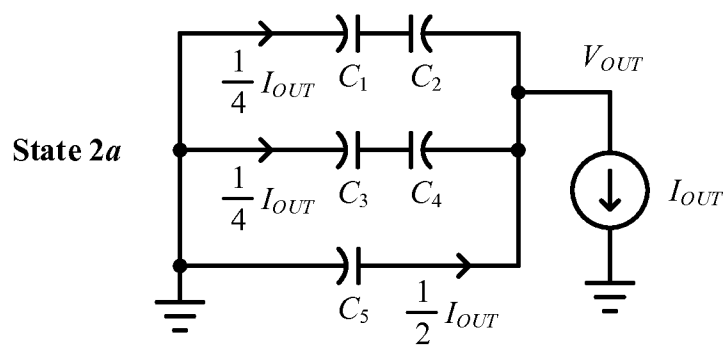


FIG. 6C

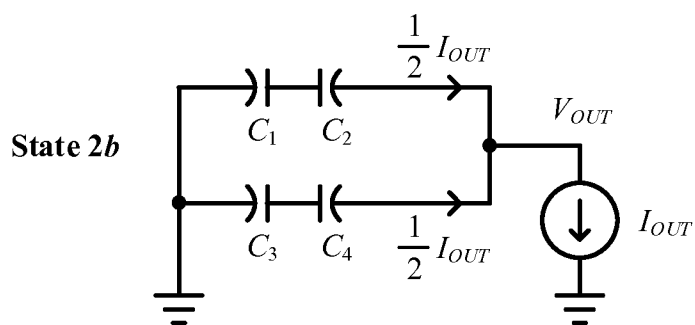


FIG. 6D

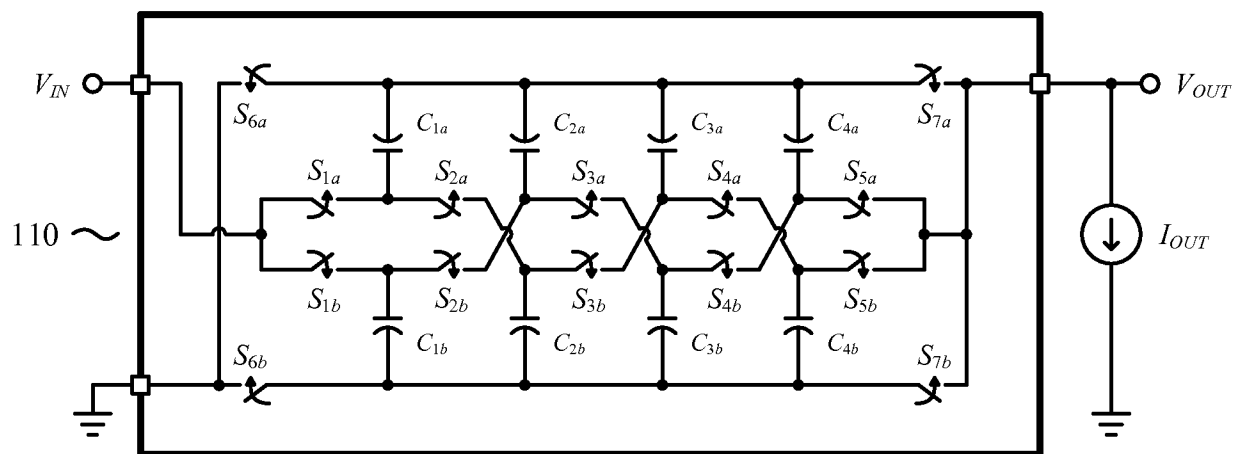


FIG. 7

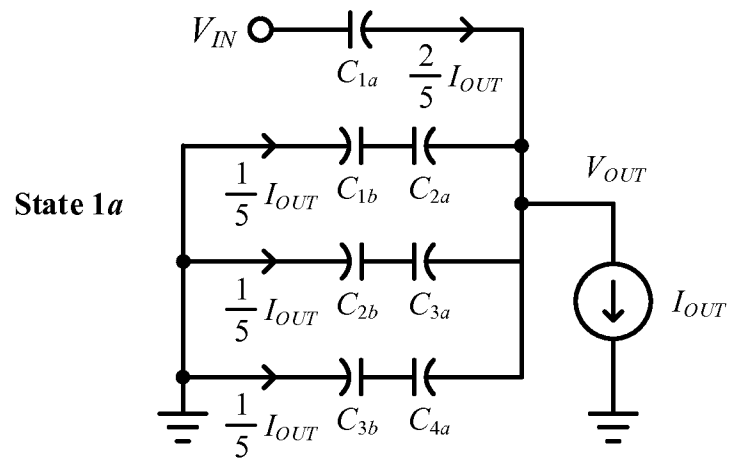


FIG. 8A

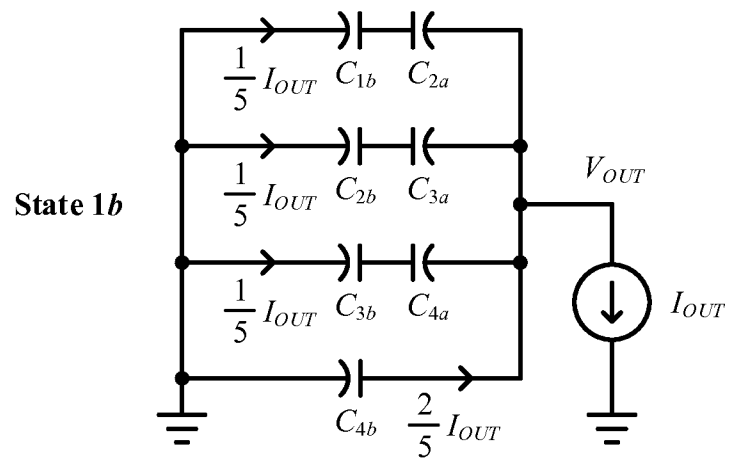


FIG. 8B

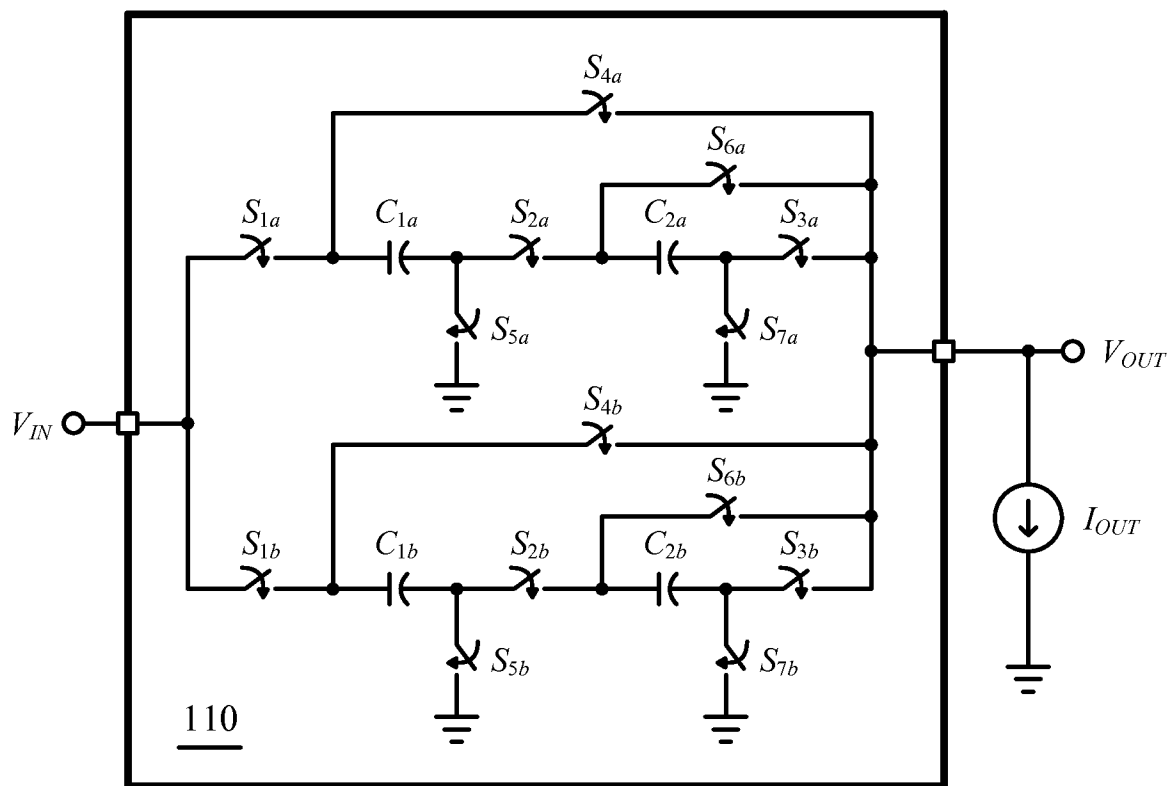


FIG. 9

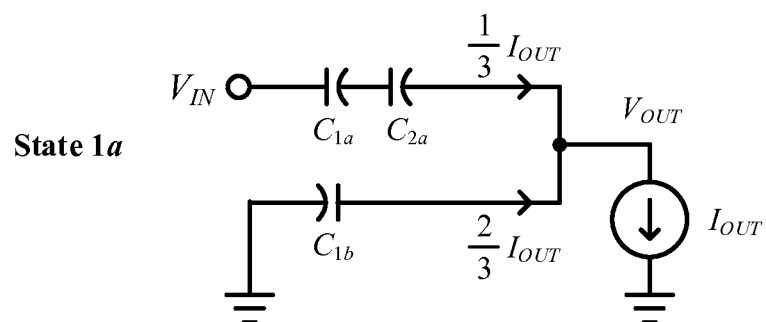


FIG. 10A

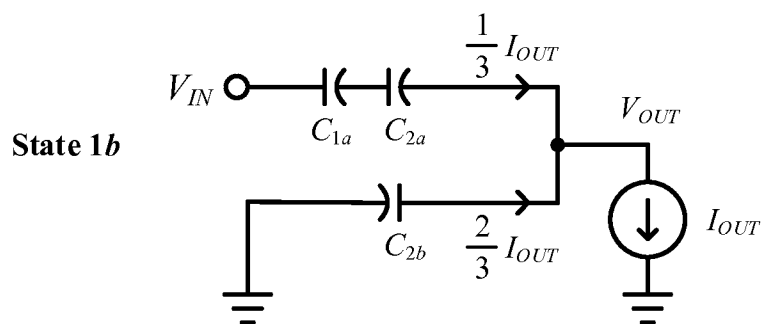


FIG. 10B

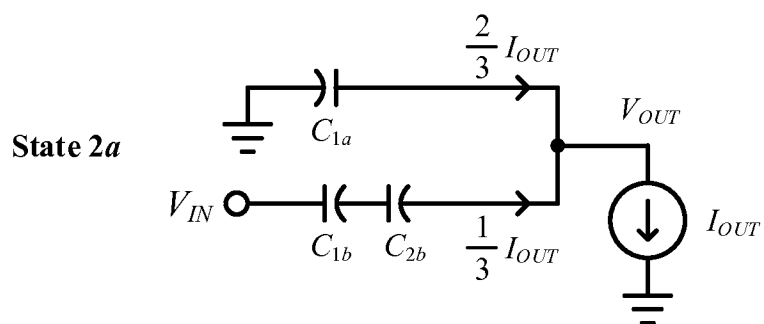


FIG. 10C

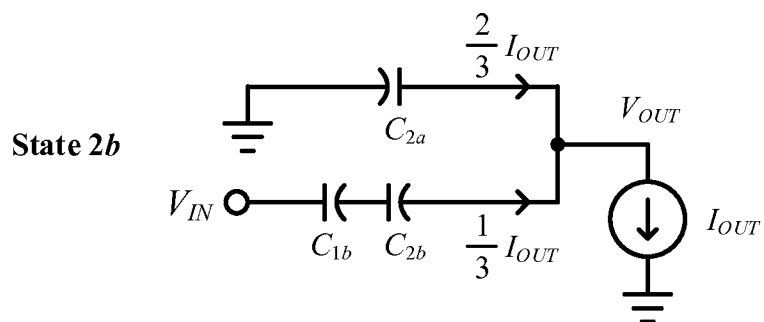


FIG. 10D

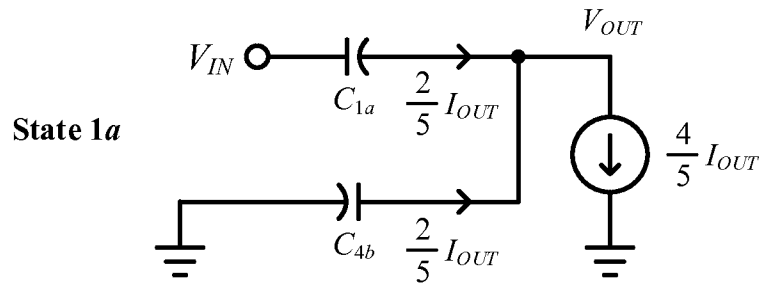


FIG. 11A

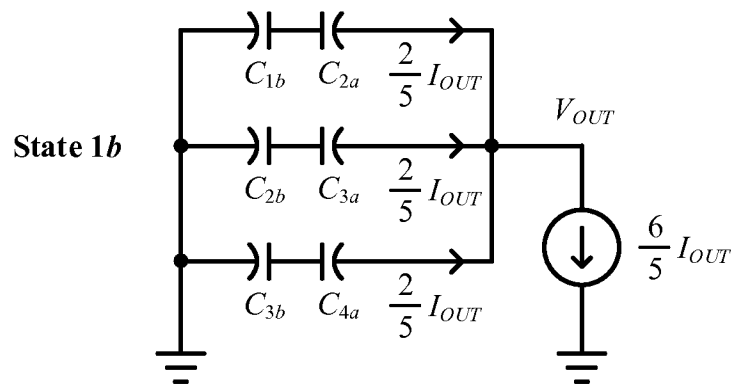


FIG. 11B

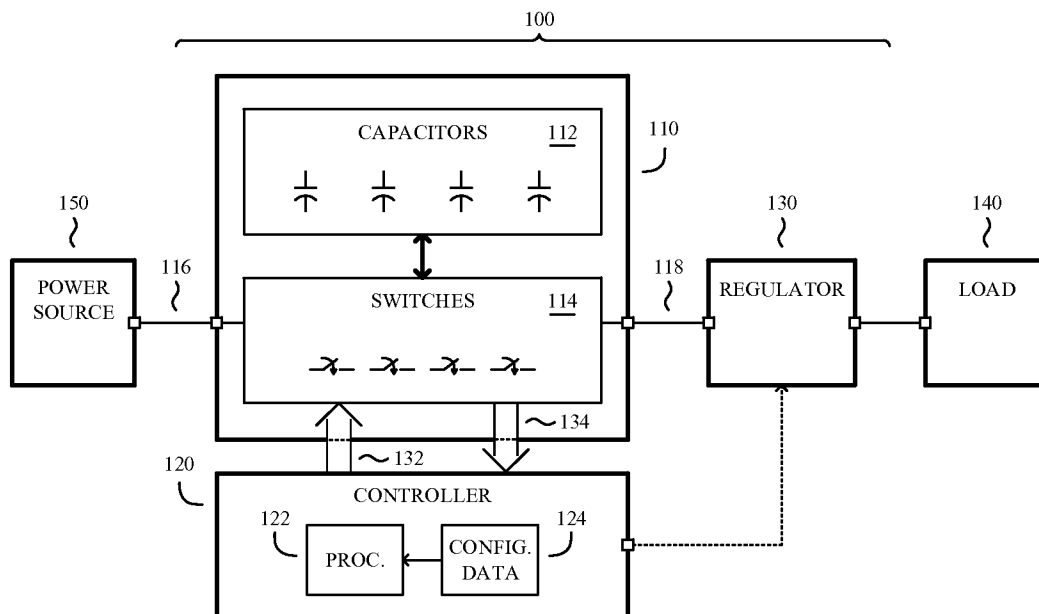


FIG. 12

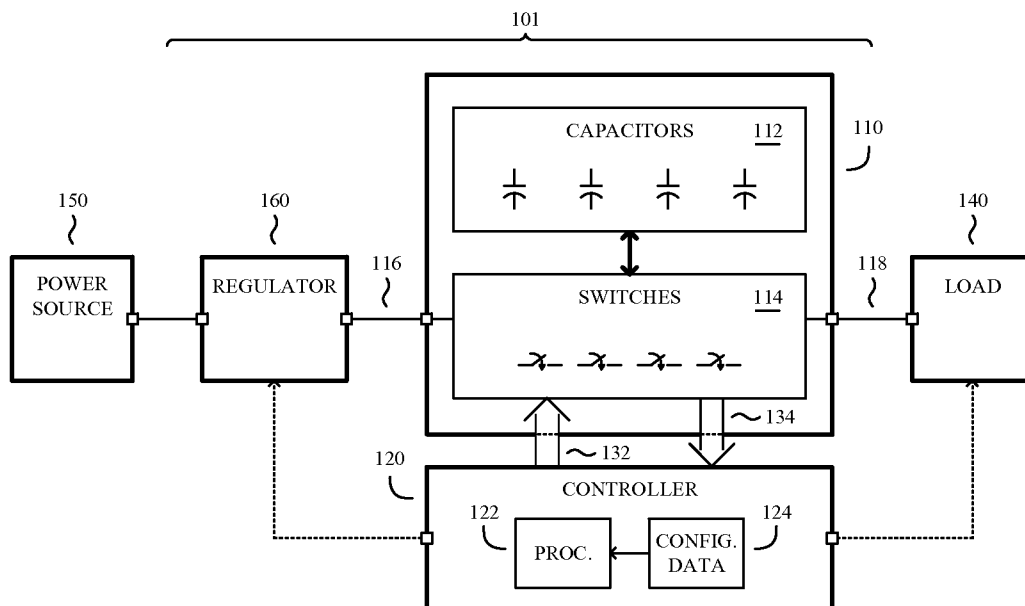


FIG. 13

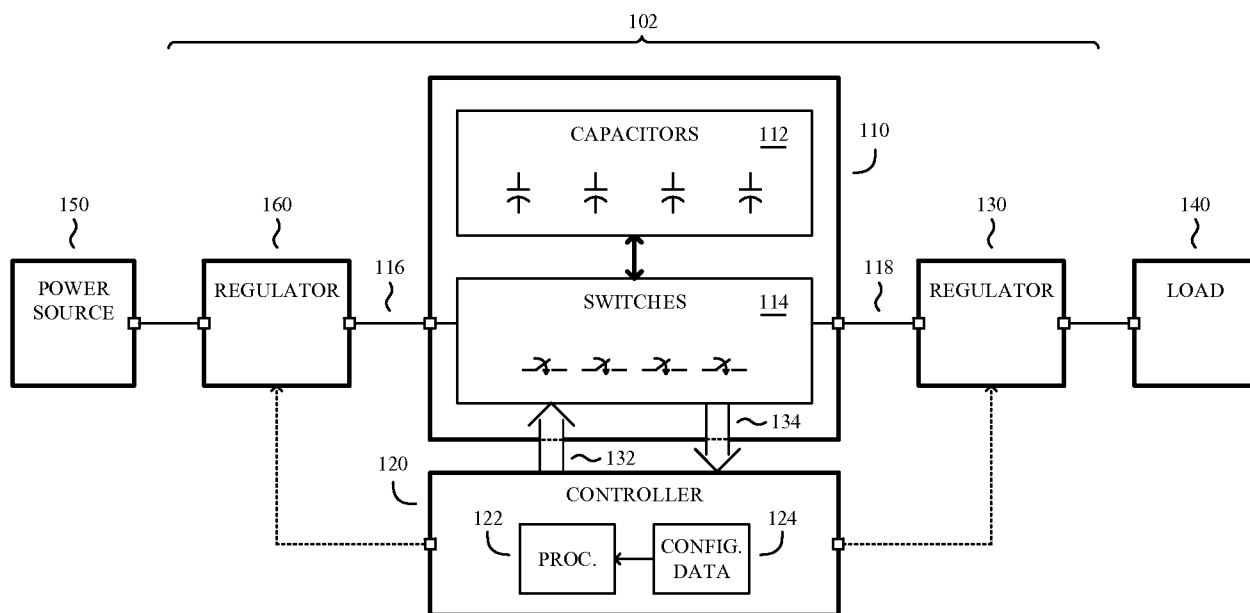


FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/019579**A. CLASSIFICATION OF SUBJECT MATTER****H02M 3/07(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 3/07; G09G 3/36; H02M 3/18; G05F 1/10; H01L 27/04; G02F 1/133

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: circuit, controller, charge pump, switch, cycle, states, balancing, voltage, capacitor, filter

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 8503203 B1 (ARCTIC SAND TECHNOLOGIES, INC.) 06 August 2013 See abstract, column 5, line 16-column 7, line 41 and figures 3-4.	1-3, 22-25, 27-28 , 47-50
Y	ALON CERVERA et al. 'A high efficiency resonant switched capacitor converter with continuous conversion ratio.' In: Energy Conversion Congress and Exposition (ECCE), IEEE, 15-19 Sept. 2013, pages 4969-4976 See abstract, pages 4969-4973 and figures 1-6.	1-3, 22-25, 27-28 , 47-50
Y	US 2013-0069614 A1 (CHUNG-HSIEN TSO et al.) 21 March 2013 See paragraphs [0034]-[0039], claims 1-7 and figures 6-8.	22-25, 28, 47-50
A	JP 2006-067783 A (SANYO ELECTRIC CO., LTD.) 09 March 2006 See paragraphs [0008]-[0018], claims 1-4 and figures 1-3.	1-3, 22-25, 27-28 , 47-50
A	KR 10-2011-0061121 A (LG DISPLAY CO., LTD.) 09 June 2011 See abstract, paragraphs [0021]-[0043] and figures 1-3.	1-3, 22-25, 27-28 , 47-50

☐ 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

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

18 June 2015 (18.06.2015)

Date of mailing of the international search report

19 June 2015 (19.06.2015)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/019579

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 6-11, 18-20, 26, 34-37, 40-43
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claims 6-11, 18-20, 26, 34-37, 40-43 refer to multiple dependent claims which do not comply with PCT Rule 6.4(a).

3. ☒ Claims Nos.: 4-5, 12-17, 21, 29-33, 38-39, 44-46
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/019579

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 8503203 B1	06/08/2013	WO 2014-062279 A1	24/04/2014
US 2013-0069614 A1	21/03/2013	KR 10-1328882 B1	13/11/2013
		KR 10-2013-0029712 A	25/03/2013
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JP 2006-067783 A	09/03/2006	CN 1728518 A	01/02/2006
		KR 10-0682006 B1	15/02/2007
		US 2006-0028849 A1	09/02/2006
		US 7468898 B2	23/12/2008
KR 10-2011-0061121 A	09/06/2011	None	